

Intermediate and High Level Earthquake Testing at the HDR — Overview, Objectives, Results

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This paper serves as an introduction to the following papers presenting details on the earthquake-studies performed at the "Heißdampfreaktor" (HDR) near Frankfurt, West Germany. The HDR earthquake studies are part of the HDR Safety Program which is sponsored by the German Federal Ministry of Research and Technology. The main objective of these earthquake investigations is the verification of calculation methods relating to structure dynamics which are used for the seismic design of nuclear power plants.

Structures analyzed by tests and precalculations were the reactor building, the reactor pressure vessel, two large-diameter piping systems and one of the flood water tanks. Excitation methods used were eccentric mass shakers, snapback devices, explosives and solid propellant rockets. Some of the tests involving excitation of the building by shakers and two of the blast tests were carried out with the reactor pressure vessel and the pipes under operating conditions.

The precalculations using both linear and nonlinear methods were made by German industry groups, independent experts groups and international partners.

Soil-structure interaction can be determined accurately by means of simplified methods using frequency dependent soil springs. The reduction in the eigenfrequencies of the building (caused by the nonlinear soil behaviour) when the load was increased by a factor of 25 could be predicted. Comparison of the results obtained for the vibrational behaviour of the building show that a simplification to the rotationally symmetric shell model appears to be a reasonable compromise between simple beam models and sophisticated 3D-shell models.

The strong decrease in eigenfrequencies observed in the experiments during the transition from empty to partly filled reactor pressure vessel, and the resultant change of the mode shapes was perfectly reflected if the virtual mass of water was introduced in the calculation.

Damping values evaluated from the measurements demonstrate that for some structures damping can remain low, even at levels of response leading to local yielding, while for other structures damping was very high at a rather low level of response. It appears that the use of generalized damping values for the seismic analysis of mechanical and structural systems is not appropriate.

1. Objectives

The decommissioned Superheated Steam Reactor (HDR) at Kahl offers an excellent opportunity of studying systematically real nuclear power plants, both structural and mechanical components, with a view to their vibrational behavior when exposed to shaking. The earthquake studies performed under the HDR safety program have been conceived on the basis provided by this opportunity. The objective is to verify the structural dynamics techniques and methods of calculation used in the seismic design of nuclear power stations and to assign the various techniques in current use to their optimum range of relevance. In the integral tests, as normally performed at the HDR, the wish is dominating of coming close to reality as regards loading due to an accident and the components and systems under investigation.

Fig. 1 shows a simplified diagram of the basic procedure applied in the HDR earthquake studies. For defined excitations the responses are measured at a considerable number of reference points in the reactor building and on the mechanical equipment and, in addition, these responses are determined analytically with the help of blind precalculations. Relevant parameter studies yield a broader field of analytical results. The comparison of calculated and measured results forms the basis of post-test calculations which are carried out when the measured results are known.

2. Experimental Studies

The studies relate to the

- reactor building with its concrete and steel containment
- reactor pressure vessel with the core barrel
- pipes of the recirculation loop and primary steam line
- flood water tank.

The problems of interactions, couplings, load propagation and non-linear boundary conditions as well as the influences of operating conditions on the whole system can be better studied under the real conditions prevailing in a completed overall structure than on sub-structures in a laboratory-scale test.

Obviously, it would be desirable to simulate seismic shaking for the whole facility in support of studies on the seismic design. Since this is not possible, the typical features of an earthquake, relating to

- type of vibration
- level of vibration
- duration of vibration

have been investigated in separate groups of testing by means of different types of artificial excitation (cf. Fig. 2).

The blast tests offer a good means of reference to comparable points of excitation as involved in an earthquake. In these tests the entire facility is excited globally via the soil structure.

However, due to the constrictions imposed by a neighboring nuclear power station, it was not possible to attain the level and duration of excitations resembling a real earthquake.

In the shaker tests performed at the building the frequency range was covered which is interesting in an earthquake. The levels of excitation to be expected in an earthquake for buildings and mechanical equipment was only approximated. Load propagation through the building up to the mechanical equipment can be compared with the events taking place in an earthquake. In case of direct excitation of the components by a shaker the frequency range, the duration of excitation and the level of excitation attained in the test comprise the values to be considered with respect to an earthquake.

The snapback tests were performed in order to achieve high excitation of components also in the low-frequency range.

A synopsis of the maximum responses obtained relative to the point of measurement and the propagation of load via the chain of structural components for different types of excitation is contained in Fig. 3.

By solid propellant rockets the HDR reactor building was excited to vibrate through local pulses. These tests were prerunners of planned study program on the airplane impact load case.

