ANALYSIS METHODOLOGY AND ASSESSMENT CRITERIA FOR BOLTED TRUNNION SYSTEMS OF TYPE B PACKAGES FOR RADIOACTIVE MATERIALS

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ABSTRACT

Packages for the transport of radioactive material are generally equipped with particular components for crane operations and supporting the package during transport. This paper describes the bolted trunnion systems of Type B packages as an example of such devices.

The analysis of functional capability of trunnion systems is a constituent part of package safety design. The components of the trunnion systems (trunnion, fastening bolts) have to be analysed focusing on the assembly state, strength under maximum loads and, if necessary, fatigue in view of the overall load history. Safe handling of the package during crane operations (lifting, tilting) and secure package tie-down to the transport vehicle, if the trunnions are used as attachment point during transport, have to be ensured.

According to the draft of the BAM guideline [6] for analysis and assessment of bolted lid and trunnion systems, the finite element method is to be used preferably in the analysis of such structures to obtain more accurate and detailed information about their loading. The finite element model of a trunnion system should envelop the trunnion, the bolts and an appropriate part of the container wall with necessary contact conditions on all interfaces between these components. The application of solid finite elements, which is generally recommended in the BAM guideline draft [6], leads to local stress and strain fields as a result of the calculation. However the assessment concept and the corresponding safety factors in the technical standards, which have to be considered in case of the trunnion system, are usually based on nominal stresses.

This paper will discuss some aspects of finite element modelling of the trunnion system. The approaches for preparation and interpretation of calculation results in connection with local or nominal assessment criteria will be discussed with general reference to BAM experience in the approval procedure of Type B packages.

INTRODUCTION

The trunnion system as a part of Type B package for radioactive materials (RAM) has to meet the requirements of IAEA regulations TS-R-1 [1], regarding safe handling (lifting, tilting from vertical and horizontal position) and secure tie-down under routine conditions of transport, if the trunnions are used as attachment point during transport. The loads and the criteria for strength assessment of trunnion systems subjected to these loads are, however, not specified in IAEA regulations [1]. The loading assumptions for the routine conditions of transport defined as maximum acceleration levels depending on transport mode (road, rail, sea, air) are available in Annex IV of the IAEA Advisory Material TS-G-1.1 [2] or in the draft of ISO 10276 [3]. This draft [3] includes the loading assumptions for the lifting operation as well, but, if a RAM package is handled inside a German nuclear power plant, the standard KTA 3905 [4] has to be applied. The design relevant loads

regarding handling outside of “KTA area” (outside the nuclear power plant), e.g., for transhipment operations during the transport can be alternatively determined according to German standard for classification and calculations of cranes DIN 15018-1 [5].
A complete strength assessment concept should generally include information concerning the load assumptions, the allowable level of stress or deformation, and the methods of structural analysis. In this regard there are some differences in requirements in the mentioned standards, but they generally base on evaluation of nominal stress. As discussed below, nominal stress concepts are not an adequate approach for components like trunnion, especially in connection with methods like finite elements analysis (FEA). To ensure the compatibility of modern analysis methods with established standards the Federal Institute for Materials Research and Testing (BAM) is developing a new guideline [6]. The approaches recommended in [6] for preparation and interpretation of FEA for trunnion systems in connection with local or nominal assessment criteria will be outlined in this paper.

GENERAL DISCUSSION

A bolted trunnion system, which will be discussed here, consists of trunnion (load attaching point, LAP [4]), fastening bolts and threaded bolt holes in the packaging body (Figure 1). A typical trunnion is a compact, cylindrically shaped, hollow element having a spigot, base flange, and one or two shoulders (journals). The spigot is fitted into a recess in the packaging wall and the trunnion is bolted to the wall through the base flange. The inner shoulder is used for support during transport, the outer one for crane operations. At locations where the diameter is changing, fillet radiuses are arranged to improve the fatigue resistance.

