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# FEASIBILITY STUDY OF A SEISMIC DAMAGE-RESISTANT SYSTEM FOR MODULAR STEEL STRUCTURES

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## ABSTRACT

As part of a research project, a seismic damage-resistant system consisting of a passive energy-dissipating slider device has been developed and has the potential to enable multi-level stacked modular steel buildings to remain stable and functional during a major earthquake. According to time-history analyses of a representative six-storey modular steel structure incorporating the damage-resistant system, the desired performance characteristics have been achieved. When subjected to the 1940 El Centro north-south earthquake record applied in both the longitudinal and transverse directions, modules slid within a 2.5% drift at each level and subsequently returned to the original positions within a tolerance range of 2-3mm. While sliding, all modules remained stable and were not prone to any collapse, soft storey failure at lower levels, and undesired mode of vibration (e.g., torsional mode). A prototype slider device has been manufactured so far and will be subjected to several series of experimental tests during the years 2010 and 2011.

## Introduction

Multi-storey modular construction is a new form of construction in New Zealand and involves the use of factory-made volumetric units (i.e., modules) as fitted-out and serviced building blocks. Modular construction may be used for a variety of buildings such as hotels and apartments, student accommodation, and school and university buildings (Lawson et al., 1999).

There are numerous benefits associated with the use of modular construction:

- The factory environment in which modules are made is considered to be safer and healthier and less disruptive to local community than a construction site;
- Modular buildings are more adaptable, demountable and reusable, leading to less new material consumption; and
- The fast speed of construction ensures early occupation and minimises the accumulated, time-dependent financial costs such as interest charged by a commercial bank (Lawson, 2007; Lawson et al., 1999).

These benefits are being increasingly realised, leading to a rising trend in the use of modular construction globally.

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However, modular construction is currently severely limited due to seismic requirements in high seismic regions such as New Zealand. A research project is in progress, funded by the New Zealand Government and the metals engineering industry to develop a seismic damage-resistant system which will enable multi-level stacked modular buildings with cold-formed steel framing to perform during a major earthquake according to the following desired performance characteristics:

- At any level, the allowable relative displacement between modules is limited by the 2.5% drift requirement;
- All modules at all levels slide in alternate directions and subsequently return to their original positions within a tolerance range of 2-3mm;
- More than 80% of the input seismic energy is dissipated through kinetic friction generated in the damage-resistant system; and
- While sliding, the structure remains stable and is not prone to any collapse, soft-storey failure at lower levels, and undesired mode of vibration (e.g., torsional mode).

The system developed will be primarily used to protect multi-storey stacked modular steel buildings in seismically active regions. In general, the system has potential for wider application to where multi-level stacking of rigid structural units is required and where these structural units are required to remain stable under the attack of a major earthquake.

To date, the research team has proposed a damage-resistant system which consists of a novel energy-dissipating friction slider device made of steel and rubber. The device has two contacting parts, which slide against each other to dissipate seismic energy through kinetic friction during a major quake and self-centre at the conclusion of the severe shaking.

This paper presents a feasibility study of the proposed system in a typical six-storey modular structure with cold-formed steel framing. The study has shown that the current system has the ability to achieve the desired performance characteristics.

## Development of Prototype Device

A novel working concept has been proposed to create a flexible layer in the horizontal plane at each floor level of a modular steel structure with the use of a series of sliders incorporated between upper and lower modules, which are allowed to move relative to each other in alternate directions. The sliders are expected to have dynamic self-centring capability to ensure that all sliding modules return to their pre-earthquake positions after the severe shaking. Most of the seismic energy is dissipated through kinetic friction generated between the sliding modules to minimise the damage suffered by the building.

