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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PRESTRESSED BOLT CONNECTIONS UNDER LATERAL DISPLACEMENTS

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ABSTRACT

The containment system of transport packages for spent nuclear fuel and high-level waste usually includes bolted lids with metal gaskets. The packages are assessed to specific transport conditions which are specified in the IAEA safety standards SSR-6 (IAEA 2018). These transport conditions, especially the so-called accident conditions of transport, imply high dynamic loading on the lids and the bolt connections of the package. The response of the lid systems on the mechanical accident conditions is generally investigated by experimental drop tests or numerically, e.g., by finite element analyses. The interpretation of the drop test results for the verification of the numerical models is often not obvious due to the complex superposition of different effects in the real tests. BAM has started a research project to get a better understanding about the behavior of prestressed bolt connections under loadings typical for these drop tests. In this context an experimental test set-up was developed to investigate the response of a single bolt connection under a prescribed lateral displacement of clamped parts. The bolt is instrumented by strain gauges to get the pretensional, the torsional and the bending stress in the bolt shank. Furthermore, the lateral movement and the tilt of the bolt head is measured during the test. A finite element model of the test set-up has been created in Abaqus FEA (Simulia 2021). The very detailed instrumentation of the test set-up shall give the opportunity to investigate and validate the numerical model. The aim of this paper is to give an overview about the proposed research project and to present first results.

INTRODUCTION

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 the Type B(U) packages used in Germany for transport and interim storage is closed by two bolted lids (primary and secondary lid).

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

According to IAEA SSR-6 (IAEA 2018), the containment system must fulfill, amongst others, the activity release criteria under the specified routine, normal and accident conditions of transport. The limitations for the activity release will be ensured by the integrity of the containment and the leak tightness of the lid system. The demonstration of the leak tightness is typically provided by a combination of analyses, drop and thermal tests. Additionally, there are component tests, e. g. seal performance tests.

In the regulatory drop tests, the lids are loaded by their own inertial forces and by the interaction with other components of the cask (e.g., the radioactive content, the basket, the impact limiter, etc.). The dynamic response of the lid on the impact loads (its deformations and axial or lateral movements) results in the change of the lid-flange contact with the unloading or the potential dislocation of the seal as well as in the additional tension and bending of the lid bolts. Plastic deformations of the bolts up to the loss of their pretension or their complete failure could impair the containment function and must be precluded by the cask design.

The application of the strain gauges (SGs) onto the bolts is a common practice for the drop tests (see Quercetti, 2011). However, the instrumentation of the bolts is only possible to a limited extent and the experimental results are only valid, in the strict sense, for the specific conditions of the test (temperature, pretension of the bolts, etc.). The pretension of the bolts for example is one of the determining factors for the dynamic characteristic of the lid system and its dynamical response on the impact loads. 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 inaccuracies of the bolt tightening technique. Due to these uncertainties and the physical nonlinearities of the friction contact conditions at the interfaces of the lid system the transfer of the experimental results for the bolts onto other possible pretension states is generally not elementary.

Numerical analyses, e.g., finite element analysis (FEA), are usually carried out for the interpretation of the test results (see Linnemann 2014 and Sterthaus 2014). However, a reliable verification of numerical models using only the drop tests is in many cases difficult according to the experience of BAM because of limited test data but also in view of a complex superposition of inevitable random effects in the preparation and the performance of the real tests. Therefore, BAM has started a research project to get a better understanding about the behavior of prestressed bolt connection under the loads typical for drop tests. In this context, an experimental test stand was developed to investigate the response of a single bolt connection under a prescribed lateral displacement of clamped parts. A finite element model of the test stand has been created in Abaqus FEA.

