Development of Energy Dissipating Devices Using Real Time Hybrid Testing

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ABSTRACT :

Dissipative devices aim to absorb seismic energy during an earthquake, thus limiting inter-storey drifts, reducing damage to the main structure and improving the chances of immediate occupancy. Probably the simplest devices are based on yielding and hysteresis of metallic elements. This paper presents experimental work on a recently proposed mild steel shear panel hysteretic device. Its stability, low-cycle fatigue life and dissipative capacity are explored. Thermal imaging is used to view the energy flow through a cyclic test to destruction. Hysteretic capacity and low-cycle fatigue life are determined through a series of cyclic tests at constant strain amplitude. Finally, the performance of the device under repeated seismic loading is evaluated using the real-time hybrid technique, in which the test on the device is coupled to a numerical simulation of a surrounding structure. The device is shown to have great potential as a seismic energy absorber. Suggestions are made to improve the device through the use of alternative materials in place of steel.

KEYWORDS: Dissipative devices, cyclic testing, hybrid testing, low-cycle fatigue, thermal imaging.

1. INTRODUCTION

Passive seismic energy absorbing devices are a relatively recent innovation and have been gradually incorporated into seismic design, especially over the past 20 years as a structural protection system. From a simplified energy perspective they work by absorbing energy input into a structure that would normally be absorbed by the main structural sections, thus reducing damage to them by lowering inter-storey drift. They are placed in parts of a structure that experience relative movement during an event and work to reduce this motion. Devices tend to be most useful in moderate earthquakes and are used where immediate occupancy is of concern. They offer excellent versatility and have been used with success in retrofit of many structures (Soong and Dargush, 1997; Soong and Spencer 2002).

Metallic devices provide the simplest yet one of the most effective ways of absorbing seismic energy. They absorb energy by yielding sacrificially and once significantly degraded must be replaced. Current metallic yielding devices include the ADAS and TADAS devices (Soong and Dargush, 1997) which work by spreading yielding through the device by bending. Shear panel dissipators have a potential advantage of higher stiffness or energy dissipation for amount material used and the shear mechanism may potentially improve the fatigue life over other metallic devices. The device studied in this paper is a mild steel shear panel originally proposed by Dorka (Schmidt et al, 2004; Dorka and Garcia, 2005) and subsequently tested and developed by Williams and Albermani (2006), Chan et al (2008) and Bonnet et al (2008).

There are numerous energy dissipation devices each with their own inherent advantages and disadvantages. Common to them is that they tend to display strongly non-linear behaviour and often include frequency and temperature dependent effects. Essential to their development is the evaluation of how the device and the complete structure will behave under realistic loading conditions. Due to their nature an experimental approach to determine critical properties such as hysteretic capacity, strain rate, thermal response, stability and fatigue life is required. Currently the most common tests carried out on devices are quasi-static or dynamic, multiple strain cyclic tests. Less common are constant plastic strain limit tests, which are designed to give an appreciation of the hysteresis shape and fatigue life (Soong and Dargush, 1997). Also random loadings may be applied to the device to determine its fatigue life under seismic loads. Typically the data gathered from the above tests are used to build a numerical model of the device which can be used together with a numerical structural model to determine overall response. The success and accuracy of this approach tends to be limited by how well the device can be numerically modelled or how realistic the random loads applied are. However, large structures may be modelled and the response under multiple loading situations determined cheaply. An alternative approach is to use shake-table testing, allowing a scaled model of the combined structure and device to be tested under realistic seismic loads (e.g. Aiken et al, 1993). Such tests tend to be expensive to carry out and time consuming to set up. The scale of testing is also limited by the size and performance of the shake-table.

A third approach, real-time hybrid testing, aims to combine the benefits of other test techniques (see e.g Blakeborough et al, 2001; Bonnet, 2006). This is particularly attractive for dissipative devices, as it allows the device to be tested at full or large scale without the need for a very large test facility. The physical test of the device runs in parallel with a numerical model of the surrounding structure, with the interface forces and displacements between the physical and numerical sub-structures provided by hydraulic actuators. The test follows a time stepping approach, with interface forces and displacements passed between the numerical and physical parts at each step. For devices without time dependent features such as steel, tests may be conducted pseudo-dynamically. However, to capture thermal and strain rate effects, such as found in visco-elastic devices, real-time testing (i.e. the test duration equals the actual earthquake duration) is essential. Using the hybrid test technique, it is a simple matter to vary the loading to which the structure is subjected to, or to alter the structure within which the device is located or indeed the location the device is placed, making it possible to simulate a wide variety of device operating parameters with one test rig.

