CONF-890855--8

Received APR 1 1989

High–Level Seismic Tests of Piping at the HDR

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CONF-890855--8

DE89 009781

1. Introduction

As part of the second–phase testing at the Heissdampfreaktor (HDR) Test Facility in Kahl/Main, Federal Republic of Germany (FRG), high–level seismic experiments, designated SHAM, were pertormed on an in–plant piping system during the period of 19 April to 27 May 1988. The objectives of the SHAM experiments were to (i) study the response of piping subjected to seismic excitation levels that exceed design levels manifold and which may result in failure/plastification of pipe supports and pipe elements; (ii) provide data for the validation of linear and nonlinear pipe response analyses; (iii) compare and evaluate, under identical loading conditions, the performance of various dynamic support systems, ranging from very flexible to very stiff support configurations; (iv) establish seismic margins for piping, dynamic pipe supports, and pipe anchorages; and (v) investigate the response, operability, and fragility of dynamic supports and of a typical U.S. gate valve under extreme levels of seismic excitation.

The SHAM experiments were undertaken by the HDR Safety Project (PHDR) of the Kernforschungszentrum Karlsruhe (KfK) as a cooperative effort among a number of organizations in Europe and the USA. These included

KfK/PHDR, with the participation of the Fraunhofer Institut für Betriebsfestigkeit (LBF), Darmstadt, FRG, and the Kraftwerk Union (KWU), Offenbach, FRG; the Central Electricity Generating Board (CEGB), UK; the Electric Power Research Institute (EPRI), Palo Alto, California, with the participation of Bechtel Corp. and R. C. Cloud & Associates; and the U.S. Nuclear Regulatory Commission, Office of Research (NRC/RES), which supported the efforts of Argonne National Laboratory (ANL) and Idaho National Engineering Laboratory (INEL).

A brief description of the SHAM tests is provided, followed by highlights of the test results that are given primarily in the form of maximum response values. Also presented are very limited comparisons of experimental data and pretest analytical predictions.

2. Description of the SHAM Experiments

A sketch of the VKL piping as used in the SHAM testing is shown in Figure 1. The VKL piping includes multiple stainless steel pipe branches ranging from 100 to 300 mm in diameter, with the main two flow loops connected to the HDU vessel and the DF15 and DF16 manifolds. Aside from the pipe hangers and dynamic supports, the system is fixed to the structure at the bottom and two–thirds height of the HDU and at the DF15 manifold. As in the earlier tests [1,2], the test loop again included an 8" U.S. gate valve from the decommissioned Shippingport Atomic Power Station. The VKL piping was excited directly by means of two servohydraulic actuators rated at 40 tons (metric) of force each. As shown in Fig. 1, both actuators were acting in the horizontal x-direction at hanger location H5 and at location H25 (DF16 manifold) and were capable of producing up to 6 g acceleration for the VKL piping, with a maximum displacement (stroke) of ± 125 mm [3].

Six different dynamic support systems of the VKL piping were designed by the various participants in the SHAM testing. These ranged from the very stiff U.S. system designed by INEL with rigid struts and snubbers to a very flexible HDR system which used only the rigid struts at locations H4 and H23 that were necessary to stabilize the input motions of the actuators. Two support configurations, provided by EPRI in collaboration with industrial partners, contained snubber replacement devices. The first of these, designed by Bechtel Power Corp., uses Energy Absorber (EA) devices with plastically deforming steel plates. The second snubber replacement system consisted of Seismic Stops (SS) designed by R. L. Cloud & Associates, Inc. Two other support configurations, designed by KWU and CEGB, rely only on rigid struts for dynamic restraint. Figure 2 shows an overview of the support configurations, all of which used the same dead–weight hanger system shown in Fig. 1 and the same rigid struts at locations H4 and H23.

All dynamic support systems, except the CEGB system, were designed for the common HDR spectrum shown in Fig. 3. The actuators were displacement controlled, and the basic earthquake displacement history used was an artificially generated displacement–time function of 15 seconds duration, fitted to the preselected common Safe Shutdown Earthquake (SSE)–floor–response spectrum with a 0.6 g peak acceleration (ZPA), shown in Fig. 3. The U.S. stiff support system was designed with typical U.S. struts and snubbers using ASME Code level "C" allowables. The KWU, EPRI/EA, and EPRI/SS, were also designed for the same floor response spectrum and a ZPA of 0.6 g, but they were sized for more conservative allowables. The HDR flexible support system was essentially not designed for seismic loading and the CEGB hanger system was designed for the Sizewell B spectrum (see Fig. 3). To study the behavior and fragility of typical pipe mountings and anchorages, trunions were installed at locations H2 and H22 (see Fig. 1). At the same time, the anchor plates and anchors at these locations were replaced with typical U.S. hardware, sized for the design spectrum and SSE level.

Nearly 300 channels of data were recorded, with major measurements being strains (142 channels), accelerations (90 channels), displacements (29 channels), and forces (27 channels). In addition, 10 channels were used to monitor the operating parameters of the U.S. 8" gate valve. All important aspects of the experiments were monitored. Details of the instrumentation can be found in References [3] and [4].

Fifty–one individual experiments were performed with the VKL piping and the six different pipe support configurations. Two random excitation tests of 120–s duration, with each of the hydraulic actuators singly and separately (H5 and DF16) were performed for each hanger configuration. These tests provided dynamic characterization of the systems in the frequency range from 2 to 40 Hz.

