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Applications of applied mechanics to the solution of problems connected with transportation and storage of spent nuclear fuel

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Abstract

The paper is devoted to description of methods and procedures of applied mechanics that are used for solution of problems connected with transportation and storage of spent nuclear fuel or other nuclear waste. The safety of nuclear fuel includes questions of cask reliability, safety of transport complex and problems of cooling of casks in a storage system. The solution of those problems is based on the numerical (finite element method) as well as experimental methods of mechanics.

1. Introduction

Transport complexes and transport containers (casks, packages) serve for manipulation and transport of spent nuclear fuel from reactors of nuclear power stations. During the certification of packages for transporting radioactive materials it is necessary to provide analyses that this equipment meets requirements of Regulations of Nuclear Regulatory Authority of the Slovak Republic – UJD SR No.57/2006 Z.z. for normal and failure conditions of transport [1]. Safety verification of transport complexes and transport containers was realized recently by analytical and numerical methods [2] on the workplace of authors. Because of fact that abovementioned verification recommends for the assessment of container safety experimental methods, the authors had elaborated methodology

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for such a test of nuclear waste packages [3, 4]. One part of extensive experimental analysis [5–7] was a modal analysis and analysis of vibration of real transport complex during its moving as well as analysis of container by numerical and experimental methods including drop tests realized on scale model.

2. Modal analysis and vibration of transport complex

According to regulations, the consignment have to withstand any accelerations, vibrations, or resonances that can occur under conditions presumable during normal transport without decreasing of tightness of closure mechanisms in different parts of package or without violation of its integrity. From this reason has been accomplished modal analysis and analysis of vibration of system container – wagon, during its movement with prescribed velocity, starting, breaking as well as movement through twists and locations, where mechanical vibration of system could occur [8]. Container (Fig. 1) is positioned during the transport on special railway wagon (Fig. 2). Selected transport conditions and technical parameters of transport complex are: max. velocity of loaded coach 100 km.h\(^{-1}\), weight of container 68 t, weight of wagon 35 t, maximum loading capacity of wagon 85 t.

Modal analysis of carrying part of wagon bridge was realized for two positions of three-axis acceleration sensor Brüel & Kjær 4506B. Sensor S1 was positioned on a lid of container and sensor S2 on a frame of undercarriage above pan of wagon bearing. Locations of sensors allow gaining information about transmission of vibration excitation during movement of complex. The locations of hammer impact were chosen in such a way that the longitudinal and transversal symmetry of wagon has been exploited. 9 locations were chosen for excitation by impact hammer. The locations were the same for both sensors (S1 and S2). Acceleration sensors S1 and S2 had axis \( x \) in vertical direction, axis \( y \) was oriented perpendicular to axis of wagon and axis \( z \) was identical with wagon’s axis. Functions of frequency transfer measured for individual positions of excitation were processed in program Pulse Reflex. Software algorithms using function CMIF (Complex Mode Indicator Function) has been used for estimation of eigenshapes and eigenfrequencies. It have to be mentioned that results of modal parameter measurement in which sensor S2 was used, are identical with those gained by sensor S1.

Measurement of operational vibration of transport complex during its movement was realized on railway road of length approximately 3600 m. The road was divided to 5 sections with considerably different characteristics of driving. In section No. 1 (length 800 m) vibrations during starting of complex and during its movement through railway switches of railway station were recorded. Section No. 2 (length 400 m) is characterized by driving through right bend. Section No. 3 (length 600 m) is a straight road on the beginning of which is a railway bridge above road communication. Section No. 4 (length 150 m) is left bended. In the section 5 (length 1650 m) that can be considered as straight road, the complex was stopped, accelerated and halting at the end of section. Maximum velocity of complex during measurement was 40 km.h\(^{-1}\), which corresponds to value received from operator. From vibration analysis of transport complex accomplished during its moving results that maximum effective vibration velocity was 40 mm.s\(^{-1}\). This velocity was reached during acceleration through railway switches at the first section of road. The biggest amplitudes of vibration velocity during movement were reached at the range frequency 3.8 – 5.0 Hz which correspond to eigenfrequency 4.342 Hz. Maximum allowable velocity 100 km.h\(^{-1}\) of transport complex can be, on
the basis of modal and vibration analysis, considered being suitable for transport. At the same time it is recommended to over cross the velocity $42 - 43 \text{ km.h}^{-1}$ as fast as possible, because the excitation of system at this velocity is near frequency 4.3 Hz.

