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Calculation of the response behaviour of a modern German BWR reactor building including fluid-structure interaction

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ABSTRACT

Recent concepts for future German PWR and BWR provide for high-lying water storage pools to ensure core cooling by gravitation (passive system) in the event of loss-of-coolant accidents with rupture of small pipes. Dynamic excitation (e.g. earthquakes) will lead to an interaction between the water in the pools and the reactor building structure. The response behaviour of the reactor building under dynamic excitation is calculated using the finite element codes ABAQUS and PERMAS including fluid-structure interaction and the influence of the subsoil conditions on the response behaviour.

The use of nonlinear constitutive equations leads to cracks in the concrete in those regions of the floors where the tensile strength is exceeded.

1 INTRODUCTION

Recent concepts for future PWR and BWR provide for high-lying water storage pools to ensure core cooling by gravitation (passive system) in the event of loss-of-coolant accidents with rupture of small pipes. Earthquakes will lead to an interaction between the water in the pools and the reactor building structure. The response behaviour of the reactor building under earthquake excitation is calculated including fluid-structure interaction and the influence of the subsoil conditions on the response behaviour (Kloster 1993).

The finite element programs ABAQUS (Hibbit et al 1992a-c) and PERMAS (Wandinger 1989,1991,1992) are used for the calculations. The preprocessor DIAMOS (GfS 1992) is used for net and data generation and the postprocessor RAPS (Koschmieder and Altes 1980) for the representation of results. The calculations are performed on a DEC 3000-800 AXP workstation and a CRAY M94.

2 REACTOR BUILDING

A simplified cross section of the reactor building based on Siemens/KWU material (Siemens/KWU 1994) is shown in Fig.1.

The reactor pressure vessel (RPV) including the complete set of fuel rods inserted during operation and the water volume contained on average in the RPV has a total weight of 1370 t. The RPV is vertically supported by a ring-shaped concrete segment approximately in the centre of gravity of the RPV. The RPV is surrounded by 4 water pools with up to 8000 t water. The entire plant is placed on

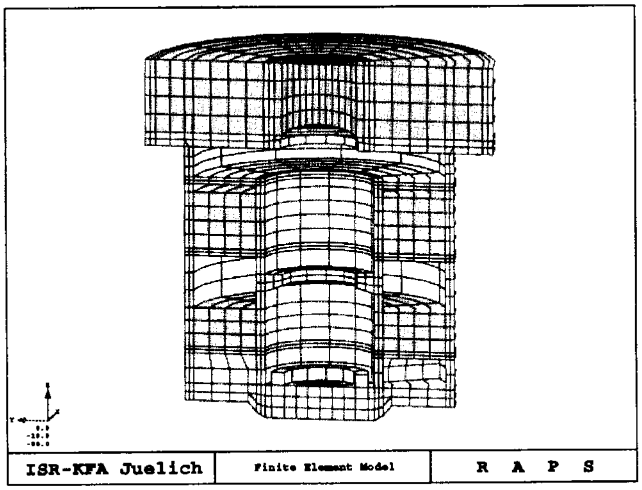

Figure 1. Cross-section of the Reactor Building

a foundation with increasing thickness towards the bottom below the RPV. The reactor hall simultaneously constitutes the containment and encloses the entire plant. It has the basic dimensions of the foundation and a height of 54.60 m with a wall thickness of 1.80 m.

3 FINITE ELEMENT NET

The structure is assumed to be rotationally symmetric. However, a rotationally symmetric finite element calculation cannot be performed because the imposed earthquake acts translationally and produces stresses in the concrete structure which are not rotationally symmetric.

The concrete structure is composed of volume elements. A sufficiently accurate approach for modelling the reinforcement is by 'smearing' the steel bars into steel plates on the concrete surface. The steel dome is formed of two-dimensional rectangle elements. The water volumes are formed of volume elements. For coupling the structure with the fluid interface elements are used. Two-dimensional elements are added on the water pool surfaces to represent free surface sloshing.

The only degree of freedom for the fluid elements is pressure. Since the pressure fluctuations at the beginning are not known for any location, the compressibility matrix of the fluid becomes singular. Every individual fluid net has therefore a constant-pressure mode.

