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RECENT DEVELOPMENT ON SEISMIC CONTROL FOR STRUCTURES IN CHINA

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ABSTRACT

This paper briefly introduces the recent research, design and application on seismic isolation, energy dissipation, tuned mass damper and semi active control for structures (buildings and bridges) in China. Paper introduces some typical 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 buildings and bridges. Also the paper makes discussion for the tendency of future development and some problems existed on passive and active control technique in China.

Progress of Techniques for Seismic Resistance of Structures in China

There are two kinds of techniques of seismic resistance for structures at present. One is the traditional Anti-seismic technique (Sheng 2000), 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).

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

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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 1988).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

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. ,2,3).
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.

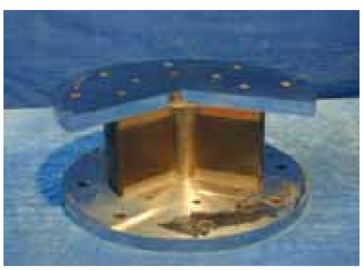
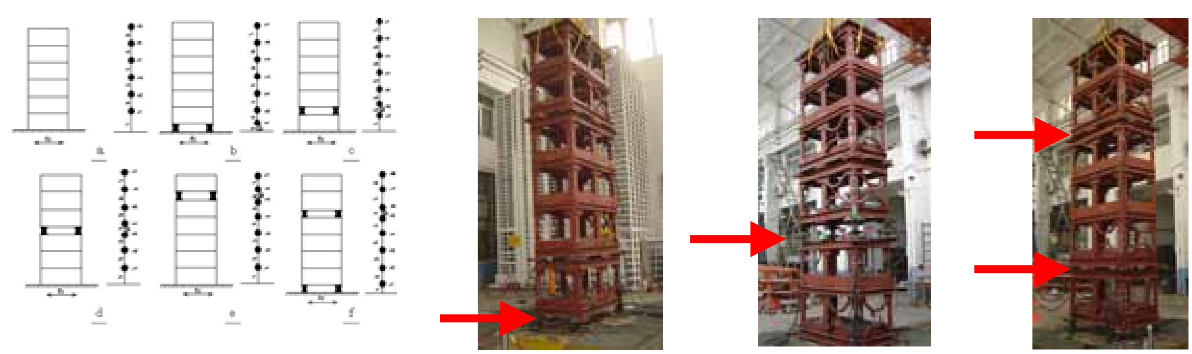


Figure 1. Design of rubber bearing   Figure 2. Comp.--shear test for bearing   Figure 3. Tests of Creep



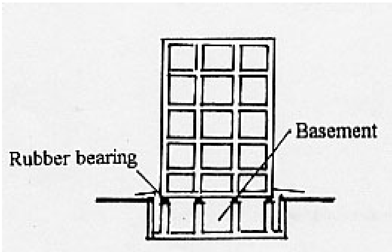
(a) Different location of isolation layers   (b) On the base   (c) On the Story   (d) Multi-layers

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

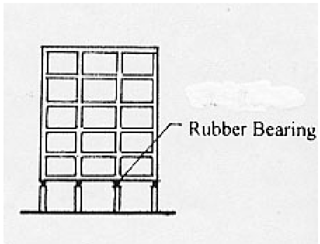
Different isolation Structural Systems

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

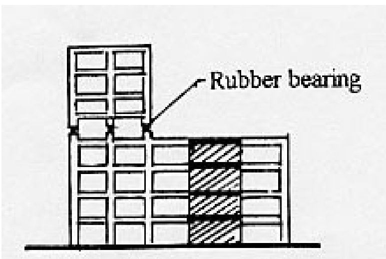
- **Base isolation**. Isolation layer is located on the base of building.
- **Basement isolation**. Isolation layer is located on the certain story of the basement (Fig.5a).
- **Story isolation**. Isolation layer is located on the top of the first story (Fig.5b) or certain story of supper structure (Fig. 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



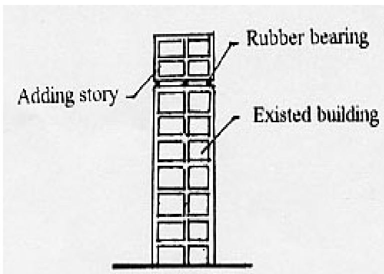
(a) Basement isolation.



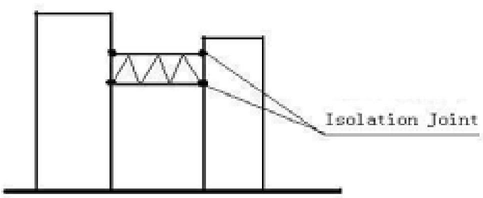
(b) Story isolation with isolators on the top of the first story



(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.

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.
- 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

There are three design levels of isolation buildings depending on the Design code 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.

***Level 2*.** Important structural design level for important isolation buildings: The compression stress of bearing is controlled in 10～12 MPa.

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.

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 base 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 basement isolation.

Figure 8. RC frame-shear 13 stories museum with story 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.

Example 4. 3D isolation, the largest area using stories isolation in the world. 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 house buildings (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 stories isolation in the world. 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 compression stress of bearing is about 10 MPa. The size of rubber bearings mainly is ϕ 700.

The isolation used a new type of isolator with 3D(Fig. 11,12) isolation which could isolate the horizontal ground motion, also could isolate the vertical vibration from the trains in subwa. The shaking table test (Fig. 13) 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. 13). 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 (Huang 2003).

