© 2015 IJEDR | Volume 3, Issue 2 | ISSN: 2321-9939

Dynamic Response of Two Adjacent Structures Connected by Friction Damper (Coulomb Friction Model)

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***Abstract* - In the last few years, efforts were carried out to develop the concept of energy dissipation in structures to bring it into an applicable technology. The conventional structural systems are highly unlikely to provide adequate performance in the event of a major earthquake. Several devices based on different energy dissipation principles have been developed and implemented worldwide. Connecting the adjacent structures with passive energy dissipation devices has attracted the attention of many researchers due to its ability in mitigating the seismic responses. Friction damper is one of the energy dissipating devices which dissipate the energy during earthquake. Further, effectiveness of dampers in terms of the reduction of structural responses namely, displacement, velocity and acceleration is investigated using Newmark's step by step method. A parametric study is also conducted to investigate the optimum slip force of the damper. In this study, seismic responses of two connected structures are compared with the seismic responses of a single structure.**

***Index Terms* – Adjacent structures, friction damper, seismic response, slip mode, non-slip mode.**

I. INTRODUCTION

Over the past few decades world has experienced numerous devastating earthquakes, resulting in increased number of loss of human life due to collapse of buildings and severe structural damages. Occurrence of such damages during earthquakes clearly demonstrates the high seismic hazards and the structures like residential buildings, lifetime structures need to be designed very carefully to protect from earthquakes. Various experiences show that for the development of new construction, establishing earthquake resistant regulations and their provision is the critical safeguard against earthquake induced damage. It is necessary to evaluate and strengthen the existing structure based on evaluation criteria before an earthquake. To protect structures from significant damage under such severe earthquakes has become an important topic in structural engineering. Conventionally, structures are designed to resist dynamic forces through a combination of strength, deformability and energy absorption. Sometimes structures designed with these methods are susceptible to strong earthquake motions. In order to avoid such critical damages, structural engineers are working to figure out differ types of structural system that can withstand strong motions.

Structural vibration control, as an advanced technology in engineering, is to implement energy dissipation devices or control systems into structures to reduce excessive structural vibrations, enhance human comfort and prevent catastrophic structural failure due to strong winds and earthquakes. Structural control is necessary because big buildings require more protection. In big buildings, lots of material is used. Many historical buildings are destroyed due to large or sudden earthquake. The concept of structural control theories and devices has been recently developed and introduced to large-scale civil engineering structures. Structural control technology can also be used for retrofitting of historical structures especially against earthquakes. The generally adopted approach to vibration control of structures is with vibration damping that is added to a structure either passively or actively. The damping dissipates some of the vibration energy of a structure by transforming it directly to the connected structure. Connecting the adjacent structures with energy dissipation devices has attracted the attention of many researchers due to its ability in mitigating the dynamic responses as well as to reduce the chances of pounding.

Various methods of structural control are adopted as earthquake protective system. Passive control, active control, semi-active control and hybrid system are the methods of structural control system. A passive control system consists of one or more devices. These devices are embedded or attached to a structure, designed to modify the stiffness or the damping of the structure in an appropriate manner without requiring a external power source to operate, developing the control forces opposite to the motion of controlled structural system. Passive control system is generally adopted as compare to other systems because it consumes no energy, relatively less expensive .One of the passive energy dissipation devices is friction damper. Friction dampers are simple in construction and offer repeatable performance at low cost. Friction dampers can reduce the seismic responses of the innovative structures as well as the existing structures. Also, friction dampers need no repair or replacement before and after earthquake. Friction dampers perform better when frequencies of the connected structures are well separated. In this paper, the seismic response of structures connected with a friction damper is investigated under given earthquake excitation.

Figure 1 Friction Damper Device (www.zhanyichen.wordpress.com)

