UNIVERSITATEA TEHNICA DE CONSTRUCTII BUCURESTI
FACULTATEA DE CONSTRUCTII CIVILE, INDUSTRIALE SI AGRICOLE
DEPARTAMENTUL DE STUDII DOCTORALE

DAMPERS IN BUILDING DESIGN

- RAPORT DE CERCETARE 1 -

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SEISMIC DESIGN WITH FRICTION DAMPERS

Structural Analysis of Seismic Friction Dampers

The friction damped brace or yielding restrained brace (YRB) is modeled as a link element in most software. In other words, it is modeled as a fictitious yielding brace. Because the Ten-Co friction damper can be treated as an ideal elastoplastic element, this allows the application of Wen's model. While a simplification of the damper's behavior, the Wen model simplifies the analysis.

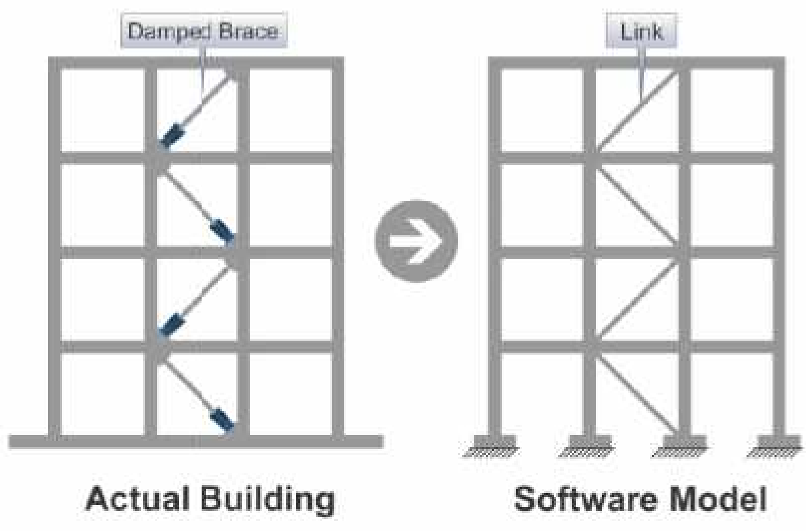
A yielding brace or a BRB would yield and begin to deform allowing the building to absorb and dissipate the earthquake's energy. However, the brace would need to be replaced after the earthquake.

In contrast, the inline seismic friction damper slips instead of yielding and by means of the elasticity of the primary structural elements return to its original position. Studies have shown that a moment frame capable of even just 25% of the slip load elastically is sufficient to recenter the damper. The damper's slip load is symmetric in tension and compression (hence the name Ten-Co) and is independent of displacement. This important characteristic simplifies modeling and maximizes energy dissipation.