To achieve the novel working concept and desired performance characteristics, an energy-dissipating slider device has been developed as shown in Fig. 1. The device consists of a bonded rubber unit (BRU) under the cap plate in both the upper and lower wall plates. As shown in Fig. 2, the BRU has a 90 by 90 by 30mm thick rubber block made of vulcanised natural rubber with carbon black filler and fully bonded to the outer confining steel box and inner sleeve of a 20mm diameter steel rod. The hardness of the rubber used is 60 on the Shore A scale.
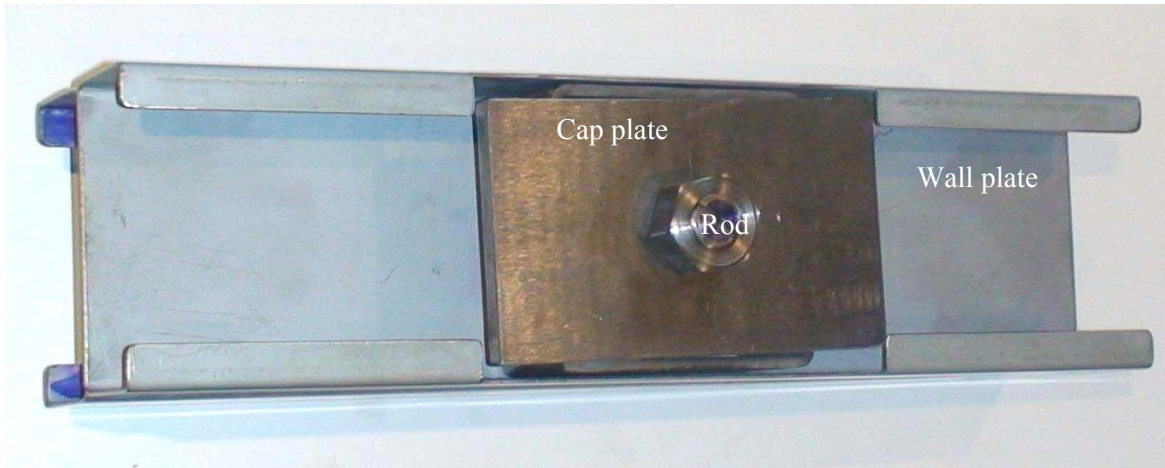
Figure 1.    Slider prototype device.



Figure 2.    Bonded rubber unit (BRU) with inner steel rod.

The BRU provides an elastic restoring force to facilitate dynamic self-centring. In a severe earthquake, the inner steel rod and sleeve in each device move horizontally with the modules at each floor level to deform the rubber, which consequently provides an elastic spring force that increases with the lateral displacement. After the earthquake, all modules are brought back to their pre-earthquake positions by the rubber spring force.