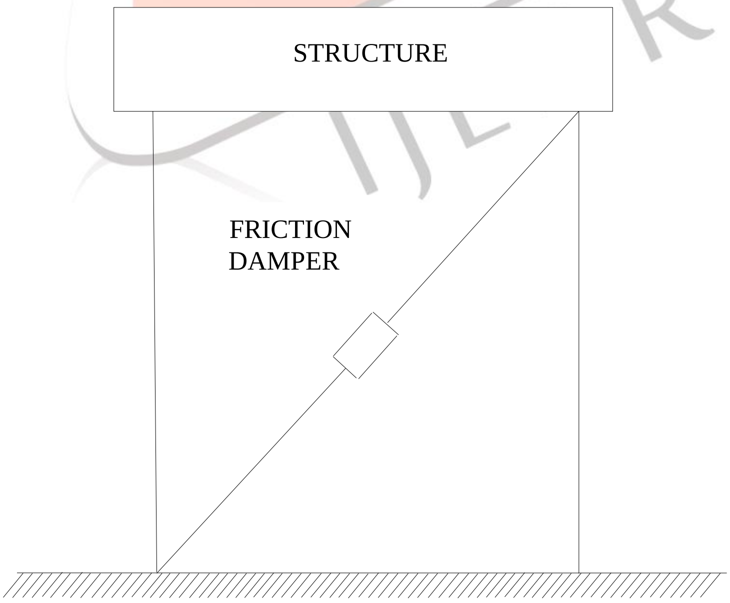
II. MATHEMATICAL FORMULATION

Assumptions and Limitations

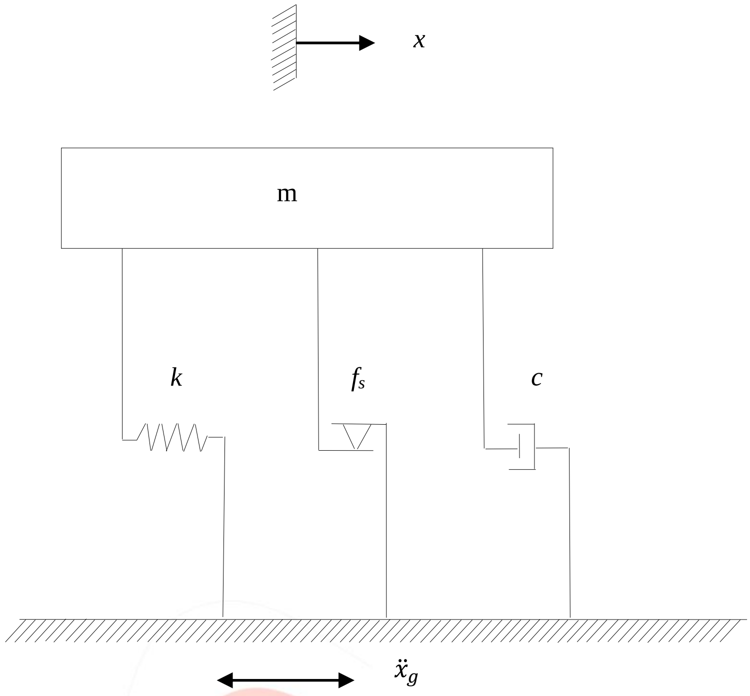
Some assumptions are necessary to highlight the important characteristics of friction damper connecting adjacent structures and to make problem manageable. Two adjacent structures are assumed to be symmetric structures with their symmetric planes in alignment. The ground motion is assumed to occur in one direction in the symmetric planes of the structures so that the problem can be simplified as two dimensional problem. Structure is modeled as a linear single-degree of freedom system where the mass is concentrated at floor of the structure and stiffness is provided by the walls or columns. These assumptions indicate that due to significant increase of energy absorbing capacity, the structures are able to remain elastic. It is also assumed that the floor elevations are same for both structures and two neighbouring floors are connected by a damper device. Both structures are assumed to be subjected to the same base acceleration. Any effects due to spatial variations of the ground motion or due to soil-structure interactions are neglected.

A SDOF Structure connected with friction damper

Consider a structure connected with friction damper. The structure is idealized as single -degree-of-freedom system. Let m, c, k be the mass, damping coefficient and stiffness respectively as shown in fig. 2(b). The system is subjected to earthquake motion. $\ddot{x}_g$ be the ground acceleration and x is the displacement of a single structure.



a) A single structure equipped with friction damper



(b) Mathematical Model

Figure 2 A SDOF structure equipped with friction damper.

Equation of motion for a SDOF structure

$$m\ddot{x} + c\dot{x} + kx + f_s \operatorname{sgn}(\dot{x}_r) = -m\ddot{x}_g \quad (1a)$$

$$\text{or} \quad m\ddot{x} + c\dot{x} + kx + \mu mg \operatorname{sgn}(\dot{x}_r) = -m\ddot{x}_g \quad (1b)$$

where sgn = signum function

f_s = limiting frictional force in the damper (slip force)

