LESSONS LEARNED FROM FULL-SCALE VIBRATION TESTS ON NUCLEAR POWER PLANT AUXILIARY STRUCTURE IN SWITZERLAND

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1. INTRODUCTION

1.1 Background

The Beznau Nuclear Power Plant in Fig. 1 is located in northern Switzerland. The plant is owned and operated by the Nordostschweizerische Kraftwerke AG (NOK) in Baden, Switzerland. It is a twin unit plant (2 x 350 MWe) which was designed in the early 1960's and placed into commercial operation between 1969 and 1971. In connection with a major backfit project, which will improve the safety of the plant against external events, the free-standing boric water tanks had to be relocated and were replaced by two boric water tanks in a new building (the so called BOTA-building).

1.2 Goals of Test and Analysis Work

The design and construction of the reinforced concrete BOTA-building gave the opportunity to plan and execute full scale vibration tests on this building. The overall aim of the tests was to validate computational models and parameters widely used in the seismic analysis of the structures and critical components of nuclear power plants. The scope of the experimental investigation was to determine the eigenfrequencies and damping values for the fundamental soil-structure interaction (SSI) modes. While still insuring the safety of the building and its internal components, the level of excitation was chosen as high as feasibly possible to approach the level of design earthquake excitations. The test results were then compared with the corresponding results from pre and post test numerical analyses.

1.3 Organization

For the planning and supervision of the tests a working group was formed of representatives of the owner and designer of the BOTA-building, the Nordostschweizerische Kraftwerke AG, the consulting firm Basler & Hofmann and Swiss Federal Institute of Technology in Zurich. The vibration tests, the data processing and data reduction were carried out by the Frauenhofer Institute (LBF) in Darmstadt, Germany. The numerical analysis work and the comparison and interpretation of the measured and computed results were undertaken by the working group.
The project's main phases were:

- the planning of the tests including the necessary pretest numerical analyses;
- the execution of the tests;
- the processing and reduction of the recorded data;
- the posttest numerical analyses using different computer models;
- the comparison and interpretation of the measured and computed results.

The major subject areas presented in this paper include:

- a brief description of the site where the plant is located, the structure of the BOTA-building and the planning and execution of the vibration tests;
- a presentation of selected test results from the ambient vibration, blast excitation and shake excitation tests;
- a description of the soil-structure interaction models used in the analyses, and
- a comparison and interpretation of the test and analysis results.

2. DESCRIPTION OF SITE, STRUCTURE AND TESTS

2.1 Site and Structure

The site of the nuclear power plant Beznau is located in the valley of the river Aare about 15 Km south of the northern border of Switzerland. The soil profile consists of a layer of dense alluvial gravel about 16 m thick overlying weathered claystone. Figure 1 shows the location of the new box-like BOTA-building close to the reactor building of unit 2. The reinforced concrete building is 26,1 m long, 13,5 m wide and 26,1 m high (see fig. 5). It is embedded into the ground at a depth of 4,4 m and has a central dividing wall which is 0,7 m thick. The two cylindrical steel tanks on the ground floor of the building are 10,6 m in diameter and 17,5 m high. Each tank has a total capacity of 1500 m3. The total mass of the building plus full tanks is 9300 t.

2.2 Planning and Execution of Tests

The planning of the tests required the following investigations:

- choice of method of excitation;

- selection of location, direction and magnitude of exciting force;
- determination of number and locations of the recording transducers;
- pretest numerical analysis to determine expected responses at different locations in the building.

The tests were executed in November 1985 by the Frauenhofer Institut fuer Betriebsforschung in Darmstadt and the results were reported to NOK (1, 2).

3. TEST RESULTS

3.1 Ambient Vibrations

Every structure vibrates according to its fundamental dynamic characteristics when excited by the natural dynamic environmental forces. Though the character of the excitation is not known, an appropriate analysis of the measured vibrations allows a reasonable estimate of the dynamic characteristics of the structure. The basis for this are the auto- and cross-spetra of the response signals. In the case of weaky damped structures, peaks occur due to peaks in the input spectrum or to the gain in resonances. A clear distinction of both types of peaks is not always possible.

