OPTIMAL SET-UP CONFIGURATION FOR TESTING STIFF ENERGY-DISSIPATING DEVICES UNDER LARGE DISPLACEMENTS

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Abstract: *This article presents the design and use of an auxiliary structure ("set-up") to perform cyclic tests on energy-dissipating devices. The quality of the test set-up is just as important as the device being tested, as it is impossible to accurately evaluate a device or specimen without a set-up of excellent quality that has undergone thorough a precise design itself. In this case, the devices tested are SLB energy dampers, which are dissipators that predominantly work under shear deformation. Testing these devices is complex due to their high stiffness and the second order effects that appear under large deformations. There are very few machines that would allow the testing of these devices in their proper boundary conditions and their cost and complexity are high. This study aims to demonstrate an optimal configuration for evaluating the performance of these devices or similar. In this case, the specimens were tested using a +-1000 kN press machine. Since the motion range of the hydraulic press is vertical, the set-up must support the devices horizontally as cantilevers allowing the press to generate a shear load. The set-up must allow free deformation in the plane of the device. To achieve this, a complementary auxiliary structure was designed to provide lateral stability to the device throughout the entire loading protocol. Furthermore, the entire set-up must be rigid to ensure negligible out-of-plane deformation and should remain elastic during the entire test so that it can be reused. This implies additional difficulty considering the large loads and deformations intended in the device (± 100mm). Different test configurations are studied to obtain the most optimal set-up that verifies all the requirements listed above. Finally, it is shown how the optimal set-up is applied in a set of 20 tests for the mechanical characterization of the SLB Devices studied. The paper shows the experimental results obtained on the most demanding tests (force and displacement), including the hysteretic curves of the devices and the response of the set-up throughout the tests.*

1. Introduction

The conventional method of safeguarding structures against earthquake forces is inefficient, as it demands that all structural elements be highly ductile to ensure a high level of protection, which intrinsically results in structural damage following a seismic event. Since the 1980s, many systems have been studied to ensure a more efficient approach to seismic design in order to design structures that can withstand seismic forces with very little structural damage and cost of reparation (Aiken et al., 1993; Bozzo and Barbat, 1999; Symans et al., 2008).

Many types of earthquake protection systems can be used to absorb and dissipate seismic energy. In this paper, we focus on the study of passive devices, particularly on shear-predominant steel dissipators, and how to adequately test them. Some of these devices are very difficult to set up for testing and a large-scale building simulation using a shaking table can be more effective to ensure proper boundary conditions. The devices studied in this paper are the SLB, a steel device which consists of very stiff plates to enhance the ductility of structures, making them ideal for protective purposes. This same advantage of high stiffness also makes them very complex to test under large deformations as the auxiliary structure to support them must be much stiffer to avoid any excess movement (LADICIM, 2020; LNEC, 2000)

The tests in this study were conducted at the University of Lima, Peru. A +-1000kN hydraulic press machine was used, as shown in Illustration1. Since the motion range of the hydraulic press is vertical, the set-up had to support the devices horizontally as cantilevers, allowing the press to generate a shear load. This required a complementary auxiliary structure to provide lateral stability to the device throughout the entire loading protocol.

Illustration1 University of Lima Hydraulic Press Machine

One of the key requirements for the set-up was that it had to allow free deformation in the plane of the device. This was achieved by designing the auxiliary structure that provided the necessary lateral stability while still allowing the device to deform in the desired plane. Additionally, the entire set-up had to be rigid to ensure negligible out-of-plane deformation and was required to stay elastic during the entire test so it could be re-used. This was particularly challenging considering the large loads and deformations intended for the device (±100mm).

This study shows the different test configurations that were explored and how the most optimal auxiliary structure was designed and selected to meet all the requirements listed above. Finally, it is shown how the selected “set-up” is tested with the SLB devices and the results are presented, including the hysteretic and monotonic curves of the devices, as well as the response of the set-up throughout all the tests.

2. Description of shear devices and test procedure

Shear energy-dissipating devices are a type of structural component designed to absorb and dissipate energy during cyclic loading. These devices are commonly used in various applications such as seismic protection systems for buildings, bridges, and other structures. They are specifically designed to withstand large displacements and provide effective energy dissipation, thereby reducing the impact of dynamic loads on structures.

Testing shear energy-dissipating devices is crucial to ensure their performance and reliability. However, under large displacements, this task can be challenging due to their high stiffness and complex nonlinear behaviour. Traditional testing methods may not be suitable or cost-effective for these devices, as they often require specialized equipment and set-ups or very high-cost large-scale testing.

