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ANALYTICAL APPROACHES WITHIN THE ASSESSMENT STRATEGY OF NUMERICAL ANALYSES OF COMPONENTS OF RAM PACKAGES

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ABSTRACT

Load attachment points, consisting of the lifting component and corresponding bolt connections, and lid systems, consisting of a lid, gaskets and bolt connections, are usually analyzed numerically using the Finite Element Method. Reasons for applying the FEM are complex geometry, specific load distribution and the violation of application criteria for analytical approaches. For example the elementary beam theory is not suitable for the calculation of compact trunnions and the Kirchhoff plate theory is not suitable for the calculation of lids with a large thickness to diameter ratio because the Bernoulli-hypothesis is violated. In addition for structural integrity assessments often local stress and for the evaluation of lid systems tightness local contact opening are needed, which can be obtained only through accurately discretized numerical models.

Independent comparative calculations are essential for complex calculations. Simplified but appropriate analytical approaches are an efficient way of examination. Is it possible to provide conservative analytical estimates of such kind of analysis problems? Are analytical calculations an appropriate approach in today's authority assessment business? Using the example of bolted trunnion and lid systems of a heavy package the possibilities and limits of analytical comparative calculations are shown.

INTRODUCTION

The transport of packages for radioactive materials is regulated to fulfill national and international safety requirements. The compliance with the regulations can be shown 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 local concepts of 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 simple analytical approaches. Such approaches can be helpful to support verification and validation 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 safety with the regulatory requirements [1]. A global structure for the PDSR (documented by the applicant) is given in the European guideline [4]. But specific, detailed analyses and safety cases are not defined in general. Therefore BAM prepared specific guidelines to explain and define detailed demands and requirements to the package design safety analyses. The guideline BAM-GGR 008 [5] should be used for numerical analyses; BAM-GGR 012 [7] describes the assessment approach for bolted lid and load attachment systems. But in general the properties of each packages component and its safety related requirements define the scope of analysis in design and assessment phases.

Analytical and numerical calculations

Depending on safety relevance of the package component, its material properties and loading conditions the strength analysis can be based on local or nominal values. In general the design of complex components according to the local concepts requires extensive numerical calculations with increased verification and validation efforts. In such a case simplified analytical approaches can provide only a rough idea about component behavior and can be used only for a plausibility check of the numerical results. Some examples for application range of analytical and numerical calculations are shown in Table 1.

Table 1: Application range of analytical and numerical calculations

<table>
<tr><th>Values to calculate</th><th>Analytical</th><th>Numerical</th></tr>
<tr><td>Nominal stresses in cask components under transport conditions</td><td colspan="2">Limited, depending on the properties (geometry, material) and loading of the investigated component</td></tr>
<tr><td>Local stresses in cask components under transport conditions</td><td>Limited, inaccurate</td><td>Yes</td></tr>
<tr><td>Pretension of bolts</td><td>Standard</td><td>Not practicable: high modeling effort</td></tr>
<tr><td>Pretension changes due to temperature and relaxation</td><td colspan="2">Yes</td></tr>
<tr><td>Nominal stresses in bolts under transport conditions</td><td>Limited</td><td>Yes</td></tr>
<tr><td rowspan="2">Local stresses in bolts under transport conditions</td><td>No</td><td>Not practicable: high modeling efforts</td></tr>
<tr><td colspan="2">Lack of any adequate assessment concepts</td></tr>
</table>

Component classification grade

In addition to the packaging component properties, the safety requirements depending on safety objectives and the corresponding degree of utilization define the effort of design and assessment. The guideline BAM-GGR 011 [6] is used for classification of safety relevant requirements in Germany. 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. But 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. The analysis depth increases with a higher safety relevance of the component:

- 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)

Effort of design and assessment strategies

The following diagram 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.

