OPTIMAL SEISMIC RESPONSE OF ADJACENT COUPLED BUILDINGS WITH DAMPERS

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ABSTRACT:

The dynamic response of building structures due to earthquakes is very important to Civil engineers. Structures exposed to earthquake exited vibrations that are damaging to their structures components. Structural pounding is an additional problem that may take place when closely spaced buildings experience earthquake excitation. This phenomenon occurs when, the structures oscillate out of phase due to their different dynamic parameters and the separation is not sufficient. Separation between the structures would avoid the problem; however, for metropolitan cities located in regions of high seismic activity, the need to maximize use of land has lead to inadequate separation often resulting in pounding of adjacent structures during a strong earthquake. The problem is complicated by the fact that, adjacent buildings usually belong to different owners, and in most cases are built at different times with different building code specifications. These buildings have also been designed with different functional objectives that translate into different dynamic characteristics. Many energy dissipation devices are presently being used to reduce both structure vibration and probability of pounding. The aim of this paper is to investigate the optimal seismic response of two adjacent structures via the use of passive energy dissipation devices, in order to minimize the pounding effect. In this work viscous and viscoelastic dampers have been considered as the devices of choice to mitigate the risk of structural pounding. For the best overall system response, efforts have been made to attain the optimal distribution of the viscous and viscoelastic dampers in the adjacent structures. The required number of dampers of known capacity and their optimal placement locations in adjacent buildings are calculated to achieve the maximum reduction in a desired response.

KEY WORDS: Adjacent buildings, Pounding, Dampers, Structural response

1. INTRODUCTION

The protection of civil structures, including their material contents and human occupants, is without doubt a world-wide priority of the most serious current importance. Such protection may range from reliable operation and comfort on the one hand to survivability on the other. Examples of such structures include buildings, offshore rigs, towers, roads, bridges, and pipelines. In like manner, events which cause the need for such protective measures are earthquakes, winds, waves, traffic etc. Indications are that control methods will be able to make a genuine contribution to this problem area, which is of great economic and social importance. One of the exciting new application areas for control system design has to do with the protection of civil engineering structures from dynamic loadings. In recent years, world-wide attention has been directed toward the use of control and automation to mitigate the effects of dynamic loads on structures. Among the different innovative techniques, which allow to control and modify the seismic response of structures, an important role have assumed the passive control techniques based on the artificial increase of the dissipation capacity, obtained by means of the insertion, in proper positions, of special energy dissipative devices.

In the past decade coupled building control has received increasing attention. Researchers have proposed passive, active, smart damping devices to mitigate the adjoining building’s responses to wind and seismic excitation. Installation of such devices does not require additional space and free space available between two adjacent structures can be effectively utilized for placing the control devices. Such types of arrangement are also helpful in reducing the mutual pounding of structures during seismic events. The present work is aimed to investigate the dynamic behavior of two adjacent multi-degrees of freedom buildings connected with dampers such as viscous and viscoelastic under earthquake induced excitations. The effectiveness of dampers and optimal values for the distribution of viscous dampers interconnecting two adjacent buildings will be studied. Also the investigation will be made for optimal parameters of the passive coupling element such as damping and stiffness under different circumstances to reduce response of adjacent buildings.

2. MODELING AND THEORETICAL FORMULATION

To capture important characteristics of damper connected adjacent buildings and to make the program manageable, only the two-dimensional system consisting of two linear elastic shear buildings connected by viscoelastic dampers at each floor level is considered in the present study. The assumption of linear elastic buildings indicates that only small and moderate seismic events are concerned. The mass of each building is concentrated at its floor and the stiffness is provided by its mass-less columns. Both buildings are assumed to be subject to the same base acceleration and any effects due to spatial variations of the ground motion or due to soil-structure interactions are neglected. Assuming that total degrees of freedom of two adjacent buildings are N (see fig.1), in which the number of degrees of freedom of the left building (A) is L, with its first floor designated as the first degree of freedom. Then, (N–L) is the number of degrees of freedom of right building (B), with its first floor designated as the (L+1) degree of freedom. For both the buildings the mass at all the floor level is kept constant while the stiffness is varied to achieve the desired time period. Both the buildings have 20 stories, so total number of degrees of freedom N = 20 + 20 = 40. As the building A is stiffer than building B, the time period of building A will be less than building B.

