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Recent progress and application on seismic isolation energy dissipation and control for structures in China

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Abstract: China is a country where 100% of the territory is located in a seismic zone. Most of the strong earthquakes are over prediction. Most fatalities are caused by structural collapse. Earthquakes not only cause severe damage to structures, but can also damage non-structural elements on and inside of facilities. This can halt city life, and disrupt hospitals, airports, bridges, power plants, and other infrastructure. Designers need to use new techniques to protect structures and facilities inside. Isolation, energy dissipation and, control systems are more and more widely used in recent years in China. Currently, there are nearly 6,500 structures with isolation and about 3,000 structures with passive energy dissipation or hybrid control in China. The mitigation techniques are applied to structures like residential buildings, large or complex structures, bridges, underwater tunnels, historical or cultural relic sites, and industrial facilities, and are used for retrofitting of existed structures. This paper introduces design rules and some new and innovative devices for seismic isolation, energy dissipation and hybrid control for civil and industrial structures. This paper also discusses the development trends for seismic resistance, seismic isolation, passive and active control techniques for the future in China and in the world.

Keywords: seismic isolation; energy dissipation; passive contro; hybrid control

1 Earthquake tragedy and lessons in china

A tragically strong earthquake, known as the Tangshan earthquake *M*7.8, happened at 3:15 on 26 July 1976. The epicenter depth was only 13 km below the surface of the earth. The fault line runs right below the city of Tangshan. The whole city was ruined, 240,000 people died, and 96% buildings collapsed, including houses, schools, hospitals, office buildings and many other types of buildings (Figs. 1 and 2).

Another devastating earthquake, the Wenchuan earthquake *M*8.0, happened at 14:28 on 12 May 2008. The epicenter depth was only 17 km below the earth's surface. The fault also ruptured right below the city. The whole city was turned to ruins, 90,000 people died, and 80% of buildings collapsed (Fig. 3).

In the same area of the Wenchuan earthquake, just five years after the *M*8.0 earthquake, another severe earthquake, the Lushan earthquake *M*7.0, happened on 20 April 2013. Over 75% of buildings were damaged or collapsed in Lushan County.

But after the Lushan earthquake, it was noted that one of the buildings in the Lushan County hospital had used an isolation technique. The structure had not sustained any damage, and it performed very well during and after the earthquake!

There are three buildings in the Lushan County Hospital, all of which are seven story reinforced concrete structures with single level basement (Fig. 4). The one building that has an isolation system, was not damaged at the structural level nor was the interior damaged; no fixtures fell down off of walls or ceilings and equipment inside the buildings survived. The people inside that building did not feel the shaking. This seismically isolated hospital building became the lone rescue center for the whole county after the earthquake. Thousands of injured people were treated there (Fig. 6). People in the other two hospital buildings that were designed without an isolation system experienced severe shaking, and the buildings' structure, walls, ceilings, and equipment were all damaged (Fig. 5).

Many lessons have been learned from severe earthquakes in China (Zhou, 2016):

1.1 Most of severe earthquakes are exceed predicted peak ground accelerations in China

Earthquake	Design ground acceleration	recorded ground acceleration	time
2008.05.12 Wenchuan earthquake	0.10 g	0.96 g	10
2013.04.20 Lushan earthquake	0.15 g	0.80 g	6

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Fig. 1 One school in Tangshan

Fig. 2 One hospital in Tangshan

Fig. 3 Buildings collapsed in Wenchuan

Fig. 4 Lushan County Hospital, including three buildings

Therefore, structural engineers need to design for the high recorded accelerations seen recently.

1.2 Most fatalities are caused by structural collapse

As much as 90% of the people that die during an earthquake are killed by building collapse. An earthquake not only causes severe damages or collapse of structures, but can also severely damage of non-structural components. This damage disrupts a city's functionality and close critical facilities like hospitals and power plants.

