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Optimal Design of Base Isolation and Energy Dissipation System for Nuclear Power Plant Structures

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ABSTRACT

This paper suggests the method of optimal design of base isolation and energy dissipation system for earthquake resistant nuclear power plant structures. This method is based on dynamic analysis 、 shaking table tests for a 1/4 scale model、 and a great number of low cycle fatigue failure tests for energy dissipating elements. A set of calculation formulas for optimal design of structures with base isolation and energy dissipation system were introduced, which are able to be used in engineering design for earthquake resistant nuclear power plant structures or other kinds of structures.

1 DEVELOPMENT OF CONTROLLING METHOD FOR SEISMIC RESPONSE OF STRUCTURE

During earthquake attack, the structure which fixed on the ground will respond graduallуy increassing from the bottom (ground) to the top, liking a "Amplifier" (Fig. 1). This will result in damage of structure or its contents due to the large response of structure. In order to reduce the response and avoid the damage of structure, some controlling methods have been developped :

1. Increasing the structural stiffness very more, form a " Rigid Structure System "(Fig. 2) which structural response may be nearly as same as the ground motion. But this kind of structure system is very expensive and very difficult to realize in some cases.
2. Decreasing the structural stiffness to very small, form a "Flexible Structure System " (Fig. 3) which structural response may be very small. But this kind of structure system is not suitable for normal usefulness because it is too flexible in wind load or minor earthquake.
3. Increasing the structural ductility and allowing the structural elements or joins to work in inelastic range to dissipate the energy of structure in earthquake, then reduce the structure response, form a "Inelastic Structure System " (Fig. 4), it is the general structure system for earthquake resistance in many countries at present. But its usefulness is limited or not very safe in some cases,especially for nuclear power plant structures. The controlling methods described above for seismic response are not very perfect. The "Base Isolation System "(Fig.5) supplys a new way to control the seismic response of nuclear power plant structure and it is very effective, safe, simple and can be used in very wide range. But how to get the optimal design of this structure system is an existing problem which need to be solved very urgently.

2 CHARACTERS AND COMBINATION OF BASE ISOLATION STRUCTURE SYSTEM

In general case, the base isolation device requires to possess three basic characters (Fig.6)

1.Soft sliding : The structure can softly slide on the base in severe earthquake. This character can isolate the horizontal vibration from ground motion to structure, make the natural peried of structure very long then reduce the acceleration response of structure effctivelly (Fig.7).

2. Certain amount of damping C, it will dissipate the energy input to the structure then attenuate the response of structure in earthquake (Fig. 8)

3. Suitable horizontol stiffness K,it will provide the primary stiffness in wind load or minor earthquake while $P < Py$ (Fig. 9)

There are some kinds of combination of base isolation and energy dissipation system:

1.Rubber pade (steel plates reinforced) as isolator (Fig.10.a).

2.Rubber pade (steel plates reinforced) as isolator combines with leadplug or steel elements as energy dissipator (Kelly J.M. et al. 1980) (Fig.10.b).

3.Roller as isolator combines with steel elements as energy dissipator (Zhou Fu Lin et al. 1983) (Fig.10.c).

4.Dry friction layer or sand (or other material) sliding layer as isolator also energy dissipator (Li L. 1984) (Fig.10.d)

5.Combination each other described above.

3 SHAKING TABLE TESTS AND ANALYSIS

The tests were carried out on an earthquake shaking table.The overall dimension of steel modelis 10ft×4. 6ft in plan and 12.8ft high. The totle mass of structure model and loading concrete blocks are 16 kips (Fig. 11).

The roller and mild steel curved plates were used as isolating and energy dissipating device (Fig.12). Five kinds of curved plates were fitted and tested in order of priority. A series of pseudo tests were finished for curved plastes (Stiemer S.F. and Zhou Fu Lin 1984) before shaking table tests. Four sine-waveforms (Freq. w=1.0, 2.0, 3.0, 4.0 HZ) and three simulated earthquake records (EL Centro, Sanfernando, Parkfield) were inputed to the shaking table, which predominant Freq. w was found from the Fourier spectra of acceleration record.

Four accelerometers were used to measure the structure acceleration response X at every levels of structure. The relative displacement D between the first story column and the shaking table was measured with Linear Variable Differential Transformer (LVDT). All of the measured data were then processed by a computer with a operating software system.

The testing results show that :

1. The acceleration responses $\ddot{X}_a$ on each levels of structure model are nearly the same. It means that the structure with base isolation nearly work within elastic rang only.