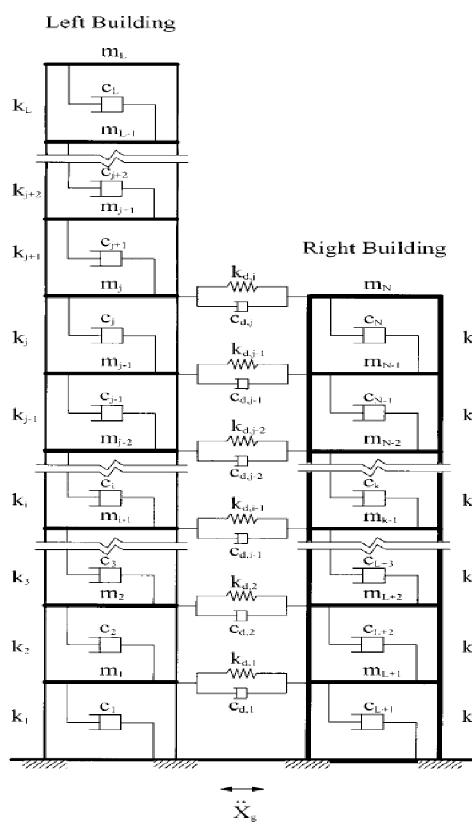

Figure 1 Structural model of adjacent buildings with joint dampers

3. FORMULATION OF COMBINED SYSTEM

The connected buildings can be described using the following equation of motion,

$$M\ddot{Y}\,(t) + C\ddot{Y}\,(t) + KY\,(t) = -M\ddot{Y}g\,(t) \tag{3.1}$$

Where, $M = \begin{pmatrix} M_L & \\ & M_R \end{pmatrix}$

It is the mass matrix of the combined system. M_L, M_R are the individual mass matrices for the stiff and soft building.

$$M_L = \text{diag}[\, m_1 , m_2 , m_3 \ldots\ldots\ldots m_N \,]$$
$$M_R = \text{diag}[\, m_1 , m_2 , m_3 \ldots\ldots\ldots m_N \,] \tag{3.2}$$

Where, m_1 , m_2 , m_3 ……… m_N are the masses at each floor level.
The stiffness matrix of the combined system is given as,

$$K = k_S + k_D$$

Where, $k_S = \begin{pmatrix} k_L & \\ & k_R \end{pmatrix}$

k_L is the stiffness matrix for the stiffer building and k_R is the stiffness matrix for the softer building. k_D is the stiffness matrix for the external dampers.

$$k_L = \begin{pmatrix} k_1 + k_2 & -k_2 & & & \\ -k_2 & k_2 + k_3 & & & \\ & & -k_{L-1} & k_{L-1} + k_L & -k_L \\ & & & -k_L & k_L \end{pmatrix}$$

$$k_R = \begin{pmatrix} k_{L+1} + k_{L+2} & -k_{L+2} & & & \\ -k_{L+2} & k_{L+2} + k_{L+3} & & & \\ & & -k_{N-1} & k_{N-1} + k_N & -k_N \\ & & & -k_N & k_N \end{pmatrix}$$

$$k_D = \begin{pmatrix} k'L*L & -k'L*L \\ -k'L*L & k'L*L \end{pmatrix} \tag{3.3}$$

Where, $k'L*L = \text{diag}[\, kdi , kd2 , kd3 \ldots\ldots\ldots k_dL \,]$
k_d is the stiffness of individual viscous damper attached to floors at each floor level.
The damping matrix of the combined system is given as,

$$C = c_I + c_D \tag{3.4}$$

Where c_I is the internal damping matrix of the system and c_D is the damping matrix for the external dampers.

