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Design of supplemental steel damping devices for buildings

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ABSTRACT: Single element steel plate damping devices were tested to experimentally establish the appropriate hysteretic mathematical models. These mathematical models were verified by comparing shaking table test data with corresponding nonlinear analytical results. A parameter study of device and building response characteristics lead to an assessment of device design sensitivity and thereby the appropriate designs of devices for building applications.

INTRODUCTION

A number of imaginative approaches to improved earthquake response performance and damage control in buildings have been developed and others are being developed. These approaches can be divided into two groups, passive systems of which base isolation and supplemental mechanical damping are examples and active systems which require active participation of mechanical devices whose characteristics will be determined from measured building response. This paper deals only with one member of a family of passive supplemental mechanical damping systems.

The steel plate added damping and stiffness (ADAS) device is an assemblage of steel plates which is designed for installation in a building frame such that the relative story drift causes the top of the device to move horizontally relative to the bottom, as shown in Figures 1 and 2. By yielding a large volume of steel, the ADAS device can dissipate substantial energy during an earthquake.

There are a number of benefits of dissipating energy through the yielding of ADAS devices: 1) earthquake energy dissipation is concentrated at locations which have been designed for this purpose, 2) energy dissipation demands on other structural members can be substantially reduced, and 3) because the devices are part of the lateral load resisting system only, yielding of the ADAS devices will not affect the gravity load service capacity of the structural system. The ADAS devices can be easily replaced after an earthquake, if necessary.

The mechanical characteristics of yielding steel devices were investigated by a number of researchers (Steimer, et al. 1984; Hanson 1986; Bergman and Hanson 1986, 1990; Whittaker, et al. 1989; Scholl 1990; Su and Hanson 1990). The tests of ADAS devices and frames with ADAS elements showed that the ADAS devices are very reliable energy dissipators which exhibit stable hysteretic behavior for displacement amplitudes as large as 14 times the device yield displacement, X_y, and are well suited for use in building structures sited in high seismic risk zones (Whittaker, et al. 1989). The tests at

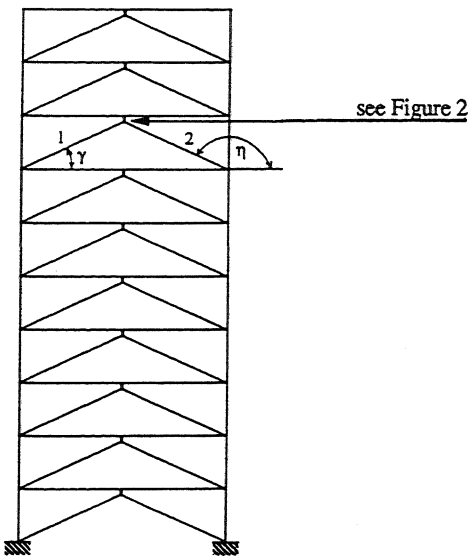

Figure 1. Typical ADAS installation in a building frame.

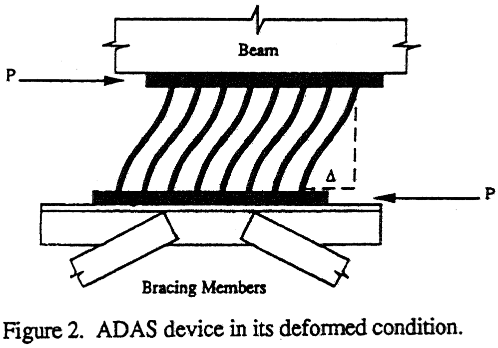

Figure 2. ADAS device in its deformed condition.

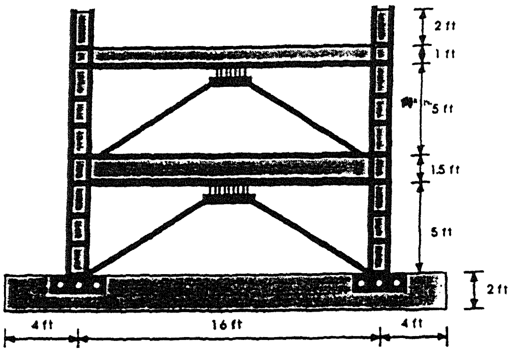

Figure 3. Concrete frame strengthened with ADAS devices. (1 ft = 12 inches = 305 mm = 0.305 m)

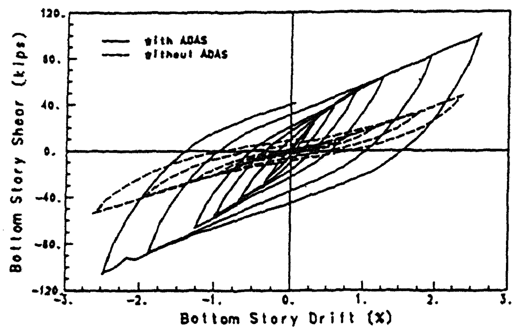

Figure 4. Hysteresis curves for bottom story of the reinforced concrete frame before and after installation of ADAS devices. (1 kN = 4.45 kips)

the University of California at Berkeley found that in the displacement range of $6X_y$ or less, the ADAS device hysteretic behavior is dependent only on the yield force P_y and the yield displacement, X_y and can sustain an extremely large number of yielding reversals (more than 100 cycles in the tests).