2. The acceleration response $\ddot{X}_a$ on structure with base isolation is only (1/6-1/10) reaponse $\ddot{X}_{aF}$ on structure fixed on shaking table. It means the base isolation is more effective to attenuate the structural response in earthquake than any other methods (Fig.13).

3.The acceleration response $\ddot{X}_a$ of structure with base isolation depends on the Ratio of exciting frequency W to natural frequency W_n of structural system (W / W_n). In order to attenuate effectively the structure response, it is very important to make both (W and W_n) having more disparity (Fig. 14).

4. The relative displacement D between the structure and the shaking table are very close to the displacement $\ddot{X}_g$ of shaking table (Fig.15) . It means the horizontal

displacement of structure with base isolation are rether large and need to be controlled by providing certain amount of damping in design.

4 TESTS OF LOW CYCLE FATIGUE FAILURE OF STEEL DISSIPATOR AND ANALYSIS

Because the steel elements were used as energy dissipater, these may deform into plastic regions withstanding large number of cyclic loads, and may fail due to the low cyclic fatigue in earthquake. The permanence of resisting low cycle fatigue failure can be represented by a parameter --Number of loading cycles to fail N .

There are 36 pieces of X-shaped mild steel plates with different thickness t and length L cyclically loaded to fail under certain strain ε on surface. The tests were carried out on the "MTS Model 904.55 Struture Testing System ". Tests were displacement controlled. The loading cyclic frequency is 0.1 HZ. The number of loading cycles to fail N was recorded by recorder automatically. The strain ε was measured at 4 pieces of strain guages placed on each side of the X-shaped plate (Fig. 16)). The testing results of values ε and N were ploted in Fig.17.

From statistic analysis (Zhou Fu Lin et al. 1987), A theoretical curve (Fig.17) to represent the relationship betweenm ε and N was expressed by equation :

$$\varepsilon = 0.22 \;/\; N \qquad \text{———————— (1)}$$

Where ε — The maximum strain on surface of steel elements.

N — The number of loading cycles to fail.

The theoretical curve is very close to the testing records, and always smaller than the testing values. The designer can use Eq. (1) to predict the permanence of resisting low cycle fatigue failurer by controlling the strain value ε on the surface of steel elements very simply.

5 OPTIMAL DESIGN OF BASE ISOLATION AND ENERGY DISSIPATION SYSTEM

5.1 Equivalent Damping Ratio E_e

From Mathematic model, the basic differential equation of motion is given as:

$$M\ddot{X}_a + C_e\dot{X}_a + K X_a = C_e\dot{X}_g + K X_g \qquad \text{———————— (2)}$$

Where M is the structural mass. C_e is the equivalent viscous damping of isolating and energy dissipating system. K is the elastic stiffness of isolating and energy dissipating system. $X_g \dot{X}_g \ddot{X}_g$ are the ground response of displacment, velocity and acceleration respectively in earthquake. $X_a \dot{X}_a \ddot{X}_a$ are the structure response of displacement, velocity and acceleration respetively in earthquake.

Define $E_e = C_e / 2 M W_n$ as EQUIVALENT DAMPING RATIO,

$W_n = K / M$ as the NATURAL FREQUENCY of system.

Solve Eq. (2) with finding transfer function and get :

$$E_e = \frac{1}{2(W/W_n)} \sqrt{\frac{1 - AR^2[\,1-(W/W_n)^2\,]^2}{AR^2 - 1}} \qquad \text{———————— (3)}$$

Where $AR = \ddot{X}_a / \ddot{X}_g$ is called ACCELERATION ATTENUATION RETIO of systen.

5.2 Maximum Relative Displacement D_u

The basic differential equation of motion can be written :

$$M\ddot{D}_u + C\dot{D}_u + K D_u = -M\ddot{X}_g$$

Where D_u $\dot{D}_u$ $\ddot{D}_u$ are maximum relative displacement, velocity and acceleration respectively between structure and ground.

Solve this equation wuth finding transfer function and get :

$$D_u = \frac{\ddot{X}_g}{W^2} \sqrt{\frac{(1 - AR^2)(W / W_n)^2}{(W / W_n)^2 - 2}} = X_g * r \quad \text{———————(4)}$$

$$\text{Define } r = \sqrt{\frac{(1 - AR^2)(W / W_n)^2}{(W / W_n)^2 - 2}} \quad \text{as DISPLACEMENT FACTOR}$$

Comparing the theoretical value D_u with measuring value $[D_u]$ from tests show that, the D_u /$[D_u]$ = 0.98—1.67, D_u are almost all greater than $[D_u]$. It means Eq. (4) is suitable and conservative in designing.