Where, $c_I = \begin{pmatrix} c_L & \\ & c_R \end{pmatrix}$

c_L($c_L = \alpha_L\, M_L + \beta_L\, k_L$) is the internal damping matrix for the stiff building, which is proportional to mass and stiffness matrix for the stiff building. c_R ($c_R = \alpha R\, M_R + \beta_R\, k_R$) is the internal damping matrix for the soft building, which is proportional to mass and stiffness matrix for the soft building.

$$c_D = \begin{pmatrix} c'L*L & -c'L*L \\ -c'L*L & c'L*L \end{pmatrix} \tag{3.5}$$

Where, c’L*L = diag[c_{di} , c_{d2} , c_{d3} ……… c_{dL}]
c_d is the damping coefficient of the viscous dampers attached to floors at each floor level. k_D and c_D are the matrices of order N x N.

4. CASE STUDY

For application, a simplified model of two adjacent 20 storey buildings having same floor elevations with dampers connecting two neighboring floors are used. The damping ratio for both the buildings is taken as 5%. For both the buildings, the mass at all floors is kept constant, taken as 1.29 x10^6 kg. The inter-storey stiffness of each floor is varied for both buildings to achieve desired time period. The building ‘A’ is considered as stiff building while the building ‘B’ is considered as soft building. As the building A is stiffer than building B, the time period of building A will be less than building B. Also, the natural frequencies are smaller in the building B than building A. Time History Analysis will be carried out to find the maximum top floor displacements for three cases. The first case is that of unconnected structures, the second being the case when the two buildings are connected at all the floor levels and the third being the case when the two buildings are connected at optimal locations.

4.1 Modal frequencies

The modal frequencies of each building without dampers connected are calculated. The first four modal frequencies of right building (soft) are 2.884, 9.717, 18.80, 28.17 rad/sec, respectively and the first three modal frequencies of left building (stiff) are 3.749, 14.493, 29.973 rad/sec, respectively. The damper stiffness coefficient is chosen such that, the addition of dampers does not change the modal frequencies of the individual buildings. When the damper stiffness is 5 x 10^4 N/m, the first five modal frequencies of combined system are 3.482, 5.546, 10.412, 14.711, 19.184 rad/sec respectively. Clearly, using viscoelastic dampers to link adjacent buildings only slightly change the modal frequencies of the individual building. The retention of the natural frequencies of the unlinked buildings after the installation of joint dampers is especially desirable for the adjacent buildings that have been already built and need to be strengthened.

5. RESULTS AND DISSCUSSIONS

5.1 Determination of the optimal stiffness coefficient (kd) for the external viscoelastic damper

To determine the optimal stiffness coefficient for the external viscoelastic damper, it is seen that after the application of dampers to connect both buildings, the natural frequencies of the two individual buildings must not change though the displacements of both buildings are reduced. Numbers of iterations are performed for the damper stiffness values from 1N/m to 1.0 X 10^6 N/m. Following fig 2 shows the variation of natural frequencies of both buildings against the damper stiffness.

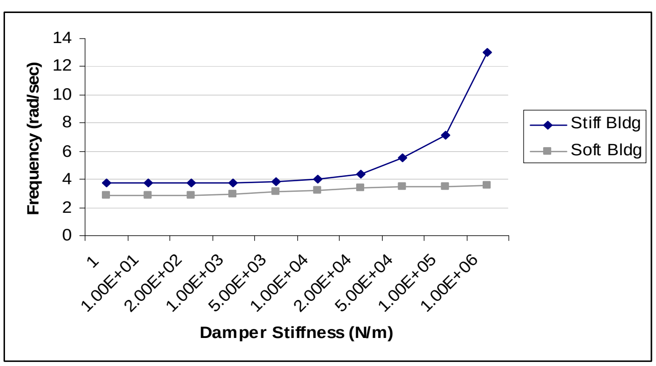

Figure 2 Damper Stiffness vs. Modal Frequency

It is seen that, the modal frequencies of stiff building 'A' will start increasing, when the damper stiffness is between 2.0 X 10^4 N/m to 5.0 X 10^4 N/m. Beyond these values, the modal frequencies of stiff building becomes very large. However, the modal frequencies of soft building 'B' will have very moderate variation over the damper stiffness. Comparison of these values with the corresponding values without dampers (unconnected buildings) shows that the frequencies are almost similar when the damper stiffness is up to 5.0 X 10^4 N/m. Hence, the value of 5.0 X 10^4 N/m is selected as the optimal stiffness for the dampers. When the value of stiffness is increased up to 1.0 X 10^9 N/m, the relative displacement between the adjacent buildings becomes nearly zero, implying that both buildings are rigidly connected.