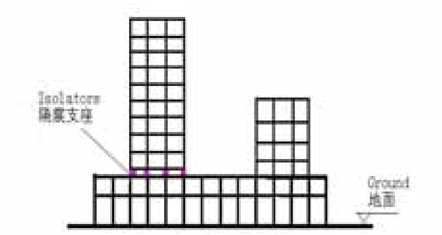


Figure 9. Stories Isolation.

Figure 10. A Part of view of 3D isolation.

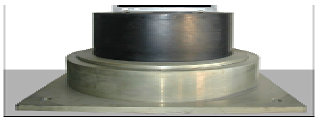


Figure 11. 3D isolator.

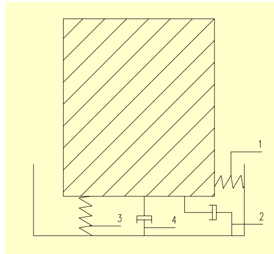


Figure 12. 3D isolation system.

Figure 13. Shaking table tests Isolation structural model.

Energy Dissipation

There are over 30 buildings with Energy dissipation dampers until 2005. Three kinds of dampers have been used in China now, including Metallic Damper, Friction Damper and Viscous Fluid Damper.

Metallic Damper

A Square Frame Steel Damper has been developed in 1978. A full scale test of Square Frame Steel Damper have been finished (Fig. 14) and the 1st industry structure have been constructed in northern China in 1979 (Fig. 15).

Figure 14. Full scale test of Metallic Damper.

Figure 15. 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. 16) 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. 17).

Figure 16. Full scale test of Friction Damper.

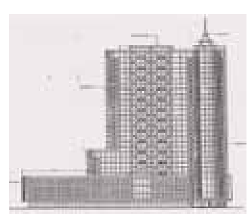


Figure 17. High rise building with Damper.

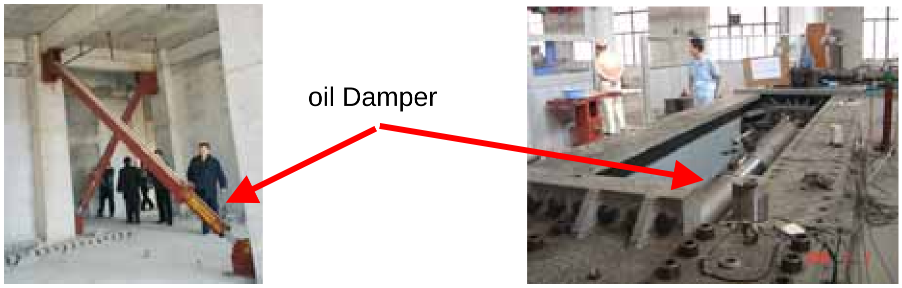


Figure 18. Building bracing with oil Damper. Figure 19. Full scale tests for oil dampers.

Viscous Fluid (oil) Damper

A series of Viscous Fluid Dampers are produced in China and widely been used as bracing (Fig.18), the damping force from 20 ton to 200 ton. The tests of characteristics for dampers have been carried out (Fig.19). Nearly 30 buildings used these dampers for new design or retrofit of existed building (by Pro. W.Q. Liu). This Viscous Fluid Dampers also been combined used with the isolation systems.

Design and Application of Energy dissipation system

There are three kinds of energy dissipation system being used now in China:
(1) Energy Dissipation Bracings: 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: 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: Energy dissipaters put on the gaps between adjacent buildings to avoid impact damage during earthquake.

Tuned Mass Dampers System (TMD)

In China, the TMD Filial Structure may be formed by adding one or more stories supported by rubber bearings on the roof of main building structure (Fig. 20,22), or adding a certain mass, such as water tank, supported by rubber bearings on the roof or other floors in main building structure (Fig. 21,,23).

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 1997)

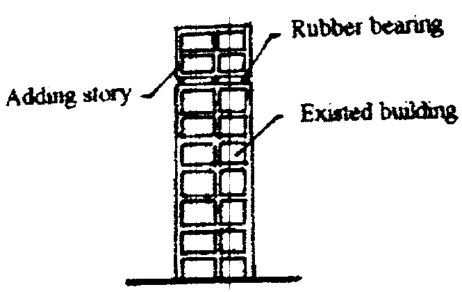


Figure 20. Adding stories as TMD.

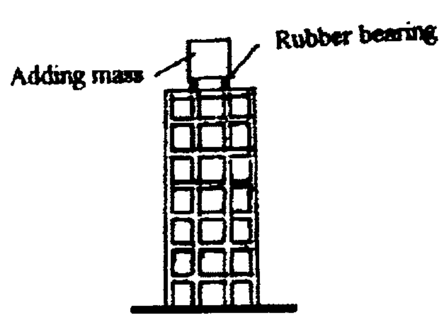


Figure 21. Water tank as TMD.

Figure 22. Adding Stories on Top of Building.

Figure 23. 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 24,25), 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 results of shaking table testing (Figure 26,27) 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. 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. 28), 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).

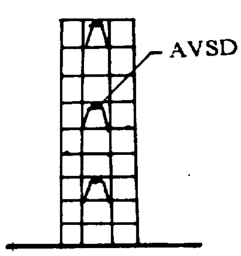


Figure 24. AVSD on Certain Stories.

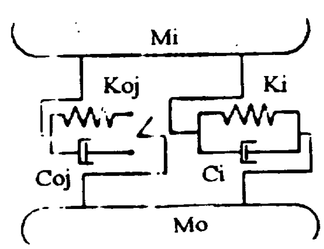


Figure 25. Mathematic Model of AVSD.

Figure 26. Full Scale AVSD.

Figure 27. Shaking Table test for AVSD System.

Figure 28. MR is used in Ton-Tin Lake Bridge in China.

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