EXPERIMENTAL TESTING

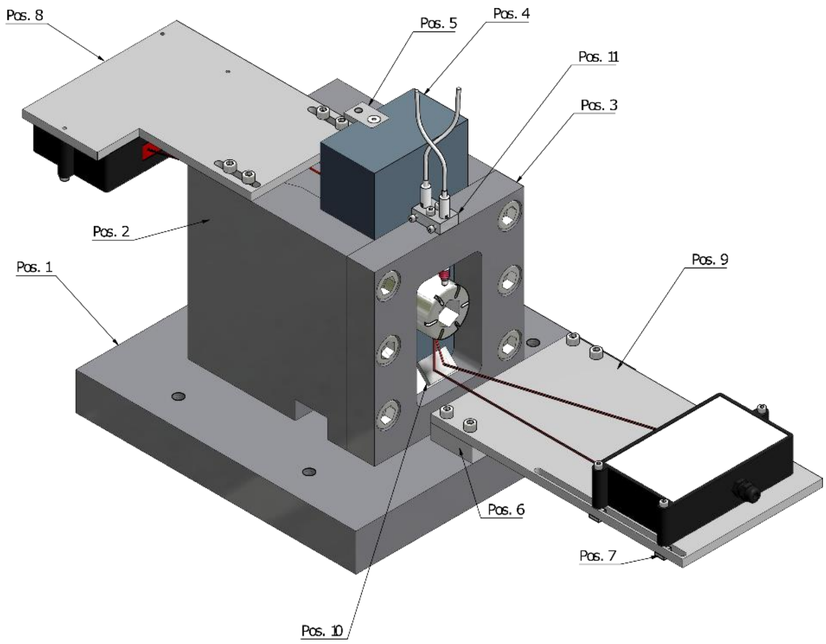

Figure 1. Sketch of the experimental test stand.

The test set-up represents a single bolt connection (see Figure 1). It consists of a steel block (Figure 1, Pos. 2) with a blind hole for the bolt, a slider (Figure 1, Pos. 4), representing the lid of a transport package and the bolt. The design allows the lateral displacement of the slider up to a maximum of 3 mm in the vertical direction. The relevant dimensions are inspired by an existing package design. This includes the dimensions of the bolt, the thickness of the slider and the diameter of the hole in the slider. The load onto the slider to induce the lateral displacement is applied with a quasi-static testing machine (see Figure 3). It also planned to perform dynamic tests in the further course of the project.

The test set-up is equipped with an extensive instrumentation. The displacements of the slider and the bolt head are measured by laser triangulation systems. Additionally, two inductive displacement sensors are used to measure the tilting of the bolt head. The shank of bolt is instrumented by strain gauges (SGs) which is also very common for experimental drop tests (see Quercetti, 2011). In this case, there are multiple layouts for the SGs on the bolt shank planed. The bolt used for the first test series is instrumented with four layers of uni-axial SGs along the axis to the bolt shank. Two layers are equipped with eight SGs and two layers have four SGs. That means that there are 24 SGs in total (see Figure 2 right hand side).

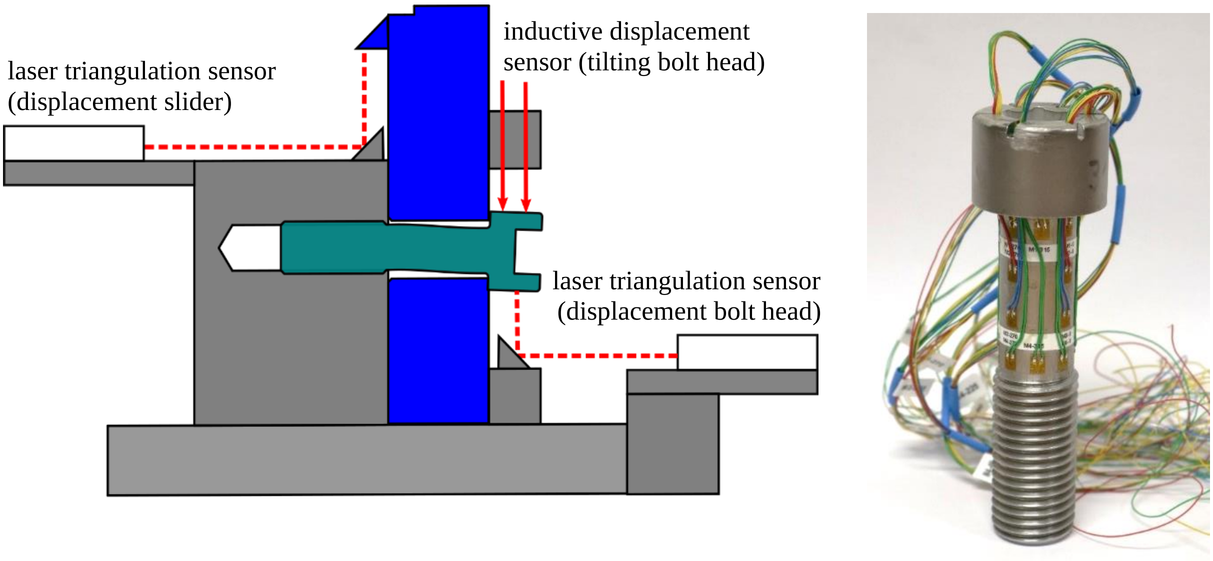

Figure 2. Instrumentation of test stand and bolt.

