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VISCOUS DAMPERS AT EXPANSION JOINTS FOR SEISMIC PROTECTION OF BUILDINGS

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ABSTRACT

This study investigates the use of viscous dampers installed across the gap between adjacent frame structures that could be subjected to pounding during seismic event. For this purpose, an analytical model was developed to simulate two frame structures that are subjected to pounding. The model was calibrated based on Shake Table test results. After calibration, the analytical model then used to generate pounding response for cases that could not be tested on shake table. Results of this study showed that viscous dampers can reduce the amplified pounding response. Viscous dampers are more effective for design earthquakes of higher intensities and for frames having small gap spacing between them compared to frames that are in direct contact with each other before excitation.

Introduction

To measure the effectiveness of the viscous dampers in reducing pounding, a shake table test program was carried out for two adjacent steel frames towers one representing a rigid frame adjacent to a flexible frame. Both frames were subjected to pounding and then retrofitted by installing viscous dampers across the gap between them. Results of the tests where used to calibrate an analytical model, that was used to generated structural response for additional test cases that was not practical for shake table testing.

Experimental Study

Two steel-frame towers were designed and built as test specimen. The first frame was a scaled model to an eight story steel structure representing a flexible frame with an adjacent three story structure representing a rigid frame. The frames where excited using El Centro and Northridge records after scaling the two time history records based on the peak ground acceleration (PGA). Pounding responses were generated on shake table testing, then viscous dampers were incorporated into across the gap between the frames to study their effect in reducing the pounding response.

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Figure 1. Test Frames

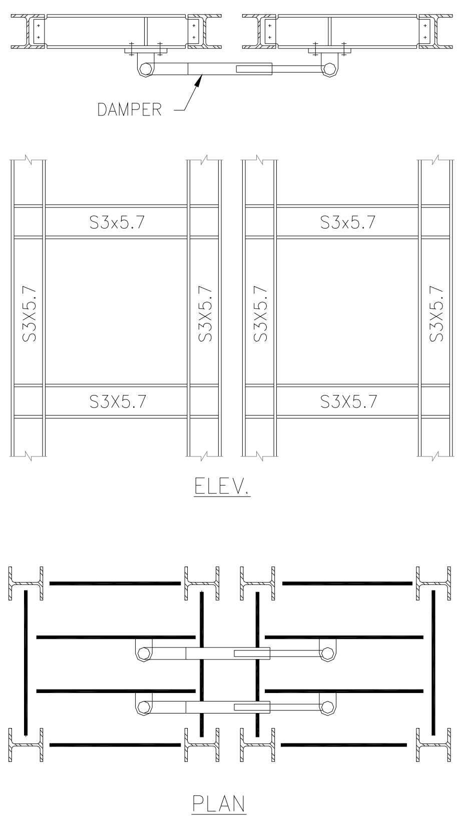

Figure 2. Schematic Diagram for Viscous Damper Installed Across the Gap between Frames

The testing was performed on a biaxial shake table at the structural laboratory of the Henry Samuel School of Engineering at the University of California, Irvine. Floor acceleration at each floor level was measured by using piezoelectric accelerometers. Diagonal linear variable differential transformers (LVDTs) were installed at each floor of the flexible frame to measure the story drift. Impact forces were measured using a compression-only load cell. Impact forces between the frames were controlled so that it occurred only at the top of the rigid frame. The gap between the frames was designed and configured to simulate three main conditions:
a) Zero gap: the two frames that are touching each other are at rest, b) Large gap: the frames are separated sufficiently to allow them to vibrate freely under strong earthquakes without colliding, c) Small gap: a case between the zero and the large gaps.

Analytical Model

The analytical model in this study was formulated is shown in Figure 2. The two frames that were tested in the experimental phase of this study are idealized as series of lumped masses connected at the floor levels. Pounding between the two frames is modeled using the visco elastic impact element known as. Kelvin Volget element previous research suggested that this element produces the most reliable results with fewer difficulties of numerical solutions conversions(Ksai).