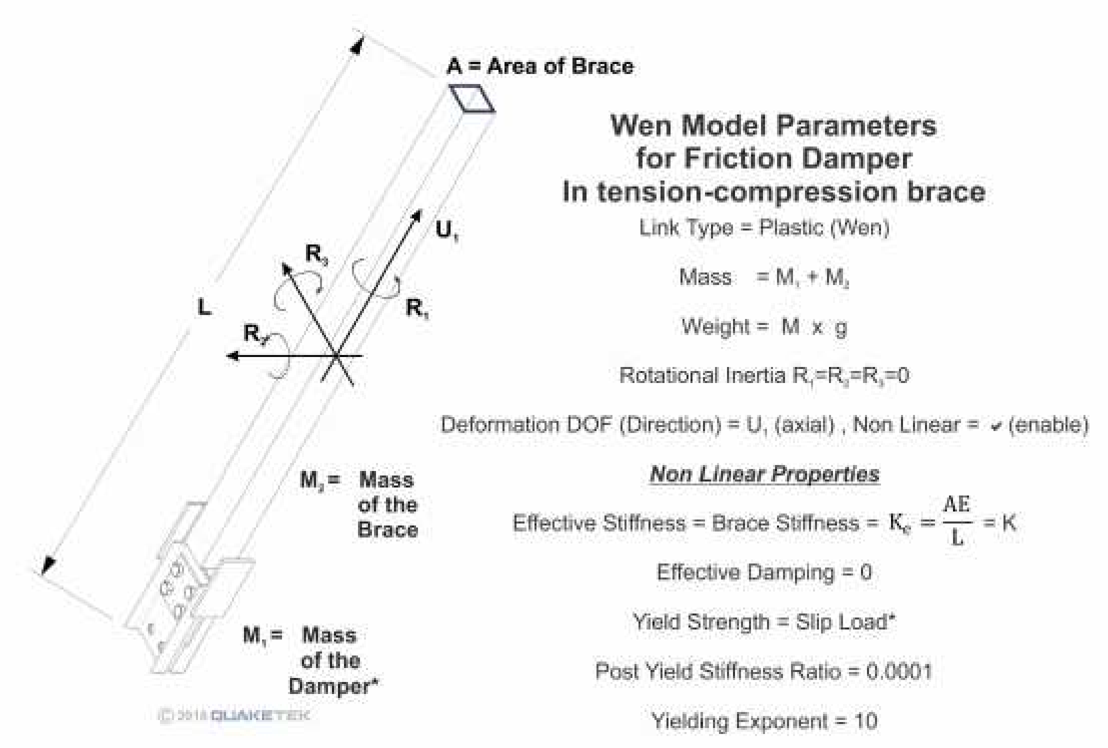
The damper's hysteretic curve allows the damper to be modeled as a link in static, dynamic and non-linear analysis. The only information needed is the properties of the link which in this case is a fictitious yielding brace with its own linear and non-linear properties. This can be modeled in popular software such as ETABS or SAP2000 using the parameters below.

Slip Load should be equal to 75% of the actual brace's yield strength and 130% of the service loads (e.g.wind shear). The mass of the damper will vary depending on the slip load and travel required.

This technology allows new ways to answer architectural and customer constraints.



ETABS PARAMETERS FOR FRICTION DAMPERS

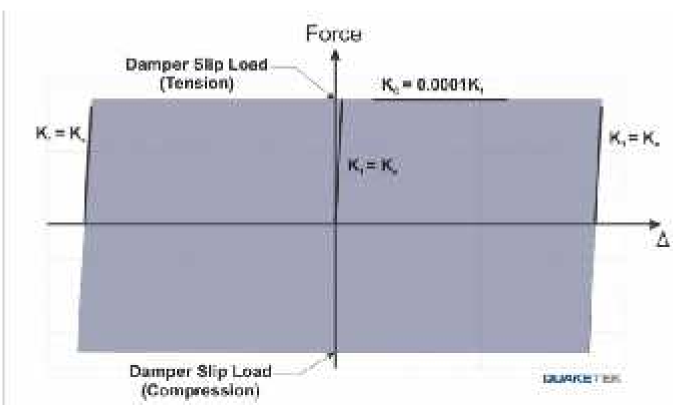


Hysteretic Loop

Some software allows for the direct input of the hysteretic loop. In the case that the engineer would like to perform the analysis using these features, the quasi-rectangular hysteretic loop can be used

Since the damper stiffness is equal to the brace stiffness up until it slips, the effective and brace stiffness are equal.

The damper slips at approximately constant load and therefore the post-yield stiffness ratio can be estimated at near zero, 0.0001.



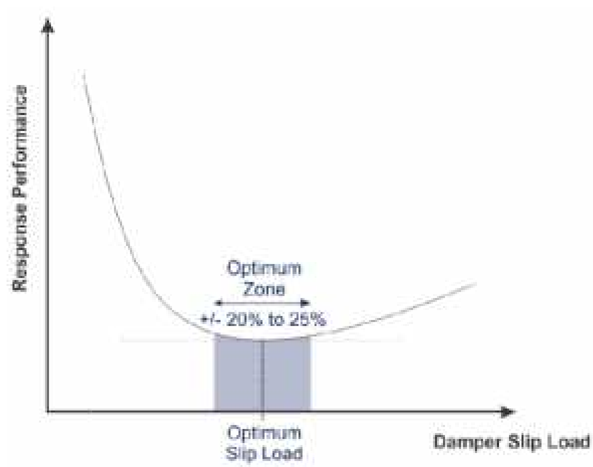
Theoretical Friction Damper Hysteretic Loop

Finding the Optimal Slip Load

The optimum slip maximizes energy absorption for a given frame configuration and a given lateral force. It has been found that this force is below 50% of the story shear but different forces are often selected by the structural designer depending on his/her constraints and objectives.

