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ABSTRACT

As part of the second phase of vibrational/earthquake investigations at the HDR (Heissdampfreaktor) Test Facility in Kahl/Main, FRG, high-level shaker tests (SHAG) were performed during June and July 1986 using a coast-down shaker capable of generating 1000 tons of force. The purpose of these experiments was to investigate full-scale structural response, soil/structure interaction, and piping and equipment response under strong excitation conditions. While global safety considerations imposed load limitations, the HDR soil/structure system was nevertheless tested to incipient failure. The performance of pipe support systems in as many as seven different multiple support pipe hanger configurations, ranging from flexible to stiff systems, was evaluated in the tests. Data obtained in the tests are used to validate analysis methods.

The vibrational/earthquake investigations at the HDR are continuing with the SHAM experiments, planned for the Spring of 1988. In these experiments the VKL piping loop will be subjected to direct multiple-point excitation at extremely high levels. The objective is to investigate different pipe support configurations at extreme loading, to establish seismic margins for piping, and to investigate possible failure/plastification modes in an in situ piping system.

1. Introduction

The Heissdampfreaktor (HDR) Test Facility in Kahl/Main, Federal Republic of Germany (FRG), has been used since 1975 to perform vibrational, thermal hydraulic, blowdown, and other experiments related to the design and safety of nuclear power plants. During the current second phase of the HDR Safety Project (PHDR) vibrational/earthquake investigations, the HDR system is being tested at high levels of excitation. The centerpiece of these investigations is the high-level shaker tests (SHAG), which were performed at the HDR facility in June and July 1986. Their purpose was to investigate full-scale structural response, soil/structure interaction, and piping and equipment response under strong excitation conditions, i.e., under excitation levels that will induce significant strains in the structure and soil and produce nonlinear effects in the soil/structure system and piping. As with all HDR experiments, the primary intent of the SHAG tests is to verify and validate calculational procedures and analysis methods. At the same time, the experimental data provide direct information on the response and performance of structural systems, piping, and equipment under high dynamic loading; such information may have direct applicability to understanding the behavior of nuclear power plant systems.

The SHAG experiments were performed as part of the PHDR tests conducted by the Kernforschungszentrum Karlsruhe (KfK), and were supported by the FRG government and the U.S. Nuclear Regulatory Commission, Office of Research (NRC/RES). The NRC involvement relates primarily to a program on the validation of seismic calculational methods conducted by Argonne National Laboratory (ANL) for NRC/RES. Additional participants in the SHAG experiments included the Electric Power Research Institute (EPRI), German as well as U.S.

industries, and the Idaho National Engineering Laboratory (INEL), which represented the equipment qualification interests of NRC/RES.

The details of the SHAG experiment design and test performance have been described previously [1-3]. Here a brief overview of the SHAG tests and highlights of test results are presented as are some preliminary results of the validation of a piping analysis method. Finally, the plans for the upcoming HDR-SHAM experiments are described. In these tests the in-situ VKL piping system will be subjected to direct very-high-level multiple-point excitation. The objectives of these experiments are to study pipe behavior/failure at extreme loading and to establish seismic margins for piping. At the same time the behavior and fragility of equipment (valves, snubbers, pipe mounts) will be evaluated.

2. SHAG Experiments

In the SHAG experiments a large eccentric-mass coast-down shaker capable of generating forces in excess of 1000 tons (metric) was mounted on the operating floor of the HDR building as shown schematically in Fig. 1. The shaker was designed to develop maximum accelerations of HDR building of the order of 5 m/s^2 and maximum displacements of about $\pm$ 7 cm. Test starting frequencies ranged from 1.6 to 8.0 Hz [1,2].

The purpose of the SHAG tests was to investigate full-scale structure/soil, equipment, and piping response under strong vibrational excitation and to validate predictive analyses. While the interests of PHDR/KfK and NRC/RES include all aspects of the SHAG testing, most other participants focused primarily on the behavior of piping systems. In particular, the response of the Versuchskreislauf (VKL) piping system with different multiple support (hanger) configurations was of interest to all participants.

The VKL piping (Fig. 2) consists of a number of pipe runs ranging in nominal size from 100 to 250 mm. The piping is attached to the HDU vessel and associated manifolds and forms part of the experimental piping system at the HDR facility. The top of the pipe runs at about 28 m above ground level, just under the HDR operating floor (where the shaker is located). The original HDR hanger system provided primarily vertical dead weight support, and consisted of 6 spring and constant-force hangers and one threaded rod. To avoid possible permanent damage to the VKL piping two rigid struts, adjacent to the spherical tee (Fig. 2) were added to the support system. The intent was to compare in the SHAG tests the performance of this very flexible conventional support system with a typical U.S. stiff support system containing snubbers and struts. Also, as part of the NRC/RES Equipment Qualification Research Program, INEL intended to evaluate the performance of a typical U.S. gate valve during SHAG testing. Accordingly, an 8-in. valve was incorporated into the VKL piping system. INEL then designed a typical U.S. hanger system, adding six snubbers and six rigid struts to the VKL hanger system and replacing one of the German spring hangers with a much higher rated hanger of the same type to accommodate the added weight of the valve.

EPRI and its industry associates intended to evaluate two additional hanger configurations. The first of these, designed by Bechtel Corporation, consists of four energy absorber supports that damp out the motion of the piping through the plastic deformation of an assembly of steel plates incorporated into the support. The other configuration uses seismic stops, designed by R. L. Cloud and Associates, that replace all six snubbers. This system allows free motion until a certain displacement is reached, at which the pipe impacts the stops, limiting further movement in the given direction.

As part of German industry contribution to the SHAG experiments, Kraftwerk Union (KWU), Offenbach, FRG, designed a hanger system for the VKL piping that uses, in addition to the dead weight supports, only five rigid struts placed so as to prevent large dynamic motions of the piping. With the agreement of all participants, two additional hanger configurations were incorporated into the test program. In one case, two viscoelastic dampers designed by Gerb, Berlin, were added to the KWU hanger configurations. In the other case, the six U.S. snubbers were replaced by modified viscoelastic dampers designed by ANCO Engineers, Inc. All the alternative hanger designs of the VKL piping system were motivated by the desire to replace snubbers, which have proved troublesome in nuclear power plants. Therefore, the objective of these experiments was to compare and evaluate the behavior of the VKL piping system with the different support systems under identical loading conditions. Table 1 provides an overview of all the VKL hanger configurations used in the SHAG experiments.

A total of 460 channels of instrumentation used during the SHAG tests, provided measurements of all important response parameters including the safety aspects of the HDR and neighboring facilities [3]. In planning the SHAG tests it was the intention that the loading of the HDR facility be limited not by the excitation system but rather by the capacity of the building itself. Nearly all tests were designed to generate nominally the same peak force of 10^4 kN, at different starting frequencies of the shaker. Higher shaker frequencies (8.0 to 4.5 Hz) were intended primarily for piping excitation, while the lower frequencies (1.6, 2.1, and 3.1 Hz) were intended primarily to challenge the soil/structure system.

Results of safety calculations [3,4], best estimate calculations [5] and the functionality tests indicated that some of the test runs would challenge the HDR building beyond its capacity limits. In particular, it appeared that test runs which strongly excite the building's rocking mode (nominally at 1.4 Hz) and its out-of-phase bending mode (at 2.5 Hz) would have to be curtailed. This was confirmed by some early test runs [3].

The tests actually performed and their sequence are listed in Table 2. As indicated, only the 8.0, 5.6, and 6.0 Hz tests were performed at or near full load (10^4 kN); all other tests were performed at reduced loads. Only the 4.5-Hz runs were performed with hot conditions in the piping system. All tests at 3.1 Hz and 2.1 Hz (at full load) were dropped to avoid challenging the walls of the outer shield building, which experience their most severe strains in the out-of-phase bending mode. The 1.6-Hz tests, which involve the rocking mode, were limited to a maximum eccentricity of 67,000 kgm or about two-thirds of full load.

3. Highlights of SHAG Results

In spite of the limitations imposed on the testing, the overall goals of the SHAG tests were achieved. Peak accelerations and displacements in the HDR building were quite substantial, reaching maxima of 0.4 g and 5 cm, respectively. Nonlinear behavior of the soil/structure system was clearly observed. Much local damage occurred, such as concrete cracking and interior masonry wall collapse. Substantial amounts of energy were transferred to the surrounding soil, particularly during experiments challenging the rocking mode (1.6-Hz runs). This is evidenced by the high accelerations measured in the soil, cracking of soil (circumferential) away from the building, separation at the soil/structure interface, and soil subsidence (~ 10 cm). Impact occurred between the HDR building and the equipment tower as well as the connecting bridge to the office building. Strains in the walls of the HDR shield building approached or exceeded their estimated limit values. Accelerations and motions of the VKL piping measured in the SHAG tests are comparable with values expected during strong-motion earthquakes. Settling measurements made after the tests indicate a maximum differential settlement of the foundation basemat of 8 mm, which corresponds to a horizontal displacement at the top of the reactor building of 20 mm.Because of the large amount of data accumulation from the SHAG tests, data analysis is still in progress at all of the participating organizations and will continue for some time. However, preliminary results on the response of the site and structure, soil/structure interaction, and the behavior of the VKL piping system have already been reported [6,7].

3.1 HDR Site and Building Response

Of major concern during the experiments was the response of the spent fuel-storage pool at the VAK. Figure 4 shows the decay of the peak vertical acceleration in the soil with radial distance from the HDR containment. The peak value of 0.031 m/s^2 at 100 m (VAK location) is approximately one-thirtieth of the acceleration measured adjacent to the HDR building and is more than one order of magnitude lower than the stipulated safety limit.