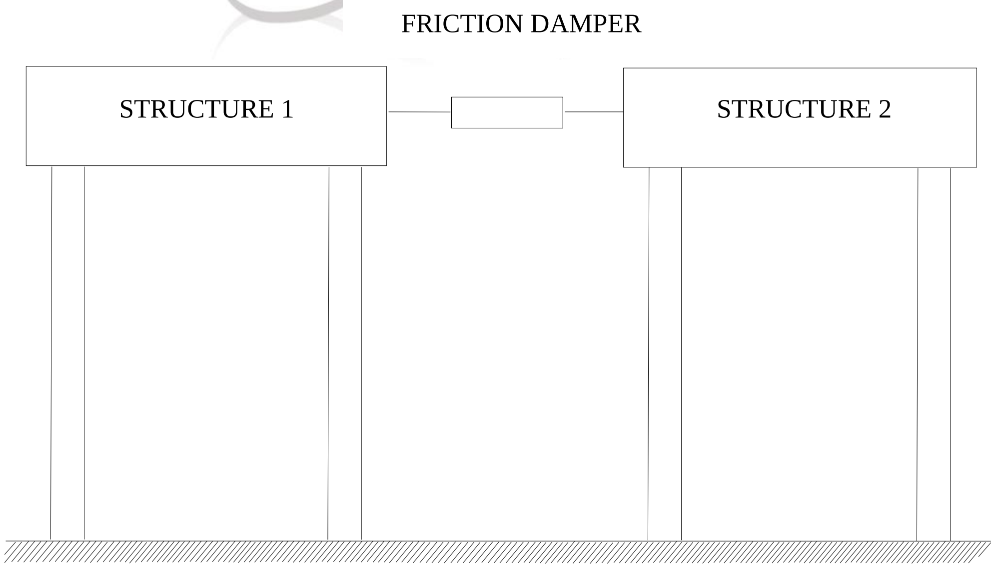
= μmg

μ = friction coefficient

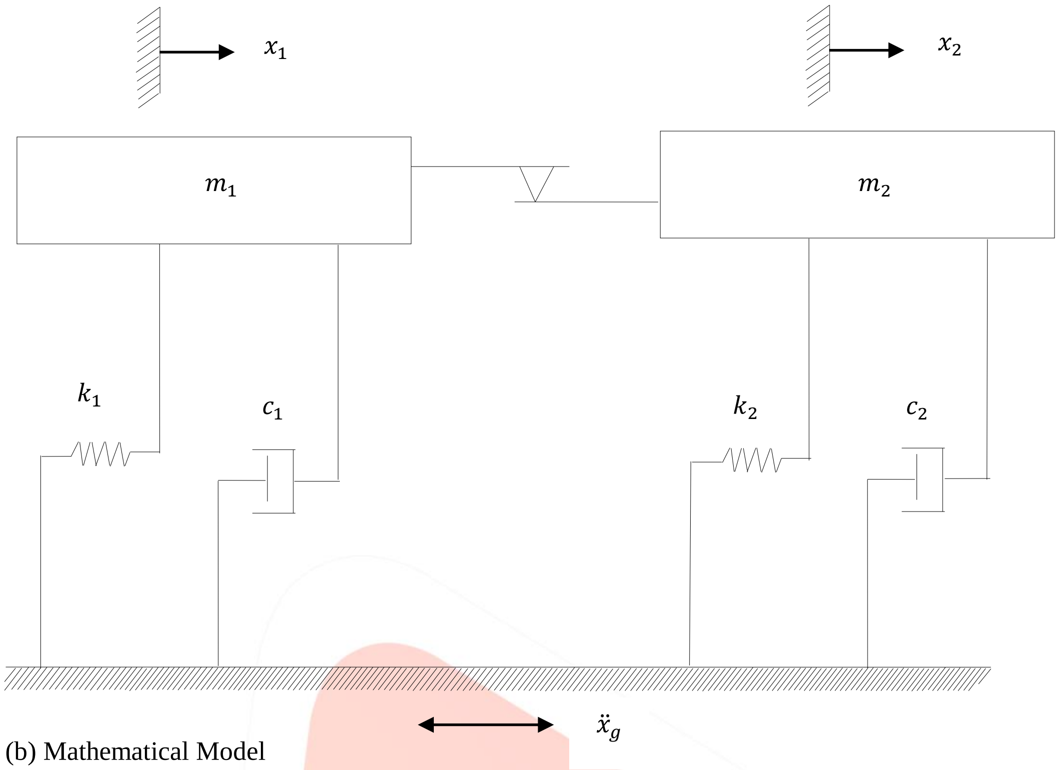
$\dot{x}_r$ = sliding velocity of the damper

Two SDOF structures connected with friction damper

Consider two adjacent structures connected with friction damper. The adjacent structures are idealized as single-degree-of-freedom systems and referred to as Structure 1 and Structure 2 as shown in fig. 3(a). Let m_1, c_1, k_1 be the mass, damping coefficient and stiffness of the Structure 1, respectively. Similarly, m_2, c_2, k_2 denote the corresponding parameters of Structure 2 as shown in fig. 3(b).