Once found, small changes to the slip load(e.g. +/-20%) have minimal effect on the structure's response.

For quick calculations use 1/3 of the story shear, ensuring that the ratio of lateral brace stiffness to total lateral story stiffness (frame + braces) is strictly greater than 0.5 and constant throughout the building height.

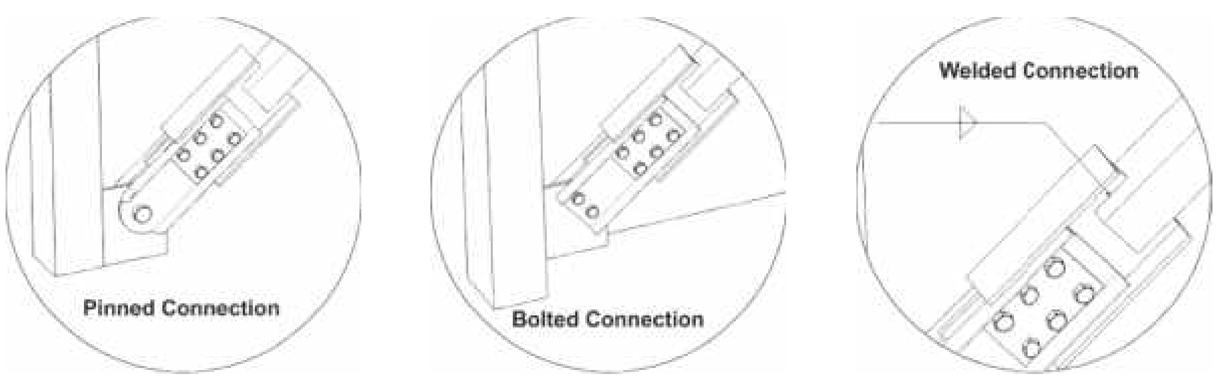


Can be used in any lateral force resisting system as a damping system or as a reusable safety "fuse" to protect structures from inelastic deformation or failure.

While there are many possible methods of installing the friction damper the single diagonal tension compression configuration is commonly used.

The next most common installation method tends to be in chevron where the damper is installed in the diagonals or sometimes installed at the interface between the beam and the braces.

Friction Dampers can be customized to fit almost any building and the link below has commonly used slip loads and strokes.



Friction Damper Catalog

The Catalog will provide you with some examples of standard dampers, their dimensions, and masses. Although small strokes are shown with small dampers the inverse is common: we can also provide large strokes on small dampers and small strokes on large dampers.
When you complete your analysis provide us with the required slip load and stroke and Quaketek will custom design the damper you require.

ENERGY DISSIPATION DEVICES FOR EARTHQUAKE RESISTANT BUILDING DESIGN

Another approach for controlling seismic damage in buildings and improving their seismic performance is by installing Seismic Dampers in place of structural elements, such as diagonal braces. These dampers act like the hydraulic shock absorbers in cars – much of the sudden jerks are absorbed in the hydraulic fluids and only little is transmitted above to the chassis of the car. When seismic energy is transmitted through them, dampers absorb part of it, and thus damp the motion of the building.

