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Design Approach for Friction Spring Dampers in Steel Framed Buildings. Experiences from Christchurch / NZ.

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Abstract

The 2010/2011 Christchurch earthquake series comprised 6 strong earthquakes that severely damaged New Zealand's second-largest city. One of these, in February 2011, delivered the highest peak ground accelerations recorded to date worldwide. This event caused damage to all multi-storey buildings in the city and rendered most of them unrepairable. It therefore highlighted the advantage of design for low damage in a major event, so that the building remains functional. Friction springs are key components in many low damage solutions. Friction springs can be used by themselves as base isolation or together with other low damage systems such as sliding hinge joints (SHJ) or lead rubber bearings (LRB). The friction spring damper is integrated in the SAP2000® software for the structural analysis and design of buildings.

There already are buildings in New Zealand, which are equipped with friction springs as part of a low damage design solution, for example Te Puni Village Student Accommodation. The Te Puni Village was completed in 2008 and on July 21st 2013 was struck by an earthquake measuring 6.5 on the Richter Moment Magnitude Scale (MMS) and the following aftershock measuring 5.8 on the MMS. The main earthquake exceeded the elastic threshold of the building, activating the low damage features, which then returned the building to its original position with no structural damage and full functionality.

This typically involves incorporating mechanisms in the structure that can control loads and sustain large deformations without causing damage. Structural damage needs to be planned for in design, controlled and limited, to ensure a building can remain useable after a large earthquake. Friction springs can be a key part of the solution for controlling seismic damage in taller steel framed buildings and the application of these has now been developed, applied in practice and in one example subjected to a severe earthquake, delivering the expected low damage outcome.

Keywords: base isolation; sliding hinge joint; shear wall; rocking steel frame; self-centring,

1. Introduction

A severe earthquake subjects buildings to much greater deformation demand than any other design event, with the possible exception of severe fire. However, the likelihood of such an event in the lifetime of a particular building is low. To avoid the need to design the building to be sufficiently strong to withstand a severe earthquake without damage, the concept of ductile design was introduced some 40 years ago. This involves the building being designed to remain elastic during a moderate earthquake and to undergo controlled damage in a predictable manner under a severe earthquake. This concept has been adopted and implemented worldwide in high seismic regions since the 1970's. However, the cost of this after a severe earthquake is the need to repair or replace buildings, with considerable financial and business interruption losses. The impact of these losses in recent severe earthquakes, such as the 1994 Northridge earthquake, the 1995 Northridge earthquake and the 2010/2011 Christchurch earthquake series has led to a reconsideration of ductile design towards providing a low damage solution, in order to limit the very large financial losses which in the case of Christchurch are over 20% of New Zealand's annual GDP. In a low damage solution, the components of the building which are traditionally designed to yield and protect the rest of the structure instead absorb this deformation in a way that does not require replacement or are designed and detailed for easy replacement.

This typically involves incorporating mechanisms in the structure that can control loads and sustain large deformations without causing damage. Structural damage needs to be planned for in design, controlled and limited, to ensure a building can remain useable after a large earthquake. Friction springs can be a key part of the solution for controlling seismic damage in taller steel framed buildings and the application of these has now been developed, applied in practice and in one example subjected to a severe earthquake, delivering the expected low damage outcome

2. Design Features

Friction springs are employed in the mechanical engineering sector when high kinetic energies must be absorbed and damped or when springs of relatively compact dimensions are required for high forces.

