SELF-CENTERING RING SPRING DAMPERS FOR SEISMIC DESIGN OF STEEL FRAMES

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ABSTRACT

Ring springs, also known as friction springs, are made of spring steel that can withstand cyclic loads. The application of ring spring dampers in seismic design and strengthening of engineering structures is less or even not investigated. Ring spring dampers are extremely robust, heat-resistant, durable, and have almost no maintenance requirements. Another benefit is their superelastic behavior, whereby the spring always returns to its initial state despite high energy dissipation. The self-centering capability prevents permanent deformations after an earthquake event. The advantage is a high level of reliability, which is particularly important in the nuclear field. The objective of the present work is to give an overview of the properties and damping of ring spring dampers.

INTRODUCTION

Ring spring dampers are not widely investigated by civil engineers, several perspectives have to be explored such as the damping effect. One of their features is high heat resistance and durability. Through an innovative design, they combine self-centering characteristics with a high seismic energy absorption capacity. Another advantage is their superelastic behavior, whereby the spring always returns to its initial state despite high energy dissipation. The self-centering capability prevents permanent deformations after an earthquake event. Therefore, it is possible to develop low-damage and high-performance systems with self-centering capabilities as an alternative to conventional systems [1]. This is to ensure that functionality is maintained immediately after the earthquake, and therefore only the elastic structural behavior is exploited. The advantage is a high degree of reliability, which is particularly important in the nuclear field.

In this paper, the novel use of ring springs to increase earthquake resistance and reduce vibration of structures is investigated. Classical bracing elements are replaced by ring springs in a steel structure.

PROPERTIES

Ring springs, or friction springs, are constructed from a steel material that can withstand cyclic loads. They are composed of outer and inner rings, each with conical surfaces. The springs can be loaded axially and, as a result, the outer rings expand in diameter while the inner rings are compressed. Since the deformation of the rings is elastic, the friction forces are so high that the restoring force is 66 % percent less than the deformation force. Figure 1 shows the typical flag-shaped load-deformation curve. The area with an orange background represents the hysteretic damping D_{rel}. A direct correlation can be introduced between the max force $F_{\max}$ and the restoring force F_{R} which is presented in the next formula. [2]

$$F_R = (1 - D_{rel})\, F_{max}$$

The frictional damping D also depends on the lubrication, so in addition to the standard value of 66 %, damping values of 55 %, 45 %, and 35 % are also possible. The sliding surfaces are lubricated ex-factory and, in general, relubrication during operation is not necessary.

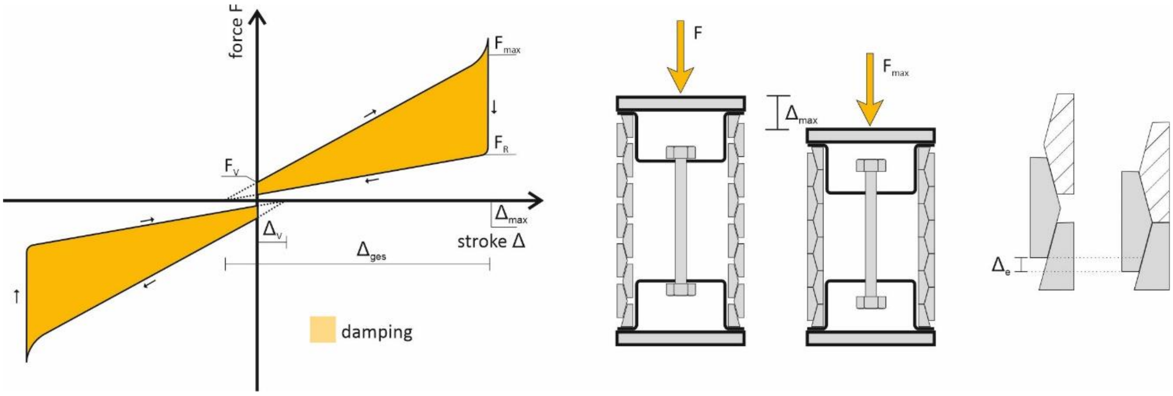


Figure 1: Design and typical load-deformation curve of a ring spring [2]

