METHODOLOGICAL ASPECTS FOR NUMERICAL ANALYSIS OF LID SYSTEMS FOR SNF AND HLW TRANSPORT PACKAGES

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ABSTRACT

The regulatory compliance of the containment system is of essential importance for the design assessment of Type B(U) transport packages. The requirements of the IAEA regulations SSR-6 for accident conditions of transport implies high load on the containment system. The integrity of the containment system has to be ensured under the mechanical and thermal tests.

The containment system of German transport packages for spent nuclear fuel (SNF) and high level waste (HLW) usually includes bolted lids with metal gaskets. BAM Federal Institute for Materials Research and Testing as the German competent authority for the mechanical and thermal design assessment of approved transport packages has developed the guideline BAM-GGR 012 for the analysis of bolted lid and trunnion systems. According to this guideline the finite element (FE) method is recommended for the calculations. FE analyses provide more accurate and detailed information about loading and deformation of such kind of structures. The results allow the strength assessment of the lid and bolts as well as the evaluation of relative displacements between the lid and the cask body in the area of the gasket groove.

This paper discusses aspects concerning FE simulation of lid systems for SNF and HLW transport packages. The work is based on the experiences of BAM within safety assessment procedures. The closure system of a generic cask is modeled to analyze its behavior under the mechanical load complying with IAEA regulatory accident conditions of transport. The issues considered include modeling strategies, analysis techniques and the interpretation of results.

GENERAL ASPECTS OF NUMERICAL ASSESSMENT OF LID SYSTEM

Type B(U) packages for transport of spent nuclear fuel (SNF) and high level waste (HLW) mostly consist of thick-walled cylindrical shells with plane bottoms. The containment of Type B(U) packages used in Germany for transport and interim storage is closed by two bolted lids (primary and secondary lid)*. According to IAEA regulations SSR-6 [1] the containment system has to fulfill the activity release criteria under specified routine, normal and accident conditions of transport (RCT, NCT and

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*Double barrier system is implemented in Germany due to interim storage requirements. Only one barrier is necessary for the transport condition.

ACT). The limitations for activity release will be ensured by the integrity of the containment and the tightness of the lid system.

A lid system (or a barrier) consists of the lid, covers for openings in the lid, bolts, the corresponding cask area (flange) and metallic or elastomeric gaskets. Usually, two gaskets are located in special grooves on any lid and cover: the inner metallic gasket with aluminum or silver outer jackets to ensure long-term leak tightness, and the outer elastomeric gasket for testing reasons mainly.

Demonstration of leak tightness is typically provided by a combination of analyses, drop tests, and gasket performance tests. In this paper some aspects of numerical analysis of a lid system are discussed with respect to guideline BAM-GGR 012 [2, 3] developed by BAM Federal Institute for Materials Research and Testing. The guideline gives advices for load assumptions, use of analysis methods and assessment criteria for numerical analyses of bolted lid and trunnion systems.

LOAD ASSUMPTIONS AND ANALYSIS METHODS

At first, the assembly state of the bolted connection should be calculated. During the lid assembly, the gasket is compressed until contact of the flange surfaces is achieved. Further tightening leads to additional preload (pretension) in the bolts, which is balanced by the clamp load on the lid flange. Increasing the preload after the contact in the flange is achieved does not change the gasket compression practically. The pretension in the lid bolts has an essential influence on the sealing function. There is a considerable scatter in the bolt pretension by an appointed torque because of the dispersion of friction conditions at the threads and under the bolt heads as well as an imprecise bolt tightening technique. Thus, it must be ensured that the necessary compression of the gasket is achieved under this dispersion, but the bolts also have sufficient strength reserves to resist all external loads under specified conditions of transport (RCT, NCT, and ACT). According to BAM guideline [2], the minimum pretension in the lid bolts has to prevent impairment of the sealing function under routine transport conditions. The criteria for the maximum pretension are shown in Table 1, where σ_v is the effective (von Mises) stress in the bolts and $R_{p0.2}(T_0)$ is the 0.2% proof stress of the bolts material at room temperature. Specific load situations under accident conditions for large cask lids and small covers for openings in these lids are the reason for different assembly criteria. The interaction with the content or shock absorber has to be taken into account for large cask lids, whereas the covers for openings are generally only loaded by their own inertia forces.

While the calculations for the assembly state are based on the well-known analytical approach [4], the FE analysis is recommended in [2] for the investigation of the lid system under transport conditions. Depending on the objective of evaluation as well as on the amount of experimental data for the verification of the numerical analysis, the dynamic or quasi-static FE approaches can be applied.

