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SEISMIC RESISTANT SCHOOLS FOR SICHUAN

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Dr Derry Yu, Senior Engineer, Hyder Consulting
Dr Ruffina Thilakaratne, Research Leader, Woods Bagot
Stephen Jones, Regional Managing Principal, Woods Bagot
John Harkins, Director, Hyder Consulting
David Wincey, Associate Woods Bagot

Article at a glance

According to earthquake damage investigation results, poor construction quality, inadequate seismic fortification, intensity demarcation and improper structural configuration and detailing adopted in schools have been the major causes for devastation in the Sichuan earthquake. Reconstruction of schools is among the listed priorities in the government plan. This study addresses this issue through innovative design strategies that consider different configurations, structural systems and materials. Based on engineering and cost analyses, this paper discusses benefits and disadvantages in each option with recommendations for a more robust system.

1 INTRODUCTION

1.1 Aftermath of the Sichuan Earthquake

China has recorded three of the worst earthquakes in the world in terms of death toll: Shanxi earthquake in 1556; Tangshan earthquake in 1976; and Haiyuan earthquake in 1920 with death tolls of 830,000; 242,000 and 234,000 respectively. Over the past 10 years, five major earthquakes measuring higher than 6.2 Richter scale magnitude have occurred in China, with the Sichuan earthquake being the seventh deadliest earthquake this century.

On May 12 2008 an earthquake measuring eight on the Richter scale struck Sichuan province in China reporting a massive death toll over 70,000, affecting over 45.7 million people and causing disruption to daily operations amounting to a reported economic loss of $1000 billion. Reportedly more than 80 per cent of buildings collapsed including a large number of school buildings. Not only did this inhibit the rescue operations, a large number of young children were buried under the debris adding to the extensive death toll and causing severe trauma to the nation.

> *“Teenagers buried beneath the rubble of the three-storey Juyuan Middle School building were struggling to break free, while others were crying out for help…” [1]*

In a country with a ‘one child policy’ this disaster has left many families with little hope for future generations. The devastation attracted international attention with foreign aid channel into emergency management and redevelopment.

In the aftermath of any disaster, there is an immediate need for relief shelters. Often school buildings are adopted as relief shelters in post disaster operations due to several reasons: schools are located in every community with easy access and adequate infrastructure; schools have adaptable spaces such as multi-purpose halls and gymnasiums where a large number of people can be accommodated; often schools are public property where acquisition of spaces can be easily worked out. Schools also can be converted to multiple alternative uses such as hospitals or even elderly homes in the long run if they are designed in an adaptable way.

Reconstruction of schools is amongst the listed priorities of the government:

> *“Priority should be given to the reconstruction of public facilities, including schools and hospitals, and these buildings should be the “safest, most solid and trustworthy”[2]*

Learning from the tragic experience of the Sichuan earthquake, reconstruction of schools must consider the stability and safety of the buildings in future earthquake events.

1.2 Why did schools collapse in Sichuan?

Schools were amongst the most damaged structures during the Sichuan earthquake. About 7000 schools were seriously affected; some collapsed, others were seriously damaged. Collapse of Juyuan Middle School and Dujiangyan School, burying many young children and teachers in the debris caught national and international attention calling for the need for immediate investigations. According to records nearly 2 million square metres of school areas crumbled in the quake, killing 4737 students and injuring more than 16,000. Sichuan Construction Bureau reported that 6898 classrooms collapsed across Sichuan. Whether schools in China are more prone to collapse than other buildings was a core question during investigations. An investigation of several schools in Sichuan reports that whereas the schools were completely destroyed by the quake, many other buildings in the vicinity survived. Investigations revealed fatal issues that frequently exist in design and construction in China. [3]

Although the seismic codes in China are rigorous, the massive destruction to schools was due to failing to meet earthquake prevention standards, poor structural design and substandard construction. Investigations also report that some schools that collapsed had not undergone a geological survey prior to construction.

In addition, the typical nature of classroom block design may also have been partly to blame for the destruction. Most schools are built with non-reinforced masonry with precast panels or masonry infill. Often classroom blocks are modular and the modular structures are prone to topple off their foundation unless they are securely fastened or braced to the structure.

1.3 Sichuan

Sichuan Province is the most populated province in China with a population of 87 million. Severe destruction of the earthquake spread across an area of more than 38,610 square miles.

