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EXPERIMENTAL VALIDATION OF A STRAIN HARDENING FRICTION DAMPER

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The general aim of the research program is to establish the seismic performance of multistorey steel concentrically braced structures equipped with strain hardening friction damper in the braces. This paper presents the experimental program conducted at the CEMSIG research center of the Politehnica University of Timisoara to validate the behaviour of the damper and to determine the performance of a brace with damper assembly. The experimental results are used to calibrate a numerical model for the damper and damper with brace assembly in order to determine the performance of this structural system. A companion paper (Norin FILIP-VACARESCU et all.) presents the numerical model for the combined behaviour of a brace equipped with such a friction damper calibrated on experimental data and used in numerical simulations to determine the performance of concentrically braced frames equipped with strain hardening friction dampers in the braces.

Key words: friction damper, strain-hardening, seismic performance.

1. INTRODUCTION

Recent earthquakes around the globe proved that the current degree of seismic protection is unsatisfactory and buildings suffer extensive damage or even collapse when subjected to severe or even moderate earthquake activity. As a consequence the building design codes increase seismic demands and aim to improve structural response capacity through accuracy of design and enhanced technical solutions. In current practice there are three efficient strategies to reduce seismic risk (Fig.1): (1)reduce seismic forces, (2) appropriate the structural response to seismic demand and (3) enhance structural damping.

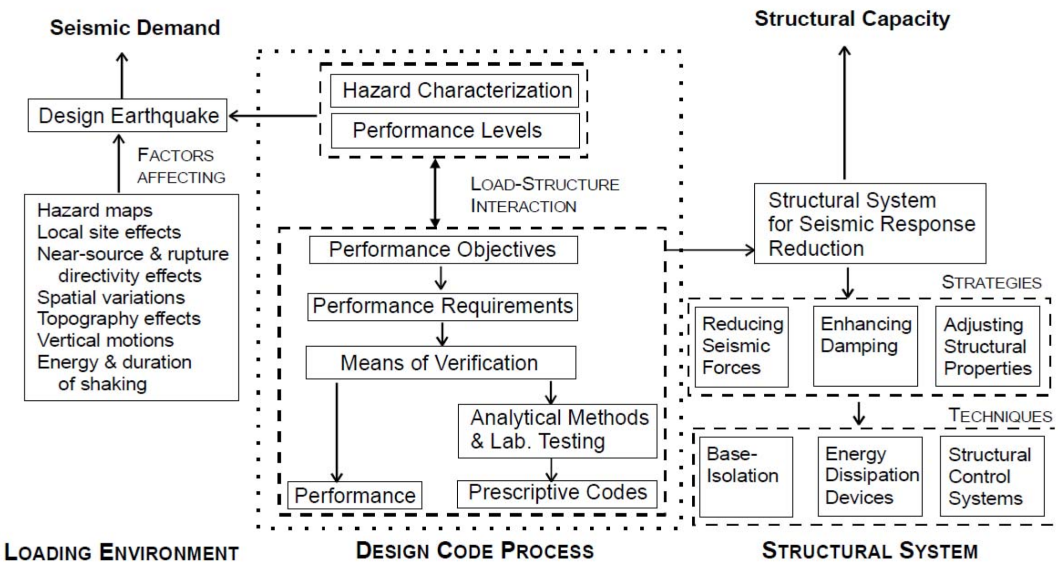

Fig.1 – Seismic demand vs. structural capacity: protection strategies [1].

Reducing seismic forces leads to capacity design of structures. Dissipative structures are designed to consume the energy induced by the seismic motion in the structure by allowing some specific elements to enter plastic domain. These dissipative elements act as fuses for the structure consuming energy, while the rest of the elements that are considered non-dissipative are designed to remain in elastic domain.

Enhancing damping strategy will imply base isolation and introduction of energy dissipation devices in the structural system. For structures isolated from seismic action and those with supplemental damping the structure is conceived as not to undergo plastic deformations by implementing devices which can absorb the seismic energy and can modify the period of vibration of the structure to more favourable values for global behaviour. In general these devices can be of three types: (1) seismic isolation devices, (2) passive energy dissipation devices and (3) active and semi-active energy dissipation devices.

