Earthquake tragedy and application of seismic isolation, energy dissipation and other seismic control systems to protect structures in China

90% of the Chinese territory is seismic. Earthquakes cause victims, but also damage to non-structural elements and inside facilities, stopping the city's life. New techniques, as base isolation and energy dissipation, protect both structures and inside facilities. In China there are many structures with seismic isolation or passive or hybrid control systems. Some recent application, experimental records of real earthquakes, shake table tests as well as future trends on seismic isolation and passive and active control technique in China and in the world are described

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Earthquake tragedy in China

A tragically strong earthquake, the Tangshan earthquake of magnitude M = 8.5, happened at 3:15 a.m. on July 26, 1976. The epicenter depth was only 13 km. The broken faults run through the city. The whole city became ruins, 240000 people died, 96% of buildings collapsed, including houses, schools, hospitals, office blocks, all buildings (Figures 1-3).

Another tragically strong earthquake, the Tangshan earthquake of magnitude M = 8.0, happened at 2:28 p.m. on May 12th, 2008. The epicenter depth was only 17 km. The broken faults run through the city. The whole city became ruins, 90000 people died, 80% of buildings collapsed (Figures 4-6).

Just 5 years after the Wenchuan earthquake that hit the Sichuan Province in 2008, a very severe earthquake, the Lu Shan earthquake of magnitude M = 7.2, happened in the same province on April 20th, 2013. The epicenter depth was 13 km. The local horizontal Peak Ground Acceleration (PGA) for structures was only 0.15 g, but the recorded ground acceleration was 0.5-0.8 g, that is the 5-8 times the predicted design value. So it caused damage or collapse of 75% of buildings (about 40,000 buildings) in the Lu Shan County (Figures 7-9), let's say a standing ruin. 196 persons died, 21 were not found, 250000 were injured and the directness economy losses were 5.57 billion Yen.

Lessons learned from strong earthquakes in China

Just after the Lu Shan earthquake, a very positive message came: one of the buildings of the Lu Shan County Hospital, which was protected by seismic isolation, was not damaged at all and performed in an excellent way during the earthquake!

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FIGURE 1 Tangshan city after the shock of 1976

FIGURE 4 The Wenchuan earthquake in China

FIGURE 2 A school in Tangshan

FIGURE 5 Most buildings collapsed in Wenchuan

FIGURE 3 A hospital in Tangshan

FIGURE 6 A school collapsed in Wenchuan

Actually, there were 3 buildings in the Lu Shan County Hospital; all were reinforced concrete structures with 7 storeys and 1 story basement (Figure 10). One building was seismically isolated and, as mentioned, did not suffer any damage to the structure and decoration, any fall down of the facilities and equipment that were installed inside it. The persons inside it had no panic during the earthquake, this Isolated hospital building become an unique rescue

FIGURE 7 Damage of an office building during the Lu Shan earthquake

FIGURE 8 Collapse of a house building during the Lu Shan earthquake

FIGURE 9 Structure damaged during the Lu Shan erathquake

FIGURE 10 Lu Shan County Hospital, formed by 3 buildings

FIGURE 11 The two buildings without seismic isolation in the Lu Shan County Hospital

center in the whole county after the earthquake, thousands of injured people received first aid in it (Figure 12). On the contrary, the other 2 hospital buildings had been built according to a traditional anti-seismic design without isolation: the persons inside them felt the shaking very severely, the buildings suffered damages in the structure, walls and ceilings, all facilities and equipment fell down and the hospital was fully out of service (Figure 11).

FIGURE 12 The building with seismic isolation in the Lu Shan County Hospital

Many lessons have been learned from strong earthquakes in China, in particular:

1. Most strong earthquakes have been underestimated in China: during the May 12th, 2008, Wenchuan Earthquake, the recorded PGA as equal to 0.96 g, about 10 times the design PGA of 0.10 g; in the April 20th, 2013 Lu Shan Earthquake, the recorded PGA as equal to 0.80 g, about 6 times the design PGA of 0.15 g. So, the designers should take into account the underestimation of strong earthquake provided by the usually adopted design PGA values.
2. The death of most people was caused by the collapse of structures. Earthquakes cause severe damages not only of structures, but also of non-structural elements and inner facilities. They stop the city's life. They stop the operation of hospitals, power plants and so on.
3. Designers should use the new techniques. Seismic isolation and control of seismic vibrations are effective techniques. They protect people's life; they protect both the building and its inner facilities even in strong underestimated earthquakes.

