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RECENT RESEARCH AND APPLICATION ON SEISMIC CONTROL FOR STRUCTURES IN MAINLAND CHINA

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ABSTRACT

This paper briefly introduces the recent research、testing analysis、design and application on seismic isolation、energy dissipation、tuned mass damper and active control for buildings and bridges in mainland China. Paper introduces some typical researches、testing and analysis, including the mechanical tests for bearings and control devices, and the shaking table tests for structural models with different control systems. Paper also introduces the Chinese design codes for structures with seismic isolation and energy dissipation. Paper describes the recent application status and typical examples, especially introduces the largest isolation buildings group in the world, and the using passive and semi active control for structures. Also the paper makes discussion some problems existed on passive and active control technique now and the tendency of development on seismic control in future

Keywords: Seismic Isolation, Energy Dissipation, TMD, Active Control

DEVELOPMENT OF TECHNIQUES FOR SEISMIC RESISTANCE OF STRUCTURES

During earthquake, the building structure which is fixed on the ground will respond gradually increasing from the building bottom (ground) to the building top, liking an "Amplifier". This will result in damage or collapse of structure or results in damage of nonstructural components, decorations and equipment or facilities in buildings due to the large response of the structure. In order to reduce the response and avoid damage of structure, some techniques of seismic resistance for structures have been developed (Sheng, 2000)

There are two kinds of techniques of seismic resistance for structures at present. One is the traditional Anti-seismic technique, another is the new technique---Seismic control of structures which will discussed in this paper. The traditional Anti-seismic technique uses the methods of strengthening the structure then rises the structural stiffness, which will induce to increase the structural response then to loss the safety of structure during earthquake. The new technique, Seismic control of structures, uses the methods only changing the structural dynamic characters (damping, frequency or tuned mass) to reduce the structural response in earthquake, instead of strengthening the structure. The new technique, Seismic control of structures, is very effective to control the structural response in earthquake or wind, also is able to ensure the structure to be safe during unexpected higher intensity earthquake. So the new technique may be safer, reliable, inexpensive and simple to be implemented in many cases, suitable to be widely used in general civil or important buildings, bridges, facilities or other structures in the regions of seismicity (Zhou, 1997).

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Some problems are existed in the traditional Anti-seismic technique for seismic resistance for structures:

(1) It is not very safe: It is difficult to control the structural damage level due to the inelastic deformation in earthquake, also it may be dangerous in severe unpredicted earthquake.

(2) It is limited to be used: The designing aim is only to protect the structure, but not protect the facilities inside the structure. So it is not able to be used in some important structures whose inside facilities could not be damaged in earthquakes, such as hospitals, City lifeline constructions, nuclear power plant, museum building, and the buildings with precise instruments in it.

(3) It is more expensive: The anti-seismic way of traditional technique is to strengthen the structures: making the columns, beams, shear walls or other structural elements bigger or stronger, increasing the stiffness of the structures. It will cause to increase the seismic load (by increasing the stiffness), then, cause again to strengthen the structures. Finally, it will rise the cost of structure, but the safety level of anti-seismic is still unsure. The cost of building using traditional anti-seismic technique will rise as bellow comparing with the cost of no-anti-seismic building depending the present design code in some countries (Zhou, 1995):

- For moderate earthquake (Ground 0.125g), rise the cost 3- 10 %.
- For major earthquake (Ground 0.250g), rise the cost 10-15 %
- For strong earthquake (Ground 0.400g), rise the cost 15-25 %
- For worst earthquake (Ground >0.500g), rise the cost 30-60 %, also the design is difficult.

Because the traditional method and system are not satisfied in many cases for earthquake resistance, so it is limited to be developed in future although it is used very common at present. Many experts have paid more attention to find out some new systems for earthquake resistant structure: Seismic Isolation, Energy Dissipation and Structural Controlling System. Some available results of research have been obtained, and the some systems have been used successfully in engineering application in China and many countries (Zhou 1989, 1990a).

The range of application and technical maturity of Seismic Control of Structures are shown in Table 1 (Zhou, 1997).