2.1 Basic design of a friction spring

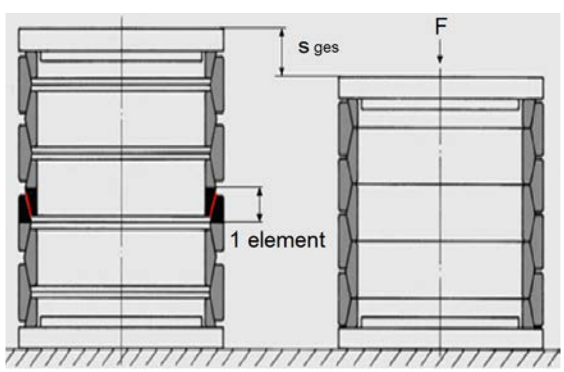

Fig.1 – RINGFEDER® friction spring

Friction springs consist of closed outer and inner rings with tapered contact surfaces. A spring element is understood to be one single mating taper surface, i.e. half one inner and half one outer ring. For example, the spring shown in Fig.1 consists of 4 outer rings, 3 inner rings and 2 half inner rings that means the spring has 8 elements. When the spring column is axially loaded the tapered surfaces overlap causing the outer rings to expand and the inner rings to contract in diameter. The outer and inner rings are made of special spring steel. Application of high loads causes elastic deformation to the rings. The total spring travel of a friction spring results from the number of elements whereas the spring force does not change with the number of elements. In contrast to other spring types, the peripheral stresses are distributed almost uniformly over the cross-sectional area; each element of a friction spring is hence utilised uniformly as regards to volume so that the weight of the spring is less than that of other types of springs.

2.2 Dampening

The special feature of the ring spring is the powerful dampening of about 66% of the energy introduced, the remaining 34% (return force) are needed to bring the spring back in its original position. This value is reached by using the standard grease F-S1. Oscillations and shocks hence are attenuated very quickly. If the damping spring is installed so as to act in both directions (impact and traction), Energy depletion occurs twice during an oscillation process. The energy EO introduced decreases with increasing number of oscillations z in accordance with the following equation Eq. (1):

$$\frac{E_Z}{E_O} = (1 - D)^{2Z} * 100[\%] \tag{1}$$

This function is plotted in Fig.2 for various percentage damping values. In ring springs in which D = 66% the energy introduced had fallen to 1.3% of the initial value after only two oscillation! Resonance phenomena are therefore completely suppressed.

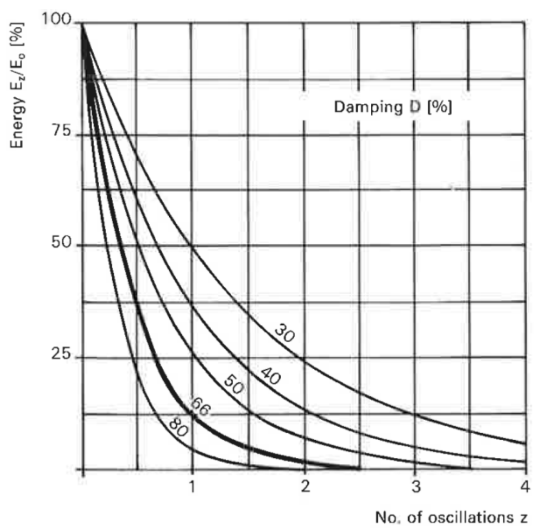

Fig.2 – Decrease in the energy Ez (referred to the initial value E0) as a function of the numbers of oscillations z for different dampening values.

If the characteristic of a friction spring has to be changed, there are three different possibilities to do this:

- The friction coefficient can be influenced by using another grease.

- The angle of the tapered surfaces can be changed.

- The thickness of the rings can be changed.

For example, in certain seismic designs it is necessary to reduce the dampening and to increase the force when the spring is unloaded to help to push the building back to its vertical position.

2.3 Fire and high temperatures

Ring springs are made of special spring steel and coated with grease. In case of a fire, rubber products, hydraulic or fluid elastomeric dampers will be destroyed, but friction springs will endure the fire. As long as the tempering temperature of the steel will not exceeded, they only need to be re-greased.

2.4 Long life

Friction springs are designed to last through many cycles and are reusable. If one of the rings in a friction spring assembly breaks, the spring will still work and become slightly stiffer. The end force and the dampening remain unaffected as shown in Fig.3.

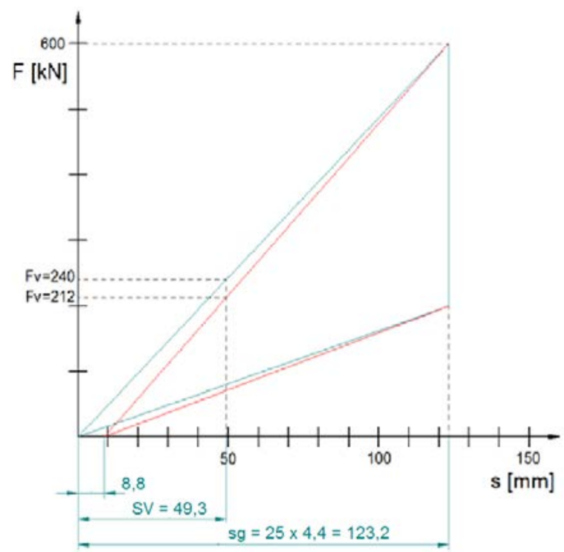

Fig.3 – Effect if one ring fails

2.5 Lubrication

Before dispatch, the sliding surfaces of the rings are lubricated with special high performance grease, designed to remain effective for the lifetime of the spring.