For all but the CEGB configuration, earthquake experiments were then performed at the low to intermediate level, i.e., at excitation levels ranging from one SSE (0.6 g ZPA) to three (four) SSE. These experiments were carried out with a 15–s duration displacement history based on the common HDR spectrum scaled to the proper SSE level. The two hydraulic actuators (at H5 and DF16) were operated together and in phase; both were programmed to provide identical displacement histories. The purpose of these tests was to study the behavior of piping systems at load levels exceeding the design load and to compare the performance of different support configurations. To make these tests possible with all configurations, strains in the piping were required to remain below significant plastification, i.e., about 0.2% of strain. These tests were also intended to provide seismic–margin information for dynamic supports, and data for the validation of linear analyses.

Two configurations, namely the KWU system and a slightly modified NRC system, were then tested to high levels of excitation (up to 800% SSE) again with scaled–up displacement histories and both actuators operating in phase. The purpose of the high–level tests was to obtain information on possible pipe plastification, seismic margins for piping, and pipe supports, and to provide data for the validation of nonlinear analysis methods.

The CEGB configuration was subjected to its own test program. Low– and intermediate–level earthquake tests were performed with displacement histories of 20-s duration derived from its design spectrum and the Allsites spectrum. Intermediate– and high–level tests were also performed with sine burst histories. To provide a comparison with the other configurations, a 100% SSE earthquake test was performed with the displacement history derived from the common HDR spectrum.

3. SHAM Results

Analysis of the very large volume of SHAM test data is still in progress. The following preliminary overview of the results is based primarily on the exposition of maximum responses for selected variables in the experiments. In order to obtain consistent and comparable results in the earthquake testing of all the support configurations that were subjected to the common HDR spectrum, it was intended to control the input acceleration spectra for the two actuators within a tolerance of ± 10% in amplitude. Spectra derived from measurements indicate that this tolerance was at times significantly exceeded, in particular in the higher frequency region [5].

Figures 4 and 5 show peak bending stresses in the VKL piping at 100%–SSE–input load (HDR common spectrum, 0.6 g ZPA) for all six support configurations. For the 200–mm piping (Fig. 4), one sees that the NRC configuration gives the highest stresses in the branch emanating from the DF16 manifold as indicated by points QA100 just upstream of Elbow 1 and QA102 upstream of the Tee. On the other hand, in the branch connecting the Tee and the Spherical Tee (QA104), in the pipe coming from the HDU (QA106) and at the valve (QA937), the NRC configuration gives the lowest stresses. In the smaller diameter pipe (Fig. 5), the bending stresses are consistently high for the more flexible configurations (HDR and CEGB), and in particular at points adjacent to the reduction tee (RA767 and RA760). The stiff NRC configuration, in general, exhibits the lowest peak stresses. The stress results are confirmed by the maximum strain measured in the elbows.

Comparing the maximum forces in the rigid struts, the stiff NRC configuration, in general, gives lower peak forces than the snubber replacement configurations and the more flexible KWU configuration. If forces at snubber locations are compared, one finds that the seismic stops result in the highest forces at four locations (H7, H8, H12 and H22). At H6, the peak seismic–stop force is somewhat lower than for the NRC snubber. At location H2, the seismic stop made no contact with the impact disc spring and no force was recorded.

Only the KWU support configuration and the modified NRC configuration, with a bridging between the DF16 manifold and 200–mm pipe, were tested to 800% SSE. Multiple snubber failures occurred (H8, H12, H22) during the 600%–SSE test of the Modified NRC Configuration. These snubbers were not replaced for the 800%–SSE test. During the latter test, snubber H7 also failed (at 60 kN), as did the bridging and the anchors at location H2. At lower levels of excitation, snubbers H6 and H8 failed in the original unmodified NRC configuration during the 300%–SSE test. The other configurations did not experience support failures, in particular, none of the rigid struts failed in any of the tests.

Comparing the maximum bending stresses at the most highly stressed straight–pipe section in the 200–mm pipe, directly adjacent to Elbow 1, one finds that at excitation levels up to 300% SSE, most support configurations gave similar results, with the flexible HDR system exhibiting the lowest stresses. The peak bending stresses for the KWU configuration reaches a maximum of about 380 MPa at a load of 800% SSE. Since the stress level corresponding to a 0.2% offset strain for the pipe material is about 260 MPa, some plastification did occur in both the 600% and 800% tests. The plastification level was barely reached by the modified NRC configuration.

A comparison of the maximum bending stresses at the most highly stressed straight–pipe section of the 100–mm pipe adjacent to the reduction Tee (RA767), shown in Fig. 6, reveals that the more flexible configurations (HDR and KWU) give the highest stresses at the lower load levels. Both the energy absorbers and seismic stops result in somewhat lower stresses than the snubber configuration. The stress increase for the KWU configuration is nonlinear at high excitation levels, and even more so for the modified NRC system. The peak recorded bending stress of 580 MPa for the KWU configuration exceeds the 0.2%–offset strain level by more than a factor of two. Thus, significant local plastification is to be expected at this section.

Examining the effect of load increase on the maximum forces in the rigid struts at locations on the 100 mm pipe, one finds that the more flexible support configurations give higher values at all load levels. However, for supports on the 200 mm pipe the situation is mostly reversed, with the NRC Configuration often giving the highest values.