Table 1. The range of application and maturity of seismic control of structure

Name of control	Application Ranges	Technical maturity
Seismic isolation	2-50 stories buildings (New design or existed) Bridges, subway Equipment or facilities	Mature technique Have rich theoretical and testing results Widely application Successfully experienced the Strong earthquake.
Energy dissipation	High rise building Long span bridges High tower or skeleton	Mature technique Have rich theoretical and testing results Application for seismic or winds
Passive control (TMD,TLD,etc)	High rise buildings Long span bridges High tower or skeleton	Basically mature technique Have some research and testing results Application for seismic or winds
Active control	High rise buildings Long span bridges High tower or skeleton	Does not become a mature technique Have some research and testing results Application for seismic or winds

SEISMIC ISOLATION

There are over 500 buildings with isolation rubber bearings built in China until 2005. These buildings include houses (about 70 %), office, school, museum, library, and hospital. The story of buildings is 3～19 stories. The most of structural types of buildings are concrete frame or shear wall-frame and brick wall structures. Some railway bridges and highway bridges with seismic isolation have been built also in China. It has become a very strong tendency to widely using seismic isolation rubber bearings system in China now

Many significant advantages of structures with seismic isolation system (Table 2):

Safe in strong earthquake
Comparing the seismic isolation structures with the traditional anti-seismic structures, the response of isolating structures can be reduce to 1/2-1/8 of the response of traditional structures, according the testing results and the records in real earthquake also. It is very effective to reduce the response of structures in earthquake and is able to prevent the structure from damage or collapse in earthquake. So it can ensure the structures with isolation system to be safe in strong earthquakes.

Save the Structure cost
Comparing the seismic isolation structures with the traditional anti-seismic structures, the building cost of isolation structures can be saved 3～15 % of the general building cost in some cases, because re-designing the supper structure which seismic response is very small, according the final statistics results of 30 buildings with rubber bearings completed in southern, western and northern China [Zhou,1990b,1994].

Wide ranges of application
The seismic isolation rubber bearings system can be used in, both new design structures and existed structures, both important buildings and civil buildings especially for house buildings, both for protecting the building structures and for protecting the facilities inside the buildings [Zhou, 1995] .

Free architectural design
The seismic isolation system can be used in the buildings with irregularities configuration, by putting the isolation layer on the suitable vertical level and, by arranging the isolators with different stiffness and damping in plan of isolation layer. But it is impossible to be done for the traditional anti-seismic buildings that must be regular configuration very strictly [Zhou, 1998].

Table 2: Technical and economical comparing of seismic isolation and traditional buildings

	Traditional anti-seismic buildings	Seismic isolation buildings
Acceleration response	1.00	1/2 - 1/8
Working state of structure During earthquake	inelastic	basically elastic
Building cost	1.00	0.85 – 1.05
Building configuration Requirements	regular	irregular

Testing and Design of seismic isolation system

There are five kinds of material have been used for isolators in China, including Sand layer, Graphite lime mortar layer, Slide friction layer, Roller and Rubber bearing (Fig.1,2) --- This is the laminated steel sheet rubber bearing with or without lead core..

Many tests have been finished and whole sets of computation theory of seismic isolation rubber bearings system have been established in China now. The tests include two kinds of work:

1. Test of mechanical characteristics for isolator, includes compression tests (capacities, stiffness), compression with shear cycle loading tests (stiffness, damping radio and maximum horizontal displacement) (Fig.3).
2. Tests of Durability for isolator, includes low cycle fatigue failure tests, creep tests and ozone aging tests
3. Test of structural system, includes shaking table tests for large scale structural model, including one 6 stories steel frame models with different location of isolation bearings layers are tested on the shaking table (Fig.4). The testing results show that the acceleration responses on each stories of structural model are nearly the same. It means that the elements and joints of structure with isolation rubber bearings nearly work within elastic range only. The acceleration response on structure with isolation is only (1/3 - 1/10) response of structure fixed on shaking table. It means the isolation structure is more effective to attenuate the structural response in earthquake than any other methods.

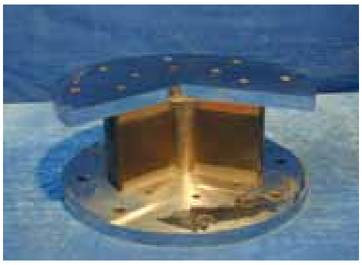
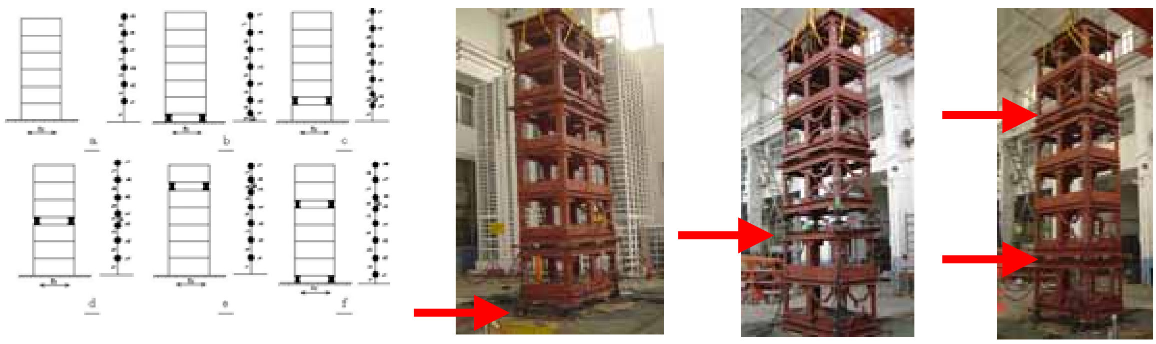