The main loads acting on the lid system are the inertia loads and the interior pressure. The inertia load assumptions for RCT defined as maximum acceleration levels depending on transport mode (road, rail, sea, air) are available, e.g. in Annex IV of the IAEA Advisory Material TS-G-1.1 [5]. The load assumptions for NCT and ACT depend on cask design and have to be determined in each specific case. The inertia loads can be derived from drop test results and/or by appropriate analyses.

Although the drop tests according to NCT and ACT are typical dynamic problems, it is quite common to use a quasi-static approximation in the mechanical analysis of the lid system under these conditions. The need of numerous input data for an adequate simulation of the drop tests is one of the main complexities of the dynamic approach. The material model describing the behavior of the wood filled shock absorber can be mentioned as an example of the specific problems in dynamic FE calculations. This material model should have the ability to describe the softening of wood, which occurs, e.g. by loads in parallel to the fiber. If such model works numerically stable, its material parameters will have to be determined. It is unlikely that the needed parameters may be derived directly from the experimental data [6]. Rather, the material properties are determined by use of an optimization tool solving the inverse problem. Additionally an exhaustive set of parameters would be required to cover rate-dependent effects. The dynamic FE model would also include the cask internal components, e.g.

basket and fuel assemblies with consideration of all their physical characteristics necessary to describe the impact response. Due to the time increment's dependency on the characteristic element length for the explicit formulation of a globally modeled solution means high numerical effort to obtain detailed information on stresses.

From the above, it is obvious that the generation of a complex dynamic model for a specific design would be a time consuming and expensive process. Therefore, the quasi-static approach is often used as an alternative way with possibilities to reasonable reduction of modeled components. Such a quasi-static model usually considers an acceleration field based on the calculation carried out by a simplified (analytical or numerical) tool. The necessary prerequisite is the verification of this tool by experimental data. The quasi-static model can appropriately include details like bolt pretension, reaction force of the gasket, inertial loads due to cask content, internal and external pressure or pre-calculated deflection of the lid. However, the quasi-static approach gives rise to disadvantages as well. The constant and homogenous acceleration field can often be the source of unrealistic results. On the other hand the dynamic effects like internal impacts (multiple-mass effect [7]) are not included directly and have to be considered by extra load factors or similar substitutes. The bounded nature of the load assumptions in the quasi-static analysis has always to be ensured.

ASSESSMENT CRITERIA

The FE calculations provide local stresses over the entire component structure. To avoid lid deformations which can impair the sealing function, the assessment criteria for lids are defined in [2] for local values of stress. In general the assessment against local plastic deformation is successful if the condition $\sigma_v \leq R_{p0.2}(T_{max})$ is fulfilled ($R_{p0.2}(T_{max})$ is the 0.2 % proof stress of the lid material at operating temperature). In case this criterion is violated, additional considerations regarding the effect of plastic deformation on the sealing function are necessary. It should be noted that the assessment of safety against brittle fracture is not a subject of the guideline BAM-GGR 012 [2]. The need of brittle fracture assessment and the corresponding criteria depends on the material of the lid. In particular for lids made of ductile cast iron the guideline BAM-GGR 007 [8] has to be applied in Germany.

Owing to their simple rod shape, it is reasonably to apply the nominal stress concept for strength assessment of bolts. BAM guideline [2] recommends transforming local stresses in the bolts from FEA into nominal ones; hence, the following analysis can be performed according to the well-known VDI 2230 guideline [4]. Axial forces and bending moments derived from the nodal forces for each section along the clamping length of the stressed bolt should divided by the section area and section modulus to obtain the nominal tensile and bending stresses. The assessment criteria for the nominal stress are listed in Table 1. The criteria are different for the bolt material having a limited ductility (value in brackets).

In addition to the strength assessment of the bolts and lids, the deformations or displacements of cask components under the regulatory IAEA transport conditions and their effect on the sealing function can be analyzed and assessed by means of FE calculations. With respect to the gasket, a multiple compression and repositioning have to be considered for the axial loads on the lid (e.g. vertical drop position). Due to radial loads on the lid (e.g. horizontal drop position), a sliding of the lid onto the cask gasket surface can occur. The numerical analysis provides results for the possible change of the lid position under loads associated with transport conditions (opening or sliding of lid) in relation to the assembly state of the lid system. To assess the sealing function and to verify the design leakage rate these results have to be compared with the experimental results from drop tests or correspondent component tests [3, 9].

SELECTED POINTS OF MODELING STRATEGY

The assessment criteria mentioned above govern the grade of accuracy for the FE modeling of the components of the lid system. If not only the global response of the lid but also the local stress values are necessary (e.g. for brittle fracture analysis), the geometry of the model has to consider the

technological orifices with their covers and the FE mesh should guarantee reliable results for the local stress values.