2.6 Speed

The force-travel characteristics of ring springs are insensitive to the rate of deformation across a wide range of travel speeds, from pseudo static (loading rate of 10-4 (ΔL/L)/sec) to seismic dynamic (loading rate of 10-1 (ΔL/L)/sec) or faster. This makes them very well suited to seismic applications.

2.7 Return force

This is determined for each application and customised to the particular requirements.

2.8 Operational characteristics

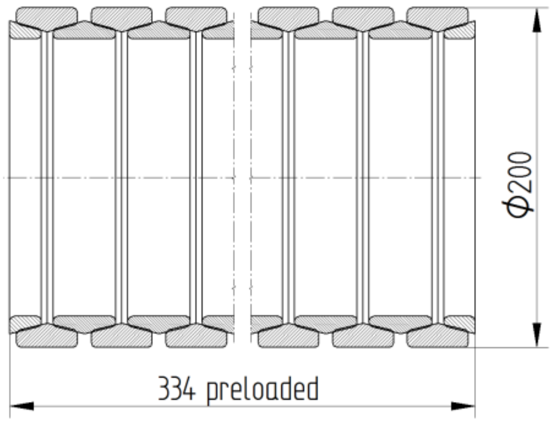

Fig.4 – Preloaded spring

Fig.4 represents the diagram of a friction spring type 20000, which is a typical one for earthquake applications. It consists of 8 outer rings, 7 inner rings and 2 half inner rings. It is preloaded with 200 kN to a length of 334 mm. With these values, it has a maximum stroke of 38 mm and a capacity of 13400 Joules. The requirement, for example, is to absorb a maximum energy of 6000 Joules.

When the ring spring receives an impact energy (Fig.5), it compresses by 21 mm and absorbs 6000 Joules from which 4000 Joules respectively = 66% are converted to heat. After the compression, the friction spring discharges back by the same 21 mm due to a reaction force and there are 2000 Joules which have to be absorbed.

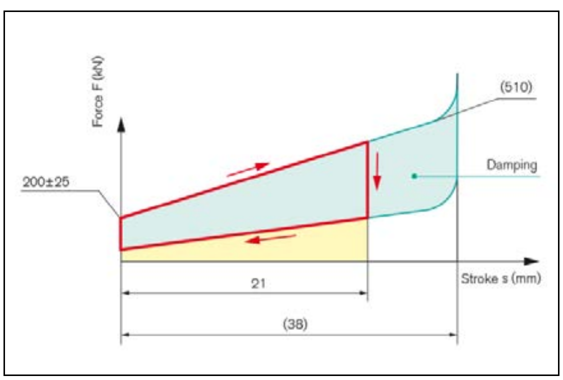

Fig.5 – First impact

Fig.6 shows that the impacting body strikes again on the ring spring with the remaining 2000 Joule and compresses it by 8.5 mm. After the compression, the buffer springs back by the same 8.5 mm due to the reaction force.

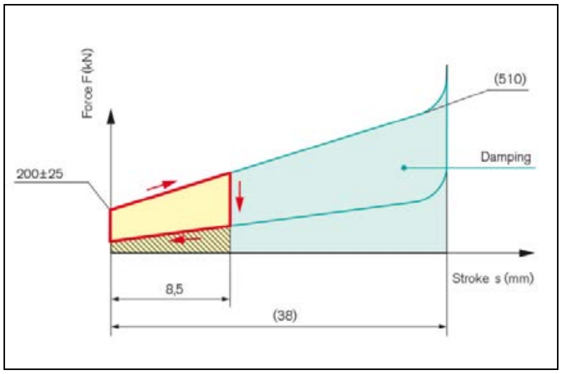

Fig.6 – Second impact

Based on the fact that the friction not only occurs between the rings of the ring spring but in the whole system, the complete 6000 Joules are now absorbed and the system comes to rest. Fig.7 shows a low theoretical 3rd oscillation.