4. Pretest Computational Efforts

Design calculations were performed prior to the SHAM experiments, by each of the organizations developing a specific support configuration. The only true predictive calculations were carried out by ANL for the NRC support configuration, using the piping analysis module of the SMACS code [6], which performed time history analysis with independent support motion input. Dead–weight stress and modal analyses were performed for the NRC system by means of SUPERSAP. The first eigenfrequency was found at about 5.56 Hz.

The peak calculated forces in the rigid struts of the NRC configuration at excitation levels of 100%–300% SSE are compared in Fig. 7, with the measured values. As shown, all peak forces were underpredicted, often by as much as a factor of two. A similar result was obtained for the permanent struts H4 and H23, where the discrepancies are even larger. Also, the calculations generally predict substantially lower peak snubber forces than those measured.

Figure 8 compares the calculated and measured peak bending stresses in the most highly stressed straight–pipe sections of the 200-mm (QA100 – next to Elbow 1) and 100-mm (RA767 – adjacent to the reduction Tee) pipe. Again, the calculations generally underestimate the stresses. Similar results are found when one examines the stresses at other locations in the pipe. While there are some locations, particularly in the 100–mm pipe, where the predictions overestimate the stresses at the 100%–SSE level, the situation in general reverses at higher loads, i.e., the calculations underpredict.

The underprediction of the peak dynamic support forces and of the peak bending stresses are now being investigated. While the more conservative design calculations, performed by other investigators, exhibit some of the same deficiencies as the ANL "best estimate" prediction, none of the stress allowables were exceeded in the tests.

5. Conclusions

The results given here are preliminary and incomplete, nevertheless it is possible to make some qualitative observations. It appears that stiff support systems with snubbers and struts offer no particular advantages over systems with snubber replacement devices or reasonably compliant systems (KWU). However, long, unsupported pipe runs may lead to excessive displacements and high stresses under seismic loading. In general, failures of dynamic supports (in particular, snubbers) and of anchorages occur only at load levels that substantially exceed the design capacity. Pipe strains and deformations at excitation levels of up to 300% SSE remain quite small (about 0.3%) and even at extreme excitation levels of 800% SSE are quite tolerable (about 1.2%). Therefore, pipe failure under typical seismic loading histories, even at extreme load levels (800% SSE) and in spite of multiple serial support failures, is highly unlikely. Linear piping analysis may substantially underpredict the peak loads in dynamic supports, and is not necessarily conservative in estimating pipe stresses. However, design conservatisms in general assure that "stress allowables" are not exceeded and piping integrity is not compromised.

ACKNOWLEDGMENT

This work was supported by the U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research.

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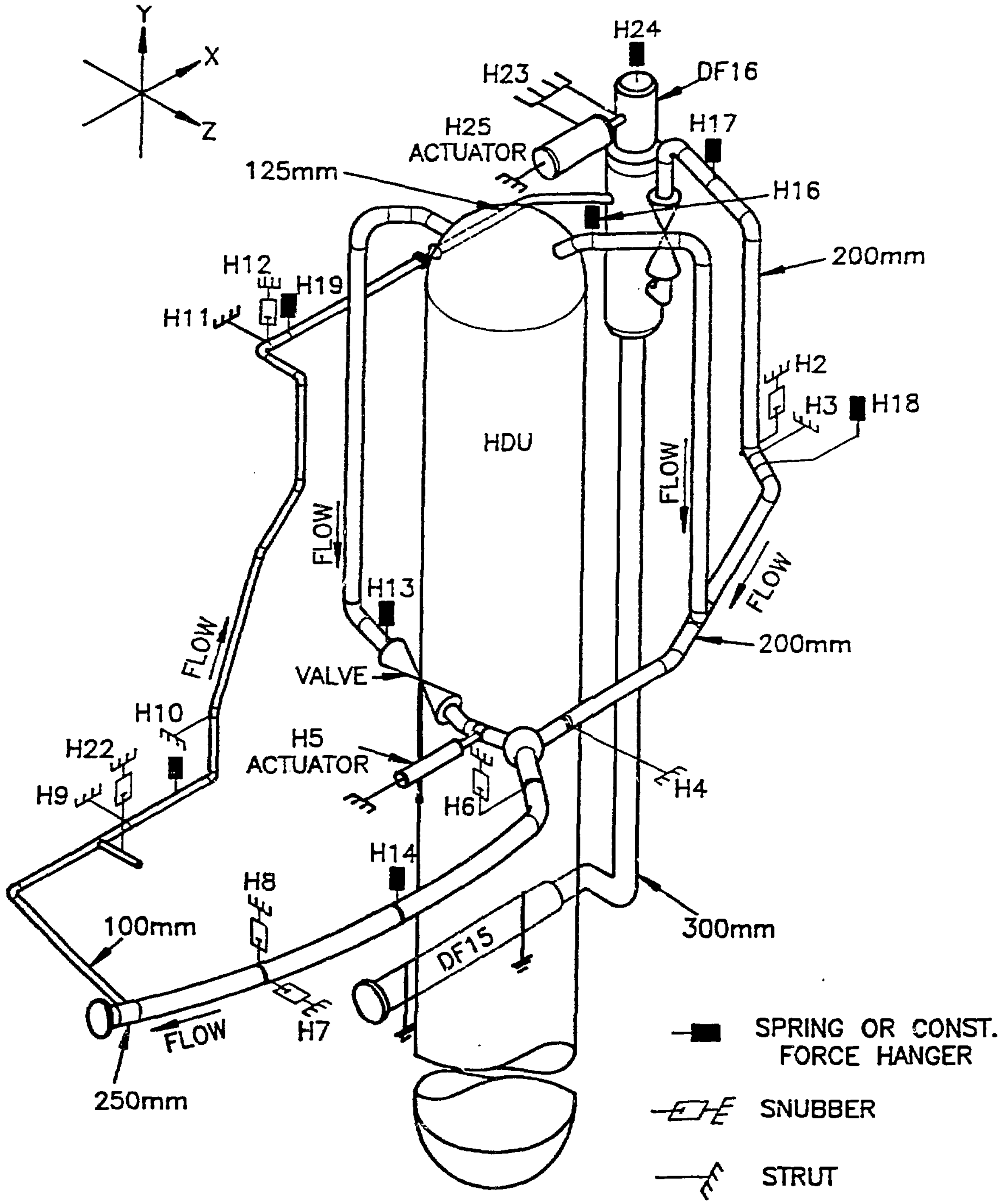