This paper presents work on determining the suitability of a newly proposed shear type metallic device for seismic use. It provides the basis for an approach under development to allow numerous similar shear type devices to be quickly and rigorously assessed and compared. For this device the hysteretic capacity, stability and low cycle fatigue life are critical factors that determine its performance. Therefore, a testing strategy is proposed to allow the suitability of the device to be assessed. Firstly, thermal imaging is used to determine how the device uses it geometry to dissipate energy and how well it does this throughout its fatigue life, this progresses to also determining the role temperature measurement plays in monitoring the life of this device. Secondly, a series of constant strain amplitude sinusoidal tests to failure at 2, 5, 10, 20 mm amplitude at 1 Hz are presented to determine the low-cycle fatigue life of the device using conventional techniques. Finally the performance of the device is assessed under realistic loading using the real time hybrid test method.

2. EXPERIMENTAL SETUP: THE DEVICE AND TEST RIG

The shear panel device tested is composed of a mild steel welded square hollow box section 100 mm in length (and depth) with 5 mm wall. At the centre of the box a mild steel shear web is welded, thickness 2 mm. The length of the box and the width of the web may be changed to suit the expected strain conditions and required stiffness. The stiffness and hence energy dissipation capacity of the device is determined by the shear modulus and thickness of the web. Webs thinner than 2 mm buckle during manufacture, resulting in undesirable unsymmetrical yielding. Thin webs including the 2 mm web, tend to buckle on loading, significantly reducing their stiffness – buckling here is governed by the ratio of web thickness to length. The device for testing purposes is welded onto tapered bolted shear plate (Fig 1) which is suitable for this testing but the complex machining required would make this unsuitable for in-situ placement. The best approach is to weld the device in place perhaps using weld plates, or bolting if slip can be avoided and similarly to the ADAS device, this device may be placed inside a stiff chevron or shear wall bracing system. The device is also cheap to manufacture and requires no special welding equipment which may make it more acceptable for developing countries.

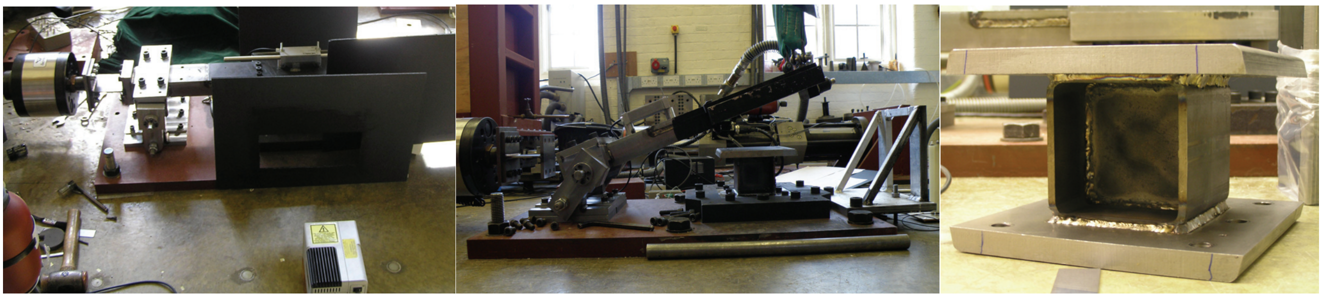


Fig 1. The shear panel device and test rig

The device is tested in a rig as shown in Fig 1, using a 100 kN Instron dynamic actuator, mounted via a swivel onto a 1 tonne dowelled and bolted steel anchor on top of an isolated concrete strong floor. The device is bolted onto female tapered shear plates which are also bolted and dowelled. This arrangement is to prevent slip of the device and connector arm and movement of the actuator body during tests. The rig is set up to allow one dimensional lateral load to be applied to the device and is used for cyclic and hybrid testing of the device.