Some specialized machines are designed to simulate the real-life conditions that these devices will experience during earthquakes or other dynamic events (SISTEM machine, Franchioni, 2001). They are capable of applying different types of loads, such as shear, compression, and tension, to the devices in a controlled manner. These machines can also measure and record various parameters, such as displacement, force, and acceleration, allowing researchers to analyze the performance of the devices under different conditions. By using these machines, researchers can confirm that the energy dissipators and base isolators meet the requirements and can effectively protect structures from seismic forces. However, these machines are extremely expensive and have many limitations, such as space and force; therefore, not many laboratories are equipped with them (Franchioni, 2001).

An optimal and cost-effective setup configuration is essential for promoting the use and testing of shear energy-dissipating devices. This set-up configuration should allow for the devices to be tested in their desired boundary conditions, while also providing the necessary support and stability. Additionally, the set-up should allow for free deformation in the plane of the device, while minimizing out-of-plane deformation.

Typically, a hydraulic press machine with a vertical motion range is most commonly used to test these devices. Therefore, it is necessary to have a set-up that supports the devices horizontally as cantilevers, allowing the press to generate a shear load. To achieve the desired condition of free deformation, a complementary auxiliary structure is designed to provide lateral stability to the device throughout the entire loading protocol.

The devices tested in this article (SLB Dissipators) have been studied since the beginning of the 2000s. Many auxiliary configurations have been used to accurately represent the boundary conditions required by the devices, as they changed with the continued development of the devices. This includes the use of specialised equipment as mentioned previously (Franchioni, 2001), different dynamic tests (Bozzo, 2018) (UNAM, 2017), and multiple tests using hydraulic press machines.

In 2015 the SLB dissipators were tested in the University of Naples Parthenope. At that time, the boundary conditions of the devices were fixed on both sides through bolt connections, and, in order to accurately test them, an auxiliary support was designed that would allow the constraint of the devices and the application of the deformation in the desired plane of work (Illustration 2*Illustration 4. First steel frame set-ups*) (Nuzzo et al., 2017). That set up was only used in that set of tests due to its limitations. Firstly, it only allowed bolt connected devices with double fixed boundary condition and secondly, the distance between both connections had a very small range of motion, making impossible to test larger devices. Both limitations listed above forbid this setup from being useful in further testing as the devices require flexibility in geometry and boundary conditions and has not been used again.

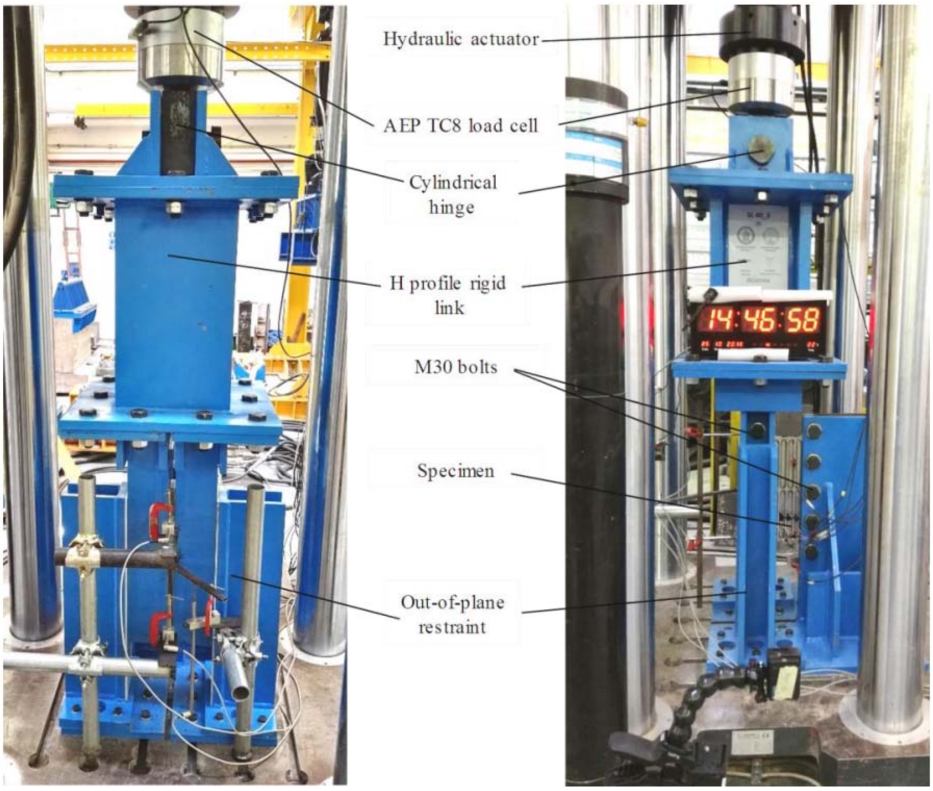


Illustration 2 Auxiliary structure configuration (extracted from I. Nuzzo Phd Thesis)

As SLB dissipators have evolved in order to reach higher maximum displacement capacities, so have their boundary conditions. Shortly after 2015, the idea of working with them in a double-fixed condition was abandoned, and a “comb” connection emerged that allowed for one end to be articulated while also transferring the shear load to the dissipator. This connection resulted in a significant increase in the difficulty of testing the devices on a small scale (on a large scale, they have been tested by constructing concrete frames installed with the dissipators and tested on a shaking table (Bozzo, 2018). Owing to the design of the auxiliary structure presented in this study, it was possible to test the devices with their “comb” connection. The tests, carried out at the University of Lima, started on November 2022 and the same auxiliary configuration has been used to date with very few fixings, and with over 20 tests on different devices that required displacements of +-100mm and over 700 kN.