Passive systems are designed to be used both for new structures and for seismic retrofit of existing structures. In general these devices function on principles such as friction between surfaces, yielding of components, and phase transformation of steel alloys, viscoelastic deformation of solids or fluids combined with the control of the flow of liquid.

Active/hybrid/semi-active control systems are an evolution of passive devices that have sensors and real time control and evaluation systems that modify partially or completely the properties of the damping devices during the recorded ground motion in order to obtain an optimal behaviour of the structure. A general classification of passive dampers might be done in reference to their governing parameter as follows:

(i) Velocity dependent devices – these devices are dependent of the velocity of application of the load. They modify their hysteretic behaviour according to velocity. As an example we can mention here fluid viscous dampers and fluid spring dampers.

(ii) Displacement dependent devices – in the category enter devices with non-linear behaviour such as: steel hysteretic dampers, shape memory alloy devices, and with linear behaviour such as: elastomeric viscoelastic devices.

This paper presents the evaluation of the behaviour of a particular type of friction damper. For this purpose experimental and numerical analyses have been conducted. Based on the experimental data numerical models were calibrated and applied to evaluate the performance of concentrically braced frames equipped with such devices in the braces.

2. SERB DAMPER

The damper studied herein is also a friction damper but has a completely different behaviour concept. The damper studied is a strain hardening friction damper with 2 distinct zones. A starting zone with low stiffness, aimed at increasing the period of vibration of the structure, and subsequently reducing the seismic forces by conducting it on the descending path of the spectrum ($T>T_C$) and a second zone with increased stiffness conceived to limit displacements for high values of seismic action (Fig. 2).

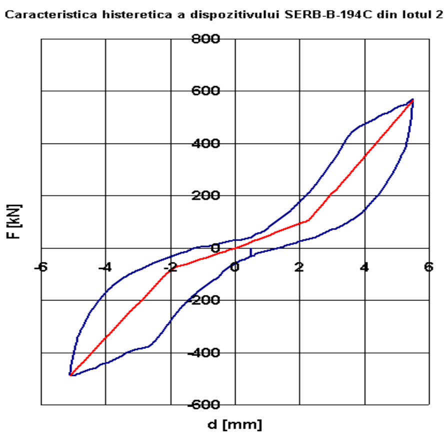

Fig. 2 – Hysteretic behaviour of SERB friction damper [3].

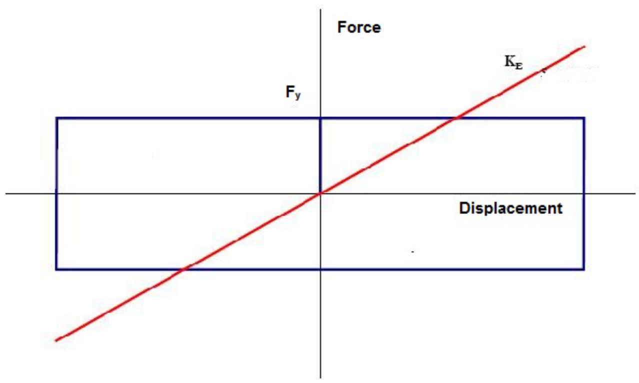

Fig. 3 – Behaviour of normal friction damper [2].

This concept of this friction damper is different to “classical” friction dampers (Fig. 3), and what is more important involves a different approach for the philosophy of dissipative structures. This was the reason which motivated the present study.

The damper dissipates energy through the elongation of a set of prestressed circular steel coils around a central steel core (Fig. 4). The damper is characterised by 4 main parameters:

- Slip
- Stiffness of strengthening branch
- Maximum force
- Maximum stroke.