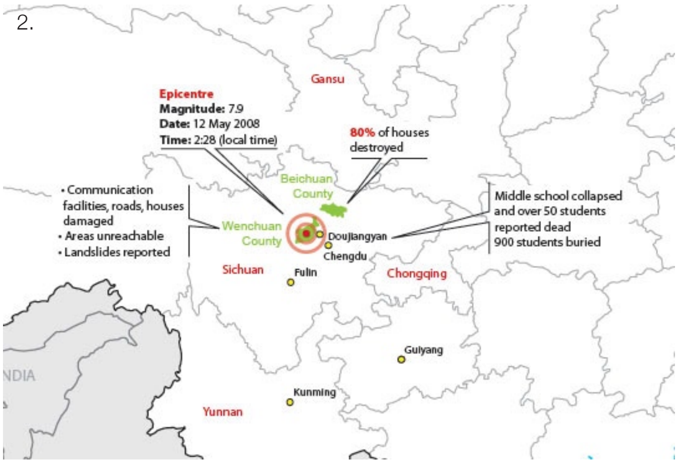
A major part of Sichuan is prone to earthquakes. According to Dr Densmore, “the location of the active faults is crucial. Knowing where the active faults lie and how much they are likely to move in future events, can help the Chinese authorities in planning new buildings and towns to reduce the likelihood of future casualties”. [4]

Figure 1. Location of epicentre and strongly felt area of 512 Sichuan Earthquake

Figure 2. Detailed location of epicentre of 512 Sichuan Earthquake [5]

1.

2.



Therefore a prime consideration would be to plan in low risk areas and to ensure stability of the structures to withstand a strong earthquake. Sichuan consists of two distinct terrain conditions: Eastern Sichuan formed predominantly by hilly terrain and Western Sichuan based on a plateau.

It experiences a cold and humid climate during most of the year with average temperatures of about 16–18 ºC, therefore, choosing materials with good insulation properties is also an important consideration.

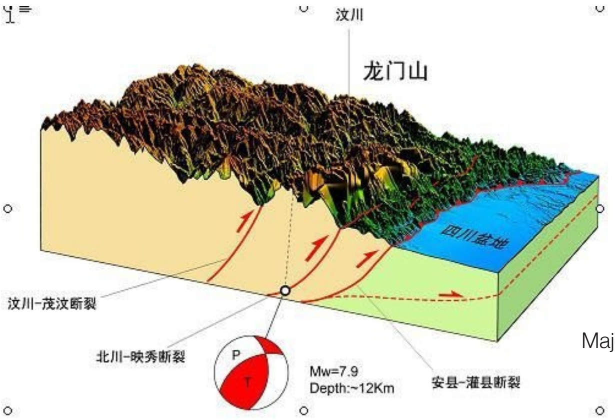
2. SEISMIC RESISTANT DESIGN

An analysis of the destruction to schools, seismic resistant design principles, location conditions in Sichuan, drawbacks in typical school designs and cost effectiveness of the solutions were the key considerations when deriving design strategies for school reconstruction in Sichuan.

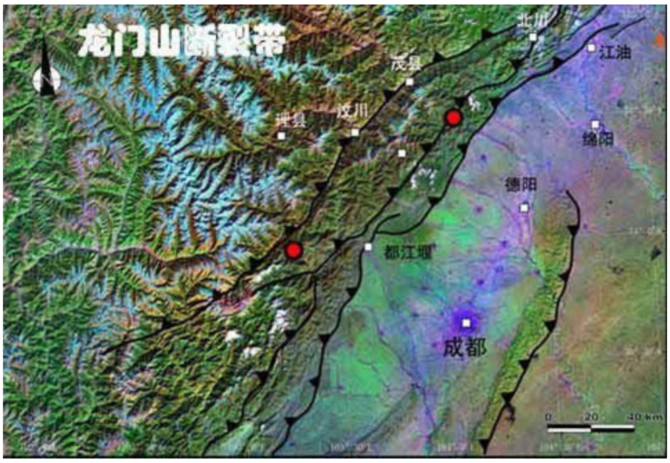
2.1 Design strategies

Seismic resistant design strategies are a key aspect reviewed and considered in this study. Based on existing knowledge, it is apparent that a holistic approach should be adopted to maximise earthquake resistance. In terms of configuration, regular plan forms and elevations are recommended compared to irregular plan forms and elevations. Soft stories in lower levels, long spans, large windows and high volumes should be avoided. Shear walls need to be distributed evenly and structure should be well connected together [8].