Figure 1: Design of rubber bearing   Figure 2: Comp.--shear test for bearing   Figure 3: Tests of Creep



(a) Different location of isolation layers   (b) On the base   (c) On the Story   (d) Multi-layers

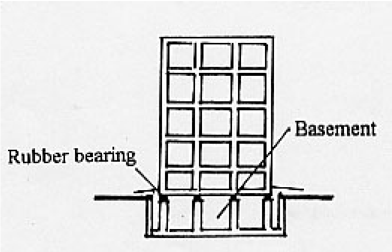
Figure 4: Shaking table test for different location of isolation bearings layers

Different isolation Structural Systems

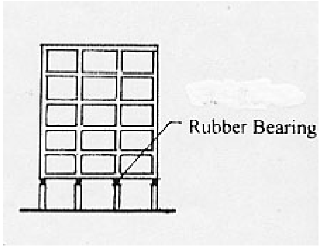
There are five kinds of locations of isolation layer with rubber bearings in China (Fig. 4, 5)

- **Base isolation**. Isolation layer is located on the base of building.
- **Basement isolation**. Isolation layer is located on the certain story of the basement (Fig.5a).

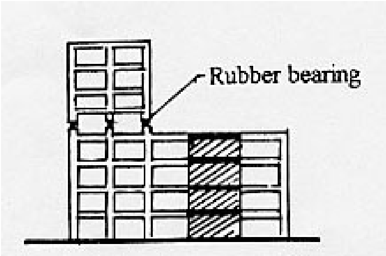
- **Story isolation**. Isolation layer is located on the top of the first story (Fig.5b) or certain story of supper structure (Fig. 5c).
- **Top isolation**. Isolation layer is located on the top of building (Fig. 5d), like TMD, is always used to add 1-2 stories on the top of existed building for seismic retrofit.
- **Over bridge linking isolation**. Isolation layer is located at the linking joints between over bridge and buildings (Fig. 5e) to decouple the different model shapes of buildings linked by over bridge



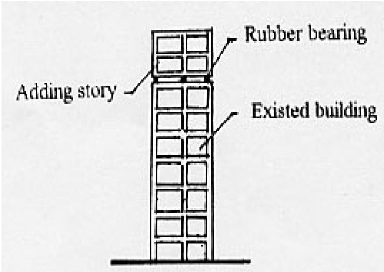
(a) Basement isolation.



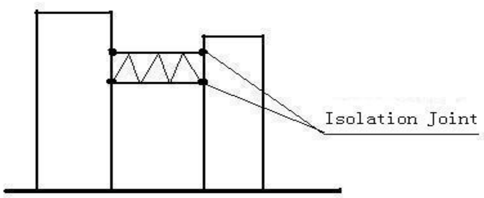
(b) Story isolation with isolators on the top of the first story



(c) Story isolation with isolators on certain story of supper structure



(d) Top isolation.



(e) Over bridge linking isolation.

Figure 5: Different locations of isolation layer in structure

Different designing levels for isolation buildings

There are three design levels of isolation buildings in China now.

Level 1. General structural design level

For common isolation civil buildings: The compression stress of bearing is controlled in 12～15 MPa. The designing horizontal seismic load for super structural is allowed being decreased to be 1/2～1/8 of traditional anti-seismic structure, and is allowed to re-design the supper structure for decreasing the section or reinforces of structural elements. In this design level, the cost of isolation building will be saved about 3～15% comparing with the traditional anti-seismic building. And the safety level will increase to be 2～4 times of the traditional anti-seismic structure.

Level 2. Important structural design level
For important isolation buildings: The compression stress of bearing is controlled in 10～12 MPa. The designing horizontal seismic load for super structure is allowed being decreased to be 1/2～1/4 of traditional anti-seismic structure, and is allowed to re-design the supper structure for a little decreasing the section or reinforces of structural elements, or does not need to re-design the supper structure. In this design level, the cost of isolation building will be balanced or increased about 3～5 % comparing with the traditional anti-seismic building. But the safety level will increase to be 3～6 times of the traditional anti-seismic structure.