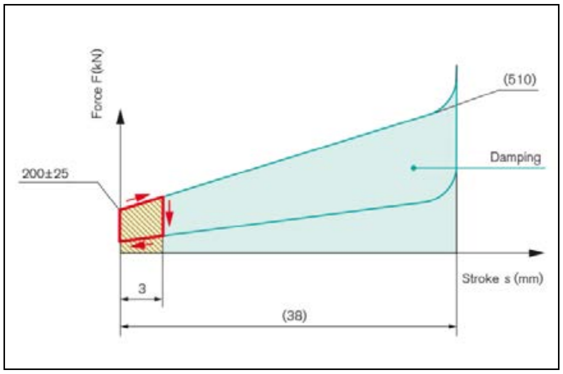

Fig.7 – Third impact (not necessarily)

2.9 Return force

This is determined for each application and customised to the particular requirements.

2.10 Re-usability

Friction springs are designed to remain undamaged and in place after a seismic event. They are maintenance free when installed in accordance with the manufacturer's specifications. For example, the company Krupp uses jaw crushers that are equipped with friction springs. These work since 50 years without maintenance. Railway buffers with friction springs have a lifetime of 30 to 40 years without maintenance.

2.11 Temperature

The force-travel characteristics are temperature independent for the operating conditions in buildings and the temperature rise in the springs during earthquake induced deformation is minimal.

3. Application examples

3.1 Base isolation

Ring springs can be used as damping elements for themselves. A good example of this is the base isolation of Tait Communication Campus in New Zealand. An excavation pit (Fig.8) is dug; tubes are piled into the ground. The depth depends on the point from where you reach solid ground. The bottom of the pit is condensed (Fig.9), the tubes cut off ~ 4” above the surface. Then the tubes are filled with concrete and reinforcement. The basic steel construction and a framework (Fig.10) for the concrete are designed.

Fig.8 – Excavation pit

Fig.9 – Condensed pit

Fig.10 – Pit with framework

The pit is filled with concrete (Fig.11). From this support base, the ground floor is built up. After this is done, the floor is completely closed (Fig.12 - 14).

Fig.11 – Support base

Fig.12 &13 – Floor integration

Fig.14 – Closed floor

These figures show one of the possible procedures while using the base isolation method . The friction spring damper has different tasks. It adds flexibility to the structure and allows the building to rock. It helps re-centering the structure and dissipates energy. Depending on requirements and dimensioning is one or the other characteristic more pronounced.

3.2 Sliding hinge joints

The Sliding Hinge Joint (SHJ) is a beam-column connection that is able to undergo large inelastic rotations with minimal damage [3]. This is achieved through sliding in Asymmetric Friction Connections (AFCs) to allow joint rotation. The SHJ has been used in practice, with many benefits over welded connections which include decoupling of joint strength and stiffness, confining inelastic demand to the bolts which are easily replaced following an earthquake, improving dynamic re-centering ability and reducing construction costs. The SHJ however undergoes a loss of elastic strength and stiffness once forced into the sliding state [2]. As the next stage of the SHJ development, the self-centering version of the SHJ (SCSHJ) was proposed, which incorporates friction springs to reduce joint elastic strength and stiffness losses, and reduce frame residual drifts to within construction tolerances following an earthquake [4].

In the Self-Centering Sliding Hinge Joint (SCSHJ) (Fig.15 and 16) the beam is connected to the column through the top flange plate which acts as the point of rotation. AFCs are installed in the bottom flange and web bolt groups. The properties of the joint can be altered by varying the percentage of moment capacity contributed by the ring springs. The joints can thus be categorized into the standard SHJ, where moment capacity is developed only by AFCs, the friction spring Joint (RSJ) where the moment capacity is developed only by ring springs and the SCSHJ where the moment capacity is a combination of AFC and ring springs. The SCSHJ was studied and analyzed on a 10-storey frame. Frames with a percentage of total joint moment capacity (PRS) of 25% had residual drifts within 0, 2 %, showing its viability in developing frame dynamic re-centering characteristics [2].