To ensure boundary conditions are maintained a hinge is placed in line with the device to ensure loading remains parallel. While originally a thin metallic element was used for this purpose, a mechanical hinge is incorporated as it provides the ability to test large displacements and does not degrade over time. The load required to move the mechanical hinge is negligible and comparable to the metallic hinge and, has no undue affects on the forces and displacements measured. Thus, it is found acceptable to use the actuator force transducer for force measurement. A linear encoder is used to measure the displacement across the device, a thermocouple measures temperature at a point on the bottom of the web and two accelerometers, a seismic PCB and a general Brüel & Kjaer are also used. More details of the rig can be found in Ojaghi et al (2008).

To carry out thermal imaging a FLIR SC3000 camera is used. Thermal imaging can provide an invaluable insight into the way the device dissipates energy. However, it can be a challenge to set up and calibrate. Relative temperature changes are easily detected but accurate temperature measurement is reliant on knowing the emissivity of the target, which may vary. To optimise the thermal data, specimens are painted using Nextel black velvet paint, which is made to a known emissivity, and a thermocouple is used to provide temperature comparisons at a point. The test rig itself is shielded from reflections using a series of black cards.

3. THERMAL IMAGING: ENERGY FLOW OBSERVATIONS

A metallic energy dissipater as a consequence of its operation during yielding dissipates energy mostly in the form of heat. By observing the heat flow or the changes in temperature throughout a test, important observations may be made about how the device operates at various stages of its life. Images are captured at a high frame rate, enabling a view of the energy dissipater that would be impossible with the naked eye, as shown in the images in Fig 2. The top left image is during the first cycle of the device cycled to failure at 2 mm and 1 Hz, the overlapping vertical and horizontal lines observed give a clue to possible imperfections present in the web plate. The top right image is taken after 61 cycles, just 14 short of the moment where this device cracks initially. As expected an X shape is visible in the temperature profile, indicating maximum plasticity along the diagonals as the device shears. The maximum temperature is recorded where yielding is at its maximum in the centre of the web as expected. The bottom left image is taken at 170 cycles and shows the observed X crack that occur due to the shearing. Depending on the loading conditions this crack will take various amounts of time to propagate as described in the following section. It is observed that the device continues dissipating energy well after the crack is formed and even when the crack is well developed. The X shape and cyclic nature of the tests mean that for each cycle there is a period where one crack in the X pattern is closed and the other is opened. It is interesting to observe that the energy dissipation or points of maximum temperature shift to the crack tips which indicate these are the points where yielding and energy dissipation is greatest.

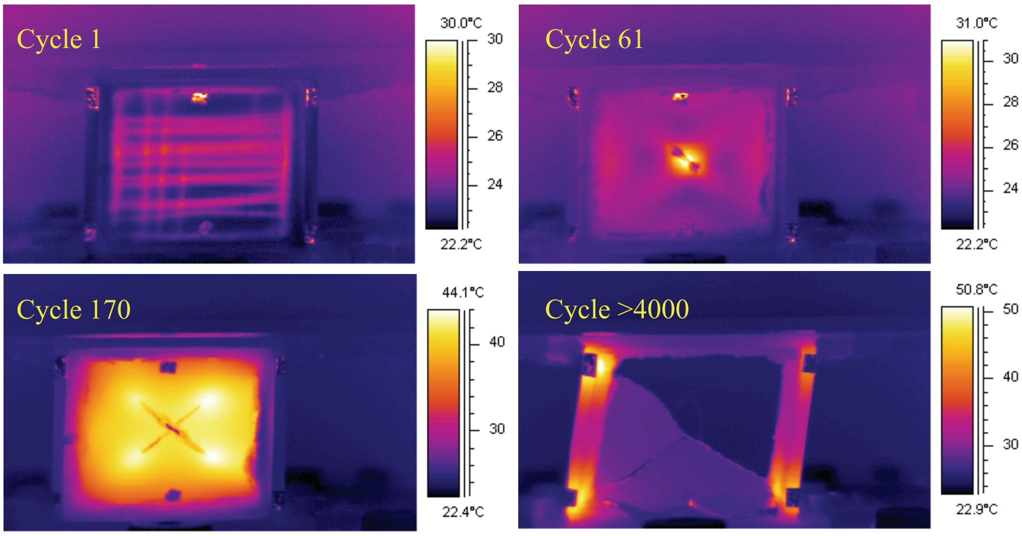


Fig 2. Thermal images of temperature or heat flow through various stages of device life.