5.2 Seismic response - Maximum top floor displacement

Seismic response analysis is carried out to investigate variations of seismic response of the adjacent buildings with damper parameters to see if the optimal damper parameters identified from the modal analysis are the same as those from the seismic response analysis under given earthquake excitation spectrum. Then, the effectiveness of the dampers of optimal parameters on seismic response reduction is examined. The variations of the top floor displacement response of left and right building respectively, with damper stiffness for several damper damping coefficients are shown in following fig. 3 and fig. 4.

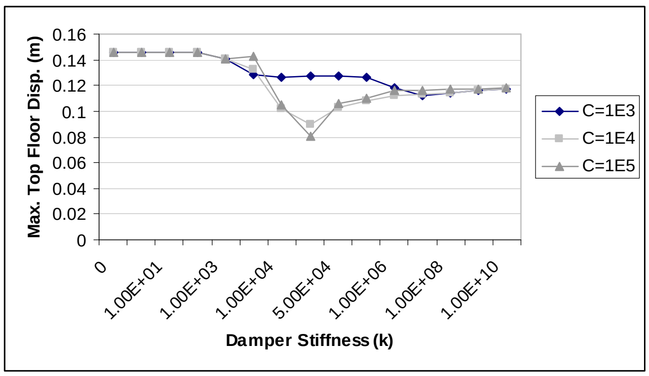

Figure 3 Maximum Top Floor Displacement vs. Damper Stiffness for left building

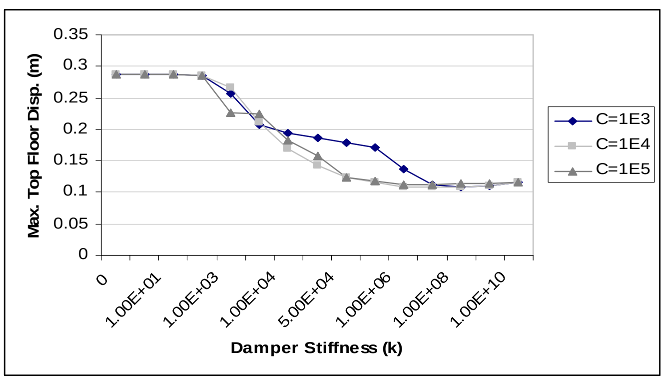

Figure 4 Maximum Top Floor Displacement vs. Damper Stiffness for right building

After comparing above graphs, it can be seen that the displacements of both the buildings are minimum, when the damper stiffness is between 2.0 x 10^4 N/m to 1.0 x 10^5 N/m. Hence, the damper stiffness 5.0 x 10^4 N/m as we selected from modal analysis is correct. The fact that the response mitigation is not sensitive to damper stiffness within a certain range is very helpful for practical application of joint dampers. Thus after certain limit, the effectiveness of dampers deteriorates rapidly. This is because the strong damper stiffness reduces the relative velocity of the damper and hence the energy absorbing capacity from the dampers decreases. In particular, when the damper stiffness reaches a value above 1.0 x 10^9 N/m, the relative displacement and velocity between the adjacent buildings become nearly zero so that the two buildings behave as though almost rigidly connected. As a result, no matter what value the damper damping coefficient is, the damper totally loses its effectiveness.