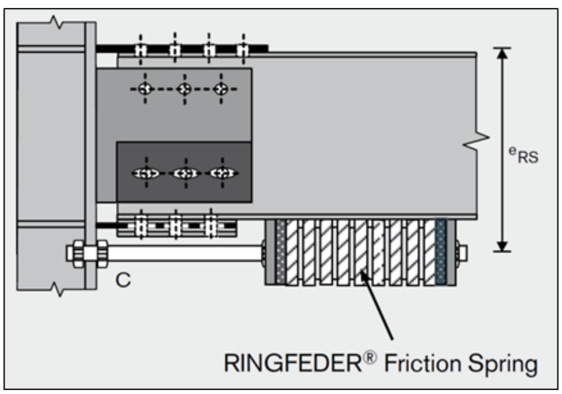

Fig.15 – Self centering sliding hinge joint

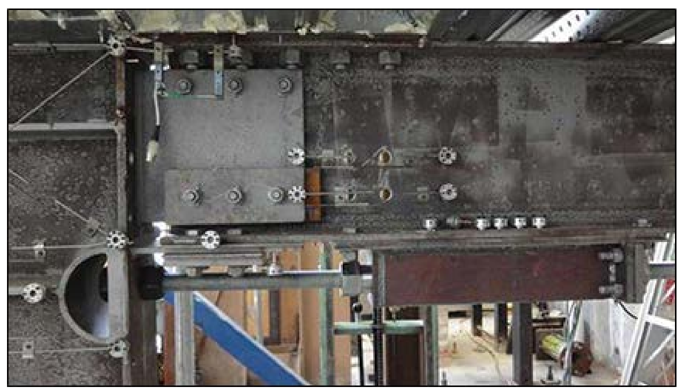

Fig.16 – SCSHJ in experimental setup

3.3 Rocking shear walls

Rocking structures avoid structural damage by shifting the burden of energy dissipation to non-critical, replaceable structural elements, and by preventing weak story failure Damage that would result in severe injury, and also damage that would prevent future serviceability of the structure, can be addressed by allowing structures to move, relative to their foundations. By enabling structures to be serviceable after a seismic event, rocking systems are a highly sustainable approach to structural design in earthquake-prone regions. There are different possibilities to integrate friction springs in rocking shear walls [7].

3.3.1 Timber constructions (design concept)

Rocking shear walls in timber constructions are providing ductility to the system. Additionally they are equipped with fuses, which work as energy dissipators by using the tensile strength of steel rods to dampen the system. After an event, the steel rods have to be replaced. Instead of these steel rods (Fig.17), push-pull friction spring units (Fig.18) that work as a double acting system can easily be integrated into the construction. These don't have to be replaced after an event.

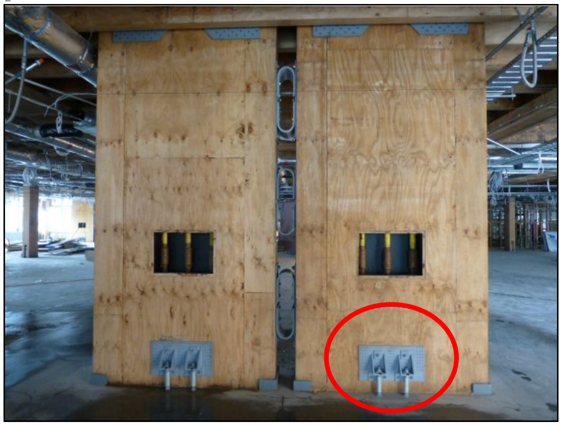

Fig.17 – Cross Laminated Timber rocking shear walls

Fig.18 – SCSHJ in experimental setup

3.4 Steel frames (design concept)

As shown in Fig.19, the rocking wall system is designed to rotate about the central base of the wall which allows the columns at the edges of the wall to move upward and downward during earthquakes. Therefore, double acting ring spring systems designed for the base of the columns are required to control the rocking under severe earthquakes. In addition to dissipating energy, these systems are intended to provide self-centring of the wall. Two double acting ring spring systems are proposed for this rocking wall system [1,5].

