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# A Rotational Friction Damping System for Buildings and Structures

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## 1. Introduction

Passive energy dissipation devices have been successfully used to effectively protect buildings and structures against earthquakes and storms. The primary reason for introducing energy dissipation devices into a building frame is to reduce the dynamic response and damage of the frame.

This paper presents the development, testing and application of a novel, worldwide patented friction damper system developed by 1st author in order to control the vibration in structures and buildings due to earthquakes and/or strong winds. The capability of the dampers to dissipate energy has been extensively studied and tested in previous research programs both experimentally and numerically, as well as in several finalized projects around the world.

Friction damper devices have been used as in many buildings and structures around the World because they provide high-energy dissipation potential at a relatively low cost while being easy to maintain.

Different damping systems are presented in this work. The dampers described in this paper are patented property of Damptech. The dampers are mainly used for vibration control of structures and base isolation of structures and are based on a unique rotational friction concept.

The Damptech damper devices are easy to manufacture and implement in structures. The dampers are economical to manufacture due to the selection of material and its availability. In the unlikely situation of damage to a damper, it can easily be replaced or readjusted.

So far Damptech dampers have been installed in many projects around the World, including the tallest building in Japan.

## 2. Description of Rotational Friction Damper Devices

The original configuration of the rotational friction damper (RFD) consists of steel plates pre-stressed together by a steel bolt (Figure 1) to form a T-shape and hence the name T-Damper, Mualla et al. [2000,1]. Between the steel plates there are circular friction pad discs made of high-tech composite material. In order to have constant pre-stressing force several disc springs are used. Between these springs and the two external steel plates hardened washers are placed so that a uniformly

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distributed pressure can be achieved. The energy absorbing potential of the device can be easily increased by adding more layers of steel plates and friction pads.

Figure 1 – Damptech T-damper model

A possible configuration of the device in a single storey frame structure can be seen in Figure 2. The center plates are connected to the girder by a pin. In order to activate the energy absorbing mechanism of the device the horizontal plates are connected to the columns by using steel bracing members. The prestressing of the members prevents them from buckling.
When the structure is vibrating the friction hinge is loaded in torsion. The friction at interface between the composite material and the steel plates resist the torsion with a sliding moment $M_s$, thus a portion of the induced energy is dissipated when there is a rotation in the frictional hinge. The resistance due to the device hinders the lateral movement of the storeys. Consequently, if no further energy is induced, the vibration of the frame structure becomes smaller and smaller with each relative rotation between the steel plates. With the pre-stressing force of the bolt and the arrangement of the damper devices in the structure the degree of the resistance of the relative rotation at the device can be controlled. The simple mechanism allows an easy handling and installation.

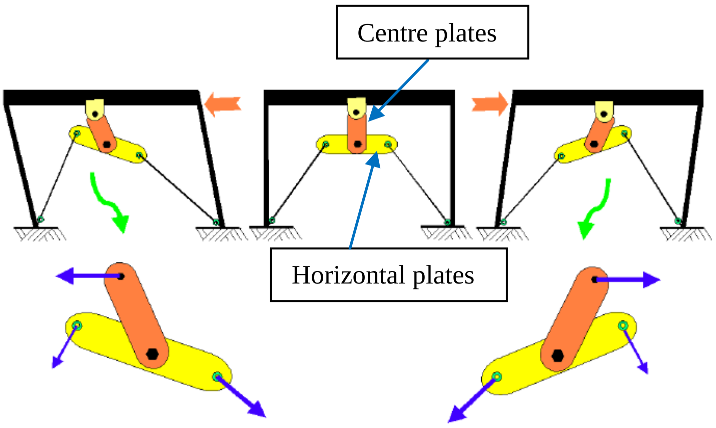

Figure 2. Activation of the energy absorbing mechanism of the device.

The energy dissipation of a device like the T-Damper depends on the sliding moment $M_s$ and the rotation of the hinge $\theta$. The hysteresis loop can be seen in Figure 3a.

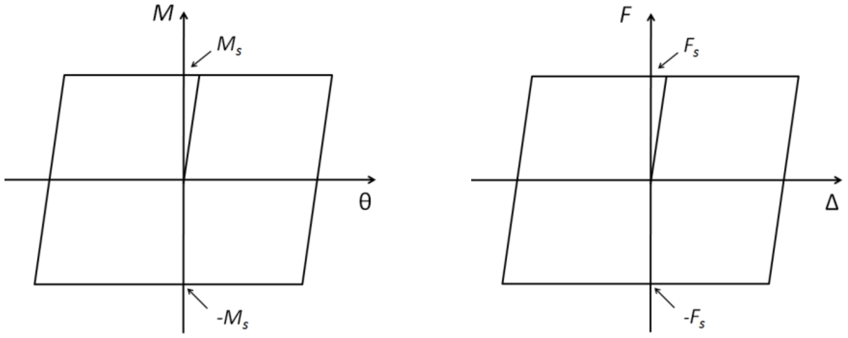

Figure 3 – a: Hysteresis loop of T-model. b: Hysteresis loop of Unidirectional damper