The layers with eight SGs are reasoned to verify the general assumption of the flatness of the bolt cross-sections during the deformation applied. Additional to the SGs on the bolt, there are 4 SGs in radial direction on the surface of the steel block around the blind hole. In total, 32 measuring signals are recorded during the experiment. For the test preparation, the SGs in the bolt shank can also be used during the tightening of the bolt by checking the bolt pretension. This data allows, in combination with a recording of the tightening torque, first conclusions on the friction conditions under the bolt head and in the thread. It is also planned to measure the torsional stress in the bolt shank by using a bolt instrumented with a modified SG layout in future test series. This will give us a more precise picture of the frictional behavior in the bolt connection.

Figure 3. Testing machine 3 MN with test set-up and data acquisition.

PRELIMINARY TEST RESULTS

The test program is still at its beginning, but first results are presented below. Figure 4 shows the data for the displacements of the slider (LT-01) and the bolt head (LT-02), both measured by the laser triangulation systems. It can be noticed that both curves behave very similar until t = 103 s and a displacement of about 0.11 mm. After that, the displacement of the bolt head does not increase any further, meanwhile the displacements of the slider go up until 0.26 mm. That means that the bolt head is sliding against the slider (or rather the lid).

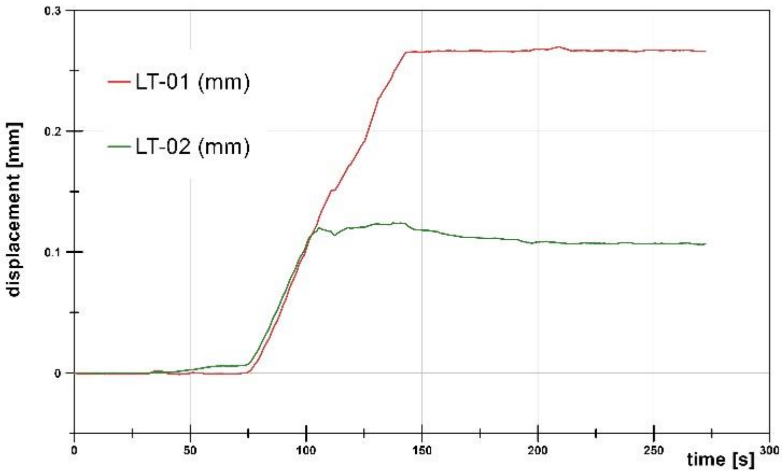

Figure 4. Displacement results for the slider (red) and the bolt head (green).

Figure 5 shows the corresponding load curve. The load is applied displacement driven. The maximum force is approximately reached with the beginning of the bolt head sliding. It has still to be investigated to what extent a so-called stick-slip-effect is present in the load curve.

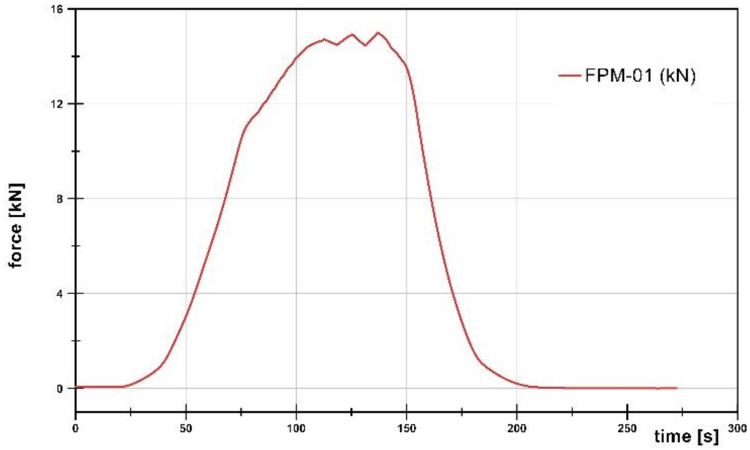

Figure 5. Force applied over the time of testing.