Fig. 1. SHAM Test Configuration – VKL Piping with US NRC Supports

<table>
<tr><th></th><th colspan="6">HANGER CONFIGURATIONS</th></tr>
<tr><th>Hang-
er No.</th><th>1
HDR</th><th>2
KWU</th><th>3
NRC</th><th>4
EPRI/EA</th><th>5
EPRI/SS</th><th>6
CEGB</th></tr>
<tr><td>2</td><td>—</td><td>—</td><td>Snubber
PSA1</td><td>—</td><td>Seismic
stop</td><td>—</td></tr>
<tr><td>3</td><td>—</td><td>—</td><td colspan="3">Strut
Size B</td><td>—</td></tr>
<tr><td>4</td><td colspan="6">Strut
Size 20</td></tr>
<tr><td>6</td><td>—</td><td>—</td><td>Snubber
PSA 1/2</td><td>—</td><td>Seismic
stop</td><td>—</td></tr>
<tr><td>7</td><td>—</td><td>—</td><td>Snubber
A/D 150</td><td>Energy
Absorber</td><td>Seismic
stop</td><td>Strut
RS-15</td></tr>
<tr><td>8</td><td>—</td><td>—</td><td>Snubber
A/D 70</td><td>Energy
Absorber</td><td>Seismic
stop</td><td>Strut
RS-7</td></tr>
<tr><td>9</td><td>—</td><td>Strut
Size B</td><td colspan="3">Strut
Size A</td><td>Strut
RS-7</td></tr>
<tr><td>10</td><td>—</td><td>Strut
Size B</td><td colspan="3">Strut
Size A</td><td>—</td></tr>
<tr><td>11</td><td>—</td><td>Strut
Size B</td><td colspan="3">Strut
Size A</td><td>—</td></tr>
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A/D 40</td><td>—</td><td>Seismic
stop</td><td>Strut
RS-15</td></tr>
<tr><td>22</td><td>—</td><td>—</td><td>Snubber
PSA 1/4</td><td>Energy
Absorber</td><td>Seismic
stop</td><td>—</td></tr>
<tr><td>23</td><td colspan="6">Two Struts
2 x Size 20</td></tr>
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Fig. 2. Dynamic Support Configurations for VKL Piping used in SHAM Tests