The device works like a kind of mechanical telescopic device that ensures an increase in flexibility of the structure and allows energy dissipation even at small displacements avoiding the formation of plastic hinges. The dampers and their hysteretic characteristic are presented in and Fig. 5:

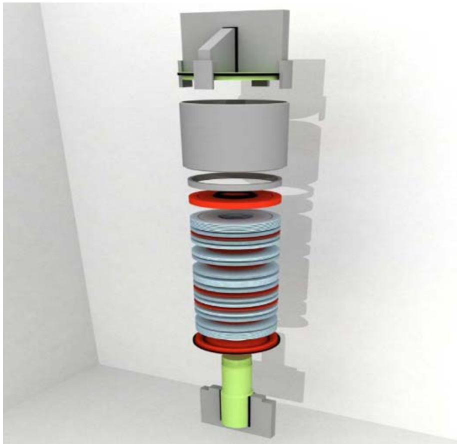

Fig. 4 – Damper geometry Serb damper SERB 194 [4].

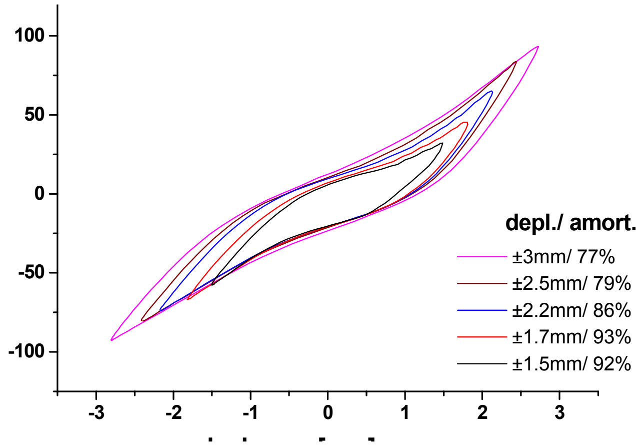

Fig. 5 – Hysteretic characteristic Serb damper SERB 194 [4].

The aim of the experimental program was to evaluate and characterise the damper, in a first step, and the behaviour of the brace-damper assembly, in the second step.

3. EXPERIMENTAL VALIDATION OF SERB STRAIN HARDENING FRICTION DAMPER

3.1. Code provisions

According to EN 15129 Displacement dependent devices can be classified as: Linear Devices (LD) and Non Linear Devices (NLD).

Non Linear Devices are used in passive control systems and can increase the flexibility of the structural system and energy dissipation capacity. Based on their force displacement behaviour different categories of devices can be identified.

According to their energy dissipation capacity [0]:

- Energy Dissipating Devices (EDD) when $\zeta > 15\%$
- Non Linear Elastic Devices (NLED) when $\zeta < 15\%$

According to their stiffness variation [0]:

- Hardening Device (HD), when $K2/K1 > 1$
- Softening Device (SD), when $K2/K1 < 1$

According to their re-centring capability [0]:

- Dynamically (Weakly) Re-Centring Devices (DRD)
- Statically (Strongly) Re-Centring Devices (RCD)
- Supplemental Re-Centring Devices (SRCD).

The studied damper is a Non Linear Elastic Device (NLED) that has its non-linear behaviour based on geometrical non-linear effects due to the peculiar shape of its core elements, in this case a set of steel rings sliding around a steel core, and the added friction between these elements. The increase of stiffness of the second branch classifies this damper as a Hardening Device (Fig. 6). These devices can produce an increase of the initial period of vibration of the structural system due to low stiffness of the first branch but can also limit displacements in the case of earthquakes with increase in force. In addition the shape of the force displacement behaviour curve for the damper suggests a good re-centring capacity.

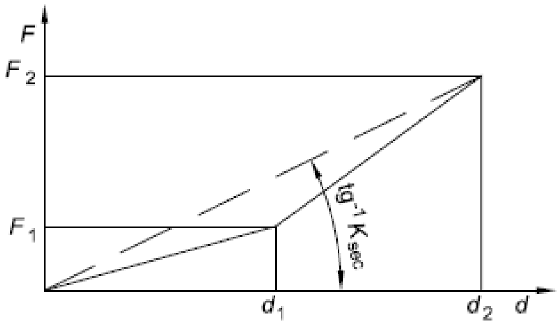

Fig. 6 – Hardening device [0].