The slider units are distributed evenly along the sides of modules in alternate horizontal directions. Fig. 3 shows two adjacent slider units incorporated in typical modular steel framing.
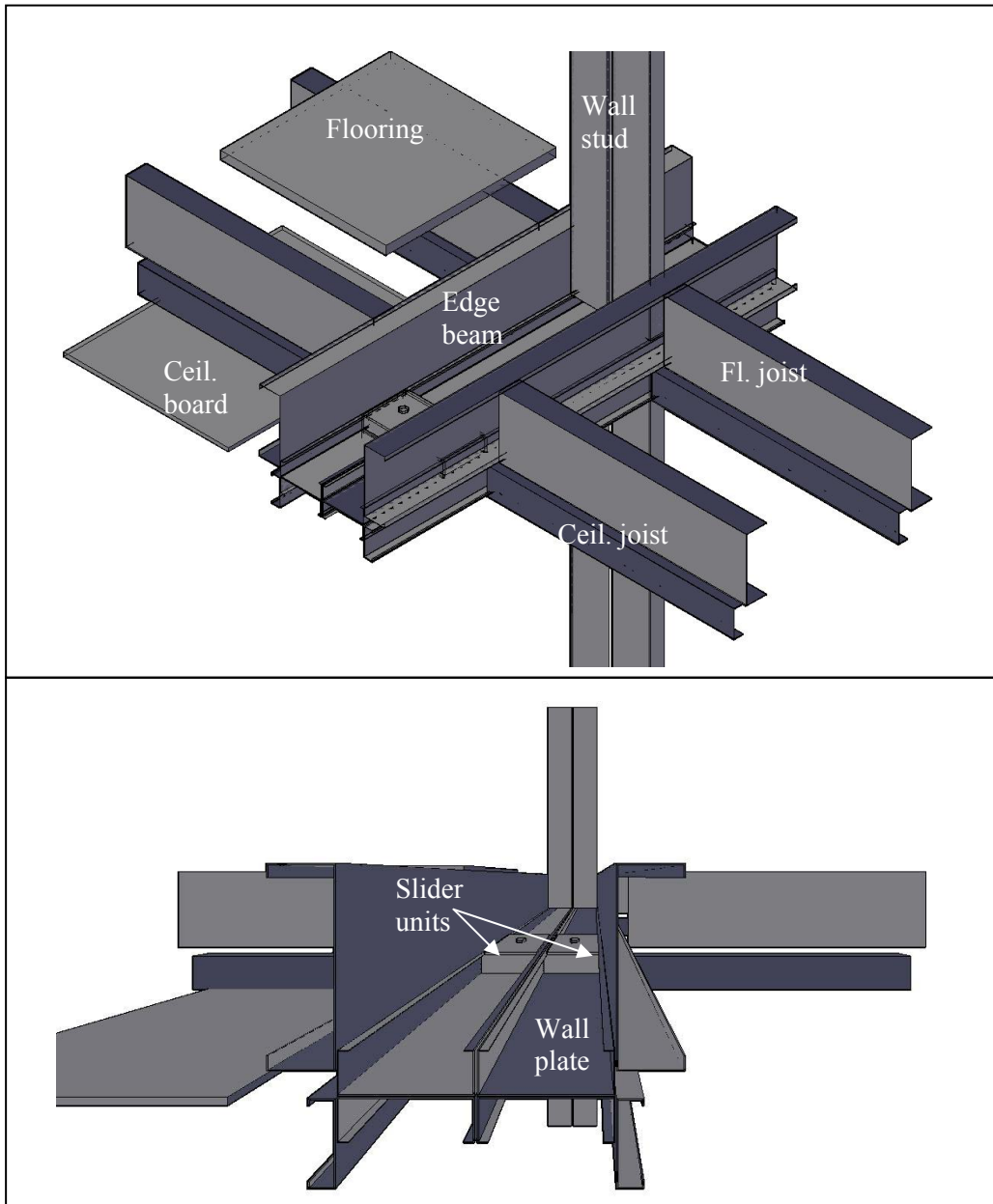
Figure 3.    Isometric (top) and perspective (bottom) views of typical modular steel framing with two adjacent slider units incorporated.

### Feasibility Study of Proposed Damage-Resistant System

A feasibility study of the concept of the proposed seismic damage-resistant system consisting of the slider device has been carried out. The study involved analytical modelling of the device and numerical time-history analyses of a typical six-storey modular steel structure with the system incorporated.

### Behaviour of Friction-Spring System Model

A friction-spring system model could be used to represent the slider device. Fig. 4 shows the proposed friction-spring system model.
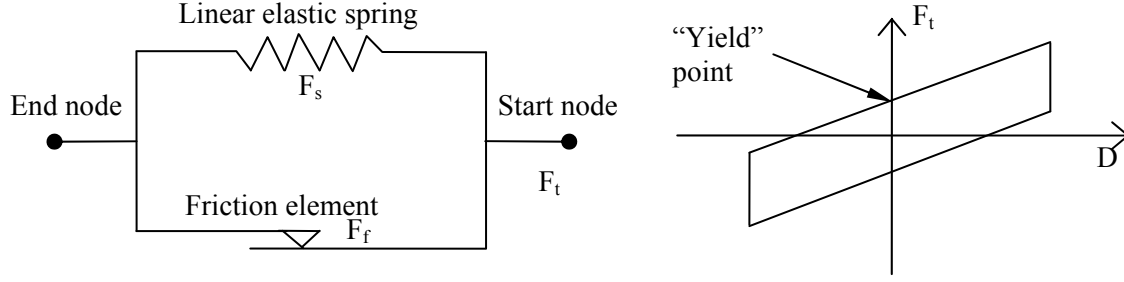
Figure 4.    Proposed friction-spring system (left) and corresponding hysteresis loop (right)

