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INTERMEDIATE STORAGE HALL UNDER BLAST PRESSURE LOADING FROM NEARBY LNG VAPOUR CLOUD EXPLOSION

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ABSTRACT

The paper addresses the analysis of an intermediate storage hall for low and medium radioactive waste in a German nuclear power plant. The focus is on assessing the stability of components (e.g. waste storage containers) in the hall against induced vibrations from blast pressure waves (BPW) resulting from a nearby liquefied natural gas (LNG) vapor cloud explosion (VCE). The VCE is modeled using the Multi Energy Method (MEM). The blast pressure wave is then applied to the finite element structural model of the storage hall, which includes the building, base slab, and pile foundation. Different model variants are considered to account for variations in container distribution and soil stiffness. The results of the structural analysis involve evaluating acceleration time histories and response spectra at selected evaluation nodes on the base plate of the storage hall. The calculated spectra are compared with earthquake response spectra, showing that the structural components of the storage hall, especially its stored waste storage containers, are verified for stability against the induced vibrations from the specified blast loading conditions.

INTRODUCTION

Since the 1970s, nuclear power plants and nuclear facilities in Germany have been designed against explosion pressure waves in accordance with BMI-Richtlinie (1976) and IfBt-Mitteilungen (1974), prevailing in DIN 25449 (2022). This design represents a conservative protection of nuclear facilities against blast pressure waves (BPW). The pressure wave is a beyond-design-basis event for the intermediate storage halls. The recommendation of the German Disposal Commission refers to these load assumptions and also to site-specific specifications as well as to the stored radionuclide inventories and their release behavior, ESK (2021).

For an intermediate storage hall for low and medium radioactive waste of a nuclear power plant building response spectra are to be calculated to check the stability of its components (e.g. waste storage containers) against induced vibrations from an external blast pressure wave due to a nearby LNG vapour cloud explosion (VCE). The building response spectra are to be compared against known earthquake response spectra for which the hall originally was designed and the components stability was shown.

Blast Loading from Vapour Cloud Explosion

A vapour cloud can form when gas escapes from a pipe or container, or when escaping liquid evaporates. The gas mixes with the ambient air and forms a vapour cloud. Depending on the local mixing and environmental conditions like temperature and pressure, areas of different gas concentrations form in the cloud. If the gas is flammable and there is an ignition source (e.g. spark or hot surface) in an area of the vapour cloud that is flammable due to a suitable gas concentration, a combustion/explosion occurs. Whether the initiated combustion/explosion can generate a relevant blast wave depends on various factors. These are, for example, the size of the vapour cloud at the time of ignition, the distribution of the ignitable mixture, the degree of confinement and the flame speed. When ignited, the combustion propagates outwards from the point of ignition. The strength of the blast wave and thus the strength of the overpressure generated depends largely on the flame speed. The higher the flame speed, the greater the overpressure generated, i.e. the mode of flame propagation plays a decisive role. In general, deflagration occurs; detonation can only

occur under special conditions. The flame front moves at supersonic speed during detonation and at subsonic speed during deflagration. Detonation results in a significantly higher overpressure than deflagration.
Figure *1*, shows two time histories one from a deflagration and one from a detonation. The shock-wave from the detonation is characterized by an instant rise to maximum overpressure. The pressure wave from deflagration shows a smooth rise to maximum overpressure.

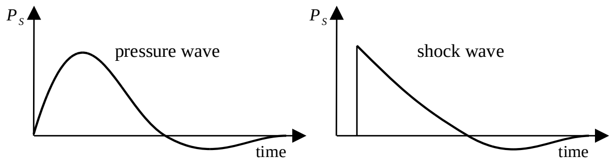

Figure 1. Overpressure time histories from blast waves: pressure wave from deflagration (left), pressure wave (shock) from detonation (right)