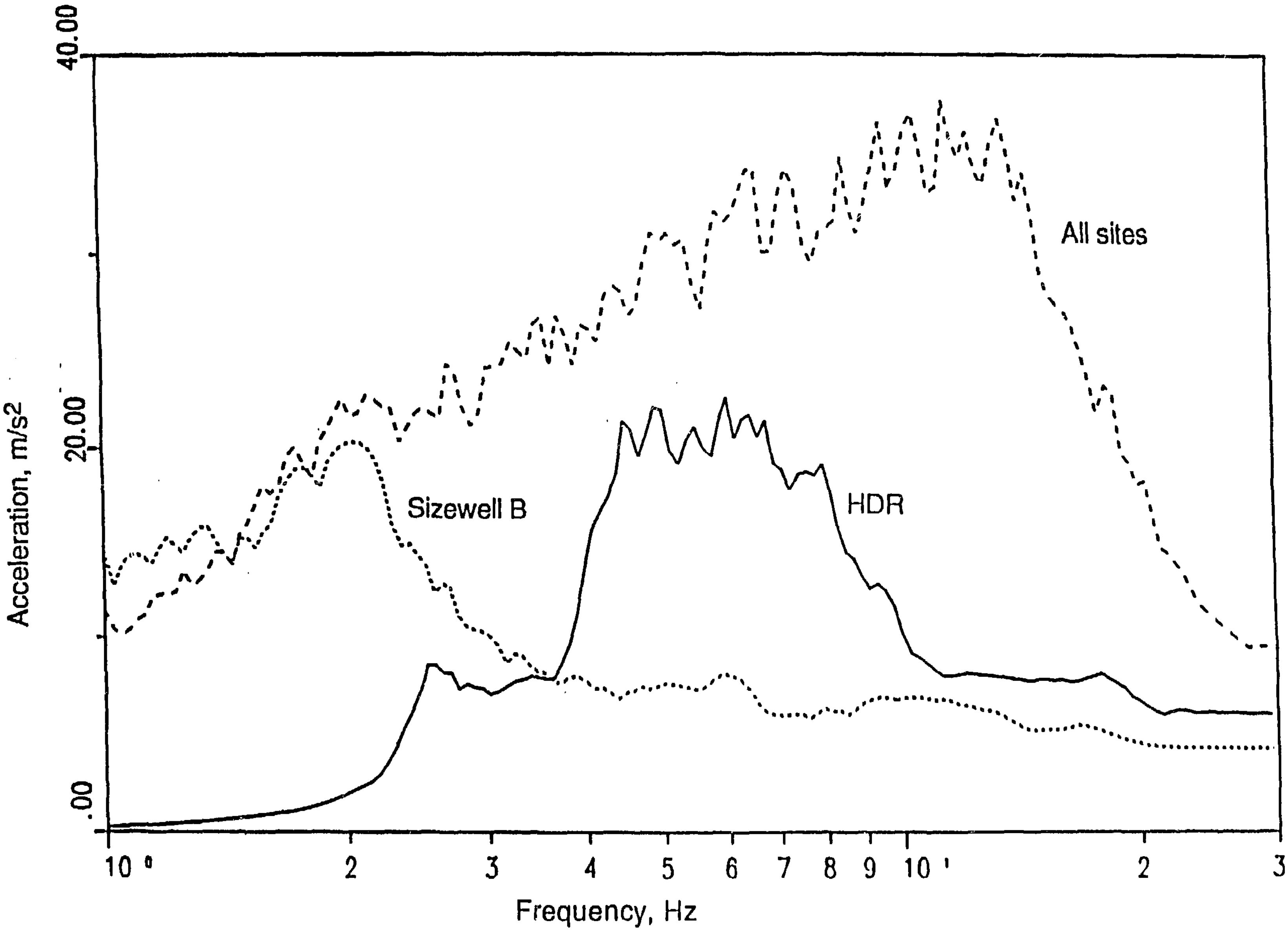

Fig. 3. Spectra of the Earthquake Excitations, 100%–SSE, 4% Damping

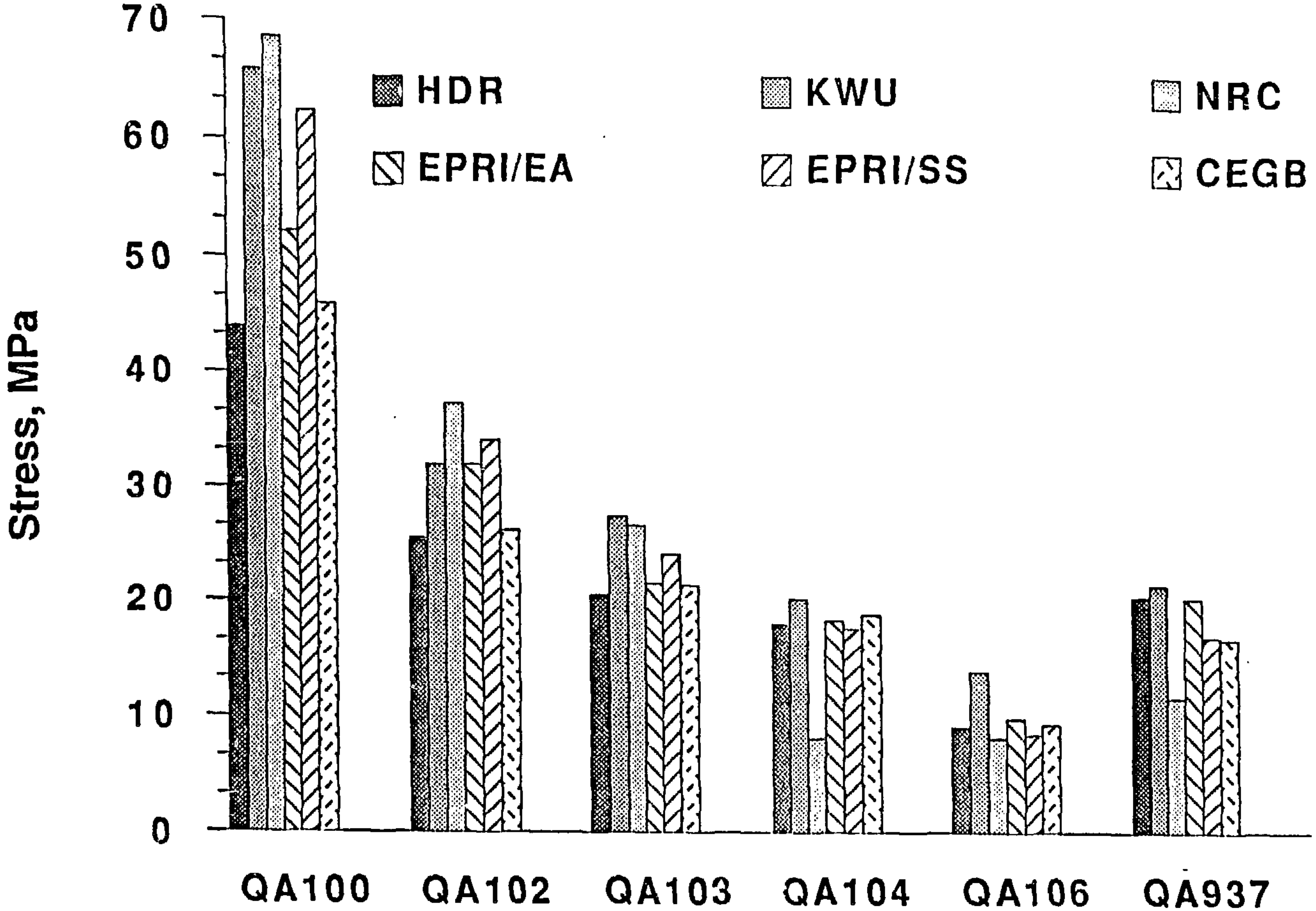

Fig. 4 Comparison of Maximum Bending Stress in 200-mm Pipe and Valve of Support Configurations at 100% SSE