The behaviour of the ground is simulated by a system of springs and dampers through which earthquake excitation is passed into the foundation. Spring stiffnesses and damping coefficients are estimated according to Newmark and Rosenblueth (1971) for a ground half-space below a rigid circular foundation.

For the design of German nuclear power plants with respect to earthquakes, acceleration amplitudes up to a maximum of about 0.25 g are assumed. For the following calculations the San Francisco earthquake (1953) is used with a maximum amplitude of 0.22 g and a total duration of 10 seconds.

4 CALCULATION OF EIGENFREQUENCIES

The finite element program PERMAS-FS can calculate eigenfrequencies of fluid nets and coupled fluid-structure nets. It is only applicable to problems with minor pressure fluctuations and almost resting fluids; flow problems or propagation shock waves cannot be calculated.

4.1 Eigenfrequencies of the Structure

The uncoupled structure analysis uses the solid net. The only boundary conditions are the suppression of the degrees of freedom 1, 2, 3 for all nodal points at the foundation bottom surface. The effective masses from the 1th eigenmode at 6.2 Hz up to the 50th eigenmode at 40.0 Hz accumulate to 67 % for the x- and y-directions and 63 % for the z direction. The balance up to 100 % lies in the higher modes. The dominant eigenmodes are the first two with over 50 % effective mass each. They show tilting of the structure to the side.

4.2 Eigenfrequencies of the Fluid

Only the fluid net is used to calculate the eigenfrequencies of the uncoupled fluid net. The four free surfaces of the pools consist of a total of 248 wave elements with 829 nodal points. A free surface has exactly the same number of eigenforms and nodal points. The first 829 eigenmodes of the fluid net are thus pure sloshing modes. The acoustic modes begin with the 830th mode with pressure eigenforms in the pools. Since the four water pools are not interconnected, they each have their own eigenfrequency behaviour. Every calculated eigenmode only belongs to one of the four pools.

The frequencies begin at 0.09 Hz and reach 0.35 Hz at the 50th eigenmode. They probably rise until the 829th eigenmode to about 19 Hz, the region in which the acoustic modes begin. The eigenform of sloshing mode 17 is shown in Fig. 2.

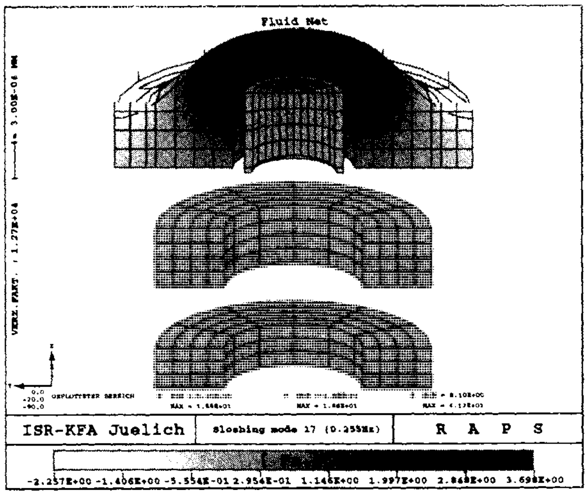

Figure 2. Eigenform of Sloshing Mode 17 (0.255 Hz)

Since the sloshing modes are exclusively vertical motions, the pressure distribution must be seen as the pressure difference from the hydrostatic pressure of the resting fluid. Positive and negative pressures occur for deflections upwards and downwards. They are of the order of magnitude from 1 to 10 Pa and can be calculated by: $\Delta p = \rho g \Delta h$. An additional pressure load on the pool walls under isolated excitation of the sloshing modes can therefore be neglected.

The acoustic modes begin at the frequency of 19.2 Hz and reach 104.8 Hz at the 50th mode. In analogy to the sloshing modes, most of the acoustic modes occur in pairs due to symmetry. Fundamental modes and harmonics also occur in the individual pools, but they are of a rotational nature with pressure gradients in the circumferential direction. The 15th eigenmode is the first occurring individually and having an eigenform similar to the pumping eigenforms with pressure gradients in the radial direction. The first compressional vibration occurs in the small upper pool for the 26th and 27th modes at 79.8 Hz.