Figure 2 shows the Fourier-Amplitudespectra of the roof responses in the x- and y-directions at 5,6 Hz and 6,2 Hz respectively. The estimation of the corresponding damping coefficient is somewhat difficult: the best guess is 3 - 5 % of the critical damping at 5,6 Hz and 6 - 9 % at 6,2 Hz. Furthermore, there are likely two weakly damped (0,8 %) modes with predominant vibration in x-direction at 8 and 8,9 Hz and three modes in the y-direction at 8,4, 9,3 and 9,7 Hz. Additional peaks are interpreted as periodic excitation because of their needlelike shape, induced probably by running main pumps or turbines in the adjacent structures.

3.2 Blast Excitations

During the blast event, the induced vibrations were measured at the same points as for the ambient vibrations. The signal intensity was higher by a factor of about 30 compared with the level of ambient vibrations.

Figure 3 shows the Fourrier-Amplitudespectra of the roof responses in the x- and y-directions. The evaluation of the data with regard to the cross-spectra and coherence yielded the two rocking modes in the x- and y-directions at 5,54 Hz and 6,56 Hz with 3,2% and 4,2% of critical damping respectively. The peaks in the frequency range from 8 Hz to 10 Hz are less pronounced than in the spectra from the ambient vibration test shown in Fig. 2. A multiple repetition of the blast excitation would have increased the quality of the spectra compared to those from one single event recorded.

3.3 Shaker Excitations

On the whole, 29 shaker tests were performed with variation of the force direction, force amplitude and frequency range. The test procedure was as follows: the frequency range associated with the specific shaker eccentricity was passed through in slow sweep with increasing and decreasing frequency (see fig. 4). The coherence between the shaker force (input) and the driving point response (output) was evaluated on-line using a 2-channel spectral analyzer. In the case of insufficient coherence in a certain frequency range the excitation of this range was extended in time during the down sweep. Some shaker runs were performed as detailed step weeps to investigate stationary response to harmonic excitation around resonance frequencies. Stationary and transient loading produced consistent results.

The number of transducers used during the shaker tests was considerably higher than during the pretests. 23 piezoelectric accelerometers with built-in charge amplifiers served to record the motion of the building and the boric water tanks. The location of the piezoelectric transducers are shown in fig. 5. Accelerations approaching the maximum stipulated value for the test (i.e. 5% g) were recorded in the building, the corresponding values in the tanks reaching 10% g. This is an increase by a factor of 300 compared to ambient excitation.

The test results include the time histories of the excitation force, the response acceleration and the corresponding transfer functions for amplitude and phase shift. Subsequently, the eigenfrequencies of the coupled soil-structure system, and the modal damping and mode shapes were evaluated using a 4-channel modal analyzer and commercial software packages to identify modal parameters and mode shapes.

4. MODELLING OF SOIL-STRUCTURE SYSTEM

The models used in the various analyses are shown in Figs. 6 and 7. Laboratory and field tests supplied the strain -dependent shear modulus and damping parameters of the soil profile. These values were selected for the anticipated strain level during the vibration test. The Lumped Parameter model (LP) shown in fig. 6 was already employed in the SSE and OBE seismic investigations for the building. The model served to obtain an initial prediction (LP-1) of expected response amplitudes and to locate approximately the eigenfrequencies for the SSI modes at the reduced level of loading of the test. Subsequently more refined analyses, i.e. (LP-2) and a Finite Element analysis (FE-1) using the computer program PLUSH were carried out (model shown in fig. 7).

In the analysis LP-1 the soil spring constants simulating the layered half space were determined by the method of Christiano et al. (3), while the viscous damping parameters accounting for radiation damping were based on an equivalent half space value.

In the analysis LP-2 the lumped masses were adjusted to represent more accurately the water masses, which in fact existed during the test. Further, the soil springs were modified to account for embedment and foundation shape according to the latest results published by Pais and Kausel (4) and Gazetas et al. (5). The effect of embedment is most pronounced on the rocking mode.

The purpose of the the FE analysis with the program PLUSH (6) was also to refine the modelling of embedment and soil layering. No use was made of the program's viscous boundary for 3-D simulation.

5. COMPARISONS OF TEST AND ANALYSIS RESULTS

5.1 Transfer functions

An initial direct comparison between measuring and computed results is afforded by the transfer function of response to harmonic excitation at various points of the structure. In this study the amplitude of the inertance function (acceleration per unit force) was used. The response to excitation in the x-direction for point 60 on the roof is shown in fig. 8. The rocking amplification of the building and tanks (8 to 10 Hz) may be clearly seen.