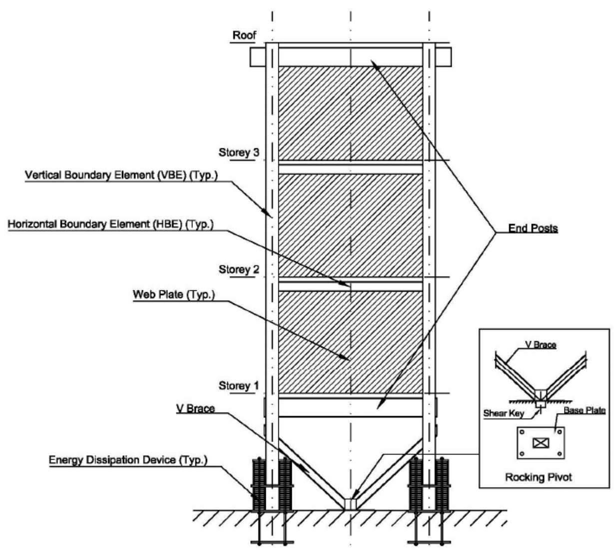

Fig.19 – Rocking wall with steel frame

3.4.1 Double acting spring type 1 – parallelogram hysteresis curve

Two stacks of ring springs are assembled in series at top and bottom of a column base plate and prestressed to 50% of the spring capacity with a high tensile grade AISI 4140 threaded rod connecting top plate to the foundation, as shown in Fig.20. The threaded rod is designed to yield after the top stack is locked up while the other components are designed to remain elastic. An exposed ring spring has to be encased with a protective casing to prevent the rings against dust, water or other contaminants and also to preserve the grease. Also, guiderails are provided to keep the ring springs located in their position in plan. When prestressing two or more sets of ring springs, it should be done simultaneously to keep the prestressing force balance at each set.

While the wall is rocking, each stack operates in parallel. When the column is in compression, the bottom stack is compressed while the top stack relaxes and when the column is in tension, the top stack is compressed and it compresses the top plate and generates tensile force in the rod while the bottom stack relaxes. When the top spring is loaded, the bottom spring is unloaded, which cancels one-third of the initial prestressing force on both sides. Hence, this system generates a parallelogram hysteresis curve as shown in Fig.21. [1,5].

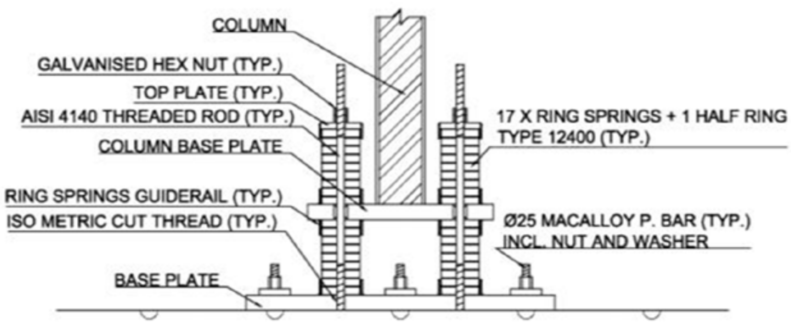

Fig.20 – Base plate detail type 1

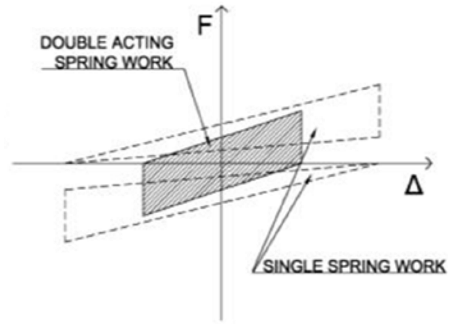

Fig.21 – Related hysteresis curve

3.4.2 Double acting spring type 1 – flag-shaped hysteresis curve

A stack of ring spring with customised endplates at its both ends is put into a steel cartridge. A high tensile grade AISI 4140 threaded rod is centrally passed through the ring spring and endplates and is fastened to connect between a column base plate and a bottom endplate. Then, the cartridge is sealed by a clamping plate which is bolted to the flanges of the cartridge. The perimeter of the cartridge base is welded to the base plate, as shown in Fig.22. The cartridge is also used to secure the rings from dust, water or other contaminants and to protect the grease. A hollow section which is a part of a column base plate transfers a compressive force to the top endplate but it is free to uplift. To ensure the spring is able to travel to the maximum spring travel, a sufficient gap has to be provided between a hollow section and a clamping plate and also between a rod bottom end and cartridge base.