As mentioned above, the calculation of nominal stresses in the lid bolts is based on axial forces and bending moments. They should be derived from the nodal forces for each section along the clamping length. Therefore the FE model has to ensure the reliable results for the nodal values. Obviously the details of the bolt shape, which determines its elastic resilience, have to be modeled appropriately to accomplish this objective. Due to the bending dominated deformation of the bolts an element formulation should be used which is not affected by shear locking. Thus fully integrated element formulations with linear shape functions should be avoided.

Table 1: Assessment criteria for the bolts of lid systems according to [2]

	Assembled state	Routine conditions of transport	Normal and accident conditions of transport
Primary lid, secondary lid, orifice lids with load caused by the content	$\sigma_v \leq \dfrac{R_{p0.2}(T_0)}{1.5}$	$\sigma_v \leq \dfrac{R_{p0.2}(T_{\max})}{1.1}$ $\sigma_z \leq \dfrac{R_{p0.2}(T_{\max})}{1.5}$	$\sigma_v \leq R_{p0.2}(T_{\max})$ $\sigma_z \leq \dfrac{R_{p0.2}(T_{\max})}{1.1}$ $\left[\sigma_z \leq \dfrac{R_{p0.2}(T_{\max})}{1.5}\right]$ †
Orifice lids without load caused by the content	$\sigma_v \leq \dfrac{R_{p0.2}(T_0)}{1.1}$	$\sigma_v \leq \dfrac{R_{p0.2}(T_{\max})}{1.1}$ $\sigma_z \leq \dfrac{R_{p0.2}(T_{\max})}{1.1}$	$\sigma_v \leq R_{p0.2}(T_{\max})$ $\sigma_z \leq \dfrac{R_{p0.2}(T_{\max})}{1.1}$

Different FE contact formulations may be used for the contact areas between lid and cask respectively bolt and lid. The frictional penalty formulation generally shows good convergence with sufficient accuracy. Contact penetrations have to be checked after the simulation. These values are assessed with respect to the upper limit of the lid opening in the gasket area.

The metallic gaskets which are used for Type B(U) packages show a reaction force under compression which has to be considered in the FE model. A conservative approach is to apply the maximal gasket force as a constant load. A more accurate modeling can be achieved by using pre-stressed springs with nonlinear characteristics based on the behavior of the gasket [3] or by using of special gasket elements [10]. In any case, the reaction should not be modeled with linear forces in the gasket area. Linear forces cause mesh dependent results for the displacements. This is not recommended with regard to the small displacements which are used to assess the maximum opening of the gasket.

CALCULATION RESULTS AND ANALYSIS OF MODEL ASSUMPTIONS

In this section FE models are presented to illustrate the analysis of the generalized primary lid system of a Type B(U) package for two typical load cases. The first quasi-static model is used to evaluate effects of the 9 m vertical drop. The lid system under the conditions of the 9 m lateral drop is analyzed by the second quasi-static model. Furthermore, the quasi-static and simplified dynamic approaches for the lid system during the 9 m drop in vertical position are discussed. All models consist only of components essential for this exemplary assessment. The orifices of the primary lids are not taken into account. The groove in the lid for the metallic gasket is modeled whereas the one for the elastomeric gasket is neglected. The reaction forces of both gasket types are considered conservatively by applying

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†criterion for bolts with high yield ratios, e.g. of strength grade 10.9

the maximum gasket forces as constant loads. The pretension of the bolts is applied by pretension elements in the center cross section of the shanks.

The modeling and the calculations are performed with the FE-Code ANSYS [12] and LS-DYNA [13]. ANSYS was used for the implicit quasi-static analyses. LS-DYNA serves for the explicit dynamic calculations.

The ANSYS models are meshed mainly with fully integrated hexahedral elements based on quadratic interpolations. Tetrahedral elements with quadratic shape function are used in the lid and cask areas not relevant for the stress analysis. To limit the number of degrees of freedom small element sizes are only used in area of the gasket and for bolts. A coarse discretization is applied for the remaining parts, without affecting the deformation behavior of the system. The thread of the bolts is not modeled and the thread areas of the bolts and bolt holes in the cask body are bounded with a tie contact. The contact surfaces between lid and body respectively lid and bolts are considered with a frictional penalty formulation.

The quasi-static calculations are divided into three load steps. In the first one, the assembly state of the lid system including the pretension of the bolts and the reaction forces of the compressed gasket is simulated. In the second step the external loads are applied. The unloading (removal of the external loads) is done in a third step to detect any irreversible changes in the lid system, if occur. The external loads are derived as the inertia loads based on the defined acceleration values. Calculations for minimum and maximum pretension were performed. The nominal stresses which are required for assessment according to the nominal stress concept [2] are estimated in each cross section along the clamping length of the bolt for each load step. To do this, the nodal forces of every element per section are integrated to get the resulting normal force and bending moment.

A similar modeling strategy was applied in the simplified dynamic approach but the LS-DYNA models were meshed with linear reduced integrated hexahedral elements using hourglass control. Some other details of the dynamic calculations will be described in the corresponding section.