Application of seismic isolation in China

Over 5,000 buildings were built with seismic isolators consisting in rubber bearings in China within 2014. These buildings include houses (about 70 %), offices, schools, museums, libraries and hospitals. The number of storeys of buildings ranges from 3 to 31. Most of these buildings are concrete frame or shear wall-frame structures and brick wall structures. Some railway bridges and highway bridges have also been built with seismic isolation in China. Nowadays, it has become a very strong tendency in China to widely use seismic isolation systems formed by rubber bearings (Zhou, 2014).

Testing and design of seismic isolation systems

Five kinds of materials have been used for isolators in China: sand layers, graphite lime mortar layers, sliding friction layers, rolling and rubber bearing. The rubber bearing is the most popular isolation device in China.

Many tests and detailed numerical modeling and analysis have already been carried out in China for seismic isolation systems formed by rubber bearings. The experimental work concerns:

1. tests on the mechanical characteristics of the isolator, which include compression tests (capacities, stiffness) and compression with shear cycle loading tests (stiffness, damping radio and maximum horizontal displacement);
2. tests on the durability of isolator, which include low cycle fatigue failure tests and creep and ozone aging tests;
3. tests on the structural system, which concern shaking table tests for large scale structural models. In particular, a 6-storey steel frame model with different locations of the isolation system was tested on shaking table (Figure 13): the test results show that the acceleration responses on each storey of the structural model are somewhat different, depending on the ratio between the super structure mass and that of the substructure (Huang, 2003).

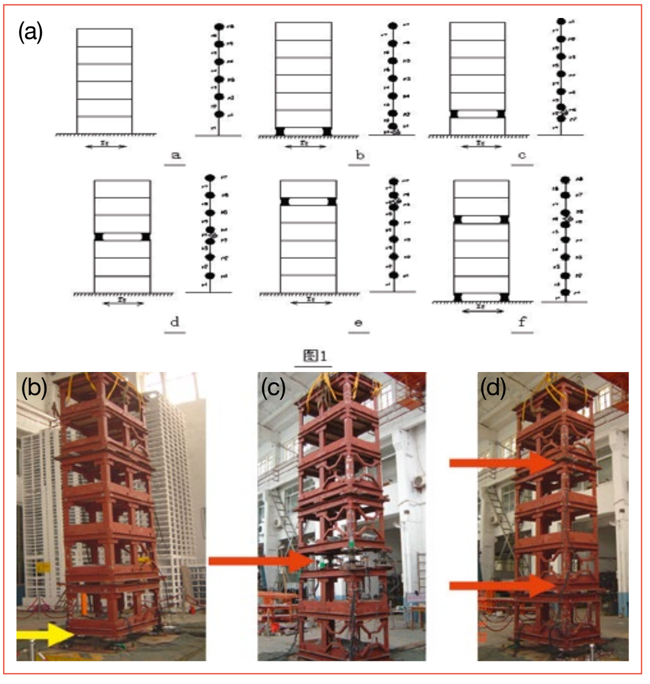

FIGURE 13 Shake table test for different locations of the isolation system. (a) Different locations of isolation system; (b) At the base; (c) On a storey; (d) Multi-layers

Technical code for seismic isolation and energy dissipation in China

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

1. Technical code for seismic isolation with laminated rubber bearings (CECS 2001). This is the national code for design and construction of buildings and bridges with seismic isolation in China.
2. Standard of laminated rubber bearing isolators (GB 20688-2006). This is the national standard of isolators for laminated rubber bearing in China.
3. Seismic isolation and energy dissipation for building design (Chapter 12 in code for seismic design of buildings, GB50011-2010). This is a part of national code in China for seismic design of buildings, in which is the chapter 12 [2].
4. Technical specification for Energy Dissipation (CECS 2013). This is the national specification for design and construction of buildings and bridges with energy dissipation in China.
5. Seismic Design Code for Isolation Structures (GB 2015). This is the national code for design of buildings structures in China.