1.3 Designers need to use the new technique

Isolation, energy dissipation, and structural control systems are effective in mitigating seismic risk. These systems could protect both human life and a building's structural and non-structural components from severe shaking.

2 Technical rules for seismic isolation and energy dissipation systems in China

There are three sets of technical rules for seismic isolation and energy dissipation systems in China (Zhou, 2014).

2.1 Technical specifications:

- **Technical specification for seismic isolation with laminated rubber bearing isolators (CECS 2001)**. This is the national technical specification for

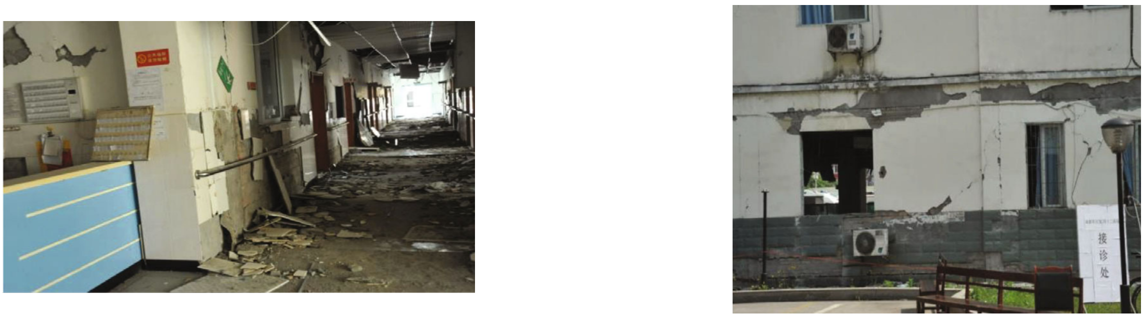


Fig. 5 Two buildings without isolation in Lushan County Hospital, damaged

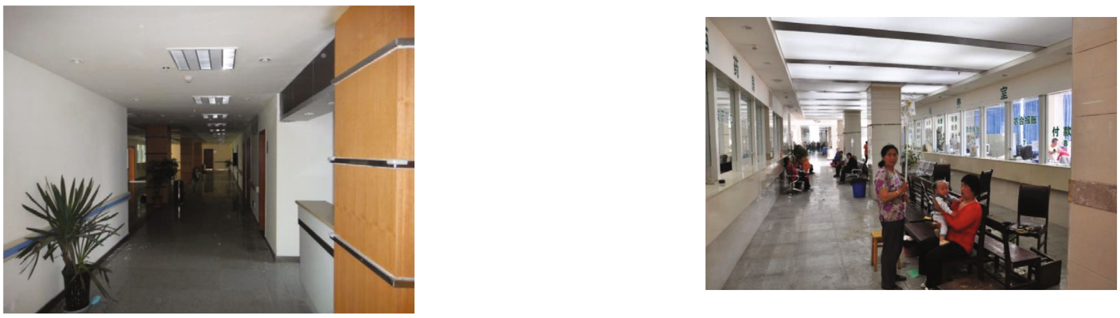


Fig. 6 One building with isolation in Lushan County Hospital, not damaged

design and construction of buildings and bridges with seismic isolation issued in 2001 in China.

- **Technical specification for Energy Dissipation (CECS 2013)**. This is the national technical specification for design and construction of buildings and bridges with energy dissipation issued in 2013 in China.

2.2 Design codes

- **Seismic design code of buildings with isolation and energy dissipation** (Chapter 12 in national code for seismic design of buildings, **GB50011-2001 and 2010**). This is a part of national code in China for seismic design of buildings issued in 2001and 2010 in China.
- **Seismic Design Code for Isolation Structures (GB 2017).** This is the national code for seismic isolation design of building structures which was issued in 2017 in China.

2.3 Standards for isolators and energy dissipation dampers

- **Standard of laminated rubber bearing isolators (GB 20688-2006).** This is the national standard of isolators for laminated rubber bearings issued in 2006 in China.
- **Standard of energy dissipation dampers (JG / T209-2011).** This is the national standard for energy dissipation dampers issued in 2011 in China.