3. Theoretical Studies

For some experimental load cases and selected reference points the responses and loads were determined analytically prior to the tests; the respective precalculations were performed by two working groups which had to solve problems in parallel.

As in practical licensing the structures of the building were investigated by means of calculation and the values of the resulting responses of the buildings were passed on to persons responsible for the calculation of the mechanical equipment. Consequently, in every working group both the load propagation "vibrational excitation - vibrational behavior of the building - vibrational behavior of the component" and the propagation of effects "excitation - vibrational behavior - dynamic load" were investigated (see Fig. 4). The real structure was described by widely used FE-models. In contrast to practical licensing, no conservative assumptions whatsoever were made in the precalculations in order to be able to describe the real behavior in the best possible way.

4. Results

Selected test results and a first comparison with the results of precalculations have been published in quick-look reports /1, 2, 3/ and will be dealt with in more detail in the following papers. The future evaluation of the investigations will be governed by the list of problems treated in the earthquake studies at HDR; it is shown in Fig. 5.

Within the first problem area the studies deal with the evaluation of reality, which means that the situation prevailing at the HDR as well as the question of possible differences between the "planned reality" normally integrated in the designing procedure and the actual conditions in the completed facility are treated with priority. The effects of deviations from reality on the calculation of the vibrational behavior and the loading of the facility under consideration are examined. Information about this point form the basis for appraisal of the precalculations using the measured results and, in addition, the knowledge so obtained provides important indications of the scattering band to be expected in a completed facility.

Under the heading description of reality the problems have been summarized which are linked to the transformation of the structure described by plans and material data into a model for calculation. This includes questions of adequate treatment in a model, the complex problem field of the simplified description of the interactions between the soil and the structure, questions of load propagation, the capability of decoupling mechanical equipment, and adequate consideration of the non-linear behavior of pipework supports. Information needed to solve the problems mentioned here of evaluating and describing reality can be obtained in most cases but indirectly via the effects different situations or approaches have on the vibrational behavior; detailed comparisons of calculated and measured results are needed here. The analysis of the natural vibration behavior must be treated first; it is essentially determined by the parameters of stiffness, mass and the real boundary conditions and their description in a model.

The resonance frequencies measured for some modes are compared in Fig. 6 with the precalculated natural frequencies for the reactor building. The frequency ranges for the individual resonance modes, determined from the measured results, have been obtained from tests performed at different levels of excitation; resonant frequencies were measured, e.g., at six different excitation levels for the basic modes of the building, i.e. rocking mode in the X and Z directions. Further details will be indicated later-on. The frequency ranges obtained by the different models for calculation are the results of computations involving parameter variation for load dependent stiffness values.

The frequencies of the rocking and in-phase torsional vibrations of the reactor building (RGE) are determined above all by the stiffness and layering of the soil and by the geometry of embedding. The building itself exerts an influence on these frequencies by its total mass and moment of inertia. The good agreement between the calculation and the measurement, especially with respect to the beam models, in which frequency dependent soil springs have been used, taking into account the layering of the soil, shows that the interaction between the soil and the structure can be satisfactorily described by soil springs and that the real conditions in the HDR soil were recorded by seismic in-situ measurements. The frequencies of the bending and out-of-phase torsional vibrations of the reactor building are mainly determined by the stiffness and masses of the structures of the building. The stiffness in the foundation at the point of coupling between the inner and outer structures plays a particular role. It is obvious from the comparison of the calculated and measured results that reference to the construction documents allowed to record with sufficient accuracy the stiffness and masses of the building. The expensive three-dimensional shell model GRS 1 describes best the real vibrational behavior. The rotational-symmetric shell model KWU 1 allows to describe similarly well the bending mode whilst the torsional stiffness of the building is estimated at a too high value.

As already mentioned, the frequencies of the fundamental modes of the building, the rocking modes on the soil, have been determined for different levels of excitation in the shaker tests. These values have been plotted in Fig. 7 versus the vibrational excitation. The arrows in the lines connecting the values indicate the time sequence of the tests. Initially, a distinct reduction in frequency can be observed with increasing excitation. In the subsequent tests performed at a lower excitation reduced resonant frequencies were measured which are well below the frequencies measured prior to the tests conducted with higher excitations. This means that the dynamic properties of the soil/structure system have undergone permanent changes by the tests performed at high excitation.