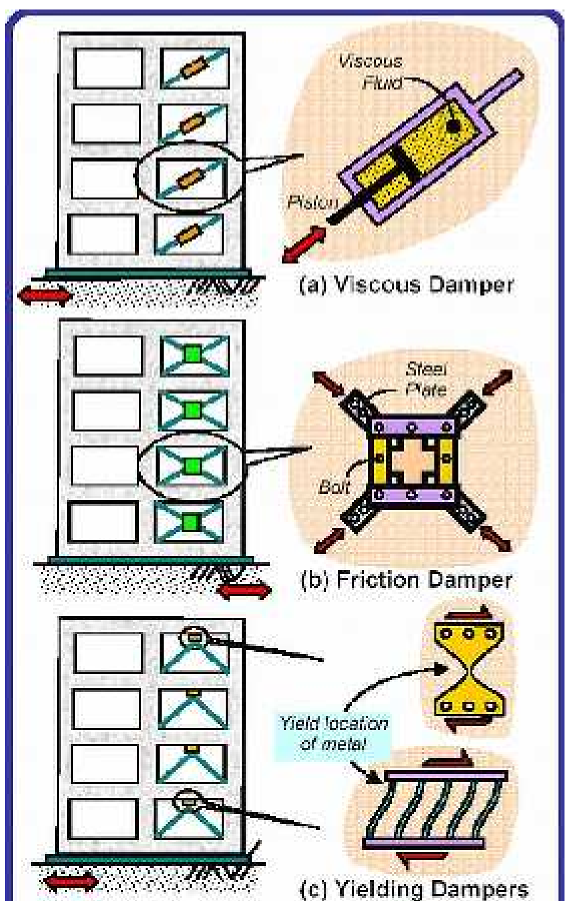
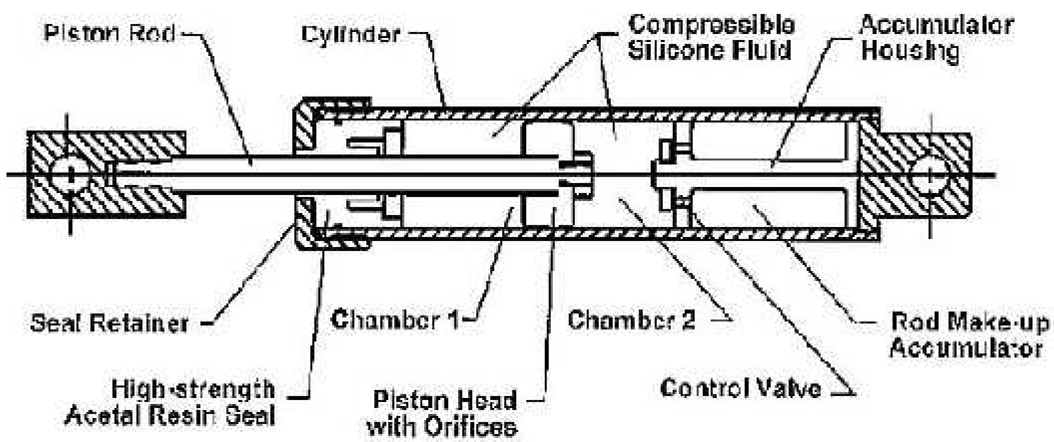


Figure 3: Seismic Energy Dissipation Devices – *each device is suitable for a certain building.*

ENERGY DISSIPATION DEVICES
Commonly used Seismic Dampers:

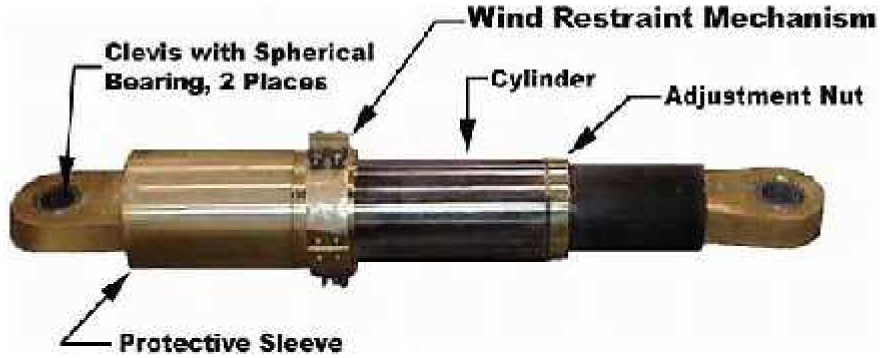
- **Viscous Dampers** (energy is absorbed by silicone-based fluid passing between piston cylinder arrangement),
- **Friction Dampers** (energy is absorbed by surfaces with friction between them rubbing against each other),
- **Yielding Dampers** (energy is absorbed by metallic components that yield).
- **Viscoelastic Dampers** (energy is absorbed by utilizing the controlled shearing of solids).