The behaviour of a displacement dependent device is identified by the effective stiffness K_{effb}, the effective damping ζ_{effb}, first branch stiffness K_1 and second branch stiffness K_2, design force V_{bd} and design displacement d_{bd}. Force displacement capacity of the device should be able to sustain a maximum displacement or load, whichever is reached first, amplified by the reliability factor and partial factors that take into account action effects other than seismic, which can affect the initial configuration of the device [0]. The maximum differences of the experimental values with respect to design values shall be within the tolerance limits given in EN15129:2009-Table 4 [0].

The design values of the constitutive parameters of the devices must be determined according to the results of the design non-linear analyses on the entire structural system including devices under the seismic loads. Experimental tests must be carried out to determine the actual mechanical characteristics of the seismic devices by imposing cyclic deformations and continuously recording displacement and force values during procedure. Mechanical tests include [0]:

- Type tests of materials;
- Factory production control tests of materials;
- Type tests of devices;
- Factory production control tests of devices.

Experimental tests on the materials used were conducted by the device supplier. Type tests of the devices are performed in cases such as the one presented here, in which the new device differs from those already qualified. The prototypes of these devices must be tested and qualified together with their connection system. All working conditions of the device must be reproduced in the experimental setup. The tests can be dynamic or, if it can be demonstrated that velocity has negligible influence, quasi-static. The test procedures recommended by EN15129:2009 [0] are:

a) Evaluation of the force-displacement behaviour. Cyclic tests with increasing amplitude cycles of 25%, 50%, and 100% maximum displacement (which is at least equal to design displacement of the device) with five cycles for each intermediate amplitude and at least ten cycles for maximum amplitude. The device shall not break and shall keep its characteristics unchanged during the test. An adequate increase in number of cycles should be considered if the structure for which the dampers is to be used has a fundamental period significantly lower than 2s.

b) Ramp test for the static evaluation of the failure displacement. Imposed displacement or force, whichever is reached first, should be no less the design values amplified with the appropriate factors.

These tests must be completed by factory production control testing of the devices prior to their installation.

3.2. Experimental test setup

The first set of experimental tests was conducted on the two dampers with 1 000kN and 1 500KN capacity were made in the INSTRON universal testing machine in the CEMSIG laboratory of the

Department of Steel Structures and Structural Mechanics of the “Politehnica” University of Timisoara, in order to validate their hysteretic behaviour and to ensure that the devices function in the desired parameters having a symmetric behaviour in tension and compression with stable hysteretic loops.

Table 1

Parameters for the SERB dampers tested:

Parameters	SERB1	SERB2
Slip [mm]	2	2
Stiffness [kN/m]	2×10^5	2×10^5
Max. force [kN]	1000	1500
Max. stroke [mm]	+/– 15	+/– 20

Data acquisition was done directly through the control and acquisition station of the machine itself without any other additional measuring instruments. Monitored parameters were total force in the damper and damper stroke. To measure the influence of the connections on the behaviour of the device the experimental test setup included the bolted end connections of the damper (Fig. 7). A cyclic load protocol with a progressive increase of force level at each step was used.

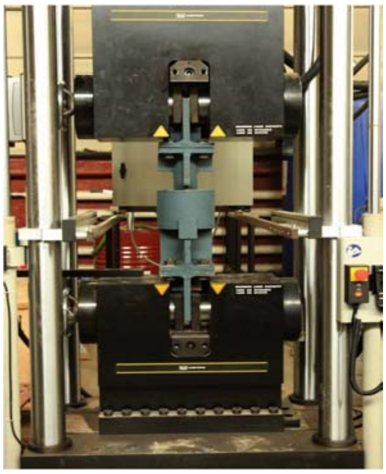

Fig. 7 – Experimental test setup for damper tests.