To illustrate the behavior of the HDR building during the SHAG experiments, reference is made to the schematic cross-section of the building shown in Fig. 1. A typical sequence of events during an 8.0-Hz test with the smallest shaker eccentricity of 4,700 kgm is shown in Fig. 4. The shaker frequency versus time plot in Fig. 4a shows the shutoff of the drive system at about -0.65 s, the start of the experiment due to the release of the movable shaker arm and the impact closing of the arms at 0 s, as well as the subsequent coastdown of the shaker. The decay of the shaker frequency is primarily due to energy transfer to the building; air drag and bearing friction play a secondary role. The decay of the shaker force, corresponding to the shaker frequency, diminishes in 100 s from a value of 118,000 kN at 8.0 Hz to about 250 kN at 1.2 Hz (Fig. 4b). In the first 20 s, at frequencies above 4 Hz, the acceleration response of the building is dominated by global torsion modes. This is followed by a relatively quiet period until at 60 to 65 s when the shaker traverses the out-of-phase bending mode of the building (at about 2.5 Hz). Finally the rocking mode (about 1.4 Hz) is reached after 90 s. This is seen from the response on top of the outer containment in Figs. 4c and 4d. It should also be noted that both the characteristics and the amplitude of the response in the two horizontal directions show significant differences, indicating asymmetries of behavior.

The sequence of events for the SHAG experiment with the largest eccentricity (67,000 kgm) and smallest starting frequency of 1.6 Hz (Test T40.13) is quite different. Immediately after the start of the test and even before the two arms are closed at time zero, the building responds with strong vibrations in its rocking mode. After 10-12 cycles, most of the energy is dissipated through the damping of the building, and the shaker passes through the resonance and subsequently coasts down with slowly diminishing frequency [6].

To investigate the dynamic characteristics of the HDR building (i.e., modal frequencies and damping), it is necessary to eliminate the effects of the forcing, which varies as the square of the shaker frequency. Thus, transfer functions between the excitation force and responses in the building were constructed [3,6]. The results clearly indicated the nonlinear behavior of the building, particularly in the rocking mode, which is dominated by soil/structure interaction, e.g., shifts in the resonance frequency were observed.

Further investigation of the building behavior showed that the maximum horizontal responses did not occur in the direction of the global coordinates x-z in which the measurements were taken [6] (see Fig. 1). Depending on the test, the principal horizontal responses occurred in two orthogonal directions, x'-z', that were rotated from the global coordinate system by an angle that varied from 35° to 55°. Recasting the measured values into this principal (x'-z') coordinate system provided consistent results for both the resonance frequency variation and damping of the rocking mode. This is illustrated in Fig. 5, which gives the rocking mode frequency and damping as a function of shaker eccentricity, i.e., load at resonance. The resonance frequency in the x'-direction is consistently lower than that in the z'-direction. Its value drops from 1.35 Hz at the smallest loading to 1.05 Hz at the maximum load. The observed rocking frequencies at minimum loading are consistent with values observed in earlier experiments conducted with forcing levels of the order of 500 kN [6]. The damping values shown in Fig. 5 indicate no specific differences between the response in the x'- and z'-directions. In general, the trend is as expected, i.e., damping increases with loading. However, the scatter of values is large with the highest damping value at minimum load exceeding the lowest damping value at maximum load. It should also be noted that all the damping values are significantly higher than the 4.4 to 5.5% damping observed in earlier lower level experiments. The results presented here fully confirm the nonlinear nature of the HDR soil/structure system response during the SHAG experiments.

3.2 Dynamic Response of VKL Piping

As mentioned earlier, the VKL piping (Fig. 2) was tested in a series of test runs with up to seven different pipe hanger configurations (Table 1). Two schematics of the VKL piping are shown in Fig. 6 indicating typical measurement locations for accelerations, stresses and forces. Measurements of acceleration were also made on the walls adjacent to the piping.

To investigate the dynamic behavior of the piping, acceleration transfer functions between the piping responses and the wall responses were constructed [3,6]. In the case of the stiff NRC snubber configuration using the location VKL 610 on the pipe (see Fig. 6), the first mode is identified around 5.7 Hz with a damping estimated to be about 3%. Eliminating snubbers (Configuration 2) or exchanging them for other supports (Configurations 4, 5, 7) leads to more response amplification in this section of pipe and to peak broadening of the principal mode. The very soft Configuration 1, on the other hand, shows very different behavior, with a multiplicity of resonances in the low-frequency range from 2 to 5.5 Hz. However, all of these modes exhibit less amplification than the peak amplification for Configuration 3. Response amplifications at other locations of the pipe may be different and it was shown that pipe stresses and strains follow a very different pattern [3,6].

No general conclusions on the relative merits of the different pipe support systems can be drawn on the basis of these examples. Because of the decaying force of the coastdown shaker with decrease in frequency, the actual force level at resonance for one pipe hanger configuration may be very different than for another system. Hence, such direct comparison of the data for the various configurations may lead to erroneous conclusions. A different approach is required and is outlined below.

4. Evaluation of Pipe Support Configurations based on SHAG Test Results

One purpose of the SHAG experiments was to compare and evaluate the performance of different pipe support configurations, and to assess their advantages and disadvantages. Of particular interest was the performance of a typical stiff U.S. support system using snubbers as well of systems using snubber replacement devices namely energy absorbers and seismic stops (see Table 1).

During the SHAG experiments each of 5 different pipe support systems was tested under 3 identical conditions (see Table 2). As seen earlier each of the different support systems markedly alters the VKL vibration response, in particular if one compares the soft support system 1 (HDR) with the stiff support system 3 (NRC). Therefore, to make a realistic comparison, it is necessary to provide broad-band excitation which covers the entire earthquake frequency range and which is identical for all configurations. For various reasons, this was not possible in the SHAG experiments; in particular the coverage of the frequency range was quite uneven. This can be readily seen in the typical HDR floor response spectra shown in Fig. 7 (upper figure) obtained for a 4.5, 6.0 and 8.0 Hz test run. The experiments with starting frequencies of 4.5 and 6.0 Hz provide significantly lower excitation than the 8.0 Hz runs, leading to lower excitation in general in the frequency range below 5.0 Hz.

This falsifies any comparisons of stiffer support systems (which have higher eigenfrequencies), with softer support systems (which have lower eigenfrequencies).

4.1 Assessment Approach

To alleviate the problem discussed above the following approach is taken:

- In each experiment the maximum values in the response spectra of the 4 most significant building response measurements are averaged.
- Using these average values, weighting or scaling factors are derived (see Table 3). These represent the ratio between an acceleration value of 40 m/s^2 and the average maximum acceleration in a given experiment. The value of 40 m/s^2 corresponds to the highest level reached in the 8.0 Hz experiments. The 4.5 and 6.0 Hz spectra can then be scaled by these factors. As shown in Fig. 7 (lower figure), such scaling results in the broad-band coverage of the relevant frequency range, and provides the necessary basis for the comparison of the support configurations.
- For each separate experiment all the maximum values of the measured parameters are then scaled by the weighting factor applicable to this test.
- For each measurement location and support configuration, the "absolute largest value" is then selected among the maximum values of the separate experiments with the three starting frequencies.
- The comparison of the hanger configurations is then performed on the basis of these "absolute largest values" at the measurement locations shown in Fig. 6.

In the above approach it is tacitly assumed that linear scaling of maximum response values is permissible. An argument in favor of this is the fact that in spite of excitation levels corresponding to a safe-shutdown earthquake (SSE) the nominal pipe stress levels remained well within the linear range. It is realized that other nonlinearities (e.g., dry friction, gaps, impact effects) are affected in different ways by excitation level and may enhance or reduce the maximum response values. Therefore, when using the linearly scaled values (rather than the direct measurements) in the evaluations, the stiffer support configurations 3, 4 and 5 (and in particular the stiffest system 5) are assessed more favorably.

Since the calculated weighting factors have coefficients of variation of only a few percent (see Table 3), the scaling causes no problems for comparisons of different support configurations within a single test series with a given starting frequency. This simplifies the comparisons of the configuration with snubbers (3) with the configurations using snubber replacements (4,5). Nearly all the scaled maximum values for these configurations occurred for the 6.0 Hz-experiments. Hence, the approach taken here only confirms that the assessment for these configurations should be made on the basis of the 6.0 Hz runs. Only for the softer configurations (1,2) is it necessary to rely to a large extent on values from the 4.5 Hz experiments. On the other hand the 8.0 Hz experiments are of little significance in the comparisons of weighted maximum values.

4.2 Assessment Results

The comparisons of configurations 1, 2, and 3, i.e., soft/intermediate/stiff pipe support system; are presented in Figures 8 and 9.

Accelerations: Accelerations of the piping provide a measure of the loading of secondary components. It can be seen (Fig. 8) that for the soft HDR configuration (1), the accelerations are throughout smaller than those of the stiff NRC configuration (3). This is not unexpected, since the eigenfrequencies for the soft system are definitely lower than those of the stiff system. The corresponding values for the intermediate KWU system (2) lie in general between the values of the soft system and the stiff system.

Strut Forces: Of the two most highly loaded struts adjacent to the Spherical Tee (see fig. 6), the loading of hanger H4, which has the lower forces, is reduced through the installation of additional supports in configuration 3. However, for hanger H5, which has the highest forces, the loading is further increased (see Fig. 8).

Pipe Bending Stresses: In the larger, 200 mm (8"), pipe, containing the NRC valve, Fig. 9 shows that for the stiff NRC support system (3) the stresses are reduced in the region of lower stress but are increased in the more highly stressed region. This correlates with strut forces and is probably caused by the strong bending mode in this region of the NRC configuration.