The results of SGs in layer M1 are used to calculate the bending stresses in the bolt. For this, the eight SGs per layer are split into two groups. The first group consists of the SGs with the axial angles 0°, 180°, 90° and 270°. The SGs with the axial angles 45°, 225°, 135° and 315° belong to the second group. The direction 0°-180° represents the main bending axis. The data of both groups are used separately to calculate the resulting bending stresses σ_{b1} and σ_{b2} according to the Equations (1) and (2) whereas E_{bolt} stands for the Young's modulus of the bolt and $\varepsilon_{0°}$ to $\varepsilon_{315°}$ are the strains of the SGs with the corresponding axial angles.

$$\sigma_{b1} = \frac{E_{bolt}}{2}\sqrt{(\varepsilon_{0°} - \varepsilon_{180°})^2 + (\varepsilon_{90°} - \varepsilon_{270°})^2} \tag{1}$$

$$\sigma_{b2} = \frac{E_{bolt}}{2}\sqrt{(\varepsilon_{45°} - \varepsilon_{225°})^2 + (\varepsilon_{135°} - \varepsilon_{315°})^2} \tag{2}$$

The derived curves are plotted in Figure 6. It can be noticed that both curves behave very similar. That means that the cross-section of the bolt can be considered as nearly flat during the applied bending deformation. Further experiments will investigate the bending behaviour of the bolt further and give a better understanding of the phenomena in the lateral loaded bolt connection.

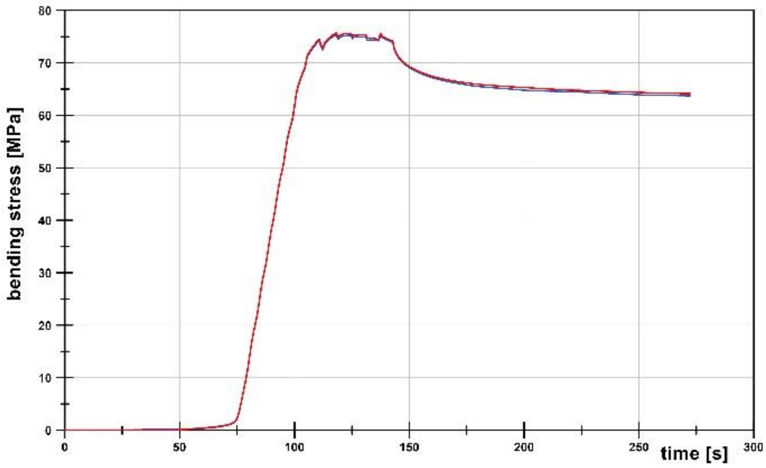

Figure 6. Experimental bending stress results σ_{b1} (red) and σ_{b2} (blue).

FINITE ELEMENT ANALYSES

The finite element model of the test set-up is implemented with Abaqus FEA (see Figure 7). Abaqus FEA (Simulia 2021) allows a relatively easy switch between implicit and explicit solution methods. The model generation is performed by Python-scripts allowing a convenient alteration of the model. Solid elements are used for the whole model except for SGs. As a first approach, the SGs are simulated with discrete truss elements tied to the nodes of the solid elements of the bolt shaft (see Figure 8). The bolt threads are not modelled. Instead, the bolt is tied into the blind hole by constraint conditions. The final mounting angle of the bolt in the experiment is considered by an axial rotation of the bolt in the simulation. That means, that the SGs are in coincident positions for test and analysis. The bolt pretension is applied by dedicated pretension elements provided by Abaqus FEA. The model consists of 31.288 elements with 208.405 degrees of freedom in total.

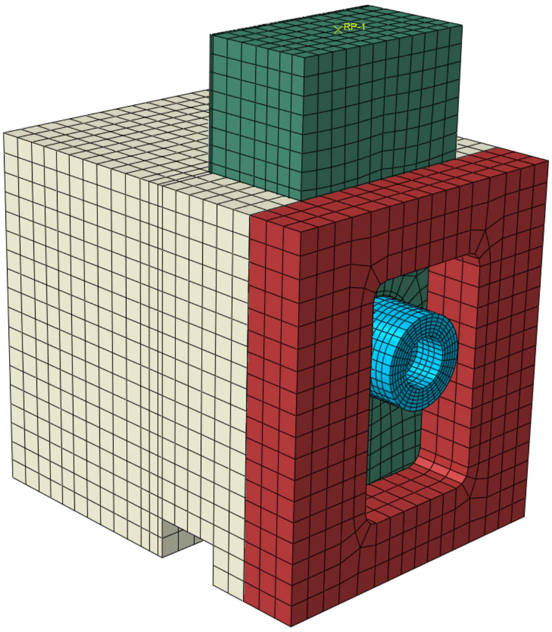

Figure 7. Finite element model of the test set-up.