Level 3. Special important structural design level
For special important isolation buildings: The compression stress of bearing is controlled in 8～10 MPa or lower. The designing horizontal seismic load for super structure is not allowed being decreased. Also it does not need to re-design the supper structure. In this design level, the cost of isolation building will be increased about 5～7 % comparing with the traditional anti-seismic building. But the safety level will increase to be 4～8 times of the traditional anti-seismic structure.

Technical codes on seismic Isolation in China

Technical codes on seismic isolation consists three different sets of codes in China:

- **Technical specification for seismic isolation with laminated rubber bearing isolators (CECS 2000).** This is the national code for design and construction of buildings and bridges with seismic isolation in China.
- **Standard of laminated rubber bearing isolators (JG 118-2000).** This is the national standard of isolators for laminated rubber bearing in China
- **Seismic isolation and energy dissipation for building design (Chapter 12 in code for seismic design of buildings, GB50011-2001).** This is a part of national code in China for seismic design of buildings, in which is the chapter 12 [Zhou, 1996].

Some main introductions for all these three codes (standards) on seismic isolation in China are described as below:

- Provide the design methods of seismic isolation for buildings、bridges、special structures and industry facilities.
- Provide the design methods of seismic isolation for new design structures also for retrofit of existed structures.
- Allow to fellow three design level depending the importance of structures and requirements of owners in the areas with different economic situation in China.
  Level 1, for general structures, using isolation will save building cost about 3～15%.
  Level 2, for important structures, using isolation will increase building cost 3～5%.
  Level 3, for special important structures, using isolation will increase building cost 3～5%. But the isolation buildings designed by any level will increase the seismic safety about 2～8 times comparing the traditional anti-seismic buildings.
- Provide two methods of structural analysis for seismic isolation of structures:
  Equivalent shear method, it is the static analysis methods for structures that are not higher than 40m or 10 stories, regular configuration and with shear deformations predominantly.
  Time –history analysis, it can be used for all structures.
- Allow reducing the seismic shear load for designing super structure for saving the building cost for general civil buildings or for some poor economic areas.
- Allow choosing the different compression stress level for isolators.
  σ= 12～15 **MPa**, for general civil buildings or for some poor economic areas.
  σ= 10～12 **MPa**, for important buildings or for general areas.
  σ= 8～10 **MPa** ***orσ≦8*** **MPa**, for special important buildings or for rich areas.
- To control the maximum horizontal shear displacement Dmax of isolation layer.

Dmax shall not be larger than 0.55 times of diameter of bearings and 300% shear strain deformation of bearings. Dmax shall be the total displacement including both translation and torsion of structural system.

- Require high quality of rubber bearing to be proved by complete testing [Zhou, 1996].

Examples of Seismic Isolation Building

Example 1. RC frame Multi-stories house building with base isolation.
Some 7～8 stories RC frame house building — one of the most popular isolation building types in China built from 1991 in China. Rubber bearings layer is located on the base (Fig. 6). The design level is level 1. The compression stress of bearing is nearly 15 MPa. The designing horizontal seismic load for super structural was decreased to be 1/4 of traditional anti-seismic structure. The supper structure was re-designed for decreasing the section or reinforces of structural elements. The cost of isolation building is saved about 7% comparing with the traditional anti-seismic building. And the safety level increases to be over 3 times of the traditional anti-seismic structure. There are about 180 buildings of this type have been built in China.

Figure 6: RC frame 7 stories house building with story isolation

Example 2. Masonry Multi-stories house building with basement isolation.
Some buildings group with basement isolation consists of over 60 buildings with 6～7 stories masonry house building — one of the most popular isolation building type in China built from 1996 in western China (Fig. 7). The rubber bearings layer is located on the top of the basement. The design level is level 1. The compression stress of bearing is nearly 15 MPa. The designing horizontal seismic load for super structural was decreased to be 1/6 of traditional anti-seismic structure. The supper structure was re-designed the cost of isolation building is saved about 8% comparing with the traditional anti-seismic building. And the safety level increases to be 4 times of the traditional anti-seismic structure. There are about 300 buildings of this type have been built in China.

