A Combined Seismic Model Testing and Analysis Program for a Typical W PWR Reactor Coolant System

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SUMMARY

Model testing on a reactor coolant system needs to be conducted to obtain information beyond the traditional objectives of confirming the analytical methods. A combined testing and analysis program on a 1/8 scale model is a logical and effective approach to gain vital knowledge on the physical behavior of the reactor coolant system during earthquake conditions. Discussed in detail in this paper is the development of such a program, suitable to achieve the objectives of 1) ascertaining the trend of damping increase with the increase in vibration amplitudes; 2) providing data to correlate with analytical results which depict important physical phenomena of the reactor coolant system such as impact and interaction with its concrete support structures; and 3) studying the significance of phase relationships among supports for the purpose of applying the multiple response spectra technique. Special consideration in the paper is given to the analysis of model similitude requirements conducted to arrive at the model design parameters, which are consistent with the need to achieve the program objectives and the constraint of the test facilities.

1. Introduction

To date, only a few seismic testing programs on reactor coolant system have been reported in the literature. Much of the testing programs reported were conducted to confirm the mathematical analysis used in arriving at the system fundamental dynamic characteristics such as natural frequencies. For instance, K. Shiraki, et. al., (Ref. 1) presented the shaker table test results of a 1/4 scale plexiglass model representing a PWR Reactor Coolant System supported by a concrete structure. The primary objective was to verify the mathematical modeling techniques used. However, the elastic properties of the plexiglass are loading and temperature sensitive. When interaction effects of concrete and steel components need to be considered, dynamic response distortions are inevitable, making it undesirable for evaluating the damping phenomenon of the system, the impact effect of support gaps, and thus the accuracy of the system response.

Currently, the modal damping values used for the reactor coolant system analysis are based on tests conducted at very small vibration amplitudes (Ref. 2). It is generally agreed that damping values increase with the increase of vibration amplitudes (Ref. 3). Although some theoretical studies have been presented to extrapolate damping values at high vibration amplitudes (Ref. 4), no test results are available to substantiate the claim. Short of in-situ tests at high vibration level, a carefully planned model testing needs to be conducted to provide more accurate design input. Preferrably, as a major model design consideration, this model should have the same material and should result in the same stress level as the prototype. As a result, the trend of increase damping with the increase in vibration amplitudes can be correlated. Further, the model test results can be combined with field test data obtained at low vibration levels to form a basis for assigning more realistic damping values for analysis purposes.

In addition to the need of determining damping values at higher vibration amplitudes, there are other physical phenomena of the reactor coolant system which require validation by tests also. For instance, it has been shown by analysis that the major equipment support gaps could produce significant impact effects. It is imperative from design safety viewpoint that such effects be ascertained by tests. This can be accomplished by conducting a combined test and analysis program on the test model.

Finally, the reduction of response loads has been predicted (Ref. 5) for the reactor coolant system supported by multi-level of supports using a composite formula. Also, the response attenuation effect between the reactor coolant system and the concrete structure and the need to obtain accurate system frequencies have resulted in the recommendations of various coupling criteria for heavy or closely tuned systems (Refs. 6, 7). These phenomena need to be substantiated by tests.

In summary, model testing on a reactor coolant system needs to be conducted to obtain information beyond the traditional objectives of confirming the analytical methods. A combined test and analysis program on a scale model is a logical and effective approach to gain vital knowledge on the physical behavior of the reactor coolant system during a simulated earthquake condition. Discussed in detail in this paper is the development of such a program, suitable to achieve the various objectives delineated above. Special consideration in the paper is given to the analysis of model similitude requirements conducted to arrive at the model design parameters, which are consistent with the need to achieve the program objectives and the constraint of the test facilities.

2. Similitude Analysis

The test model has been scaled to represent the reactor coolant system and its concrete supporting structure. It is not possible to satisfy completely the law of similitude due to the complexity of the system which includes also signifigant design nonlinearity.

While some relaxation to the law of similitude may be necessary, it is important that the priority of the test program be first established so that the important objectives of the program are not compromised.

To this end, it has been identified that an accurate determination of the damping information is one of the key program objectives. As a result, the material damping mechanism should have minimum distortion, by maintaining the stress level at the test model comparable to the prototype design. This requirement can be simply represented by the following equation:

$$\lambda_\sigma = \lambda_E \lambda_\varepsilon = 1 \tag{1}$$

where λ represents the ratio of the model to the prototype and subscripts σ, E and ε designate the corresponding quantity of stress, Young's modulus, and the strain, respectively.

Equation (1) yields immediately the following:

$$\lambda_E = 1 \tag{2}$$

which means that the test model needs to be made with the same materials as the prototype.