In the first step, the finite element model is used to investigate the influence of the modeling and material parameters, such as element formulation, meshing and friction coefficients. The next step is a comparison of the numerical results with analytical calculations by beam theory. After that, the analyses will be compared with the experimental test results.

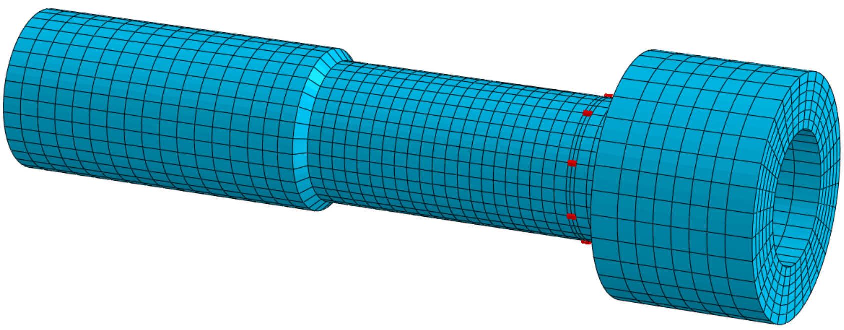

Figure 8. Finite element mesh of the bolt, the SGs on the Layer M1 are plotted in red.

CONCLUSION

A research project has been started to get a better understanding about the behavior of prestressed bolt connections under lateral displacements. Bolted lids with metal gaskets are usually used for the containment systems of transport packages for spent nuclear fuel and high-level waste. A lateral displacement of the lid cannot always be prevented due to the high inertia loadings which typically occur under the regulatory defined accident conditions.

An experimental test set-up was developed to investigate the response of a single bolt connection under a prescribed lateral displacement of the clamped parts. A prescribed lateral displacement of the slider is applied to simulate the lid movement. The test set up is equipped with an extensive instrumentation. Laser triangulation devices are used to measure the displacement of the slider and the bolt head. Two inductive displacement sensors record the tilting of the bolt head. Additionally, the bolt shank is instrumented by 24 strain gauges. This extensive use of strain gauges is reasoned to depict the bending state of the bolt adequately. The first experiments show that the designed test stand is suitable for its foreseen task. Additionally, the results show that the cross-sections of the bolt can be considered as nearly flat for the range of the deformations applied.

For the second task of the project, a finite element model of the test set-up has been created in Abaqus FEA. The influence of the different modeling and material parameters, such as element formulation, meshing and frictions coefficients has been investigated yet. The next step is a validation of the numerical model with respect to the experimental results. The results will be presented in the upcoming publications.

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REFERENCES

IAEA (2018). Regulations for the Safe Transport of Radioactive Material (2018 Edition), Specific Safety Requirements No. SSR-6 (Rev. 1).

Linnemann et al. (2014) Safety Assessment of Lid Systems of Transport Packages for Radioactive Materials by Use of Finite Element Analyses. *PVP2014 - ASME 2014 Pressure vessels & piping division conference (Proceedings).* Anaheim, CA, USA, 20-24 July 2014.

Quercetti, T. et al. (2011). Instrumented Measurements on Radioactive Waste Disposal Containers During Experimental Drop Testing. *Proceedings of the 14th International Conference on Environmental Remediation and Radioactive Waste Management, paper no. 59142, ASME 2011, Reims, France, September 25-29.*

Simulia (Dassault Systèmes), Abaqus FEA, Version 2021HF4, 2021.

Sterthaus et al. (2014) Numerical approach for containment assessment of transport packages under regulatory thermal test conditions. *PVP2014 - ASME 2014 Pressure vessels & piping division conference (Proceedings).* Anaheim, CA, USA, 20-24 July 2014.