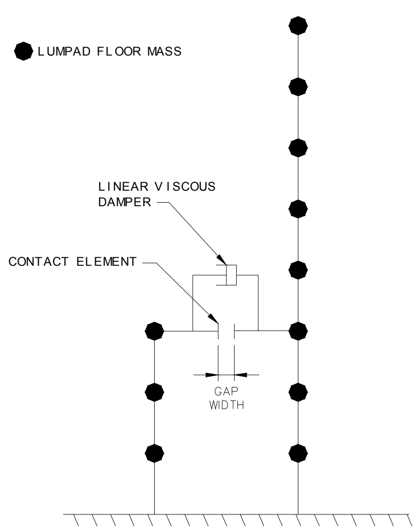

Figure 3 Idealization of the Analytical Model

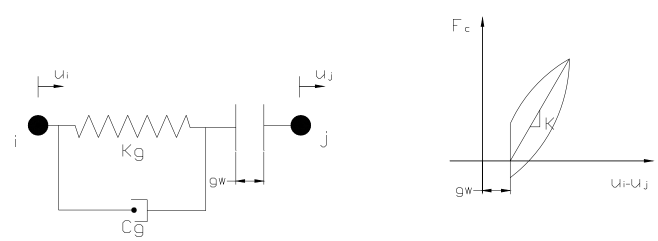

Figure 4 Kelvin-Voigt Impact Element (Ksai)

The impact force during the colliding Fc (t) was calculated using the following expression:

$$F_c(t) = K_g \delta(t) + C_g \delta^{'}(t) \quad (1)$$

Where,

δ(t) $= u_i - u_j$ is the relative displacements between nodes, i and j ,

δ' (t) is the relative velocities between the two nodes,

K_g is the impact stiffness simulating local stiffens at impact,

C_g is the impact element damping, which can be obtained from the following equations

$$C_g = 2\xi \sqrt{(k \frac{m_i m_j}{m_i + m_j})} \quad (2)$$

Where,

m_i is the mass of node i, m_j is the mass of node j, ξ is a damping ratio obtained from the coefficient of restitution e and can be obtained from the following expression:

$$\xi = -\frac{\ln e}{\sqrt{\pi^2 + (\ln(e))^2}} \quad (3)$$

$$e = \frac{v_j - v_i}{v_{0i} - v_{0j}} \quad (4)$$

Where e is the coefficient of restitution, v_j is the velocity of body 2 after the impact, v_i is the velocity of body 1 after the impact, v_{0i} is the velocity of body 1 before the impact, v_{0j} is the velocity of body 2 before the impact

The experimental impact force-displacement relationship between the two frames indicated that the value of K_g can be estimated to be 500 k/in

In order to obtain the coefficient of restitution shown on equation (4), the acceleration data records at 3rd floors of both frames were numerically integrated with baseline corrections to obtain the velocity time history. Algebraic values of velocities before and after impact were identified by locating the velocity at the time step where colliding occurred. The average of all the values obtained for e is used in the calculation of the coefficient x in equation (3). Substituting the value of x in equation (2) the damping coefficient in the contact element was estimated.

The equation of motions of the two frames can be expressed in equation (5)

$$Mu^{\cdot\cdot} + Cu^{\cdot} + Ku = -Miu_g^{\cdot\cdot} \quad (5)$$

Where: M, C& D are the mass, damping and stiffness matrices of the two structures. The equation of motions were solved using step by step direct integration method. A Matlab© script was developed to solve the equation of motions using modified Ralph method.

Verifications of the analytical model

Figures 5 and 6 show a comparison of the 3rd floor acceleration of the rigid frame and the 8th floor acceleration of the flexible frame between earthquake simulator test results and the numerical simulations results for large gap configuration due the El-Centro and Northridge records. As it can be seen from these figures, the 8th floor analytical results almost match the experimental results in the time domain. In the frequency domain, the analytical modal captures of the first mode; however, there is a slight phase shift in the second mode. Since that the first mode has a mass participation factor greater than 92%, this slight phase shift is considered to have a minor effect on the response of the frame. The response of the rigid frame shows minor deviations from the experimental results in the time domain and it is also reflected in a small phase shift in the frequency domain. This can be explained due to the fact that the experimental modal data that was obtained for the rigid frame was contaminated with higher levels of electric noise when compared to the flexible frame.