As the rings themselves are not fixed, the spring must be preloaded to secure its position. This must be at least 5 to 10 % of the final force and can also be increased to up to 60 % if required. The preload displacement Δ_V is calculated from the total stroke Δ_{ges} and the preload force F_V:

$$\Delta_V = \frac{F_V}{F_{max}}\, \Delta_{ges}$$

The available stroke is determined by the number of rings. The stroke results from the relative displacement of two rings Δ_e and this unit is defined as one element e. The total stroke can be calculated as follows:

$$\Delta_{ges} = e\, \Delta_e$$

Considering the preload, the usable stroke results from:

$$\Delta_{max} = \Delta_{ges} - \Delta_V$$

Although the springs themselves can only absorb compressive forces, a tension spring element can be created by appropriate design. A possible solution is shown in figure 2. [3,4]

After exceeding the maximum stroke, the spring is in the block state in which it is still able to carry greater loads but behaves like a stiff element. When the load is reduced, the spring returns to its initial position and remains fully operational. This results in a high level of safety because the greatest transmissible static force is limited by the design and not by the ring springs. Ring springs are currently employed in the mechanical engineering sector for absorbing and dissipating high kinetic energies even though their properties also offer great advantages in earthquake engineering. They can withstand many cycles, are reusable, and are suitable for continuous use. As a result, they are always ready for use, even in the event of an aftershock or clustered seismicity. Furthermore, if a ring in a friction spring assembly were to break, the spring would still be functional and the maximum transmissible load would be maintained. However, the use of the ring spring is also extended to the mechanical engineering field with maintenance intervals of up to 50 years [5]. The ring springs are not only robust to cyclic loading, but they are also favorable in case of fire and maintain their function until the critical temperature is reached [6]. Another advantage is their self-centering capability after an earthquake event whereby permanent deformations are prevented.

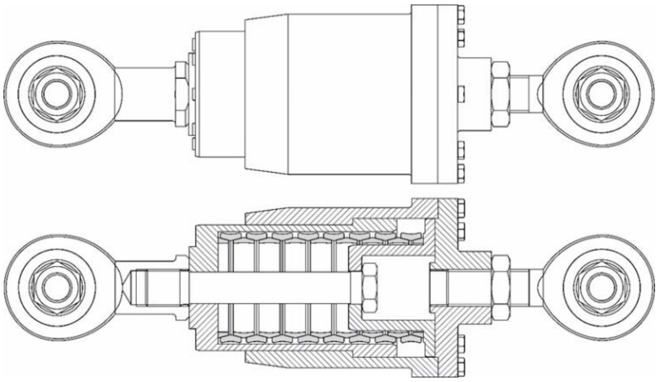


Figure 2: Design of a double-acting ring spring: tension and compression

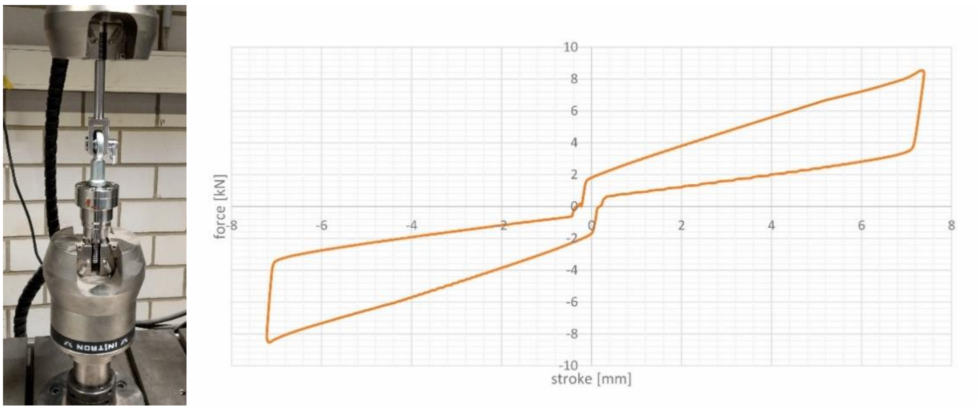
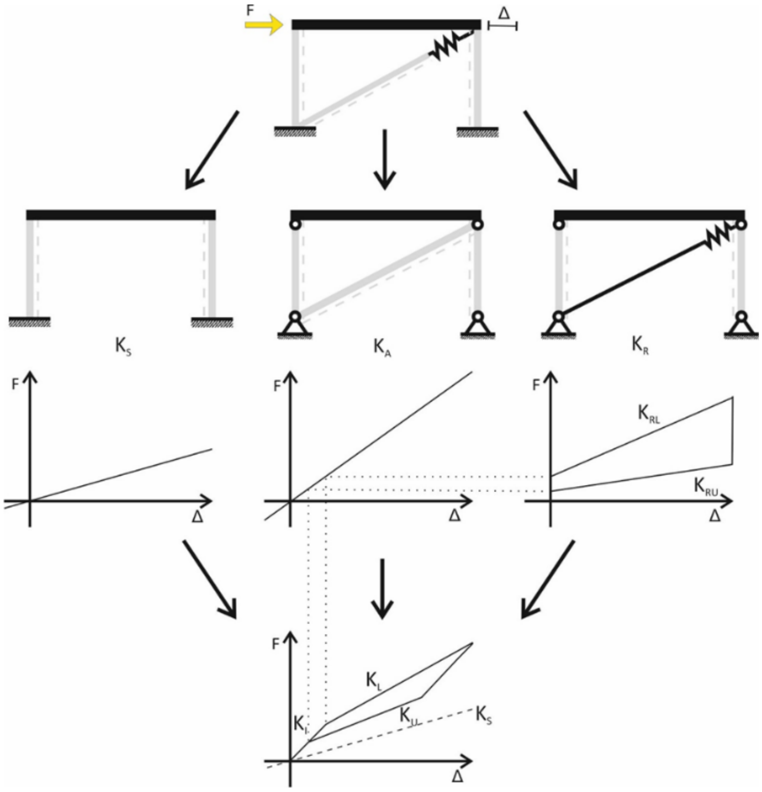