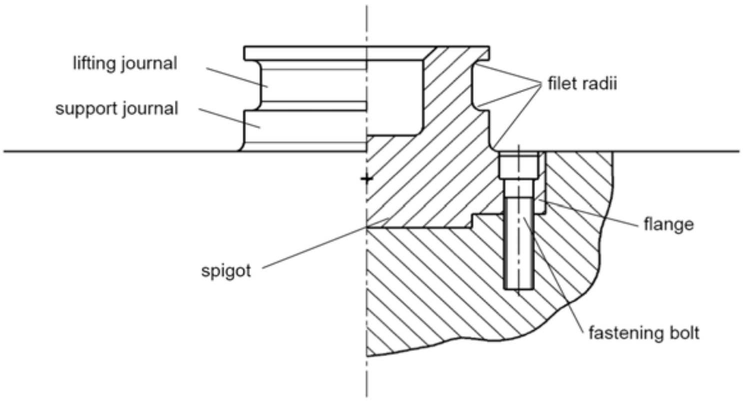

Figure 1. Conceptual sketch of a bolted trunnion

Conventional analytical methods referring to such analysis base on the beam theory. The compact structure (relation of height to diameter) combined with evaluation points near the load exceed the formally applicability of these methods.
Advanced methods such as FEA lead to more accurate results and allow furthermore a direct simulation of interactions between components of the trunnion system in the same calculation step. For this reason the FE model should content the trunnion, fastening bolts, and an appropriate part of packaging wall around recess for trunnion spigot. Based of such models the stress and strain distributions in the trunnion itself and in the bolts can be calculated for all loading conditions to be considered.

MODEL DESCRIPTION

General Modelling Aspects

A three-dimensional model of the LAP consisting of the trunnion and the bolted flange is generated by a specially evolved program. This program is written in *python* and runs in the FEA code *ABAQUS*. It is used to parameterize the geometry of the model, number of bolts, assembly preloads of bolts, external loads, boundary conditions and contact properties. Due to the symmetric conditions of the geometry and the loading only one half of the trunnion system is modelled.
A submodel is derived from the global overall model. The finer meshed submodel captures the highest stressed sector of the trunnion including the highest stressed bolt. This sector is the first one viewed from the plane of symmetry.