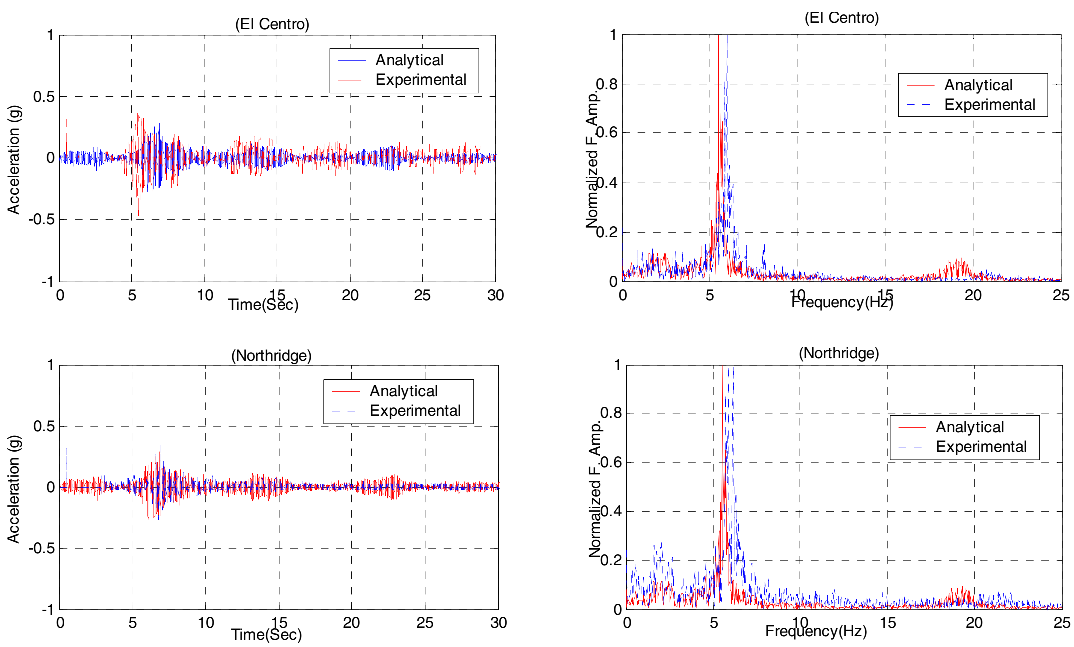

Figure 5 3rd Floor Acceleration of the Rigid Frame

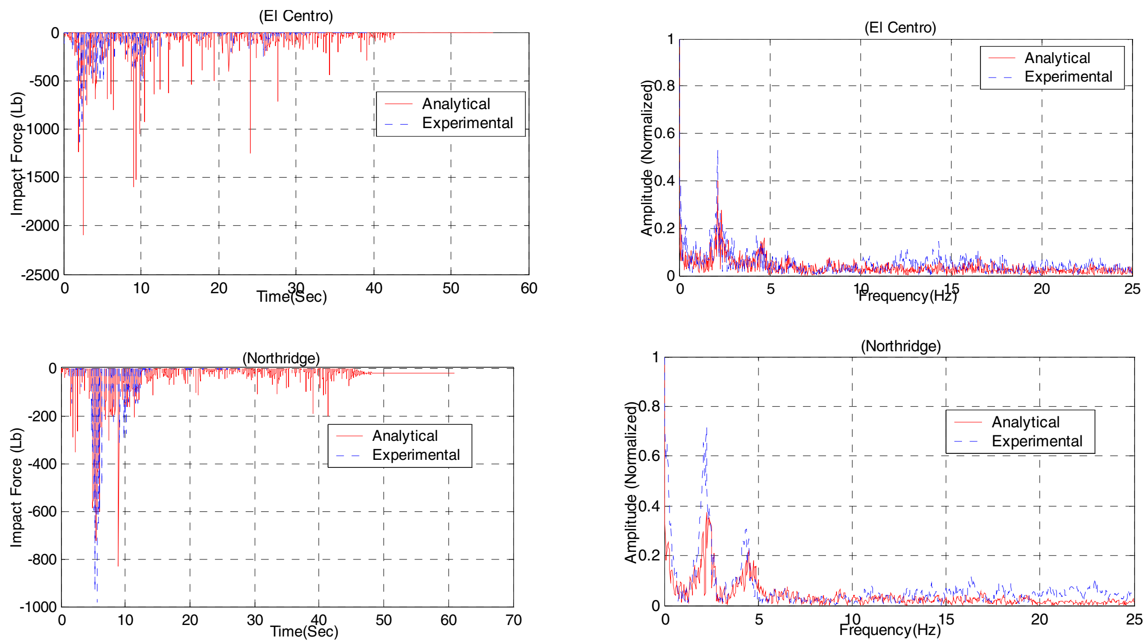

Figure 6 Impact Force between Frames during Colliding

Parametric Study

After calibrating the analytical model from shake table tests results, The calibrated model was used to perform simulations using ground motion records with higher intensities. The parameters that were presented in these simulations include the stiffness ratios between the flexible frame and the rigid frame; the damping coefficient Cv of the supplemental damping device (which is a representation of the magnitude of damping forces that are added to the system); the spectral accelerations of the input seismic ground motions; and the gap configurations between the frames

Parameter	**Values**
Frames Stiffness Ratio (K_1/K_2)	0.2, 0.3, 0.5, .65, 1.0
Spectral Acceleration Ratio (Sa_1/Sa_2)	0.82,1.15,1.5,2.18,2.5,2.8,3,4,7,65, 8.35