Figure 3: Load-deformation measurement of a double-acting ring spring

A measurement is shown in figure 3. The expected hysteresis curve is reliably reproduced by the experiment. The hysteresis is generally independent of the loading velocity (Ringfeder), which is to be investigated with further experiments at the university.

EFFECTIVE STIFFNESS

The stiffness of a system with bracing and ring springs is made up of several components, as shown in figure 4. The stiffness of the system K_S, the bracing K_A and the nonlinear friction spring K_R itself act. The latter in turn consists of K_{RL} and K_{RU}. The bracing and the friction spring act in series and parallel to the system and thus the nonlinear force-deformation curve can be calculated. The initial stiffness K_I, the loading K_L and unloading K_U stiffness are given in Figure 4.



$$K_I = K_S + K_A$$

$$K_L = K_S + \frac{K_A\, K_{RL}}{K_A + K_{RL}}$$

$$K_U = K_S + \frac{K_A\, K_{RU}}{K_A + K_{RU}}$$

Figure 4: Stiffness of a system with bracing element replaced by ring spring

EFFECTIVE DAMPING

Ring springs have damping of approximately 66 %. However, this value refers to the amount of the restoring force and thus describes the hysteresis or the force-deformation curve. For oscillatory systems, the degree of damping, also known as Lehr's damping coefficient, is commonly used. Despite this value being defined for linear vibration equations with viscous damping, an analogous value can be determined. For this purpose, the logarithmic decrement or the hysteresis curve can be utilized to quantify the damping for a better characterization of the vibration behavior.

Figure 5 shows the work done over the displacement without preload. Here, W_S is the work of stiffness and W_D is the work of damping. From their ratio, the degree of damping can be estimated.

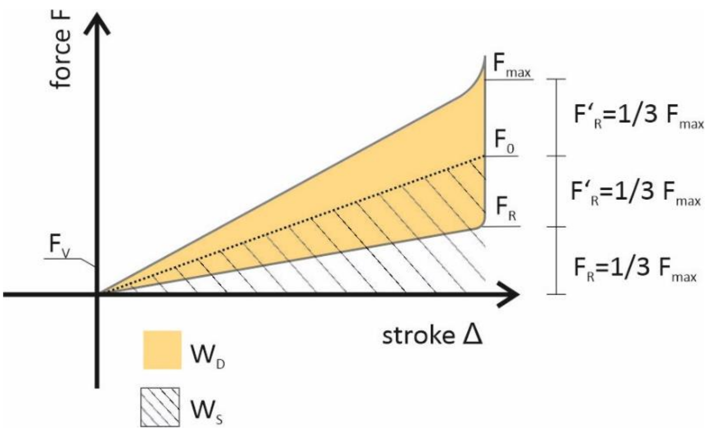


Figure 5: Work done, W_S work of stiffness, W_D work of damping [2]

$$\xi = \frac{2\,W_D}{4\pi\,W_S} = \frac{2\,\frac{2}{3}\,\Delta}{4\pi\,\frac{2}{3}\,\Delta} = \frac{1}{2\pi} \approx 16\,\%$$

This simple consideration results in approximately 16 %, though the preload cannot be counted for this approach. In an alternative analytical approach, the vibration amplitudes are calculated. The logarithmic decrement subsequently provides the damping factor through the reduction of the amplitudes. Initially, the range of the preload is calculated. In this case, the constant spring force $-F$ is assumed for small displacements. The mass m starts at the displacement Δ_0 and is now accelerated to the maximum velocity v by the constant spring force. The new amplitude $\Delta_{0,5}$ can then be calculated based on this, as shown in figure 6.