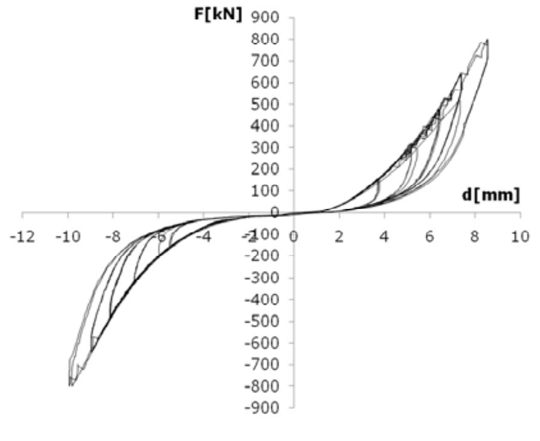

Fig. 8 – Damper behavior determined experimentally.

The hysteretic behaviour of the SERB damper obtained experimentally is presented in Fig. 8. Both devices had a similar behaviour with stable hysteretic behaviour in tension and compression.

The second set of experimental tests was conducted on the brace with damper assembly using two different concepts. A first concept is to design the braces to remain in elastic domain controlling the response of the structure solely through the friction dampers. In this case the structure has no ductile elements and is designed with a behaviour factor corresponding to low dissipative structures of $1 < q < 2$ and benefits from the reduction of design seismic forces due to the increase in global damping. However, introducing supplemental damping in the structure leads to a much smaller reduction of design seismic loads compared to the reduction that comes from using a higher behaviour factor value that corresponds to a dissipative design approach in which the brace itself is the main energy consuming element. For example an increase of damping in the structure to 15% critical damping leads to a reduction of the loads with only 35%. Furthermore these types of dampers have a brittle failure that must be avoided in all configurations. All the above mentioned lead to a second design concept in which the damper has sufficient overstrength compared to the brace to assure that the brace has deformation in the plastic domain and is the weaker element in the configuration. This concept should benefit in theory from both the energy dissipation capacity of the brace and the supplemental damping from the device, and the failure will occur in the brace and not in the device. For seismic motion levels corresponding to ultimate limit state the brace is the “active” element according to the dissipative design concept and for service limit state the damper is the “active” element ensuring that the brace remains in elastic domain and provides an overall damping increase. According to P100/2006 [0] the relative story drift criteria for SLS is 0.008 h, where h is the story height. For the structure analysed here this corresponds to a drift value of 28 mm which leads to a displacement of 20 mm in the brace. The damping devices were selected to satisfy this displacement criteria corresponding to SLS. Both design concepts presented above will be used in the configuration of the experimental tests that will be presented further on. The two design concepts will be referred to as the “Strong” brace concept and “Weak” brace concept. The experimental configuration was designed starting from the general geometry and consists of half of the beam and one of the central braces in a triangular configuration, hinged at both ends. The brace and beam assembly were rotated 90 degrees from their positioning in the frame to facilitate load application on the brace which was done through a 1 000kN hydraulic actuator which was fixed on the pre-existent experimental test frame. In addition to the initial configuration presented above a secondary frame was constructed around the specimen to prevent out of plane deformation. Two profiles were attached to the front and back of the vertical beam element that ensure a 4 point contact with the two guidance beams to prevent any out of plane displacements (Fig. 9). The same test setup is used both for the experimental test on braces alone and for experimental tests on brace with damper assemblies with the damper connected at the base of the brace through bolted end plates (Fig. 10).

Fig. 9 – Experimental test setup for brace tests.

Fig. 10 – Experimental test setup for brace with damper assembly tests.

For the experimental tests on single brace and brace with damper configurations recorded parameters were: total applied force, total displacement of the specimen, relative displacement between certain predetermined points relevant for each type of test. A load protocol recommended by European Convention for Constructional Steelworks was used (ECCS, 1985 [0]) was used. The protocol consists of a monotonic test to determine the force-displacement relationship of the specimen. With the determined values of yield displacement (e_y) the displacement based cyclic load protocol is constructed with one cycle at each elastic step of $0.25e_y$, $0.5e_y$, $0.75e_y$, $1e_y$ and 3 cycles at each load step multiple of $2e_y$ (2ey, $4e_y$, $6e_y$,$8e_y$, etc.). The cross sections used for the brace reflect these two design concepts as follows: „strong” brace concept: HEA240 and „weak” brace concept: circular hollow section D133x5 and HEA100 profile.