Comparing the bending stresses of the smaller 100 mm (4") pipe, it is readily seen that the soft HDR configuration (1) has significant drawbacks. The normalized (scaled) maximum stresses are the highest observed in any of the systems. This is due to the fact that the 100 mm piping in this configuration has absolutely no horizontal supports. For the KWU configuration (2) with three additional supports on this pipe the stresses at both ends are easily reduced to acceptable levels.

Based on the above comparison it appears that the KWU configuration (2) with 5 struts provides overall (for all measurements) the most favorably balanced response. An assessment based on normalized values, which tends to even out the possibly lower excitation of the softer support systems in the SHAG experiments, does not indicate any advantages for the stiff NRC configuration (3) relative to a reasonably compliant support system. On the other hand a very soft system with completely unsupported pipe runs such as the HDR configuration, may experience unacceptable high stresses (and probably displacements) under earthquake-like loadings.

The second important evaluation of the SHAG data concerns the performance comparison of the NRC snubber system (3) with the snubber replacement systems, i.e., energy absorbers (4) and seismic stops (5). The results are shown in Figures 10 to 12.

Accelerations: The maximum values of the accelerations (Fig. 10) for the snubber replacement configurations are in general comparable or smaller than those of the snubber-system (3), with two exceptions:

- For the seismic stops (5) accelerations are high in the vicinity of the pipe reducer (VKL 601). Here, the seismic stops permit unrestrained axial motion, while the other two systems provide a certain amount of axial restraint.
- The energy absorbers (4) exhibit high accelerations in the region of the small diameter pipe (VKL 610). Since no attempt was made to replace the function of vertical snubber H12 in the energy absorber system, this could be considered as a design error.

Strut Forces: The maximum values of the strut forces (Fig. 10) are all comparable, with the exception of the very large force at H5 for the NRC configuration (3). As noted earlier, this is attributed to the strong bending mode in this region of the pipe for the NRC configuration.

Pipe Bending Stresses: In the larger (200 mm) pipe the bending stresses (Fig. 11) are again comparable, except for the high values at location VKL 621 adjacent to hanger H5 for the NRC configuration (3). In the smaller (100 mm) piping all values of the bending stresses (Fig. 11) are comparable, with one exception, namely for the energy absorber system (4) at location VKL 616. This is at the end of the small pipe near the DF 16 manifold. The result correlates well with the high accelerations recorded at location VKL 610. The reason for this is that no attempt was made in the energy absorber system to compensate for the action of the snubber at H12.

Snubber and Snubber-Replacement Device Forces: As seen in Fig. 12 the energy absorbers (4) in general apply somewhat smaller forces to the piping than the snubbers (3). On the other hand because of the impacts in the seismic stops (5) loads with high impulse-like forces are introduced into the piping.

In summary it can be stated that, based on the SHAG experiments, the energy absorbers exhibit no basic disadvantages relative to snubbers. The high acceleration and stresses in the small diameter (100 mm) pipe line are, according to this evaluation, attributable to an error in the support system design. The experimental evaluation also indicates that seismic stops may be another possible alternative to snubbers, in particular in their new strut-like design. However, it remains to be demonstrated if pipelines and components can tolerate the high impact forces, or if the seismic stops concept must be modified through some sort of impact damper.

5. Calculational Efforts

Pretest and blind posttest calculational predictions were performed by a number of organizations; other calculations are still in progress [7]. Besides the already mentioned safety [4] and best-estimate [5] calculations for the HDR soil/structure system, other computational efforts were concerned with the applicability and limits of approximate methods for nonlinear soil/structure interaction, quantification of safety margins in seismic design calculation and load determination of plant components, and the applicability of probabilistic structural analysis for seismic design and load determination of plant components. Some of these computations included the modeling of the coupled shaker-building response while others started with the measured force inputs of the shaker. Evaluation and comparison with measured values are nearing completion.

Similarly, computational efforts were also undertaken with respect to predicting the response of the VKL piping system. The calculations include static design calculations, quantification of the safety margins of the linear methods used for design, evaluation of the effect of different hanger configurations on the stresses in the pipe system, and validation of a piping code with multiple support load input [7]. Some of the calculations, evaluation of the results, and comparison with the SHAG test measurements are still in progress.

Of particular interest are preliminary results obtained in the validation of the multiple support piping analysis of the SMACS Computer Code [8]. The analysis evaluation is based on the response of the VKL pipe system in the 6.0 Hz test run with the HDR configuration (1), i.e., Experiment T40.11 in

Table 2. Only two dynamic supports are employed in this case, namely rigid struts at H4 and H5 (see Fig. 6). Two different finite element models were constructed for the analysis. The first model includes the HDU vessel (see Fig. 2), and represents the dynamic supports by means of pipe and beam elements with hinged ends. As input wall/floor response measurements of the HDR building in the vicinity of the VKL piping are used. The calculational results grossly underpredict the measured piping acceleration. It is thought that this discrepancy is due to the boundary conditions used for the HDU vessel, which is assumed to be fixed to the building both at its bottom support and at a collar support at about two thirds of its height. These assumptions make the HDU vessel move nearly rigidly with the building motion. On the other hand, measurements on the top of the HDU vessel indicate acceleration values which exceed the wall motion by factors of 3 to 4.

To avoid the modeling of the uncertain HDU boundary conditions, the second model omitted the HDU. The response measurements at the top of the HDU vessel were used as input to the calculations. Other inputs were either the wall or the pipe accelerations measured at other points of attachment, namely the DF16 manifold and the struts H4 and H5 (see Figs. 2 and 6). The dynamic supports in this case were modeled according to common practice, as rigid. It was found that using the wall motion as input, again underpredicted the pipe accelerations, albeit not as much as the first model. On the other hand, using the pipe response measurements at the point of dynamic support attachment as input to the calculations, in general resulted in overprediction of the pipe response at other locations.

The differences between the calculated results and measurements were also examined in the frequency domain. The first major response peak, both in the experiment and the computations, occurs at frequency of about 4 Hz. The Fourier Transform Moduli at this peak are approximately the same for the calculations using pipe motion input and the experiment, for the wall-input calculations the value is much lower. The second major response peak in the experiment occurs at about 10 Hz and is lower than the first peak. In the calculations the second peak is shifted to about 12.5 Hz and is the dominant peak in the response, being a factor of 6 higher than the first peak for the case of pipe-input to the calculations. Again the calculational discrepancies appear to be due to the modeling of the boundary conditions and of the dynamic supports. Effort is continuing to clarify these problems for the multiple support piping analysis of the SMACS code.

6. Conclusion - SHAG Experiments

In spite of the limitations imposed on the SHAG testing by the safety considerations of the HDR building, the experiments were an unqualified success. The wealth of data, which will require substantial analysis efforts, should provide insights into many aspects of concern to the nuclear industry. Specifically, the results will contribute to a better understanding of the nonlinear behavior of soil/structure systems under high-level excitation. The data lend themselves to the investigation of load transmission in buildings. The effect of different hanger configurations on pipe behavior at loadings equivalent to strong motion earthquakes can be evaluated. Most importantly, the data will serve to validate and verify analysis procedures for piping and soil/structure system response, including typical linear design methods, simplified techniques, and state-of-the-art nonlinear computational procedures.

In the SHAG experiments, the HDR building and equipment were repeatedly subjected to the same excitation (see Table 2). At the same time, multiple predictive calculations were carried out for single experiments. This combination of experimental and analytical results provides an opportunity to investigate the variabilities in response that are due both to parameter variability and modeling uncertainties. Finally, the SHAG data also provide information on the behavior and response of specific equipment, e.g., valves and snubbers, under earthquake-like excitation.

7. SHAM Experiments

Because of the very fruitful collaboration in the SHAG testing, the PHDR/KfK and NRC/RES are already planning further cooperation in the HDR-SHAM experiments scheduled for the spring of 1988. In these tests the VKL piping will be subjected to direct multiple-point excitation (using hydraulic actuators) at extremely high levels. Pipe plastification and/or failure may be expected. The objective of these experiments is to investigate piping behavior at extreme loading (including the effects of different pipe hanger configurations), to establish seismic margins for piping, and to investigate possible failure modes in an in situ piping system. Other goals include the investigation of equipment (valves and snubbers) operability and fragility at extreme excitation levels. Also, the response and fragility of various pipe mountings and supports will be evaluated.

Planning for the SHAM experiments is still in progress. However, the essential elements of the tests have been defined. Excitation will be provided by means of two 40 ton (metric) hydraulic actuators applied at the H5 hanger location and at the DF16 manifold (see Figs. 2 and 6). Both actuators will apply forces in the global HDR x-direction (see Fig. 1).

Again, a number of pipe support configurations will be evaluated, including the first five support systems listed in Table 1. The actual configurations for the SHAM test will differ in some details from those in SHAG tests. In particular the NRC configuration with snubbers (3) is designed for a 0.6 g (ZPA) safe shutdown earthquake (SSE) using Level C criteria. All hanger configurations will be tested to about 400% SSE accelerations using an earthquake acceleration time history agreed upon by all participants. Beyond that level it is currently planned to test only the stiff NRC system (3) and the very compliant HDR support system (1). The intention is to establish seismic margins for a typical US designed piping support system and ultimately to reach failure/plastification of piping. Again earthquake acceleration histories will be applied

Linear test design calculations indicate that acceleration levels of the order of 8.0 g should be feasible with the available actuators. Should it not be possible to obtain significant pipe plastification with earthquake-like excitation, it is intended to repeat the tests, at the capacity limit of the actuators, with sine-burst excitation centered around piping resonances. All piping configurations will be dynamically characterized using low level sine sweep testing.

