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SEISMIC RESISTANT ANALYSIS OF COUPLED MODEL OF REACTOR COOLANT SYSTEM AND REACTOR BUILDING

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ABSTRACT

Reactor coolant system(RCS) and reactor building are actually coupled with each other. SRP (Revision 2) edited by USNRC particularly pointed out in§3.7.2 that RCS, which is considered a subsystem but is usually analyzed using a coupled model with building.

Under this background, this paper selects PC-NPP as a study object, and seismic resistant analysis is performed with a coupled model of building and RCS using response spectrum method and time history method. Finally, analyzed results are compared with those of uncoupled RCS model. In the analysis, building is simulated with cantilever beam model of shear wall combination. In the uncoupled model, each supporting of equipment is modeled using elastic beam element with actual supporting stiffness, which is connected to a rigid cantilever (single-point input) and to an elastic cantilever (multipoint input). Seismic load of coupled model is input from the bottom of building. After comparison, it is shown that the effect of interaction between RCS and building can not be ignored, and the uncoupled model for seismic resistant analysis is inappropriate to be applied in actual seismic design.

Through this research, we can control the seismic analysis technique in coupled model and enhance our analysis level of NPP.

Keywords: Coupled，Reactor Building，Reactor Coolant System

1. INTRODUCTION

In nuclear power plant, reactor coolant system(including reactor vessel, main pump, steam generator and main pipe in PWR) is actually supported on the different floors of reactor building and always coupled with reactor building.

In the actual design of domestic NPP, the seismic analysis was performed separately for reactor coolant system(RCS) and reactor building after these two systems were decoupled firstly. Although this method was permitted by the past standard, Standard Review Plan (Revision 2) edited by US Nuclear Regulatory Commission particularly pointed out in Section 3.7.2 Seismic System Analysis that reactor coolant system, which is considered a subsystem but is usually analyzed using a coupled model with reactor building. Under the requirement of new standard some new analysis has been complemented for the established overseas NPP for which the analysis was not generally performed like that before.

Under this background, considering engineering practice, this paper selects PC NPP as a study object, and seismic resistant analysis is performed with a coupled model using response spectra method and time history method, where reactor building and RCS are coupled together according to actual connections (or supports). Finally, analyzed results are compared with those of uncoupled reactor coolant system model. In the analysis, reactor coolant system and reactor building are modeled with elastic beam elements. Reactor building is simulated with cantilever beam model of shear wall combination. In the uncoupled model, supporting of every equipment is modeled using elastic beam element with actual supporting stiffness, which is connected to a rigid cantilever (single-point input) and to an elastic cantilever (multipoint input). According to actual condition, seismic load of the coupled model is input from the bottom of reactor building. After comparison, it is shown that the effect of interaction between RCS and reactor building can not be ignored, and the old uncoupled model for seismic resistant analysis is inappropriate to be applied in actual seismic design.

2. EXORDIUM

2.1 DOMESTIC AND OVERSEAS DESIGN STATUS

a) Multistep method is adopted in the seismic analysis for all the domestic constructed NPP.
Firstly, dynamic analysis is performed for the reactor building with the model considering only the mass of all the main equipments of RCS and assuming that mass is rigidly connected to the building.
Secondly, the floor response spectra are generated from the dynamic response of each mass node with above model.
Finally, detailed dynamic analysis of RCS is performed with the floor response spectra as the seismic input.

b) Multistep method is usually adopted in the seismic analysis for overseas constructed NPP.

In this method the RCS is essentially analyzed as a decoupled system from the building without considering the effect of interaction between the former and latter.

2.2 CONTROVERSY ABOUT DECOUPLING PROBLEM

Until now there is no strict verdict on the decoupling between the primary structure and subsystem. In the process of the radication of the decoupling criteria, the comparison between the system in the coupled model and the uncoupled model must be done to decide whether the primary structure and subsystem can be separately analyzed upon the dynamic characteristics of the interacting systems. In the course of comparison, the parameter or variable selected to be compared decide the base of decoupling criteria.

Standard Review Plan (June 1975) edited by US Nuclear Regulatory Commission put forward a decoupling criteria about the primary structure and subsystem in Section 3.7.2 Seismic System Analysis.

The mass ratio R_m and the frequency ratio R_f are defined as:

$$R_m = \frac{\text{Total mass of the supported subsystem}}{\text{Total mass of the supporting system}} \qquad \text{Eq.1}$$

$$R_f = \frac{\text{Fundamental frequency of the supported subsystem}}{\text{Dominant frequency of the support motion}} \qquad \text{Eq.2}$$

(i) If $R_m < 0.01$, decoupling can be done for any R_f.

(ii) If $0.01 \leq R_m \leq 0.1$, decoupling can be done if $R_f \leq 0.8$ or $R_f \geq 1.25$.