After over 4000 cycles well after the web crack had propagated to the box edges and a period of cyclic stability entered, the loadings were increased leading to a loss of web. At this point as shown in the bottom right image the box takes over the role of energy dissipation. While energy dissipation is much less at this point since the box is not as stiff as compared to the web as corroborated by the hysteresis loops, the hinge points of the box are yielding and dissipating energy. Indeed, it is at these points where fatigue cracks propagate from either inside or outside the box progressing from one edge until ultimate failure when reaching the other edge. It is clear from these results that the device is robust, maintaining some level of performance even after initial cracking. Energy dissipation as observed by the hysteresis loops is greatest prior to cracking however, these images show that the device dissipates energy well and indeed is achieving much higher temperatures for a period well after the web has cracked. Energy dissipation reduction and subsequent drop in temperature is observed after the web crack reaches a certain size depending on the amplitude of the loading. Finally after web failure it is shown that the box remains intact for a long period, ensuring in practice that the braces remain attached and offers a small but significantly reduced level of energy dissipation.

4. CONSTANT PLASTIC STRAIN LIMIT TESTS

From the thermal imaging results it is clear that the device will dissipate energy well after initial cracking, which is useful as it shows that the device will maintain some level of performance for quite a period, well after this initial failure. In order to determine the fatigue life and dissipative capacity conventional plastic strain limit tests were carried out at 2 mm, 5 mm, 10 mm and 20 mm amplitudes (non-dimensionalised to strain by the box length - 100 mm, which is not fully representative of actual web strain but used for plotting purposes) at 1 Hz. While steel is not known to display any significant rate dependent behaviour, through cycling at a frequency within the range typically experienced in an earthquake, important observations may also be made of the temperature changes in the device. The tests were repeated once for each amplitude. They show very good agreement for the time of crack initiation. The accelerometers were used to assist in determining the approximate period when web failure (web crack reaching box) and box failure occurs as they spike in response to audible cracking/clashing occurring at or immediately after these periods. One case (10 mm) is shown in Fig 3. Here the device displays cyclic stability prior to web cracking after 5 cycles, immediately followed by a loss of stiffness. Web failure occurs after around 21s. In this case this corresponds to the period where the maximum temperature is achieved, though this is not exclusively true for all cases. The device degrades gradually but significantly to box failure at around 64 cycles where large cracks are observed in the box. Catastrophic failure occurs at around 85s.