(a) Adjacent Structures connected with friction damper



(b) Mathematical Model

Figure 3 Structural model of two SDOF adjacent structures connected with friction damper

Let ω_1 and ω_2 be the natural frequencies of Structure 1 and Structure 2 respectively. Let λ and β be the mass and frequency ratios of the two structures respectively.

$$\text{Mass ratio } (\lambda) = \frac{m_1}{m_2} \qquad (2)$$

$$\text{Frequency ratio } (\beta) = \frac{\omega_2}{\omega_1} \qquad (3)$$

When the adjacent structures, connected with the friction dampers, are excited to ground motion, the connected floors may move together sticking with each other or slippage may occur between the floors which depend on the system parameters and the excitation. When the slippage occurs, the floors are to be in slip mode and when the slippage does not occur, the floors are said to be in non-slip mode.

To find out the seismic responses of the two structures, a numerical approach is employed in which the number of degrees-of-freedom remains constant. This can be achieved by modeling the friction damper as a Coulomb friction model, which is very approximate and still largely used because it is easy to handle and provides a sufficient level of approximation in engineering problems.

$$f_d = \mu\, m\, g\, \mathrm{sgn}(\dot{x}_r) \qquad (4)$$

where f_d = frictional force of damper

$\dot{x}_r = \dot{x}_1 - \dot{x}_2$

The governing equations of motion of the two connected structures are given by

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 + f_s\,\mathrm{sgn}(\dot{x}_r) = -m_1\ddot{x}_g \qquad (5a)$$

or

$$m_2\ddot{x}_2 + c_2\dot{x}_2 + k_2x_2 - f_s\mathrm{sgn}(\dot{x}_r) = -m_2\ddot{x}_g \qquad (5b)$$

In matrix form

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = -\begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix}\ddot{x}_g - \begin{Bmatrix} -\mu mg\, sgn(\dot{x}_2 - \dot{x}_1) \\ \mu mg\, sgn(\dot{x}_2 - \dot{x}_1) \end{Bmatrix} \qquad (6a)$$

or

$$M\ddot{x} + C\dot{x} + Kx = ML\ddot{x}_g - f_d \qquad (6b)$$

where

$$f_d = \begin{Bmatrix} -\mu mg\, sgn(\dot{x}_2 - \dot{x}_1) \\ \mu mg\, sgn(\dot{x}_2 - \dot{x}_1) \end{Bmatrix}$$

$$L = \begin{Bmatrix} 1 \\ 1 \end{Bmatrix}, \text{ called unit vector}$$

where x_1, $\dot{x}_1$, $\ddot{x}_1$ are displacement, velocity and acceleration of Structure 1 respectively and $\ddot{x}_g$ is the ground acceleration. Similarly, x_2, $\dot{x}_2$, $\ddot{x}_2$ are the displacement, velocity and acceleration of Structure 2 respectively. The connected floors may move together sticking with each other or slippage may occur between the two floors when the adjacent buildings, connected with friction damper, are excited to ground motion. The floors are said to be in non-slip mode when the slippage does not occur and they are said to be in slip mode when slippage occurs. The formulation of the equations for this system and the derivation of equations of the two connected structures are

Non-slip mode

Both the structures vibrate together during the non-slip mode as a single-degree-of-freedom system under ground excitation. If the frictional force in the damper is less than the limiting frictional force then the coupled system remains in the non-slip mode. By considering the dynamic equilibrium of either structure 1 or 2, the frictional force in the damper can be obtained.
Thus, the non-slip mode of the damper is valid until the inequality hold good-

$$\left| m_1 (\ddot{x}_1+\ddot{x}_g) + c_1 \dot{x}_1 + k_1 x_1 \right| \le f_s \tag{6a}$$

or

$$\left| m_2 (\ddot{x}_2+\ddot{x}_g) + c_2 \dot{x}_2 + k_2 x_2 \right| \le f_s \tag{6b}$$

Slip mode

The system moves into the slip mode whenever the force in the friction damper attains its slip force. The condition for initiation of slippage is

$$\left| m_1 (\ddot{x}_1+\ddot{x}_g) + c_1\dot{x}_1 + k_1x_1 \right| > f_s \tag{7a}$$

or

$$\left| m_2(\ddot{x}_2+\ddot{x}_g) + c_2 \dot{x}_2 + k_2x_2 \right| > f_s \tag{7b}$$

Results and Discussions

The earthquake time history selected to examine the seismic behaviour of a single structure and two SDOF adjacent structures is N00S component of Imperial Valley, 1940. The floor mass and stiffness is considered to be uniform for both the cases. Also, the damping ratio of 5% is considered for a single structure as well as for two adjacent connected structures.