5.2 Modal Parameters

The next stage of comparison was by means of modal parameters derived both from test and analysis. The respective eigenfrequencies and modal damping values are summarized in Table 1. Figures 9 and 10 show the most important mode shapes in the x-direction of the building. In the following the most significant findings resulting from the comparisons are discussed.

5.3 Rocking of Building

In the case of rocking motions the predicted values are in close agreement with those derived from the measured results. The analysis LP-1, with a lower predicted eigenfrequency, shows that embedment cannot be neglected. The rocking amplitudes in the test are somewhat larger than the computed ones (see fig. 8 in the range 5 to 6 Hz). This may be attributed to the greater sway of the foundation and the greater bending displacement above ground level as indicated by the experimentally determined mode shape (fig. 9).

5.4 Vertical and Torsional Behaviour of Building

Vertical response was observed under vertical excitation, but only weakly. (fig. 11) The measured eigenfrequency was lower than that predicted by the 3-dimensional LP-analyses (Table 1). The difference between the damping values is large, probably due to the effects of ground layering (reflections from bedrock surface). The structural deformations of the building itself may also explain the differences observed. The FE analysis has not yet been carried out for this loading case. For the torsional vibration of the complete embedded structure the eigenfrequency was adequately predicted by the LP-analyses, but the damping was overestimated.

5.5 Bending of Tanks

It was also possible to predict quite well the eigenfrequencies of the tanks in the analysis LP-2 (Table 1). However, the damping values given by the test are much smaller than those computed. Whereas the tank vibrations were observed in the transfer function for the top of the tanks, this effect does not show up in the computed curves.

5.6 Out-of-Phase Bending Modes

With regard to the out-of-phase bending of building and tanks all three models produced the mode shape in the x-direction (fig.10), while the LP-models also gave a similar mode in the y-direction. In the test two modes were obtained in the x-direction (fig. 8) and five in the y-direction (Table 1). The eigenfrequencies for the test and the analyses were similar but the measured damping was smaller. This effect may be due to structural elements which were neither instrumented nor accounted for in the modelling.

6. CONCLUSIONS

The vibration tests allowed identification of the important modes of the soil -structure system in the range 3 to 15 Hz. The excitation was strung enough to generate accelerations in the structure comparable to those of a small earthquake. From the comparisons of computed and measured results it is concluded that the rocking frequency can be reasonably well predicted by either Finite Element or Lumped Parameter models with springs simulating the soil-foundation stiffness, provided in the case of the latter the embedment is taken into account. The prediction of the amplitude of structural response appears to be more difficult, as shown by the differences in the mode shapes. In the frequency range 8 to 10 Hz the agreement between computed and test results was less satisfactory. The actual structural behaviour turned out to be more complex than expected and needs further investigation with the aid of more refined models for the soil-structure system.