Damping Coefficient C_v	0.5,1.0,1.5,2.0,2.5,3.0,3.5
Gap Configurations	Large gap, Small gap, Zero gap

Table 1: Variables Used in Parametric Study

Five seismic ground motions were used for the numerical simulation. These ground motions were selected based on their maximum peak ground acceleration (PGA), which range from 0.3g to 0.8g, and their frequency contents. Figure 7 shows an overlay of the normalized response spectra of these records.

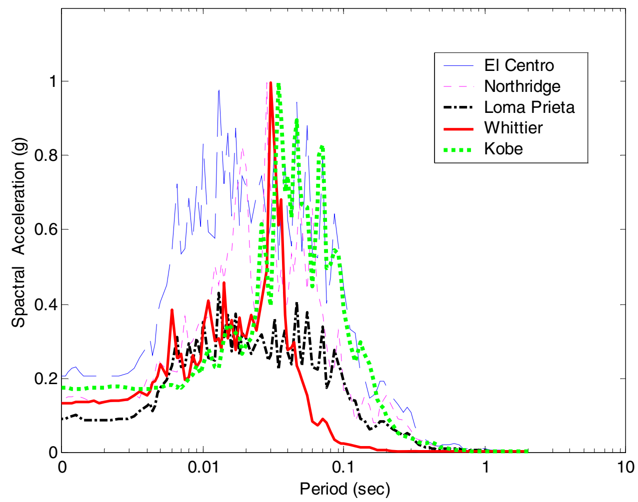

Figure 7 Normalized Response Spectra of Ground Motions Used in the Parametric Study

Results of Parametric Study

The pounding response was presented in the floor acceleration and impact forces between the frames. Since it was found in a previous study that story drift is insensitive to the pounding response, it was not recorded in this study. The effect of increasing the damping coefficient between frames subjected to pounding is discussed in the following section.