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TABLE 1 VKL HANGER CONFIGURATIONS

CONFIGURATION NO.	VKL SUPPORT SYSTEM	DESCRIPTION OF SUPPORT CONFIGURATION
1	HDR	Spring and constant-force hangers + two rigid struts (flexible system)
2	KWU	Five rigid struts; simplified design concept
3	USNRC	Six snubbers and six rigid struts (stiff system)
4	EPRI/EA	Four Bechtel-designed energy absorbers
5	EPRI/SS	Six Cloud-designed seismic stops
6	GERB	Two viscous dampers designed by Gerb
7	ANCO	Six modified viscous dampers

TABLE 3 SUMMARY OF SCALING FACTORS USED FOR THE EVALUATION OF PIPE SUPPORT CONFIGURATIONS

EXPT. GROUP	STARTING FREQUENCY HZ	CONFIGURATION					AVERAGE	STD. DEVIATION
		HDR	KWU	NRC	EPRI/EA	EPRI/SS		
T40.*0	8	1.01	0.95	1.04	0.98	1.00	0.99	0.034
T40.*1	6	1.17	1.20	1.23	1.22	1.20	1.20	0.023
T40.*2	4.5	1.72	1.74	1.71	1.72	1.69	1.71	0.019

TABLE 2
SHAG TEST MATRIX: RUNS PERFORMED

RUN NO.	TEMP., °C	VKL SUPPORT SYSTEM	ECCENTRICITY, kgm	STARTING FREQ., Hz	MAX. FORCE, kN	TEST WEEK
34	20	USNRC	4,700	6	6,600	
35	20	USNRC	4,700	8	11,800	1
36	20	USNRC	8,200	5.6	10,100	
37	20	USNRC	27,800	2.1	4,800	
40	20	EPRI/EA	4,700	8	11,800	
20	20	KWU	4,700	8	11,800	2
60	20	GERB	4,700	8	11,800	
						3
50	20	EPRI/SS	4,700	8	11,800	
70	20	ANCO	4,700	8	11,800	4
10	20	HDR	4,700	8	11,800	
30	20	USNRC	4,700	8	11,800	
31	20	USNRC	6,450	6	9,100	
41	20	EPRI/EA	6,450	6	9,100	
21	20	KWU	6,450	6	9,100	5
11	20	HDR	6,450	6	9,100	
51	20	EPRI/SS	6,450	6	9,100	
52	210	EPRI/SS	8,200	4.5	6,500	
32	210	USNRC	8,200	4.5	6,500	
42	210	EPRI/EA	8,200	4.5	6,500	6
12	210	HDR	8,200	4.5	6,500	
22	210	KWU	8,200	4.5	6,500	
12.1	210	HDR	8,200	4.5	6,500	7
14	20	HDR	33,000	1.6	3,300	
16	20	HDR	54,000	1.6	5,400	8
13	20	HDR	67,700	1.6	6,800	