4.3 Eigenfrequencies of the coupled Fluid-Structure Net

In analogy to the behaviour of the fluid net, two frequency ranges must also be differentiated in the coupled net. The lower range is dominated by the sloshing behaviour of the fluid and the upper range by the acoustic behaviour. However, no isolated pure sloshing forms of the fluid can be identified in the lower frequency range due to interaction with the structure, and the same applies to the acoustic pressure forms in the upper frequency range.

The first 50 eigenfrequencies of the lower range extend from 0.03 Hz to 0.19 Hz. The deflections of the structure are only caused by sloshing of the fluid. The kinetic and potential energies of the first 50 modes are with 97 - 100 % in the fluid net because the eigenfrequencies of the structure only begin at 6 Hz and are thus not excited at all in this frequency range.

The upper frequency range begins at about 3.0 Hz and reaches 32.6 Hz in the 50th mode. Sloshing of the fluid in this range cannot be interpreted due to the lack of WAVE elements. The deflections of the structure in this region are caused both by eigenmodes of the structure and by sloshing of the fluid. The pressures involved are in the range of 100 to 500 Pa and thus clearly exceed those of the uncoupled fluid net. The difference is caused by the additional impact of the vibrating pool walls on the fluid.

5 CALCULATION OF THE RESPONSE BEHAVIOUR

The ABAQUS finite element program is selected for the response analysis because it contains the option for dynamic coupled fluid-structure analysis with non-linear constitutive equations.

5.1 Static Analysis

In a first step, the loads produced by the weight of the water and RPV on the structure are calculated and substituted as external forces in the response analysis. The maxium occurring tensile stresses of $4.2 \cdot 10^6$ N/m^2 are to be found at the bottom of the upper pool above the support points and exceed the tensile strength of pure concrete amounting to $3.2 \cdot 10^6$ N/m^2. The elastic yield strength of the reinforcing steel is $4.2 \cdot 10^8$ N/m^2 and the structure thus only comes up to 1 % of this value. The ultimate elastic compressive strength of the concrete is $-2.0 \cdot 10^7$ N/m^2 and is not reached at any location of the structure.

5.2 Dynamic Analysis

For reasons of capacity and computer time, the earthquake analysis cannot be performed for the entire duration of the earthquake of 10 s. In order to estimate the impact of an earthquake despite this deficiency, an acceleration amplitude curve is assumed with 5 values covering a period of 0.14 seconds. This amplitude curve represents a segment of the above described earthquake around its peak of 2.2 m/s^2.

The vertical stresses σ_{zz} at time 0.14 s are shown in Fig. 3.

The relative deflections of the structure in the upper region become larger with progressing time. The largest stresses occur at the stress peaks already determined by the static analysis, i.e. in the water pool floors, especially in the upper pool. The

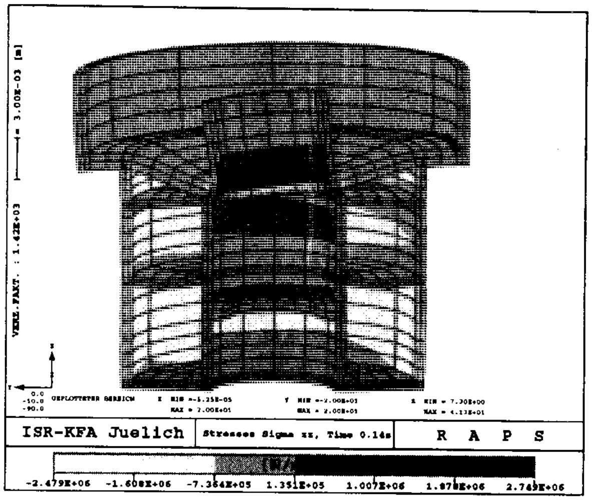

Figure 3. Vertical Stresses and Displacements after 0.14 s

tensile stress peak increases from $4.2 \cdot 10^6$ N/m^2 in the static loadcase to $9.4 \cdot 10^6$ N/m^2 at the time 0.14 s and is thus clearly above the tensile strength of concrete ($3.2 \cdot 10^6$ N/m^2). The maximum compressive stresses reach $-1.1 \cdot 10^7$ N/m^2 and are thus below the elastic compressive strength of concrete ($-2.0 \cdot 10^7$ N/m^2). The elastic limit of the reinforcing steel is not reached at any time.