Floor Accelerations

Figures 8 and 9 show the relationship between the maximum floor accelerations for both frames at different damping coefficients of the viscous damper devices (Cv) and different period ratios between them. The graphs indicate that the maximum floor acceleration is highly dependent on the period ratios between frames and the PGA of the input ground motions. The floor acceleration is also dependent on the configurations of the gap between the frames where the supplemental damping were more efficient in the case of small gap compared to the case of the zero gap. Introducing the viscous dampers between the frames (which are represented numerically by the value of Cv that ranged from 0.0 to 1.0), reduced the floor acceleration significantly to a level comparable to the condition of frames with the large gap where no pounding occurred. The numerical value of Cv that is required to reduce the high acceleration observed in case of zero and small gaps varies with the input ground motions and the frequency ratios of the frames. However the incremental increase of Cv values will eventually damp out all the impulsive accelerations associated with the zero and small gaps configurations for all input ground motions.

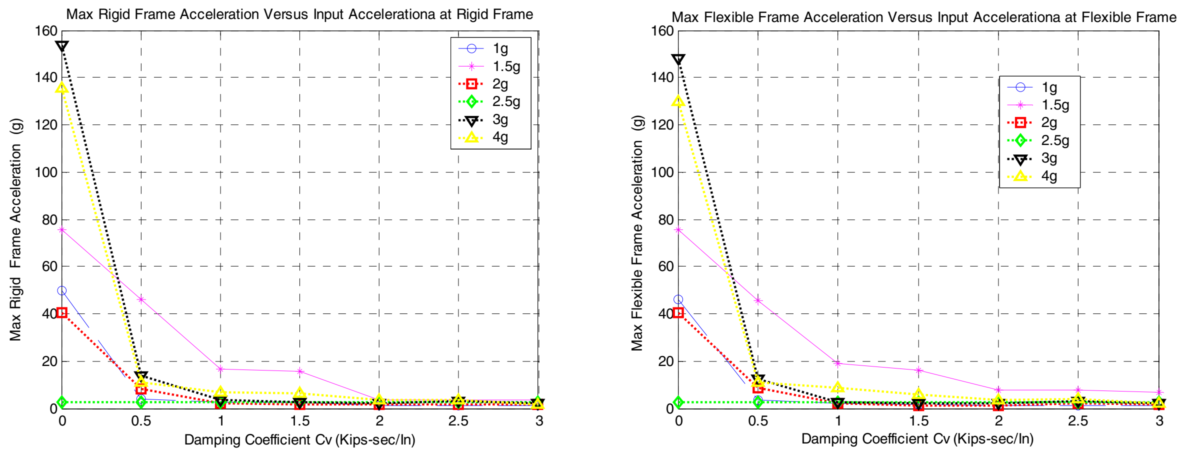

Figure 8. Max Frame Floor Acceleration versus Damping Coefficient at Zero gap

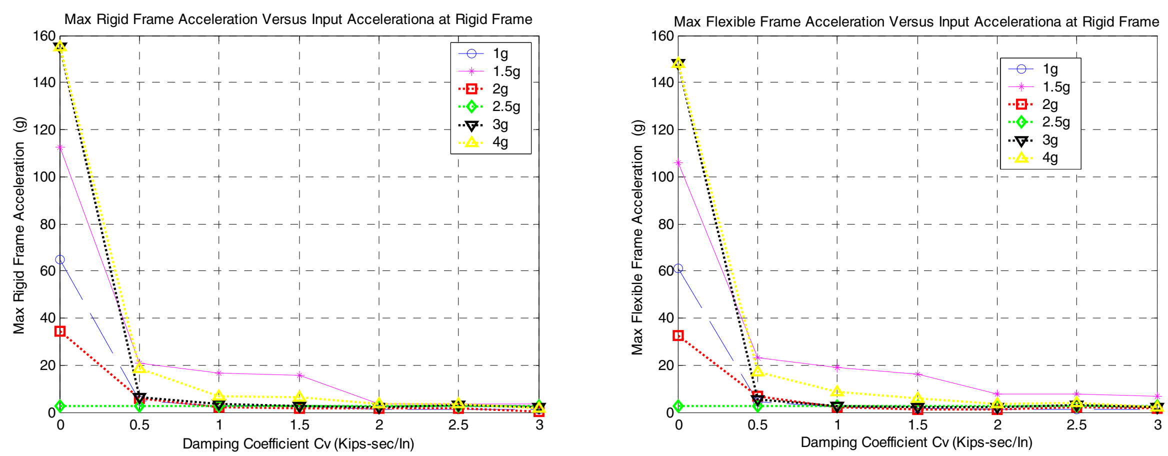

Figure 9. Max Frame Floor Acceleration versus Damping Coefficient at Small gap

Impact Force

Figure10 shows the maximum impact force for the zero gap and small-gap configurations versus the period ratio between the frames. The impact force for the case of no damper between frames (which is represented by CV=0) produces the highest impact force for all input ground motions. This maximum impact force changes with the variations of the ratios of the natural period