5.3 Determination of optimal damping coefficient (cd) for the external viscoelastic damper

As we can not increase the damper stiffness of the interconnecting dampers beyond certain limit, the damper damping coefficient should be such that the displacements of both the buildings are reduced. Hence, for obtaining the optimal damping coefficient, a variation of the maximum top floor displacement versus the damper damping coefficient is plotted for different earthquakes. It is seen from fig. 5 that, the maximum top floor displacement is minimum, when the damper damping coefficient is 1.0 x 10^4 Ns/m. beyond this value, there is no significant reduction in the displacements of both the buildings. Hence, 1.0 x 10^4 Ns/m is selected as optimal damper damping coefficient value. If we choose very high value of damper damping coefficient, the structure becomes over-damped and hence stiff. Both the buildings behave as if they are rigidly connected. As a result, the top floor displacements of both the buildings become same.

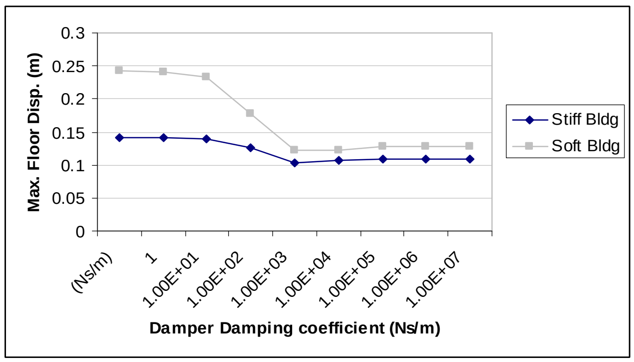

Figure 5 Damper Damping Coefficient vs. Maximum Floor displacement

5.4 Seismic response - Base Shear

To verify the optimal damper damping coefficient, the seismic responses including the base shear response and the top floor acceleration response of both buildings are computed over a wide range of damper damping coefficient with an optimum damper stiffness being 5.0 x 10^4 N/m.

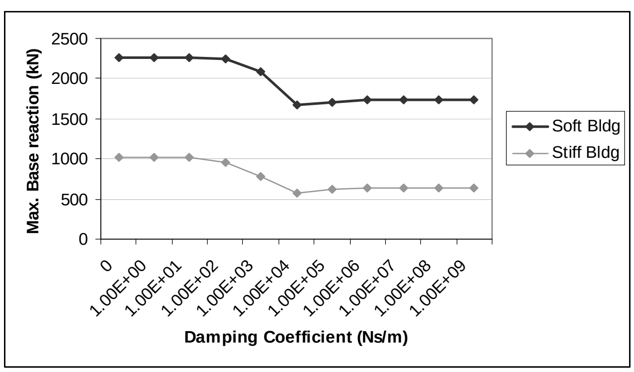

Figure 6 Base Shear vs. Damping Coefficients

It is clear from above fig. 6 that at the optimal damping coefficient of 1.0 x 10^4 Ns/m, the base shear force in both buildings is minimum. Hence, the optimal value selected is correct.

5.5 Seismic response - Top Floor Joint Acceleration

The optimal damper damping coefficient is also verified by comparing the top floor acceleration responses of both buildings as shown in fig.7. Here, the top floor accelerations of both buildings are determined for a wide range of damper damping coefficient with an optimum damper stiffness being 5.0 x 10^4 N/m. Also, the top floor acceleration is minimum at the optimal damping coefficient of 1.0 x 10^4 Ns/m. Hence, the optimal value selected is correct.