3. Methodology

We utilized a combination of industry-standard codes to accurately design the auxiliary structure, as its adequate behavior is essential for conducting reliable energy-dissipation tests. Our approach involved adhering to the AISC 360-16 code for designing the connections and the loading protocols for the devices, and ASTM 370-21 to define the test tube geometry required to characterize the mechanical properties of the steel components.

The AISC 360-16 code served as the cornerstone for our structural design, ensuring that the connections within the dissipator set-up are engineered to meet rigorous safety and performance standards. By following this code, we could guarantee the structural integrity of the connections, which is paramount for the reliability of the tests and its reuse for further tests. To determine the loading procedures and protocols, the AISC 330-16 provided comprehensive guidelines for applying forces and stresses to buckling-restrained braces (BRB), very similar to our SLB dissipator (AISC 360, 2016).

The mechanical properties of the steel materials used in the structure were characterized according to ASTM 370-21. This code provided us with the necessary procedures and specifications to measure and assess the properties of steel, such as its strength, ductility, and other essential parameters. These data were crucial to ensure that the structural components met the required standards and could withstand the intended testing conditions.

By integrating these codes into our design and testing processes, we verified the accuracy and reliability of the auxiliary structure in the experiments. The careful adherence to these industry standards not only reinforces the quality of our research but also contributes to the overall advancement of structural engineering practices

To design and manufacture the auxiliary structure we used software tools that would ensure precision, structural integrity, and optimal performance. Our approach involved mainly the following programs: SAP2000, SolidWorks and AutoCAD.

We employed SAP2000 (CSI, 2016) for a comprehensive structural analysis of the entire assembly. This powerful software allowed us to simulate and evaluate the behavior of the dissipator set-up under loading conditions. This enabled us to assess the analysis of the structure with a shell finite element model, integrating non linear properties of the material and the geometry in order to carry out the pushover non linear analysis and a linear eigenvalue buckling analysis.

Once the analysis met the desired requirements, we utilized SolidWorks and AutoCAD for detailed design and fabrication drawings. SolidWorks, renowned for its 3D modeling capabilities, allowed us to create sophisticated 3D representations of the components within the dissipator assembly and even to include hydraulic press machine elements. This facilitated visualizing the design and ensured that all parts fit seamlessly. AutoCAD, on the other hand, was instrumental in generating precise 2D fabrication drawings, offering detailed instructions for manufacturing and assembly.

By integrating these software solutions into our design process, we achieved a synergistic approach that combined accurate structural analysis, validation, and meticulous design documentation. This holistic strategy not only enhanced the quality and performance of our dissipator set-up but also streamlined the manufacturing process, resulting in an efficient solution for our dissipator testing needs.

4. Auxiliary structure configurations

During the design of the auxiliary structure, several alternatives were studied. The purpose of the structure was not only to be able to support the devices during the tests but to be able to reuse the auxiliary structure for different tests and even for different hydraulic press machines. The first set-ups were originally designed for the hydraulic press machine of the University of Stanford and later on, with few modifications, it was adapted to the machine at the University of Lima (*Illustration 3*).