## *2.1 Features of RFDs*

The friction dampers are classified as displacement dependent devices and the features of the friction dampers are:

- For a given slip force ($F_S$) and displacement ($\Delta$) in a damper, the energy dissipation of a friction damper is greater than those of other damping devices (Figure 4).
- The dampers are not active during low velocity wind and service loads.
- The dampers do not contain any liquids so they cannot have any leakage and therefore they do not need to be inspected regularly and maintenance requirements are very low.
- The damper sliding moment $M_s$ is independent on velocity.
- The damper sliding moment $M_s$ is independent temperature.

## *2.2 Equivalent Viscous Damping*

It is possible to estimate the equivalent viscous damping ratio of a single degree of freedom system with friction dampers that is subjected to sinusoidal loading, Mualla et al. [2001].

However the equivalent viscous damping ratio depends on the amplitude of the sinusoidal load.

If the amplitude of the load is very low then the dampers will not activate and there will be no increase of equivalent viscous damping by using the dampers.

If the amplitude of the load is moderate or high (compared to the damper capacity) then the dampers are activated and dissipating the kinetic energy into thermal energy. In this case the dampers will increase the equivalent viscous damping ratio of the system.

The two phases of damper deformation are the sticking and sliding phases. The frictional moment $M_f$ limits the moment in the frictional hinge. This type of friction damper is defined by a slip load, $F_s$, an elastic stiffness, $K_{bd}$, and a ductility ratio, $\mu_d=D_u/D_{yd}$, where $D_u$ and $D_{yd}$ are the ultimate and yield displacements of the RFD, respectively. Energy dissipation $ED$ per cycle in the frictional hinge can be written approximately as

$$ED = 4K_{bd}D_{yd}\left(D_u - D_{yd}\right) \tag{1}$$

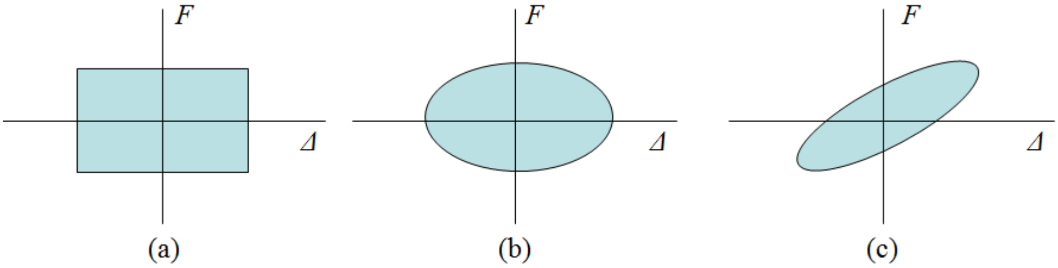

Figure 4 – Comparison of hysteresis loops of different dampers

(a) Friction damper; (b) Viscous damper; (c) Viscoelastic damper

Structure and RFD act in parallel and can be described as a dual system. For a system with a single degree of freedom and assuming that basic system remains elastic, the equivalent viscous damping ratio is obtained by

$$\zeta_{eq} = \frac{2FR\left(SR-FR\right)}{\pi\left(SR+FR^2\right)},\quad \frac{FR}{SR}<1 \tag{2}$$

Where, $FR$ is the ratio of the total structure force $F_{hf}$ exhibited by the structure, to the damper yield force $F_s$:

$$FR = \frac{F_{hf}}{F_s} \tag{3}$$

And $SR$ is the ratio of damper stiffness $K_{bd}$ to the total structure stiffness $K_s$:

$$SR = \frac{K_{bd}}{K_s} \tag{4}$$

The total structure force $F_{hf}$ exhibited by the structure depends on the amplitude of the sinusoidal load and therefore $FR$ and also the equivalent viscous damping ratio $\zeta_{eq}$ depend on the amplitude of the sinusoidal load.

This formulation is well suited for making a first order estimate of the required damper properties for the design. The relation for $\zeta$ can be used to generate a family of curves as a function of *FR* and *SR* as shown in Figure 5.