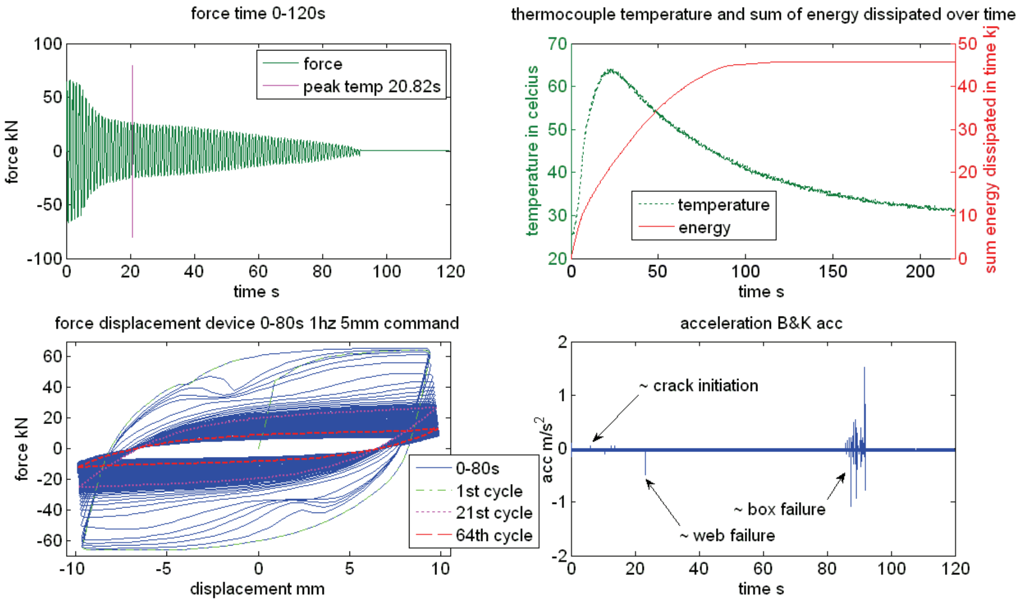


Fig 3. Captured data typical of the response for a device cycled at 10 mm amplitude 1 Hz.

Fig 4 shows the state of the device at various stages for the loading of Fig 3. From top left; the initial state. Top centre; buckling (pinching) of the web is observed (3s) and cracking occurs at 5s, (top right). Bottom left (7s) the crack grows fairly rapidly with one X crack side shown open. At large strains the web fails at the weld early on too. Bottom centre shows web failure after 21 cycles. Bottom right shows significant cracking in the box, defined as box failure after 64s; this is highlighted in red.

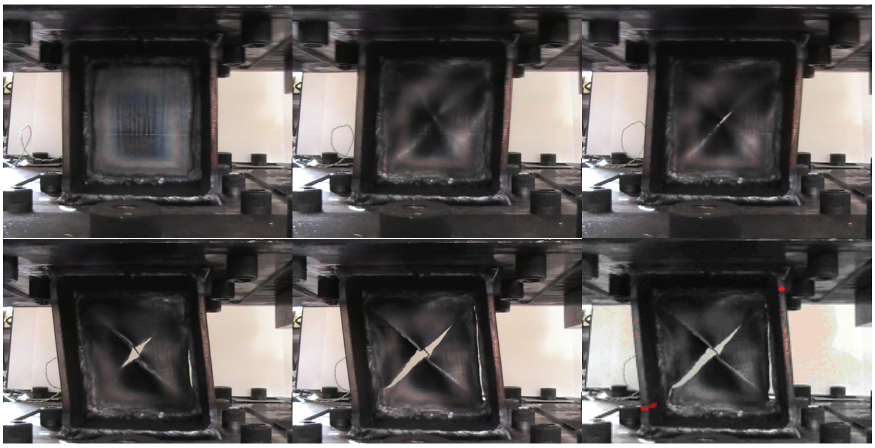


Fig 4. Images of various stages of device life after cycling at 10 mm 1 Hz to failure.

It is clear that there are three important stages to the device life, that prior to web cracking where energy dissipation is greatest, that up to web failure where due to cracks opening and closing significant but reduced energy dissipation capacity and strength remain in the web, and the final failure of the box. It is found that the box will last for a relatively long period after the initial web cracking and web failure (Fig 5 which also shows the life of the box cycled at 5mm without a web). For low strain levels the device will last an acceptable number of cycles however, at higher strains the life is significantly lower as expected. Therefore the device should be scaled according to expected strain levels. Cyclic tests especially at higher amplitudes may exaggerate the real loading that must be absorbed by the device. Depending on the earthquake the device life may be significantly different than that observed by using sinusoidal fatigue life data alone. This is especially true because of the buckling behaviour of thin webs. It is therefore essential to model the response of the device under realistic seismic loading. This is achieved through real-time hybrid testing.

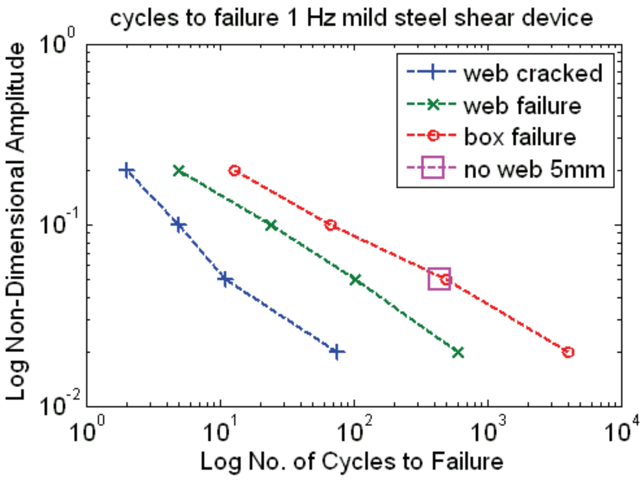
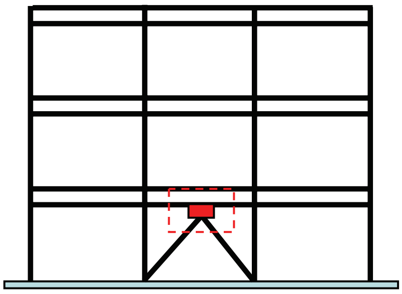