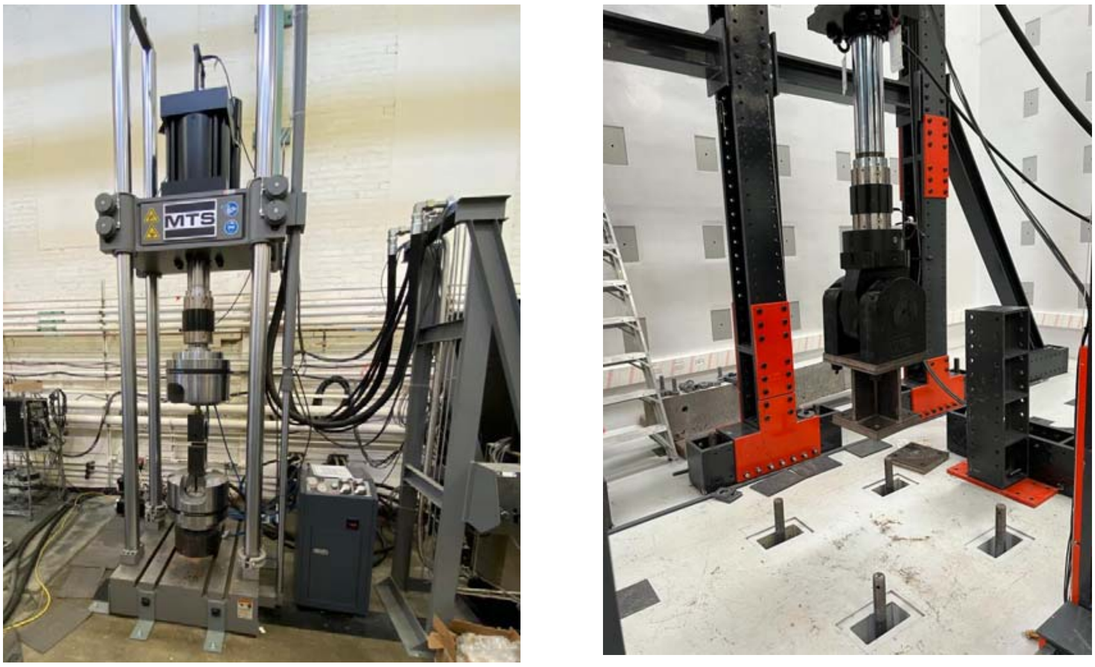


Illustration 3 A)University of Stanford (left) and B)University of Lima (right) Hydraulic Press Machines

As the tests carried out in the devices require the application of cyclic loads, the first approach for the auxiliary support was a symmetric steel frame, that would be able to support both traction and compression loads (*Illustration 4*).

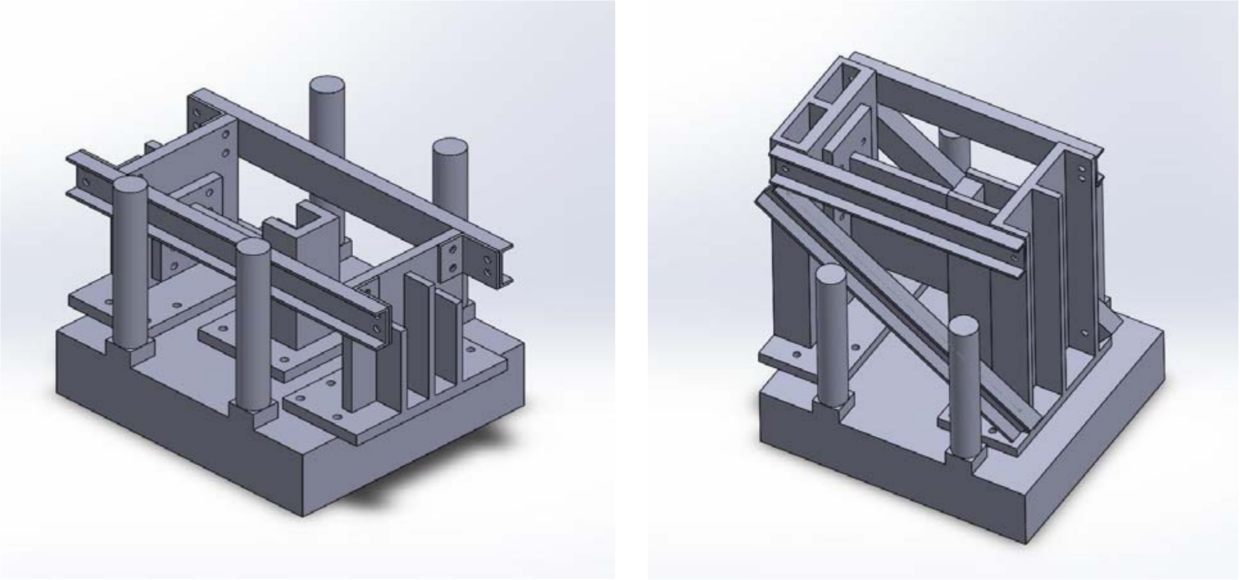


Illustration 4. First steel frame set-ups. A) Simple frame structure (left); B) Diagonal reinforced frame structure (right)

The initial support configuration that was studied (*Illustration 4*(left)) proved to not be rigid enough as the analysis showed that it exceeded the yielding stress of 351.5 MPa, which would have resulted in significant out-of-plane deformations. As a result, an alternative set-up configuration was needed to meet the specific requirements of testing stiff energy-dissipating devices under large displacements. Following the reasoning of a symmetric structure, other *set-ups* were studied, even reinforcing the first steel frame (*Illustration 4* (right)), resulting in very complex set-up configurations that barely fit the stiffness requirements.

At that point, it became evident that the common yielding stress 351.5 MPa was not sufficient for the requirements of the set-up, and high elastic limit steels were studied. Finally, the CHRONIT T-1 400, commonly used in excavator buckets, with a yielding stress of 1000 MPa was chosen. This way, the new setup not only fulfilled the conditions of stiffness required, but it was possible to design a simplified, asymmetrical structure with fewer steel plates, resulting in a setup design that was economical and easier to manoeuvre (*Illustration 5*).