Figure 3. Distribution of the fault of 512 Sichuan Earthquake



Major faults in Longmenshan Fault Zone



2.2 Analysis of collapsed schools

The main cause of the collapse of school buildings was found to include poor construction quality, bad site locations, inadequate seismic fortification intensity demarcation and improper structural configuration or detailing. The China government has revised the seismic fortification intensity demarcation for these areas after the 512 Sichuan Earthquake and more strict measures had been taken to enhance the supervision of construction quality. Herein, main attention is focused on the improper structural configuration and detailing.

Strong and high frequency vibrations caused by an earthquake can damage buildings in two ways, brittle or ductile failure. A brittle failure is usually caused by compression or shear failure of the structural members. Such failure means the energy dissipation ability of the structure is poor and it can fail in a few seconds without any early warning. In a ductile failure the structural members absorb more earthquake energy and the failure is usually flexural or tension failure with excessive visible deformations. After an earthquake, the damaged building might remain standing for a short while or may not fully collapse even if some structural members fail. Ductile failure often allows time for an evacuation saving human life, therefore an effective seismic design for buildings must possess good ability to absorb earthquake energy to allow ductile failure.

Figure 4. Massive landslide caused by 512 Sichuan Earthquake [7]

Figure 5 shows the situation of the brittle failure of RC columns. It can be seen that the shear links failed first, followed by buckling of the vertical reinforcement, then the concrete cover delaminated and then the confined concrete lost restraint, resulting in a brittle failure of the column. To avoid such failure, link spacing at the end of a column must be reduced and links must have enough anchorage length with minimum 135° hook.

Figure 6 shows a reinforced concrete frame structure with a brittle failure caused by poor construction quality, improper structural design and detailing. An unconfined masonry wall has collapsed in the left photo. In the right photo, a precast RC slab has collapsed due to poor connections between precast slab and RC beams.

2.3 Design brief

Considering the number of schools damaged, it is apparent that high schools are now in great demand. The design concept is to design a school that will survive a future large magnitude earthquake and remain adaptable to other uses; help elevate community confidence and facilitate a new pedagogy of learning. The design concept also considered addressing issues related to structural configuration, sustainability and cost.

Figure 5 a & b.Brittle failure of RC columns in 512 Sichuan Earthquake [9]

Figure 6 a & b. Collapse of apartment in 512 Sichuan Earthquake [10]

5a.

5b.

6a.

6b.

2.4 Design and technology options

Although base-isolation is an effective option for seismic structures whereby substantial earthquake energy is absorbed by a laminated base-isolation system they are ineffective for small vibrations. The up-front and maintenance costs are relatively high and more space is required to install or replace the base-isolation system. Flexible connections are required for the building services at the foundation level and recovery after an earthquake is difficult. For these reasons, this option is not further considered in this paper.

Alternatively, structures equipped with damping systems (e.g. damping brace or damping wall) can overcome the disadvantages of a base-isolation system, usually with a damping brace or damping wall installed in a portion of partition wall. Extra space is not required, daily maintenance is minimal and damping is also effective for small earthquake and dynamic wind pressures.

The main focus is on comparison of the earthquake resistant ability between structures equipped with damping systems and conventional structure. The possible configurations for the above two systems are listed in Table 1. These options were derived based on experience from analysis of collapsed schools, knowledge of configuration, forms and structures, seismic resistant construction technologies, material properties and cost of technology. Twelve options were subject to an engineering and cost analysis based on a typical classroom block design.

Reinforced concrete and steel are the most common materials in building structure. Reinforced concrete has good durability and stiffness with relative low cost. Good seismic ability can be achieved through adequate design and detailing. Steel is a ductile material with good strength and is ideal for seismic buildings. Disadvantages of steel includes cost, higher skill levels, fire and corrosion protection.