Figure 7: Group of masonry multi-stories house building with basement isolation

***Example 3. RC frame-shear 13 stories museum with story isolation*.**
One 13 stories RC frame-shear museum is built in 1996 with 28,000 meter square in southern China (Fig.8). The rubber bearings layer is located on the top of the column in the first story because the building without basement. The design level is level 2. The compression stress of bearing is nearly 12 MPa. The designing horizontal seismic load for super structural is allowed to be decreased to be 1/4 of traditional anti-seismic structure. The cost of isolation building is increased about 2% comparing with the traditional anti-seismic building. But the safety level increases to be 4 times of the traditional anti-seismic structure. It satisfies to protect not only the structure, but also the history relic inside the building.

Figure 8: RC frame-shear 13 stories museum with story isolation

Example 4. RC frame 2 stories platform + 9 stories house with story isolation.
The Seismically isolated artificial ground which is the largest area in the world (Fig.9, 10). There is a very large platform (2 stories RC frame) with 1500m wide and 2000m long to cover a railway area in Beijing City. There are 50 isolation buildings (7～9 stories RC frame) built on the top floor of the platforms The rubber bearings layer is located on the top floor of the platform to isolate the seismic motion also to isolate the railway vibration.

The Isolated Buildings which is the Largest Area in the World

The background of using isolation for this large area of buildings

- The very large area of subway and railway communication hub on the ground is located nearly the Beijing City center, where the land is very expensive. The City Government urgently wants to effectively use the land in this large area as house buildings, also want to solve the seismic and environmental problems of railway vibration and noise in this city center area. This project is named Isolation House Buildings on Subway Hub (IHBSH).
- There is a very large platform of two stories RC frame, which is used to put all equipment and facilities for railway hub in it, and cover the noise from the railway trains. The size of platform is 1500m wide and 2000m long. There are 50 house buildings (7～9 stories RC frame) built on the top floor of the platforms. The floor area of all isolation house buildings is approximately 480,000 M^2 which is the largest area using seismic isolation in the world. From the results of analysis and testing, using Stories Isolation is the best way for seismic design (Design ground motion 200-300 gal). The rubber bearings layer is located on the top floor of the platform. (Fig. 9, 10)

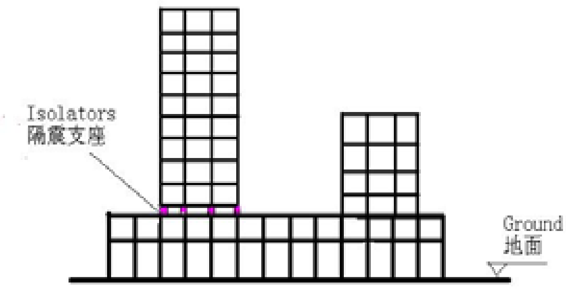


Figure 9: Stories Isolation used in IHBSH

Figure 10: A Part of view of IHBSH

Design and shaking table tests

- The design level is level 2. The compression stress of bearing is about 10 MPa. The size of rubber bearings mainly is ϕ 700.
- The shaking table test shown that the horizontal seismic loads were decreased to be 1/4 for super structural and 1/2 for platform structure comparing with the traditional anti-seismic structure (Fig. 11). During the strong earthquake (400 gal) input, the structure is perfect with no any damage for putting isolators between the platform and the building, but the structure is severe damaged and nearly collapse for fixing joint between the platform and the building.

Figure 11: Shaking table tests for structural model of IHBSH

Technical and economical comparison of isolation with no-isolation

The comparison results of isolation, energy dissipation and traditional design from analysis are listed in Table 3 (Huang, 2003).

Table 3: Comparison of isolation, energy dissipation and traditional design

	Seismic shear force	Construction cost
Traditional design	100 %	100 %
Energy dissipation	80 %	95 %
Isolation	25-35 %	75 %

The large benefits of using Stories Isolation are described as below:

- The seismic safety of structures increases to 4 times.
- The construction cost could save 25%.
- The number of building stories could rise from 6 stories to 9 stories, therefore, The building floor area increase from 380,000 M^2 to 480,000 M^2, adding 100,000 M^2
- The whole pure profit of real estate reaches RMB 240 million--￥600,000,000 Calculated from pure profit RMB ￥6000/ M^2 × 100,000 M^2 (whole pure profit USD 75 million --＄75,000,000)
- The environmental problems of railway vibration and noise in the city center area could be solved

ENERGY DISSIPATION

There are over 30 buildings with Energy dissipation dampers until 2005. Energy dissipation system is formed by adding some energy dissipaters into the structure. The energy dissipaters provide the structure with large amounts of damping which will dissipate most vibration energy from vibration sources previous to the structural response reaching the limitation, then ensure the structure to be safe in earthquake or to satisfy the using requirement in wind. The energy dissipaters may be set on the bracing, walls, joints, connection parts, nonstructural elements or any suitable spaces in structures, which may reduce 40-60% of the structural response comparing the traditional structure without energy dissipaters. This technique is very reliable and simple, suitable to be used for general or important new or existed buildings or facilities in seismic regions(Zhou,1991,1992).