In the case of a vapour cloud, where no turbulence occurs during combustion, i.e. combustion is laminar, only low flame velocities occur, which do not lead to any relevant overpressure, the vapour cloud just burns. If turbulence occurs during combustion, e.g. as a result of the outflowing gas or due to the flow around obstacles caused by the spreading flame front, this leads to an increase in the flame speed with increasing turbulence and thus to an increasing blast wave with higher overpressure. In the extreme case, increasing turbulence can transform a deflagration into a detonation, which itself no longer requires turbulence. Detonation can also occur if the gas mixture is ignited by a high-explosive charge. Further details are found in CPR 14 E (2005).
When a Vapour Cloud explodes, the combustion process ends at the edge of the cloud and the generated pressure wave spreads outwards in a spherical shape. If it hits an obstacle, e.g. a building, it is reflected on its outer surface. The impacting pressure wave and the reflected pressure wave overlap in their effect on the building. As free reflection is not possible due to incoming particles, an additional dynamic pressure is created; the superposition results in the reflection overpressure, which is more than twice the peak pressure of the incident pressure wave. Newmark 1956 gives for peak overpressures P_{s0} of up to 138 kPa a simplified formula for normal blast wave reflection coefficient c_r:

$$c_r \approx (2 + 0.0073 \cdot P_{s0}) \text{ with: } P_{s0} \text{ in [kPa]} \quad (1)$$

Prediction methods for blast wave overpressure from VCE

There are various approaches to determining the overpressure of VCE, see DECHEMA (2017) or CRP 14 E (2005) or CCPS (2010). The simplest method is the TNT equivalency method. The TNT equivalence method assumes that the evolution of the overpressure in a VCE is equivalent to that of a TNT detonation. For this purpose, the combustion enthalpy stored in the gas cloud is converted proportionally into an equivalent TNT mass. This value is used to determine the side-on overpressure at a distance from the detonation center by using a diagram. Although this method is quick and simple, VCE-typical parameters are only indirectly taken into account in the overall yield factor of the explosion, which can lie in a wide range, see CPR 14 E (2005). The most sophisticated method is the numerical calculation of the VCE using Computational Fluid Dynamics (CFD), where all local parameters of the VCE and its surrounding can/must be regarded accordingly. In order to achieve results that are less subject to uncertainties than with the TNT method, but also to avoid the individual effort of a detailed local CFD simulation, other methods have been developed in the past, such methods are given in CPR 14 E (2005), CCPS (2010) or DECHEMA (2017). One of these methods, is the so-called multi-energy method, which is discussed in more detail. The Multi Energy Method (MEM) was developed in van den Berg, A.C. (1985) for VCE. As described above the presence of turbulences is important for higher flame speeds and thus overpressure to develop. Turbulences/ higher flame speeds are generated in obstructed, congested or confined regions, thus the consideration of these regions and its ignition sources in the MEM is essential.

The initial strength of the blast wave in each region is to be given by a class number. Class number 1 represents a very low, class number 10 a very strong blast (detonation). A tabular decision aid for determining the explosion class (1 to 10) of a region is found, for example, in CRP 14 E (2005), where the parameters ignition energy, obstruction of the vapour gas cloud and confinement in the considered region are qualitatively determined. The MEM provides three diagrams (blast charts) that show (scaled) peak overpressure, (scaled) dynamic peak pressure and (scaled) positive phase duration with shape of blast wave. Each diagram shows ten curves, one curve for one blast class ranging from 1 to 10, see Figure 2.

