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Optimal design of seismic isolation for multistoried buildings

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ABSTRACT: This paper suggests the method of quantitative controlling of structural response for earthquake resistant structures with base isolation and energy dissipation system. This method is based on dynamic analysis、shaking table tests for a 1/4 scale steel frame model、and a great number of low cycle fatigue failure tests for energy dissipating elements The comparing theoretical results with testing results was described. A set of calculation formulas for quantitative controlling of structural response of the structures with base isolation and energy dissipation system were derived , and are able to be used in engineering design for earthquake resistant structures.

1 DEVELOPMENT OF CONTROLLING METHOD FOR SEISMIC RESPONSE OF BUILDING STRUCTURE

During earthquake attack, the building structure which fixed on the ground will respond gradually increasing from the building bottom (ground) to the building top liking a "Amplifier" (Figure 1). This will result in damage of structure or building 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 developed by Kelle (1986):

1. Increasing the structural stiffness very more, form a " Rigid Structure System "(Figure 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" (Figure 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 " (Figure 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. First, it is difficult to control the structural damage level due to the inelasticdeformation, and it may be dangerous in severe earthquake which is not predicted before. Second, it is not able to be used in some important structures which elements is not allowed to work in inelastic range, such as some buildings which decoration is very expensive nuclear power plant, museum building, and so on. Third, it is not able to be usedfor some buildings there are precise instruments in it.

4. Making the first story columns very soft and allowing it to deform in inelastic range to dissipate the energy then reduce the response of upper structure, form a "Soft First Story Structure System "(Figure 5) . This system can reduce the upper structure response very effectively, but the building may collapse in severe earthquake because of the large inelastic deformation of first story columns.

The controlling methods described above for seismic response are not very perfect. The " Base Isolation System "(Figure 6) supplies a new method to control the seismic response of building structure and it is very effective, safe, simple and can be used in very wide range. This new method possesses following advantages :

1. It can reduce the structure response very effectively by keeping the advantages of " Soft First Story Structure System " , but it changes from the soft first story columns into only a isolation sliding layer. The effect of torsional coupling on the transient response of base isolated structures is insignificant depending on Pan (1983). So it is more effective and safe.

2. It changes from relying the whole

structure to resist the earthquake into only relying the isolating device to isolate the earthquake. So it make the design and construction work very simple and the restore work is very easy.

3. It can keep the structure working in elastic range in earthquake, so it can be used in different kinds of important buildings in different seismic zones.

4. It can be used in new buildings, also can be used in existing buildings to improve its earthquake resistant ability.

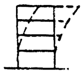


Figure 1 Structural "Amplifier"

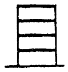


Figure 2 Rigid Structure

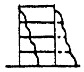


Figure 3 Flexible Structure

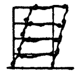


Figure 4 Inelastic Structure

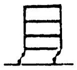


Figure 5 Soft-First Story Structure

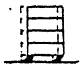


Figure 6 Base Isolation

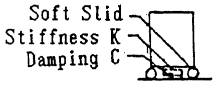


Figure 7 Characters of Base Isolation.

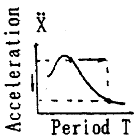


Figure 8 Acceleration Reduce

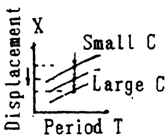


Figure 9 Displacement Reduce

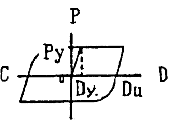


Figure 10 Load-Displacement Curve

2 CHARACTERS, COMBINATION OF BASE ISOLATION STRUCTURE SYSTEM AND APPLICATION

In general case, the base isolation device requires to possess three basic characters (Figure 7):

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 period of structure very long then reduce the acceleration response of structure effectively (Figure 8).

2. Certain amount of damping C, it will dissipate the energy input to the structure then attenuate the response of structure in earthquake (Figure 9).

3. Suitable horizontal stiffness K, it will provide the primary stiffness in wind load or minor earthquake while P < Py (Figure 10)

There are four kinds of combination of bas isolation and energy dissipation system:

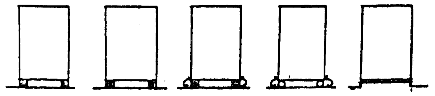
1. Rubber pads (steel plates reinforced) as isolator (Figure 11.a).