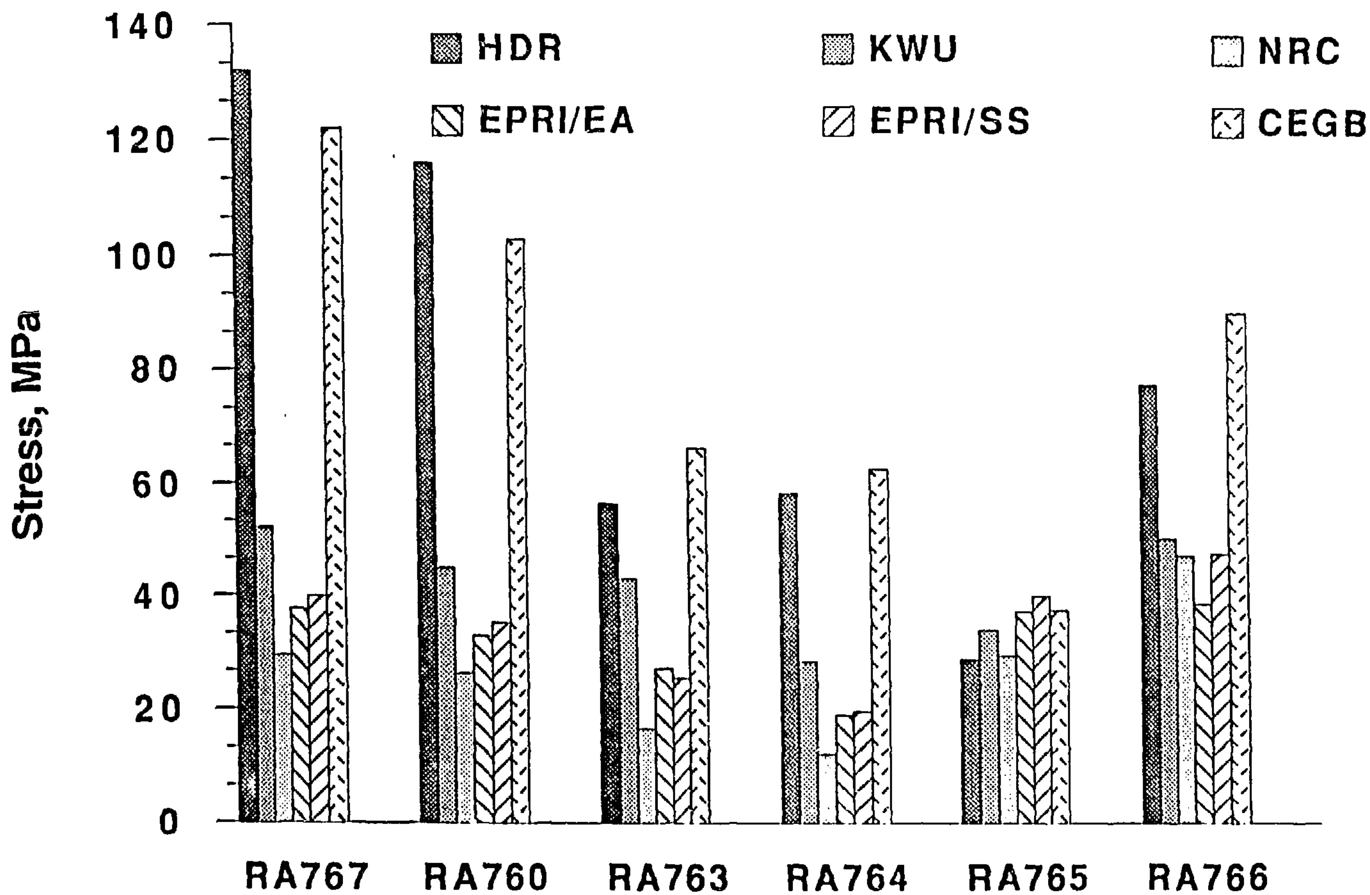

Fig. 5 Comparison of Maximum Bending Stress in 100-mm Pipe of Support Configurations at 100% SSE