Vertical drop position

Due to the symmetry of the situation to be analyzed, the quasi-static model for the load case of the vertical drop position considers a circular sector containing one bolt, see Figure 1. Distributed point masses on the inner surface of the lid and the cut face of the cask wall represent the mass of the cask content and the omitted part of cask body respectively. The appropriate boundary conditions are set by symmetry faces. The lower surface of the cask wall is fixed in all directions. The external load is applied incrementally by a vertical acceleration until $a = 100\,\mathrm{g}$ is reached. A linear elastic material behavior is assumed for all components in this calculation example. The mesh consists of 20000 elements with 75000 nodes.

The nominal average tensile stresses in the bolt along its clamping length are plotted in Figure 2. The red line indicates the margin value according to [2] for bolts of strength grade 10.9. The stresses for minimum and maximum pretension are constant along the length because the bolts are assumed with constant cross section for simplicity. The nominal equivalent stresses take into account the whole response of the bolt under the external loads (incl. bending) and the torsional stress as result of tightening torque additionally. The torsional stress is not considered in the FE model and has to be calculated separately as recommended in [4]. For the equivalent stresses a linear distribution can be noticed, which is reasoned by the bending of the bolt. The maximum values occur under the head of the bolt. The stresses shown in Figure 2 result from acceleration of 65 g applied statically to the modeled components (incl. cask content) as gravitational field. As noted above, to use such an approach in the safety analysis package, the bounded nature of the applied value for possible dynamic effects has to be validated.

Another aspect, which can be evaluated on the basis of the quasi-static method, is the evolution of the bolt stresses with increasing of the applied acceleration. Figure 3 shows the plot for maximum tensile and equivalent stresses in the bolt. The margin values according to [2] are marked by red lines. The
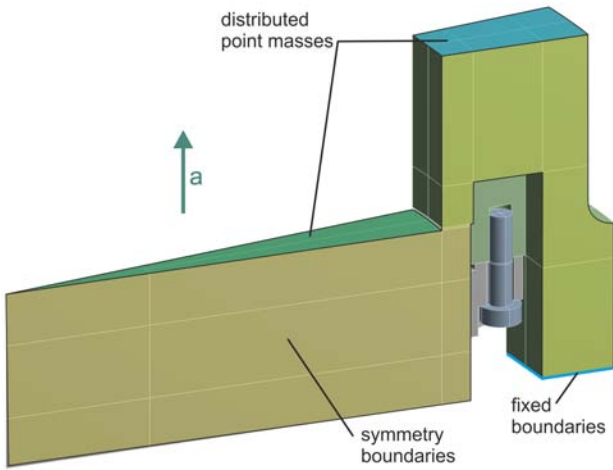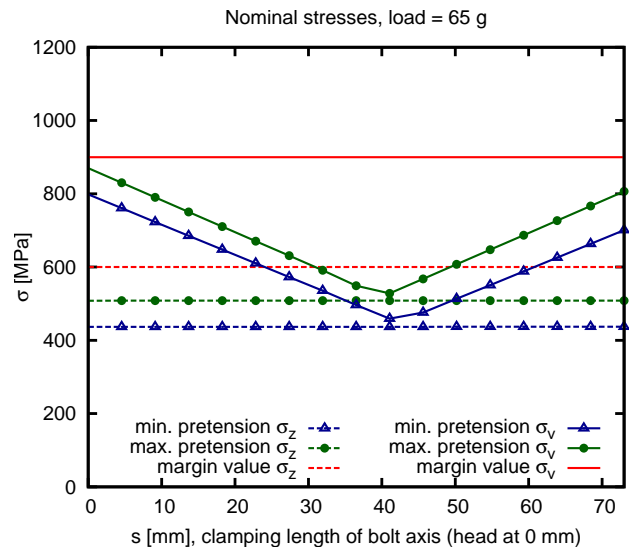
Figure 1: FE-Model used for the vertical drop position

Figure 2: Vertical drop position, nominal stresses in the bolt under a load of 65 g
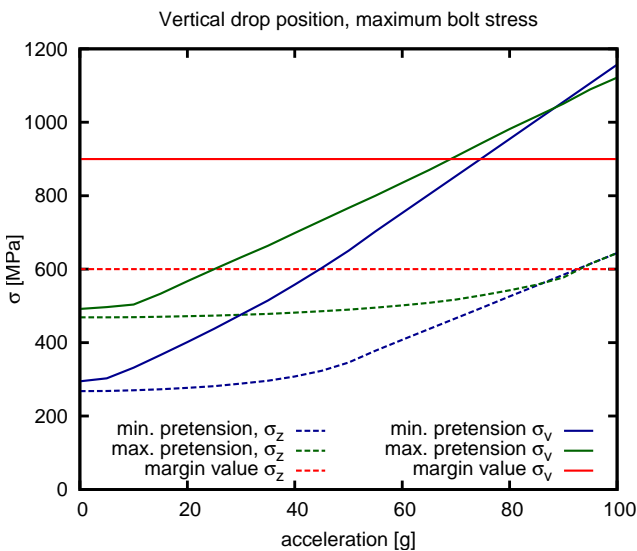

