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Experimental tests on dissipative device based on U-shaped plates for seismic isolation systems

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ABSTRACT
Seismic isolation systems often need of auxiliary dissipation devices in order to limit the forces transmitted to the superstructure and, most of all, in order to reduce the maximum displacement of the system. Such auxiliary devices should be simple to design and to realize, inexpensive and easy to replace. In this work, the behaviour of a dissipative device equipped with U-shaped steel plates is studied, such device dissipates energy by the means of the inelastic behaviour due to the bending of the plate. The principle of working and some simple design formulae to define the principal characteristics of the device are described. The results of an experimental test campaign executed on a dissipative device based on U-shaped plates according to EN15129 are shown. By using the data provided by such experimentation, the performances of the device and its effectiveness as auxiliary damper are commented. Finally, some critical observations about the effectiveness of the available design formulae are carried out.

1 INTRODUCTION

The seismic isolation is one of the most effective technique for the protection of earthquake prone buildings. This technique aims to reduce damage to buildings by decoupling them from the ground through the use of flexible devices, thus increasing the structural period of the system (Skinner et al. 1993; Naeim and Kelly 1999). As a counterpart, the shift of the periods means a consistent increase of the displacement demand on the devices, that may result in high cost of the system or, in the worst cases, may lead to the impracticability of the seismic isolation (Ryan and Chopra 2004; Laguardia et al. 2019). The displacement demand can be reduced by the means of supplementary energy dissipation within the seismic isolation systems (Kelly 1999).

Nowadays have been developed many types of seismic isolators, based on different technologies and able to provide different kind of behaviour and a certain amount of energy dissipation (Buckle and Mayes 1990; Ibrahim 2008). Moreover, there are also several devices developed to be used exclusively as dampers (Aiken et al. 1993; Soong and Spencer Jr 2002; Spencer and Nagarajaiah 2003). The energy dissipation can be obtained in many different ways, by the means of viscous or visco-elastic materials (Constantinou et al. 1993), by exploiting inelastic deformations of metals (Dolce et al. 2000; Renzi et al. 2007; Braconi et al. 2012) or by friction (Pall and Marsh 1982). Despite the enormous development over the years of these devices, they have been mainly used as dissipative systems to be positioned in elevation on the structure, usually together with stiffening systems such as braces. Studies on the application of these devices in parallel to isolation systems although present (Constantinou et al. 1993; Nielsen et al. 2004), are less numerous.

In this work, the behaviour of a U-shape dissipative device is investigated, whose dissipative properties are related to the hysteretic behaviour of the steel. The main advantage of this device is given by the optimal trade-off between affordability and effectiveness. On the other hand, some issues related to its design criteria and to its reliability are still in discussion.

The first idea of this kind of device was formalized in the 70's of the past century by (Kelly et al. 1972). Despite the idea has been formalized many years ago, there are only few developments within the scientific literature (Oh et al. 2013; Baird et al. 2014). In particular, in the design practice the U-shaped device are commonly used as dampers within stiffening intervention, while there are only few theoretical and practical developments about the use of such devices as auxiliary dampers within seismic isolation systems (Oh et al. 2013). This involves the lack of information about the reliability of these devices for high displacement demand, such as those normally required by an isolation system.

In this paper, the general behaviour and some simple rules for the design of U-shaped device are described. Further, the results of some experimental tests for high displacement demand (d_{bd}>300mm) performed according to the European code EN15129 (European Commission 2009) are shown, in order to investigate the suitability of such devices within seismic isolation systems. The experimental results are used to discuss the dissipative properties of the system and the effectiveness of the available design formulae, even considering the specific behaviour of the adopted steel plates.

2 GENERAL BEHAVIOUR OF THE U-SHAPED DEVICES

In Figure 1 it is schematically represented an example of a U-shaped device, placed between two supporting members. The specimen is formed by bending a steel plate around a support with fixed radius in order to form the characteristic U-shape. The possible ways of processing the plate are numerous, the plate considered herein have undergone a cold-working process.