Fig 5. Cycles to failure at various strain levels

5. REAL-TIME HYBRID TESTING

In order to determine the performance of the device during a realistic loading situation, a retrofit of a 3 storey shear building is considered (Fig 6). The structure is chosen to be representative of a realistic structure with special regard to the natural frequencies to be within a range typically excited by earthquakes. The numerical model is solved using linear modal superposition, since all nonlinearity is assumed to be in the device. More details of the hybrid testing approach used can be found in Ojaghi et al (2008).



3 storey, 3 DOF retrofitted with two dissipative devices/braces.
3 bays, 2 frames. Bays 4 by 6 m in direction of loading with square floor plan. Floor mass assumes 0.20m reinforced concrete, each floor column has a lateral stiffness of 8 kN/mm and the braces 80 kN/mm.
Natural frequency f_1= 1.3 Hz; f_2= 3.7 Hz; f_3= 5.4 Hz;
Damping ratio 5%
Structure excited by El-Centro NS earthquake record scaled to 50% of its original magnitude.

Fig 6. Structure to be retrofitted with dissipative devices as shown

After the initial test (El-Centro at 50%), the residual earthquake resistance of the device is tested with subsequent El-Centro loadings until failure. It is clear from Fig 7 that the device is capable of reducing inter-storey drift and hence damage to the building. While the device is most effective during the first earthquake it provides some level (though much reduced) of energy dissipation for subsequent earthquakes and box failure (not catastrophic) occurs after 4 earthquakes. This suggests there is some ability to survive aftershocks after a major earthquake. Pinching is observed prior to web failure in the first earthquake (Fig 7) hysteresis loop due to buckling of the device, while during the second earthquake the device exhibits hysteretic behaviour more comparable to other metallic devices but at a much reduced load. Since the test is carried out in real time a thermocouple is used to measure web temperature at a point though not representative of the maximum temperature but where the thermocouple will remain attached. It is observed in Fig 7 that the temperature rises to a maximum after around 20s - at this point the web crack has progressed to at least half the web length and this time corresponds to the moment where most energy has been absorbed by the device. As the web does not play such a large role in energy dissipation after failure, during subsequent earthquakes much lower web temperatures are recorded.