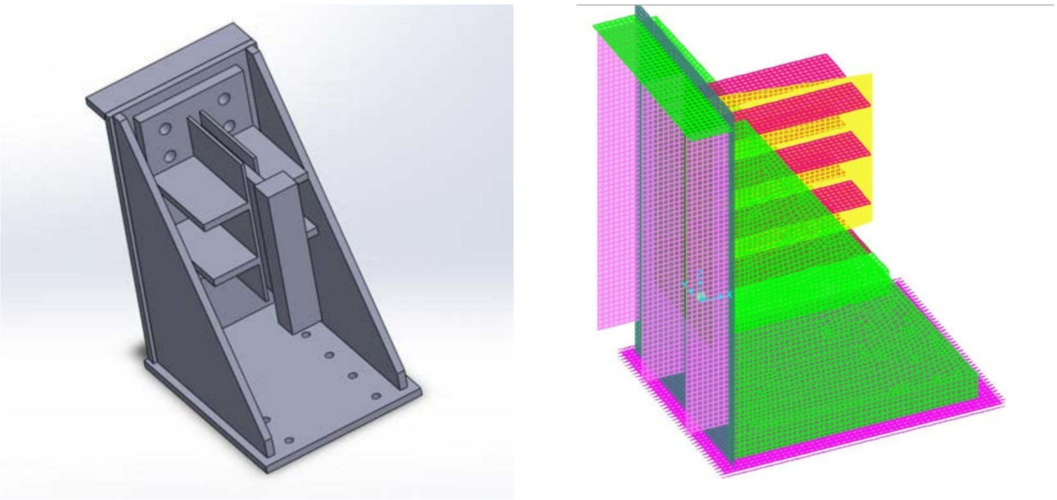


Illustration 5. Final Set-up Configuration. A) SolidWorks Model (left) B)Shell mesh SAP2000 FEM model

The final set-up configuration represents a very efficient structure, as it presents very few elements but still provides high stiffness allowing the SLB devices to be tested without exceeding the elastic limit of the set-up.

The most important aspect to consider when evaluating the auxiliary structure is its stability. The optimal setup must not only provide an elastic response with the minimum displacement possible but also ensure that the interactions/connections: 1) hydraulic press/setup and 2) setup/devices are also elastic. This allows multiple tests to be performed using the same setup. To ensure this, both connections were introduced in the finite element model, defining the contact between the steel plates as a "gap" element and the bolts as linear links so that we could obtain the stress level during the load application. Finally, high resistance bolts were used so no plasticisation occurred in the connections.

5. Data acquisition

Reliable data acquisition in such testing is paramount for accurate analysis and characterization of the devices. This section delves into the process of instrumenting the shear energy dissipator and its auxiliary structure, explaining its constituent components, calibration techniques, and data acquisition methodologies. This study places significant importance on the critical role of auxiliary structures as their use in the paper validates the performance and reliability of the instrument.

To capture all the data during the tests, Linear Variable Differential Transducers (LVDTs) were used allowing all the motions from the device and from the auxiliary structure to be captured. LVDTs are a common type of electromechanical transducer that can convert the motion of an object into a corresponding electrical signal.

Illustration 6 and *Illustration 7* show the LVDT configuration for the tests, using a total of 5 appliances to capture all the main motions during the load application: A) three LVDTs to capture the movements of the tested device, two of them for its vertical displacement and one for the horizontal (out of plane); B) and two to measure the motions of the auxiliary structure, verifying it doesn't give in during the compression or traction loads applied to the devices.