The curvature of the plate is related to its thickness, t_f, and the radius of curvature, R_a, by using the following expression:

$$\varepsilon_r = \frac{t_f}{2R_a} \tag{1}$$

In Figure 2 the schematic ideal behaviour of the U-shaped plate is shown, by assuming, for the sake of simplicity, that the shape of the plate during the motion is not affected by the strain variations due to the effective stress state. By considering the device at rest (Figure 2 left), some sections are deformed with a maximum deformation equal to ε_r, while others are assumed as not deformed because they lie on the straight section of the plate. By applying a relative displacement Δu between the two supporting elements (Figure 2 right), the U-shaped plate rolls and some sections move on the deformed part of the plate and bend, while others straighten up and lie on the straight part of the plate. The internal forces on the plate are related to this continuous bending and straightening of the sections. Such internal forces are schematically represented in Figure 3. In (Kelly et al. 1972) are proposed some analytical expression to assess the maximum force in the dissipator, F_p, by assuming that the maximum bending moment, M_p is the plastic moment of the plate section:

$$M_p = \frac{\sigma_p b_f t_f^2}{4} \tag{2}$$

$$F_p = \frac{M_p}{R_a} \tag{3}$$

where σ_p is the working stress of the steel and b_f is the width of the plate.

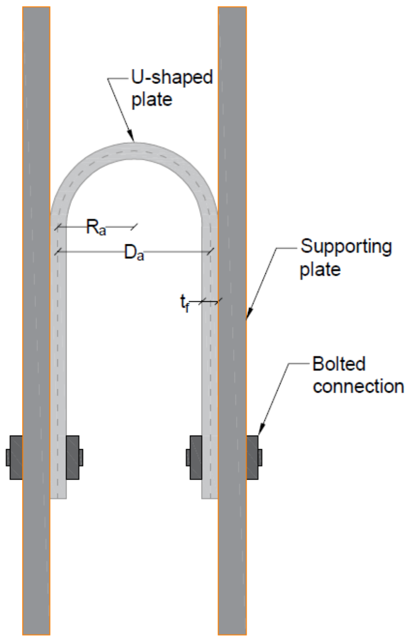

Figure 1. Typical arrangement and geometrical properties of U-shaped device.

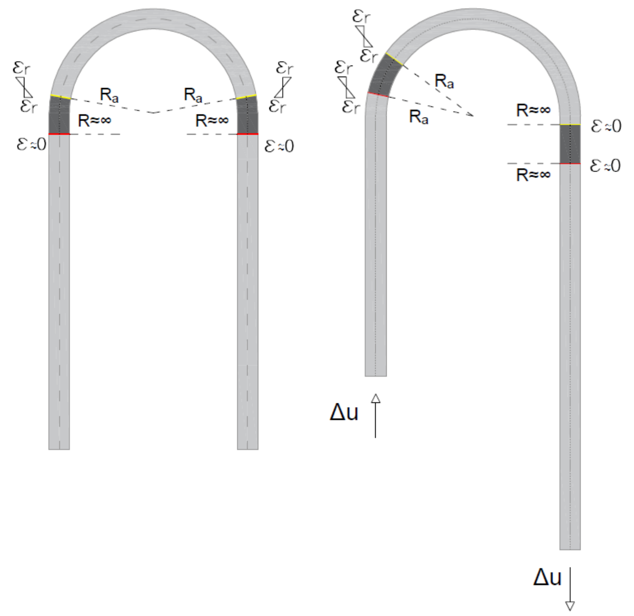

Figure 2. Ideal Schematization of the flexural behaviour of the plate.

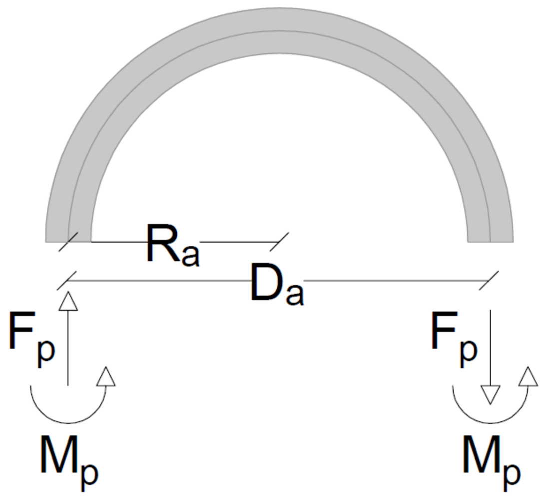

Figure 3. Internal forces of the U-shaped plate

3 DESIGN OF THE U-SHAPED DEVICES

As described in the previous section, the dissipative properties of the U-shaped device are related to the characteristics of materials and to the geometry of the plate. The most utilized materials for these applications are mild steels or stainless austenitic steels. In this work, it has been chosen to use austenitic steel due to their very high performances in terms of strength, ductility, resistance to corrosion and good suitability for cold bending. In the following will be shown the material and geometric characteristics of the plate adopted for the experimental test exposed herein.