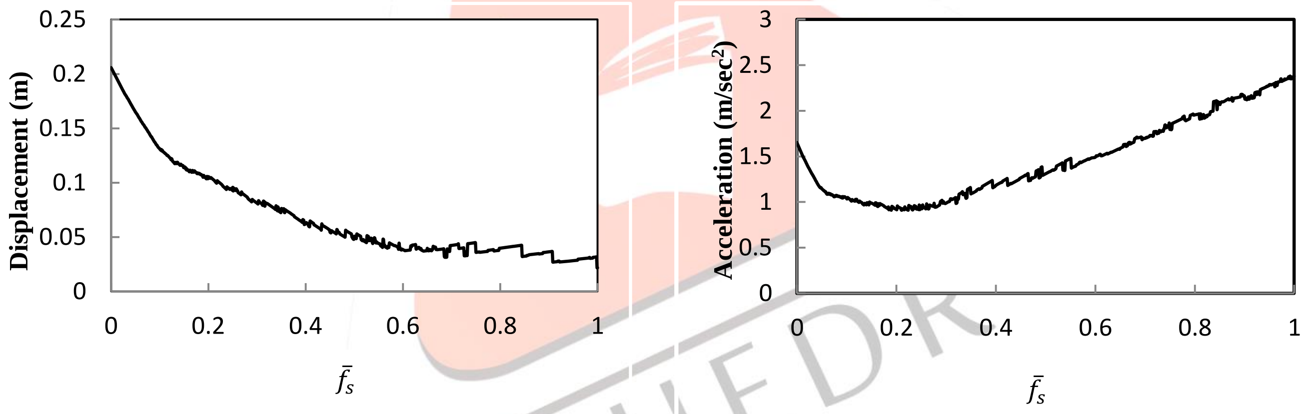


Figure 4 Variation of peak responses of a SDOF structure against normalized slip force for ω_1 = 0.9π rad/s.

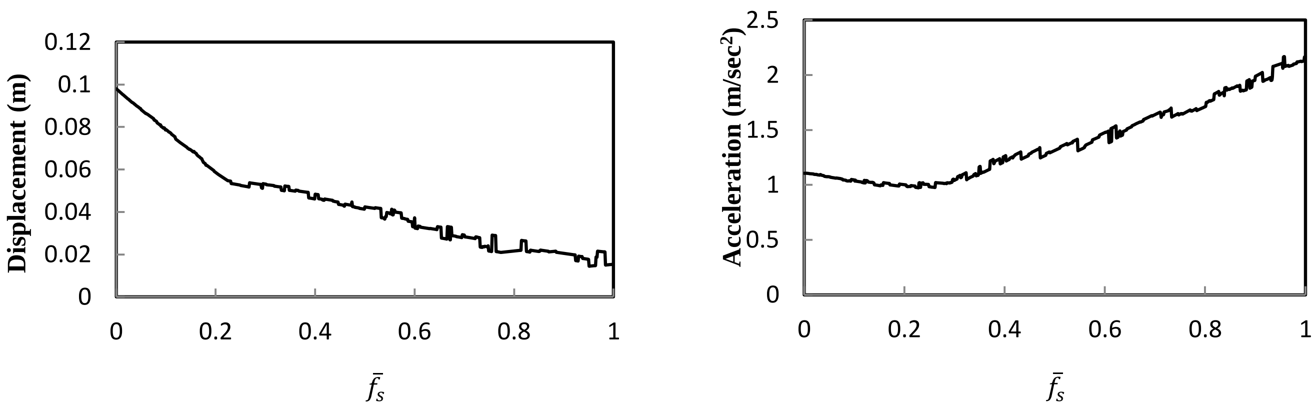


Figure 5 Variation of peak responses of a SDOF structure against normalized slip force for ω_2 =1.8π rad/s.

The slip force is normalized with the weight of the floor to get the normalized slip force, $\bar{f}_s$ (i.e. $\bar{f}_s$ = f_s / mg) where g is the acceleration due to gravity. In arriving at the optimum value, the emphasis is given on the acceleration of the structure. As displacement is decreasing continuously therefore it will not give optimum value.