STATIC EXPERIMENTS

A two-story reinforced concrete planar moment frame representing school buildings in Mexico City was constructed at The University of Michigan as part of the U.S./Mexico Research Project funded by NSF. This study considered the following three systems for strengthening existing buildings: 1) toughening of the frame members and addition of infill walls; 2) toughening of frame and adding a steel bracing system; and 3) addition of mechanical damping devices. The reinforced concrete frame had 4.9 m span and 1.5 m clear story heights with 200x300 mm top floor beam and an 200x460 mm lower floor beam. Each floor slab was 76 mm thick and 1.5 m wide. The columns were founded on a 610 mm high foundation beam which was anchored to the Structural Laboratory reaction floor.

The concrete bare frame was subjected to cyclic loading up to a top floor displacement of 2% of the frame height in the first test series. Damage was concentrated at the beam-column joints at the first floor level and at the base of the columns. The damage was not severe.

Second, the frame was infilled with weak unreinforced brick masonry and was tested using the same loading series up to a top floor displacement of 1.5%. Severe damage was observed at the beam-column joints at the first floor level. Third, a steel bracing system, consisting of braces in an inverted V-pattern, horizontal beam collectors, and column confinement was added to strengthen the concrete frame following the substantial damage from the previous two tests. The strengthened structure showed stable energy dissipation under cyclic deformations larger than 2% of the story height. The column bases were cracked due to the increased base shear and column axial forces. Following the braced frame tests, the buckled bracing members were removed and the capacity of the remaining frame was measured. The ADAS devices were added at the top of new chevron 76x50x6 mm tube braces in both stories as shown in Fig. 3. 130 mm high devices with seven 13 mm thick X-shaped steel plates in the top device and nine 13 mm thick X-shaped steel plates in the bottom device were used. These devices were assembled using both bolts and welds. A comparison of the cyclic base shear and bottom story drift before and after installation of ADAS devices is illustrated in Fig. 4. Without ADAS devices, the concrete frame had low stiffness and low energy dissipation. The addition of ADAS devices increased the stiffness, strength and energy dissipation of the frame.

From the cyclic static test results described above, it was established that a moment frame with ADAS devices is capable of effectively dissipating input energy. It is expected that the supplemental damping and stiffness provided by the device can control building response during an earthquake. A dynamic analysis is used to evaluate the devices in modifying building response characteristics; that is, whether the devices reduce the seismic demand on a structure and control its motion during an earthquake. The device hysteresis characteristics reported above can be described in terms of Ramberg-Osgood formulas or bilinear models. To define the stiffness variation of a device, three Ramberg-Osgood parameters need to be established. They are the characteristic yielding force P_y, the characteristic yielding displacement, X_y, and the Ramberg-Osgood exponent, r.

Though the equations express the displacement as function of force, the displacements were given as input to calculate the corresponding forces for comparing experimental and analytical results. This approach offers better fit, because the device displacements have significant differences while the corresponding changes in force are small after the device yields. The calculated forces compared with the corresponding experimental forces and ratio of experimental to analytical energy dissipation were used to identify the best choice for the device parameters. The best combination for the first story device of the concrete frame was P_y=131 kN, X_y=8 mm and r=7. As can be seen in Fig. 5 the analytical and experimental curves matched very well and the loops are full indicating that the device can effectively dissipate energy.

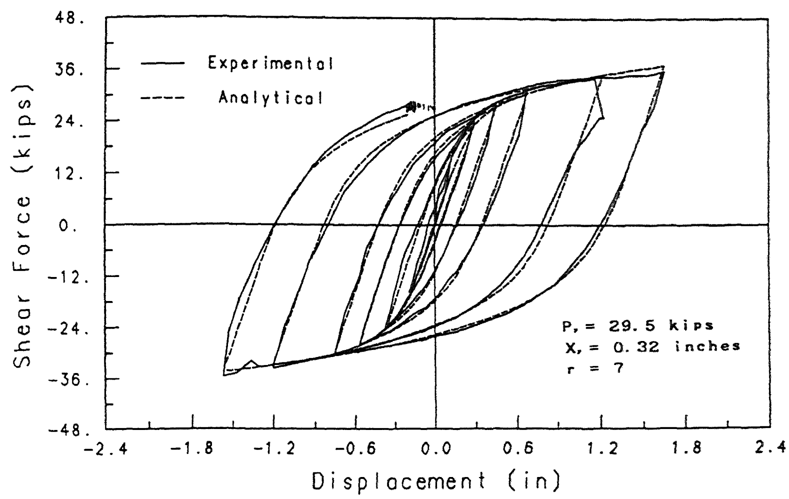

Figure 5. Hysteresis correlation between experimental and analytical results for the bottom device of the concrete frame. (1 in. = 25.4 mm, 1 kip = 0.225 kN)