7. ACKNOWLEDGEMENTS

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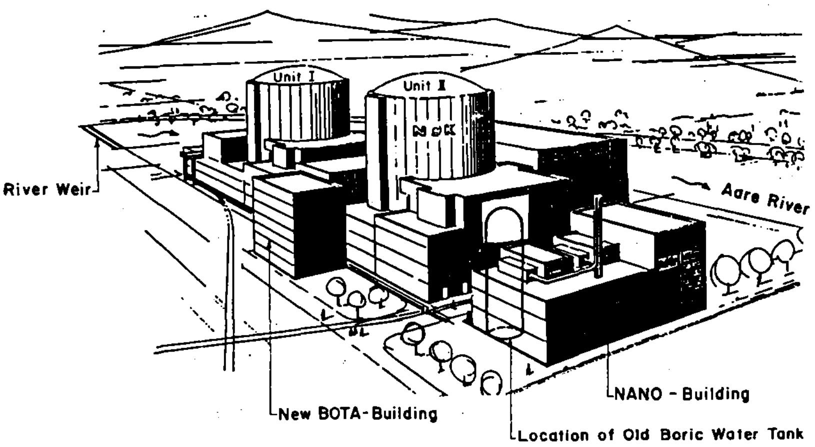
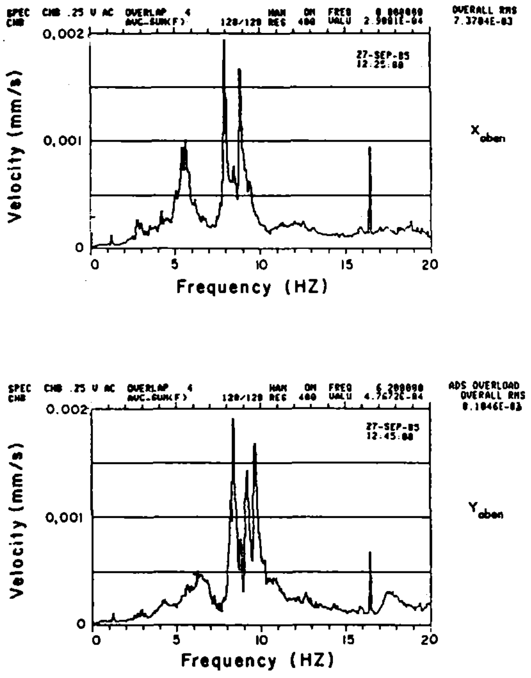
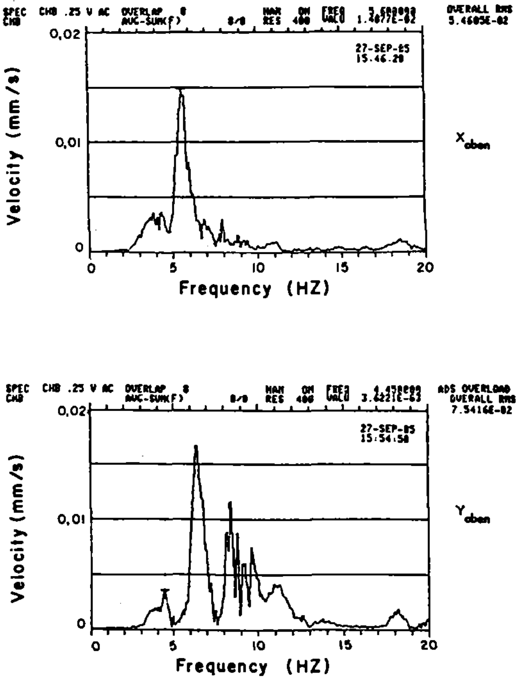


Fig. 1 Overview of Nuclear Power Plant Beznau, Switzerland



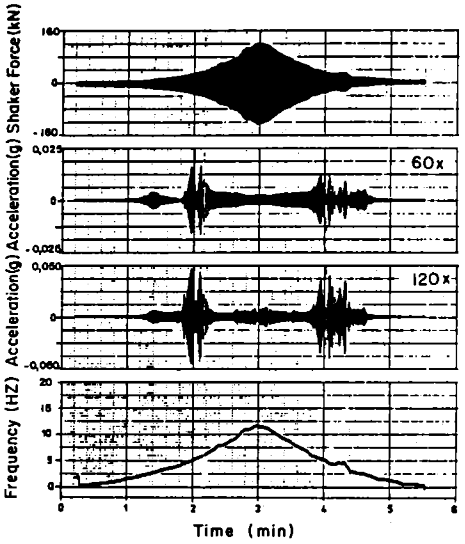
Ambient Vibrations: Fourier-Amplitudespectra of Roof responses in x- and y-Directions