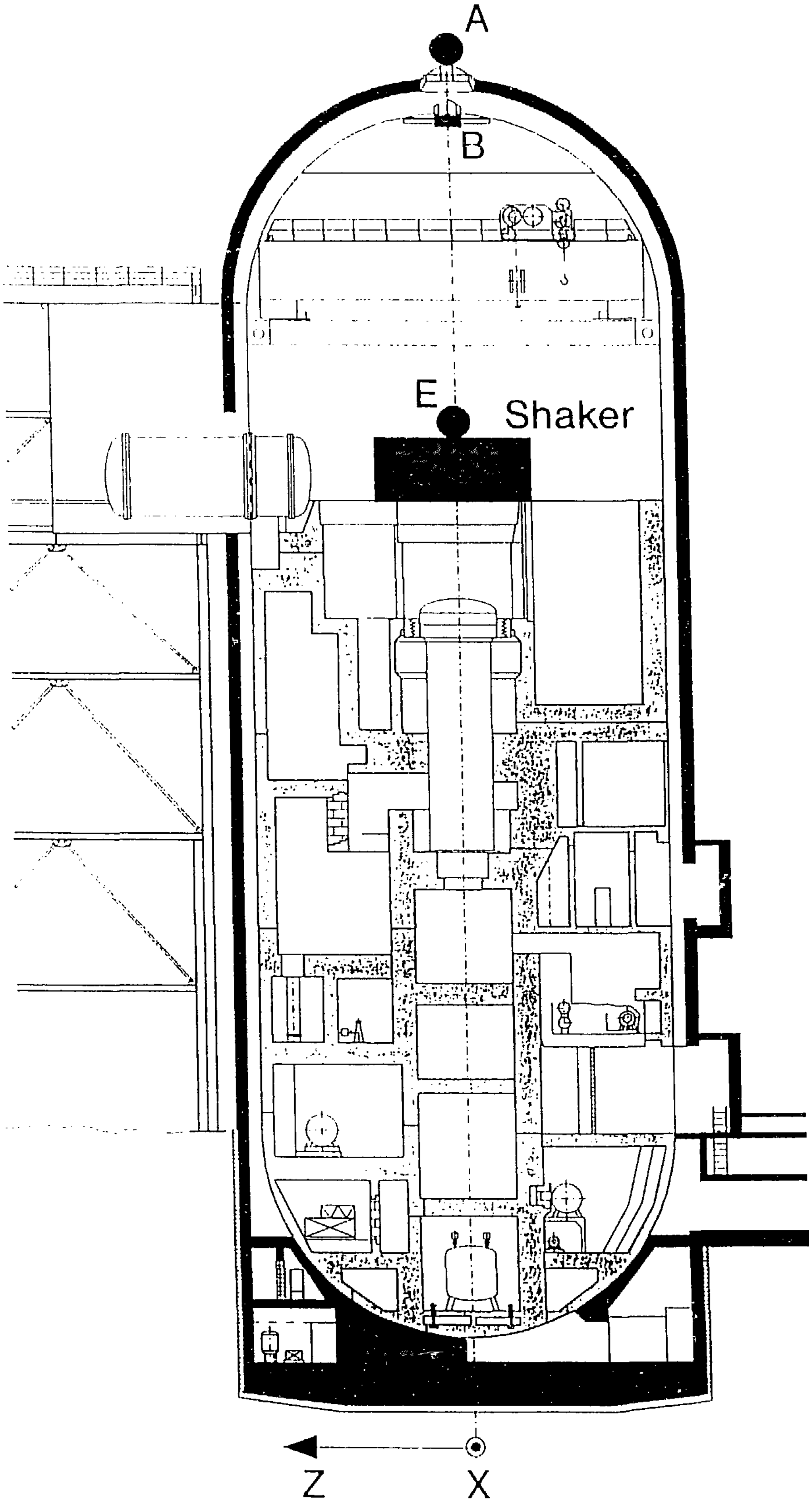


Fig 1. Schematic Cross-section of HDR Containment Building

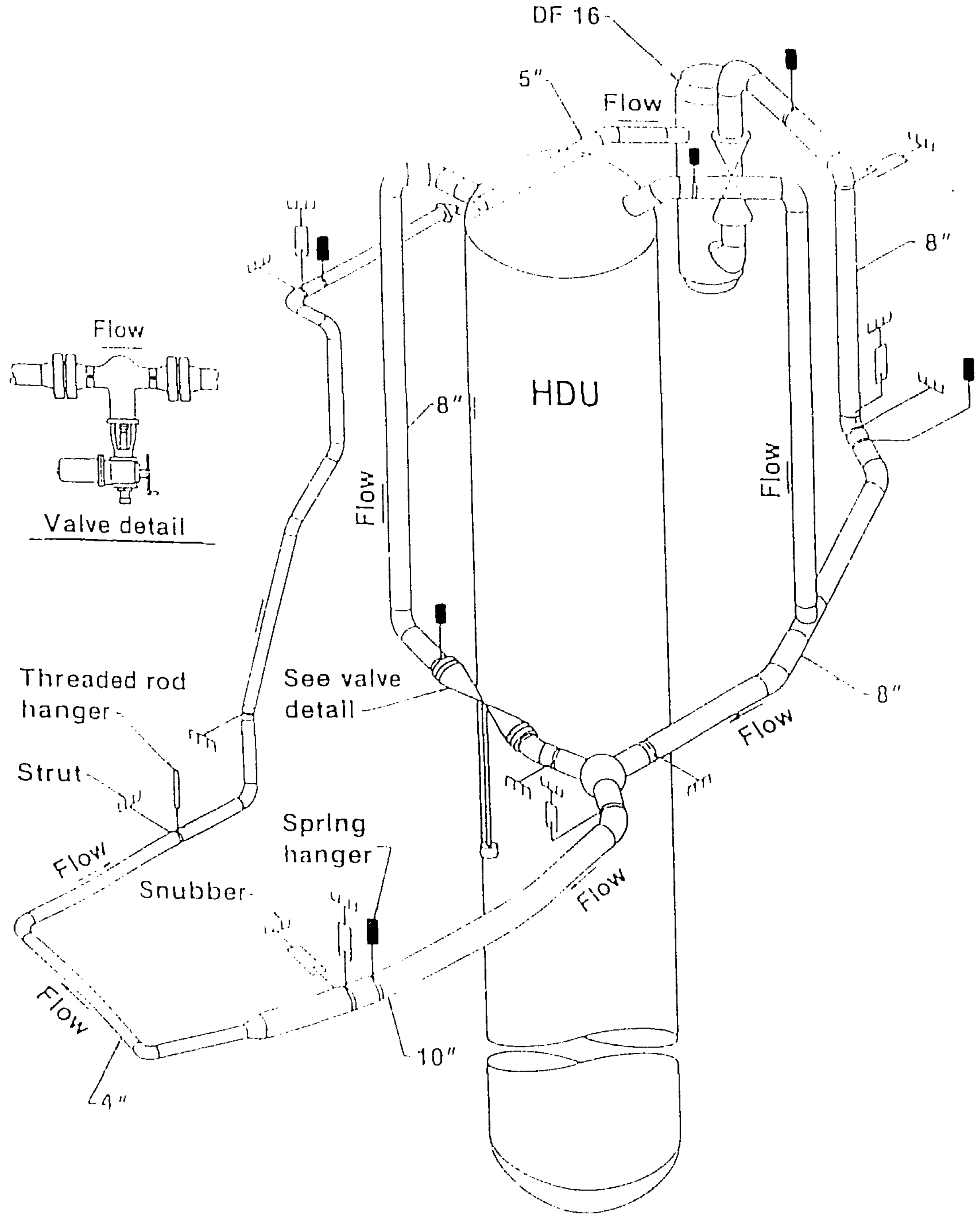


Fig. 2. VKL Piping System with NRC Support Configuration

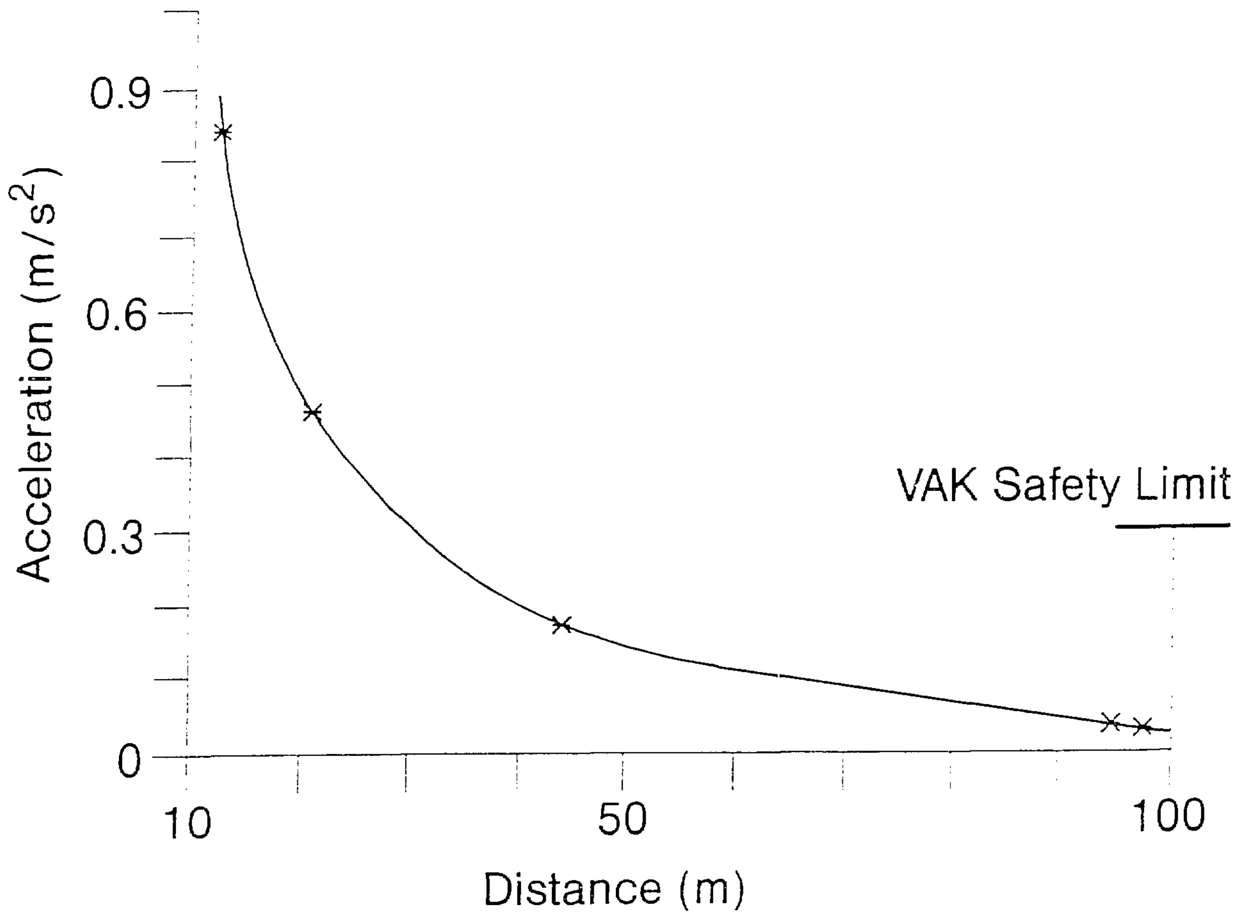


Fig 3. Attenuation of vertical acceleration in HDR soil

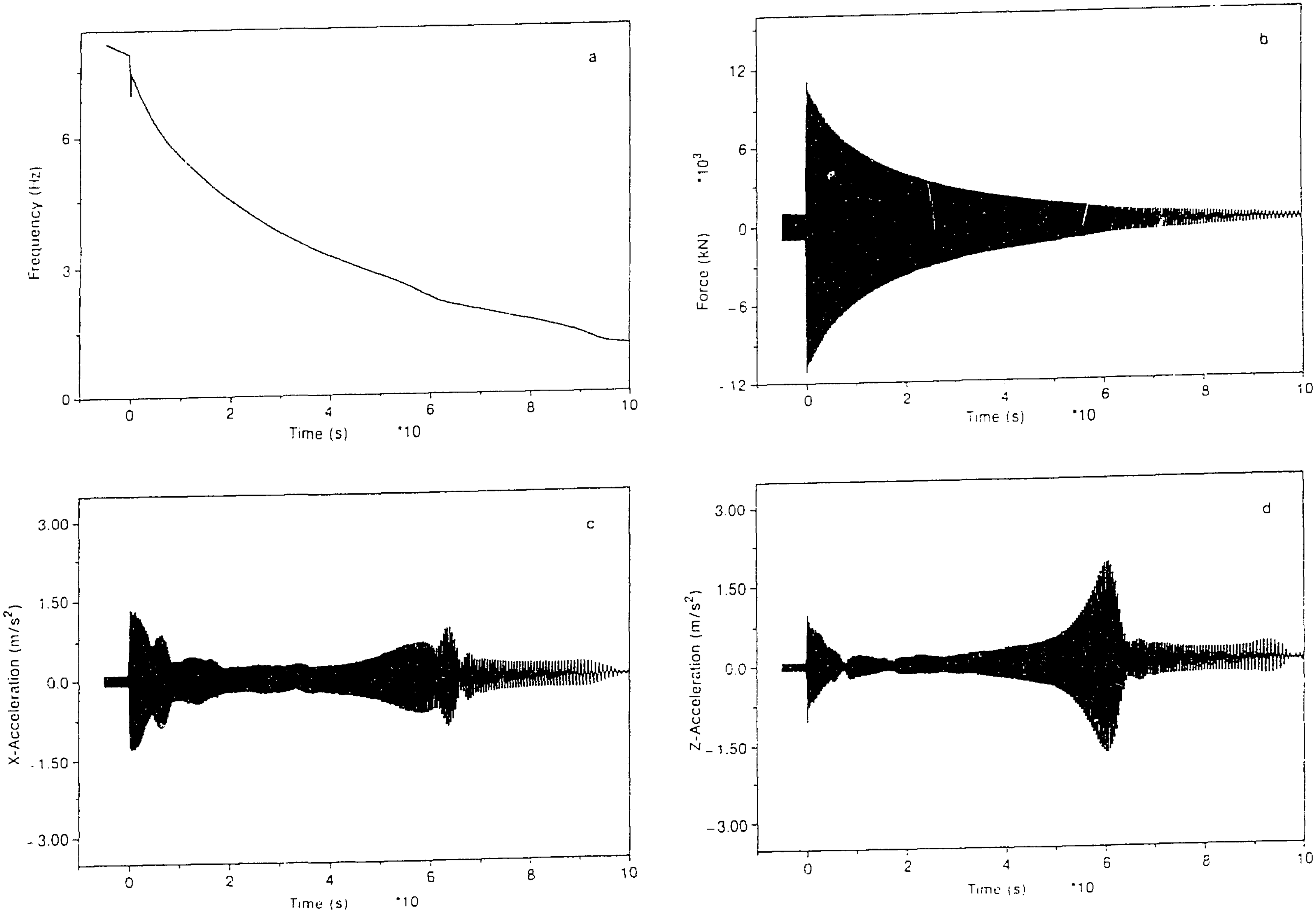
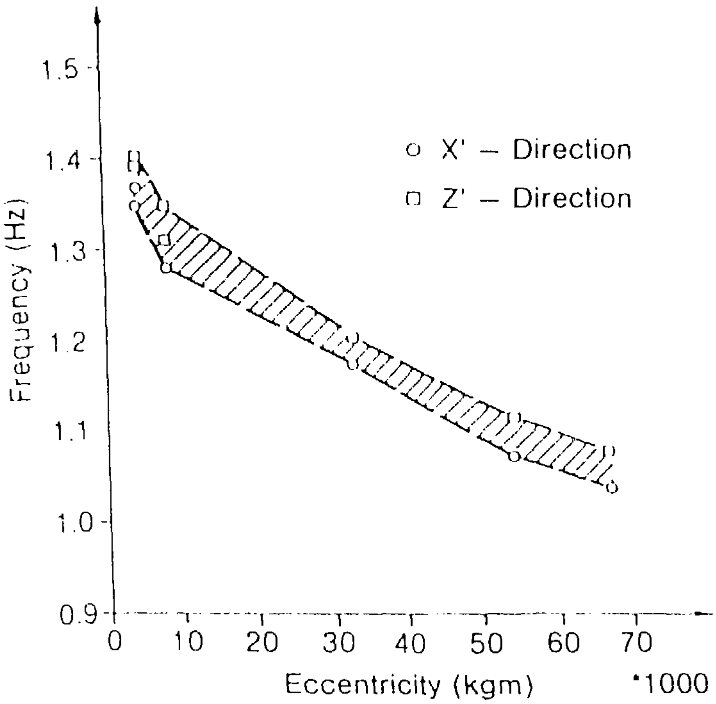