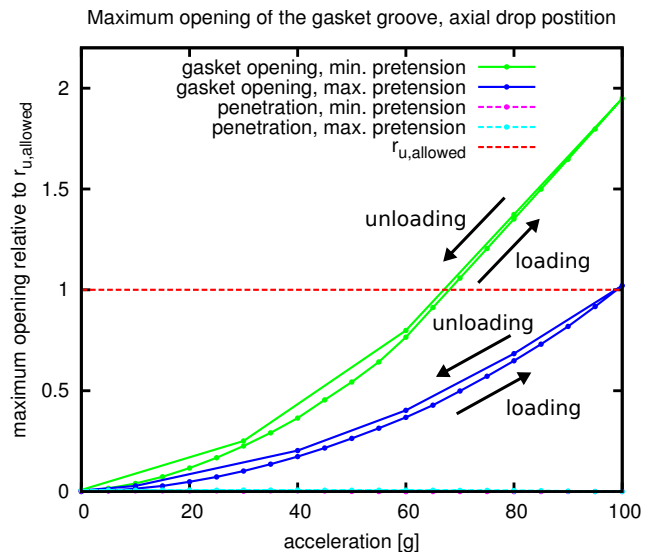**Figure 3:** Vertical drop position, maximum nominal stresses versus load

Figure 4: Vertical drop position, opening of the gasket groove

plots allow assessing the sensitivity of the bolt loadings with respect to the requirements of [2]. Here, the nominal equivalent stress for maximum pretension is the decisive load case. The criteria for σ_v is reached at a load level of 69 g while the criteria for σ_z is reached at a load applied of 94 g.

A similar analysis can be performed for the evolution of the relative axial displacement between the lid and cask flange in the area of the gasket groove (opening). A bi-linear elastic-plastic material model is used for this analysis. Figure 4 shows the opening for the maximum and minimum pretension with respect to the acceleration applied. The opening is plotted relatively to the margin value $r_{(u,allowed)}$. The unloading step is depicted, too. The remanent opening, if occur, has to be evaluated together with the opening in the fire test in cumulative assessment. However, a temporary exceed of the margin value leads to an increased leakage rate, which has to be considered for the assessment of activity release. The design leakage rates can be deduced from tests with mockup casks, cask models or cask components [9].

A further aspect in this context is the maximum penetrations which occur at the contact surfaces. The penalty contact formulation allows limited penetration into the contact surfaces. The amount of the penetration depends on the penalty stiffness. A high value reduces the penetration at the expense of the
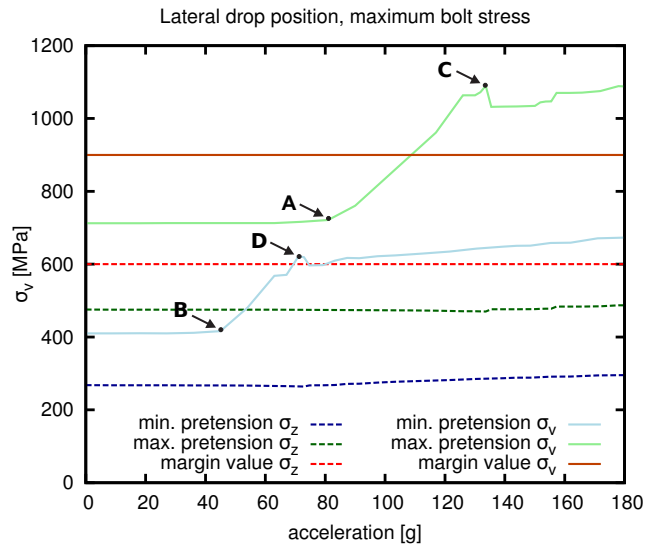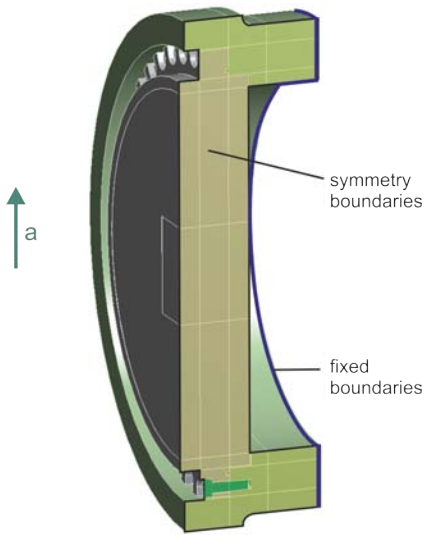
Figure 5: FE-Model used for the lateral drop position

Figure 6: Lateral drop position, maximum nominal stresses versus load

convergence behavior during the solving process. It can be noticed that the penetrations are generally low in comparison with opening in the gasket area. Thus, the maximum penetration for maximum pretension is with $0.93\,\mu m$ for the unloaded system in the same range as the remanent opening of $2.83\,\mu m$. Here, the assessment of the remanent openings would have to consider this numerical effect.