5.3 Acceleration Attenuation Ratio AR

The damping ratio E_e is related to the area enclosed by the hysteresis loop and find :

$$E_e = \frac{C_e}{2 M W_n} = \frac{2(1 - 1 / U)}{U \Pi} \cdot \frac{1}{(W / W_n)} = B \frac{1}{(W / W_n)} \quad \text{———(5)}$$

$$\text{Define } B = \frac{2(1 - 1 / U)}{U \Pi} \quad \text{as ENERGY DISSIPATION DAMPING RATIO}$$

$U = D_u / D_y$ as DUCTILITY FACTOR

Where D_u and D_y are the relative displacements at utmost point and yield point shown in Fig.9. The Value of B represent the basic of E_e, and depends on the value of U.

Substitute Eq. (5) into Eq. (3) and finally get :

$$AR = \frac{\ddot{X}_a}{\ddot{X}_g} = \sqrt{\frac{1 + 4 B^2}{4 B^2 + [1 - (W / W_n)^2]^2} \cdot \frac{W}{W_n}} \quad \text{——————(6)}$$

This is the final expression of ACCELERATION ATTENUATION RATIO AR

Now, comparing the theoretical values AR from Eq. (6) with the measured values [AR], shown in Fig.18. and know :

(a)The ratio AR/[AR] approaches 1.0, it means that Eq.(6) gives reasonable estimation.

(b) The theoretical values AR are always larger than measured values [AR], it means that Eq. (6) gives conservative results for practical design.

For a seismic zone the structure located on it which relates to a possible maximum acceleration spectrum value, the designer can select a set of isolating and energy dissipating device which is possessed of certain stiffness, damping ratio and possible strain value on element of device. Then using the method the author suggested, the designer can estimate very simply the structural acceleration response which relates to a possible maximum acceleration spectrum value on the zone ground , and predict the permanence of low cycle fatigue of device. By changing the parameters of devices (using different devices), the optimal design can finally be achieved. The structural response can be controlled to be a very small value, and the permanence of low cycle fatigue for device can reach a satisfied level.

This method can be used not only for nuclear power plant structures, but also for other kinds of structures or various kinds of industry facilities .

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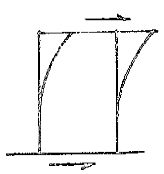


Fig. 1 Ceneral Structure

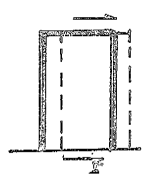


Fig.2 Rigid Structure

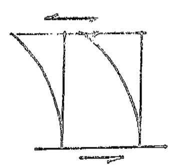


Fig.3 Flexible Structure

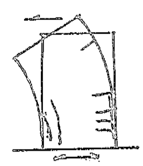


Fig.4 Inelastic Structure

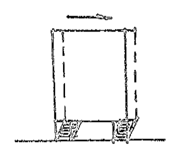


Fig.5 Base Isolation System

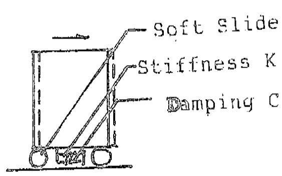


Fig.6 Characters of Base Isolation

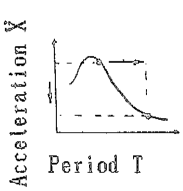


Fig.7 Acceleration reduce

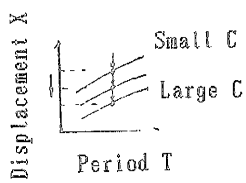


Fig.8 Displacement Reduce

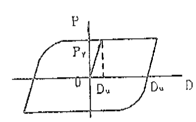
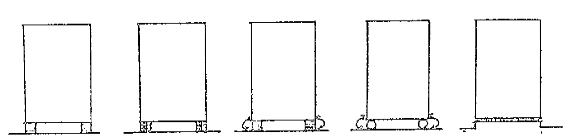


Fig.9 Load-Displacement Curve



(a) Rubber Pad (b) Rubber Pad with Leadplug or Steel Elements (c) Roller with Steel Elements (d) Friction or Sliding Layer