Non-structural partition walls using local materials such as bamboo, timber and clay bricks are low cost, but were eliminated due to durability and environmental aspects as regulated in the China code. Three options including precast panels; masonry walls; and straw bales are considered here. Precast panels could be standardised for batch production in a factory with low cost and good quality; based on the lessons learnt from 512 Sichuan Earthquake, a well-confined masonry wall has much better seismic ability than unconfined or inadequately-confined masonry walls. Seismic resistance can be achieved through robust structural detailing with reinforcement properly connected to main structural members. Masonry can also be manufactured from industrial waste with low cost. Another option for partition walls is the Straw Bale, which is more environmentally friendly, lightweight, low-cost and has good thermal and acoustic properties.

Table 1. Practical systems for seismic schools

	RC structure [D]	**Steel structure [E]**	**Infill wall type**
Structure equipped with damping system [B]	BD1	BE1	Precast panels [1]
	BD2	BE2	Confined masonry [2]
	BD3	BE3	Straw bale [3]
Conventional structure (Frame + brace/shear wall) [C]	CD1	CE1	Precast panels [1]
	CD2	CE2	Confined masonry [2]
	CD3	CE3	Straw bale [3]

2.5 Case study for a five-storey classroom building

Structural configurations symmetric in plan are usually more effective to resist and transfer earthquake forces than complex ones. Herein, a typical five-storey classroom building for high school shown in Figure 7 is used for comparison. Structural forms include conventional RC column-beam frame systems (Type B) and identical RC column-beam frame systems equipped with damping system (Type C). The column spacing is 9.0 m in long way, 7.5 m and 3.0 m in short way respectively; 1.5 m span cantilevers are used to support the corridor; storey height is 3.5 m; Concrete grade for structural members is C35.

For the Type C building, the damping panels are installed at the both ends of the short way from 1/F to 5/F (refer to the red circle portion of Figure 7), with a total of 20 damping panels to be used.

As shown in Figure 9, each damping panel consists of two units, which are fixed to steel plates, the steel plates are fixed to an RC plinth at the bottom and top of the main beams. The dimension of each damping panel is 900 x 1500 x 250 mm.

By assuming the seismic fortification intensity is VII, the PGA (peak ground acceleration) for moderate earthquake is 0.1 g based on the “Code for seismic design of buildings: China”. In the time history analysis for earthquake response, recorded earthquake ground motion of El Centro is used and adjusted its PGA to 0.1 g as input wave for both Type B and Type C building models, total duration is 80 seconds. Based on the analytical response results for both Type B and Type C building models, it could be found that the response characteristics are quite different in the following aspects:

1. As shown in Figure 10, it can be seen that the total base shear for Type C building in the short span is 18% less than a Type B building. It means design seismic loading can be reduced for a Type C building and it will result in the deduction of structural members.
2. The maximum roof acceleration for a Type C building in the short span is 22.6% less than a Type B building as shown in the middle of Figure 10.
3. The maximum roof displacement for a Type C building in short span is 31% less than a Type B building as shown in the bottom of Figure 10.
4. As shown in Figure 11, it can be seen that 32% of the total input energy of earthquake has been absorbed by the damping panels, it means the energy transferred to the structural members of Type C is only 68% of Type B.

Dimensions for main structural members are as follows:

Column	800 x 800 mm
Main beam	500 x 800 mm
Secondary beam	400 x 600 mm
Slab	150 mm