3 Testing and design of seismic isolation systems

There are five types of seismic isolators that have been used in China, including a layer of sand or graphite lime mortar, a slide friction layer, and roller and rubber bearings. Rubber bearings are the most popular system (Zhou, 1997).

Many physical tests have been conducted and extensive computational theory of rubber bearing seismic isolation systems has been developed in China. There have been three types of experiments including:

(1) Tests of rubber bearing mechanical characteristics, including compression tests to quantify capacity and stiffness, and compression with shear cycle loading to quantify stiffness, damping ratio and maximum horizontal displacement. The results of this testing show that the maximum compression stress of these bearings can reach as high as 90 MPa when horizontal strain is zero, or 35 MPa when horizontal strain is 400%. Therefore, it is more than safe to design for a maximum compression stress of less than 15 MPa (Fig. 7).

(2) Tests to investigate the durability of the isolator, including low cycle fatigue failure, creep, and ozone aging tests. From studies on rubber aging, it has been shown that the maximum thickness of rubber ozone is 5 mm exposed to sunlight and air for 105 years. Thus, if a rubber bearing is manufactured with a 10mm coverer layer to protect it from air and sunlight (Fig. 8), the rubber bearing working life could reach over 100 years,

(3) Shake table tests on large scale structural models including structures with different configurations of isolation bearing locations (Fig. 9). The testing results show that the isolation effect depends on the ratio of mass of superstructure to that of the substructure, the base isolation (isolator located at the base of the structure) is the best configuration. The accelerations of an isolated structure could reduce by 1/12-1/4 as compared with a fixed-base structure. For middle isolation (isolator located in between stories), the isolation effect is also significant (Huang, 2003).

4 Examples of application of isolation systems in China

There are over 6,500 buildings with rubber bearing isolation built in China since 2016. The kinds of buildings constructed with this system include but are not limited to houses, hospitals, schools, museums, and libraries. These buildings have between 3 and 31 stories. Most of structural systems are concrete, steel frame or brick structures. Some railway bridges and highway bridges with seismic isolation have also been built in China. The use of rubber bearing seismic isolation systems has become very widespread in China recently (Zhou, 2016)

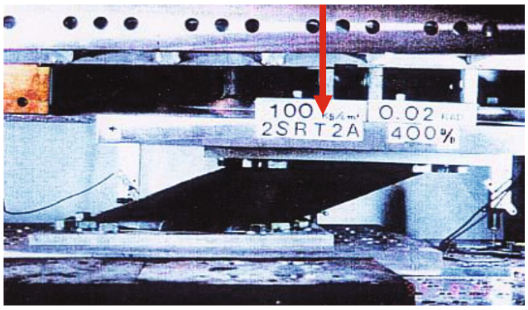


Fig. 7 Compression with shear loading tests

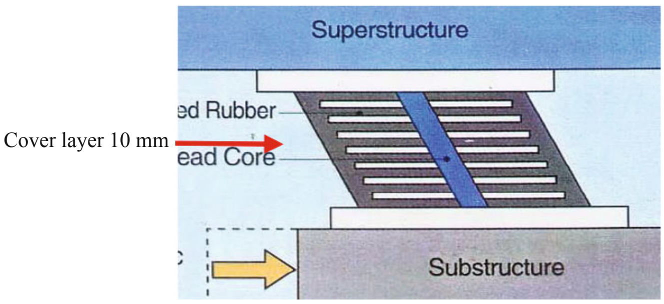


Fig. 8 Cover layer for rubber bearing

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

Fig. 9 Shaking table test for different configurations of isolation bearings layers

4.1 Residential buildings

Example 1: Reinforced concrete high-rise apartment building with basement isolation

Seismically isolated residential apartment buildings, including 24 high rise buildings (31 stories), with a total floor area of 980,000 m^2 were constructed in Beijing, China. This is the largest area of isolated apartment buildings in the world (Fig. 10). There are many similar isolated reidential buildings in Xinjiang Province, Yunnan Province, and other areas in China.