Lateral drop position

The quasi-static FE model shown in Figure 5 is proposed for the analysis of the generalized primary lid system during a 9 m drop in lateral drop position. Owing to symmetry of geometry and loading a half model is used. The model has 22.5 bolts (one bolt is cut by the symmetry plane). The boundary conditions are specified in Figure 5. The inertia load is applied incrementally until a vertical acceleration $a = 180\,g$ is reached. The maximum applied acceleration ensures a maximum sliding of the lid limited by the contact between the outer surface of the lid and inner surface of cask. The friction coefficient is set to 0.1 for the contact between lid and cask body and 0.15 between bolt and lid. A linear elastic material model is used. The mesh consists of approx. 250000 elements with 860000 nodes.

The maximum tensile and equivalent stresses in the bolts with respect to the acceleration applied are depicted in Figure 6. It can be noticed that the tensile stress is nearly constant during the whole load step. The criteria for σ_z is not reached and not decisive for the strength assessment. The plot of the maximum equivalent stresses show that the lid does not move at an acceleration applied below the points marked by **A** for maximum pretension and by **B** for minimum pretension in the bolts. Thus no bending in the bolts occurs and the values for σ_v remain constant on the level induced by the bolt pretension. By exceeding the load above the points **A** or **B** the lid starts to slide against the cask body. The frictional contact forces between lid and bolts induce bending of the bolts. The values of σ_v increase until the lid start to slide below the heads of the bolts. These points are marked by **C** and **D**. The lid slides until its outer surface hits onto the inner surface of the cask. This movement is linked with a slight decrease of σ_v. The results beyond **C** and **D** are not interpreted since dynamic effects cannot be neglected after the slide of the lid. The decisive load case for the lateral drop position is the nominal equivalent stress with maximum pretension. The criteria for σ_v is reached at a load level of $110\,g$ while the criteria for σ_z is not reached during the calculation. As well as being the reason of the bolt bending, the sliding of the lid affects also the gasket and can lid to increasing of the leakage rate. The values of design leakage rates for activity release considerations have to be deduced from tests with mockup casks, cask models or cask components [9].
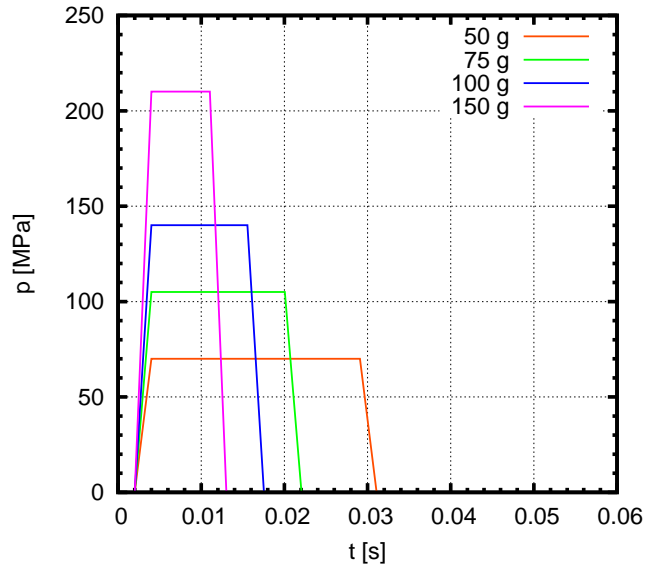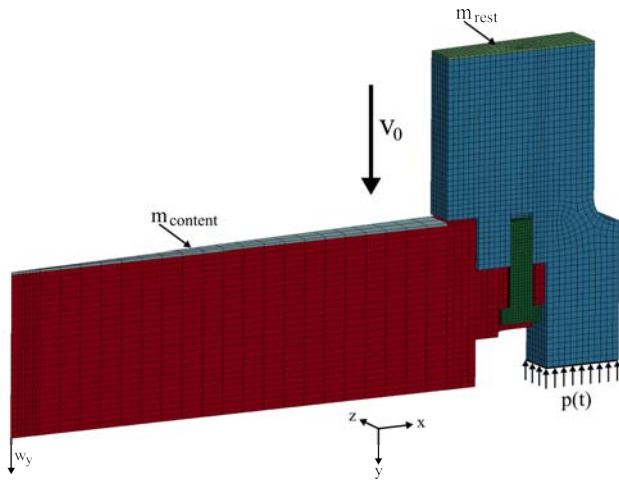
Figure 7: FE-Model used for the dynamic calculation