The influence of water filling on the vibrational behavior and the suitability of simplified methods of calculation for evaluating this behavior were of topical interest in the investigations relating to the reactor pressure vessel. In the tests without water filling a coupled vibrational behavior was recognized of the RPV and core barrel. In each of the two main planes of vibration an in-phase bending vibration of both sub-structures occurred at 12 - 13 Hz and an out-of phase bending vibration at slightly more than 16 Hz. In the tests with water in the RPV (filling level 6 m) only bending vibrations of the core barrel occurred at about 7.3 Hz already. The out-of phase bending vibrations of the RPV and core barrel were identified to occur between 12.2 and 13.2 Hz although much smaller relative displacements were measured between the vessel and the core barrel as compared with the tests without water. The comparison in Fig. 8

of the vibrational modes measured for the RPV and the core barrel in these tests with and without water filling of the RPV clearly reveals the basic differences of the measured results.

In the precalculations relating to the water filled vessel the influence of water on the vibrational behavior was taken into account by two different simplified methods:

- the real distribution of water masses, implying that the water mass actually present in the reactor pressure vessel was added to the mass of the structure as an additional weight per unit area;"
- the virtual distribution of water masses according to which a fictitious weight per unit area is calculated considering the fact that the evaluation of physical water elements (depending on the geometry of the arrangement) may give much higher or differently oriented values than those applicable to the structure elements to which the substituting masses are added (e.g. flow in the annular space between the core barrel and the RPV in case of relative displacement).

The comparison between the measured and calculated results clearly shows that the basically different vibrational behavior of the water filled vessel as compared to the empty vessel, indicated by the measured results, was much better predicted by the second method.

Damping plays a dominant role in licensing because it exerts major influence on the level of dynamic loading. Since the actual damping of the structure of mechanical equipment is in most cases determined to a greater extent by inadequacies in workmanship (e.g. welding seams), by the conditions prevailing at the points of support (friction, restraints) and by other influences than material damping proper, realistic damping values can hardly be determined from theoretical approaches and laboratory testing. But the determination of damping from the values measured in the HDR tests also involves problems. For example, in the snapback tests performed on the primary steam pipe very high damping values of 8 - 15 % were found for the fundamental modes. On the one hand, this is due to the high excitation in these tests and to the fact that damping generally increases with increasing load. On the other hand, the snapback tests in particular are susceptible to the fundamental risk that too high damping values are derived from the decay of vibration because also the energy propagated into adjacent structures and not only damping of the structure contributes to the dying down of the movement. This danger does not exist in the shaker tests as long as sufficient energy of excitation is available. For the primary steam line damping values of 3 - 6 % were obtained dependent of the degree of load. For the flood water tank partially filled with water damping values of about 0.6 % were determined from the shaker tests for the fundamental bending modes. Decay of vibration tests and a snapback test yielded values of about 0.3 %.

For this free standing vessel the transmission of energy does not play a role so that these values can be considered to be realistic. To assess the influence of the water filling level on damping, a decay of vibration test was also performed on the empty vessel. It can be calculated from the measured results shown in Fig. 9 that the frequency of the fundamental mode increased from 2.5 to 4 Hz and damping from 0.3 to 0.8 % after the vessel had been emptied. The small damping of the fundamental modes of the HDR flood water tank is probably linked to the design of the tank support which implies that great deformations occur only within a closely limited zone of the dished end near the corners of the supporting system. Actually, very high stresses were found at these points during the tests. In the snapback test local strains of up to 2.6 % occurred here; consequently, the yield strength of the material was exceeded.

The results indicated in this paper are examples of a great number of detailed information which will be evaluated during the years 1981 and 1982. The amount of knowledge expected from this evaluation will form the basis of recommendations helping to solve the problems listed in Fig. 5.

The following papers will supplement this paper and describe some details of the experiments or precalculations. They will make clear the basis from which the work of evaluation has started.

References

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CHARACTERISTIC OF EXCITATION	BLAST TESTS	SHAKER-TESTS REACTORBUILD	SHAKER-TESTS BUILD. COMP.	SHAKER-TESTS COMPONENTS	SNAPBACK
PLACE OF EXCITATION					
EXCITATIONLEVEL					
DURATION OF EXCITATION					
FREQUENCY RANGE					

 COMPARABLE WITH EARTHQUAKE
 PARTLY COMPARABLE WITH EARTHQUAKE
FIG. 2 COMPARABILITY OF ARTIFICIAL EXCITATION AND EARTHQUAKE