Thus by equipping a building with additional devices which have high damping capacity, we can greatly decrease the seismic energy entering the building.



How Dampers Work
The construction of a fluid damper is shown in (fig). It consists of a stainless steel piston with bronze orifice head. It is filled with silicone oil. The piston head utilizes specially shaped passages which alter the flow of the damper fluid and thus alter the resistance characteristics of the damper. Fluid dampers may be designed to behave as a pure energy dissipater or a spring or as a combination of the two.

A fluid viscous damper resembles the common shock absorber such as those found in automobiles. The piston transmits energy entering the system to the fluid in the damper, causing it to move within the damper. The movement of the fluid within the damper fluid absorbs this kinetic energy by converting it into heat. In automobiles, this means that a shock received at the wheel is damped before it reaches the passengers compartment. In buildings this can mean that the building columns protected by dampers will undergo considerably less horizontal movement and damage during an earthquake.



Fluid Viscous Dampers

New Breed of Energy Dissipation Devices

The innovative methods for control of seismic vibrations such as frictional and other types of damping devices are important integral part of seismic isolation systems as they severe as a barrier against the penetration of seismic energy into the structure. In this concept, the dampers suppress the response of the isolated building relative to its base.

The novel friction damper device consists of three steel plates rotating against each other in opposite directions. The steel plates are separated by two shims of friction pad material producing friction with steel plates.

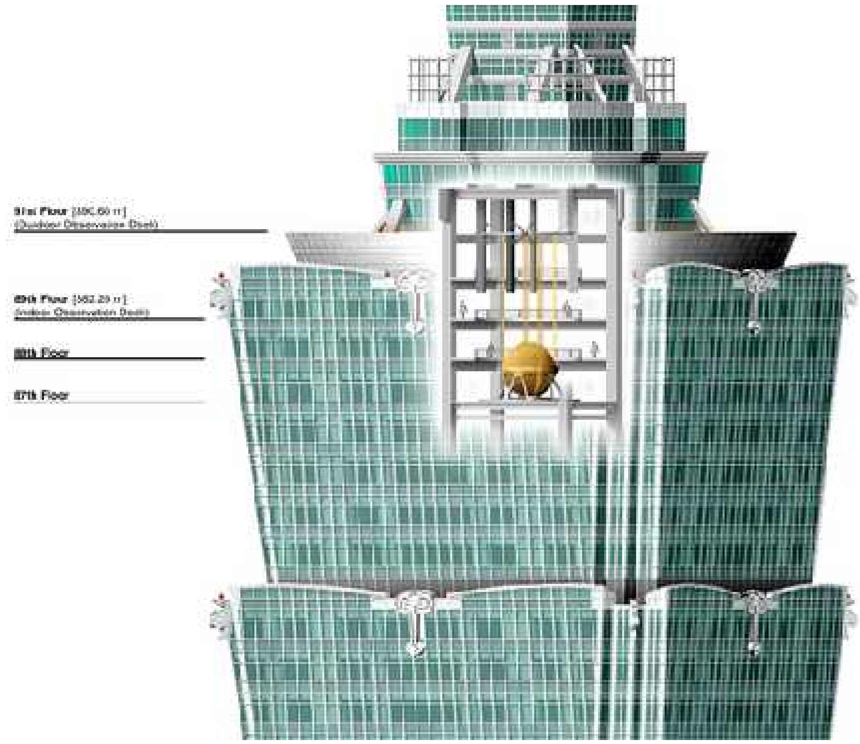
When an external force excites a frame structure the girder starts to displace horizontally due to this force. The damper will follow the motion and the central plate because of the tensile forces in the bracing elements. When the applied forces are reversed, the plates will rotate in opposite way. The damper dissipates energy by means of friction between the sliding surfaces.