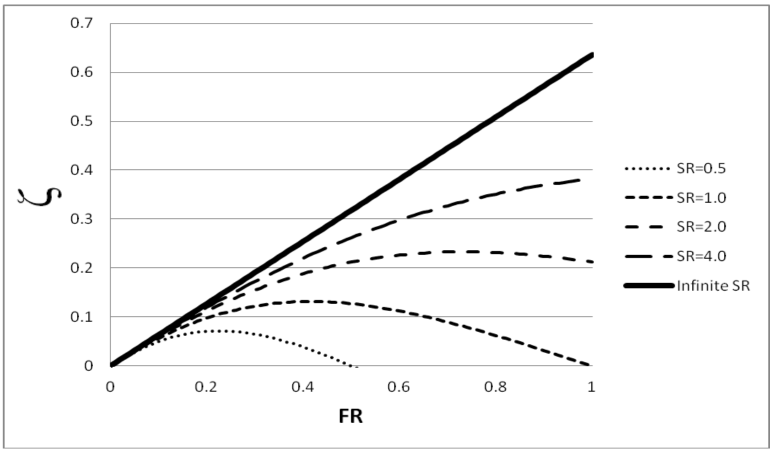

Figure 5 - Equivalent viscous damping for dual system

## 3. First Damptech Projects

The first application of the friction damper devices in a real building was in two old temple buildings in Japan. The dampers are of the T-Damper model type in Figure 2.

Both temples were soft storey buildings because of the 1st storey which had low stiffness compared to the rest of the building. By adding dampers and bracings at the 1st storey the stiffness of the 1st storey was increased while additional damping was added by the dampers.

The first temple to have Damptech dampers was the Yagurji Temple which can be seen in Figure 6 below.

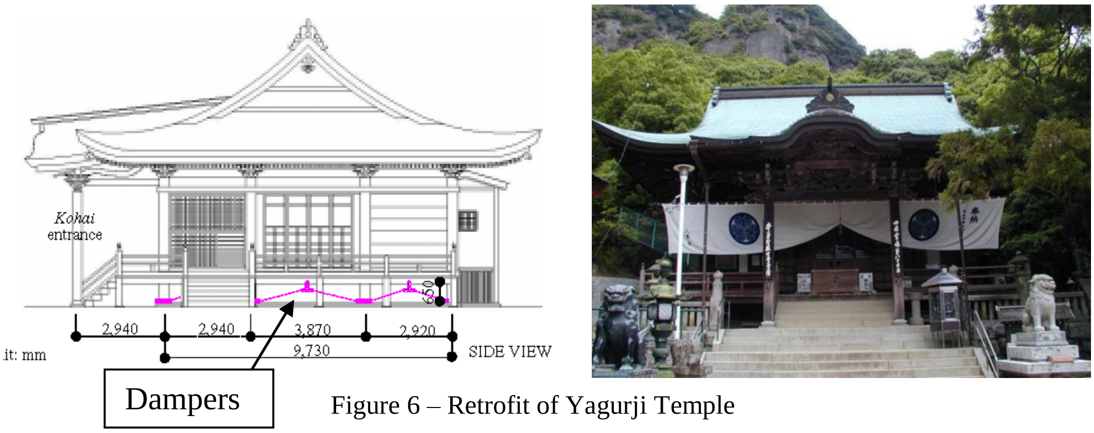

Figure 6 – Retrofit of Yagurji Temple

An example of the T-Dampers with bracings that are installed in the temple can be seen in Figure 7.

Figure 7 – Dampers with bracings installed in Yagutji Temple

Another project was a retrofit project in Greece where 2 new floors were added to an existing RC apartment building in Athens. The dampers used for this project are V-dampers and 2-joint dampers, see Figure 8.

Figure 8 – Greece retrofit

One of the damper models developed by Damptech is a Scissor Damper.
The main advantage of this model is that it is capable of very large displacements.

The first application for Scissor Dampers was for a industrial building in Greece, see Figure 9. Since the completion of the project, several earthquakes have hit the region. The most significant were in June 2008 (M 6.5) and in August 07, 2011

(M 4.7) and August 20, 2011 (M4.9). The dampers have performed very well and no excessive displacements or effects of high forces have been observed in the structure.

Figure 9 – Scissor Dampers in Industrial plant in Greece

Figure 10 – New office building in Greece

## 4. Shake-table tests of three-storey frame

During the first half of 2001, an international team conducted an intensive research on a full scale three-story building equipped with RFDs at the advanced large-scale shake-table testing facility of the National Center for Research on Earthquake Engineering (NCEER), Taiwan, Liao et al. [2004,1].
The test building has a steel moment-resisting frame structure with 3.0 m story height and 4.5 m bay in the direction of shaking, see Figure 11. The column and girder cross sections are H200x200x8x12 and 200x150x6x9, respectively. The columns are fixed at their bases and the beam-to-column joints are welded. Due to the fact that the columns resist bending about the minor axis of their cross section, the structure is relatively flexible in the direction of testing with estimated fundamental period of vibration T=0.936 s. Heavy concrete blocks are used to simulate the floor weights. The total mass of the whole building with the auxiliary base perimeter frame measured is 38.3 tons.

Figure 11– Shaking table tests at NCEER

Two RFD units were installed within each story unit of the building (6 in total). Their dimensions and mechanical characteristics were chosen based on a preliminary numerical analysis. The brace members were made from 20 mm diameter round steel bars pin-connected to the damper plates and frame joints. The prestressing was performed by tightening the bar turnbuckles. All installation works were carried out by a couple of technicians and took one day only. After the testing was complete, the RFDs and their supporting braces were removed within half a day thus implying that the dampers can be easily inspected or replaced in actual applications.