3.3. Experimental results

Experimental tests for “weak design concept” represent the main point for the research and will be detailed in the following. The results obtained for CHS and HEA braces were very similar and it is for this reason that we will present only the experimental tests for the HEA braces with and without damper configurations. All braces without dampers were first tested monotonically to determine yield displacement and yield force needed to establish the ECCS cyclic load protocol that was later used for cyclic tests. The experimental test setup had the same general configuration for all tests and the braces were positioned with their weak axis in the plane of the test frame to ensure that buckling occurs in the vertical direction.

Force displacement curves for the HEA100 brace without dampers, obtained from monotonic tests, are presented in Fig. 11. The behaviour of the HEA brace under cyclic load was very similar with the behaviour recorded for the CHS brace. At tension load cycles the brace exhibited a strength decay of approximately 20% for the second and third cycle at each load step. The brace exhibited significant stiffness degradation for each successive tension cycles. Buckling of the brace occurred for compression cycles with the formation of a plastic hinge in the middle of the brace. The first buckling of the brace was recorded at a force level of approximately 0.7 times the yield force of the brace F_y and the values of the buckling force dropped continuously for the successive compression cycles that followed. The test was stopped when the values of the compression force dropped with more than 50% of maximum compression force reached. The force displacement curve recorded for cyclic tests on the HEA100 brace without damper are presented in Fig. 12.

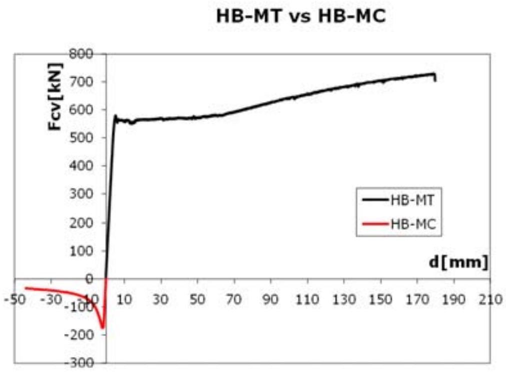

Fig. 11 – Force displacement curves for the HEA100 brace obtained from monotonic tests.

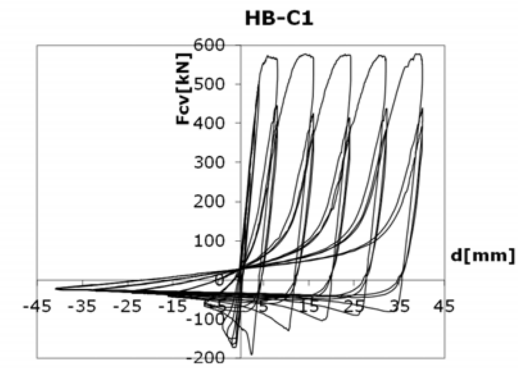

Fig. 12 – Force displacement curve recorded for cyclic tests on the HEA100 brace without damper.

In order to analyse the influence of the damper on the global behaviour of the brace the hysteretic behaviour of the brace without damper is taken as reference curve. The behaviour of the brace with damper obtained for the two design concepts of “weak” and “strong” brace is therefore compared with the hysteretic behaviour of the brace without damper.

For the “strong” brace design concept the global behaviour of the system of brace and damper is completely governed by the constitutive law of the damper and its properties. The system does not suffer any degradation in terms of strength and stiffness these being strictly dependent on the damper properties. The system will continue to take on load until the maximum capacity of the device is reached, with the brace remaining in elastic range. This high load carrying capacity without strength and stiffness degradation represents the advantage of this type of design concept but can also lead to an increase of the load levels in the beams and columns of the braced frame due to the pseudo-elastic behaviour of the damper. Furthermore failure of this type of system is a brittle one due to failure of the device and must be avoided.