3.1 Materials

The U-shaped device realized for this work is made of AISI316 austenitic steel. In Figure 4 it is shown the stress-strain relationship of the adopted material, represented by the means of the Ramberg-Osgood model (Ramberg and Osgood 1943), whose parameters has been calibrated on the base of the specifics given by the steel manufacturer:

$$\varepsilon = \frac{\sigma}{E_0} + a\left(\frac{\sigma}{\sigma_0}\right)^n \qquad (4)$$

where σ is the stress, ε is the deformation, E_0 is the initial stiffness (i.e 210000 MPa), while *a*, σ_0 and *n* are the parameters obtained by regression on experimental data, here considered equal to 0.002, 283MPa e 6.16, respectively.

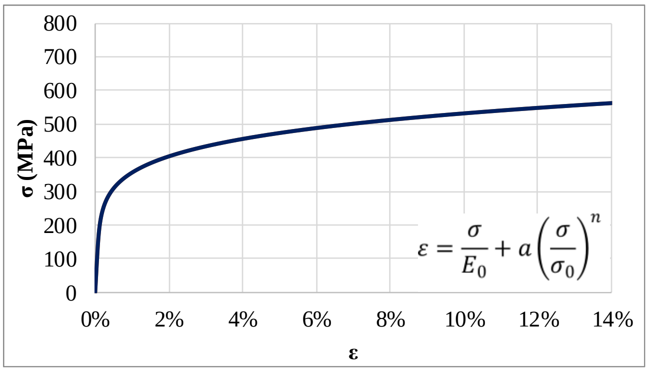

Figure 4. σ-ε relationship for the steel plate (AISI 316) of the dissipator by using the Ramberg-Osgood model.

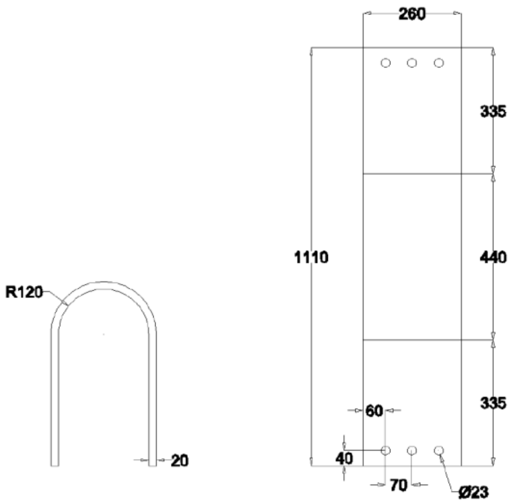

Figure 5.Geometry of the U-shaped plate tested in this work.

3.2 Geometry

Once fixed the material properties, the geometry of the plate rules the maximum force in the device. In Figure 5 it is shown the geometry

selected for the device, with a plate thickness t_f=20mm, a plate width b_f=260mm, an internal radius of curvature, R_i=120mm and a total length of the plate L_{tot}=1110mm.
Given these geometric properties, the maximum strain of the plate, by considering the average radius, R_a=130mm, is equal to ε_f=7.7%. The expected tension, obtained through Eq.4 is equal to 509MPa, thus the maximum force in the device is assessed through Eq. 3 and is equal to 102kN.

4 EXPERIMENTAL TEST CAMPAIGN

The experimental test discussed herein have been performed in the Laboratory of University of Basilicata (Potenza, Italy). The goal of the experimental test was to check the effectiveness of a device equipped with a couple of U-shaped plate. The results shown here are referred to only one specimen of a broader experimental campaign conducted on 7 specimen of plates with different characteristics, aimed to define the influence of the plate design on the performance of the system. In order to perform such experimental campaign, a specific casing structure has been designed to house two plates in parallel and to be able to carry out tests on several plate geometries. In Figure 6 it is shown a picture of such device during the tests.

4.1 Testing protocol

According to the european code EN 15129 (European Commission 2009), the U-shaped device belongs to category of displacement dependent device (DDD) with a non-linear behaviour (NLD). In Table 1 the testing protocol according to the EN 15129 is shown, it foresees 3 cyclic tests at an increasing level of displacement and one other monotonic test (#4) in order to assess the maximum displacement capacity of the device. The tests were conducted at low speed (v=5mm/s) due to the substantial insensibility of the steel behaviour to the strain rate.

Table 1. Testing protocol adopted for the devices according to EN 15129 (European Commission 2009).