The displacements and accelerations of the two frames of the model were measured by displacement transducers and accelerometers attached to each floor and base level. Strain gages were mounted on important locations in the columns, bracing bars and beams. Two linear variable differential transformers were mounted on each damper to measure the rotation. The total number of measurement channels employed was 82.

The seismic response of the bare frame and the friction-damped structure was evaluated using the 5x5 m shaking table facility capable of simulating horizontal ground motions with peak acceleration up to 3g.

It was decided to use several earthquake records of far-field and near-fault types from the 1940 Imperial Valley - El Centro (USA), 1995 Kobe (Japan) and 1999 Chi-chi (Taiwan) events.
The bare frame structure was subjected to low intensity (PGA = 0.04g - 0.05g) quakes since the frame was not capable of sustaining stronger shaking in the direction of testing without undergoing severe damage. For this reason, the recorded histories of the response displacements were further scaled to obtain an extrapolated prediction for the performance under high intensity quakes.
The performance of the damped structure was examined for 14 cases of seismic input with PGA varying from 0.05g to 0.30g.

Several arrangements of the damper slip resistance along the height of the building were used but each arrangement was kept unchanged for a couple of tests of different intensity. For example, the Kobe record was first applied with PGA = 0.1g followed by consecutive shaking with PGA of 0.05g, 0.125g and 0.15g without readjusting the bolt clamping forces and values.
This was a simulation of a series of quakes including aftershocks and could be also viewed upon as a possible situation at a site in which damper parameters deviating from the design values may be introduced due to a installation errors. None of the friction pads or other RFD components was replaced during the series of 14 tests.

### *4.1 Experimental evaluation of the damping system*

The lower intensity tests of the damped frame did not result in activating the devices to a large extent but confirmed that the structure response was predominantly in the direction of shaking with no torsional effects observed, Mualla et al. [2002,1].
The higher intensity tests with PGA = 0.15g - 0.30g demonstrated the remarkable efficiency of the damping system in reducing the lateral displacements and interstory drifts of the test building. The enhanced performance under a strong earthquake, El Centro NS, with PGA = 0.30g is evident from Table 1, in which the peak story drifts for the frame structure with and without RFDs are presented for comparison.

Table 1. Storey drift comparison for the El Centro 0.30g test

| Story | Story drifts, mm | | Reduction, % |
|---|---|---|---|
| | W/O FDDs | With FDDs | |
| First | 80.4 | 17.4 | 78.4 |
| Second | 79.2 | 19.0 | 76.1 |
| Third | 50.1 | 14.3 | 71.1 |

The time-histories for roof displacement of the building using El Centro (0.20g) and Kobe (0.175g) earthquakes are shown in Figure 12 and Figure 13.

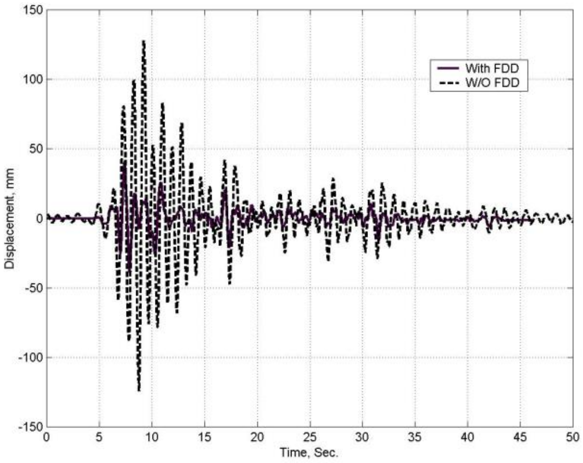

Figure 12 - Roof displacement time-histories using El Centro Earthquake with 0.20g PGA

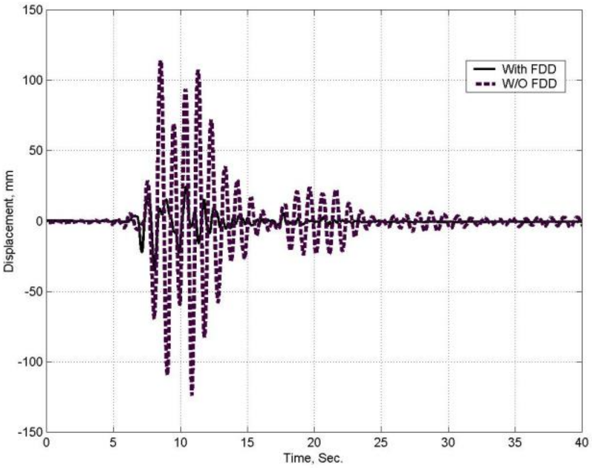

Figure 13 - Roof displacement time-histories using Kobe Earthquake with 0.175g PGA

## 5. RFDs for Base Isolation

Damptech dampers have been used in several base isolated buildings.