Fig.10 Conbination of Base Isolation and Energy Dissipation

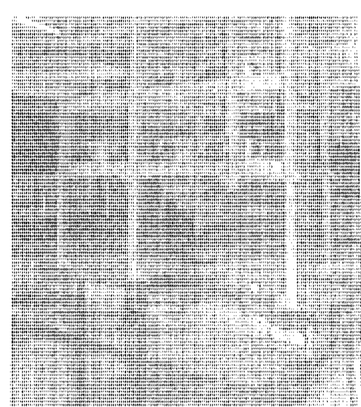


Fig.11 Shaking Table Test

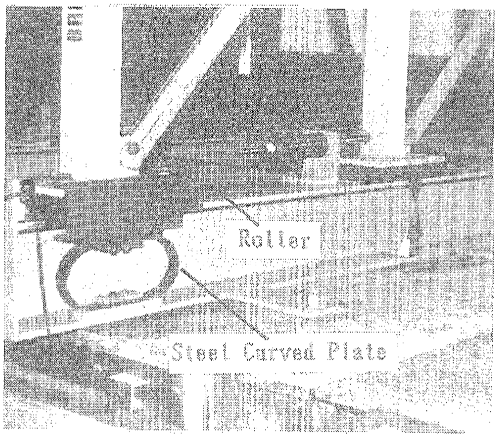


Fig.12 Roller Isolator and Steel Curved Plate Dissipater

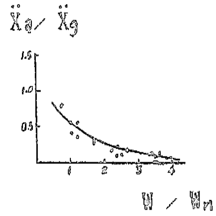


fig.14 Acceleration Attenuation with (W / Wn)

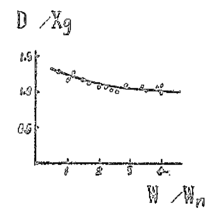


Fig.15 Displacement with (W / Wn)

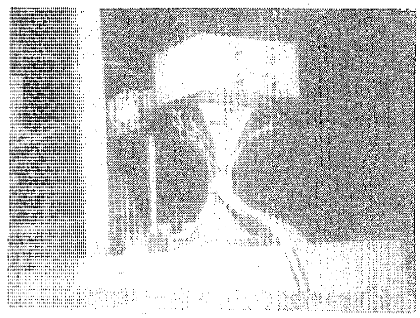


Fig.16 Cycle Load Test and Measuring Strain

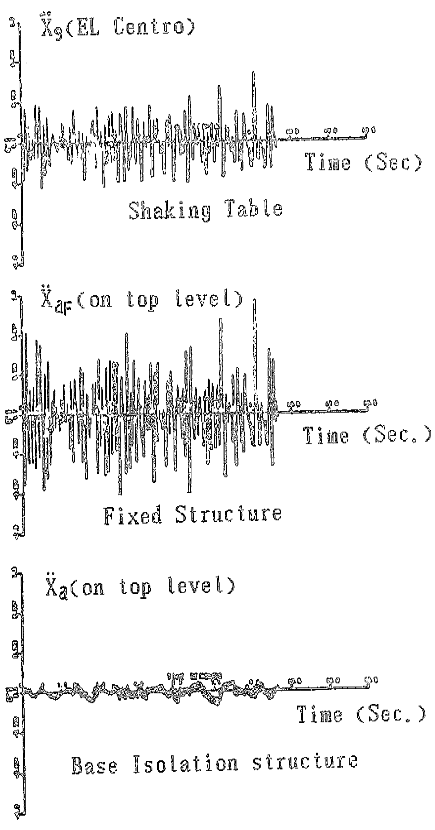


Fig.13 Acceleration Response

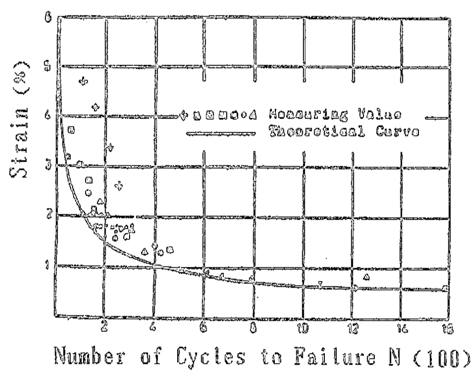


Fig.17 Relation of Strain and Loading Cycles to Fail N

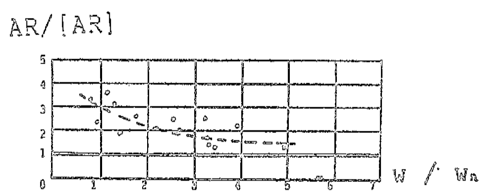


Fig.18 Acceleration Attenuation Ratio AR with (W /W)