Example 2: RC frame 6-story school building with base isolation

This seismically isolated school building was built in 2008, and was subjected to the Lushan Earthquake *M*7.0 in 20 April 2013. Compared to buildings without isolation, the response of the school's acceleration was reduced to be 1/6 of the acceleration experienced by fixed-base structures. Teachers were able to instruct the young students that, "When an earthquake happens, keep inside of the room, don't run out! This is a base isolated building; inside this building is safer than outside!" The school building did not sustain any damage and, no students were injured in this earthquake (Figs.11 and 12).

Example 3: RC frame 2-story platform + 9 story residence with interstory isolation

This seismically isolated artificial ground is the largest area with 3D isolation in the world (Fig. 13). There is a very large platform (2 stories, RC frame) with dimensions of 1500 m in width and 2000 m in length

Fig. 10 24 high rise (31 stories) seismically isolated redidential apartment buildings with floor area 980,000 m^2

Fig. 11 Seismically Isolated building school in Wenchuan County

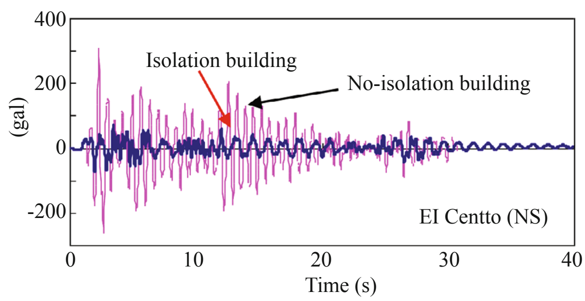


Fig. 12 The records of acceleration response in earthquake

Fig. 13 All 48 isolation buildings using Stories 3D Isolation on RC Platform

that covers a railway area in Beijing City. There are 48 isolated buildings (7 to 9-story RC frames) with a total floor area of 240,000 m^2 built on top of the elevated platforms. The rubber bearings layer is located on the top floor of the platform provide 3-dimensional isolation for the buildings from seismic motion and railway vibration.

4.2 Large span or complex structures

Example 4: Seismic isolation of new Kunming airport terminal (2007-2012)

The floor area of the isolated new Kunming airport terminal is 500,000 m^2, which is the largest area of an isolated building in the world in the recent past. Because the airport's location is near seismic faults (10 km), it is necessary to protect the complex structure of the airport, column with curve shape, large glass facades, large ceiling, and critical facilities inside the building during earthquake using several technologies. This project uses 1,892 rubber bearings (ϕ1200 mm) to isolate the structure from ground motion and 108 oil dampers to reduce displacements during an earthquake (Fig. 14). This airport terminal was subjected to an *M*4.5 earthquake, the Chonmin Earthquake, on 9 March 2015. The acceleration response records have been attained; the terminal floor F3 response is 1/4 of that of the base (Fig. 15). The isolation and mitigation technologies were very effective in reducing the structural response for the airport terminal. The new Beijing airport terminal with an isolated floor area of 700,000 m^2 (2015-2019) and the new Hainan airport terminal with an isolated floor area of 300,000 m^2 (2016-2019) are being constructed now. Many new airports with base isolation are being planned or designed in China now.

4.3 Bridges

Example 5: Isolated Bridge-HK-MACAO-ZHUHAI Crossing the South China Sea

This 26 km bridge crossing the South China Sea uses the isolation technique (Fig.16). The system is very effective in preventing cracking at the bottom of

Fig. 14 Seismic Isolation of new Kunming airport Terminal (2007-2012)