A bilinear model was selected to represent the ADAS device inelastic behavior for a parameter study because it is mathematically simple and can account for both strain hardening and hysteretic behavior. The hysteretic energy dissipated by the device in a loading cycle is a function of the yield force, P_y, the yield displacement, X_y, and the ductility ratio, (X / X_y). This hysteretic energy is independent of the strain-hardening ratio which determines the force increase due to material hardening.

ADAS PARAMETER STUDY

ADAS element and building parameters included in this study were: 1) the yield force and the yield displacement of ADAS devices; 2) the ratio of the horizontal bracing member stiffness to the ADAS device initial elastic stiffness, B/D ratio; 3) the ratio of the ADAS element stiffness to the structural story stiffness without ADAS elements in place, SR ratio; and 4) the device strain hardening ratio.

Three ten story frames were used in this study. Due to space limitations herein the interested reader will need to find the details of this study in Xia, Hanson & Wight (1990) or Xia & Hanson (1992).

Effect of B/D Ratio, Device Yield Displacement and SR

The B/D ratio effects the deformation of the ADAS devices only before the device yields. After yielding, the stiffness of ADAS device decreases significantly. It is recommended that a B/D ratio of about two be used for the design of the ADAS elements unless the brace strength necessary to yield the ADAS device without buckling in compression or yielding in tension results in a larger B/D ratio.

It was found that the ADAS ductility ratio is very sensitive to device yield displacement. Selection of the device yield displacement is more effective than either the SR ratio or the device yield force in controlling the maximum device ductility ratio. For device energy dissipation effectiveness, it is desirable to have a small device yield displacement. However, the device yield displacement must be large enough to control device ductility during severe earthquake ground motions. A device yield displacement from 0.0014 to 0.002 times the story height with a target device ductility ratio of 4 to 5 will result in a maximum story drift of about 0.6 to 1.0 percent.

Increasing the ADAS device yield force will increase the device strength and the hysteretic energy dissipation capacity for equal displacements. From the point of view of strength and energy dissipation, it is desirable to select a large ADAS yield force. However, a large yield force will increase the size of the supporting structural members and the cost of the devices. The proper selection of the ADAS yield force should consider both structural safety and cost. Based on the response of these structures subjected to the El Centro earthquake, an SR ratio about 2 was appropriate for the design of ADAS devices and bracing members.

Energy Response

The energy response of the frames subjected to a strong earthquake with and without ADAS elements was calculated to determine the effectiveness of ADAS device energy dissipation. For frames without ADAS elements, the hysteretic energy dissipated by structural members E_m, was very large, about 50% to 80% of total input energy depending on the earthquake characteristics and the intensity. For a frame with ADAS elements, the ADAS elements dissipated large amounts of hysteretic energy and reduced the hysteretic energy dissipation demands on structural members to nearly zero. Caution must be used in interpreting these results because the energy demands on the ADAS devices vary depending on the earthquake characteristics and intensity.

CONCLUSIONS

Properly designed ADAS elements can be used to effectively control the inelastic response of a building frame. In the design of frames with ADAS elements, it is important to select appropriate values of the ADAS device parameters such as the device yield force, the device yield displacement, and the stiffness ratio of the ADAS element stiffness to the frame story stiffness, SR. Based on the limited analytical results from three structural systems and three earthquake records, the following conclusions are presented:

1. ADAS elements can significantly increase the structural energy dissipation capacity and substantially reduce the energy dissipation demands on other frame members. As a result of the increased energy dissipation capacity at small displacements, structural safety is increased.
2. The selection of device yield force should consider both strength and energy demands based on the expected earthquake ground motion intensity and duration at the building site. The yield force should be large enough to provide adequate energy dissipation capacity within the desired design ductility ratio. For a selected yield force and yield displacement, the elastic stiffness of the ADAS device and the stiffness ratio SR can be calculated.
3. ADAS ductility ratio is sensitive to the device yield displacement. To avoid device ductility ratios beyond 10, proper selection of device yield displacement is very important. From the studies discussed in this paper the recommended device yield displacement for design of the ADAS elements is in the range of 0.0014H to 0.002H.
4. The effect of brace stiffness to device stiffness ratio, B/D, on reducing structural inelastic response is small. A B/D value equal to 2 is recommended for bracing member design, provided that the bracing has enough strength to yield the ADAS devices. The effect of strain hardening on ADAS device forces should be taken into consideration for design of the bracing members and other structural members supporting ADAS devices.

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