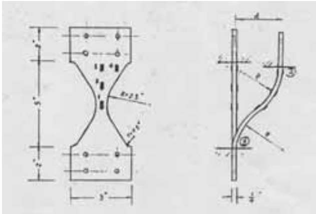
Research, Testing and Application for Energy Dissipation Dampers in China

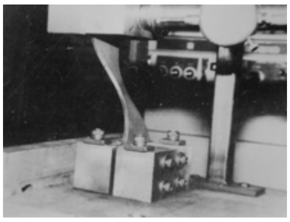
Three kinds of dampers have been used in China now, including Metallic Damper, Friction Damper and Viscous Fluid Damper.

Metallic Damper

The X shape of steel plate is chosen (Fig. 12) as damper(Zhou,1982,1988)), to avoid stress concentrations at the clamped boundaries or at the middle during bending. When this flat plate of mild steel is loaded, the bending stresses become uniform along the whole length, then allowing yielding to develop over the full length of steel plates. A series of bending cycles fatigue failure tests of X shape of steel plate have been carried out (Fig.13,14), then the relationship between Strain and the number of cycles to failure have been established for structural design (Fig. 15).

Another Square Frame Steel Damper has been developed in 1978. A full scale test of Square Frame Steel Damper have been finished (Fig. 16) and the 1st industry structure have been constructed in northern China in 1979 (Fig. 17).





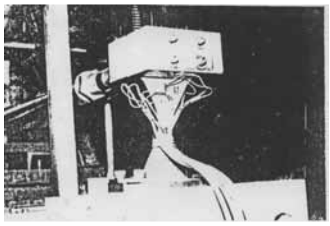


Figure 12: X shape of steel plate Figure 13: Bending cycles Figure 14: Strain records

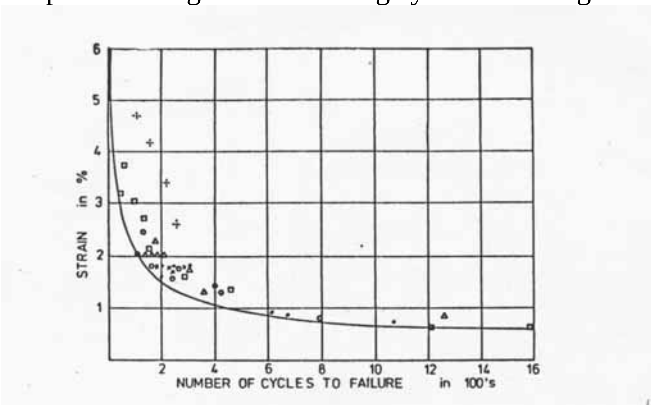


Figure 15: Relationship between Strain and the number of cycles to failure

Figure 16: Full scale test of Metallic Damper Figure 17: The 1st structure with damper in China

Friction Damper **(by Asso. Prof. Q.L Xian)**

A damper with new Composite Friction material has been developed in China. A full scale test of this new Friction Damper (Fig. 18) and the shaking table test for structural model with this new Friction Damper have been finished. The shaking table testing of large models with energy dissipaters shown that, the seismic response of structure with dampers is decreased 30-40% comparing the structure without dampers (Zhou, 1989,1997).This new Friction Damper have been used in the design for high rise building in southern China (Fig. 19).

Figure 18: Full scale test of Friction Damper Figure 19: High rise building with Friction Damper

Viscous Fluid Damper

A series of Viscous Fluid Dampers are produced in China and widely been used, the damping force from 20 ton to 200 ton. The tests of characteristics for dampers have been carried out (Fig.20). Nearly 30 buildings used these dampers for new design or retrofit of existed building (Fig.21, by Pro. W.Q. Liu). This Viscous Fluid Dampers also been combined used with the isolation systems.

Figure 20: Test for Viscous Fluid Damper   Figure 21: The building with Viscous Fluid Damper

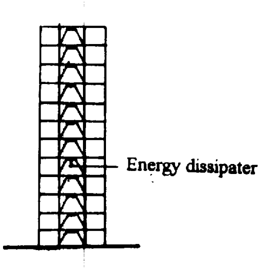
Design and Application of Energy dissipation system

There are three kinds of energy dissipation system being used now in China:

(1) Energy Dissipation Bracings (Figure 22): Energy dissipaters put on the bracing, setting along whole structural height for regular building to rise the capacity of anti-seismic, or only setting in some spaces (or stories) of structure for irregular building to avoid torsion damage during earthquake.