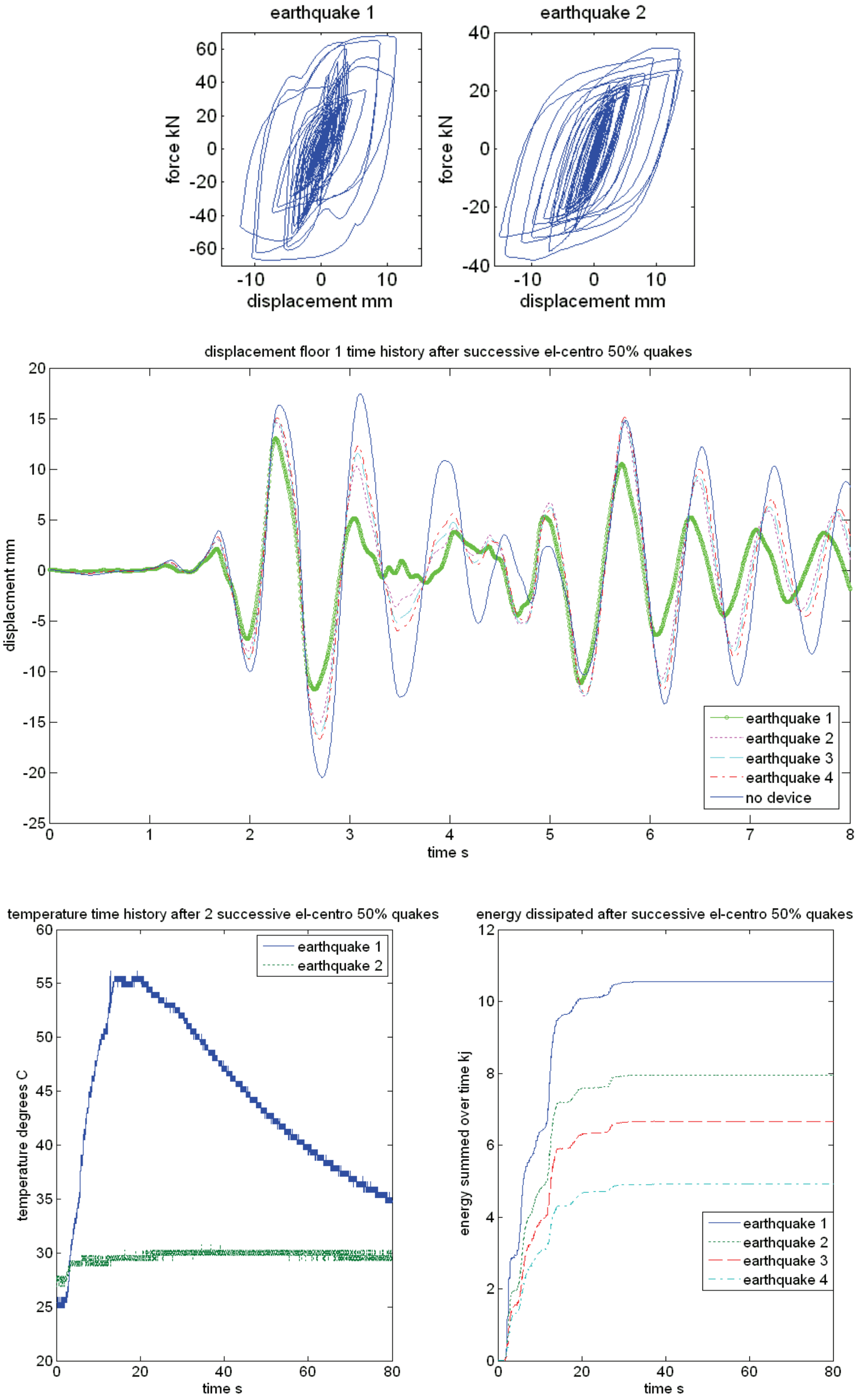


Fig 7. Real-time hybrid test results. Top left: hysteresis in earthquake 1. Top right: hysteresis in earthquake 2. Centre: floor 1 response after subsequent earthquakes compared to original structure. Bottom left: temperature measured during first 2 earthquakes. Bottom right: sum of energy absorbed over time by device.

5. FUTURE WORK

While the device is shown to be effective in reducing inter-storey drift it is desirable to attempt to improve its low cycle fatigue life. It is intended to compare the fatigue life of the device together with modifications to the material. This will start by annealing the steel to attempt to increase ductility and therefore perhaps allow a greater level of strain hardening, moving then to use austenitic stainless steel – which is known as a very tough, strain hardening material, copper which has very high ductility and aluminium which will allow devices with webs thick enough to prevent buckling but with manageable stiffness. Alternative materials such as metallic foam are also under consideration. Finally the real-time hybrid test technique will be used to compare the response of the steel device to two similar devices one utilising lead and the other rubber - both of which display significant rate effects.

6. CONCLUSIONS

A methodology for determining the performance of a shear panel hysteretic dissipater has been presented. This will provide the basis for future testing aimed at improving the fatigue life of the device and making direct comparisons to other devices. It has been shown that the device has good potential as a seismic energy dissipater and though a cheap to manufacture device it can provide high levels of energy dissipation with little material use. It has been found that the device has very good fatigue life at low strains and that there are three significant periods to the device fatigue life: life prior to web cracking, web failure, and box failure and while the device may crack early on, the box will not fail until some time later. Finally measurement and imaging of temperature can provide invaluable insights into determining how the device dissipates energy throughout its various life stages. Also temperature measurement may be used as a basis of device condition monitoring.

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