Base Isolation is a technique for protecting buildings and structures against earthquakes.

Basically the entire building stands on rubber bearings that are stiff in the vertical direction but soft in the horizontal plane (low shear stiffness).

In the event of an earthquake the ground starts to shake back and forth but because of the low shear stiffness of the rubber bearings the building remains almost stationary even though the relative displacement between building and the ground can be much larger than for a building without a base isolation system.
The dampers further lower the response of the building and ensure that the kinetic energy in the building is dissipated much quicker.

The first project where Damptech dampers where used in base isolation was for a 5 storey laboratory building in Japan.
For this project base isolation friction dampers with high displacement capacity was used and tested at the Technical University of Denmark in a 250 kN Instron dynamic testing machine, see Figure 14.
For base Isolation the displacement requirements of the dampers can be very large and the dampers are designed for a maximum displacement of +/- 600 mm.

Figure 14 – Damptech Base Isolation damper tests at DTU

The damper have a very stable performance and with no decrease in performance over 100 cycles, Nielsen et al. [2004,2] , see Figure 15.
This good performance is owing to the use of a special friction pad material between the damper plates in the frictional hinge.

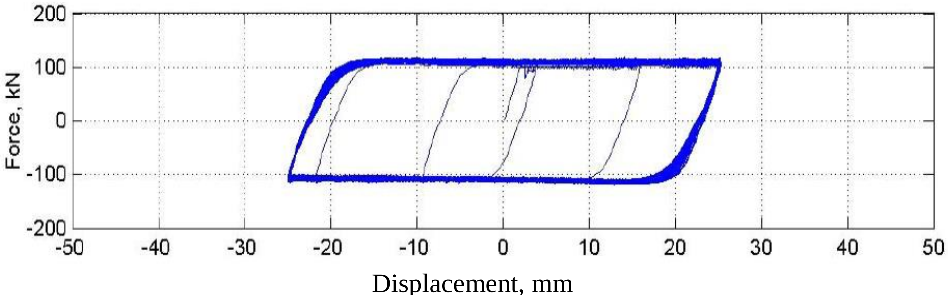

Figure 15 – 100 cycle test of base isolation damper

Figure 16 – a: 5 Storey Laboratory building. b: Damper installed at the base of the building

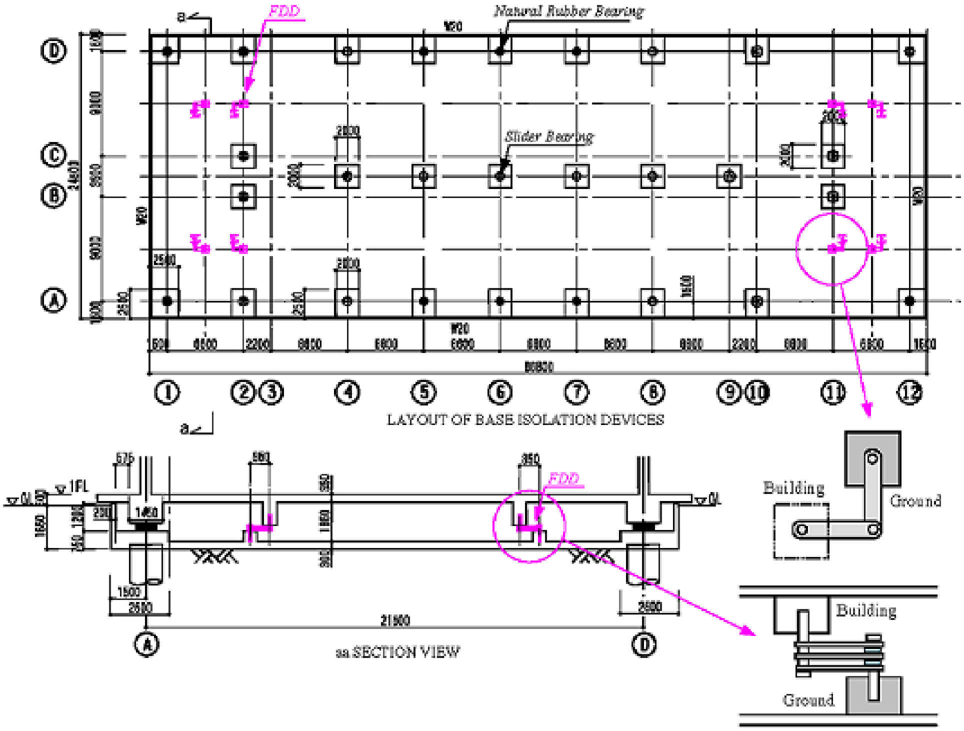

Figure 17 – Layout of damper locations at base of the building

Since the 5 storey laboratory project several base isolated buildings of similar size have been equipped with Damptech dampers.