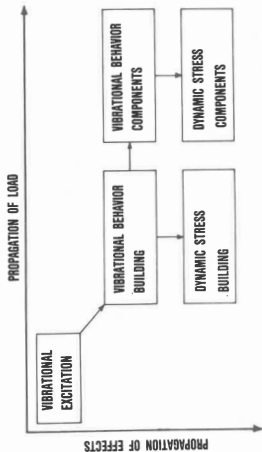


FIG. 4 PROPAGATION OF LOAD AND EFFECT

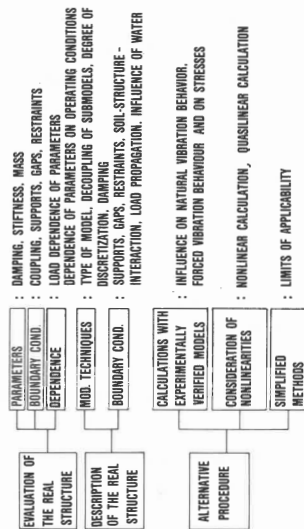


FIG. 5 POINTS OF INVESTIGATION

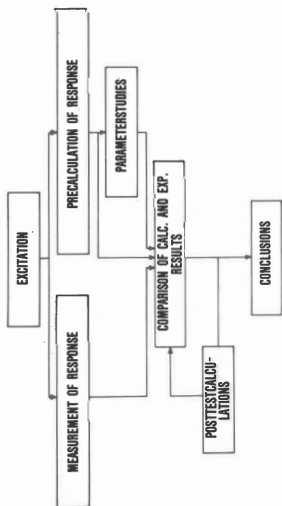


FIG. 1 PROGRAM OF HDR-EARTHQUAKESTUDIES

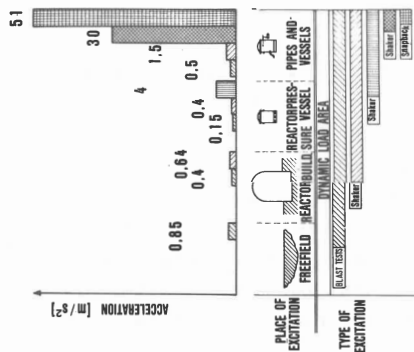


FIG. 3 MAX. RESPONSES

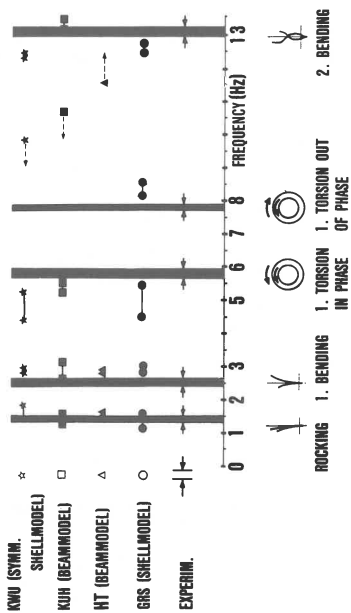


FIG. 6 / MODES OF REACTORBUILDING

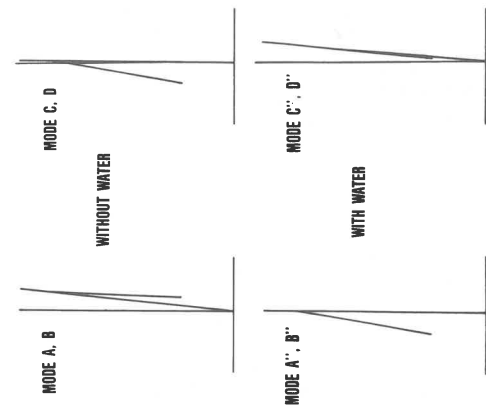


FIG. 8 MEASURED MODES OF RPV WITH COREBARREL

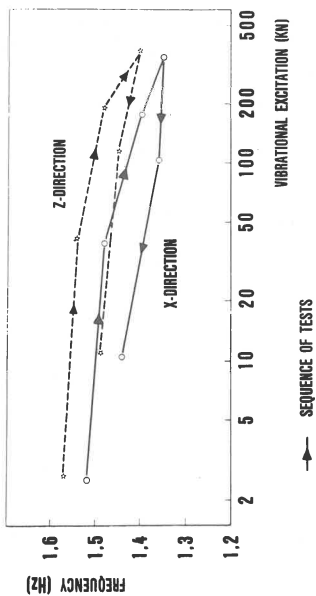


FIG. 7 RESONANT FREQUENCIES OF ROCKING OF REACTORBUILDING

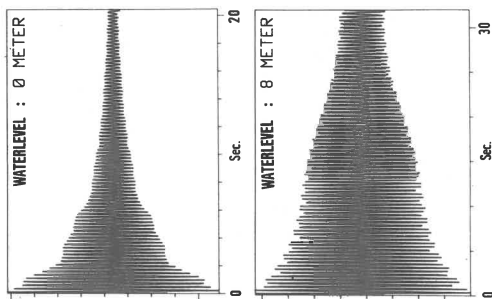


FIG. 9 SNAPBACKTEST FLOOD WATER STORAGE TANK