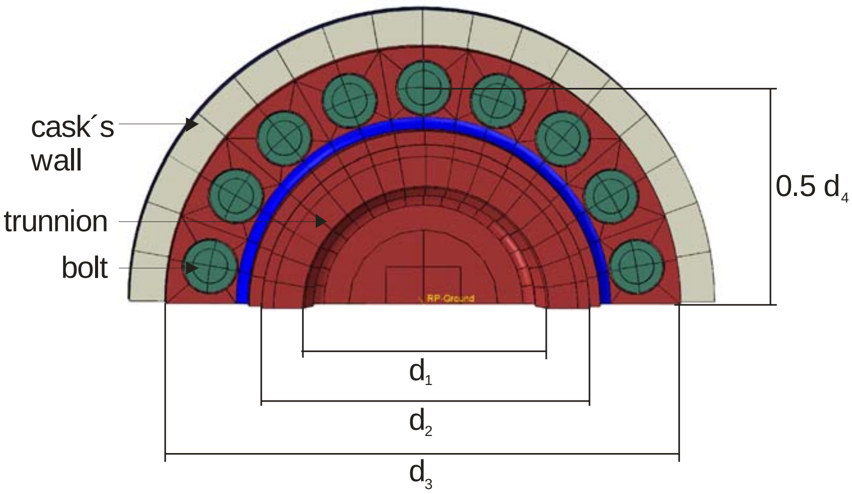

Figure 2. View to the top of the LAP model

Build-up

Figure 2 and Figure 3 show the geometry of the half global model of a reference trunnion system. The main dimensions are: the diameters $d_1 = 210\,\text{mm}$, $d_2 = 280\,\text{mm}$, $d_3 = 440\,\text{mm}$ and $d_4 = 370\,\text{mm}$ as well as the heights $h_1 = 155\,\text{mm}$, $h_2 = 80\,\text{mm}$, and $h_3 = 38\,\text{mm}$. The weight of the package is assumed to be 80 Mg for crane operations and routine transport conditions. If no particular suspension or support devices to ensure the statically determine system are used, one half of the total load (package weight multiplied by load factor) shall be taken into account for the trunnion dimensioning according to [4]. The load factors of 1.8 (handling) and 2.0 (transport) are considered.
The following data of material's properties is taken for the service temperature of 100°C. The cask body made of ductile cast iron 0.7040-04 has an Young's modulus of $E = 162000\,\text{N/mm}^2$ and a Poisson ratio of $\nu = 0.27$. The trunnion is made of high-grade steel 1.4313-04, which has a Young's modulus of $E = 195000\,\text{N/mm}^2$, $\nu = 0.3$, and a yield stress of $R_{p0.2} = 600\,\text{N/mm}^2$. The bolts are made of high-grade steel 1.7220-01 of strength grade 8.8 have $E = 207000\,\text{N/mm}^2$, $\nu = 0.3$ and $R_{p0.2} = 602\,\text{N/mm}^2$.

Figure 3 shows the boundary conditions of the half FE model. On the green coloured surface the degree of freedom (DOF) normal to surface is constrained due to the conditions of symmetry. On the outside and the bottom of the cask wall all three directions are constrained. The boundary conditions are realized by equation constrains therefore the reaction force can easily be controlled.
The calculation of stresses and displacements is divided in two steps: In a first step the state of assembly is simulated by preloading the bolts with prescribed forces at one cross section of each bolt. In a second step the section's strained state remains and the working loads are applied to the model.
The trunnion is loaded by uniform pressure distributed on the contact area with the supporting device. There are two possible positions for loading indicated in Figure 3. The position depends on the load case: handling by crane or Transport resp. The angle of the loaded area and the magnitude of pressure can be estimated by an analytic solution of Hertz' contact problem for cylinders or by another FE simulation for the given contact problem. In this example the half angle of contact is estimated as 45° for the handling by crane as well as for transport. The program which generates the model ensures that only elements which are fully located in the specified angle are loaded. For the half FE model the pressure is calculated from the half of the prescribed load and the elements of interest.

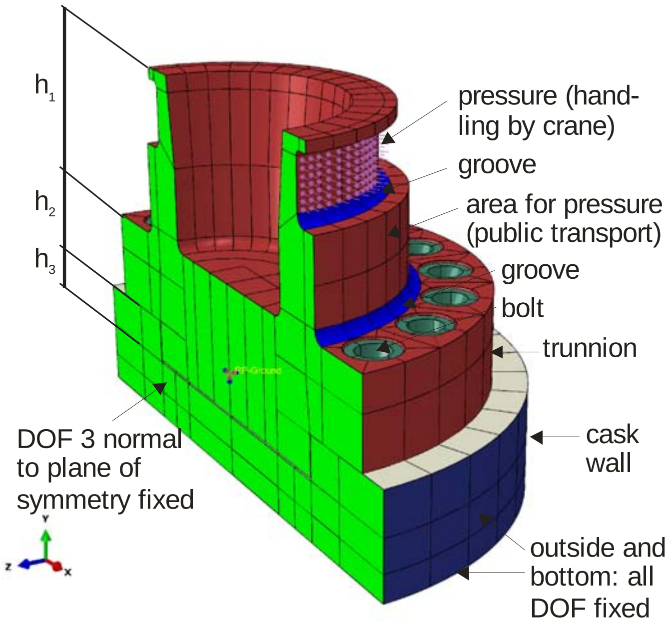

Figure 3. Boundary conditions and loading

The curved solid structure of the trunnion, the bolts and the cask's wall is modelled with reduced integrated quadratic solid elements. A skin of fully integrated quadratic membrane elements is supplemented to the model in the groove areas. Bolts and cask are modelled with reduced integrated linear solid elements. The average edge length is 7 mm for the trunnion and the bolts and 10 mm for the cask. The membrane has a thickness of 0.001 mm.
Figure 4 shows the modelling of the preloaded bolts and the surfaces for contact in detail. Additionally the trunnion is stabilized by using weak spring elements to tie DOFs 1 and 2 of a centre node to the ground. The bolt is presented in dark green. One section of a bolt has a preload force. The thread is bonded to the cask with a tie contact. The bolt shank is modelled with a preload

section. Under the bolt head there is a contact in normal direction and one in tangential direction with friction $\mu = 0.12$.