(2) Energy Dissipation Wall (Figure 23): Energy dissipaters put on the walls in weak stories of structure to improve the structural working state, avoiding dangerous damage of weak stories during earthquake.

(3) Energy dissipation Connection (Figure 24): Energy dissipaters put on the gaps between adjacent buildings to avoid impact damage during earthquake.



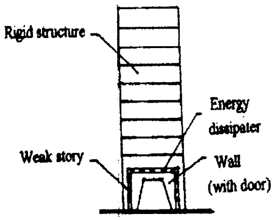


Figure 22: Energy Dissipation Bracings   Figure 23: Energy Dissipation Wall

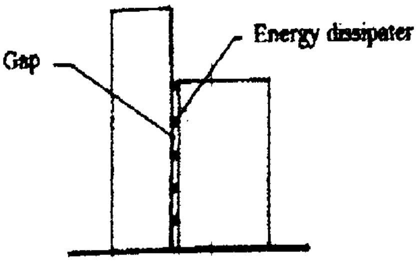


Figure 24: Energy dissipation Connection between buildings

TUNED MASS DAMPER SYSTEM (TMD)

The system is, on certain position (such as on roof) in new or existed structure (main structure), places an additional Filial Structure (possesses mass, stiffness and damping) which natural period is nearly equal to the natural period of main structure. The dynamic characteristics of structure system are changed. During the earthquake, the Filial Structure will move against the direction of main structures vibration then reduce the response of main structure.

In China, this Filial Structure may be formed by adding one or more stories supported by rubber bearings on the roof of main building structure (Fig. 25), or adding a certain mass, such as water tank, supported by rubber bearings on the roof or other floors in main building structure (Fig. 26).

The shaking table tests show that, the response of main structure adding filial structure is reduced 30-40% of response of structure without Filial structure (Zhou, 1996, 1997)

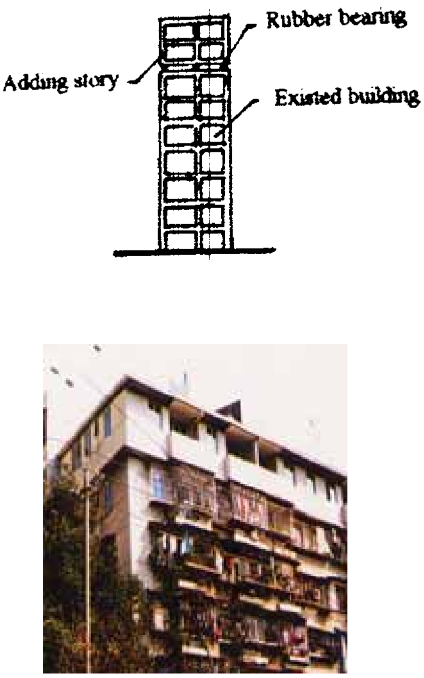


Figure 25: Adding Stories of Top of Building

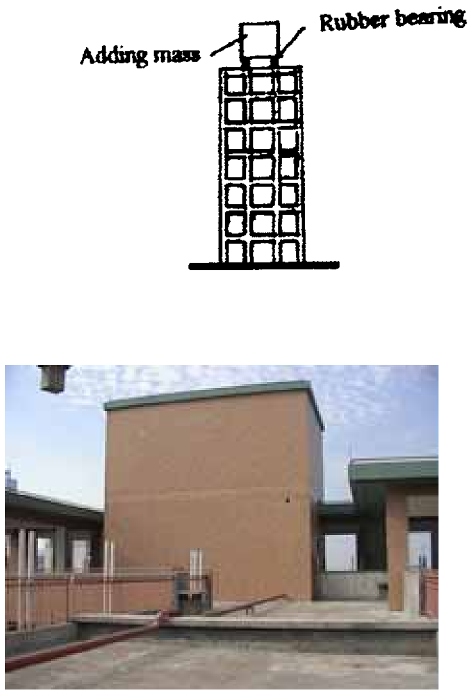


Figure 26: Water tank on top of Building

SEMI-ACTIVE CONTROL SYSTEM

Semi-active control system is formed by adding some simple devices on the bracing or walls in structure (Figure 27), which devices provide the structure with variable damping and stiffness to reduce the seismic response of structure in earthquake. The devices will work as energy dissipaters during moderate earthquake or wind, and will work as active controller during unexpected strong earthquake by inputting very small power. This semi-active control system is much more reliable and simple than general active control system, and more effective to reduce the structural response than other passive control system. This technique is suitable to be used in some important buildings or facilities.