Two other projects with Damptech dampers can be seen in Figure 18. One of them is a 12 storey apartment building in Tokyo (Figure 18 - Left) and the other is a 7 storey laboratory building in Yokohama (Figure 18 - Right),

Figure 18 – (Left) 12 storey apartment building in Tokyo. (Right) 7 storey laboratory building in Yokohama

## 6. RFDs for base isolation for high-rise buildings

After the success of using the base isolation dampers for medium-rise buildings, it was decided to use the base isolation dampers in high-rise buildings also.

The first high-rise building to be equipped with Damptech dampers in base isolation configuration is a 144 tower in Osaka, see Figure 19.

The tower is a residential tower with 44 floors and 2 pent house floors. (46 in total)

Figure 19 – Residential tower in Osaka, Japan with RFDs

Figure 20 – Dampers installed in residential tower on Osaka

Other projects with Damptech dampers in base isolation configuration for high-rise buildings are three similar residential towers with 40 floors. Each tower is equipped with many base isolation dampers.

Figure 21 - Three residential towers with RFDs

## 7. RFDs for Tallest Building in Japan

Takenaka Corp., one of the top 5 construction companies in Japan, is currently building the tallest building in Japan with a height of 300 m. The project is called the “Abeno Harukas” building and will be used for department stores, hotel, museum and more.

Currently the building is under construction with the buildings grand opening scheduled for the spring of 2014.

Because the building is located in Osaka, an area with high seismic activity, it was decided to equip the building with Damptech friction dampers to reduce the demand on the primary structural elements in the event of an earthquake. All dampers have already been installed in the building.

Figure 22- Abeno Harukas October 2012 (under construction)

The dampers used for the Abeno Harukas projects are unidirectional in the sense that a force $F_s$ is required to activate the dampers, see Figure 23 and Figure 24. The dampers in question has 4 friction joints and several layers of steel plates and friction pads to have a large damper capacity of 1500- 2250 kN . The hysteresis loop of such dampers can be seen in Figure 3b. The mechanism of the damper can be seen in Figure 24.

Figure 23 – Damper with 2250 kN Capacity

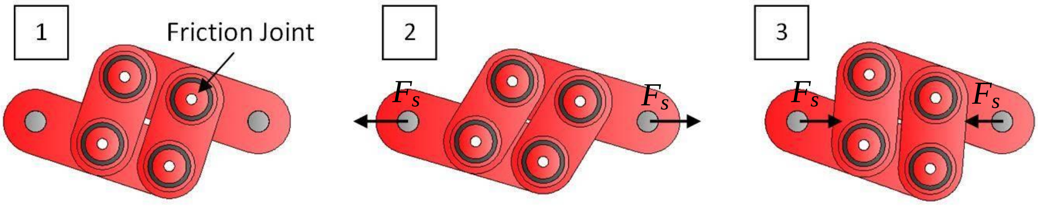

Figure 24- 1: Initial position. 2: Damper in tension. 3: Damper in compression

## 7.1 V-Bracing Configuration with RFDs

The dampers have been installed in V-Bracings through the height of the 300 m building. The V-bracing configuration can be seen for a single storey in Figure 25.

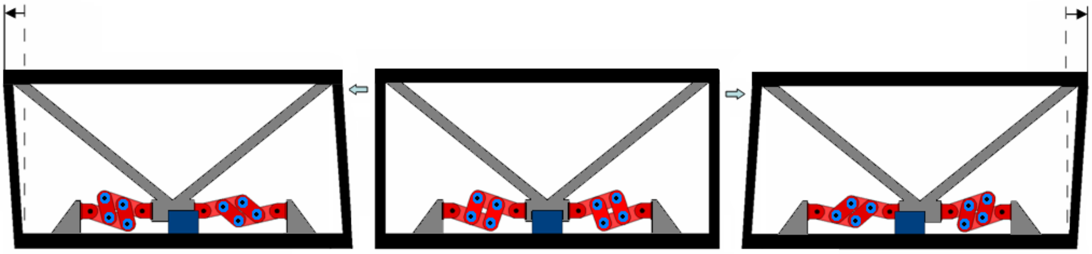

Figure 25 - Left: Frame structure moved to the left. Middle: Frame structure in initial position. Right: Frame structure moved to the right

When the top of the frame structure is moved to the left the left damper is compressed while the right damper is in tension and both dampers dissipate energy. Similarly when the top of the frame structure is displaced to the right the right damper is compressed while the left damper is in tension and the dampers dissipate energy see Figure 25. The mechanism of each individual damper can be seen in Figure 24.

During an earthquake the top story of a frame structure in a building as the one in Figure 25 and Figure 26 will be moved from left to right repeatedly while the dampers are dissipating the kinetic energy from the earthquake into heat, effectively reducing the response of the structure from the earthquake.