and reaches its peak value at a period ratio of 0.8 for all inputs. It is interesting to note that, for all period ratios, the presence of the viscous damper will rapidly dissipate the impact force. The value of Cv which is a representation of the damping force provided by the supplemental damping devices that would be needed to completely dissipate the impact forces varies based on the input ground motions and the period ratios between frames. Generally Cv values of 0.5 to 1.0 are sufficient to dissipate most of the impact forces. It is also interesting to note that increasing the Cv value higher than 1.5 does not have any additional benefit for dissipating the impact forces.

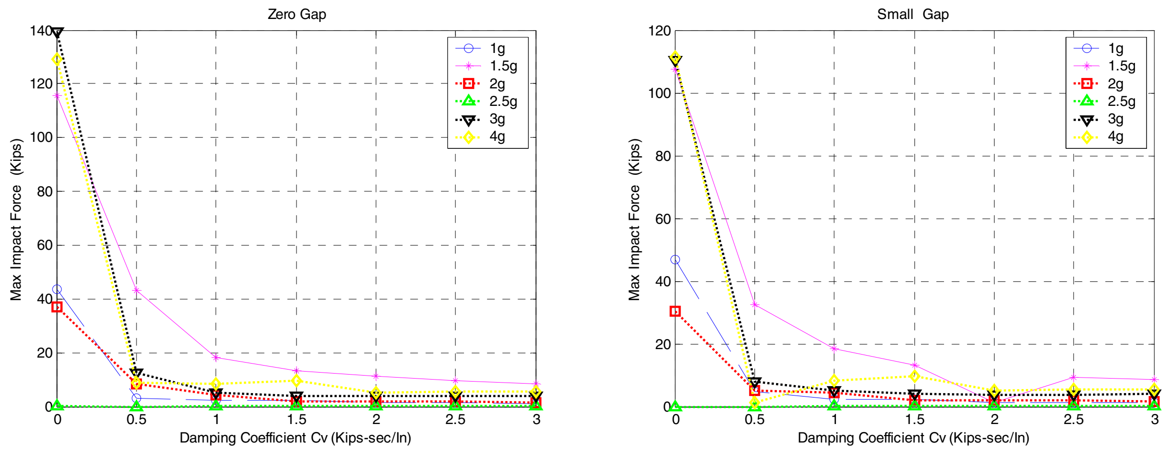

Figure 10 Max Impact Force between Frames versus Damping Coefficient at Different Spectral Acceleration

CONCLUSION

1. The impact force and floor acceleration of the structures subject to pounding are highly dependent on the natural period ratios of the two structures and the frequency content of the input ground motions.
2. The damping coefficient of the supplemental damping devices that need to be incorporated in the structural system to reduce the pounding responses is dependent on the natural period ratio between the frames and the input ground motion. However, the supplemental damping devices with high damping coefficients were effective in dissipating impact response.
3. Incorporating viscous damper between the frames can dissipate most of the pulse impact force and floor acceleration to a level comparable to floor acceleration where frames are separated by large gaps.
4. The viscous dampers are more effective in the case of small gaps compared to the case of zero gaps.
5. Viscous dampers would be more beneficial for earthquakes with larger PGA levels.

Acknowledgments

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