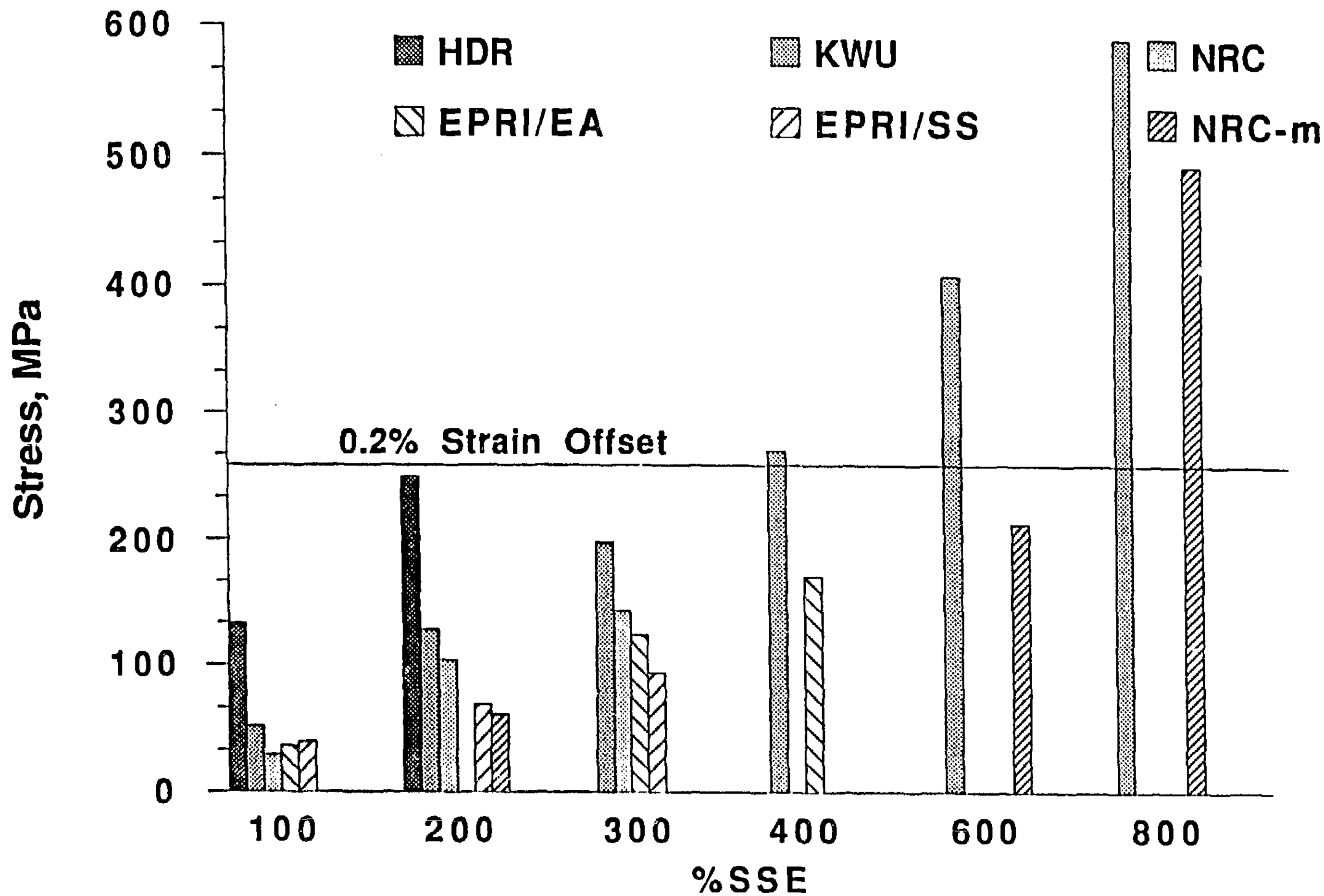

Fig. ~~12~~ 6 Maximum Bending Stress at Tee, RA767-100-mm Pipe: Effect of Increasing Excitation Levels