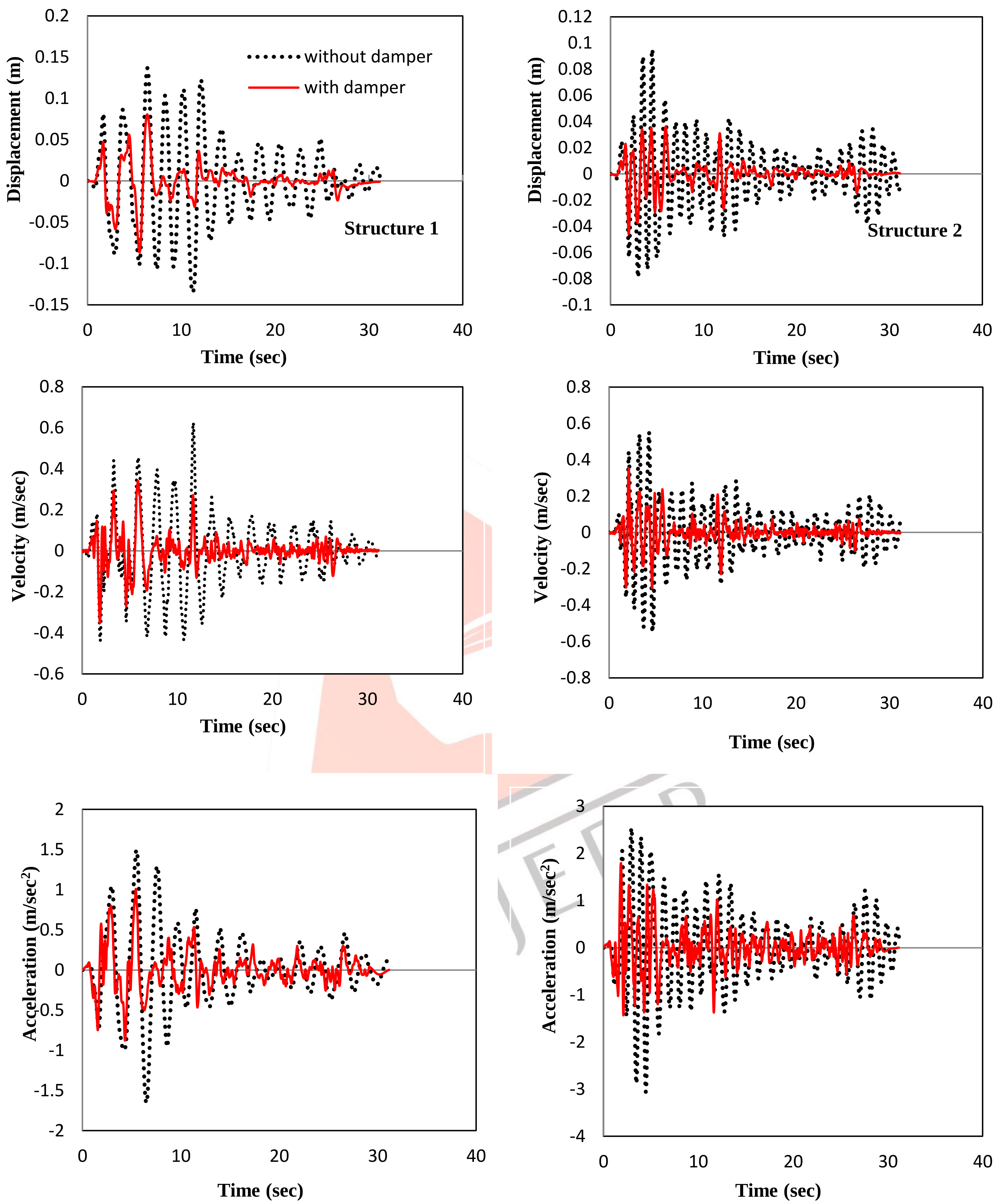


Figure 6 Time histories of the displacements, velocities and accelerations of a SDOF structure for Structure 1(ω_1= 0.9π rad/s) and for Structure 2 (ω_2=1.8π rad/s), respectively.

Table 1: Seismic responses of a SDOF structure for a given earthquake when connected with friction damper ($\bar{f}_s$ = 0.228,ω_1=0.9π rad/sec)

Earthquake	Displacement (m)		Velocity (m/sec)		Acceleration (m/sec^2)	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Imperial Valley, (1940)	0.20572	0.09899 (51.88)	0.61300	0.38212 (37.66)	1.65238	1.17522 (28.88)

Table 2: Seismic responses of a SDOF structure for a given earthquake when connected with friction damper ($\bar{f}_s$ = 0.233, ω2=1.8π rad/sec)

Earthquake	Displacement (m)		Velocity (m/sec)		Acceleration (m/sec^2)	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Imperial Valley, (1940)	0.09523	0.04285 (55.00)	0.55318	0.33538 (39.37)	3.06135	1.99495 (34.83)

Case 1 : Unconnected.
Case 2 : Connected.
Quantity within the parenthesis denotes the percentage reduction.