The latest **Friction-ViscoElastic Damper Device (F-VEDD)** combines the advantages of pure frictional and viscoelastic mechanisms of energy dissipation. This new product consists of **friction pads** and **viscoelastic polymer pads** separated by steel plates. A prestressed bolt in combination with disk springs and hardened washers is used for maintaining the required clamping force on the interfaces as in original FDD concept.

Tuned Mass Dampers in Skyscrapers

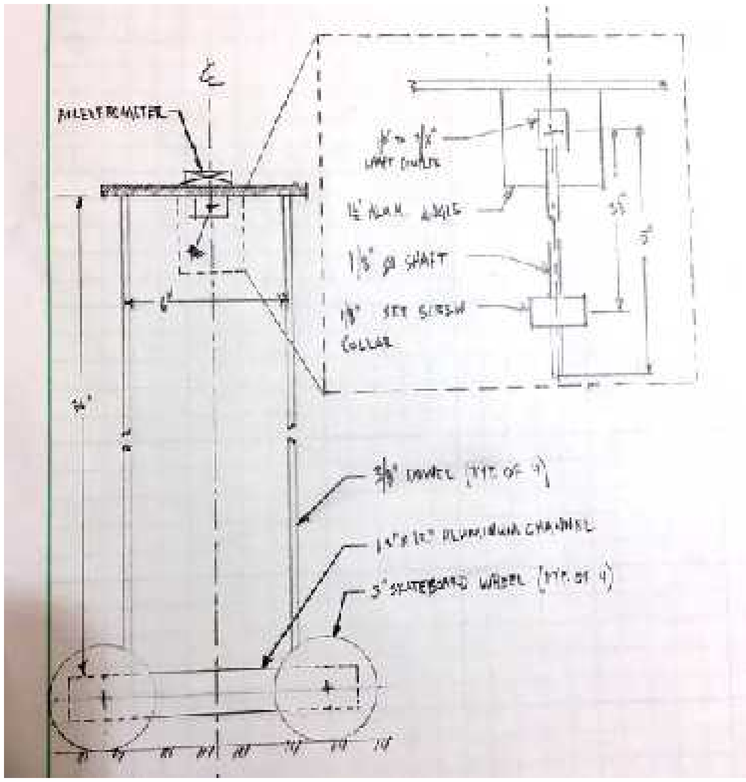
In many of the world's tallest skyscrapers, there's a secret device protecting the building and the people inside from strong motion due to wind and earthquakes. Did you know you can tune a skyscraper just like a guitar?

Sometimes to the detriment of the hedge fund managers and penthouse denizens on the top floors, a skyscraper can act as a oscillator just like a guitar string. Wind can induce oscillation in a building similar to a tie down strap on a vehicle. A strong earthquake can also excite the building's resonant frequency just like plucking a guitar string. In most cases, the movement is not enough to threaten the safety of the building itself. All structures exhibit some level of deflection, since strength doesn't necessary equal rigidity. On a very breezy day, the tallest skyscrapers can sway up to three feet on each side. The building may be fine, but that amount of movement can be profoundly uncomfortable to its occupants.

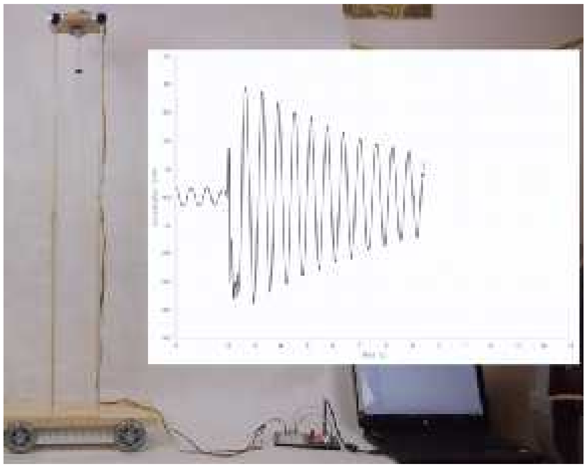


Most of us hold an intrinsic belief that buildings should not move. We don't even think about it. For our entire lives Wednesday has come after Tuesday, the sun has risen in the east, and our domiciles and dwellings have remained static beneath our feet. So you can forgive your subconscious for feeling some amount of terror when such a fundamental belief is shaken, especially when the shaking is literal. It may not be enough to harm the building's structure, but it's certainly enough to cause a one-percent on the top floor to lose his caviar, and buildings aren't good for much if people don't want to be inside them.