(iii) If $R_m > 0.1$, a subsystem model should be included in the primary system model.

From engineering point of view, Mr. Chang Chen pointed out that decoupling criteria should be based on the deviation of the system response which was very complex. He discussed the decoupling problem after the solution of eigenvalues(natural frequencies) and the eigenvectors(mode shapes) with a coupled model for a two degree of freedom system as an example. And the statistical properties of the responses was calculated and discussed by the random vibration theory with the white noise input. This part of work was quoted from Mr. Crandall, S.H. & Mark, W.D.

Many papers and persons also discussed this decoupling problem such as RDT, Aziz and Duff, Hadjian, A.N.Birbraer, ASCE4-86 Standard ect. and they all pointed out their own decoupling criteria. But there is no criteria can be known as perfect.

Simultaneously considering the economics and the safety of NPP, the decoupling criteria mentioned in the USNRC SRP and ASCE4-86 Standard is usually recommended.

The above discussions are all within the range of single-point support. As to the multipoint constraint like RCS supported on different floor of reactor building, the decoupling problem is much more complex. ASCE4-86 Standard(1)definitely pointed out that until now there is no decoupling criteria for the multipoint support system. Therefore USNRC SRP (Revision 2, 1989) particularly pointed out in Section 3.7.2 that one important exception to the decoupling criteria is the RCS, which is considered a subsystem but is usually analyzed using a coupled model with reactor building.

3. ANALYSIS PROCESS

Under the new requirement of USNRC SRP §3.7.2, the interaction effect between RCS and reactor building is discussed for the PC NPP as a study object.

1. Build up appropriate coupled model for the RCS and the reactor building.
   Considering that the RCS and reactor building are all very complex system, the coupled model needs not only to be relatively simplified but also to present their typical dynamic characteristics such as mass, stiffness and damping ratio.
2. Perform the dynamic analysis with response spectrum method for the coupled model.
   According to the actual situation, the seismic load is input with the floor response spectrum of 0.0m from the bottom of the reactor building.
3. Build up the uncoupled model for the RCS and perform the analysis separately. In this model the RCS is supported at the different fix point not at the different point of reactor building any more. Assume different cases for the seismic load:
   a) Assume the seismic input of all the fix points is a sigle spectrum, , viz. single-spectrum input.
   b) Assume seismic input for the different points is different floor spectra according to the different floor of the reactor building, viz. multi-spectrum input.
4. Perform the dynamic analysis with time history method for the coupled model and uncoupled model.
   The seismic input is the acceleration time history compatible with the floor response spectrum in the response spectrum method.
5. Compare the analysis results of coupled model and the uncoupled model in the response spectrum method and also in the time history method, discuss the interaction effect between the two systems and arrive at instructional conclusion from the point of engineering.

4. DAMPING

The physical mechanism of damping relates to vary kinds of complex ingredient which leads to extreme difficulty in simulating damping and also in the analysis process (especially in the seismic analysis of a system). Until now, the decoupling of this kinds of coupled damping in the complex system composed of different subsystems with different damping is quite intractable. In this analysis, the composite modal damping which is based on the distribution of dissipating energy in different subsystems is selected to simulate the modal damping characteristics of subsystem [2,3].

In this analysis the program DYNAS chooses the mass as the weighting factor to generate the composite modal damping as following:

$$\beta_j = \frac{\sum_{i=1}^{n} \{\phi_j\}^T \beta_i [M]_i \{\phi_j\}}{\{\phi_j\}^T [M] \{\phi_j\}} \qquad \text{Eq.3}$$

where β_j = composite modal damping for mode j ,

β_i = critical modal damping associated with component i ,

$[M]$ = mass matrix of the system,

$[M]_i$ = subregion of mass matrix associated with component i ,

ϕ_j = modal shape vector for j^{th} mode.

5. ANALYSIS MODEL

5.1 UNCOUPLED MODEL FOR THE RCS

1. The model includes the reactor vessel, main pump, steam generator and main pipe in PWR.
2. The elastic beam element is selected to simulate the main equipments of RCS.
   The critical damping is chosen 0.03 based on the equipments and the piping system under SSE.

3. The elastic beam elements are lain to present the supports for all the equipments according to the equivalent stiffness of the supports in three directions of the coordinates.

5.2 COUPLED MODEL FOR THE RCS AND THE REACTOR BUILDING

1. Based on the comparison conclusion of some references [(4)], the combined cantilever beam model of shear wall without flange can preferably reflects the physical characteristics of nuclear auxiliary building such as mass and stiffness. In this analysis the reactor building is also simplified with the combined cantilever beam model without flange. In the model the floors in the horizontal direction are all treated as rigid.
2. The RCS is directly supported on the correspond points of reactor building and the supporters are considered as elastic structures.
3. Damping ratio is selected as 0.03 for the RCS and as 0.07 for reactor building.