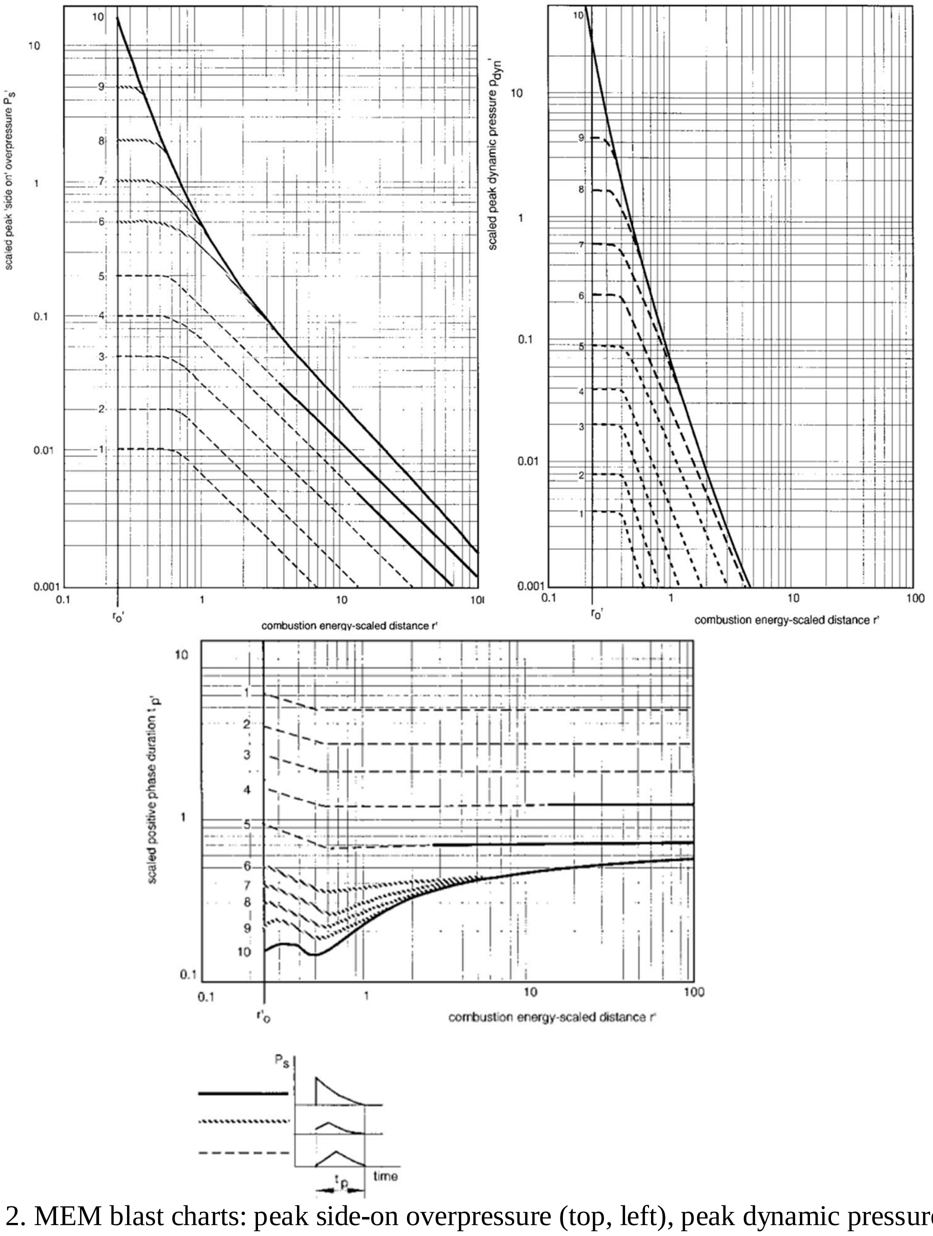

Figure 2. MEM blast charts: peak side-on overpressure (top, left), peak dynamic pressure (top, right), positive phase duration and blast-wave shape (bottom), CRP14 E (2005)

The formulas to determine the further input parameters for the evaluation of the three blast charts are found in CRP 14 E (2005). The approach to determine the pressure loading by modern methods like the MEM for the loading of nuclear structure structures, instead of using the conservative BMI-Richtlinie (1976), is addressed in Cantay, C., Blömeling, F. (2022), too.

MODEL DESCRIPTION

Below the loading and calculation model is described. The derivation of the blast pressure wave using the multi energy method is presented, as well as the finite element structural model of the intermediate storage hall.