2. Rubber pads (steel plates reinforced) as isolator combines with lead plug or steel elements as energy dissipator described by Kelly (1980) (Figure 11.b).

3. Roller as isolator combines with steel elements as energy dissipator described by Chow (zhou) (1983) (Figure 11.c).

4. Dry friction layer or sand (or other material) sliding layer as isolator also energy dissipator (Li (1984)), (Fig.11.d).

There are some kinds of buildings with base isolation for investigetion : One 8 stories RC frame building with Rebber Pads (Figure 12.a, b), two 5 stories masonry buildings with sand sliding layer (Figure 12.c, d).



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

Fig.11 Conbination of Base Isolation and Energy Dissipation

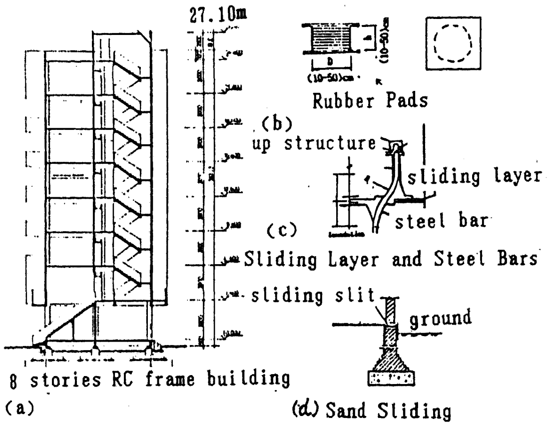


Figure 12 Building with Base Isolation in China

3 SHAKING TABLE TESTS AND ANALYSIS

The tests were carried out on an earthquake shaking table which has a floor dimension of 10ft×10ft in THE UNIVERSITY OF BRITISH COLUMBIA. The overall dimension of four stories steel frame model is 10ft×4.6ft in plan and 12.8ft high. The total mass of structure model and loading concrete blocks are 16 kips (Figure 13).

The roller and mild steel curved plates were used as isolating and energy dissipating device . Five kinds of curved plates were fitted and tested in order of priority. A series of pseudo tests were finished for curved plates (Stiemer and Zhou (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 Centre, Sanfernando, Parkfield) were inputted to the shaking table, which predominant Freq. w was found from the Fourier spectra of acceleration record.

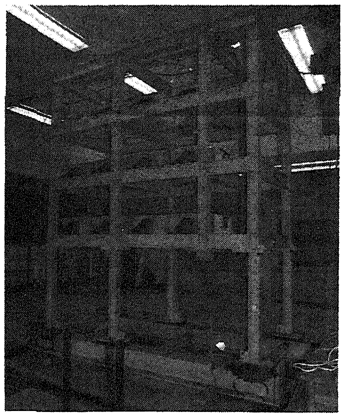


Figure 13 Shaking table test with 1/4 scale steel frame

The testing results show that :

1. The acceleration responses $\ddot{X}a$ on each stories of structure model are nearly the same. (Figure 14). It means that the elements and joins of 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) response Xaf 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 (Figure 14).
3. The acceleration response $\ddot{X}a$ of structure with base isolation depends on the Ratio of exciting frequency W to natural frequency Wn of structural system (W/Wn). In order to attenuate effectively the structure response, it is very important to make both (W and Wn) having more disparity (Figure 15).
4. The relative displacement D between the structure and the shaking table are very close to the displacement Xg of shaking table (Figure 16) . It means the horizontal displacement of structure with base isolation are rather large and need to be controlled in design.

