



SHAKING TABLE TESTS OF A TWO STORY FRAME EQUIPPED WITH DISSIPATIVE BRACINGS

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ABSTRACT

The present paper illustrates the design stage and the first results of an experimental program which deals with dynamic tests on a shaking table of a two-storey, one-bay frame, with dissipative bracing systems. After a description of the general criteria used for the design of the test structure and the definition of the characteristics of the special bracing system, the results of the first tests carried out, aimed at identifying the dynamic parameters of the structural model, are presented.

KEY WORDS

Experimental tests, Shaking table, Dissipative bracings, Passive control, Steel structures

INTRODUCTION

The present paper deals with the evolution of some studies included in a wide program of research, carried out for some years at the University of Rome "La Sapienza", Italy, on the possible applications of dissipative bracing systems for seismic protection of buildings, to be used either in retrofitting or in the design of new constructions.

The studies carried out deal with systems which include dissipating devices based on flexural yielding of steel plates. This class of dissipative devices has been applied, specially in Italy, in the seismic protection of bridges: the devices show a reliable and stable behaviour in the plastic range under cyclic loading: their low-cycle fatigue life, whose study is aimed at giving safety assessment against possible premature failure, has been found to be well represented by using suitable damage functionals.

At this stage of the research it has been planned to begin investigating constructional aspects using experimental tests, as realistic as possible. Hence shaking table tests using a full scale model have been started.

With the contribution of ENEA, the National Agency for Energy and Environment, which has, in its

laboratories near Rome, a 4.00×4.00 m shaking table with good performance characteristics, a two-storey one-bay steel frame with a dissipative bracing system is being tested. The test structure was designed to accommodate different types of dissipative systems, and to be used again for other tests.

The paper describes the design criteria, the experimental program, the instrumentation set up and the results obtained so far.

TESTS OF DISSIPATIVE DEVICES

In recent years, at the University of Rome "La Sapienza", several types of dissipative devices, based on flexural yielding of steel, have been proposed and tested. Although they appear differently shaped, all of them are obtained, without joints or weldings, from a thick steel plate, and present in their active parts a geometry which assures almost uniform flexural plasticization for small deformations.

One of the devices which more easily can be used within frames with "K" bracings is the "E" shaped device (fig.1). Its installation in a portal one-storey, one bay frame, with hinges at the base, was recently tested under quasi-static cycles of horizontal loading. The behaviour of the system was very satisfactory and showed no malfunctioning.

A large number of "E"-shaped devices were directly tested under displacement control: for slow cycles, with either constant or variable amplitude, they showed, during their performing life, minimum decay of strength and of energy dissipation capacity.

In order for dissipation to occur, the active part of the device is led to an anti-symmetrical deformation in the plastic range: the central and the lateral arms, which are designed to remain in the elastic range during the deformation cycles, have to be connected to different parts of the structure, which undergo relative displacements during the earthquake.

The advantages of the "E" shaped devices follow from the anti-symmetrical deformation pattern which permits the neutralization of the geometric effects on the global response. Moreover, as a consequence of the flexural moment distribution, it is possible to realize a uniform plasticization using beams of constant section: this implies cost savings and simplification in the production control.

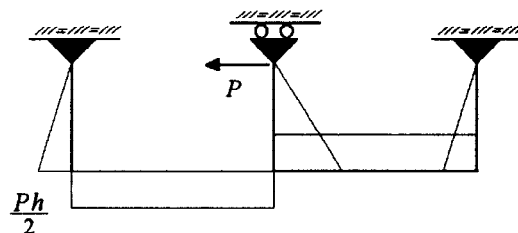


fig.1

One of the most important problems in evaluating the behaviour of a dissipative device inside a structure relates to the possibility of characterizing, at every stage, its cyclic life, by the assessment of the residual performance.

A rational way to proceed is to refer to the value of a properly defined functional which indicates the attained level of damage, to be compared with the expected ultimate value at collapse.

An appropriate functional which weighs the dissipated energy with a suitably defined amplitude of the plastic deformation has been proposed by some of the authors (Arcangeli *et al*, 1994). Its expression is:

$$DF = \int dW_p \left| \delta_p \right| \quad (1)$$

This functional has been validated by a series of laboratory tests on several devices, with cycles of either constant amplitude or of completely general type. The results of the test have shown that the proposed functional attains, at collapse, notably constant values, independently of the different imposed displacement histories; these values appear to be much less scattered than those obtained by other formulations based, for example, on the dissipated energy.

DESIGN OF THE TEST STRUCTURE

The aim of the design was to realize a structural model which permits to focus some of the constructive problems which are generally encountered in the design of structures with dissipative devices, rather than to get a scaled version of a particular real structure.