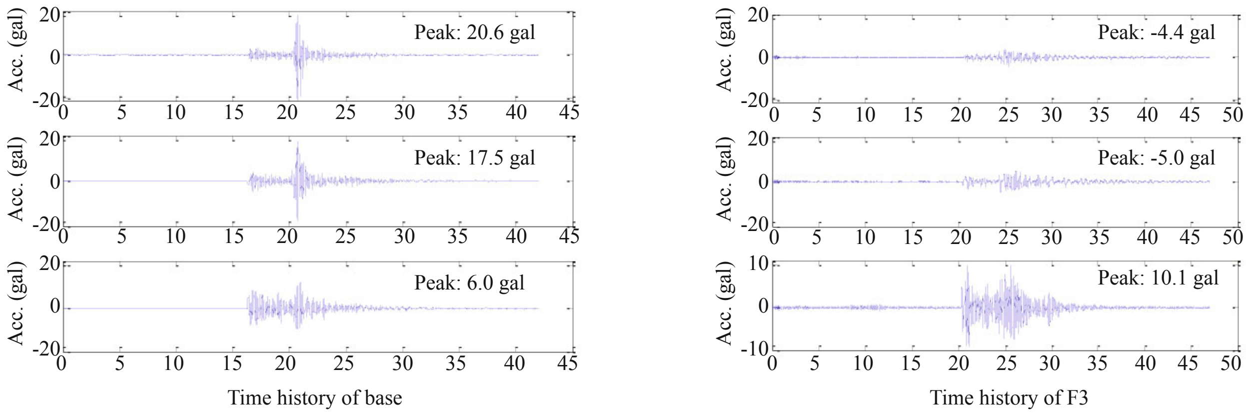


Fig. 15 Acceleration response records: airport floor F3/base = 1/4

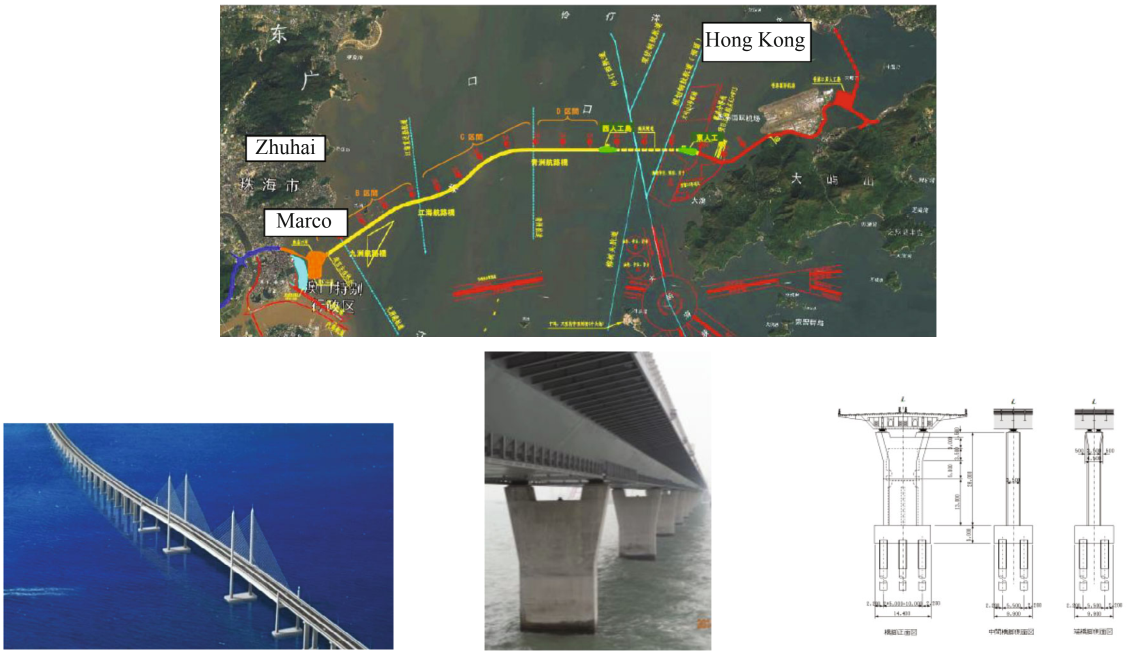


Fig.16 Seismically Isolatied Bridge-HK-MACAO-ZHUHAI 26 km

piers in the sea water, and in moving the nonlinear area from the bottom of the piers to the isolators on the top of piers, thus keeping the pier in its elastic range during an earthquake. The system also reduces the seismic response to be 1/4 response of traditional bridge.