Definition of blast pressure wave from VCE

Different scenarios of vapour cloud explosion were considered in the surrounding of the site. Potential vapour clouds can originate form remotely located LNG storage tanks, from LNG vessels on a nearby river way, other potential sources are close natural gas transport pipelines, propane gas transports by truck and by rail, all potential events were considered. As decisive source for a vapour cloud, a passing Q-Max LNG carrier is identified, releasing LNG from one of its tanks, through a leak. A part of the LNG evaporates and in the case of an unfavorable wind direction, the evaporated gas cloud is blown towards the site. In this scenario, a largely free propagation is possible up to the vicinity of the building; a low number of obstructions is assumed in its vicinity. The available ignition energy is estimated to be low. Using these parameters, a blast of class 3 is conservatively assumed. With this and other factors, the MEM determines the peak overpressure to be p_s = 50,7 mbar. The reflection coefficient for this overpressure is determined by equation (1) to be c_r = 2.04, thus the reflected pressure is 103.4 mbar, conservatively a value of p_r = 110 mbar is chosen for further calculations. For comparison, the BMI-Richtlinie (1976) uses conservatively a pressure of 450 mbar.

Instead of using the time histories given by the MEM, reference is made to BMI-Richtlinie (1976), IfBt-Mitteilungen (1974) and DIN 25449 (2022). The BMI-time histories are scaled to a peak value that equals the reflected pressure of 110 mbar.

The overpressure time histories to be applied on the walls (horizontal) and roof (vertical) of the intermediate storage hall according to DIN 25449 (2022), are shown in Figure *3*. In contrast to the original BMI time characteristic, a slope of 50 ms duration is introduced in the vertical excitation at 0.2 s to avoid an excitation due to a switch-off effect.

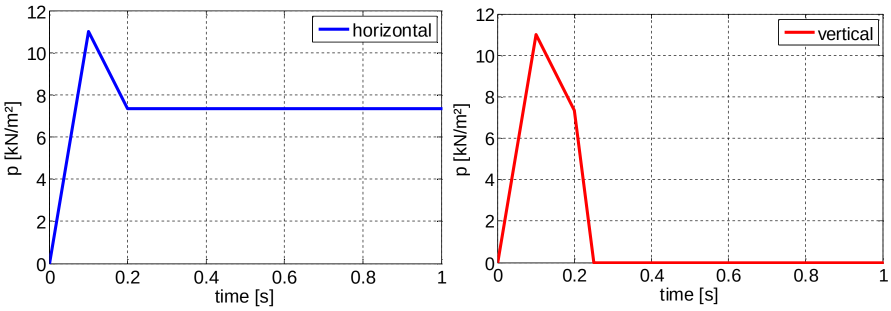

Figure 3. Pressure loading: vertical (left), horizontal (mid), application 'across the corner' for box-shaped building

For a box-shaped building, as illustrated in Figure 4, the pressure loads must be applied on three sides "across the corner".

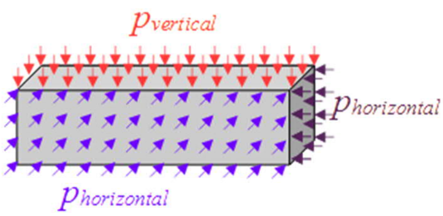

Figure 4. Application of pressure loading 'across the corner' for box-shaped building, DIN 25449 (2022)

Finite Element Model

A 3D finite element model is set up to simulate the structural dynamics of the intermediate storage hall. The hall consists of the storage hall and a small adjoining neighbouring office building. Both buildings share a common base slab. Below the base slab the pile foundation is modelled. For the hall and the base slab mainly shell elements are used, the neighbouring building uses beam, intertia and stiffness elements to simulate its dynamics. The pile foundation is modeled by beam elements and so-called "interpile" elements (Software SASSI) to map the soil between the piles. The FE model of the hall is shown in Figure 5, it includes the soil-structure interaction at the site. The FE model was originally build for seismic qualification according to KTA 2201.1 (2011) and KTA 2201.3 (2013) and reused for blast loading simulation. The soil dynamic model is derived from the documented soil parameters. The shear moduli G_{max} (max. stiff soil) and G_{min} (max. soft soil) are taken into account in the blast pressure wave investigations. To account for the variation range of the foundation stiffnesses and the distribution of the waste storage containers in the hall, four parameter variants of the FE model are established:

- Variant 1: Minimum mass (without waste containers, i.e. building mass only), soil: G_{max}
- Variant 2: Maximum mass (full occupancy with full containers), soil: G_{max}
- Variant 3: Maximum mass, soil: G_{min}
- Variant 4: Maximum mass eccentricity around the y-axis (Building mass plus mass from half-sided occupancy in longitudinal direction, maximum torsion), soil: G_{max}

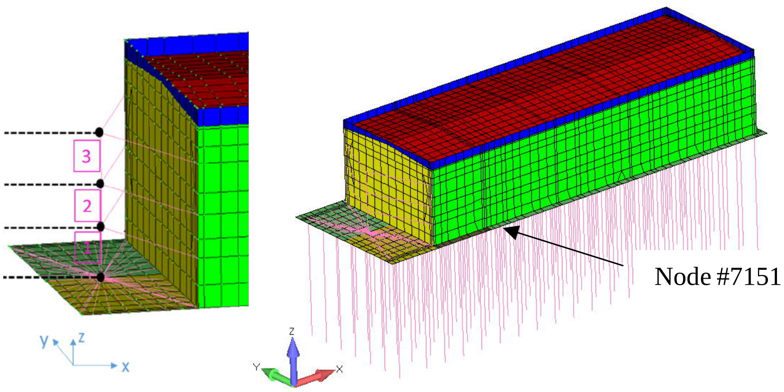

Figure 5. FE model of intermediate storage hall:
detail of modeling of office building (left), overall model (right)

The pressure time histories are applied to the FE model ‘across the corner’, i.e. simultaneously on the roof, on the wall and on the side-wall, as depicted in Figure 6.

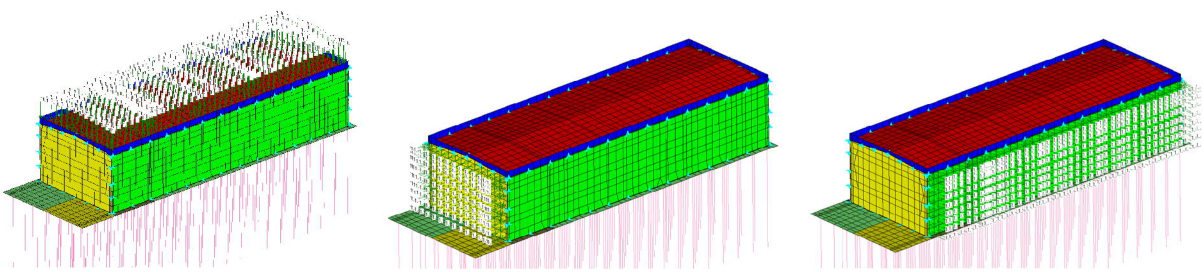

Figure 6. Application of blast loading: on roof (left), on wall (mid), on side wall (right)

For the storage hall 4 % structural damping is considered, additional damping results from the layered model of the soil.

RESULTS

Representative evaluation nodes of the FE model of the building are selected for comparison with the earthquake spectra. In the following evaluation nodes on the base plate are considered. The calculations are performed by SASSI (2019). For the four model variants the acceleration time histories of the evaluation nodes are determined. Figure 7, left, shows exemplarily the time histories of Node #7151 for Variant 2 due to blast pressure loading.