Figure 26 - 2250 kN Dampers installed in the tallest building in Japan

### *7.2 EXPERIMENTAL TEST PROGRAM*

As a part of the Abeno Harukas Prjoect a number of experiments for 1500-5000 kN dampers where been conducted at the Technical University of Denmark and testing facilities in Japan. The parameters examined are velocity dependence, displacement amplitude dependence, many loading cycles tests and etc..

### 1500-2250 kN Damper Tests

The tests for the 1500 kN damper was performed with a 3 MN dynamic servo testing machine at testing facilities in Japan, Mualla et al. [2012]. The test setup can be seen in Figure 27.

Figure 27 - Test setup of 1500 kN damper in testing facilities in Japan

### 5000 kN Damper Tests

Tests of a 5000 kN dampers where tested at testing facilities at the Technical University of Denmark. The damper was tested in a Instron machine with 5000 kN capacity in dynamic tests, Mualla et al. [2010].
The test setup can be seen in Figure 28.

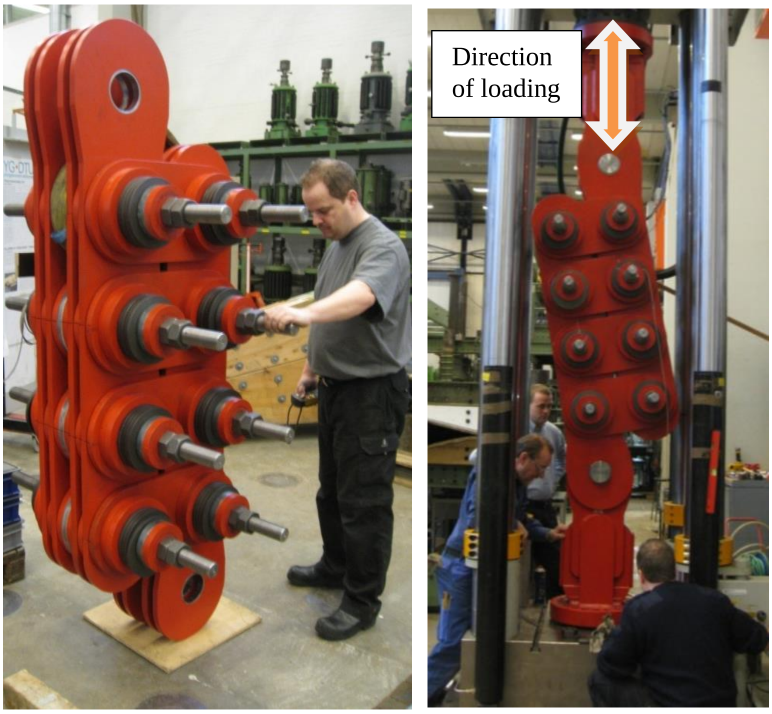

Figure 28 - 5000 kN Damper Tests in Technical University of Denmark

Some of the building projects in Japan where Damptech dampers have been installed can be seen in Figure 29 below.

Figure 29 - Some Damptech projects in Japan (including tallest building in Japan)

## 8. Panel Dampers

A new Panel Damper has been developed by Damptech that can be used to secure new and existing buildings against the damaging effects of earthquakes and strong winds.

The damper can fit in small and narrow places, where the use of bracings is not possible because of limited space. The width of the panel is around 0.9 m with variable height of around 1.8 – 2.8m.

The panel damper can be made with many different geometries and installed in frame structures as seen in the Figure 30.

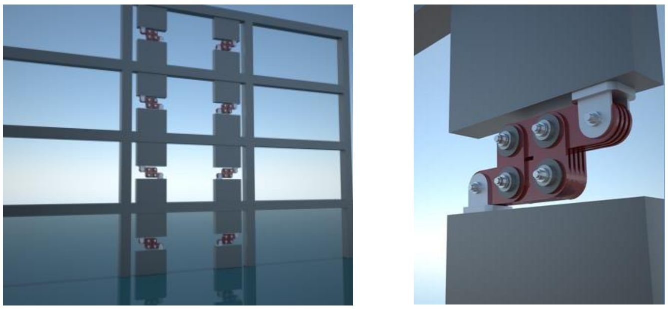

Figure 30 – Left: Panel dampers installed in frame structure. Right: A single panel damper

The Panel damper basically consists of two single panels and a rotational friction damper installed between the panels.

Figure 31 – Panel Damper installed in building in China

## 9. Rubber Bearing Friction Damper for Base Isolation

A new way of adding damping to elastomeric isolators has been proposed by Damptech. Instead of using rubber bearings and friction dampers separately, 4 friction dampers are placed around the rubber bearing to make a single device. The friction dampers used are V-dampers. Each V-damper is connected to the bottom bearing plate at one point and to the top bearing plate at the other point, see Figure 32. This type of damper is called a Rubber Bearing Friction Damper (RBFD). The dampers can be installed in a similar manner as the base isolation system in Figure 17 but here the friction dampers and rubber bearings are not placed separately.