3. Analysis of container

3.1. Residual stresses in the container body

For the measurement of residual stresses strain gage method using drilling of hole [9] was applied. With respect to conditions of drilling, it was necessary to choose strain gages RY 21, which have soldered output from their manufacturing. Equipment RS 200 was used for the drilling of holes. Methodology of hole-drilling was in accordance with standard ASTM E 837-01 and TECHNOTE TN 503-6 [8, 10]. In Fig. 3 are shown analyzed container as well as position and orientation of strain gages for the hole-drilling. Locations of measurement were selected on the basis of results of analytical and numerical methods [2]. They include areas of possible overloading during operation or radiation and thermal influences.

![Fig. 3. Localization of strain gages for the hole-drilling method on the container body.](image)

Application of strain gages was realized by strain gage joint cement X60 and isolation silicone protective coating SG-250. For the measurement was used strain gage apparatus P3. The diameter of holes was 3.2 mm, hole depth 5 mm reached by steps of length 0.5 mm (10 steps). Radius of strain gage rosette was 5.15 mm. In Tab. 1 are given magnitudes of principal residual stresses and their directions in individual locations determined according to standard ASTM E 837-01. The table represents for every location of measurement results measured on two containers.

![Table 1. Magnitudes of residual stresses according to standard ASTM E 837-01.](table)

<table>
<thead>
<tr>
<th>Location of measurement</th>
<th>$\sigma_{\text{max}}$ (MPa)</th>
<th>$\sigma_{\text{min}}$ (MPa)</th>
<th>Inclination angle $\sigma_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.8</td>
<td>-13.7</td>
<td>47.5</td>
</tr>
<tr>
<td>2</td>
<td>30.5</td>
<td>15.8</td>
<td>72.3</td>
</tr>
<tr>
<td>3</td>
<td>57.0</td>
<td>23.9</td>
<td>-77.8</td>
</tr>
<tr>
<td>4</td>
<td>-3.7</td>
<td>-20.3</td>
<td>5.4</td>
</tr>
<tr>
<td>5</td>
<td>33.5</td>
<td>-26.8</td>
<td>6.1</td>
</tr>
<tr>
<td>6</td>
<td>17.0</td>
<td>-9.1</td>
<td>-33.5</td>
</tr>
</tbody>
</table>
3.2. Experimental verification of container fixture

In accordance with supplement No. 1 of Regulation No. 57/2006, the lifting pins of container have to withstand all loadings resulting from manipulation with container by prescribed manners. It means that fixing equipment and whatever part of container used for lifting have to allow manipulation with container. The analyzed container has four footings that serve for fixation of container to transport means, and two pins serving for manipulation with container (Fig. 4). Because, according to the operator, the footings cannot be used for lifting, there were experimentally checked only pins of container. The container pins were verified by classical manual computation as well as by using FEM and dynamic loading [2]. For the experimental verification of computed values of stresses (including verification of dynamic coefficient, which was assigned to be 1.4 in accordance with tables for lifting machines) the method of strain gage method based on electrical resistance was used. On top sides of container pins were applied strain gage rosettes XY 91 (for thermal compensation) in locations 9 and 10, near to the connection of pins to the container body (Fig. 4). Measurement was realized by strain gage apparatus SPIDER for various regimes of lowering and lifting by lifting equipment of operator.

Fig. 4. Location of strain gages in positions 9 and 10 on the container pins.

3.3. Drop and penetration test of container model

The drop tests of packages can be accomplished, according to relevant regulations, on real containers or on models that properly represents their properties [1, 11, 12]. The tests were performed on 1:8 scale model according to Fig. 5, made of steel 11523 and weight approximately 130 kg. Weight of real container without fuel bin is approximately 68 000 kg. In accordance with Regulation of Nuclear Regulatory Authority of the Slovak Republic – ÚJD SR No.57/2006, the packages for transport of radioactive materials have to meet requirements declared for normal and accident conditions of transport. During the test, the container is falling onto a target (punch) – whereby the aim is to cause the maximum possible damage. Impact effect caused by container drop can be modeled by falling from height 1 m on a steel punch of prescribed shape and dimensions and fixed perpendicular to the target (penetration test) [1]. Drop tests of packages were realized by free fall on test equipment. Drop tests of model were accomplished on test stand (Fig. 6) that was designed and manufactured especially for this occasion and allow positioning of model.