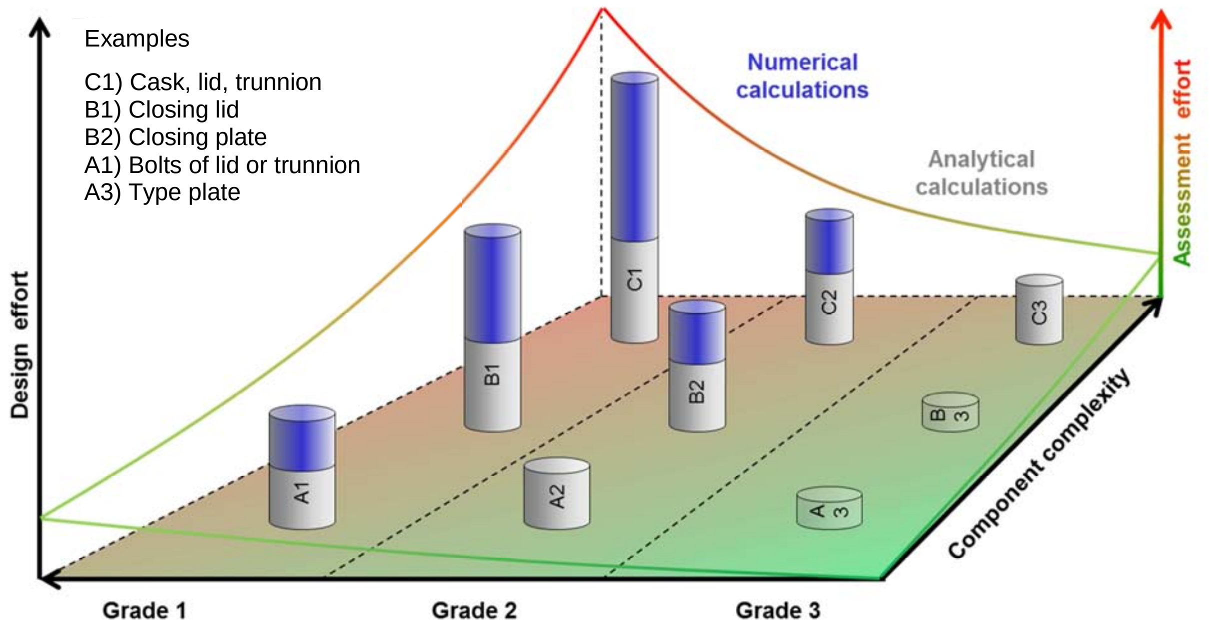


Figure 1: Main influences on effort for design and assessment

As before the safety relevance classification grade of a component, the complexity of a component can be divided into three grades (Fig.1, A: not complex, C: very complex). Some examples of components lying at intersections of both influence factors are indicated. Thereby 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 experiences show that the effort for the assessment phase is increasing in the same way as for the design from A3 to C1.

Therefore it is necessary to search for optimization possibilities in the assessment procedures, especially concerning the numerical part, but without impairing the safety requirements.

As shown, both design calculations and assessment of their results for complex and safety relevant components 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.

ANALYTICAL APPROACHES FOR COMPARATIVE 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 certain basic structure and 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.

It is important to be aware of application limits of the mechanical theories. If an application limit is exceeded moderately, the results of the analytical recalculation can still be used to assess the magnitude of the numerical results.

EXAMPLES

The following examples concentrate mainly on bolted joints, which have found wide use in packages for transport of radioactive material 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 loading. The methodical aspects of FE modelling and corresponding assessment concepts for lid and trunnion systems are discussed in [11] and [12]. In this paper some possibilities and limits of analytical approach in plausibility check of numerical analyses are considered.

Bolt connection under lid displacement

In the first example the bolt loading due to lateral displacement of the clamped plate are considered (figure 2). Such loading can occur in the lid connection under horizontal drop conditions or in bolted trunnion 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 M30x120) 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 bolt pretension of 200 kN is applied. 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.