Unlike other yielding devices, the proposed slider device is not expected to physically fail to absorb energy. However, it must operate beyond the "yield" point in the friction-spring system model to dissipate energy through dynamic friction.

The system force, $F_t$, is given by:

$$F_t = F_s + F_f \tag{1}$$

In Eq. 1, $F_s$ and $F_f$ are the spring and frictional forces respectively.

The friction model was developed by Wen (1976) and Park, Wen and Ang (1986) and recommended for base-isolation analysis by Nagarajaiah, Reinhorn and Constantinou (1991). The friction force, $F_f$, is related to the normal force, $P$, as follows:

$$F_f = P\mu z \tag{2}$$

where $\mu$ and $z$ are the coefficient of friction and internal hysteretic variable respectively. The coefficient of friction, $\mu$, is defined as:

$$\mu = \mu_{fast} - (\mu_{fast} - \mu_{slow})e^{-rv} \tag{3}$$

where $\mu_{slow}$ and $\mu_{fast}$ are the coefficients of friction at zero and fast velocities respectively. The rate parameter, $r$, is the inverse of the characteristic sliding velocity. The sliding velocity is denoted as $v$.

The internal hysteretic variable, $z$, has a range of $z \leq 1$, and for the yield surface, $z$ is unity. The values of $z$ are zero initially and then vary according to Eq. 4:

$$\dot{z} = \frac{s}{P\mu}\dot{d}(1 - z^2) \text{ if } \dot{d}z > 0, \tag{4}$$

or otherwise Eq. 5:

$$\dot{z} = \frac{s}{P\mu}\dot{d} \tag{5}$$

where $\dot{d}$ is the relative velocity between the start and end nodes shown in Fig. 4 and s is the elastic shear stiffness of the friction element of the system.

The elastic spring in the system has a linear force-deformation relationship:

$$F_s = kD \qquad (6)$$

where k and D are the spring stiffness and displacement respectively. The stiffness, k, is of the bonded rubber unit (BRU) shown in Fig. 2.

To obtain the stiffness, k, in Eq. 6, the BRU has been analysed as an annular rubber bushing, which is widely used in the engineering industry. In the past several decades, researchers have undertaken numerous experimental and analytical studies of the behaviour of loaded bushes experiencing the radial mode of deflection. Fig. 5 shows an annular rubber bush subjected to radial loading.
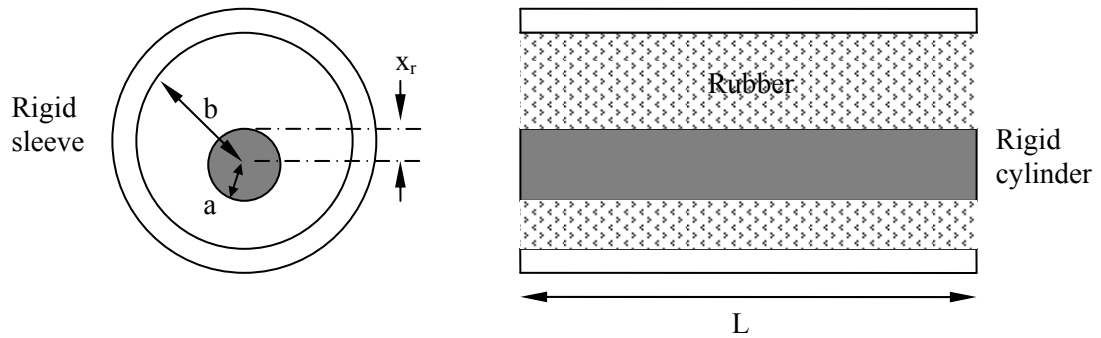


Figure 5.    Radial deformation of annular rubber bush.