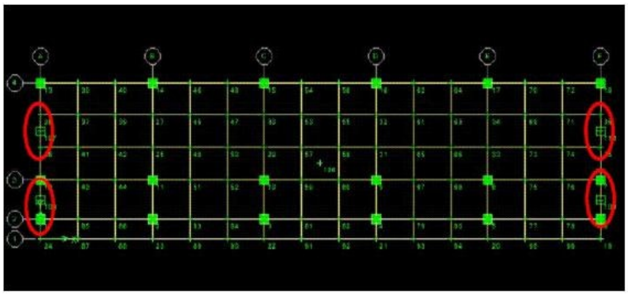


Figure 7. Framing plan or a typical classroom building

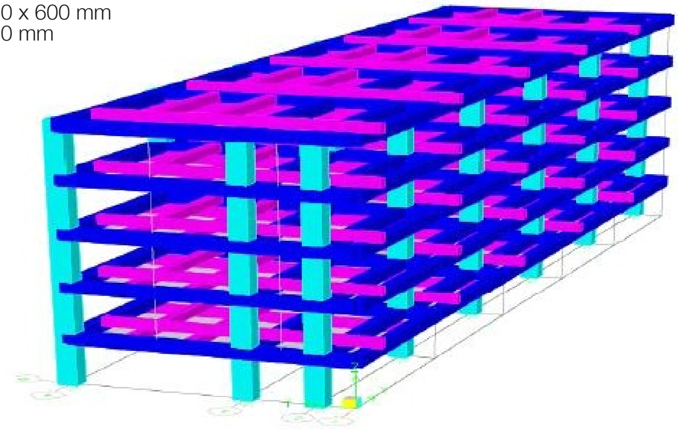


Figure 8. 3D image of the building model

3. FINDINGS

3.1 Engineering and cost analysis

The average cost for construction of a secondary school in Sichuan is about CNY1600/m^2 excluding the cost of land and foundations. As the total floor area of the target school is about 2700m^2, the total cost for a super structure is about CNY 4.32 million.

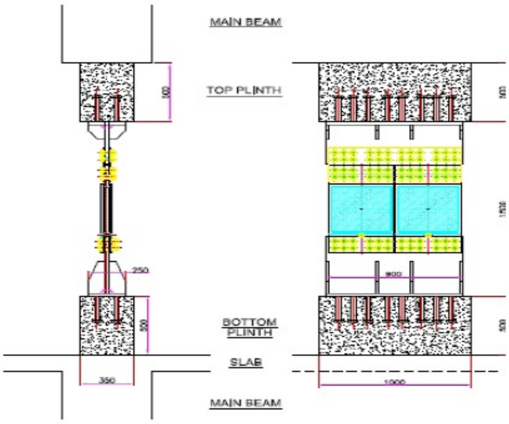
For a Type C building, the cost of the damping panel is about CNY21,000/unit, so the total of 20 units is CNY420,000 which is about 10% of the total cost for a super structure. As stated before, the base shear for Type C building is 18% less than Type B, meaning the dimensions of main structural members of Type C could be reduced while keeping the same seismic capacity as a Type B building.

Figure 9a. Section and elevation of damping panel

Figure 9b. Actually installed damping panel in building

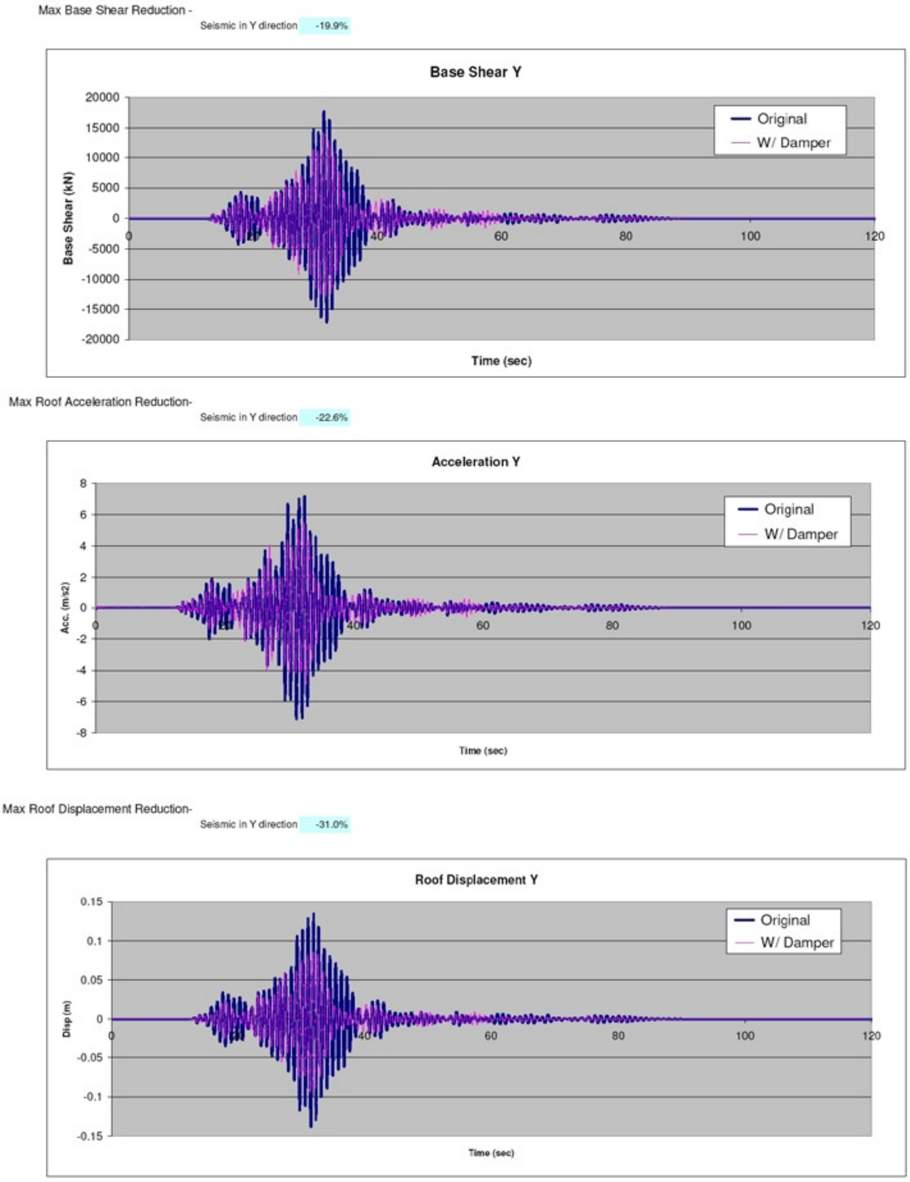
Figure 10. Responses of both Type B and Type C buildings