The coupled model is shown in Figure 1.

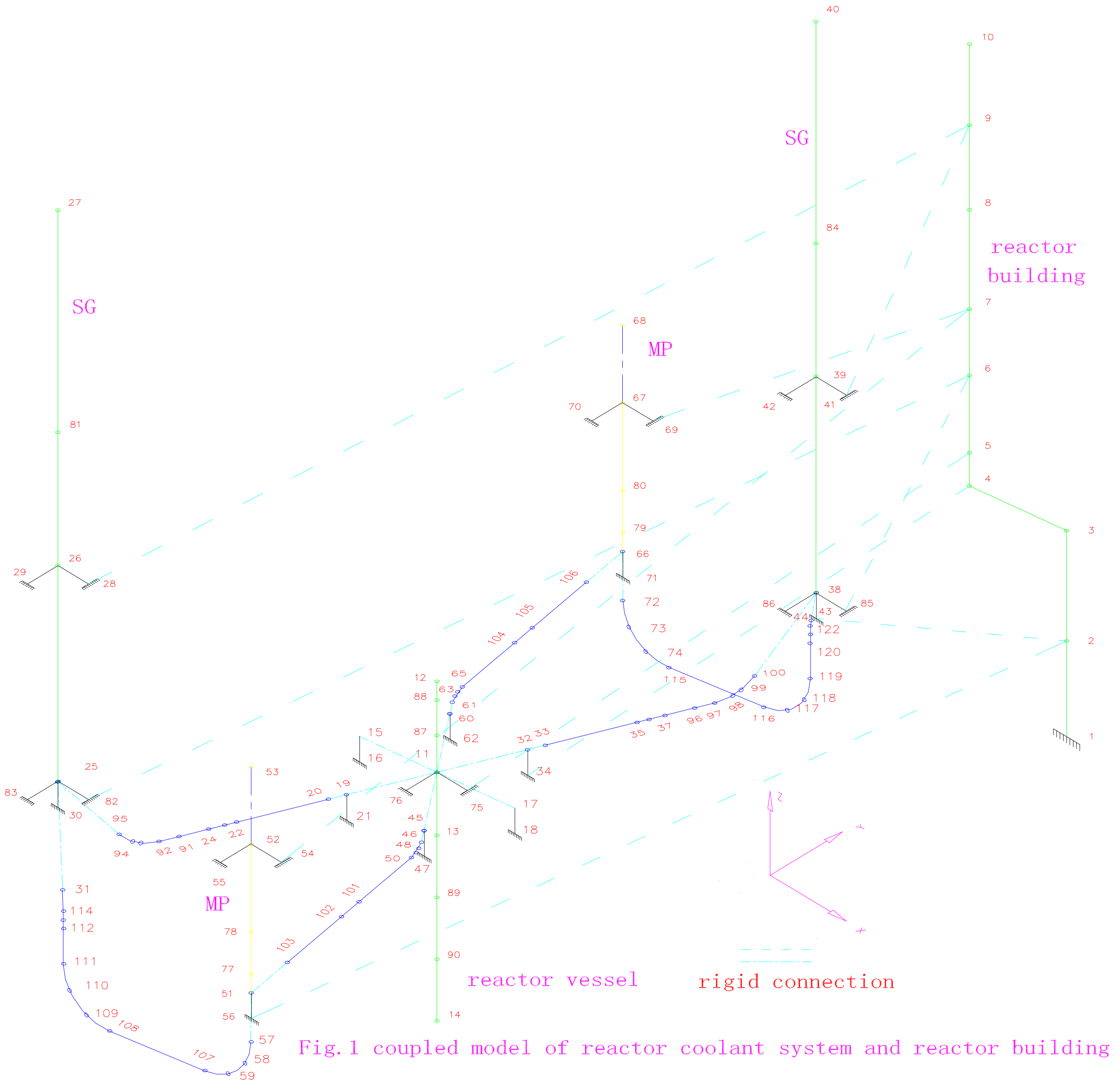

Fig. 1 coupled model of reactor coolant system and reactor building

6. ANALYSIS INPUT

6.1 RESPONSE SPECTRUM ANALYSIS

To the coupled model, the floor response spectrum of 0.0m for 3% and 7% damping ratio is input as the seismic load at the fix bottom of the combined cantilever beam model of reactor building.

To the uncoupled model, all equipments of the RCS are supported on the fix points without degree of freedom and the seismic input is assumed as following:

1. The seismic input of all the fix points is a single spectrum, , viz. single-spectrum input.
2. The seismic input for the different points is different floor spectra according to the different floor of the reactor building, viz. multi-spectrum input.