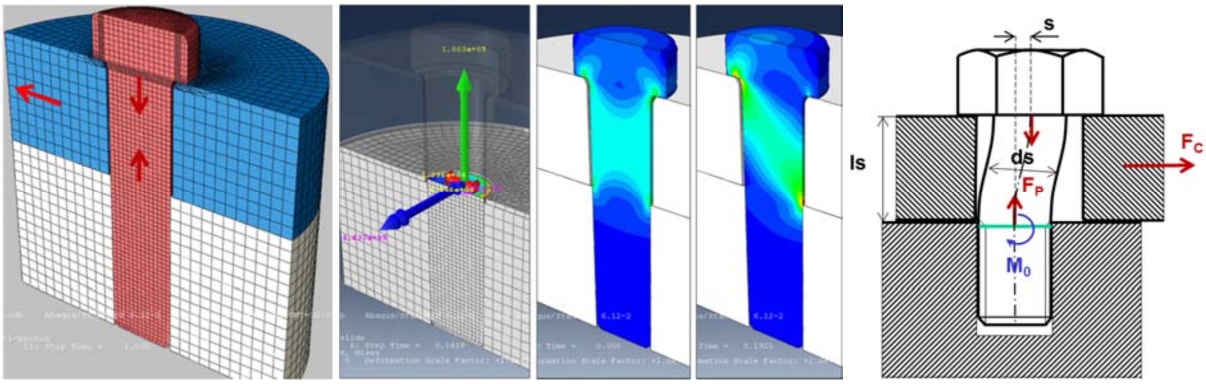


Figure 2: Models and numerical results for bolt bending due to lid displacement

As a preliminary the relationship of the classical (Bernoulli) beam theory were chosen for analytical estimations (table 2). Geometrical and structural properties are equal to the numerical model.

Table 2: Analytical equations for screw bending

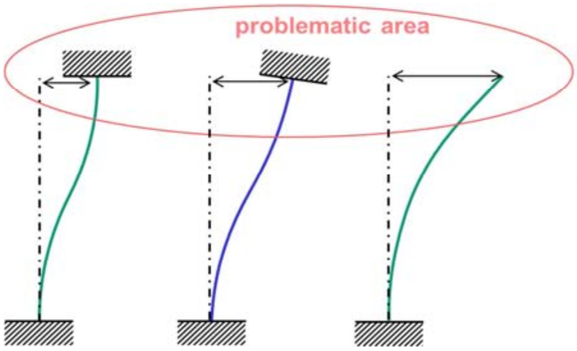
Lateral force	Max. displacement of bolt head	Bending moment due to Fp	Bending moment due to Fc	Pretension stress	Bending stress
$F_C = F_P * \mu$	$s = \frac{F_C * ls^3}{12 * E * I}$	$M_{0s} = \frac{F_P * s}{2}$	$M_{0l} = \frac{F_C * ls}{2}$	$\sigma_P = \frac{F_P}{A_s}$	$\sigma_M = \frac{M_0}{W_s}$

Relevant values for bolt bending due to plate displacement are listed in table 3 to compare analytical and numerical results. The results obtained by the two methods are in close agreement except the displacements of bolt head. This deviation has two reasons. On the one hand the bolt head rotated slightly in the numerical simulation, like in reality.

Table 3: Comparison of analytical and numerical results for bolt bending

Value	Numerical		Analytical	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 rotation was not considered in the simple analytical approach (figure 3). Furthermore the bolt diameter to length ratio (1:1.6) is beyond of the scope of the Bernoulli theory (<1:5). The correction of beam stiffness by taking into account the shear stress effect (in the following Timoshenko beam) should be carried out.



Screw head displacement in mm

Theory / BC:	fixed	undefined	free
Bernoulli	0,044		0,177
Timoshenko	0,081		0,212
FEM		0,110	

Figure 3: Analysis of undefined boundary conditions

The calculations corrected for these effects show that the numerical result of displacement lies between the analytical results for fixed and free bearing. Furthermore this example shows clearly the importance of a deliberated choice of analytical approach for checking 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 bolt connections M42 respectively M36 and a cask cutout. 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 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.