The pad (target) for drop tests has to fulfill conditions defined by regulations [1, 11]. The target for the drop test was the steel plate with mass approximately 1700 kg which was fixed to massive assembling plate. The drop tests should be realized in such position of container in which the most serious damage occurs. For the drop tests of model were chosen orientations according to Fig. 8. Before realization of drop tests analytical and numerical analysis of energy balance during the container falling was accomplished. The measurements confirmed that during the drop tests with drop height fall only $h_0 = 600$ mm plastic deformation occurs and accordingly it is not possible to extrapolate results to drop height 1200 mm, which is given by regulation [1], in case of using test object up to mass 5000 kg. In order to have data for extrapolation, the drop tests of container model were realized with fall height 0.30 and 0.60 m, respectively, and for orientation of model according to Fig. 5.
Fig. 5. Orientation of model for drop tests.

Before the drop test acceleration sensors were applied on the truck of test stand and on the lid of container model. The strains were measured by strain gages applied on container model. Figs. 6a and 6b show test stand during drop tests in model positions B2 and B3, respectively. For illustration purposes is for model position B2 and for fall height 0.60 m given in Fig. 6c time-dependent chart of velocity determined on model by acceleration sensor.

The penetration test of packages for radioactive material is prescribed by regulation [1] and it should demonstrate fact that package is able to withstand accidents during transport (failure conditions). The opinion with small-scale models of containers shows that analytical assessments and numerical computations considering real values of material properties are comparable with results of experimental measurements.

3.4. Thermal and stress analysis of container

The aim of thermal analysis of container was to show that after filling of container by spent nuclear fuel rods, the heat resulting from radioactive decay is not accumulated under prescribed transport and test conditions and the allowed limit temperatures and stresses are not exceeded in the body of container [1]. According to Regulation No.57/2006 Part VIII, outside temperature during using of transport container can lie in interval -40 °C to +38 °C. According to Section 14 Part VIII, on easy accessible part of surface the temperature cannot exceed 85 °C. It is the reason, why for this relatively high temperature the safety parameters have to be determined and these have to be verified by experimental methods. The authors have chosen, with agreement of operator, the test by heating of operation medium in container. The procedure of test realization was based on installation of heating coils in cassettes of container. Before measurement, installation of heating coils, sealing and filling of container by nitrogen to pressure 0.2 MPa had been accomplished. In order to identify loading due to heating, on the container body were applied 8 strain gages, while 4 measurement locations (assigned 1 to 4) were on cooling ribs over fixation flanges and 4 assigned 5 to 8 (in pairs, because of plane stress state) were applied on the lid of container. Location of strain gages on the container body is given in Fig. 7.
Thermal compensation was realized by compensative strain gages 5 K to 8 K applied on unloaded steel sheets near to active strain gages. Numbers 5 to 8 mark the active strain gages (Fig. 7). The strain gage measurements were accomplished during three days in four positions on fixation flanges and four sensors on two locations on a lid, Fig. 7.

At that time worked heating coils and there was measured temperature of water in the container cassette as well as temperatures of surface and environment. A thermovision camera also registered the temperatures of container surface. The charts of measured temperatures in individual time instants are given in Fig. 8. Deliberate switching off air-conditioning in a room where the container was situated caused the change of environment temperature before end of measurement. In the location of sensor was reached maximum approximately 65 °C, while the temperature of water was tightly under 80 °C. In graph in Fig. 9 are given time-dependent charts of stresses during thermal test.

Broken curves in time-dependent charts of stresses (time approximately 150000 s) resulted from switching off air-conditioning in the room, where the container was placed. At the time, when the airconditioner was turned off, the temperature of environment increased, while the increment of water temperature was constant (Fig. 8) and surface temperature increased. This results to decreasing of strains in ribs (locations 1 to 4 in Fig. 9).

The temperature of container surface was scanned by thermovision camera TiR1 during the whole thermal test. In Fig. 10 is given detail of container surface scanned by thermocamera.
4. Conclusion

In the frame of assessment of safe operation of transport complex and containers for transport of radioactive fuel was found out that in principle the same results were gained by the experimental and numerical methods. Though there were detected some small differences by application of presented test treatments, on the basis of experimental and numerical investigation can be stated that the verified containers and transportation complex have sufficient residual lifespan. Moreover, some recommendations were given for further using of transportation complex.

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References