For the radial stiffness of annular rubber bushes of finite lengths based on the principle of superposition of two separate loading cases, Horton, Gover and Tupholme (2000) have recently derived the exact expression:

$$F_r = \frac{10\pi\mu x_r L}{\dfrac{7}{2}\ln(\dfrac{b}{a}) - \dfrac{3}{2}(\dfrac{b^2 - a^2}{b^2 + a^2}) - \dfrac{(b+a)^3}{\sqrt{60}ab(b^2 + a^2)}L} . \qquad (7)$$

Based on Eq. 7, Horton and Tupholme (2006) provided a simpler formula:

$$F_r = \frac{4\pi\mu x_r L}{(1 + \dfrac{4}{1 + E_a/\mu})\ln(\dfrac{b}{a}) - \dfrac{b^2 - a^2}{b^2 + a^2}} . \qquad (8)$$

Close numerical agreement with experimental data was demonstrated by Horton and Tupholme (2006). Eq. 8 has been used to determine the stiffness (k) of the bonded rubber unit of the proposed slider device for time-history analyses in SAP2000.

In Eq. 8, the apparent Young's modulus ($E_a$) is required as a key input parameter. Based on the classical theory of elasticity, Tupholme and Gover (2002) derived a hyperbolic formula for $E_a$ of an infinitely long rubber strip, as follows:

$$E_a = \frac{4E}{3\left(1 - \dfrac{S}{\sqrt{3}}\tanh\dfrac{\sqrt{3}}{S}\right)} \; . \tag{9}$$

Eq. 9 depends upon the so-called shape factor denoted as S, which is the ratio of the loaded bonded area to the lateral force-free area.

Horton and Tupholme (2006) suggested that Eq. 9 could be used to determine $E_a$ of an annular rubber bush of finite lengths. The normal strain component at right angle to the direction of the applied load is zero for an infinitely long strip. The bush also has the zero strain component condition due to the confining outer sleeve.

As the BRU was assumed to be a bush, $E_a$ was computed to be 7.2MPa using Eq 9 for the BRU. By substituting $E_a$ into Eq. 8, the stiffness of the BRU was calculated to be 0.54kN/mm, which was then inputted into SAP2000 for subsequent time-history analyses.

**SAP2000 Modelling**

For the feasibility study, time history analyses of a typical six-storey modular steel structure have been undertaken using SAP2000. The structure was modelled in SAP2000 as per the typical modular construction details used in the UK according to Lawson (2007) and Lawson et al. (1999).

As shown in Fig. 6, the structure consisted of four identical six-level 1×1 modular blocks joined by rigid links at their corner locations. Fig. 7 shows the definition sketch of one such block.

SAP2000 has a range of predefined types of link elements. The friction-pendulum link and linear elastic link elements were used in parallel to define the friction-spring system model shown in Fig. 4 for all self-centring sliders indicated as 'X' and 'Y' in Fig. 7.
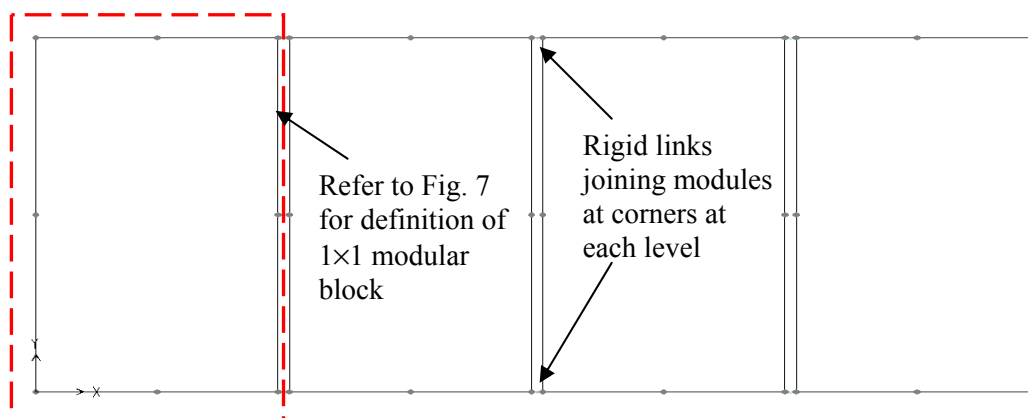