Semi-active control system --- Active Variable Stiffness/Damper AVSD (by Dr. P.Tan), corresponding advanced device and algorithm based on the energy dissipation passive control, active control and other semi-control systems (Zhou,1998). AVSD combines Active Variable stiffness (AVS) and Active Variable Damping (AVD) to become one system, which possesses the all advantages of AVS and AVD. So AVSD is more effective to control the structural response in very wide range of vibration input, more saving energy, more stable and reliable in deferent working state, more simple, economical and practical in application.

The theoretical model of AVSD is shown in Figure 28, which shows that j th AVSD device located on i th story of structure. Where m_i is the mass of i th story of structure, k_i and c_i are the original stiffness and damping of i th story of structure, k_{0j} and c_{0j} are the stiffness and damping of AVSD system. When the system switch on the k_{0j}, the AVSD works as AVS system, while switch on the c_{0j}, the AVSD works as AVD system. How to switch on, is controlled by the control algorithm, according to the sign of value of response of the structure, based on analysis of mechanism of AVSD within every sample period in vibration of structure.

AVSD system could provide two kinds of working state to control the vibration of structure: working as AVS system provided from closing the valve, working as AVD system from opening the valve. Also, this AVSD could amplify the story drift for damper, which makes the system to dissipate more energy input from ground motion (Figure 28).

The results of shaking table testing (Figure 29) and analysis show that (Zhou, 1998), AVSD is more effective than other control system. Comparing AVS, the AVSD is working in that state the original structure is replaced by an energy dissipation system, which is more effect and reliable to control and reduce the structural response (Figure 30). The control algorithm suggested by authors is reasonable. It can reach the optimal state to control the structural response in earthquake or wind load.

MR Semi-Active Control is used at Ton-Tin Lake Bridge (Fig. 32), and it is very effective to reduce the vibration in the wind load. It is the first application of MR in the world (by Prof. Z.Q. Chen).

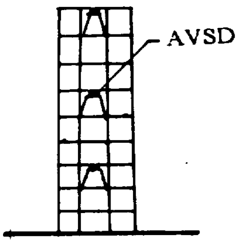


Figure 27: AVSD on Certain Stories

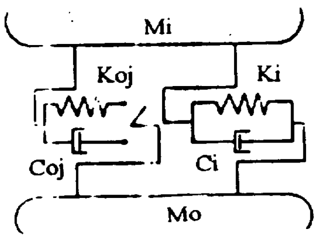


Figure 28: Mathematic Model of AVSD

Figure 29: Full Scale AVSD

Figure 30: Shaking Table test for AVSD System

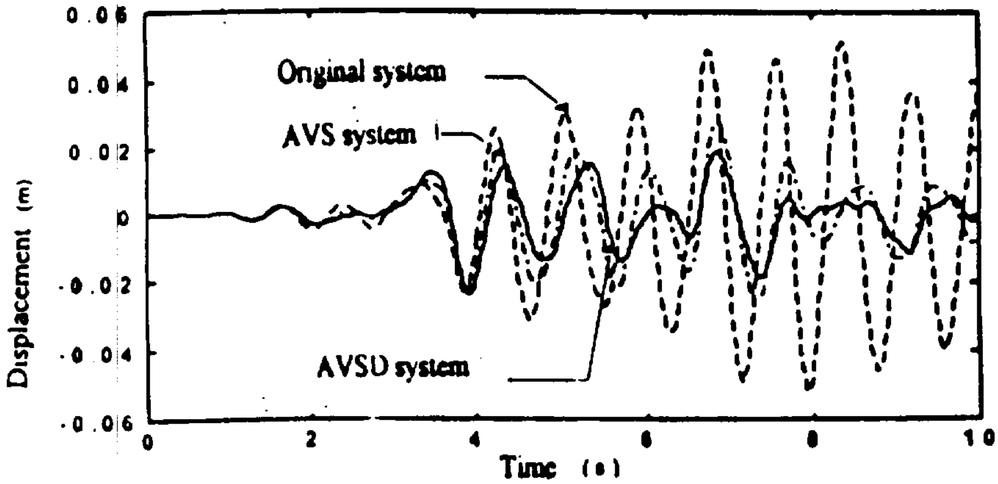


Figure 31 Time History of Response of AVSD System from Shaking Table Tests

Figure 32   MR is used in Ton-Tin Lake Bridge in China

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