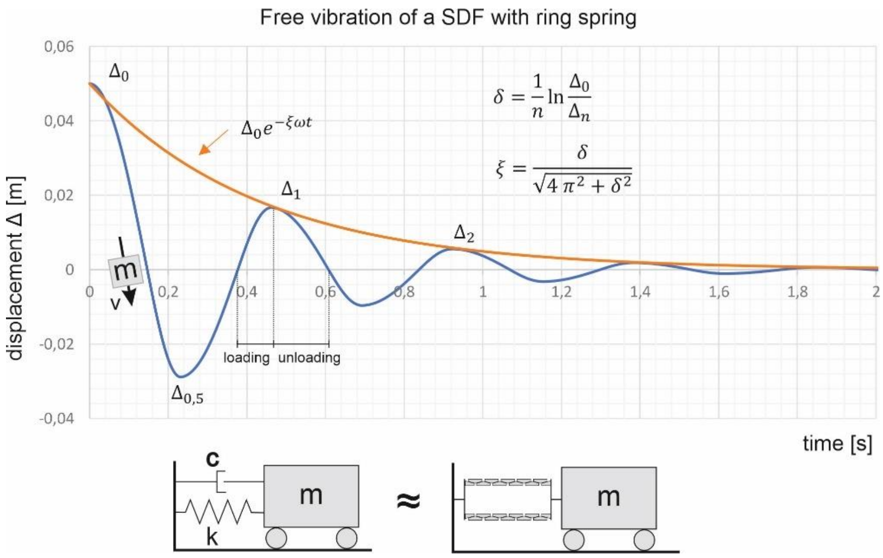


Figure 6: Free vibration of a single degree-of-freedom system (SDF) with ring spring

$$v = \sqrt{\frac{2}{3}\frac{F}{m}\Delta_0}$$

$$\Delta_{0,5} = \frac{v^2}{2}\frac{m}{F} = \frac{1}{3}\Delta_0$$

$$\delta = 2\ln\left(\frac{\Delta_0}{\frac{1}{3}\Delta_0}\right) = 2\ln(3)$$

$$\xi = \frac{2\ln(3)}{\sqrt{4\pi^2 + (2\ln(3))^2}} \approx 33\,\%$$

This results in a significantly higher damping of 33 %. The same procedure is now used to calculate friction springs without preload and the spring force is hence considered to be linear.

$$v = \Delta_0 \omega \sin(\omega t) = \Delta_0 \sqrt{\frac{\frac{1}{3} K_{RL}}{m}}$$

$$\Delta_{0,5} = \frac{v}{\omega \sin(\omega t)} = \sqrt{\frac{1}{3}} \Delta_0$$

$$\delta = 2 \ln \left(\frac{\Delta_0}{\sqrt{\frac{1}{3}} \Delta_0} \right) = 2 \ln(\sqrt{3})$$

$$\xi = \frac{2 \ln(\sqrt{3})}{\sqrt{4\pi^2 + (2 \ln(\sqrt{3}))^2}} \approx 17\ \%$$

This approach provides damping of 17 % and corresponds approximately to the calculation with the work done. The damping is between 17 % and 33 % depending on the preload. [2]

SUMMARY

This paper gives an overview of the properties and effective damping of ring spring dampers. Implementing the ring spring damper as one of the energy dissipation devices is not very well investigated by the structural engineers, one of the features, which distinguishes the ring spring damper among the other dampers, is the ability to maintain under function with high resistance after the cracking of rings. The stresses are distributed equally over the cross-section. The advantage of these springs is that they can absorb a large amount of impact energy in a structure, independently of deformation velocity. The investigation shows that the damping is approximately 16 % up to 33 % considering the preload. In addition, the nonlinear force-deformation curve can be calculated. A system equipped with ring springs can withstand an earthquake without major plastic deformation and damage, thus makes a significant contribution to investment protection (economic efficiency) and the sustainable use of scarce materials and resources. Especially in the nuclear field, high reliability is of great importance.

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