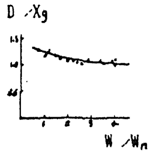


Figure 15 Displacement with (W /W_n)

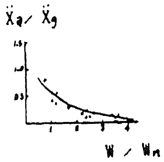


Figure 16 Acceleration Attenuation with (W / W_n)

In order to investigate the effect of base isolating system for highrise building, a 1/15 scale model of 9 stories frame building structure was tested on a shaking table. The isolation device contains the rollers and horizontal spring which provides a certain amount of stiffness and damping of isolating system .Different sine waveforms with frequency W= (3-28) HZ were input to the shaking table, the maximum acceleration of shaking table are $\ddot{X}g$ = (0.2-0.5) g. There are 8 accelerometers used to measure the structural acceleration response $\ddot{X}i$ at each stories of structure model. The testing results for structure model with fixed base and base isolation were recorded and compared. Fig.18 shows the testing records which relates to the shaking table vibration with Freq. W=15. 5 HZ and the maximum acceleration of shaking table $\ddot{X}g$ = 0.49 g.

Analyzing this results (Figure 17), some conclusions can be described below :

1. The acceleration responses at each stories of structure model with base isolation are nearly the same. It means that the elements and joins of structure with base isolation will work within elastic rang during earthquake. The "Amplifier" action resulted from fixed base structure is completely eliminated during severe earthquake.
2. The acceleration response at top story of structure model with base isolation is only 0.005 g, while the acceleration response at the same story with fixed base reaches 1.13 g. The ratio of $\ddot{X}$ (isolation / $\ddot{X}$ (fixed base) = 0.005 g /1.13 g = 1 / 226 . It means the base isolation is so significantly effective to attenuate the structure response for highrise building during severe earthquake.

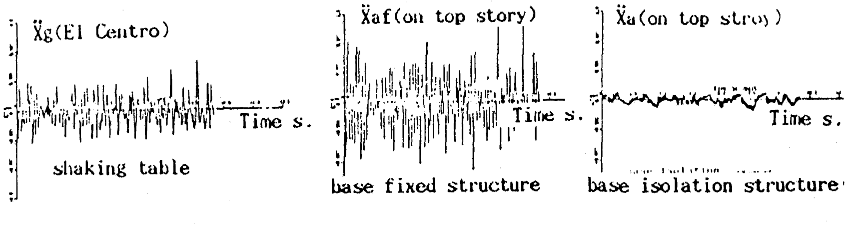


Figure 14 Acceleration response

3. Both theoretical and testing results of acceleration response at each stories in structure model with base isolation are very near, and , the theoretical values are always larger than the testing values. It means the dynamic analysis method for controlling structural response suggested by author for highrise buildings with base isolation system is reasonable and conservative. It may be applied in engineering design.

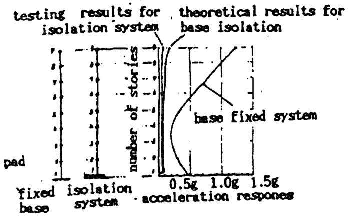


Figure 17 Shaking table with base isolation and base fixed model

4 DYNAMIC ANALYSIS AND CALCULATION FOR ISOLATION AND ENERGY DISSIPATION SYSTEM

4.1 Equivalent damping ratio Ee

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

$$M\ddot{X}a + Ce\,\dot{X}a + K\,Xa = Ce\,\dot{X}g + K\,Xg \qquad (1)$$

Where M is the structural mass. Ce is the equivalent viscous damping of isolating and energy dissipating system. K is the elastic stiffness of isolating and energy dissipating system. Xg $\dot{X}g$ $\ddot{X}g$ are the ground response of displacement, velocity and acceleration respectively in earthquake. Xa $\dot{X}a$ $\ddot{X}a$ are the structure response of displacement, velocity and acceleration respectively in earthquake.
Define $Ee=Ce/2MWn$ EQUIVALENT DAMPING RATIO
$Wn=K/M$ NATURAL FREQUENCY of system
Solve Equation (1) with finding transfer function and get :

$$Ee = \frac{1}{2(W/Wn)}\sqrt{\frac{1-AR^2\,[1-(W/Wn)^2]^2}{AR^2-1}} \qquad (2)$$

Where $AR = \ddot{X}a / \ddot{X}g$ is called ACCELERATION ATTENUATION RATIO of system.