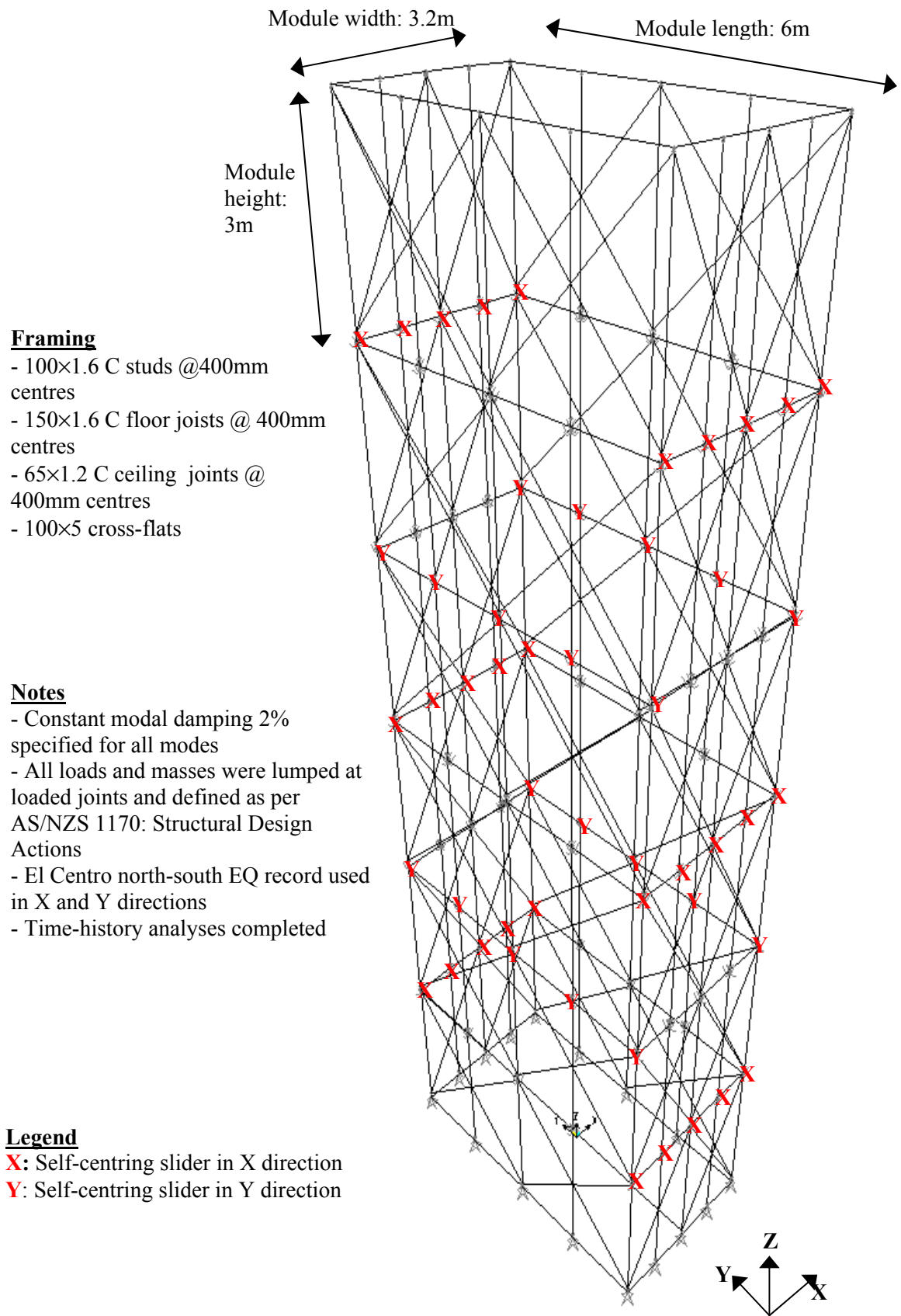Figure 6    Plan view of six-storey 4×1 modular steel structure