5.3 Influence of nonlinear Material Behaviour

If nonlinear constitutive equations are assumed for concrete and steel, changes in the impact of dynamic behaviour only result for the concrete. As discussed before the tensile stresses exceed the ultimate strength of concrete in certain regions. This leads to concrete cracking. In the event of a longer earthquake, the cracks will sum up and enlarge at the corresponding locations. The cracks thus formed will be locally restricted. They do not cause any significant changes in the stability of the overall structure.

6 SUMMARY

The eigenfrequencies were calculated separately for the structure and fluid as well as for the coupled system. The eigenfrequency behaviour for the fluid can be divided into sloshing modes of the surface in the frequency range from 0.1 Hz to 19.2 Hz and acoustic modes with pressure eigenforms in the frequency range above 19.2 Hz. The eigenfrequencies of the structure begin at 6.2 Hz. Coupling of the two systems clearly revealed the interactions between fluid and structure. In analogy to the fluid, a lower frequency range from 0.03 Hz to 3.0 Hz with fluid behaviour dominated by sloshing and an upper frequency range above 3.0 Hz with behaviour dominated by acoustic modes were distinguished.

The assumed earthquake is approximately effective in the frequency range from 0.1 to 20 Hz with the present structure and thus covers the largest portion of the region dominated by sloshing as well as approximately the first 25 modes of the acoustic-dominated region. The dynamic behaviour of the system was calculated for an amplitude curve of 0.14 seconds duration assuming linear constitutive equations. Major displacements in the structure were to be observed, in particular, in the large upper pool with vibrations of the inner and outer pool walls. The major fraction of total stressing is allocated to static load due to dead weight. The superimposed dynamic fraction only shows major effects in some regions, especially in the floor of the upper water pool and, in part, in the floor of the central pool. These locations already showed strong deflection under static load.

REFERENCES

GfS (1992) - ANTRAS-DIAMOS. Benutzerhandbuch. Aachen.

Hibbit,Karlson & Sorensen Inc.(1992a) - ABAQUS Theory Manual.

Hibbit,Karlson & Sorensen Inc.(1992b) - ABAQUS User's Manual.

Hibbit,Karlson & Sorensen Inc.(1992c) - ABAQUS Example Problems.

R.Kloster (1993) - Finite-Element-Berechnungen zum Antwortverhalten eines Stahlbeton-Reaktorgebäudes mit mehreren Wasserspeichern bei einem Erdbeben unter Berücksichtigung der Fluid-Struktur-Wechselwirkung. Forschungszentrum Jülich, Interner Bericht KFA-ISR-IB-10/93.

D.Koschmieder and J.Altes (1980) - RAPS. Ein dreidimensionales Plotprogramm zum Test und zur Ergebnisdarstellung von Finite Element Berechnungen. Jül 1596, Jülich.

N.M.Newmark and E.Rosenblueth (1971)- Fundamentals of Earthquake Engineering. Prentice-Hall, Englewood Cliffs.

Siemens/KWU (1994) - SWR 1000. Technik der Zukunft. Ein Siedewasserreaktor mittlerer Leistungsgröße mit passiver Sicherheit. Erlangen.

H.Wandinger (1989) - PERMAS-FS. Dynamic analysis of coupled fluid-structure systems. User Manual. INTES Publication UM 407 Rev.A, Stuttgart.

H.Wandinger (1991) - PERMAS-FS. Dynamic analysis of coupled fluid-structure systems. Examples Manual. INTES Publication UM 507 Rev.A, Stuttgart.

H.Wandinger (1992) - PERMAS-FS. Dynamic analysis of coupled fluid-structure systems. Theory Manual. INTES Publication UM 307 Rev.B, Stuttgart.