For the “weak” brace with damper the brace is allowed to have plastic deformation and the global behaviour of the damper brace system is a mixed one. The weak element in this configuration is the brace which will ultimately fail. The behaviour of this system is presented in Fig. 13 in comparison with the behaviour of the same brace, under the same load protocol but without damper. In both configurations the force level drops significantly after the first cycle at each load step and the next two cycles of the same deformation step. The brace with damper has a higher flexibility and yields at the same load step but at a displacement of approximately 50% higher. For this system up to a level of $2e_y$ the global behaviour is governed by the behaviour of the damper and by the behaviour of the simple brace at higher load steps. The difference between these two systems can be observed more closely up to a level of two times yield deformation e_y (Fig. 14).

Up to this level the behaviour is that given by the damper parameters. At tension cycles the brace remains in elastic domain and the load level in the system is significantly smaller than that of the brace without damper with a higher overall flexibility. For compression cycles the brace with damper buckles at the same load level as the one without damper but has a higher deformation capacity due to the damper properties. The test was stopped when the values of the compression force dropped with more than 50% of maximum compression force reached.

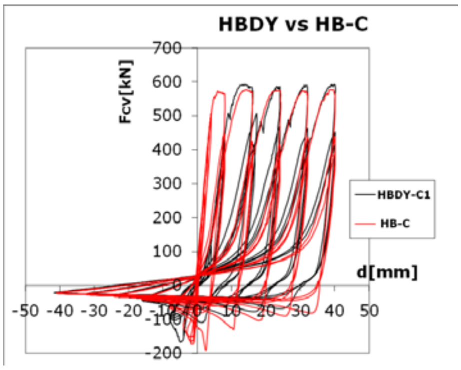

Fig. 13 – Hysteretic behaviour of the brace with (HBDY) and without damper (HB-C).

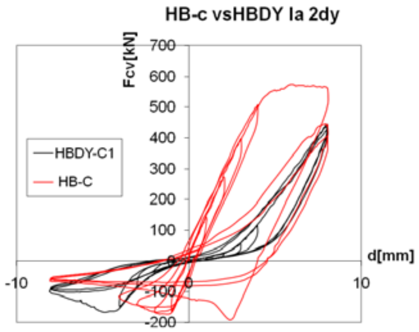

Fig. 14 – Hysteretic behaviour at 2dy of the brace with (HBDY) and without damper(HB-C).

The experimental results are in agreement with the two design concepts considered. For the starting load levels of up to $2e_y$ the brace remains in elastic domain and has a lower level of energy dissipation but there is a significant decrease in load level due to the damper and also an increase in flexibility. After this level the hysteretic behaviour of the system is very similar to that of the brace without damper, with energy dissipation due to the formation of a plastic hinge in the brace. Failure in this design concept is represented by the failure of the brace in compression.

4. CONCLUDING REMARKS

The damper prototype studied in this article is a displacement dependent device with hardening. It has a different behaviour concept compared to classical friction dampers with a starting zone with low stiffness, aimed at increasing the period of vibration of the structure, and a second zone with increased stiffness conceived to limit displacements for high values of seismic action. These devices can be implemented in braces in two design concepts: “strong” brace concept in which the global behaviour is governed strictly by the damper and a “weak” brace concept in which the brace with damper exhibit a combined behaviour .Experimental tests were conducted on two damper prototypes to validate their behaviour followed by experimental tests on brace-damper assembly in the two design concept to determine the combined behaviour of the system.

As a conclusion it is expected that this type of damper could improve the behaviour of rigid structures that are sensitive to formation of plastic hinges at levels corresponding to service limit state. The efficiency of this type of damper for a multistorey steel structure will be determined from numerical analyses using the behaviour of the damper and the behaviour of the damper with brace assembly obtained experimentally to calibrate a numerical model.

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