4.4 Historical or cultural relic

Example 6: Protection for a historic statue and stone tablet (1200 years history)

There are many historical relics that are thousands of years old in China. It is very important to protect these historical relics, such as statues, tablets or pictures, from severe earthquakes. Isolation techniques are the best option. Putting one isolation layer at the base of relics could reduce the horizontal response of relics to be 1/12 of the ground motion and ensure the safety of the relics in severe earthquakes (Fig. 17).

4.5 Seismic retrofit

Example 7: Seismic isolation retrofits for old Buildings

Millions of old buildings used for schools, hospitals, or other critical facilities lack seismic resistance in China. These buildings need to be retrofitted to satisfy the safety requirements in a severe earthquake. Shaanxi Province successfully used isolation to retrofit school buildings. The Government has held a National Meeting to extend this demonstrate (Figs.18 and 19).

4.6 Low rise residential buildings

Example 8: Low rise residential building with "elastic isolation brick"

There are many houses in rural areas of China. These houses always are low rise, low cost simple design, and

Fig. 17 Protection for a history statue and stone tablet (1200 ys history)

Fig. 18 Base Isolation retrofit in Shaanxi Province

Fig. 19 1st story isolation retrofit in Shaanxi Province

have simple construction plans, but most of them are lack of required seismic risk mitigation. A new isolation system called an “elastic isolation brick” has been invented for this requirement for safety, and they have begun to be popularly used in large countryside areas in China (Fig. 20). The cost of this elastic isolation brick is only 1/4 of the general rubber bearing, its design is very simple, and it can be constructed by hand. Shake table tests showed that low rise residential buildings with an elastic isolation brick could withstand very strong earthquakes with ground accelerations up to 0.80 g without being damaged; these buildings could become the “safety island” in a very strong earthquake.

5 Energy dissipation

There are over 3,500 buildings with energy dissipation dampers that were constructed since 2016. An 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 vibrational energy from ground motion, thus preventing structural damage and avoiding severe damage or collapse states during earthquake. These systems can also be used to satisfy safety requirements for wind loading. The energy dissipaters may be set on the bracing, walls, joints, connections, non-structural elements or any suitable spaces in a structure. It is possible to reduce the structural response to 20%-50% of that of a traditional structure without energy dissipaters. This technique is very reliable, simple, and suitable for general or important new or existed buildings in seismic regions.

Six kinds of dampers are now being used in China, including:

- Steel yielding
- Lead yielding
- Oil damper
- BRB bracing
- Smart material (SMA)
- Eddy-current damper (ECD)

Example 9: Tunnel with smart material (SMA) energy dissipation

There are tunnels that cross the rivers or seas that need to control the open width of tunnel joints to avoid water entering the tunnel during a severe earthquake which could kill the people in cars or trains inside the tunnel. One such tunnel is 6 km long tunnel under the sea, and is located in seismic area with seismic intensity of 0.40 g in Southern China (Fig. 21). This tunnel follows the soft design concept that incorporates soft joints and uses smart material (SMA) to control the open state of the tunnel joints during an earthquake, thus allowing for recovery to the closed state after earthquake. This ensures that the tunnel becomes watertight when it experiences a strong earthquake. Theory development and testing results for this new soft design tunnel system have shown that this kind of design could reduce the tunnel response by about 30%-50%, and could ensure that the tunnel becomes watertight in very strong earthquakes (Fig. 22).