6.2 TIME HISTORY ANALYSIS

The time history analysis is performed for the coupled model and the uncoupled model separately and the seismic input is the acceleration time history compatible with floor response spectrum used in response spectrum analysis.

7. ANALYSIS RESULTS

7.1 FREQUENCIES COMPARISON BETWEEN COUPLED&UNCOUPLED MODEL

1. The fundamental frequency of nearly every equipment of RCS for the uncoupled model is a little higher than that of coupled model.
2. In the coupled model, the elastic translation of reactor building, treated as elastic beam, put the supports of all equipments in motion, which results in the slight decrease on the fundamental frequency of equipment.
3. The difference of frequency is only at the magnitude of one percent, which can be absolutely ignored in dynamic analysis.

7.2 RESULTS COMPARISON OF RESPONSE SPECTRUM ANALYSIS BETWEEN COUPLED & UNCOUPLED MODEL

It’s shown from the results comparison of coupled and uncoupled model with single-spectrum input that the acceleration response of every equipment in the coupled model is generally 20% greater than that in the uncoupled model and exceptionally the response of main pump in the coupled model is 5 times of that in uncoupled model. Two main reasons are as following: 1) The reactor building is simulated with elastic beam in the coupled model. So the input spectrum for the equipments of RCS supported at different elevation floor correspondingly gets enlargement which results in the increase of final response. 2) The interaction effect between equipments and the building also enlarge the response of the equipments. For example, the fundamental frequencies of main pump in horizontal direction is quite close to that of reactor building which generates the effect similar to resonance and this is the key point that our paper is concerned about.

It’s shown from the results comparison of coupled and uncoupled model with multi-spectrum input that some equipment response in coupled model is larger than that in uncoupled model such as reactor vessel, main pump and the main pipe and also the other equipment response in coupled model is less than that in uncoupled model such as steam generator. This illustrates the interaction effect can not only enlarge the response of the equipments but also reduce the response of some others. The interaction effect is quite complex and the results difference between the coupled and uncoupled model could not be ignored.

7.3 RESULTS COMPARISON OF TIME HISTORY ANALYSIS BETWEEN COUPLED AND UNCOUPLED MODEL

It’s shown from the results comparison of coupled and uncoupled model with the same acceleration time history input that the acceleration response of every equipment in the coupled model is generally 10% to 15% greater than that in the uncoupled model and exceptionally the response of main pump in the coupled model is 50% greater than that in uncoupled model. On one hand, the elastic response of building magnifies the acceleration input at the equipments supporters and consequently enlarges the equipment response. On the other hand, the interaction effect between the building and the equipments also enlarge the equipments response even more.

In summary, the time history analysis of coupled model also illuminates the essence of the interaction effect.

7.4 RESULTS COMPARISON OF TIME HISTORY ANALYSIS AND RESPONSE SPECTRUM ANALYSIS

It's shown from the comparison results of two different method that the response result of response spectrum method is generally greater and also at sometime less than that of time history method varying from -20% to 20%. The maximal response of each equipment between its different parts in response spectrum method is usually greater than that in time history method.

In the response spectrum method, the conservative combination principle of all the modal responses generally results in the enlargement of the response. It's shown from the different larger grade that interaction effect in response spectrum method is excessively enlarged.

8. DISCUSSIONS AND SUGGESTIONS

8.1 DISCUSSIONS

1. From the point of safety, the method used at the beginning stage of NPP engineering is now considered quite dangerous, which chosen the uncoupled model of RCS with single-spectrum input at the bottom in the seismic analysis.
2. Now the pandemic method used in seismic analysis of equipments is to choose the uncoupled model with the multi-spectrum or one envelope spectrum input, which sometimes is also quite dangerous from the point of safety. One key problem of the analysis method lies at the uncoupled model for which the interaction effect between the equipments and the reactor building couldn't be considered. Only the seismic analysis of the coupled model can present the essence of interaction effect between the two systems.
3. The result of time history analysis can truly show the enlargement of interaction effect, but the result of response spectrum analysis generally over evaluates the interaction effect. If the uncoupled model is used even with the accurate method like time history method, its safety and rationality can not be accepted.

8.2 SUGGESTIONS

1. The comparison result speaks volume for the rationality of supplementary emphasis for the decoupling criteria of seismic analysis model in SRP Rev.2 published in 1989 especially the requirement of coupled model of RCS and the reactor building. Only the analysis of coupled model can present the essence of the interaction effect between the two systems.
2. It's recommended in the seismic analysis of the equipments in RCS for the future NPP that the time history analysis should be performed for the above coupled model considering that the time history method is well known precise and it is also the requirement of detail seismic analysis of inside members of equipments. But according to the standard the acceleration time history of input should be compatible with the floor response spectrum of the corresponding bottom of reactor building.

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