To dimension the structural model and its details, the adopted design criteria have been:

- To realize a full scale structure in order to avoid problems related to scale effects, while respecting the geometrical and loading limitation of the available shaking table.
- To face the design problems of real construction details.
- To obtain, even in the case of static vertical loads alone, stresses of some importance in the frame.
- To use masses of relevant weight: in real applications in fact, a single braced bay has to take the entire seismic action due to all the present masses of the structure

In order to meet all these targets and noting the need to get a model that may be reused many times and that is able to show the protection effectiveness of dissipative systems, in terms of reduction of floor displacements, the unbraced frame was designed to be earthquake resistant according to Code.

In designing the frame and its details, particular care has been given to the following aspects:

- The absence of risks of instability in the columns and in the struts of the "K" bracing.
- The limitation of energy dissipation in the joints at the base of the frame and in the bolted connections: these were designed like friction connections so that no relative sliding should occur under dynamic actions.
- A good elastic deformability, that is the frame remaining elastic up to a 1.5% storey drift. This is necessary to avoid damages to the model during all the tests.

The design of the frame under vertical and seismic loads was carried out using linear elastic dynamic analysis. To verify the unbraced structure, artificial accelerograms, compatible with design spectra given by the EC8 European Code, were employed. For peaks of acceleration equal to about 0.35 g, plastic hinges would start forming at the bases of the columns.

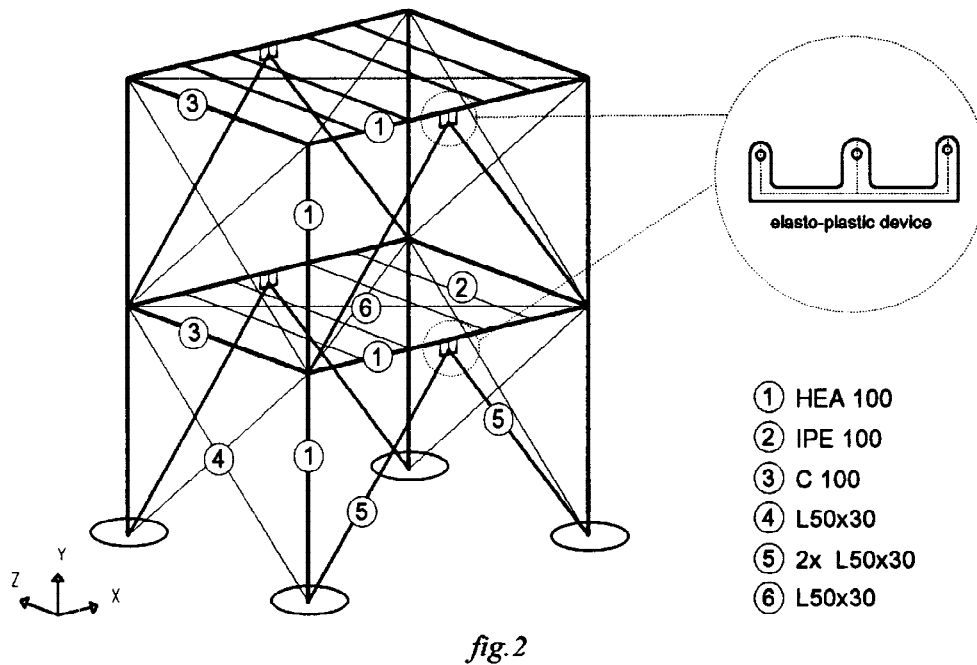
DESCRIPTION OF THE TEST STRUCTURE

The model is a three-dimensional steel frame, 3.00 m long, 2.40 m wide and 4.00 m high. It is composed of a couple of two-storey, one-bay, frames built using beams with HEA 100 sections, linked by secondary beams which represent the floor structures. The bracings are "K" shaped in the longitudinal direction and cross shaped in the transversal direction. While the latter are traditional, the former are prearranged for the installation of the dissipative devices (fig.2) adjacent to the midspan of the beams: otherwise they may be completely disconnected, to realize the unbraced frame case.

The lumped masses consist of eight blocks of concrete, four at the first floor, four at the second: every block having a mass of about 1200 kg. These blocks are constrained by couples of secondary beams (IPE 100 shapes), directly linked to the beams of the main frame.

The constraint in the horizontal direction, which is very important to assure the no-slide connection between masses and floors, is realized by using these rigid beams; the slacks being taken up by means of adjusting screws. To improve the constraint the masses were also fastened to the main beams with pre-tensioned ropes of steel-wire.