4.2 Maximum relative displacement De

From the basic differential equation of motion can write :

$$M\ddot{D}u + Ce\,\dot{D}u + K\,Du = -M\ddot{X}g$$

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

Solve this equation with finding transfer function and get :

$$Du = \frac{Xg}{W^2}\sqrt{\frac{(1-AR^2)\,(W/Wn)^2}{(W/Wn)^2-2}} = Xg * r \qquad (3)$$

$$\text{Define } r = \sqrt{\frac{(1-AR^2)\,(W/Wn)^2}{(W/Wn)^2-2}}$$

as DISPLACEMENT FACTOR

Comparing the theoretical value Du with measuring value [Du] from tests show that. the Du /[Du] = 0.98 - 1.67, Du are almost all greater than [Du]. It means Equation(3 is suitable and conservative in designing.

4.3 Acceleration attenuation ratio AR

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

$$Ee = \frac{Ce}{2\,M\,Wn} = \frac{2(1-1/U)}{U\,\Pi}\cdot\frac{1}{(W/Wn)} = B\,\frac{1}{(W/Wn)} \qquad (4)$$

$$\text{Define } B = \frac{2(1-1/U)}{U\,\Pi}$$

as ENERGY DISSIPATION DAMPING RATIO

$U = Du/Dy$ as DUCTILITY FACTOR

Where Du and Dy are the relative displacements at utmost point and yield point shown in Figure 10. The Value of B represent the basic of Ee, and depends on the value of U.

Substitute Equation(4) into Equation(2) and finally get :

$$AR = \frac{\ddot{X}a}{\ddot{X}g} = \sqrt{\frac{1+4B^2}{4B^2+[1-(W/Wn)^2]^2}}\cdot\frac{W}{Wn} \qquad (5)$$

This is the final expression of ACCELERATION ATTENUATION RATIO AR

Now, comparing the theoretical values AR from Equation(5) with the measured values [AR], shown in Figure 18 and know :

1. The ratio AR/[AR] approaches 1.0, it means that Equation(5) gives reasonable estimation.
2. The theoretical values AR are always larger than measured values [AR], it means that Equation(5) gives conservative results for practical design.

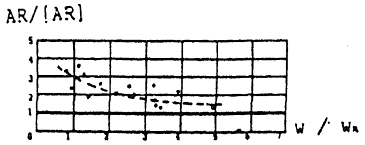


Figure 18 Acceleration Attenuation Ratio AR with (W/W_n)

The isolation and energy dissipation system for highrise building structure can be simplify to a multi degree of freedom system with isolating pad which is replaced by roller and spring (Figure 19) . The stiffness of isolating pad is :

$$K = G\,As / h$$

Where G is the horizontal shear module of isolating pad, As is the area of cross section of isolating pad, h is the height of isolating pad.

For any point i on the structure, the differential equations of motion can be written:

$$Mi\ddot{X}i+\sum_{j=1}^{n}Cij(\dot{X}i-\dot{X}g)+\sum_{j=1}^{n}Kij(Xi-Xg)=0$$

Develop and rearrange the equation above, then get :

$$Mi\ddot{X}i+\sum_{j=1}^{n}Cij\dot{X}i+\sum_{j=1}^{n}KijXi= \sum_{j=1}^{n}Cij\dot{X}g+\sum_{j=1}^{n}KijXg \qquad (6)$$

Where Mi is the lumped mass at any point i on structure.

$\ddot{X}i$, $\dot{X}i$, Xi are the structural horizontal response of acceleration, velocity and displacement at Mi during earthquake

$\ddot{X}g$, $\dot{X}g$, Xg are the ground horizontal response of acceleration, velocity and displacement during earthquake.

Cij is the damping influence coefficient of point i, the force corresponding to point i due to unit velocity of point j.

Kij is the stiffness influence coefficient of point i, the force corresponding to point i due to unit displacement of point j .

Then the matrix formulation of differential equation for multi degree of freedom system can be written below :

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\dot{X}g[C]\{1\}+ Xg[K]\{1\} \qquad (7)$$

That is the Differential Equation of Motion of base isolation system of multi degree freedom for highrise building structures. Where [M] is the mass matrix of system, [C] is the damping matrix of system, [K] is the stiffness matrix of system, $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$ are the structural horizontal response vectors of acceleration, velocity and displacement of structural system during earthquake, $\dot{X}g$, Xg are the ground horizontal response of velocity and displacement during earthquake, {1} is the unit vector.

