Dynamic tests of a dissipative bracing system for seismic control of framed structures

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ABSTRACT

The paper illustrates the results of an experimental program which deals with dynamic tests on a shaking table of a two-storey, one-bay frame, equipped 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 tests are presented and compared with results obtained by a numerical model of the structure.

1 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 energy dissipating devices based on flexural yielding of steel plates. This class of dissipative devices has been largely applied in Italy to the seismic protection of bridges: the devices show a reliable and stable behaviour in the plastic range under cyclic loading and extended low-cycle fatigue life.

At this stage, the research has been investigating constructional aspects using experimental tests, as realistic as possible. Shaking table tests have been conducted using a full scale model, at the 4.00 × 4.00 m shaking table facility, of ENEA, the Italian National Agency for Energy and Environment.

A two-storey one-bay steel frame with a dissipative bracing system has been tested. The test structure was designed to accommodate different types of
dissipative systems, and to be used again in subsequent tests.
The paper describes the design criteria, the experimental program, the instrumentation set up and the results obtained.

2 Design of the test structure

The aim of the design was to realize a structural model which would permit to focus the attention on 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.

In dimensioning 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 may have to sustain the entire seismic action due to all the present masses of the structure.

In order to meet all these targets and to get a model that might be reused many times, the unbraced frame was designed to be earthquake resistant according to Code prescriptions.

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 to prevent any sliding 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.
3 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.1) 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 for assuring a 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 wires.

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

The tests reported in this paper make use of a particular energy dissipating
device which has been defined E-shaped. Its schematic functioning may be deduced by fig.2. Its advantages follow from the anti-simmetrical 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 an uniform plasticization using beams of constant section: this implies cost savings and simplification in the production control.

4 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, even for 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 [2]. The global structural reaction of the system results from the contributions of the frame and of the bracing arranged in parallel; both contributions are 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 equally divided 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.

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

5 Test equipment and instrumentation

The shaking table used in the tests is the six-degree-of-freedom, 4.00×4.00 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 aimed to obtaining:
• displacements and accelerations at the base and at each floor, to follow the global behaviour
• loads and deformations in the dissipative devices to identify their dynamic behaviour.

To obtain the global measures at every floor, an accelerometer and a displacement trasducer, 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, (see fig.3).

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 bracing struts, through strain gages.
6 Test program and results

The experimental program has been divided into two parts: the first one has been directed to the identification of the model, the second one to testing the behaviour of the passive control system.

The preliminary dynamic characterization tests are presented in [3]. The most significant parameters are summarized in tab. 1

<table>
<thead>
<tr>
<th>$f_1$ (Hz)</th>
<th>$f_2$ (Hz)</th>
<th>$\xi_1$</th>
<th>$\xi_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.93</td>
<td>5.7</td>
<td>0.05</td>
<td>0.063</td>
</tr>
</tbody>
</table>

*frequencies and modal damping*

Seismic tests have been conducted both on the unbraced frame and on the braced frame. In this second case two series of dissipative devices have been used, the “small” ones, designed for the intensity level corresponding to PGA=0.35g, and the “big” ones designed for PGA=0.70g.

Different tests with artificial and natural accelerograms, suitably scaled (see tab. 2), have been conducted: the targets for these tests were:

- to verify the efficiency of the passive control in terms of energy absorption with reduction of stresses in the structure to be protected.
- to validate the design method for the dissipative devices, at the two selected intensity levels.