Module width: 3.2m

Module length: 6m

Module height: 3m

**Framing**
- 100×1.6 C studs @400mm centres
- 150×1.6 C floor joists @ 400mm centres
- 65×1.2 C ceiling joints @ 400mm centres
- 100×5 cross-flats

**Notes**
- Constant modal damping 2% specified for all modes
- All loads and masses were lumped at loaded joints and defined as per AS/NZS 1170: Structural Design Actions
- El Centro north-south EQ record used in X and Y directions
- Time-history analyses completed

**Legend**
X: Self-centring slider in X direction
Y: Self-centring slider in Y direction

Figure 7    Definition of six-storey 1×1 modular block in SAP2000

## Analysis Results

The displacement time-history results are shown in Fig. 8. Modules slid in the alternate X and Y directions. The total time period was 30 seconds. The earthquake loading started at zero second and finished at 20 seconds. During the last 10 seconds, the structure vibrated freely for dynamic self-centring. Fig. 9 shows the energy function plots.
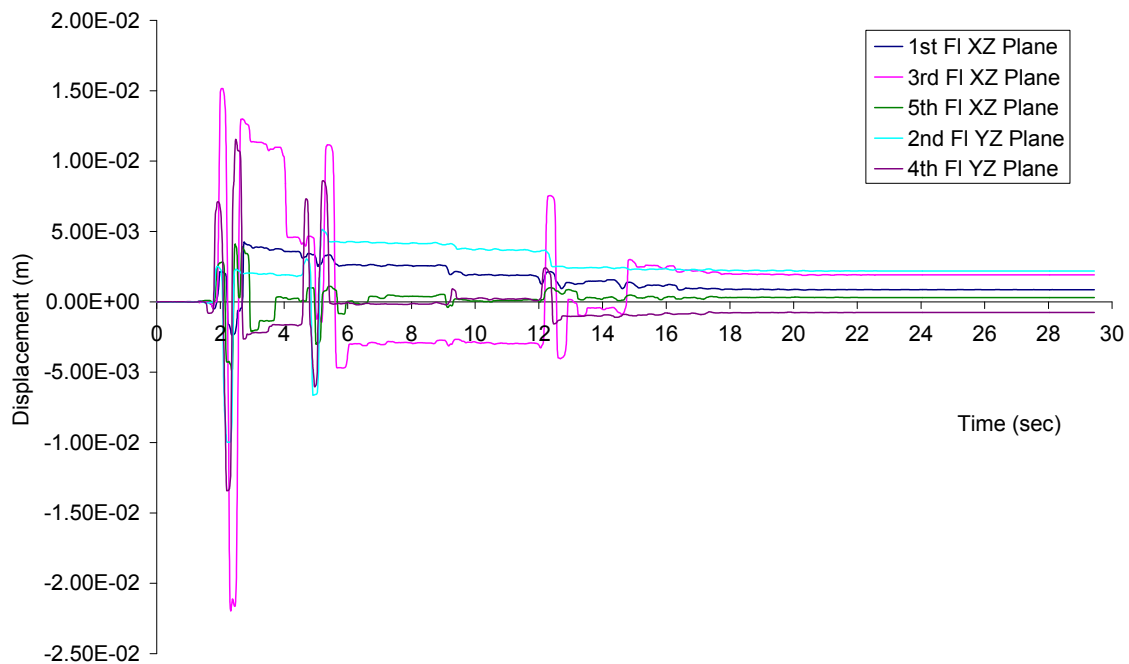