In case of two SDOF adjacent structures, it is observed that the response of both the structures are reduced upto a certain increase in the value of the slip force and with further increase in the value of the slip force they are increased again. Therefore, it is clear from the fig. 7 that the optimum slip force exits to attain the minimum responses in the structures. Optimum slip force is not exactly the same for both the structures. Therefore, optimum value is taken as the one, which gives the minimum sum of the responses of the two structures.

The time histories of the displacements, velocities and accelerations of the two structures with and without damper at optimum slip force are shown in fig. 8. These figures clearly indicate the effectiveness of dampers in controlling the earthquake responses of the both the structures. Masss ratio and frequency ratio is taken as 1 and 2 for both the structures, respectively.

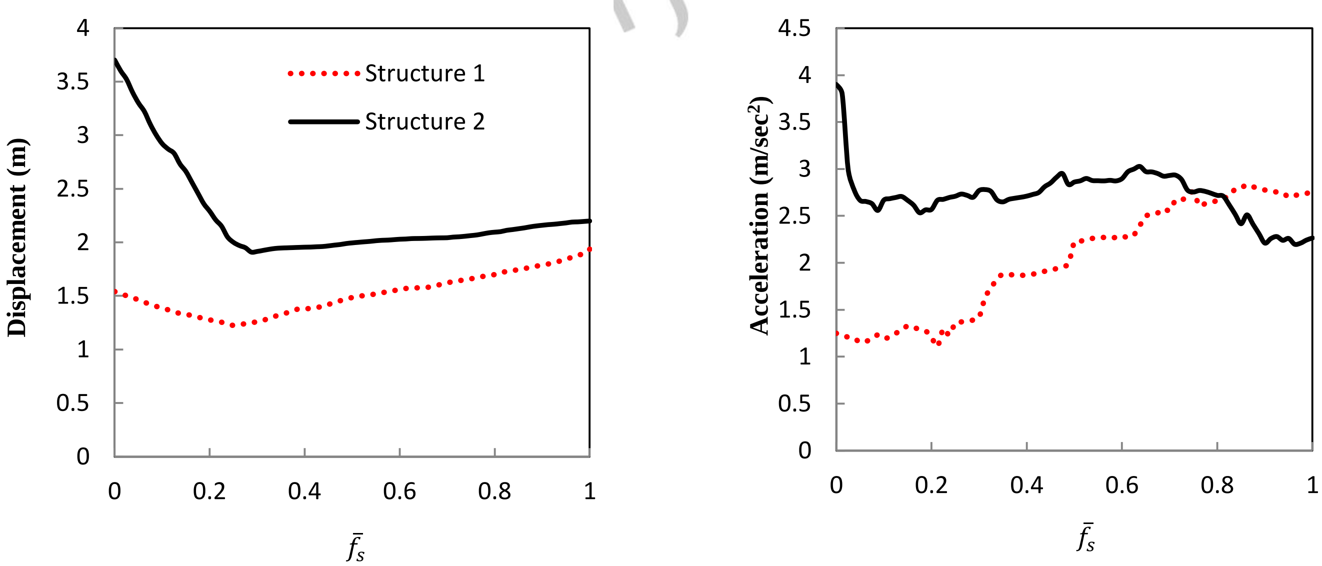


Figure 7 Variation of peak responses of two SDOF structures against normalized slip force (λ= 1, β= 2).