Figure 8: Load impulse $p(t)$ for the dynamic calculation

Dynamic Calculation of vertical drop position

In the quasi-static model the stationary gravitation field is applied to the lid system and the content, which is fixed to the inner side of the lid. To estimate the response of this system configuration to the load applied dynamically some simplified analytical and FE calculations are additionally carried out. For the FE calculations the explicit code LS-DYNA is used. The FE model is shown in Figure 7. The analytical approach is based on the reduction of the lid system to a single degree of freedom (SDOF) model corresponding to the first fundamental frequency as described in [11].

As an example the trapezoidal form of the impact force represented the deceleration reaction of the shock absorber during the impact onto the target are considered (pressure impulse $p(t)$, Figure 8). An initial velocity of $v_0 = 13.3$ m/s equivalent to velocity reached during the 9 m drop test is applied. The duration of the force $p(t)$ is chosen to be in consistent with the kinetic energy of the cask, i.e. the velocity is reduced to zero at the end of impact. Different load cases are considered with the maximum rigid body decelerations of 50 g, 75 g, 100 g and 150 g, see Figure 8.

The bolt is pretensioned prior to the impulse load in the first 2 ms. Both bolt pretension and impulse $p(t)$ are ramped to avoid unnecessary oscillations. A linear elastic material behavior is assumed for simplification. The symmetric boundary conditions are applied according to Figure 1. Furthermore, the cask wall is fixed in radial direction to minimize the unrealistic deformations of the short wall section. The masses of the lid content and the omitted part of cask body are simulated by element layers with increased mass density analogously to the quasi-static model, see Figure 1. Gasket forces are neglected in the model.

The solution of the dynamic problem is compared with a quasi-static calculation performed with ANSYS for the maximum deceleration values mentioned above. The lid displacement and the nominal stresses in the bolt were analyzed. To show the equivalence between the ANSYS and LS-DYNA models (meshing, contact and boundary conditions, etc.) a preliminary LS-DYNA calculation with slowly increasing loads were carried out.

The dynamic deflection of lid (displacement of the lid center) related to the static deflection under the corresponding maximum gravitation load is shown in Figure 9. The dynamic amplification factor of approx. 1.8 can be derived from these curves. This result agrees well with the analytical estimation for SDOF model of the lid, as can be seen in Figure 10: analytical value for the dynamic factor is by 1.84. The comparison between the dynamic and static solution for the stress in the bolts is shown in Figures 10 (for σ_z) and 11 (for σ_b). Because of the complex nonlinear nature of interactions in the
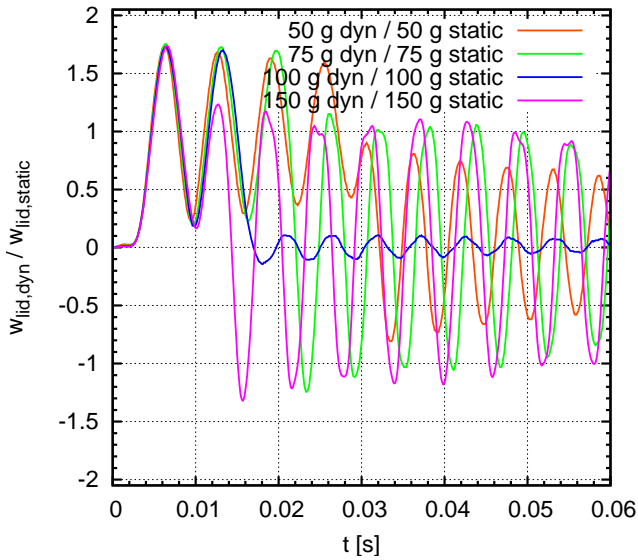
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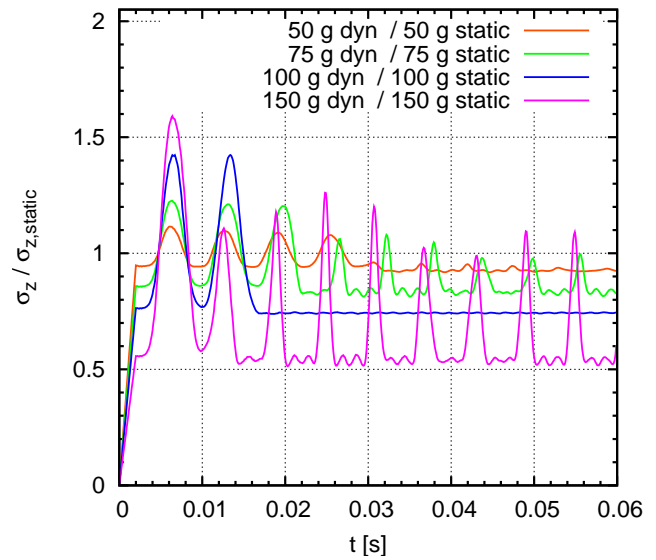**Figure 9:** Bending of lid center with respect to static solution