Between the trunnion and the cask there is a normal contact and a tangential one with friction $\mu = 0.18$.

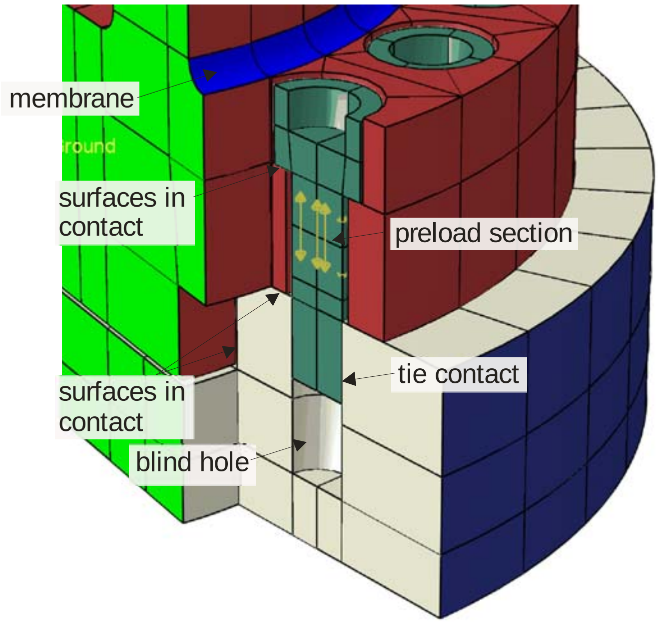

Figure 4. Details of preloaded bolt and the surfaces for contact

CALCULATION RESULTS

Bolts

Uncertainties of the torque-controlled tightening, dispersion of friction coefficients as well as losses of preload due to embedding and relaxation lead to dispersion of assembly preloads of the bolts. In this case the preloads of 110850 N and 180200 N were calculated by means of [8]. These two cases of varying preload are taken into account in the calculations for crane handling or transport resp.

The bolts are evaluated by calculating their nominal stresses according to beam theory. Axial forces and bending moments are derived from the nodal forces for each section along the clamping length of the highest stressed bolt, which is the cut one seen in Figure 4. The evaluation of the average tensile stresses and the maximum total stresses including bending is shown in the diagram in Figure 5. The maximum average tensile stress occurs in both load cases by maximum preload while the maximum total stress is caused by the load of transport and maximum preload. The highest total stress of $570 N/mm^2$ is below the yield stress of the bolt material. It should be noted that in the reference model under consideration the possibility of elastic slip is included in the formulation of tangential contact behaviour. This circumstance leads to a conservative estimation of bending stress in the bolts.

In the diagram it can be noticed that the graph of the total stress does not touch the membrane stress exactly which is an artefact due to the absence of a discrete value at this point.