9a.



9b.

10.



Based on the results of further study for Type C and Type B buildings with the same seismic capacity, it is found that Type C columns could be reduced from 800 x 800 to 650 x 700, the main beams could be reduced from 500 x 800 to 450 x 750, meaning the concrete volume could be reduced by about 10%. If the cost of a super structure can be reduced by 5%, the cost increment for a school building equipped with damper walls can be about 5% higher when compared with a conventional one.

In case of a commercial building, land and foundation costs will often be much larger, therefore the total cost impact will decrease when damper walls are adopted. As the damping technology is relatively simple and suitable for broader application in buildings, it is predicted that damping systems costs will decrease, making them a practical and reliable option for schools.

4. CONCLUSIONS

From the outset, a combination of problematic design and poor construction quality, coupled with geological risk, meant that the only missing factor for the failure of these schools was a natural disaster.

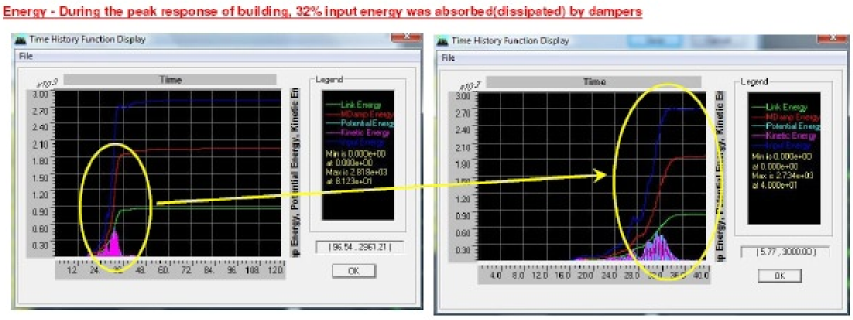
From the painful lessons learnt from the 512 Sichuan Earthquake, an effective and inexpensive seismic resistant design method for school building is urgently required. In this paper, by considering factors such as the environment, availability, cost, reliability etc. adequate structural forms are proposed for high school buildings. Case studies for structure with and without damping system have been carried out to verify the effectiveness of the structural system together with the damping system and it was found that cost effective seismic resistant design is possible and practical. New technology in design and construction aspects should be introduced to cater for the increasing social requirements in seismic structures.

5. RECOMMENDATIONS

Through the results obtained from investigation of the earthquake damage and analytical studies based on computer models, it is recommended that the following key points must be followed in the seismic resistant design of building structures:

1. Standardised structural configuration and detailing must be established and applied to seismic school structure
2. The adoption of construction material should take into account of factors such as environmental protection, sustainability, convenience and cost except for the fundamental structural requirements.
3. Designers need to keep learning and updating new professional knowledge and technologies in material, design and construction aspects so as to realise cost-effective and reliable design.
4. Comparisons should be carried out for different options of the structural system in the preliminary design stage so as to sort out the optimal option for each special case.

Figure 11. Energy input to Type B and Type C buildings respectively



Energy - During the peak response of building, 32% input energy was absorbed(dissipated) by dampers

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