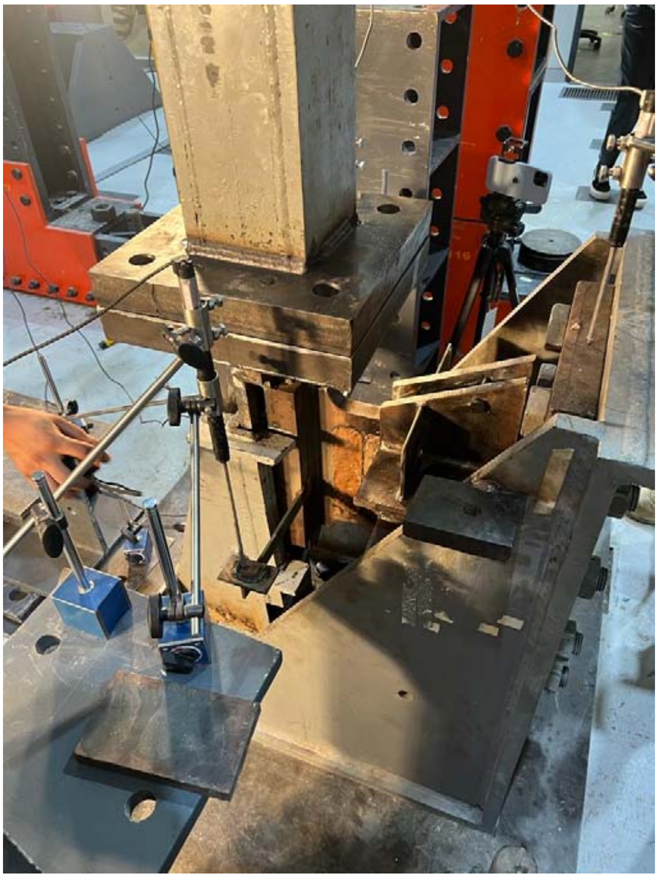
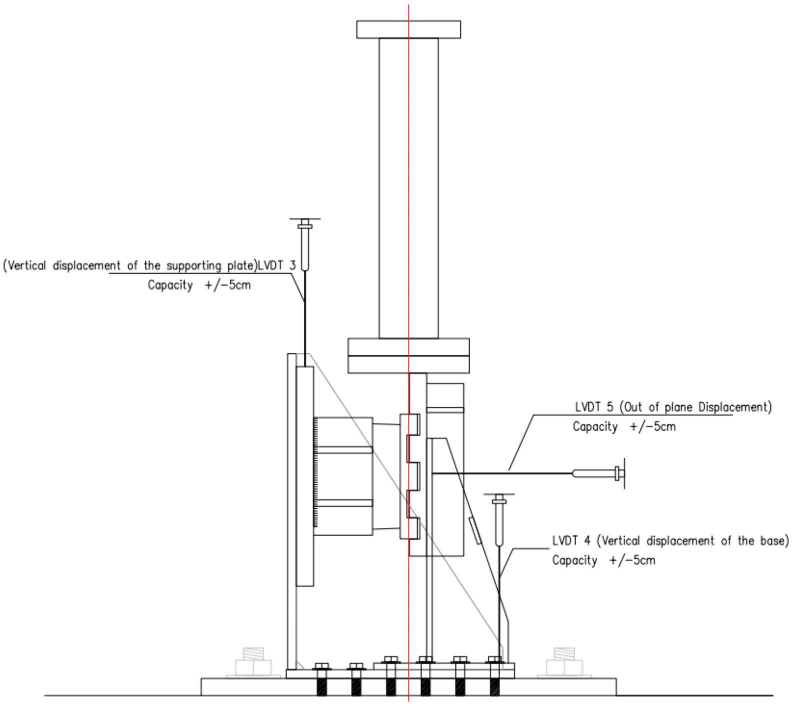
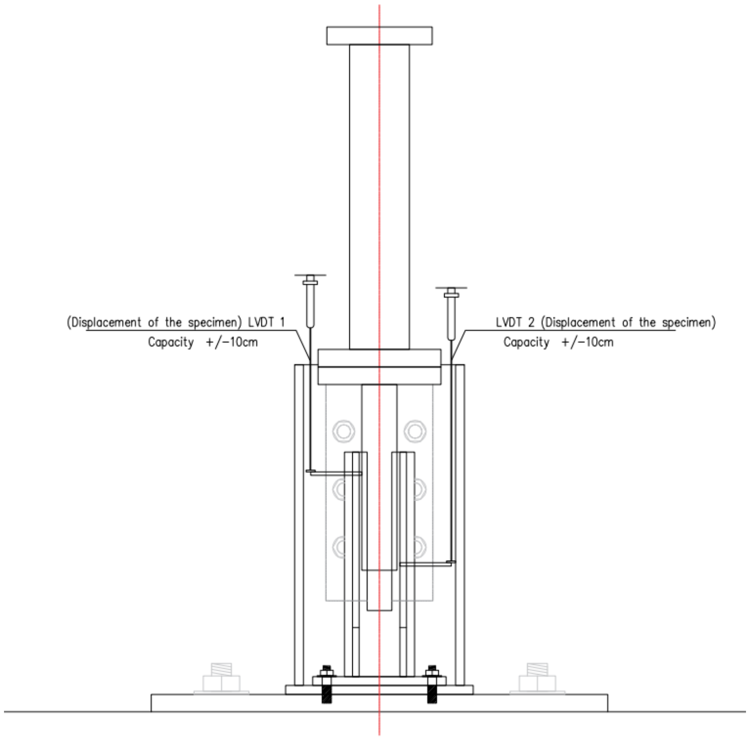


Illustration 6 Instrumentation Set-up



LATERAL VIEW OF THE AUXILIARY STRUCTURE
ELEVACIÓN 1/10



FRONTAL VIEW OF THE AUXILIARY STRUCTURE
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Illustration 7 Drawing of the instrumentation

Over 20 tests have been conducted with the same auxiliary structure for the dissipators, surpassing loads of over +/-500 kN in the majority of the tests and showing no damage or yielding neither in the plates or the bolt connections. Below, the behavior of the set-up is shown during the test that subjected the assembly to the highest deformation during cyclic testing, requiring a load from the hydraulic press of over 500 kN. As mentioned, displacements have been measured using LVDTs, but force has been measured based on the actuator force, as friction losses in this configuration are negligible.