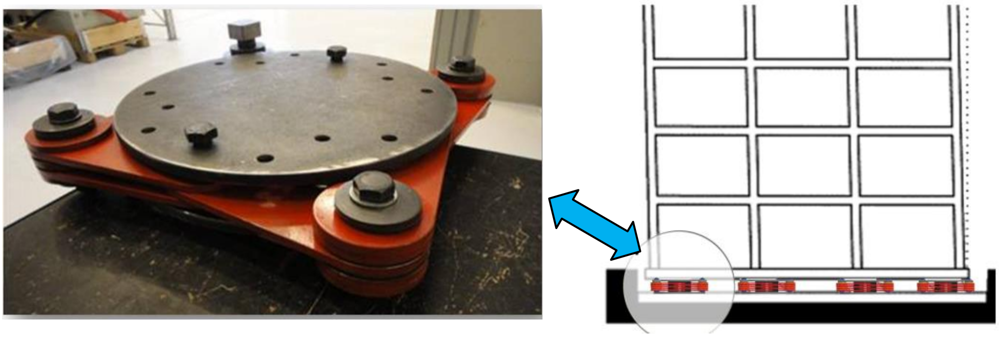

Figure 32 – a: RBFD b: RBFDs installed in building

## 10. Other Applications

Figure 33It is also possible to use RFDs to control machine induced vibrations. The control of two centrifugal machines in a multi-storey structure by using the damper devices is shown in Figure 33. The two machines produce resonance-like vibrations during their start and stop. At those moments all floors of the building experience strong perceptible vibrations. Since the adjacent machines vibrate differently, the relative vibration between them is used to activate the friction forces in the devices. The solution shows that the damper devices are flexible in the real applications.

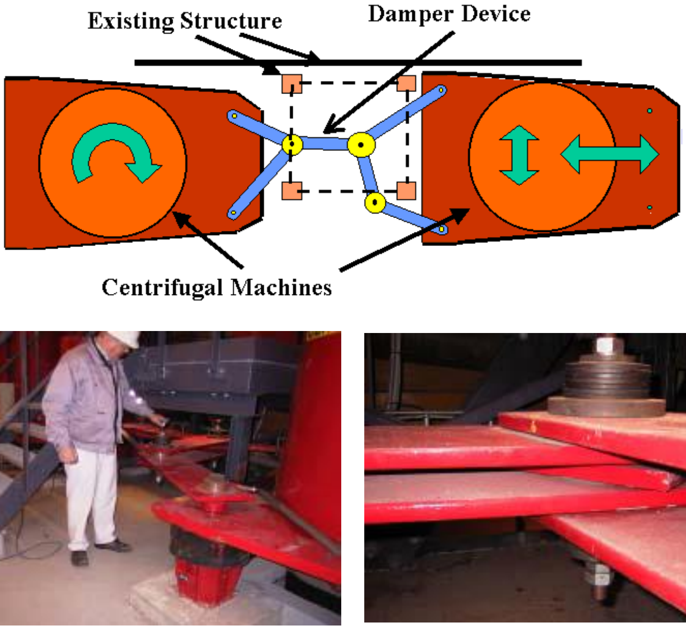

Figure 33- Friction damper devices for a simultaneous control of two centrifugal machines.

Another application of RFDs for machine vibration can be seen in Figure 34. The power plant experiences disturbing vibrations during its operation. With the damper devices the vibrations were considerably reduced.

Figure 34- Application of damper devices in a power plant in Denmark.

Figure 35 – Example of different damper models

## 11. Conclusion

A number of damping systems have been presented and discussed. These systems are very effective in damping vibration in buildings and structures.
The damping systems were developed by Damptech and are based on a unique rotational friction concept that has worldwide patents.
The dampers have been successfully used in many projects around the world including the tallest building in Japan.

The devices can be used to efficiently protect building against earthquakes, storms and can also be used for reducing machine vibration.

The devices are flexible and available in many different models that each have their own advantage for certain applications.

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## Summary

Damptech has developed several passive energy dissipation devices that are all based on a rotational friction concept developed by the 1st author.
Such devices can be used to effectively protect buildings and structures against earthquakes, storms and machine induced vibrations.
Various tests have been conducted with the dampers including a full scale shake-table tests on a three-storey frame structure.
So far the rotational friction damper devices have been used as in many buildings and structures around the World including the tallest building in Japan.

## Resumé

Damptech har udviklet flere passive energiabsorberende dæmpere, som alle er baserede på et roterende friktion koncept, der er udviklet af den første forfatter.
Disse dæmpere kan bruges til effektivt at beskytte bygninger og konstruktioner mod jordskælv, vind og maskinevibrationer.
Forskellige forsøg er blevet udført med dæmperne, herunder et fuldskala forsøg med en tre-etagers rammekonstruktion med et stort rystebord for at simulere jordskælv.
Indtil videre er friktiondæmperne blevet brugt i mange bygninger og konstruktioner rundt omkring i verden, herunder den højeste bygning i Japan.