Examples of application of seismic isolation

EXAMPLE 1: reinforced concrete (r.c.) multi-storeys house complex with base isolation.

It consists of a group of seismically isolated houses including 72 buildings (4-16 storeys), with a total floor area of 210,000 m^2, located in the Yunnan Province in Western China (Figure 14).

FIGURE 14 Group of 72 seismically isolated dwelling buildings including (4-16 storeys)

FIGURE 15 Group of 48 isolated buildings with storey isolation supported by an unique r.c. platform

FIGURE 16 Seismic isolation of the Kunming New Airport Terminal (2007-2012)

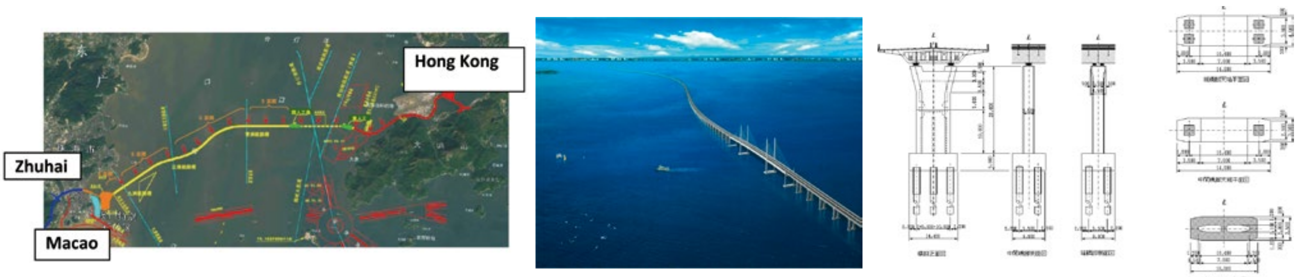

FIGURE 17 Seismically isolation bridge (Hong Kong-Macau-Zhuhai), 26 km long

EXAMPLE 2: 2-storey platform with r.c. frame supporting 9-storey houses with storey isolation.
It is the largest group of seismically isolated buildings in the world to have been erected on an unique slab (Figure 15). In fact, it consists in a very large platform (2-storey r.c. frame), 1500 m wide and 2000 m long, which covers a railway area in Beijing and supports 48 isolated buildings (7 to 9-storey buildings with r.c. frame) with a total floor area of 240,000 m^2, built on its top floor. The isolators (rubber bearings) are located on the top floor of the platform to protect the buildings from both the seismic motion and the railway-induced vibrations.
EXAMPLE 3: seismic isolation of the Kunming New Airport Terminal (2007-2012).
The total floor area of this airport is 500,000 m^2. Because its location is near seismic faults (10 km), it was indispensable to protect the complex structure of the airport, its curved columns, large glasses and large ceiling, as well as the important inner facilities. The only way was to use seismic isolation (Figure 16). This project made use of 1892 rubber bearings (1,000 mm diameter) and 108 oil dampers to reduce the displacement of the isolated superstructure during earthquakes.
EXAMPLE 4: seismically isolated bridge (Hong Kong-Macau-Zhuhai) crossing the South China sea (26 km).
For this bridge, which crosses the sea and is 26 km long (Figure 17), it was very important to reduce the seismic response of its structures, in particular to avoid damage and cracks at the bottom of the piers and to move the area with nonlinear behavior from the bottom of the piers to the isolators installed on their top. To achieve this, the use of seismic isolation was found necessary.
EXAMPLE 5: protection by means of seismic isolation of historic statues and stone tablets (1200 years old).
It is also important to protect from earthquakes the cultural heritage structures, the statues that are located inside them, paintings on their columns and walls: thus, we need to use seismic isolation to this purpose too (Figure 18).