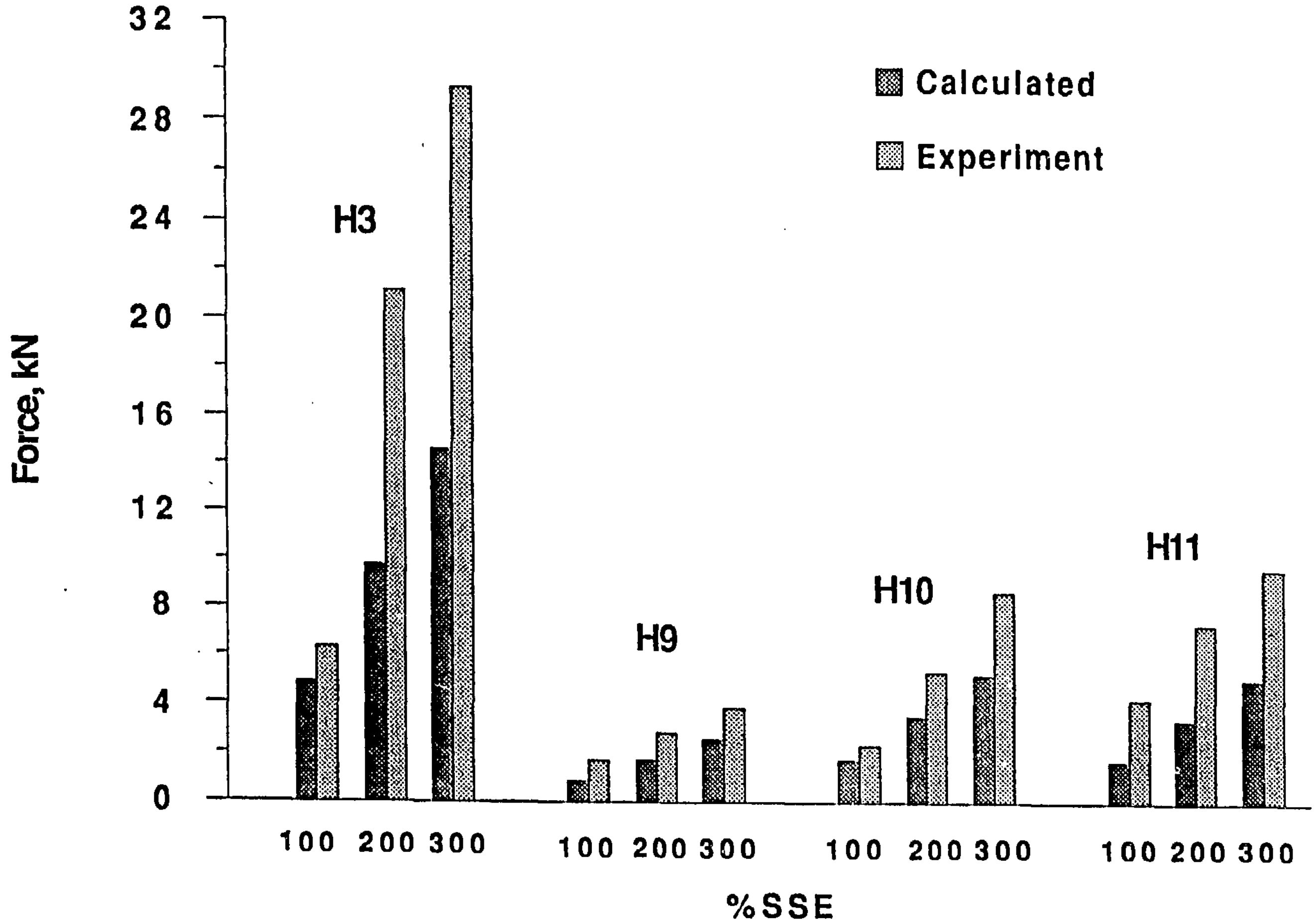

Fig.~~14~~ 7 Calculated and Experimental Maximun Strut Forces: Effect of Excitation Level – NRC Configuration

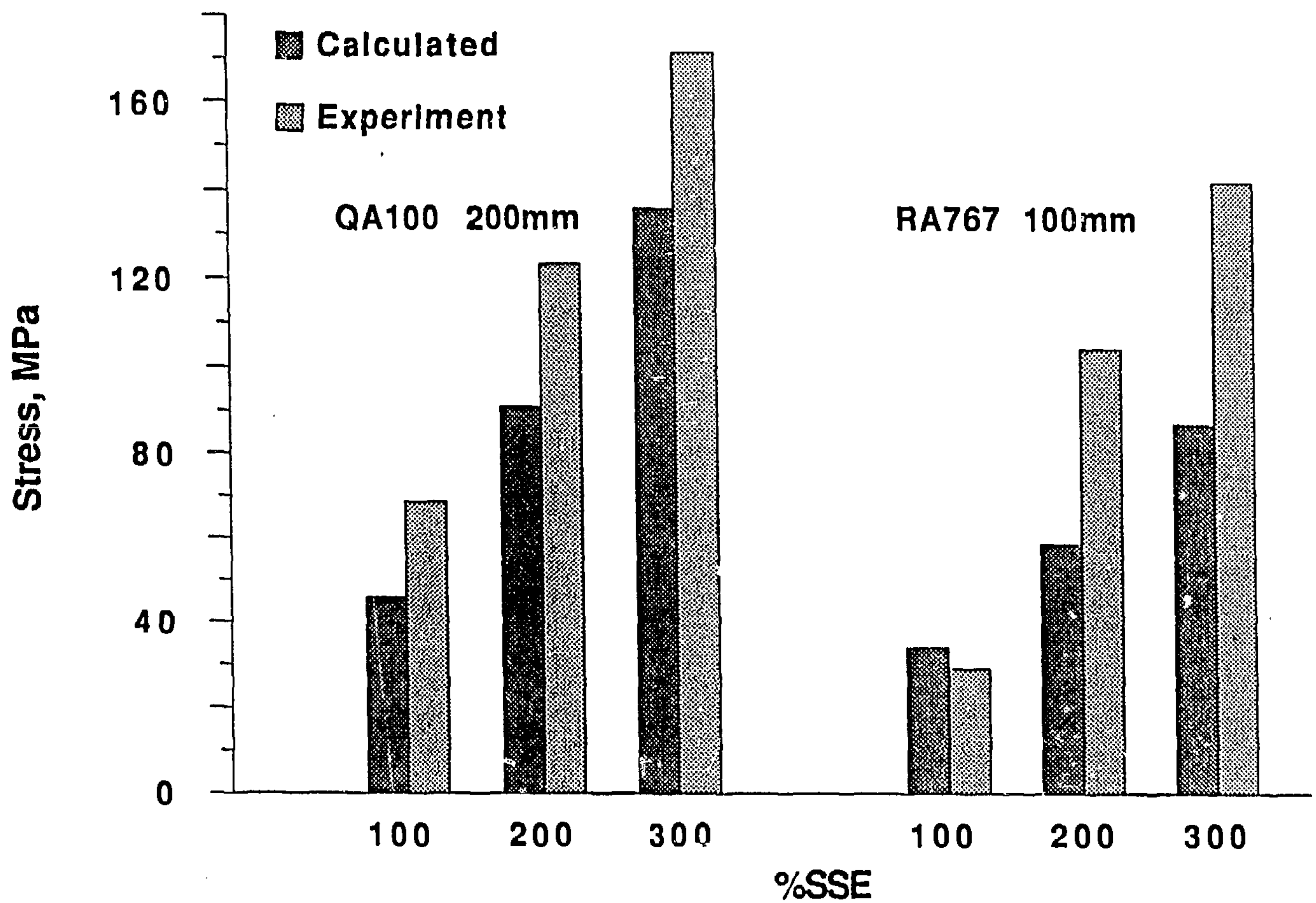

Fig. ~~10~~ 8 Calculated and Experimental Maximum Bending Stress: Effect of Excitation Level – NRC Configuration