Example 10 Eddy-current damper (ECD), a novel damper has been developed by Chen Zhengqing in China

The general concept is that when an iron plate is

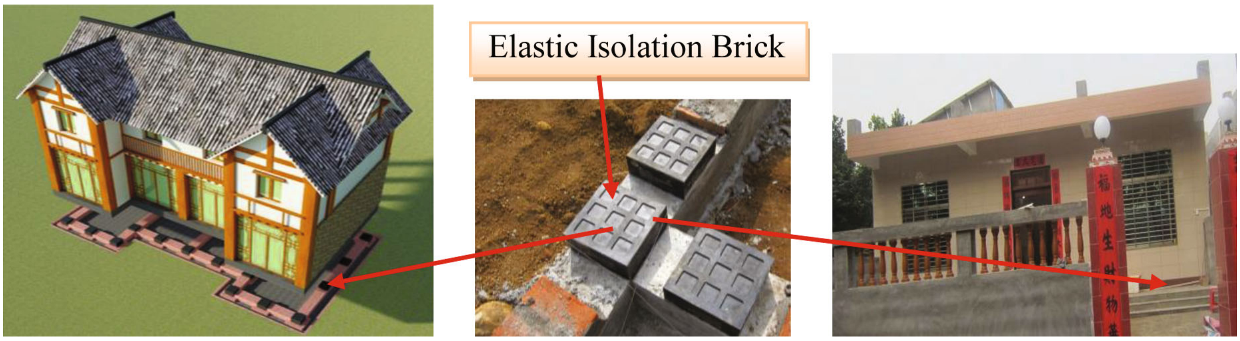


Fig. 20 Low rise residential building with “elastic isolation brick”

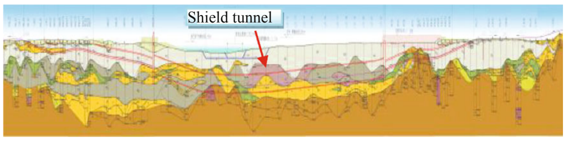


Fig. 21 Shield tunnel with a length of 6 km crossing the sea in Southern China

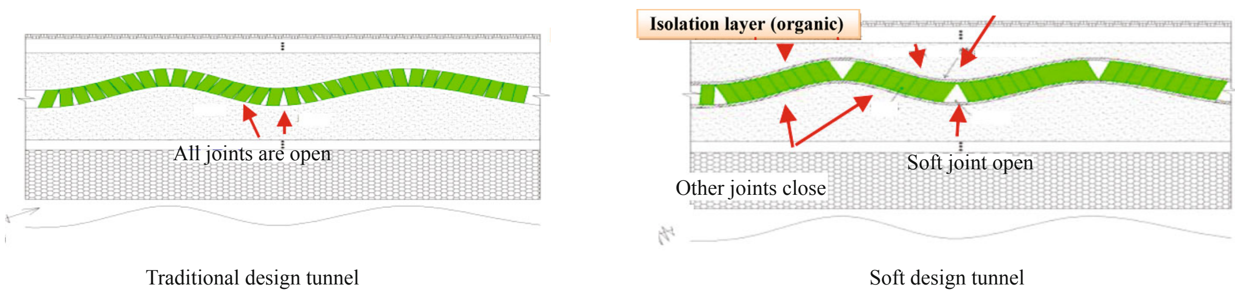


Fig. 22 New soft design concept for tunnel with smart material (SMA)

put in a magnetic field, it will induce large damping. This is a new generation of energy dissipation devices which could provide large damping for structures; these dampers are more precise and durable because there is no contact between material parts. This new damping device has been used in the Shanghai Center Tower, a 606 m tall building (Fig. 23). The building's response with this new system could be reduced by 30%-50% during strong wind events.

Eddy-current damping has many attractive properties and excellent operational performance. This is done by employing a ball screw mechanism capable of producing sufficiently large damping coefficients and apparent mass. This new device has been used on TMD's damper in highrise buildings and on bridges. It is more effective, durable and economical than other types of dampers mentioned above.