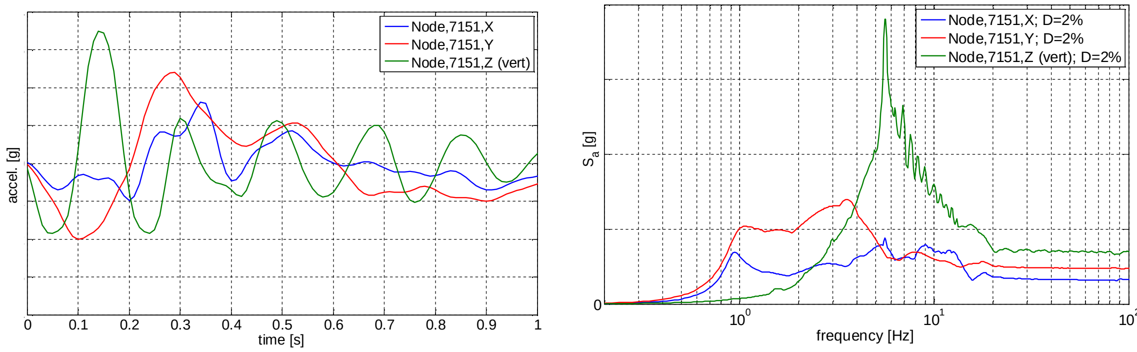

Figure 7. Variant 2, Node #7151, acceleration responses: time histories (left), response spectra (right)

Node #7151 is located at the edge of the base plate, see Figure 5. It shows a high time history response in vertical direction, the lowest response is in x-direction.

From all time histories of the evaluation nodes the response spectra are calculated for different damping values. Figure 7, right, shows the associated spectra for damping D = 2 % of Node #7151.

As SASSI does not calculate eigenfrequencies, from the response spectra of the various evaluation nodes, the eigenfrequencies can be estimated from the spectral peaks of spectra. It is found, that the lowest eigenfrequencies of the building ranges from 0.7 Hz up to 1.6 Hz, depending on model variant and direction.

In the next step the spectra are enveloped over the model variants and the evaluation nodes, afterwards a spectral design is established. This design is compared against the response spectra of a seismic calculation, for which the intermediate storage hall is already verified. Figure 8 shows the comparison for the base plate.

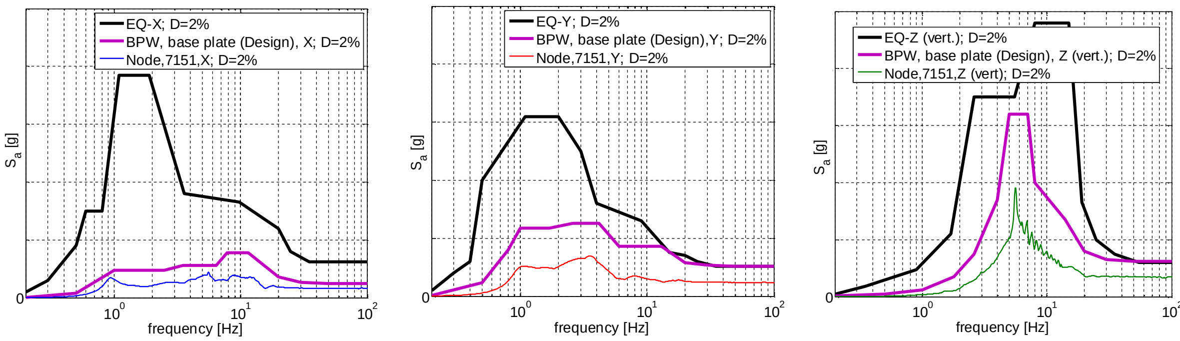

Figure 8. Comparison of response spectra: earthquake (EQ) and blast pressure wave

It can be seen from the spectra in Figure 8, that the design spectra for the blast pressure wave are below the design spectra for earthquake in each direction, thus the stability of its components is verified.

CONCLUSION

The structural analysis of the intermediate storage hall for low and medium radioactive waste in the German nuclear power plant indicates that its components, especially waste storage containers, are capable of withstanding induced vibrations from blast pressure waves resulting from a liquefied natural gas vapour cloud explosion. Utilizing the Multi Energy Method and qualitative time histories of the German BMI guideline for modeling the BPW, the study applied the blast pressure wave loading to a finite element structural model. The results, encompassing acceleration time histories and response spectra at the evaluation nodes, demonstrate that the design spectra for the blast pressure wave are below those for earthquakes, showing the stability of the storage hall's components under induced vibrations from the specified blast loading conditions.

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