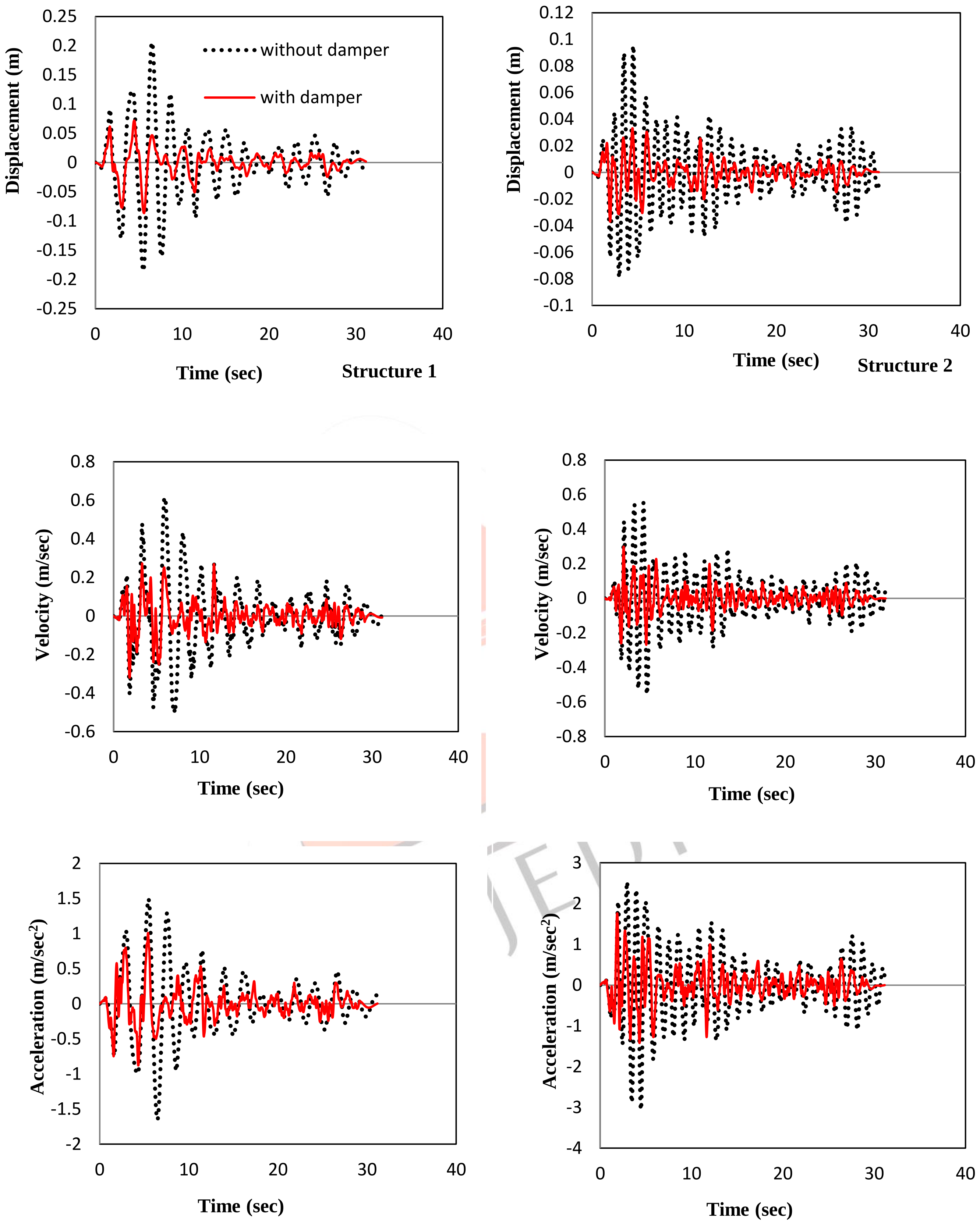


Figure 8 Time histories of the displacements, velocities and accelerations of the two SDOF structures.

Table 3: Seismic responses of two adjacent structures for a given earthquake when connected with friction damper ($\bar{f}_s$ = 0.275)

Earthquake	Structure	Displacement (m)		Velocity (m/sec)		Acceleration (m/sec^2)	
		Case1	Case 2	Case 1	Case 2	Case 1	Case 2
Imperial Valley, (1940)	1	0.20572	0.08632 (58.04)	0.61300	0.33930 (44.65)	1.65238	1.04524 (36.74)
	2	0.09523	0.03700 (61.14)	0.55318	0.29799 (46.13)	3.06135	1.75765 (42.58)

Case 1 : Unconnected.
Case 2 : Connected.
Quantity within the parenthesis denotes the percentage reduction.

The peak displacement of the structures decreases with the increase of the frequency ratio. This implies that the friction damper performs better when the structures have different natural frequencies. This is expected due to the fact that when frequencies are different for both the structures, the adjacent structures vibrate out of phase causing large displacements in the damper thereby dissipation of large input energy through friction and subsequent reduction in the seismic response of the system.

III. CONCLUSION

The behaviour of a single structure equipped with a friction damper and two adjacent structures connected with a friction damper is investigated under given earthquake excitation, assuming a linear elastic behaviour of the structures. Coulomb friction model for the evaluation of frictional force in the damper connecting SDOF are also proposed. The use of Coulomb friction model may result in useful estimation of the peak response. The comparison of the time histories of the displacements, velocities and accelerations of a single structure and two adjacent structures obtained from the coulomb friction model is made in this study. The friction damper is found to be more effective when the natural frequencies of the connected structures are well separated and it is only possible when two adjacent structures are connected with damepr. Also, connecting two adjacent structures with a friction damper is more economical as compared to a single structure equipped with friction damper. It is also found that the proposed model is working a quite satisfactorily.

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