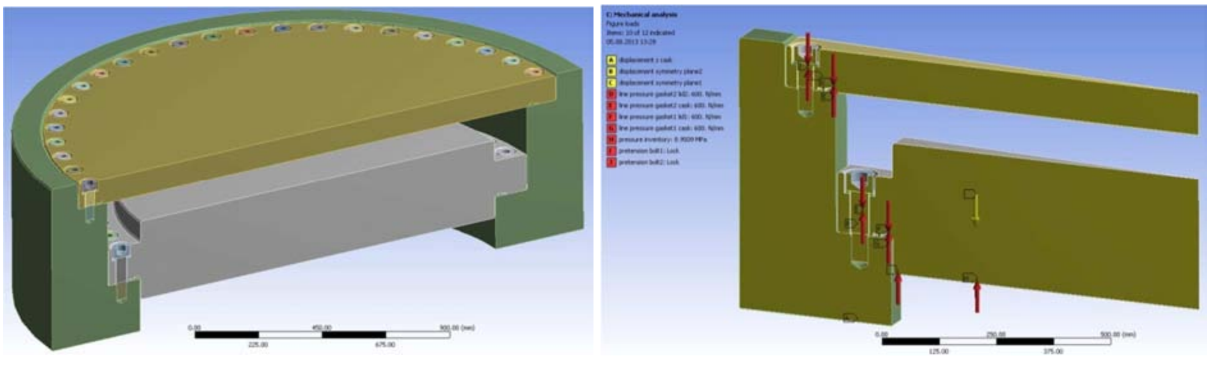


Figure 4: Lid system, discretized slice

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 figure 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. In the other contact pairs friction conditions are defined. 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. The figure 5 shows the results of the finite element calculation.

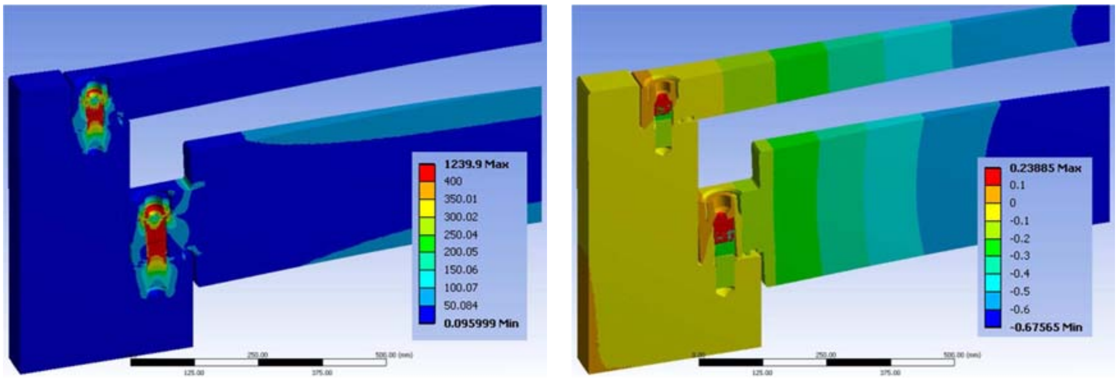


Figure 5: FE results: equivalent stress [MPa], deformation [mm] in vertical direction

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:

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

Herein r is the radius, 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 jump 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 bolt connection, the second for a light-duty connection.