The model structure is able to accomodate bracings of different shapes, in order to make possible the extension of the test program to other dissipative systems.



DESIGN CRITERIA OF THE DISSIPATIVE SYSTEM

To verify the protection effectiveness of the dissipative bracing, in this experimental program, it was decided:

- To control the reduction of the floor displacements under a seismic action characterized by a peak acceleration of 0.35 g.
- To ensure, with respect to a suitable safety margin, the permanence of the structure in the elastic range also under seismic actions of double intensity (peak acceleration equal to 0.70 g).

To respect the above targets, two different dissipative devices were designed.

The methodology used for designing the dissipative bracing systems is the one described in (Ciampi, 1995). The global structural reaction of the system results from the contributions of the frame and of the bracing arranged in parallel; their contribution is assumed elasto perfectly-plastic. The parameters which govern the response of the model are the stiffness and yield strength of both the frame and the bracing. The design methodology is based on the construction and the utilization of force spectra at fixed frame ductility, for single degree of freedom models. The needed total strength has to be divided between the frame and the bracing system. A simple procedure allows then to transform the results obtained for the equivalent single degree of freedom systems into characteristic data for the different bracings at different floor levels.

For the two design cases examined, the global strength was divided in equal parts between the frame and the

bracing system. Taking into account the available strength of the frame, it turns out that the structure remains elastic for both design and input cases.

Preliminary characterization of the steel and design of the devices

The design of the devices was preceded by the characterization of the mechanical properties of the steel to be used in their construction.

Two different types of steel, easily available, were tested: the first one AISI 304, a stainless steel, and the second, Fe 360, a common low carbon steel. The two materials present similar yield strengths, between 220 and 280 N/mm², suitable for the design requirements. These steel types had been used, in previous tests, for the construction of dissipative devices and both of them had given good results for cyclic actions.

From two 20 mm thick plates, two specimens were built, to be tested under monotonic axial deformation. The tests gave the following results:

- Fe360 steel: $f_y = 270 \text{ N/mm}^2$ $\epsilon_t = 30\%$
- AISI304 steel: $f_y = 250 \text{ N/mm}^2$ $\epsilon_t = 45\%$

The σ - ϵ diagrams drawn for the two steels show many differences: while in the case of Fe360 after yielding, the behaviour did not present any significant hardening, AISI 304 did not show a definite yielding point and always presented hardening in the plastic range.

To test the flexural behaviour of the two materials under cyclic actions, two identical specimens were used (one for each kind of steel). Their shape derives from the "E" shape, dividing it in half, along the central arm. They were tested with symmetric cycles, at increasing displacements amplitude.

The specimens showed a similar cyclic life, but different isotropic hardening: in the last cycles the load for the AISI 304 sample was 25% greater. (see fig.3)

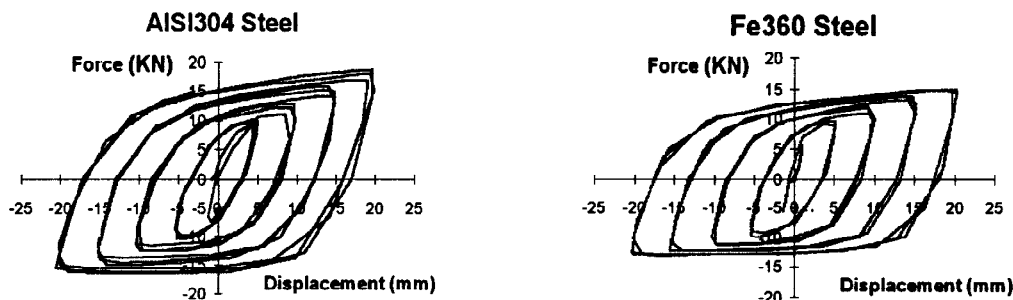


fig.3

The tests were very useful in giving indications as to which material to choose. The Fe360 steel was chosen, because of a more constant behaviour during cycles.

Using the data resulting from the application of the above referred design methodology, and simple formulas related to the selected E shape two sets of dissipative devices were designed, corresponding to the two levels of seismic action to be used in the tests.

TEST PROGRAM

The sequence of experimental activities may be divided into two stages. The first one, carried out by identifying the dynamic parameters of the model in the elastic range, uses the following configurations:

- traditionally connected "K" bracings at the upper floor only, with the added masses only at the first floor.
- traditionally connected "K" bracings at the upper floor only, with all the added masses.
- unbraced frame, (K bracings disconnected), with all the added masses.

the identification tests were carried out using:

- sinusoidal table motions with variable period, between 1 and 0.1 sec, to search for the resonance frequencies and the structural amplification.
- a series of pulse shocks to identify either the resonance frequencies or the damping.
- a series of scaled-down accelerograms, duration 20 sec, to test the elastic behaviour.