Test	n. cycles	d_{max}	
N°	\		mm
#1	5	25% d_{bd}	83.33
#2	5	50% d_{bd}	166.67
#3	10	100% d_{bd}	333.33
#4	0.5	$\gamma_x\ \gamma_b\ d_{bd}$	440

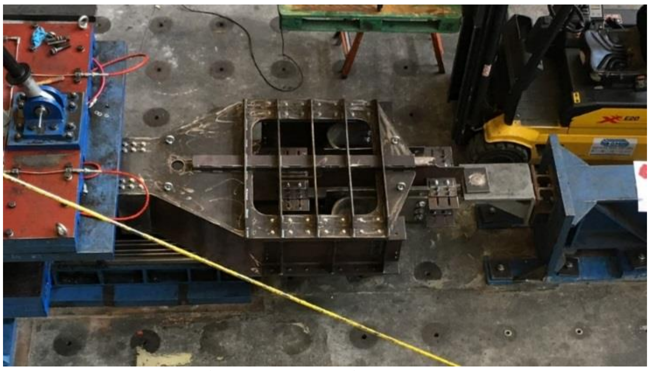

Figure 6. Picture of the casing of the U-shaped device taken during the tests at the University of Basilicata.

4.2 Experimental results

In Figure 6 are shown the force displacement relationship obtained for the 3 cyclic tests and the relative applied displacement histories. It can be seen that the force displacement relationship has a quite smooth and stable shape along the tests.
By observing the maximum force history, shown in Figure 7, it can be seen that the maximum force in the device tends to increase with the number of cycles. Specifically, the maximum force is equal to 169kN at the first cycle while it is 242kN at the last cycle (i.e. 10th cycle of the third test). This means that the maximum force increase is of about 43% during the test and after 20 cycles. This increase is consistent with other literature reference (Baird et al. 2014) and it could be explained with the cyclic hardening of the adopted austenitic steel (Dutta et al. 2010; Pham and Holdsworth 2011; Xie et al. 2019). Nevertheless, in Figure 8 it is shown the ratio between the maximum force recorded at the maximum displacement at each cycle and the design force obtained through Eq.3 (i.e. F_d=204kN). It can be seen that the maximum force in the device is overestimated of about the 17% in the first cycle of motion and, as a counterpart, it is underestimated of about the 19% during the last cycle of the tests.
In Figure 9 the trend of dissipated energy is shown for each cycle of the test, this value is almost constant within each test, with variations among the cycles lower than 10%, providing an equivalent damping ratio of about 53% at the third cycle of Test #3. It should be noted that, as the displacement demand increase, new sections yield, therefore the number of cycles done by each section is not always the same number of cycles of the device. For this reason and by considering the

hardening of the material, the first cycles of tests # 2 and # 3 exhibit a slight reduction in strength.

Finally, the results of the test #4 are shown, proving that the device has shown enough displacement capacity without any malfunction.

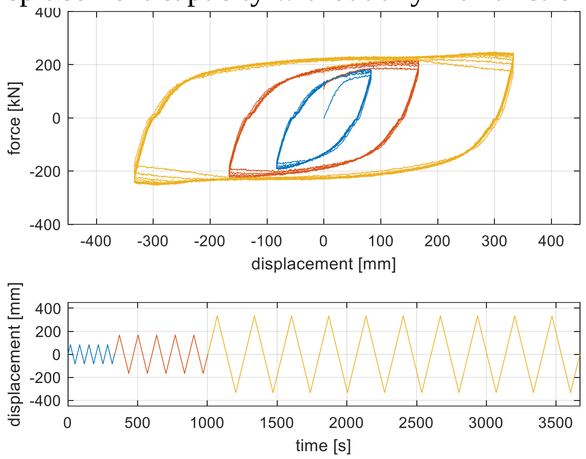

Figure 6. Force-displacement obtained from the experimental tests (top) and applied displacement history (bottom).

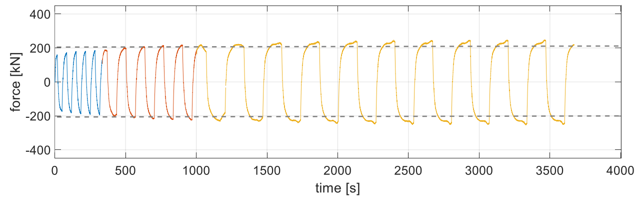

Figure 7. Force history obtained from the experimental tests.