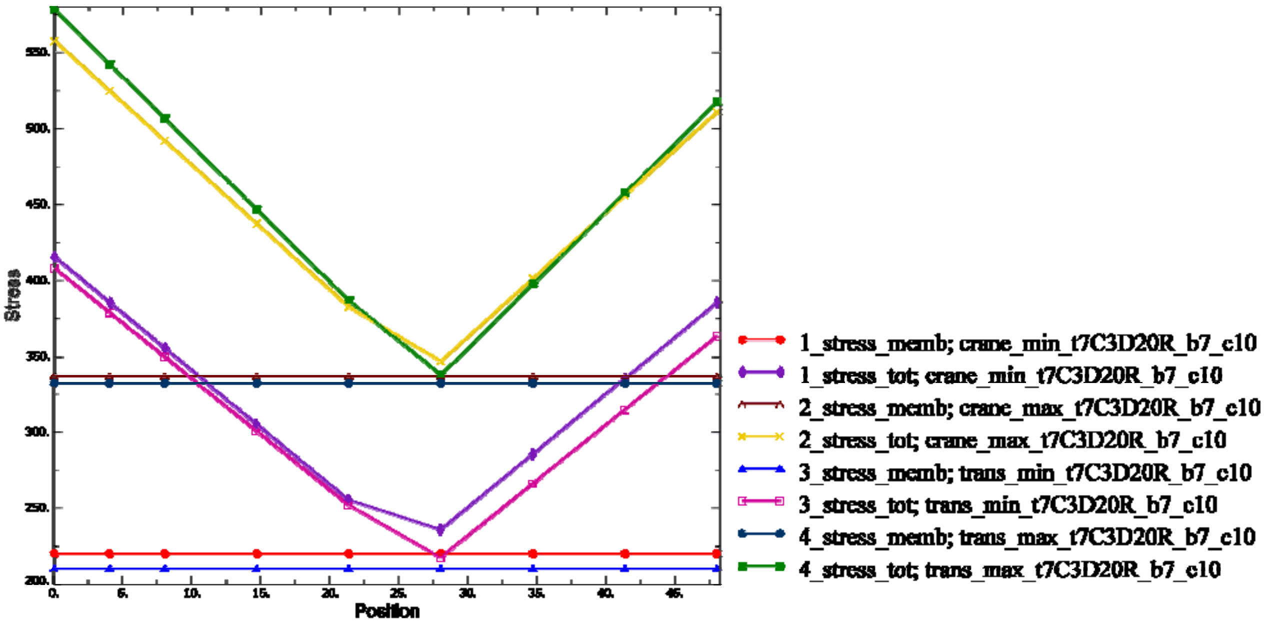

Figure 5. Diagram shows nominal membrane and total stress of a bolt

<u>Grooves of trunnion</u>

The local stresses like the principal or von Mises stress should be evaluated on the grooves of trunnion. Evaluating the integration points on the curved membrane elements supplemented to the model on these areas delivers a stable result for this model. Even using a finer mesh like in the submodel described next changes the result only slightly. If the integration points of reduced integrated quadratic or fully integrated linear solid elements next to the surface are evaluated, the integration points closest to surface have still a distance of 22% of the edge length. In the case of evaluating solids the refining of mesh has not only the effect of a better representation of the region with a high gradient of stress, but also moves the location of the points of interest closer to the surface. This may cause a significant change of the results in the first attempts to find an edge length ensuring a reliable result.

<u>Submodelling</u>

To get further information in the region of high stress gradients a finer meshed submodel can be used. As shown in Figure 6 the highest stressed sector which is the one next to the plane of symmetry is taken for the submodel. All nodes lying on truncated faces are defined as driven nodes. These nodes use the displacements calculated in the global model as boundary conditions for the submodel. All other components of the submodel, e.g. pressure loads, preloaded sections, boundary conditions, contact definitions are the same as in the global model.