The second stage is addressed to assess the behaviour and the effectiveness of the dissipative system and the cyclic life of the devices in a real dynamic test; with the same accelerograms adopted in the first stage and increasing intensity up to the already defined maximum peak accelerations of 0.35g or 0.70g, corresponding to the two different sets of devices designed: in this case the test configuration adopts all the dissipative bracings and all the added masses.

TEST EQUIPMENT AND INSTRUMENTATION

The shaking table used in the tests is the six-degree-of-freedom, 4.00x4.00 m shaking table installed at the Innovation Department of ENEA/Casaccia.

Its performance characteristics are: frequency up to 50 Hz, acceleration peaks up to 3 g, displacements up to ± 125 mm, admissible rigid mass up to 10000 kg, with centroid 2.00 m high.

The instrumentation was decided with the scope of obtaining:

- displacements and accelerations at the base and at every floor, to follow the global behaviour
- loads and deformations in the dissipative devices to identify their dynamic behaviour.

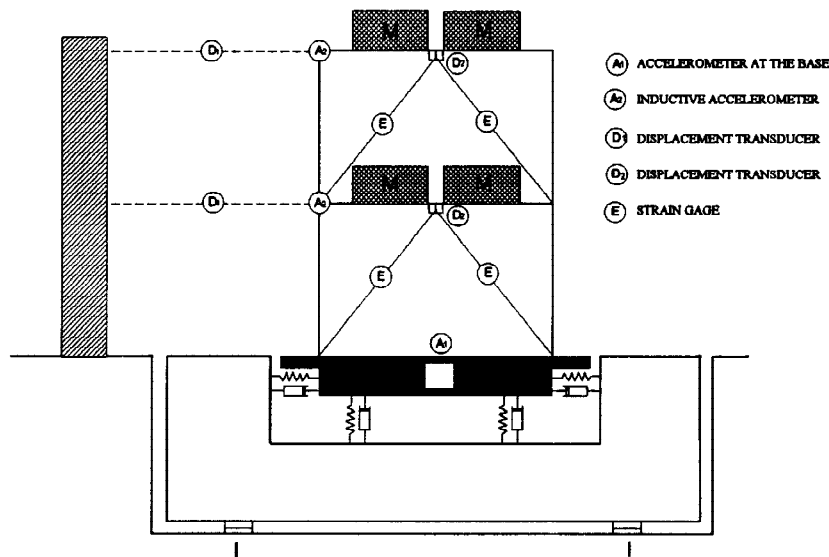


fig.4

To obtain the global measures at every floor, an accelerometer and a displacement transducer, range ± 250 mm, were set on both the main frames, the displacements being measured with respect to a fixed frame external to the shaking table. The table motion was measured directly by the table transducers, after checking their

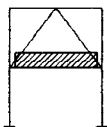
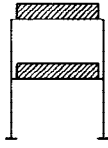
calibration (see fig.4).

As for the devices , while it is very simple to measure the relative displacements between one of the two lateral arms and the central one, it is more complicated to read directly the loads without changing the connection set up; so it was decided to use an indirect evaluation of the load by measuring the stresses in the bracings, through strain gages.

For data acquisition and motion control, two separate systems are implemented: both on line data and post processing are available

PRELIMINARY TEST RESULTS

So far only the first stage of the test program has been completed; the second stage is still in progress. The found natural frequencies of the unbraced structure are summarized in the following table:

1st Configuration	1st Mode Frequency (Hz)	2nd Mode Frequency (Hz)	2nd Configuration	1st Mode Frequency (Hz)	2nd Mode Frequency (Hz)
	3.64	--		1.92	5.77

The amplification of the acceleration at the first floor for the two configurations, as resulting from the tests, are shown in fig.5 and 6. This corresponds to a first mode damping of about 4%.