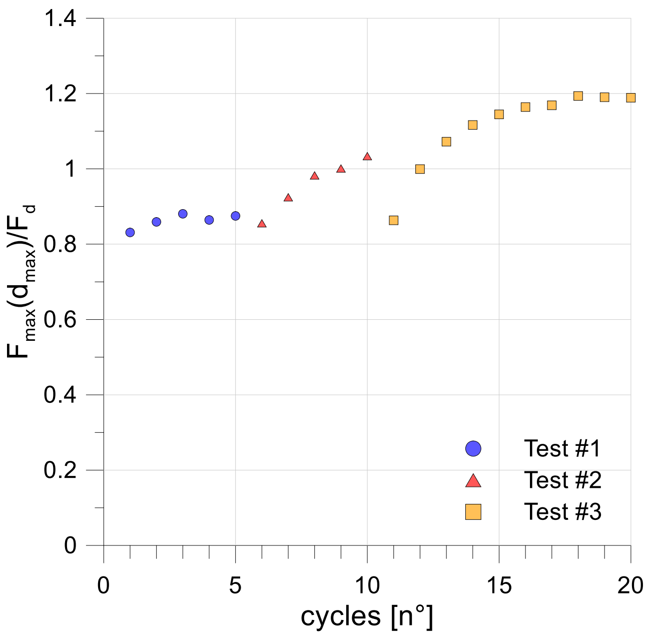

Figure 8. Ratio between maximum force recorded for the design displacement and design force (F_d=204kN) for each cycle along the three tests.

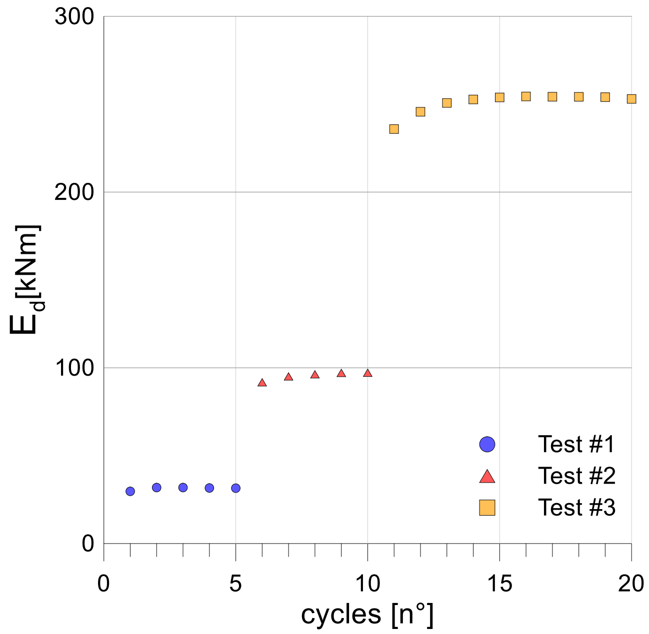

Figure 9. Energy dissipated calculated for each cycle along the three tests.

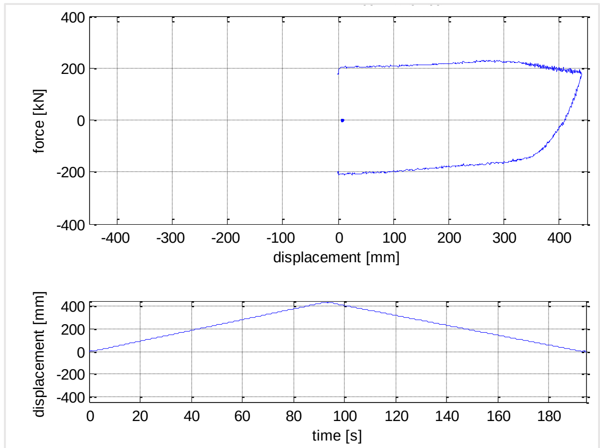

Figure 10. Force-displacement obtained from the experimental tests.

5 CONCLUSIONS

In this work the characteristics of a dissipative device equipped with U-shaped plates to be used as an auxiliary damper for a seismic isolation system has been studied. Some formulae for its design have been shown, based only on the geometry of the plates and on the characteristics of the stress-strain relationship of the austenitic steel plate adopted. The comparison with experimental tests carried out according to UNI EN 15129 on an example device, showed how these simplified formulations provide a useful but approximate evaluation of the maximum force in the device with errors up to 18%. Nevertheless, the dissipative characteristics of the device were satisfactory, with an equivalent damping ratio of about 50% or higher for the design displacement d_{bd}=333mm. Furthermore, the dissipative properties were very stable over the cycles, with variations in the energy dissipated lower than 10% in each single test runs. Therefore, the device has proved to be effective in fulfilling its functions also in the presence of large displacement demands, such as those required by a seismic isolating system. Whilst the simplified formulations for its design have proved to be a useful tool that does not allow to fully grasp the features of the device, in particular due to the cyclic hardening, which involves a continuous variation of the steel tension. In conclusion, this device appears as an interesting solution to provide auxiliary dissipation within seismic isolation systems, fulfilling the requirements of efficiency and cost-effectiveness, given the observed performances and the entirely steel composition which greatly limits its cost.

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