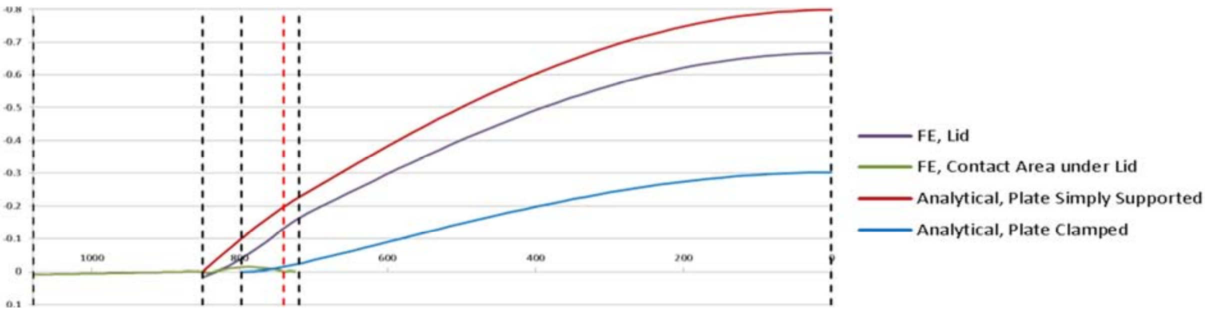


Figure 6: Comparison results, primary lid deformation [mm] in vertical direction

In figure 6, the numerical and analytical results for 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 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: reduction of trunnion to the basic mechanical structures like beam or closed circular rings is very questionable. The complex stress field (figure 7) under operational load can be adequately investigated only by numerical approach as requested in [7].

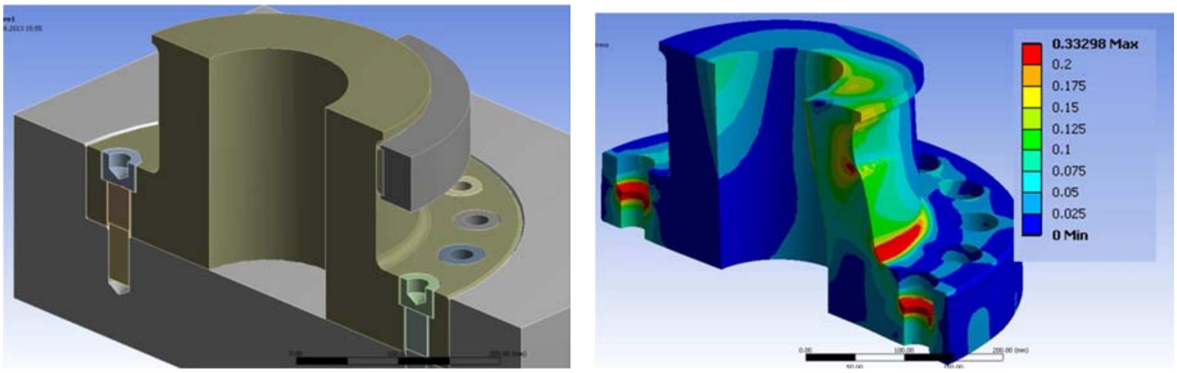


Figure 7: Numerical model of a trunnion

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

Effort for component design 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. Therefore it is necessary to search for optimization and support possibilities of the assessment, especially in the numerical range, but without impairing the safety requirements.

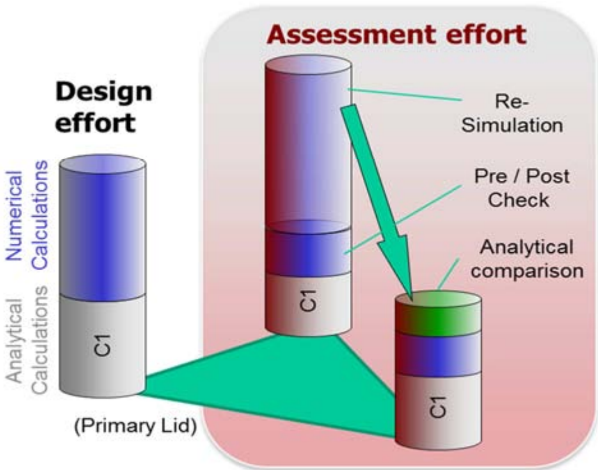


Figure 8: Schemata of assessment optimization

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. But there are still more possibilities like standardization and intensive data exchange, as well as the application of new methods for numerical calculations which helps the assessment. The present paper describes the use of analytical approaches within the assessment strategy of numerical analyses. With three examples it has been shown which possibilities and limits exist to support the assessment of numerical analyses using analytical comparative calculations.

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. Bolt-lid example showed the influence of component and boundary stiffness on the results. Thickness to length ratio was higher than specified in the theories and for the boundary only fixed or free conditions could be analyzed analytical. Nevertheless the analytical approaches could help to evaluate the numerical results for the assessment. The example of a trunnion analysis showed a complex deformation behavior and local reactions and shows where approach limits exist. 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 useable but often effective to reduce the effort of assessment.

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