6 Hybrid (passive add active) control for structures

Structural control has been used in about 30 buildings and bridges. A passive TMD is low cost and stable, but it could not be satisfied for earthquake or wind. Active AMD is effective, but it is too expensive. So, a new control system has been developed called Hybrid Control, or HTMD (TMD+AMD), which is stable and low cost, and could satisfy the requirement for earthquake or strong wind. Therefore, this new system has become one of the best options for structures in China.

Example 11 Hybrid control for Guangzhou Tower with a height of 645 m

The reasons for using hybrid control for Guangzhou Tower are:

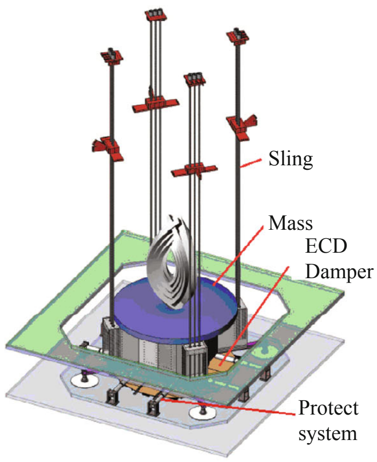
●With a height of 610 m, earthquake and wind loading are both big problems

●The structural plan is an ellipse, which will be subject to torsion in an earthquake or wind load

●The slender conformation is not be satisfied in strong wind (Fig. 24).

●TMD is low cost, but could not satisfy the safe requirements. AMD is effective, but too expensive

TMD+AMD=HTMD may be the best balance (Figs. 25 and 26)



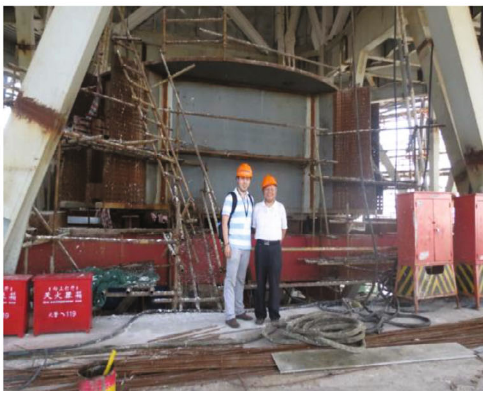
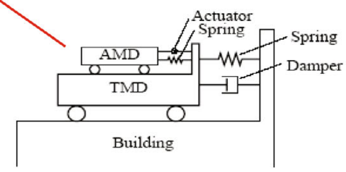


Fig. 23 Shanghai Center Building with a height of 606 m and Prof. Chen Zhengqing in the construction site



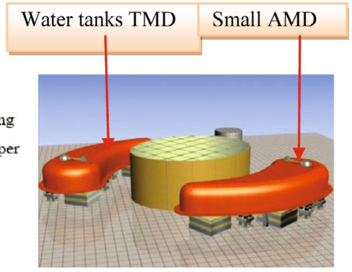


Fig. 24 Guangzhou Tower Fig. 25 HIBRID (TMD+AMD) Fig. 26 Using 2 Water tanks as Mass of TMD

Using two water tanks as the mass of the TMD will effectively reduce the cost of new system.

7 Conclusion

Damage prevention and resiliency in structures has become the goal for seismic design of buildings structures; seismic isolation, energy dissipation and structural control have become the best options at present in China.

There are many advantages for seismic isolation, energy dissipation and structural control including:

● Increased safe, even in earthquakes with magnitudes higher than design intensities.

● Increased effective protection for both structures and facilities inside of the structure during earthquakes.

● It is more effective to keep superstructures in their elastic range in an earthquake.

● It is more economical and inexpensive to include, only adding about 5-10% of the structural cost.

● More Satisfied for irregular architectural design for anti-seismic or wind load.

So, it could be said that in the coming years:

● Traditional fixed-based structures will remain the main type of structural system.

● Seismic isolation, energy dissipation, and structural control will be the main systems for seismicly designed structures, and will be more widely used in the coming years in China.

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