With equation (1), it can be deduced that

$$\lambda_F = \lambda_\sigma \lambda_A = \lambda_L^2 \tag{3}$$

where subscripts F, A, and L represent the force, area, and the length, respectively.

By maintaining the model materials the same as the prototype, the scale factor for density becomes 1. This leads to a scale factor of λ_L^3 for mass. However, from equation (3), which can also be written as the product of λ_m and λ_a (where m is the mass and a the acceleration), λ_m would have to be equal to λ_L^2 if the gravitational scale factor (λ_g) is assumed the same as acceleration (λ_a) and is equal to 1. Therefore, there is a discrepancy of a factor of λ_L for mass. This shows that the traditional approach of modelling may have underestimated the effect of mass, or force, by a factor of λ_L.

As a remedy, Ref. 8 has proposed to increase the mass of a test model by adding lead. This is a feasible approach provided that the amount of lead to be added is not large. Also, it is necessary to ensure that the model behavior is not unduly affected by the added lead. Since it is desirable to make the test model as large as practicable, the amount of lead to be added needs to be limited. A workable solution to this problem then is to add only a partial amount of lead and only at specific locations.

For instance, λ_m can be increased from λ_L^2 to $\lambda_L^{5/2}$ instead of λ_L^3. That is

$$\lambda_m = \lambda_L^{5/2} \tag{4}$$

which leads to the following weight scale factor:

$$\lambda_w = \lambda_m \lambda_g = \lambda_L^{5/2} \qquad (5)$$

using equation (4) and the results of equation (3), it can be easily shown that

$$\lambda_a = \lambda_L^{-1/2} \qquad (6)$$

which indicates that the acceleration scale is no longer the same as the gravitational scale. This is a distortion which needs to be reconciled during the data interpretation. And it should present no difficulty as the gravitational (or vertical accelerational) effects are considered insignificant, and the system response are basically uncoupled in the horizontal and vertical directions.

With the scale factor for acceleration determined, the scale factors for time, frequency, velocity, and impulse can be readily determined. These are shown in Table 1.

3. Design of the Test Model

In designing the test model, the arrangement of the reactor coolant system and its steel and concrete supports is reduced from the prototype design, with the exception that a minimum concrete wall thickness of 3 1/2" is maintained. Also, since it is not desirable to add lead to the concrete walls, the weight distribution of the walls need to be rearranged so that the natural frequencies and mode shapes are comparable to a typical prototype design.

As for the components such as steam generator and the reactor coolant pump, lead is only added to the interior (represented by a steel pipe supported by baffle plates) of the steam generator. The remaining of the additional weight is taken by the solid steel plates simulating the rigid portion of the steam generator and the reactor coolant pump. To ensure that the impact effect between the supports and the steam generator shell is not distorted, no additional weight is added to the steam generator shell close to the supports. Also, no lead is added either on the loop piping, main steam line, or metal supports. The effect of mass in these areas is not considered to be significant.

A simple sketch showing the test model arrangement is presented in Figure 1. The scale of the model is 1/8 of the prototype.

4. Correlated Testing and Analysis

Several types of tests are planned. These include low magnitude portable shaker test and tests employing random base inputs, and synthesized time history tests with increasing vibration magnitudes. These tests should provide useful design information concerning damping value, in particular, its relationship with vibration magnitudes. In addition, the test data should provide the best means of qualifying the methods and the analytical models used in the analysis of the prototype design.

Therefore, analyses will be conducted first on the test model using the methodology currently adopted for the prototype design. Two types of analyses are planned. One is the response spectrum analysis to evaluate the model integrity under the intended test response spectrum input, and a multiple response spectra analysis using the recorded support spectra to study the predictive value of the multiple response spectra approach proposed in Reference 9.

Finally, time history analyses using the recorded time history reactions will be conducted to assess the nonlinear time history analysis techniques, in particular, the significance of the impact effects.

5. Concluding Remarks

A combined test and analysis program is described herein to facilitate the study of 1) damping characterics of the reactor coolant system subjected to design earthquake motions; 2) evaluating the impact phenomenon due to support nonlinearities; and 3) correlating the analytical results with test data on system response characterics which are deemed to be significant.

To overcome the similitude difficulty, a means has been found to scale the parameters by partially adding weight to the model. The 1/8 scale model is optimum designed for meeting program objectives and overcoming the constraints of the test facilities.