Fig. 4. Shaker frequency, shaker force, and horizontal accelerations at the top of the HDR building; Experiment T40.10 at 8.0 Hz



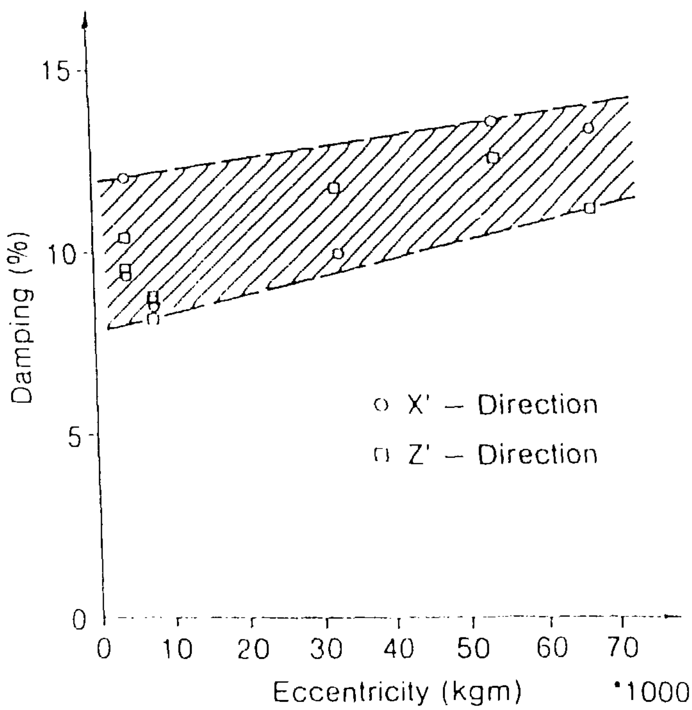


Fig. 5. Variation of rocking frequency and damping with shaker excitation level in SHAG tests.

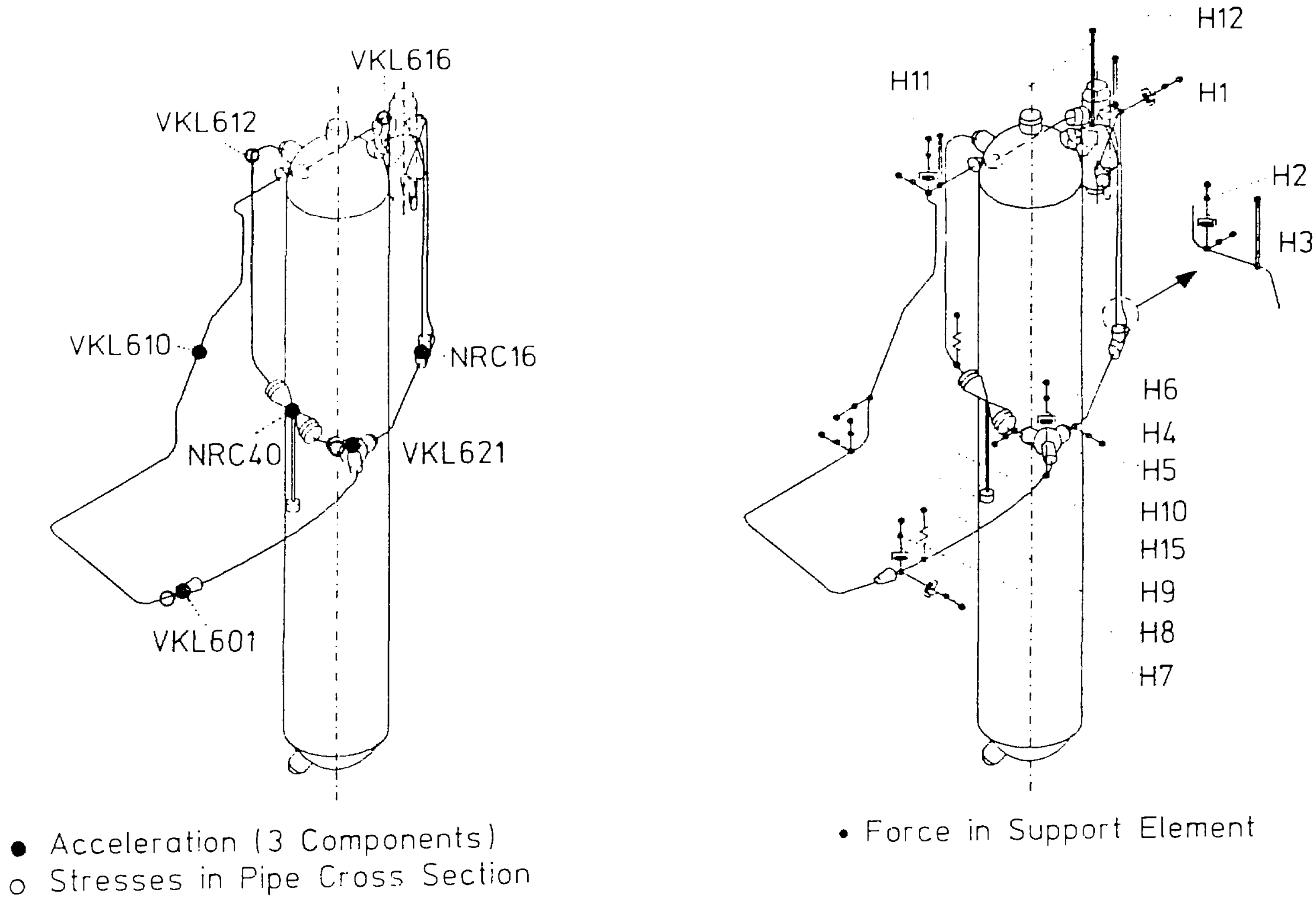


Fig. 6. Hangers and measurement locations of VKL piping.