<table>
<thead>
<tr>
<th>Signal Used</th>
<th>PGA</th>
<th>Response Spectrum</th>
<th>Duration</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2 g</td>
<td><img src="image" alt="Signal 0.1-0.2 g" /></td>
<td><img src="image" alt="Response Spectrum 0.1-0.2 g" /></td>
<td>25 s</td>
<td>UBF</td>
</tr>
<tr>
<td>0.2-0.5 g</td>
<td><img src="image" alt="Signal 0.2-0.5 g" /></td>
<td><img src="image" alt="Response Spectrum 0.2-0.5 g" /></td>
<td>25 s</td>
<td>BF - SD</td>
</tr>
<tr>
<td>0.2-0.85 g</td>
<td><img src="image" alt="Signal 0.2-0.85 g" /></td>
<td><img src="image" alt="Response Spectrum 0.2-0.85 g" /></td>
<td>25 s</td>
<td>BF - BD</td>
</tr>
<tr>
<td>0.77-1.0 g</td>
<td><img src="image" alt="Signal 0.77-1.0 g" /></td>
<td><img src="image" alt="Response Spectrum 0.77-1.0 g" /></td>
<td>62 s</td>
<td>BF - BD</td>
</tr>
</tbody>
</table>

UBF : unbraced frame - BF : braced frame

Tab. 2
Artificial accelerograms of 25 sec duration and PGA between 0.1 g and 0.85 g have been applied; while on the unbraced frame it has not been possible to reach intensity values greater than 0.2 g, in the case of the braced frame, the maximum used PGA were 0.50 g with the small devices and 0.85 g with the big ones.

At the design PGA, for the two series of devices, as shown in fig. 4, the following targets have been achieved.
- the ratio between shear forces in the frame and in the bracings equals 1 and, the reduction of the total base shear is greater than 40%
- the reduction of the maximum storey drift reaches 80%
- the maximum value of the ratio between dissipated energy and input energy is around 65%
The normalized values of the base shear and of the storey drift, for accelerograms at different PGA, are presented in fig. 5.

The analysis of the behaviour of the test structure under seismic actions, at different PGA, confirms a favourable protection effect of the passive control system, even at intensity levels different from the ones considered in the design. The tests on the model, carried out with natural, non stationary accelerograms, have shown a similar good behaviour of the system also with an impulsive type accelerogram like Corralitos N-S (Loma Prieta 10.18.89).

In all cases the measured cycles show a very good behaviour of the devices with no degradation.

In order to evaluate and to facilitate the interpretation of the physical tests, a numerical non-linear model has been developed. Using this model it has been possible to reproduce the observed behaviour and to obtain further information about:

- quantities not directly measured during the tests,
- influence of some parameters on the behaviour of the model,
- simulations of tests not carried out.

In the development of the numerical model, it has been important to take into account many particularities of the real structural behaviour and its interaction with the table; in particular it has been important to model the internal springs which constrain the added masses to the frame, elastic restraints at the bases of the columns, the rigid zones at the frame joints and, the elastic restraints to the rotation of the table which serve to simulate the imperfections of the control system of the table motion (see fig. 6).

The constitutive model used for reproducing the hysteretic behaviour of the energy dissipating devices is based on a differential formulation which stems
from the endochronic theory of plasticity. The constitutive model is described in detail in [4]. Although the most interesting aspect of the model is its ability to trace the continuous evolution of damage, so typical of the actual hysteretic behaviour of materials, in this case the model has been utilized only for its ability of presenting a smooth transition between the elastic and the plastic range. The calibration of the numerical model has been obtained on the basis of the preliminary dynamic identification tests. The seismic analyses have provided results in accordance with the experimental tests, validating the calibration. For example fig. 7 shows, for the case of the natural accelerogram of Corralitos, a comparison between experimental and numerical results; in particular the comparison is presented for the 2\textsuperscript{nd} storey displacement and for the hysteretic force - displacement loops in a dissipative device at the 2\textsuperscript{nd} floor.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{2\textsuperscript{nd} storey drift - Corralitos N-S}
\end{figure}

8 Conclusions

The shaking table tests presented in this paper have confirmed the effectiveness of the proposed dissipative bracing system for seismic protection of buildings. The test results have permitted the validation of both the design methodology
adopted and of the construction details realized. Further research activity is being planned to experiment, using the available frame, with different bracing arrangements and different energy dissipation device types.

References