The following results show the data captured for the highest intensity test that was carried out, reaching the highest deformation and force during cyclic loads. The test provided great results, highlighting the stiffness of the auxiliary support, as shown in images Illustration 9 and Illustration 10 with less than 3mm displacements during the entire duration of the test both in the base of the auxiliary support and the vertical element that allows supporting the device as a cantilever. It is important to note that the 85mm displacement reached for a 350mm length device implied significant second order effects that must be accommodated by the auxiliary structure. This second order effects require end rotations at the device interface with the set up and was solved with an special “comb” element, connecting the device to the press machine and allowing the rotation.

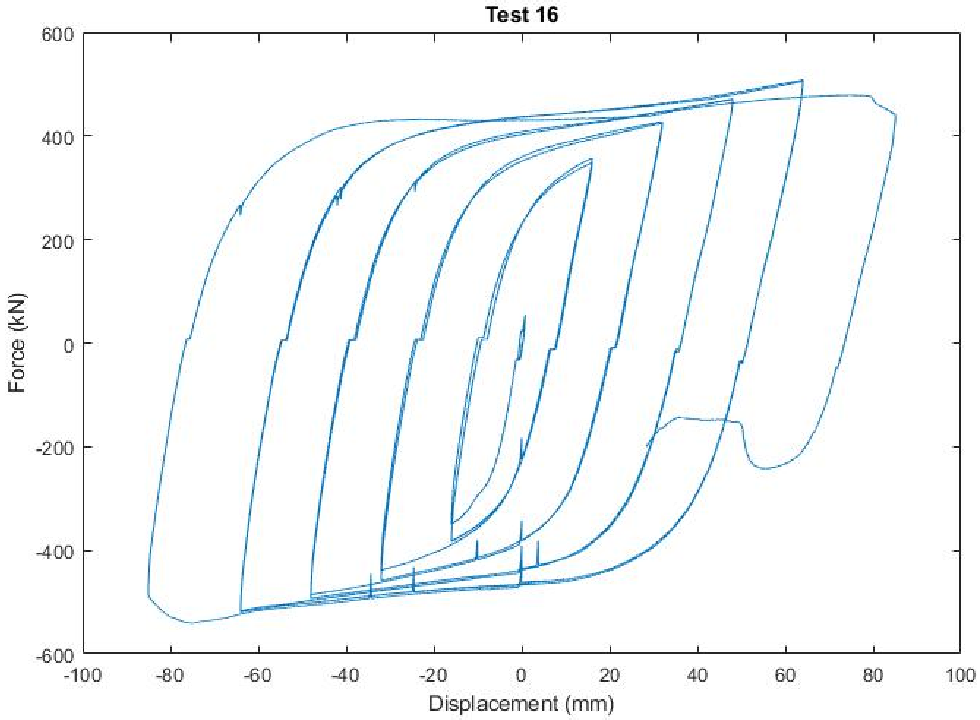

Illustration 8 Test 16, Force-Displacement Measurements in the device

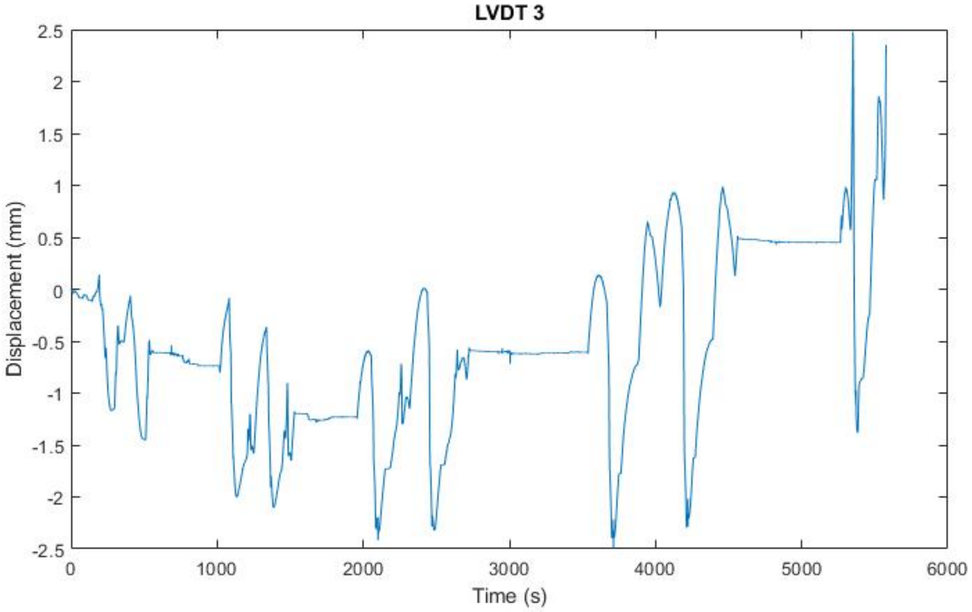

Illustration 9 LVDT 3 Measurements in test 16

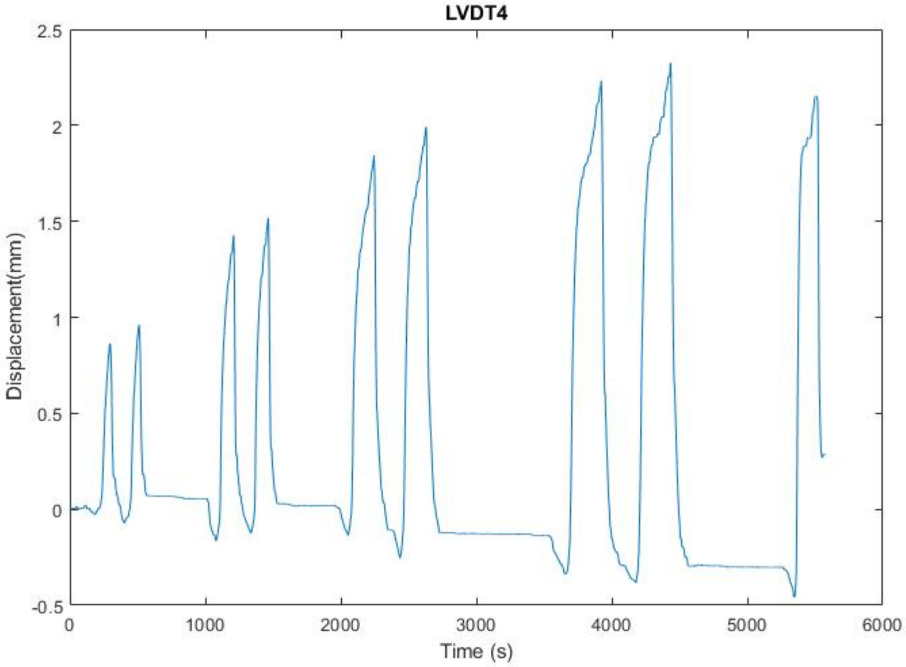

Illustration 10LVDT 4 Measurements in test 16

Illustration 9 and *Illustration 10* provide valuable results regarding the performance of the auxiliary structure as they show displacements of under 3mm in both LVDTs. Those displacements captured by the appliances are attributed to the tolerance of the bolts and they confirm the complete elastic behaviour of both the connections and the plates during the entire duration of the test. Similarly, this elastic behaviour is further confirmed by the successful completion of over 20 tests utilizing the same structure with no observable damage.

6. Conclusions and recommendations

In this study we have explored the critical aspects of manufacturing auxiliary supports for testing stiff energy-dissipating devices, emphasizing the need for an optimal and efficient set-up configuration that meets the demanding requirements of such devices. Our findings can be summarized as follows:

1. **Importance of High-Resistance Materials**: One of the key takeaways from our research is the crucial role played by high-resistance and high-yielding stress materials in the manufacturing of auxiliary support. Shear dissipating devices with high stiffness require the use of materials with exceptional strength properties to withstand the applied forces effectively during their testing. Our investigation underscores the significance of selecting and utilizing such materials to ensure the longevity and performance of these supports.
2. **Design validation**: The design of the auxiliary support was validated as it withstands high loads and displacements without plasticisation, allowing reliable data to be captured from testing. Enduring +/- 700 kN tests show the high stiffness of the auxiliary structure, meeting the initial objectives of an efficient and simple configuration with high resistance.
3. **Design resistance**: We presented the results of extensive testing conducted on the same support system design. It is noteworthy that the support system endured over 20 tests without undergoing plasticization or exhibiting any signs of structural compromise. This remarkable performance serves as a robust validation of the design's efficacy and its ability to maintain structural integrity under the demanding conditions commonly encountered in shear-predominant applications.
4. **Design Adaptability:** It is very important for auxiliary supports to allow different specimens to be tested. In particular, the structure has to be flexible enough to be able to adapt to different geometries. The configuration designed in this paper allowed testing devices from 15 to 40cm high with maximum cyclic capacities from 30 to 85mm.

These conclusions collectively demonstrate the critical role played by material selection and proper design in the successful development of supports for shear dissipation devices. Our research contributes valuable insights to the field, providing a foundation for the continued advancement of such support systems and their application. Furthermore, this study opens avenues for further research, including investigations into alternative high-resistance materials and the optimization of the auxiliary support design for the same or other specific energy-dissipating devices.

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