Figure 10: Nominal bolt stress σ_z with respect to static solution
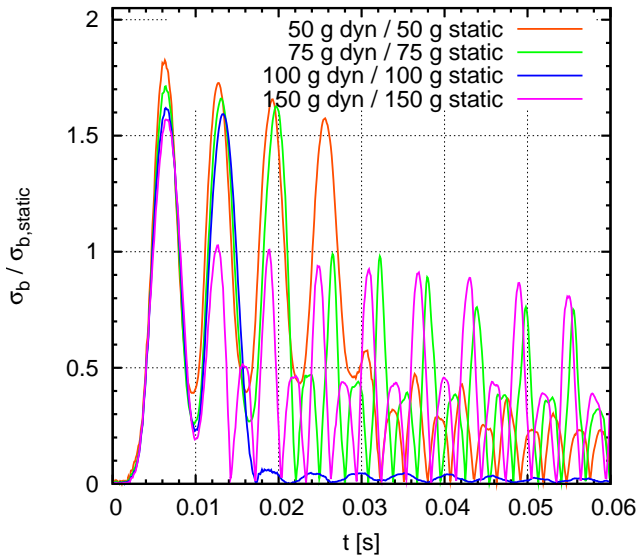

Figure 11: Nominal bolt stress σ_b with respect to static solution
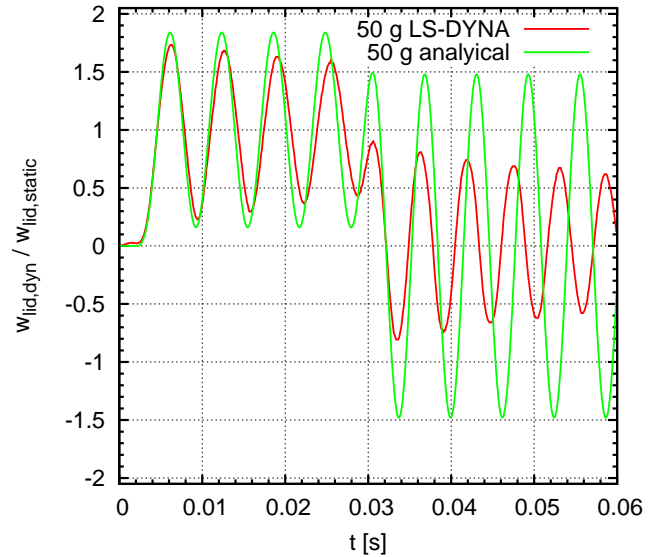

Figure 12: Comparison of the lid displacement between analytical and FE-solution for 50 g

bolt connection, there are not such clear tendency as for the lid deflection but the maximum dynamic amplification factor reaches the value of 1.8 as well (bending stress, Figure 12).

The results of this comparison show that the quasi-static analysis based on the maximum deceleration value is not conservative. The dynamic amplification factor depends on the dynamic characteristic of the structure and the form of the impact force-time function. In case under consideration the value of at least 1.9 can be recommended to cover the dynamic loading onto the components of lid system.

It should be noted, that the dynamical effects and the way to their assessment presented here is only valid for the configurations with negligible multiple mass effects (without delayed content impact due to axial gap in the cask cavity). If such kind of impact interaction between cask lid and cask content is possible additional considerations are necessary [7].

CONCLUDING REMARKS

In this paper the assessment methods of BAM for lid systems of Type B(U) transport packages under accident conditions of transport according to BAM-GGR 012 [2] are presented. General aspects for the FE modeling of bolted lid systems were discussed. Two different FE models of a generalized lid

system of Type B(U) package are considered to illustrate some points of the numerical modeling and post-calculation assessment. The first model simulates the load conditions of the 9 m drop in vertical position. The second model takes the lateral drop position into account. The bolts were assessed according to [2] for every load step of the calculation. The evolution of nominal stresses with respect to the acceleration applied was presented. The results show the sensitivity of the package design to the different assessment criteria. Apart from the bolt assessment the relative axial displacement between the lid and cask flange in the area of the gasket groove with respect to the applied load were evaluated to illustrate the effect of the load on the gasket. Simplified dynamic calculations were used to illustrate the principal prerequisite for the applicability of quasi-static calculations for the assessment of lid systems.

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