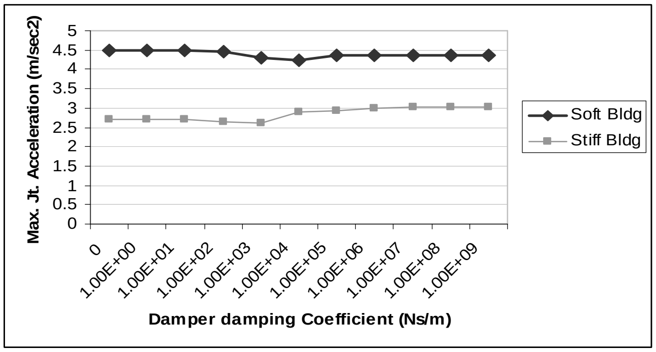

Figure 7 Maximum Joint Acceleration vs. Damper damping Coefficient

5.6 Determination of the optimal placements for the external dampers

Here, the optimal numbers of dampers required to be connected are found out. To determine this, both buildings are connected using 6, 7 and 8 dampers. The maximum displacements of both buildings at each floor level are found out. The results are compared with both buildings connected at all floor levels and both buildings unconnected as shown in fig. 8 and 9. Firstly, the maximum displacements of each floor of both buildings when the buildings are unconnected are found out. Then, dampers having optimal properties as found out earlier are provided, joining all neighboring floors of the both buildings and the respective displacements are determined. During earthquake, the floors at equal height from ground of both buildings either move toward each other or away from each other. The distance by which these floors are separated is termed as relative displacement. For determining the optimal locations, the floors having maximum relative displacements are selected. The process is carried out iteratively. Then the numbers of dampers selected are 6, 7 and 8. It is seen that in top four floors i.e. 17, 18, 19 and 20 of both buildings displacement is large. Hence, four dampers are provided at these locations. The other locations are determined by trial and error procedure.

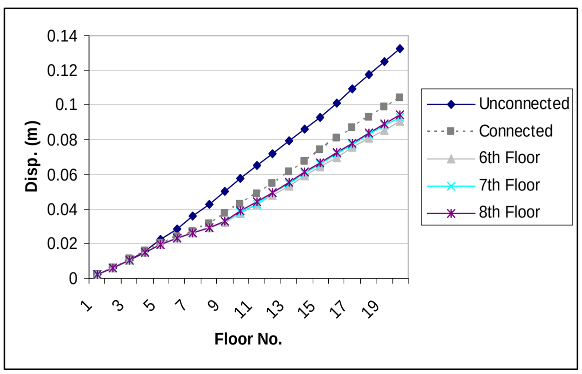

Figure 8 Floor wise displacement variation of Left Bldg.

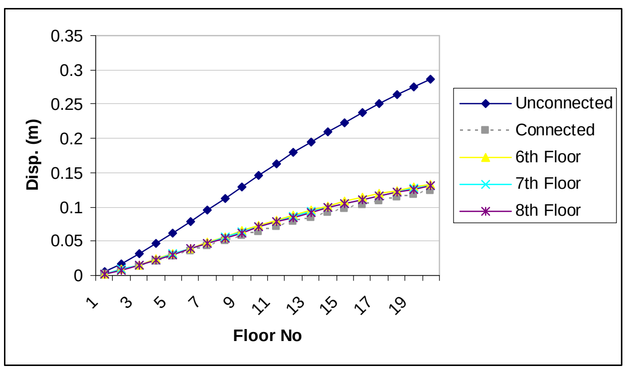

Figure 9 Floor wise displacement variation of Right Bldg.

6. CONCLUSIONS

1. In recent years, world-wide attention has been directed towards the use of control devices to mitigate the effects of dynamic loads such as strong earthquakes, extreme waves, high wind, heavy traffic etc. External damping devices such as viscous dampers, viscoelastic dampers, friction dampers etc. can be used effectively under such situations.
2. The application of control devices in coupling adjacent buildings has been recognized as an effective alternative for protection of buildings. The viscoelastic dampers connecting adjacent buildings subjected to seismic events has been proved to be most effective.
3. Structural pounding occurs frequently during strong earthquakes between two buildings or different parts of building. Coupling adjacent buildings with supplemental damping devices is a practical and effective approach to mitigate such problems.
4. The natural frequencies of both the buildings should not change after the insertion of external damping devices. This is desirable because it allows the installation of external dampers for the buildings that have already been built and need to be strengthened. The variation of natural frequencies depends on damper stiffness. Up to a certain damper stiffness there is no change in the natural frequencies of both buildings. But beyond this, as we increase the damper stiffness, the frequency of stiff building increases rapidly. Hence this value is selected as the optimal damper stiffness.
5. As we increase the damping coefficient of viscoelastic damper, there is no significant decrease of response beyond certain value. Hence, this value is selected as the optimal damper damping coefficient.
6. It is not necessary to connect the two adjacent buildings by dampers at all floors but lesser dampers at appropriate location can significantly reduce the earthquake response of the combined system. Thus, the optimal numbers of dampers reduce the cost of dampers as well as the displacements.

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