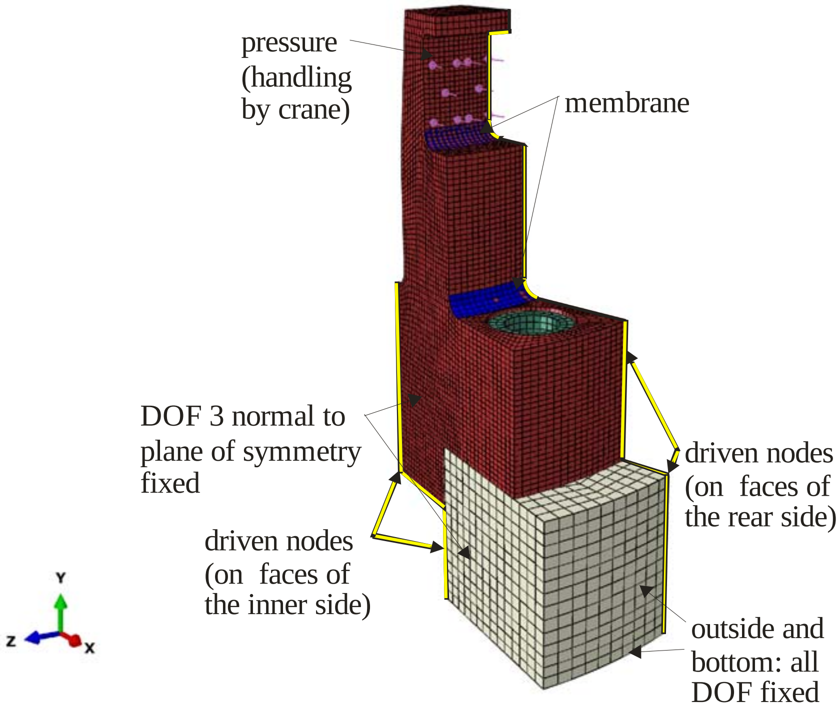

Figure 6. Meshed submodel of highest stressed sector with marked driven nodes

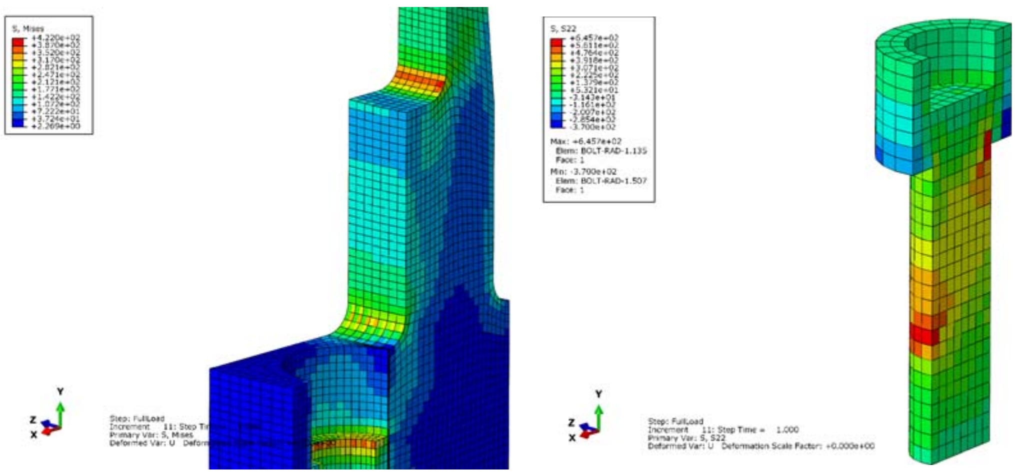

Figure 7. von Mises stresses and axial stresses on cut submodel

Figure 7 shows the non-averaged[i] results on the submodel. The left picture presents the von Mises stresses on the truncated sector and in the right picture the axial tension in the bolt is given. To get more accurate results of behaviour of the friction beneath the bolt head, the bolt can be included in the submodel.

DESIGN ASSESSMENT

The application of solid finite elements provides a complete state of local stress at the reference points of models. In contrast, the strength assessment in the standards mentioned above [7], [8] is based on nominal stress. The harmonization between calculation and assessment approaches for LAPs is therefore one of the objectives of the BAM guideline draft [6].

In general a linearization of stress fields calculated by FEA and determination of a nominal stress is not possible for trunnions having no well-defined cross section. Therefore the assessment criteria for the trunnion itself is modified in [6] for local values of stress. Since the local stresses are normally higher as nominal ones, an additional limit analysis must be carried out in the static strength examination, if the local values exceed the level for nominal stress allowed in the correspondent standards. The fatigue analysis for trunnion is recommended to be performed on basis of FKM guideline [7], where the local stress concept is established. Only the safety factors of [7] have to be additionally adjusted to fulfil the particular requirements for the LAPs of RAM packages.On the other hand it is reasonably to retain the nominal stress concept for strength assessment of the bolts owing to their simple rod shape. BAM guideline draft [6] recommends transforming the local stresses in the bolts from FEA into nominal ones, hence the following analysis (e.g. fatigue evaluation) is able to be performed according to the well known VDI 2230 guideline [8]. Consequently, it is not necessary to model the bolts in detail.

CONCLUSIONS

A general introduction to the guidelines and standards concerning the design of bolted trunnions was given. Conclusively a concept was derived how these rules can be transferred in an accurate model which gives rise to reliable results.

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[i] The results which were calculated at discrete points are normally presented artificially smoothed and extrapolated on the mesh. In this figure no smoothing is used therefore the presentation looks somehow coarse.