FIGURE 18 Protection of historic statues and stone tablets (1,200 years old) by means of seismic isolation in China

EXAMPLE 6: Retrofits with seismic isolation retrofits of school buildings.
Millions of school buildings need to be retrofitted to withstand strong earthquake. In China, in the Shanxi Province, seismic isolation was successfully used to retrofit school buildings (Figures 19 and 20). As a consequence, the Government organized a national meeting to promote the extensions of this kind of retrofits to Chinese schools.

Energy dissipation

Over 2000 buildings had already been protected in China with energy dissipation devices (dampers) in 2014. Energy dissipation is achieved by adding some dampers inside the structure in appropriate positions. The energy dampers provide the structure with a large amount of damping, which will dissipate most energy deriving from the vibration sources before the structure reaches its resistance limit. Thus, they allow the structure to be safe in earthquakes or to satisfy the used requirements concerning wind resistance. The energy dampers may be set on bracings, walls, joints, connection parts, non-structural elements or in any suitable space in structures. They may reduce the structural response of 20-50%, with respect to the traditional design without dampers. This technique is very reliable and simple, suitable to be used for general or important new or existed buildings or facilities in seismic regions.
Nowadays, five kinds of dampers have been used in China:

- Steel yielding devices;
- Lead yielding devices;
- Oil dampers;
- Buckling Restrained Braces (BRBs);
- Smart materials (Shape Memory Alloy – SMA – devices).

Hybrid (passive and active) control of structures

EXAMPLE 7: Hybrid control for Guangzhou Tower, 645 m high.
The reasons of using hybrid control for this tower were:

FIGURE 19 Base isolation system in a retrofitted school

FIGURE 20 Isolation system installed in 1st storey of a retrofitted school

FIGURE 21 Guangzhou Tower

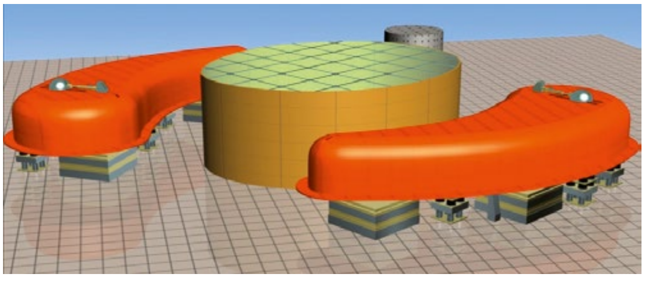

FIGURE 22 Use of 2 water tanks as mass of the Tuned Mass Damper

- Its height is 610 m, thus earthquakes and wind loads were a big problem;
- The structural plane is elliptic, which would lead to torsion in earthquakes or due to wind, without isolation;
- The design of the tower was not satisfied in case of strong winds;

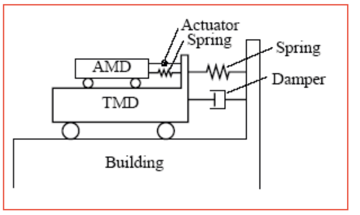

FIGURE 23 Hybrid control system (Tuned Mass Damper + Active Mass Damper)

- The use of Tuned Mass Damper (TMD) was a low cost solution, but the design requirements were not satisfied;
- Active Mass Damper (AMD) is an effective, but its use was too expensive;
- A combination of TMD and AMD, namely a hybrid system (on the top of tower), may be the best balance solution.

Conclusions

Seismic isolation and vibration control systems are techniques that:

- Are safer, even in the case that the earthquake level is underestimated;
- Provide a more effective protection for both structures and inner facilities;
- Are more effective to keep the superstructure in elastic conditions;
- Inexpensive and even more economical in some cases (with possible additional construction Costs limited to ±5 ~ 10%);
- More satisfactory for irregular architectural designs.

In China, in coming years:

- The traditional anti-seismic design will remain the most used for structures;
- However, seismic isolation and vibration control techniques will be among the main systems.

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