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TABLE 1

MODEL SIMILITUDE REQUIREMENTS

Physical Quantity	Symbol	Dimension	Similitude Requirement
1. Length	L	L	$\lambda_L = L_m/L_p$
2. Gravitation	g	LT^{-2}	$\lambda_g = 1$
3. Young's Modulus	E	$ML^{-1}T^{-2}$	$\lambda_E = 1$
4. Mass	m	M	$\lambda_m = \lambda_L^{5/2}$
5. Strain	ε	--	$\lambda_\varepsilon = 1$
6. Stress	σ	$ML^{-1}T^{-2}$	$\lambda_\sigma = 1$
7. Dead Weight	w	$ML\ T^{-2}$	$\lambda_w = \lambda_L^{5/2}$
8. Spring Constant	k	MT^{-2}	$\lambda_k = \lambda_F/\lambda_d = \lambda_L$
9. Force	F	$ML\ T^{-2}$	$\lambda_F = \lambda_s\lambda_A = \lambda_L^2$
10. Displacement	d	L	$\lambda_d = \lambda_L$
11. Velocity	ν	LT^{-1}	$\lambda_\nu = \lambda_\omega^{-1}\lambda_a = \lambda_L^{1/4}$
12. Acceleration	a	LT^{-2}	$\lambda_a = \lambda_L^{-1/2}$
13. Area	A	L^2	$\lambda_A = \lambda_L^2$
14. Volume	V	L^3	$\lambda_V = \lambda_L^3$
15. Frequency	ω	T^{-1}	$\lambda_\omega = \lambda_T^{-1} = \lambda_L^{-3/4}$
16. Period	t	T	$\lambda_t = (\lambda_a/\lambda_L)^{-1/2} = \lambda_L^{3/4}$

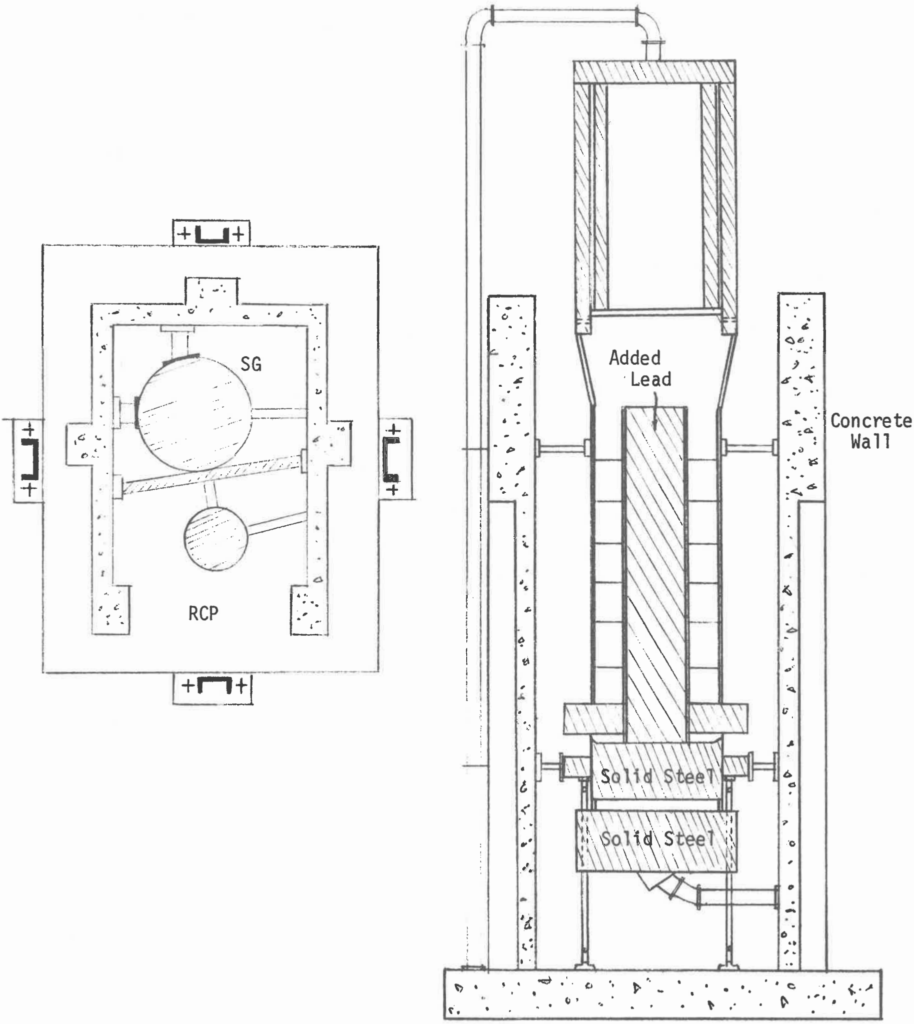

FIGURE 1 SCHEMATIC OF THE TEST MODEL