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Study of Friction Pendulum (FPS) Isolation System in Seismic Control of Structures

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Abstract —*Base isolation systems are very effective in reducing the forces transmitted to the structure, either by detuning the structure from the ground motion as in laminated rubber bearing system or by isolating the structure by introducing a sliding layer between the structure and foundation raft, thereby limiting the forces transferred to the structure. Pure friction system is the simplest sliding isolator consisting of a horizontal sliding surface; however, it may experience large sliding and residual displacements, which are often difficult to incorporate in structural design. Several systems have been suggested in the past to accommodate the restoring mechanism along with sliding in order to reduce the sliding and residual displacements to manageable levels. The FPS is based on an innovative way of achieving a pendulum motion. Based on our research study, it can be concluded that FPS system have several advantages and disadvantages. Thus based on the requirements, optimum choice has to be made in choosing the parameters so that the forces in the structure are reduced without compromising for sliding displacements.*

Keywords-*Friction Pendulum System; Seismically Structure; Structural Control*

I. INTRODUCTION

Seismic isolation is the separation of the structure from the harmful motions of the ground by providing flexibility and energy dissipation capability through the insertion of the so called isolators between the foundation and the superstructure. It is not a long time since the first application of the isolators as the first base-isolated building in the USA was built in 1985, although the idea is more than a century years old.

It was found pure friction isolation system these systems are quite effective in reducing forces transmitted to the structure. Their main disadvantage is the large sliding and residual displacements left as there is no restoring mechanism to bring the structure back to its original position. This limitation of isolation system can be overcome by introducing a suitable restoring mechanism in the isolation system to bring the structure back to its original position after the end of ground excitations. One of the most effective mechanisms has been used in the friction pendulum systems. The FPS uses a spherical sliding surface that incorporates restoring mechanism through gravity. It uses geometry and gravity to achieve the desired seismic isolation results. It is based on principles of pendulum motion. In this chapter, it is intended to study the friction pendulum system and compare the response for FPS isolated structure with that of pure friction isolated structure.

During sliding the isolator provides restoring force and frictional force. Frictional force is provided by the weight of the structure sliding on the curved surface, which always acts towards the lowest point on the isolator and frictional force acts opposite to the relative sliding velocity. The effect of isolator restoring force and sliding friction can be represented by means of a spring and friction damper respectively.

Important parameters affecting the response quantities are structural properties and the isolator properties. The structural properties affecting the response are fixed base time period, mass ratio and damping ratio. The damping ratio is usually unique for a given structure as it depends on the materials used. The investigations have been carried out for a fixed damping ratio of 5%. The isolator properties affecting the response quantities are isolator time period and the coefficient of sliding friction. In addition to these, the behaviour also depends on the ground motion characteristics, like the frequency content and the intensity of ground motion.

II. SINGLE DEGREE OF FREEDOM STRUCTURE

In the subsequent sections, parametric studies on SDOF structures isolated by two sliding type isolators namely, friction pendulum systems and pure friction isolator subjected to base excitation are carried out. The objective of this study is to critically assess the influencing parameters that control the behaviour of structures isolated by the frictional type isolators with and without restoring force mechanism and determine their relative advantages and disadvantages.

Structure is subjected to harmonic excitations and NS component of El Centro 1940 earthquake excitation. The ground motion record used has a digitized data at a time interval of 0.02s and a peak ground acceleration of 0.319g. The duration of the earthquake is 30s.

Typical time history plots for sinusoidal excitation for structure isolated by FPS are shown in Figure 1. The plot is for resonant conditions. Coefficient of friction is 0.1, damping coefficient 0.05 and mass ratio 0.5. There is a substantial reduction in the absolute acceleration and relative displacement of the structure as compared to that of the fixed base structure. From the Figure 3, the effect of restoring force of the isolator is evident. A structure isolated using PF system

displaces itself to an offset from the initial position and starts oscillating about the displaced position, while the structure isolated by FPS immediately comes back to its original position and oscillates.
The typical time history plots for a SDOF structure subjected to NS component of El Centro 1940 ground motion are shown on Figure 4-6. Time period of the chosen structure is 0.5s and mass ratio taken as 0.5. Coefficient of damping is 0.02. As it can be seen from Figures 4-6, the response is reduced throughout the time history. In the case of PF system the structure displaces itself to an offset and oscillates about that, but in the case of FPS structure after moving an offset comes back to its original position and oscillates about that. The sliding displacement after the ground motion is over is much less in case of FPS as compared to that of the PF system. This is because of the restoring force which tends to reduce the amplitudes of the sliding displacements. The effectiveness of the restoring mechanism of the isolator is again observed from the residual displacement at the end of the ground motion. As stated earlier, the structure almost comes to its original position in case of the FPS isolated structure whereas the PF system results in a very large residual displacement.