Fig. 2



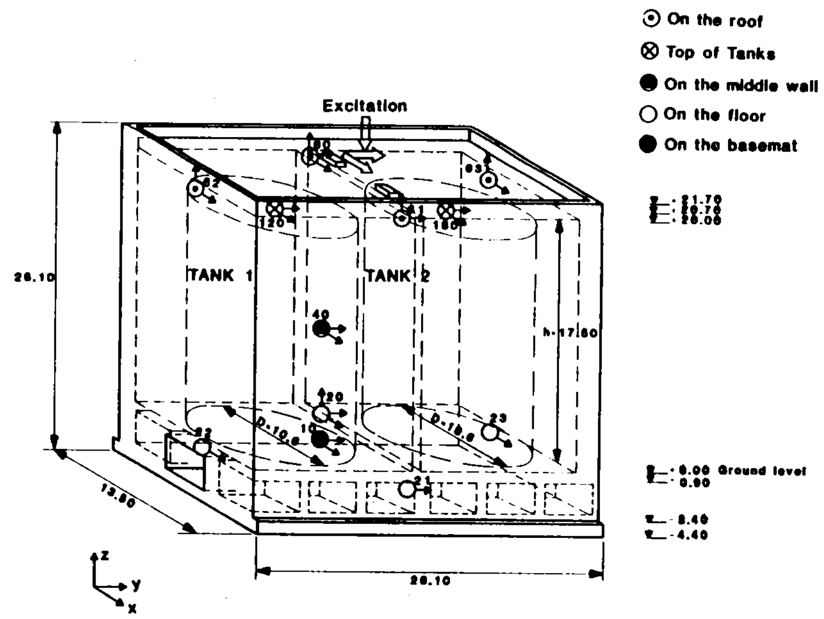
Blast Excitations: Fourier-Amplitudespectra of Roof Responses in x- and y-Directions

Fig. 3



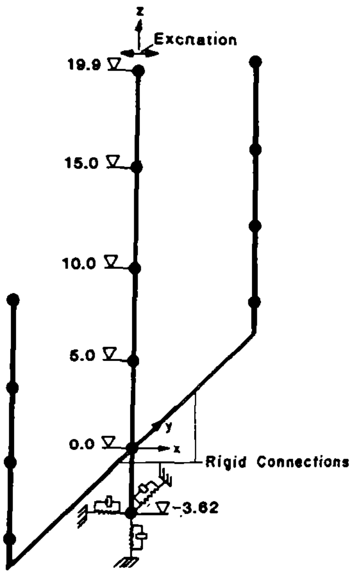
Recorded Acceleration-Time Histories for Slow Sine Sweep

Fig. 4



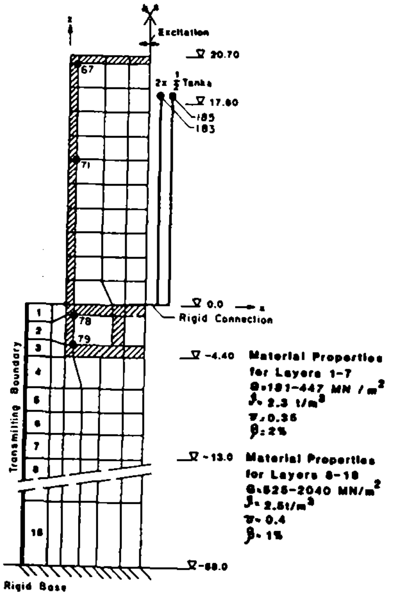
BOTA-Building Showing Location of Shaker and Locations and Directions of Response Measurements

Fig. 5



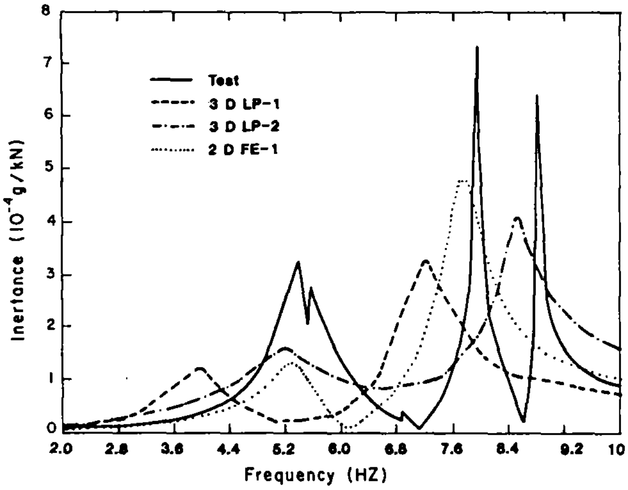
3-D Lumped Parameter Model Used for Numerical Analyses LP-1 and LP-2

Fig. 6



2-D Finite Element Model Used for Numerical Analysis FE-1

Fig. 7



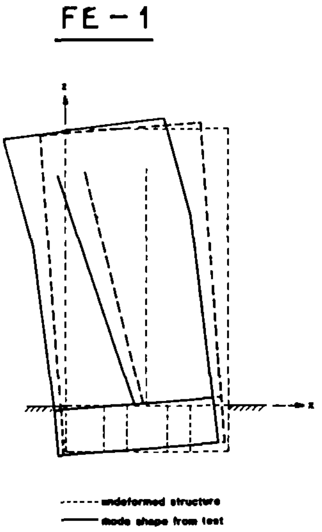
Comparison of Measured and Computed Inertance Functions in x-Direction at Point 60 due to Shaker Excitation in x-Direction on Roof