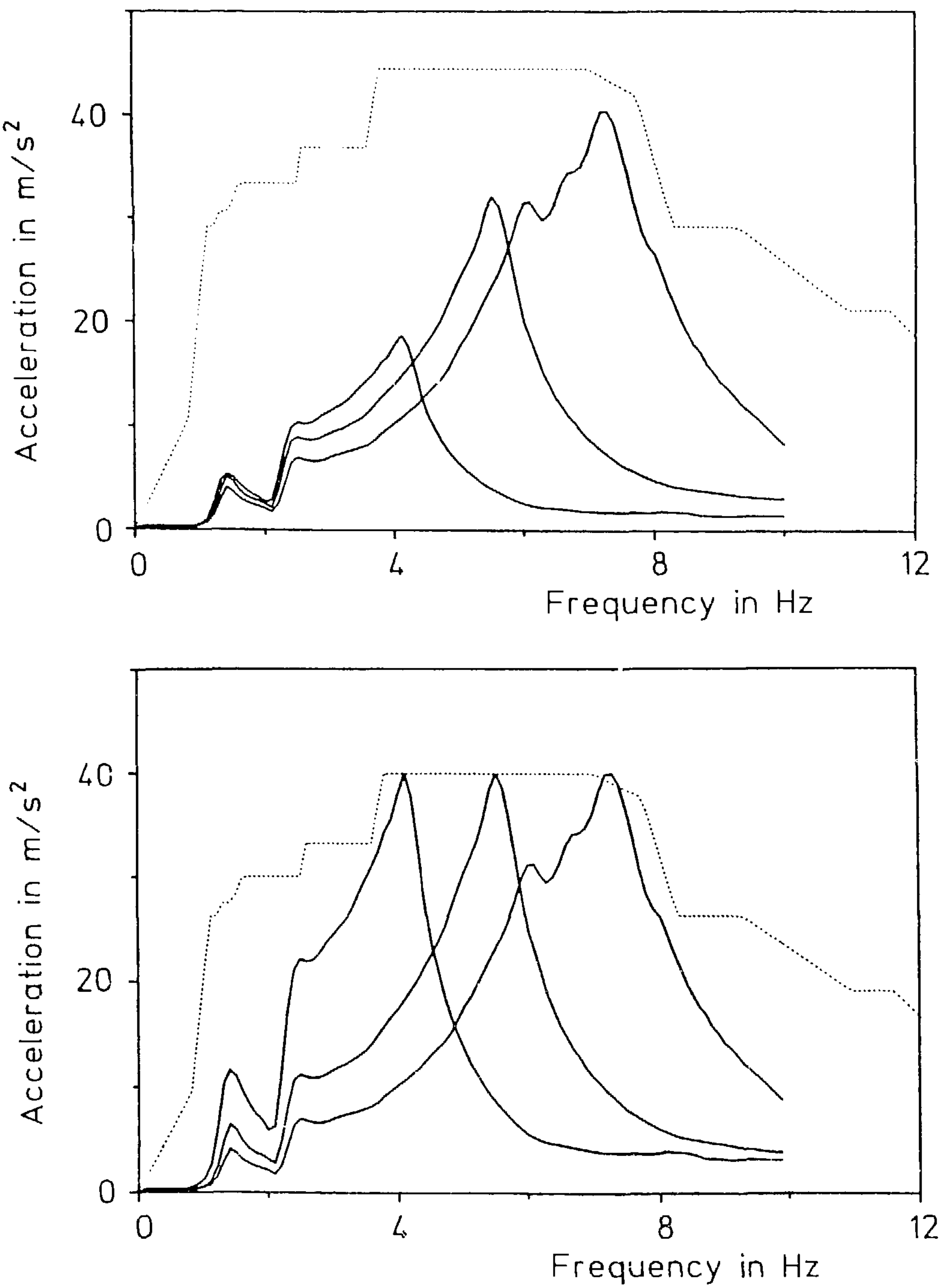
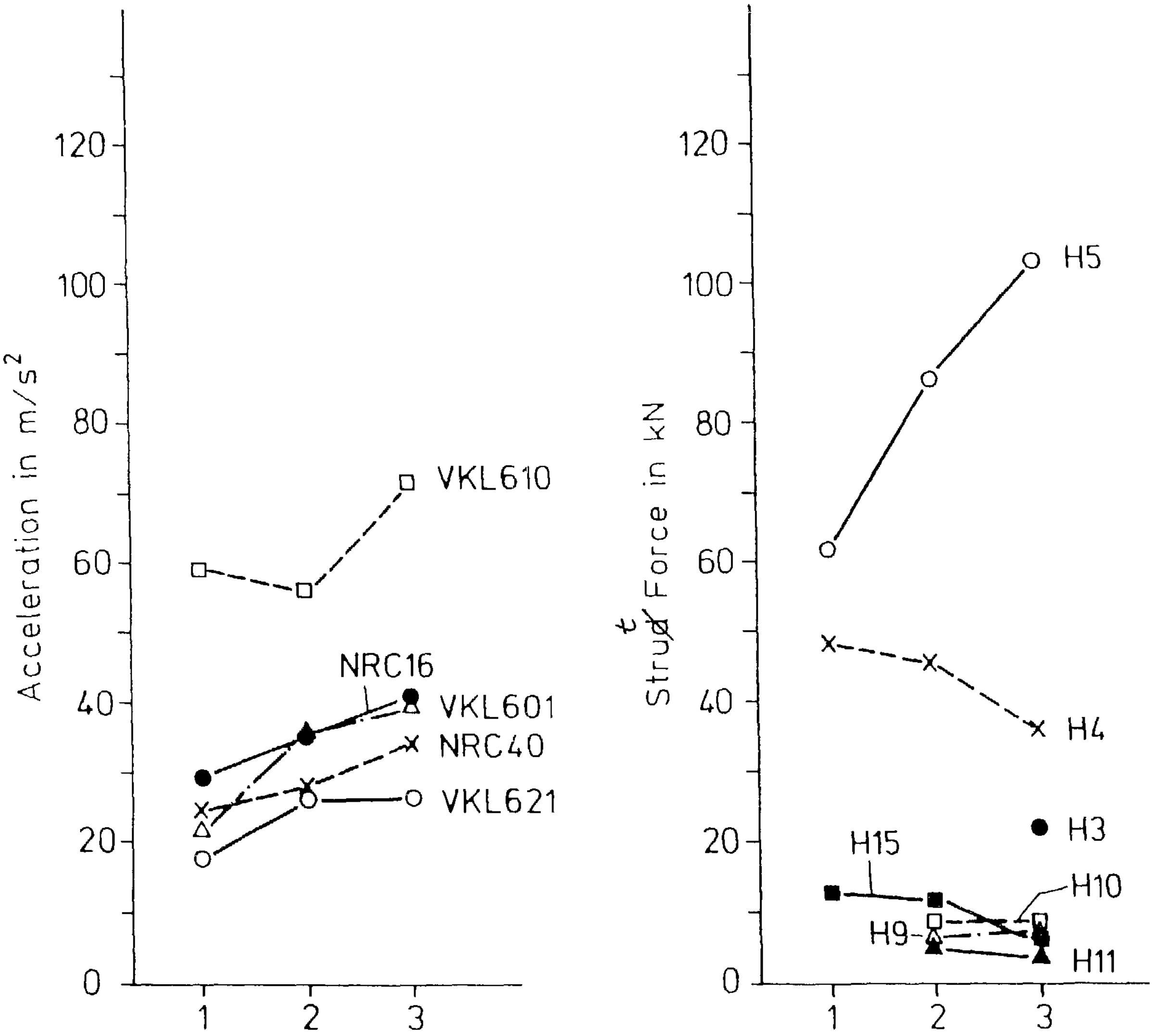


Fig. 7 SSE design Spectrum and SHAG Floor Spectra: Actual (upper) and Normalized (lower)



Support System: Flexible 1 HDR, Intermediate 2 KWU, Stiff 3 NRC

Fig. 8. Comparisons of Normalized Accelerations and Strut Forces – Effect of VKL support system stiffness

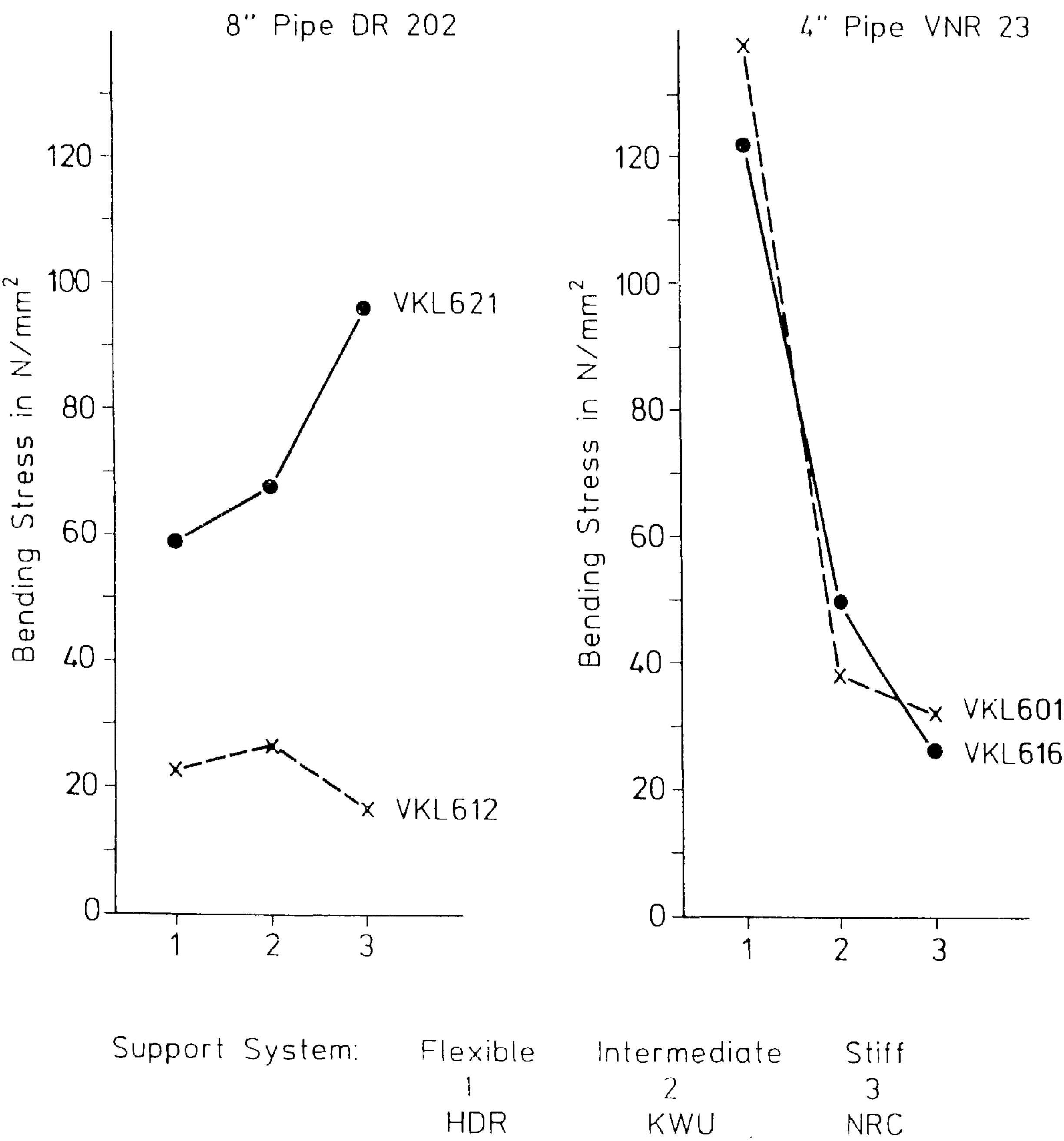


Fig. 9. Comparisons of Normalized Pipe Bending Stresses – Effect of VKL Support System Stiffness