So engineers have come up with some novel solutions for minimizing this unwelcome vacillation, one of which is the tuned mass damper, or TMD. A TMD reduces the amplitude of vibration by absorbing kinetic energy from the system, in this case the swaying motion of a tall building. For a long time, TMDs were relegated to areas with the rest of the building's mechanical equipment, hidden from public view. That changed in 2004 when the TAIPEI 101 tower finished construction in Taiwan. Rather than hide the world's largest spherical tuned mass damper, the building's designers chose to open it to the public. TAIPEI 101's TMD has become a draw for tourists, and even has its own mascot, the damper baby, which, looks like it came straight off island of misfit mascots. It's like clippie the paperclip had a child with the twitter fail whale. Anyway, the publicity associated with the Taipei 101 has sort of unveiled this really cool bit of engineering that is the tuned mass damper, and you can find tons of videos of it in action online, including its movements during the 2008 Sichuan Earthquake in China. So how does it work?

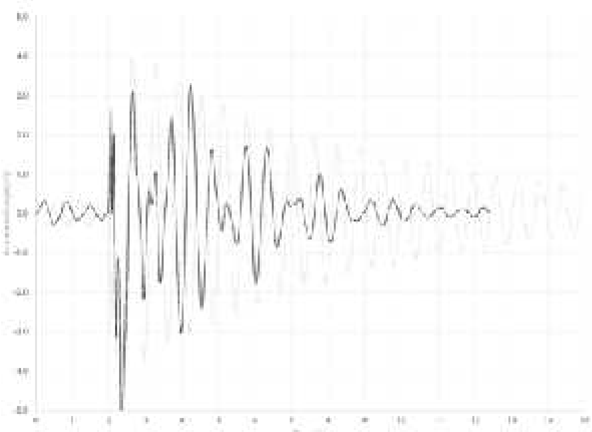


We’ve constructed this model of a pendulum-style tuned mass damper in a skyscraper (**Note: Some of the dimensions in the drawing may not reflect the final configuration of my model. E.g. I ended up using 1/4" dowels in place of the 3/8" dowels shown on the drawing. You may have to iterate the design to get the proper motion.**) I can pull the cart back and give the building a bump which excites its resonant frequency just like an earthquake or strong wind event. The benefit here is that I can do it in a somewhat repeatable fashion so we can evaluate the effectiveness of the damper. For the TMD, the damping comes from the tension of the screw which is acting as the hinge. I can tighten the screw to increase the damping. The tuning comes from moving this mass up or down on the pendulum shaft. This changes frequency of the pendulum just like a metronome, which can be tuned to the resonant frequency of the building. I have an accelerometer on top of the building so we can measure its movements, and this hooked to an Arduino clone which is sending the data to my laptop. The accelerometer I used is the ADXL345 breakout board from Sparkfun. I filtered the x-axis data with a low-pass filter, then sent it via serial port to my laptop. I just copy the data from the serial monitor window and import into Microsoft Excel for the figures. For the figure animations, I wrote a custom macro and used a screenshot program to capture them as video.