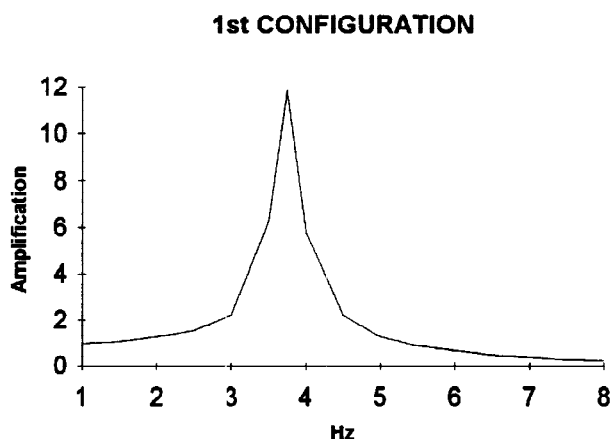


Fig.5

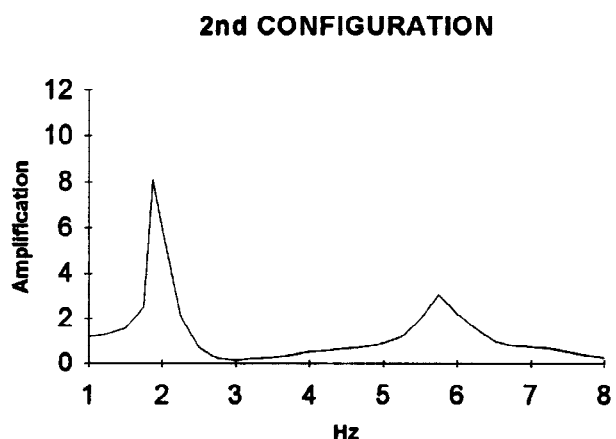
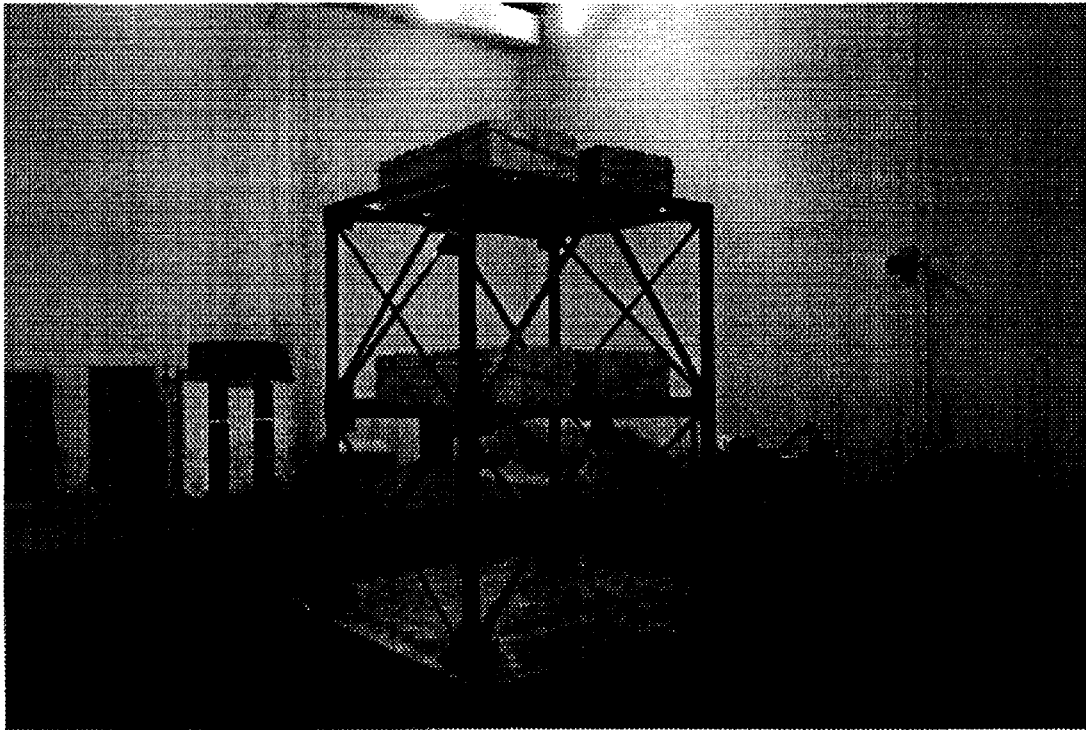


Fig.6

For the identification of a numerical model of the structure, it was necessary to take into account the deformability of the constraints at the base of the frame, by introducing rotational springs instead of rigid connections and the presence of non perfectly rigid connections between the masses and the floors, by introducing appropriate elastic elements.

The analysis of the frame in the first configuration was mainly used for calibrating the model of the constraints at the bases of the columns; the analysis in the second configuration allowed calibration of the stiffness of the elements which fasten the masses to the model.



CONCLUSIONS

Unexpected events which often happen during experimental tests have slowed the tests, so that it is not possible at this stage to report on the most interesting part of the testing program.

The first tests have allowed identification of the elastic behaviour of the unbraced frame and have permitted to set up a numerical model of the structure. The tests of the structure with the first tipology of dissipative system are still in progress and should be completed shortly.

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