Here the characters of structure and isolation devices were decided during design. then [M], [C], [K] can be got. And $\ddot{X}g$, Xg *can be found from the possible* **maximum spectrum** values of ground motion for a certain seismic zone. Solving Equation(6) and (7), the responses $\{\ddot{X}\}$, $\{\dot{X}\}$, $\{X\}$ at any story of highrise building can be controlled to be a suitable level by selecting a reasonable base isolating and energy dissipating device. Authors have compiled a set of computer programs EBIS-1 for design in engineering application.

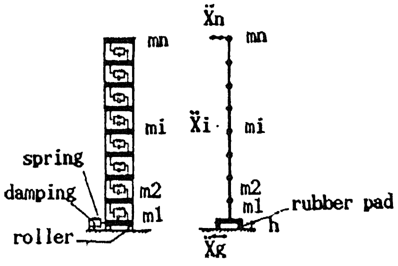


Figure 19

Model of highrise building with base isolation

5 TESTS AND ANALYSTS OF LOW CYCLE FATIGUE FAILURE OF STEEL DISSIPATOR

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. Many works indicate that N mainly depends on the absolute maximum strain value ε on the surface of mild steel elements in cyclic loads (Zhou (1987)). So, the relationship between ε and N is the key to predict the low cycle fatigue failure for mild steel elements.

In order to get the accurate results, a series of X - shaped plates made of mild steel were chosen as main specimens to be tested, because the vertical strain of section is nearly uniformly distributed during horizontal bending under horizontal loads at top or bottom of specimen (Figure 20)

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 Structure 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 gauges placed on each side of the X-shaped plate. The testing results of values ε and N were plotted in Figure 21.

From statistic analysis. A theoretical curve (Figure 21) to represent the relationship between ε and N was expressed by equation :

$$\varepsilon = 0.22 / N \qquad (8)$$

Where ε -- The maximum strain on surface of steel elements.
N -- The number of loading cycles to fail

The results of tests and analysis indicate :

1. The theoretical curve is very close to the testing records, especially in the strain range ε = (0.5 - 3.0)% which covers the general cases. The theoretical N values from theoretical curve are always smaller than the testing values. It means the appropriate conservative results can be got from Equation(8) for design.
2. The ability of resisting low cycle fatigue failure for mild steel elements under bending is very great. If yielding strain for mild steel is ε = 0.15%, while maximum strain ε on surface of elements in earthquake is about ε = 1.5 %(equivalently ductile factor U = 10 about), then the allowed number of cyclic loading N reaches more 200 from Equation(8). It means this energy dissipator can reliably withstand tens of severe earthquake attack continuously.
3. The designer can use Equation(8) to predict the permanence of resisting low cycle fatigue failure by controlling the strain value ε on the surface of steel elements very simply.

6 CONCLUSION

1. This base isolation and energy dissipation system is a very hopeful way for controlling structure response in earthquake It is more effective, reasonable and simple than other traditional way used at present.
2. The ability of resisting low cycle fatigue failure for mild steel elements under bending is very great. Using mild steel elements as energy dissipator is reliable.
3. A series of calculating formulas for controlling the structure response and low cycle fatigue failure in base isolation and energy dissipation system derived by authors in this paper have been proofed by a great number of tests. The reasonable and conservative results can be got from these formulas and can be used in engineering design.

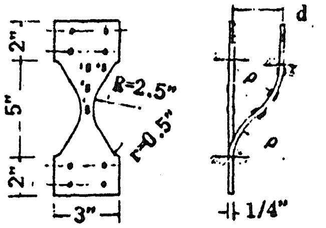


Figure 20 **Strain gauges on X shaped plate**

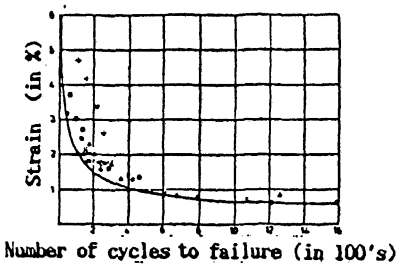


Figure 21 **Relation of strain and loading cycles up to failure**

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