Fig. 8

Mode	Frequency (Hz)				Modal Damping Ratio (%)			
	Test	Computation			Test	Computation		
		LP-1	LP-2	FE-1		LP-1	LP-2	FE-1
Rocking transverse(x)	5.35	4.0	5.2	5.35	5.0	7.2	7.1	5.3
Rocking longitudinal (y)	6.23	4.7	6.1	-	5.2	9.6	8.8	-
Vertical (z)	7.80	11.2	10.6	-	17.0	66.0	69.0	-
Torsional (z - z)	12.45	11.3	13.8	-	2.7	10.7	7.0	-
Bending of tanks (x)	7.27	5.6	7.1	-	0.5	2.4	3.3	-
Bending of tanks (y)	7.27	6.4	7.4	-	0.5	2.0	2.0	-
Out of phase bending (x)	7.91	7.2	8.5	7.74	0.65	4.1	2.9	3.9
(2 modes)	8.80				0.46			
Out of phase bending (y)	8.21	8.0	8.9	-	1.30	8.6	6.2	-
(5 modes)	8.36				0.96			
	8.74				0.63			
	9.09				1.18			
	9.67				1.70			

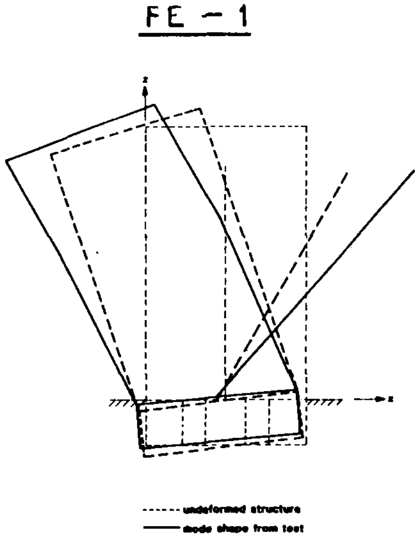
Comparison of Frequencies and Modal Damping Ratios from Tests and Numerical Analyses.

Table 1



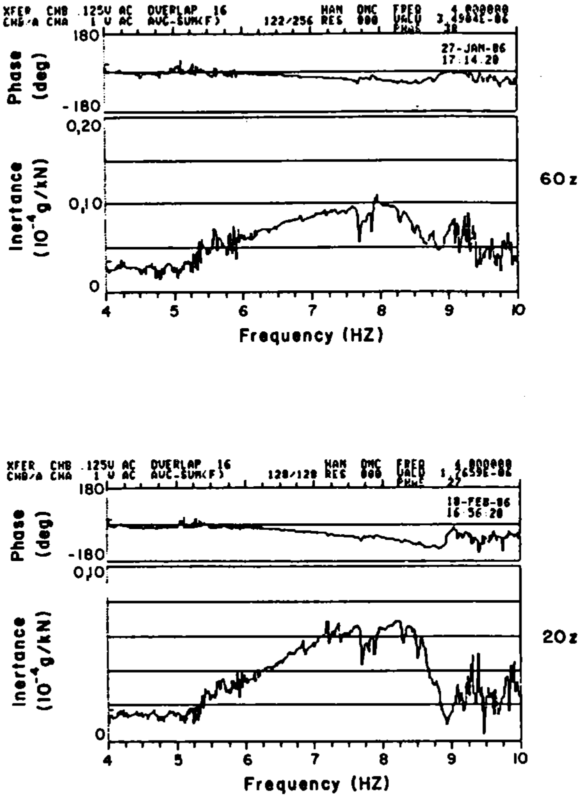
Comparison of Measured and Computed Mode Shapes for Rocking in x-Direction (f = 5,35 Hz)

Fig. 9



Comparison of Measured and Computed Mode Shapes for Out-of-Phase Bending in x-Direction

Fig. 10



Inertance Functions in z-Direction at Points 60 and 20 due to Vertical Shaker Excitation on Roof

Fig. 11