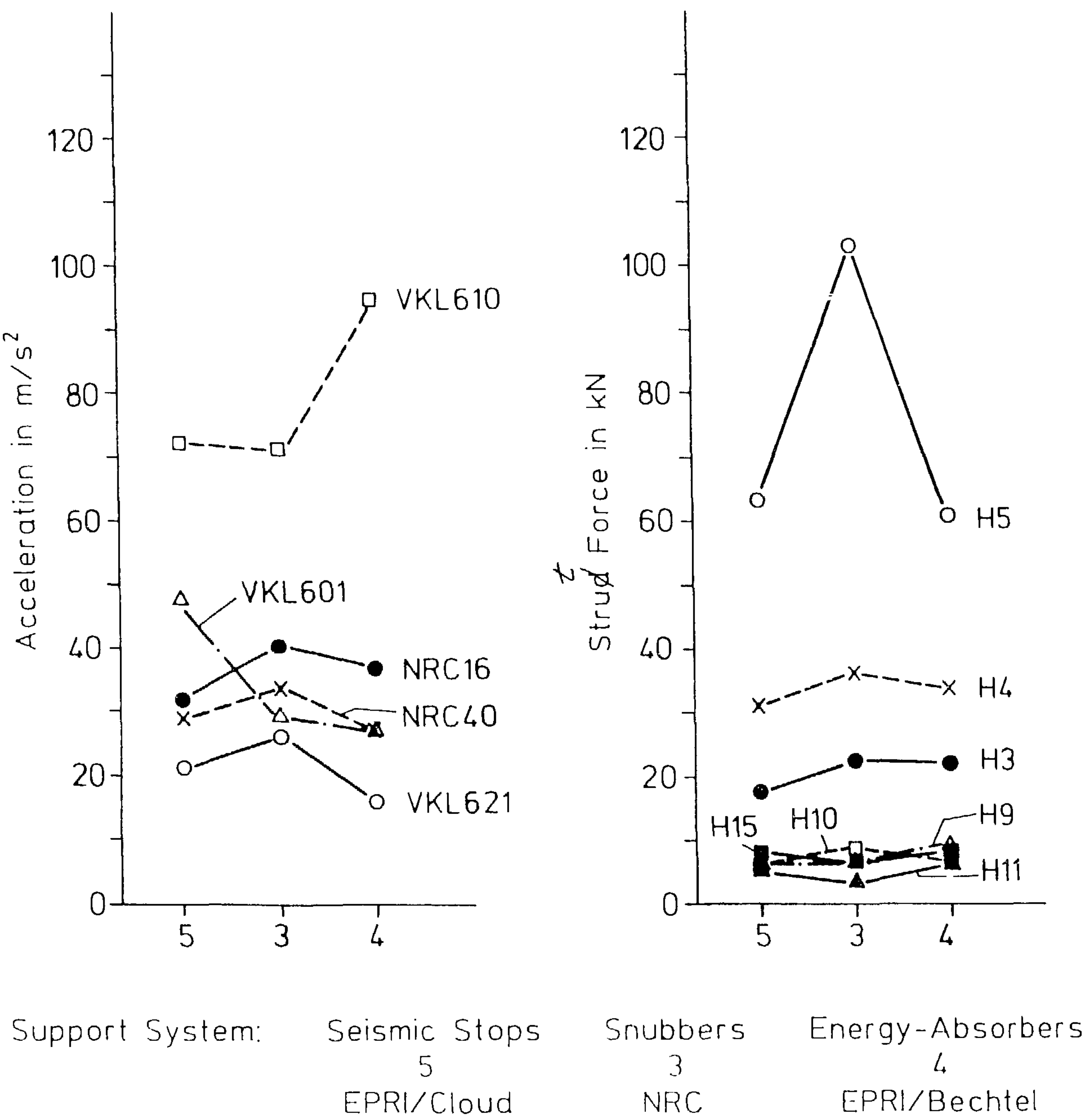


Fig. 10. Comparisons of Normalized Accelerations and Strut Forces - Snubber vs. Snubber Replacement Systems.

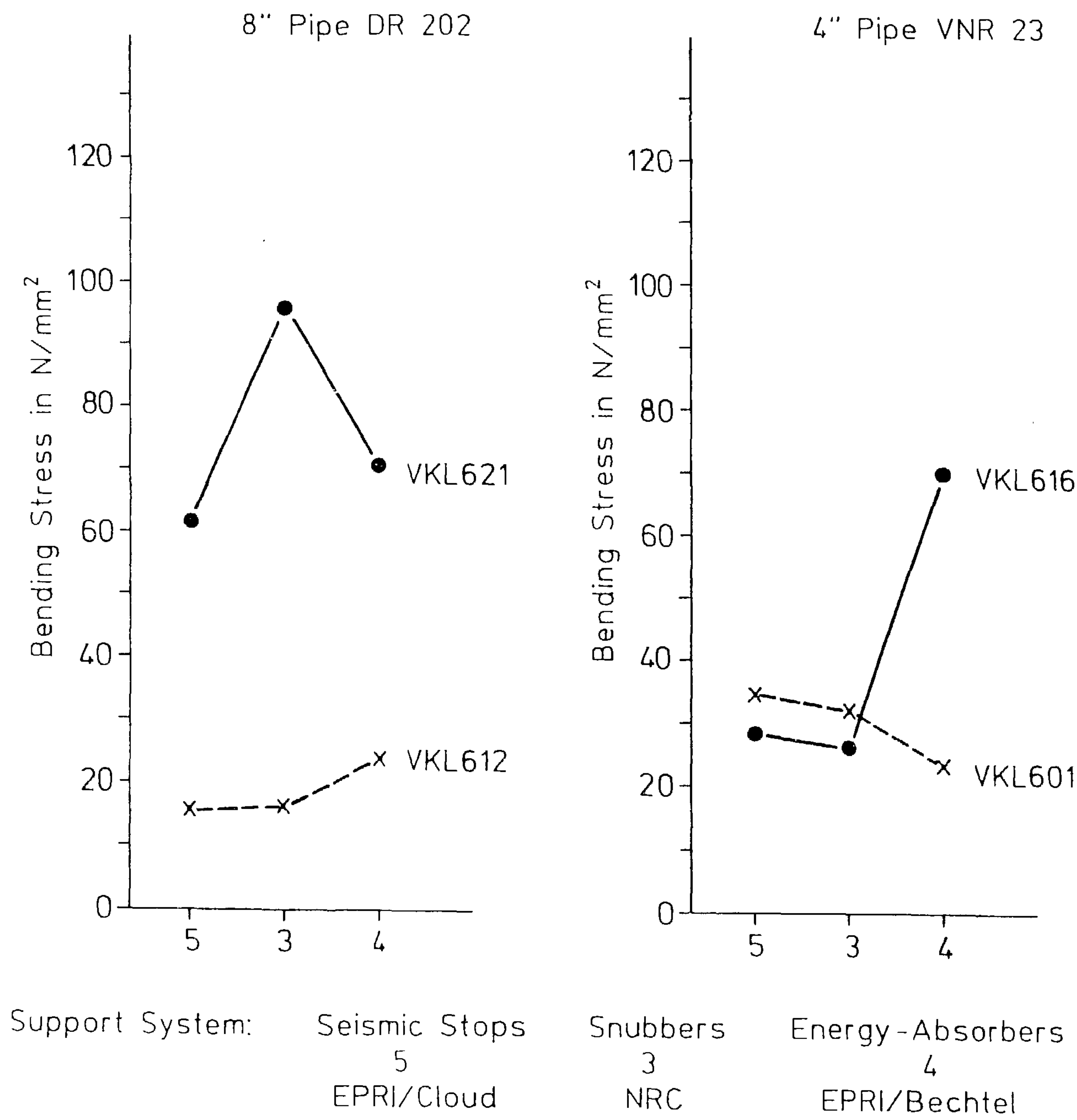
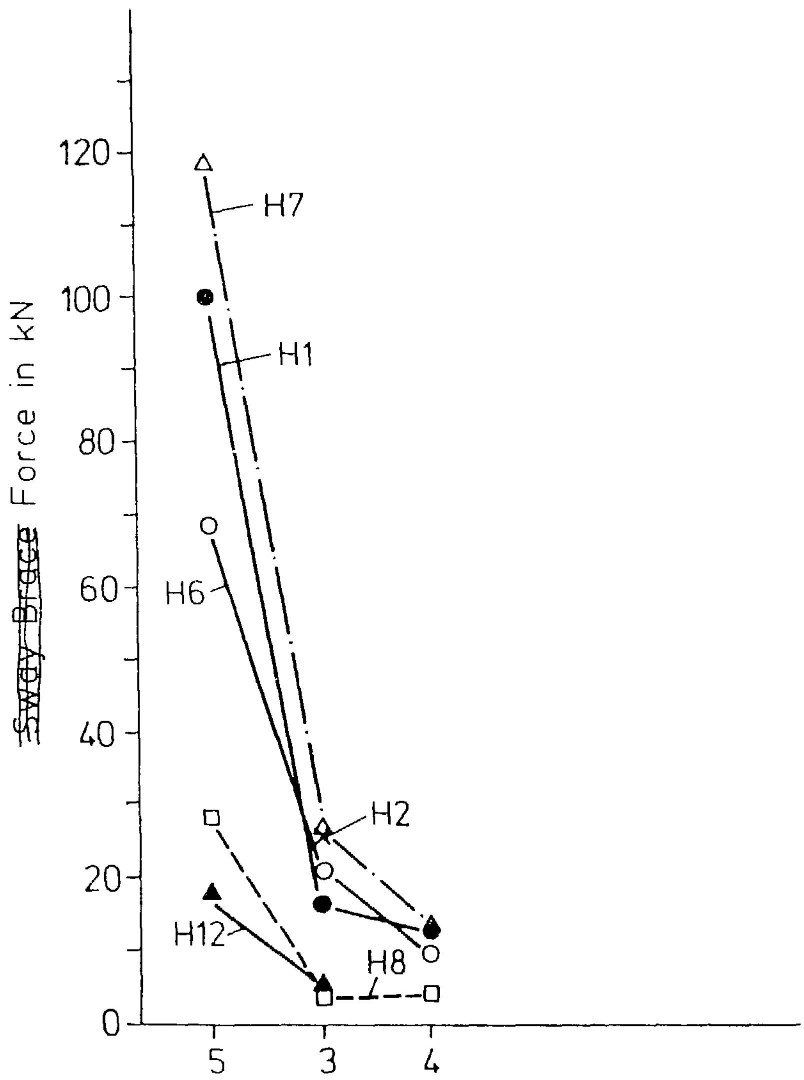


Fig. 11. Comparisons of Normalized Pipe Bending Stresses — Snubber vs. Snubber Replacement Systems



Support System: Seismic Stops 5 EPRI/Cloud; Snubbers 3 NRC; Energy-Absorber 4 EPRI/Bechtel

Fig. 12. Comparisons of Normalized Forces in Snubbers and Snubber Replacement Devices.