Taking an advantage of the linearity of the ring spring behaviour, the height of the cartridge is used to define the prestressing force by measuring the spring displacement. For example, compressing the ring spring to 50% of the total spring travel represents a prestressed force level at 50% of the compression capacity. When the column is in compression, it compresses the top endplate and the spring. When the column is in tension, the threaded rod lifts the bottom endplate to compress the spring. This system generates a flag-shaped hysteresis curve and returns precisely to initial position as shown in Fig.23. [5,6].

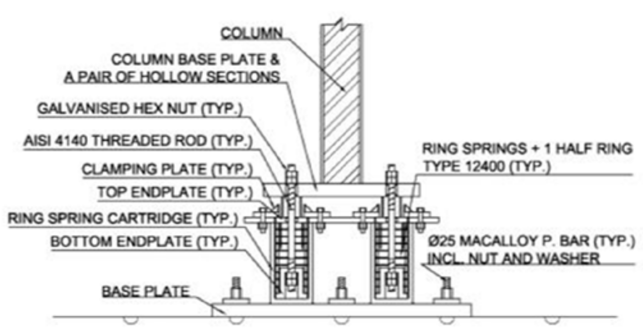

Fig.22 – Base plate detail type 2

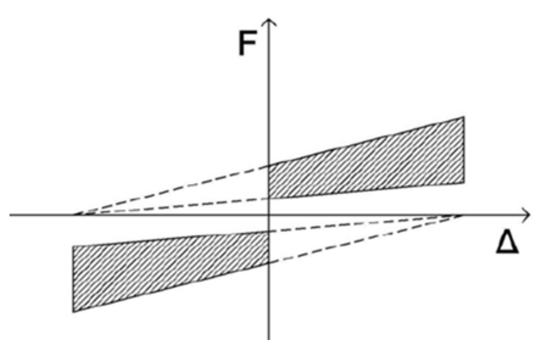

Fig.23 – Related hysteresis curve

3.5 Electrical equipment

The protection of electrical equipment is presented exemplary for capacitor bank platforms and electrical switch gears. As shown in Fig.24-25, the cross members of a capacitor bank platform are braced by the help of ring springs. This adds more flexibility to the system and allows the platform to rock. The design of the buffer was a specification of the customer.

Fig.24 – Capacitor bank platform

Fig.25 – Damper with customer design

Fig.26 shows a push-pull unit which allows the switch gear to swing. Here also you get more flexibility in the application.

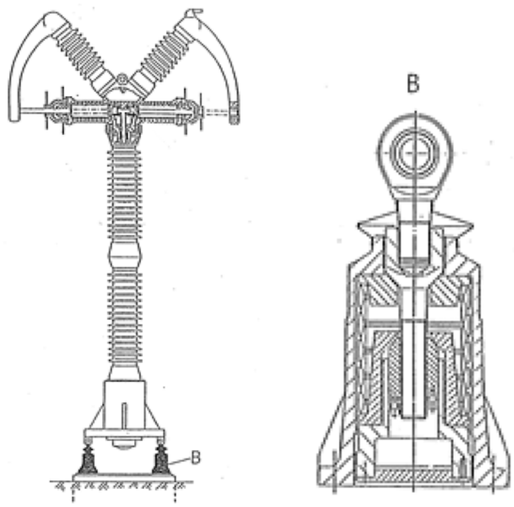

Fig.24 – Capacitor bank platform

4. Software integration

The friction spring damper is integrated in the SAP2000® software for the structural analysis and design of buildings. A table with the necessary data of the standard sizes of friction springs from outer diameter 18mm up to 400mm is deposited in the software. In this table the engineer has to fill in the values for the percentage of damping, number of elements and percentage of pretension which is required for his application. Thereupon the necessary data of every spring size will be displayed, that is needed to fill in the values in SAP2000 (e.g. effective stiffness during the loading cycle, effective damping, displacement etc., Fig.26). So the engineer is able to choose the right friction spring size for his application.

5. Conclusion

This paper has provided some background information about the use of friction springs for earthquake protection. This is only a brief overview of the capabilities that friction springs can offer. While structural engineers try to find the right system for ongoing projects, they will notice that they are limited using only one system. The combination of friction springs and other systems, for example rubber lead dampers, is possible and can be beneficial, with the lead dampers providing velocity dependent damping and the friction springs providing displacement dependent restoring force.

6. Acknowledgements

The authors wish to thank Dr G Charles Clifton and the Department of Civil and Environmental Engineering at the University of Auckland for the research regarding the use of friction springs for earthquake protection.

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