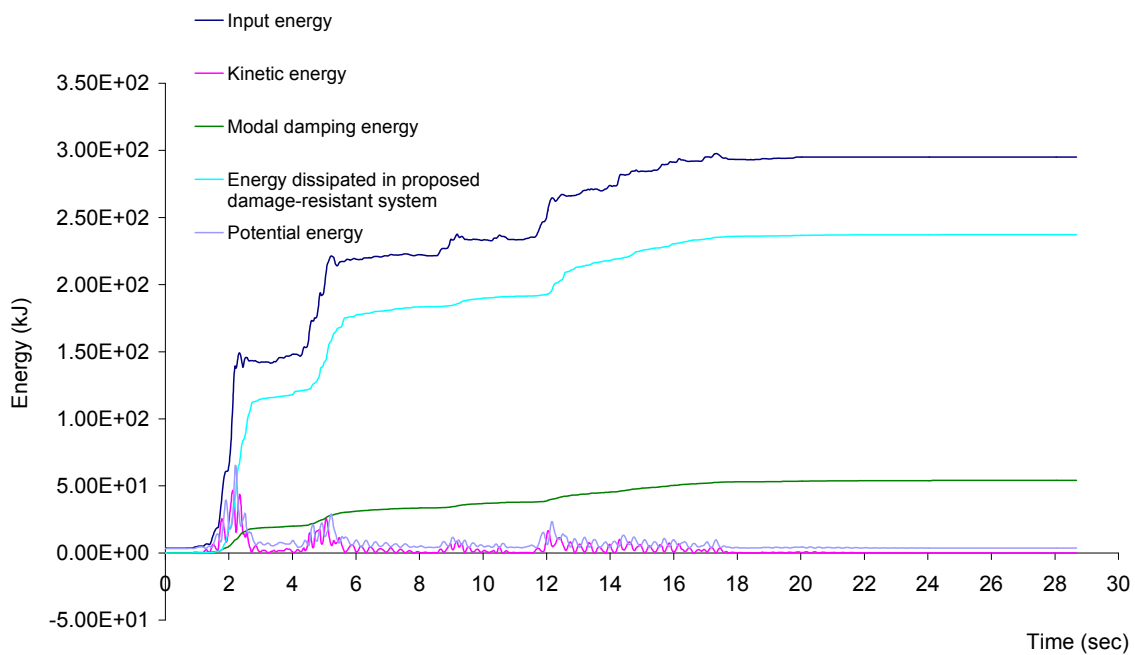Figure 8    Displacement time-history results



Figure 9    Energy function plots

The total input energy is the sum of the kinetic, potential and modal damping energy and the dissipated energy in the proposed damage-resistant system. The aim was to maximise the dissipated energy through kinetic friction, so that the damage potential would be minimised.

## Conclusion

From the analysis results, the desired performance characteristics have been achieved. The maximum inter-storey drift was 0.73% corresponding to a maximum displacement of 22mm as shown in Fig. 8. All modules returned to their pre-earthquake positions at the end of the 30-second period within a tolerance of 2-3mm, which is the typical average range of the installation tolerance for modular construction.

As shown in Fig. 9, the energy dissipated in the damage-resistant system was obviously more than 80% of the total input energy, so that the kinetic energy and potential energy were reduced to minimal levels. In conclusion, the proposed system is feasible for the intended purposes according to the analysis results. However, it is currently subject to ongoing experimental studies.

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