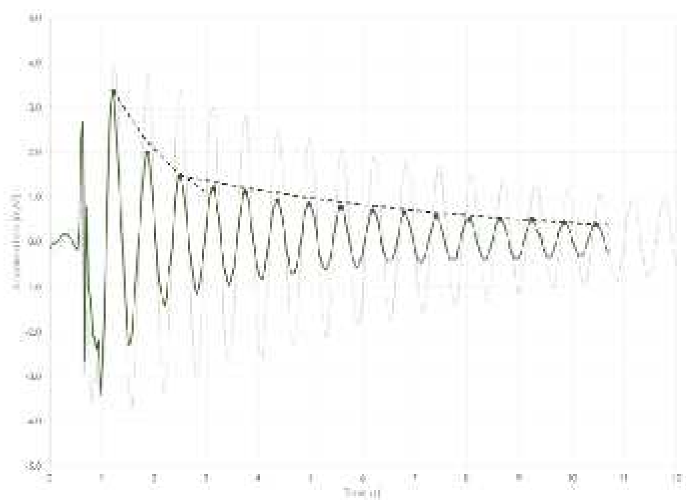
If I lock the pendulum and set the building swaying, we can get a sense of how the it would perform with only the building's own natural damping. Plotting the acceleration response, we can see that the model experienced a maximum amplitude of 4 m/s^2 or about half a gee, with period of 0.6 seconds. Frequency is the inverse of period, so we can get the building's fundamental frequency, 1.7 hertz. We can also see that the building has some natural damping just due to the internal friction in its movement - otherwise it would sway indefinitely. We can estimate the model's natural damping ratio using the logarithmic decrement between the first and second peaks. I get a damping ratio of 0.01.

The damping ratio, denoted by one of the tougher Greek letters to draw, ζ (small zeta), is a measure of how quickly the amplitude decays in an oscillating system. Systems with a damping ratio greater than 1 are said to be overdamped, because the system returns to equilibrium without oscillating. Systems with a damping ratio less than 1 are said to be underdamped, since they experience some oscillation. If the damping coefficient is exactly 1, the system is critically damped and returns to equilibrium as quickly as possible, and if the system is undamped, the oscillation continues indefinitely.



Now that we know an approximate natural frequency of the building, we can introduce the pendulum damper. You may remember from your physics classes that a pendulum's frequency depends on its length. For a frequency of around 1.7 hertz, my pendulum needs to be approximately 3.5 inches long. Now let's try the exact same experiment with the pendulum able to swing freely. The kinetic energy of the building does get transferred to the pendulum at first, but because there's no damping, the pendulum transfers the energy right back into the building. So instead of reducing the amplitude, instead the pendulum just continuously swaps the kinetic energy with the building like a hot potato. The pendulum is reducing the amplitude of acceleration, but you can only imagine that this erratic behavior would be even more alarming to our topmost tenants than steady but slowly decaying motion of the previous example.

Now let's tighten the screw to add some damping to the pendulum and see what happens. You can see a remarkable difference in the performance. The plot of acceleration response shows a peak acceleration of about 3.5 m/s^2, so a reduction of only about 12%. But the big difference is how quickly the motion decays. At the beginning when the pendulum is swinging, I calculated a damping ratio of over 0.06. That's about 6 times more damping than without the TMD. Once the pendulum stops swinging, the rest of the swaying follows the approximate natural damping ratio of the building itself, as expected, but the majority of the kinetic energy has already been dissipated by the damper, so the amplitude is much lower.



As silly as this little experiment looks, it's actually not that far off from what engineers do in the real world. The design phase for just about every major building includes some physical scale model tests. Even then, the modeled parameters may not be exactly true to the real structure, and may change over the building's lifetime, so being able to tune the mass damper is a necessity. Of course, a tuned mass damper doesn't completely eliminate movement, but we saw that it can certainly make a difference. In engineering, you have inexpensive, you have effective, and you have innovative and you usually you get to pick one, sometimes two. For solving the problem of oscillation in tall buildings, though, the tuned mass damper is truly all three, a great example of elegance in engineering.

I hope you liked the first practical engineering video, and if you did, I would really appreciate it if you subscribe to the channel. That helps motivate me to keep making cool stuff. If you want more details, have a question, or a suggestions for a topic, and especially if you live or work at the top of a skyscraper, I would really love to hear from you in the comments.

The damper in my model did not have "ideal" behavior since the force was not proportional to velocity. The coulomb damping, or dry friction damping, created with the screw tension in the video creates a stepwise function. It behaves one way under kinetic friction and another under static friction. A more ideal damper would use viscous or electrical/magnetic damping. I went through quite a few ideas (magnetic damping, off the shelf rotary damper, RC car shock absorber, etc.) but it is really hard to get ideal behavior at the scale I was working. I ultimately abandoned rigor in favor of just getting the point across.