2.1 Effect of Structural Flexibility

The structural flexibility is represented by the natural period of the fixed base structure. The effect of structural flexibility can be studied by plotting the maximum response quantities against the fixed-base time period. It is seen that the acceleration response and displacement response of structure isolated with FPS is significantly greater than that with the PF system. This is more evident for structures with higher flexibility. This is because the time period of the fixed base structure approaches that of the FPS isolator time period. It is seen that the acceleration response and displacement response of structure isolated with FPS is significantly greater than that with the PF system. This is more evident for structures with higher flexibility. This is because the time period of the fixed base structure approaches that of the FPS isolator time period. So, there is a possibility of resonance between the structure and the isolator. This is not for the PF system as the force transmitted in this case is limited to the frictional force and the time period of the isolator is infinity. There is a substantial reduction in the sliding and residual displacements in case of FPS isolated structure. The residual displacements are close to zero in case of FPS, which shows the effectiveness of restoring force mechanism. Thus it can be seen that the FPS is not effective when the excitation is of high intensity. In such a case PF behaves in a better way reducing the response significantly but with the major deficiency of large sliding and residual displacements.

2.2 Effect of Coefficient of Friction

The coefficient of friction is an important parameter directly affecting the behaviour, as it is mainly responsible for restricting the forces to the structure. The isolators with lesser coefficient of friction are more effective in reducing the peak structural acceleration but at the disadvantage of large sliding displacements. This is because the force transmitted to the superstructure is limited to the sum of the frictional force and the restoring force. As expected, a lower coefficient of friction transfers a lower force to the superstructure. At the same time this is true only if the restoring force component is less in compared to the frictional force. Otherwise there may be an increase in the acceleration with decrease in the coefficient of friction as seen for the high intensity excitation. Due to this there is a significant difference in the behaviour of FPS and PF systems for lower coefficient of friction and higher intensity of earthquake. The sliding displacements in case of FPS are significantly lesser than that of the PF system. There is a marginal increase in the residual displacements with increase in coefficient of friction because there is a higher resistance for the structure to come back to its original position with higher coefficient of friction.
From Figure 7-9, it can be seen that for low value of the coefficient of friction PF system is more effective as compared to FPS in reducing the forces in the structure but the displacements are very large. It can also be observed from Figure 5.8 and 5.9 that after some value of coefficient of friction the residual sliding displacement becomes constant, there is no significant change in the sliding and residual displacement whereas the absolute acceleration is still increasing with increasing coefficient of friction. Based on this observation it can be concluded that for an optimum values of different parameters chosen and site condition, the response of the structure can be controlled in an effective way.

2.3 Effect of Isolator Time Period

The magnitude of the isolator restoring force is inversely proportional to the isolator time period. The restoring force offered by a PF system is zero and hence its isolator period is infinity. The isolator time period refers to the time period of a rigid body on the isolator without the effect of frictional force. To study the effect of the isolator period on the response, the response spectra are plotted against the isolator period keeping the coefficient of friction constant. Figure 10 show the spectra for coefficients of friction of 0.02, 0.05 and 0.10 for El Centro ground motion. It can be observed that the isolator time period has negligible effect on the peak accelerations of the structure for higher coefficients of friction. This is because for higher coefficient of friction, the sliding displacements are lesser and the low restoring force does not affect the behaviour significantly. But for isolators with lesser friction, the accelerations decrease with the increase in isolator time period. However this decrease is negligible for higher isolator periods. This is because for large isolator time period, the restoring effect reduces and the behaviour approaches that of a PF system. It is also important to note that the response for a lower coefficient of friction is quite high for stiffer isolators. This is due to the high restoring force which leads to additional energy for high intensity excitations. So, a lesser coefficient of friction will not increase the isolation efficiency in case of FPS unlike PF system.

On the other hand, the sliding displacements and the residual displacements increase with the increase in isolator period. This is expected, as the effect of restoring force is lesser for higher isolator periods. The sliding displacements are higher for lower coefficient of friction. But the residual displacements are lesser for lower coefficient of friction. This is because the sliding surface offers less resistance for the structure to come back. However the restoring force should be sufficiently large to bring the structure back to its original position. Both the sliding and residual displacements approach that of the PF system for higher time periods. It is interesting to note that the sliding displacement may be even greater than that of a PF system in certain cases. This is possible for a low coefficient of friction and high intensity of earthquake. This is because in such a case, the high restoring force may act as a driving force inducing higher sliding displacements.

From the above discussion, it is clear that the response is affected by the total isolator force (restoring force and frictional force). For a given coefficient of friction and given isolator period the restoring force increases almost linearly with sliding displacement which means the effectiveness of the FPS is questionable for higher sliding displacements. This is not the case with PF system as there is no restoring force and so the acceleration transmitted is limited to making the response independent of the frequency content of excitation. So, in case of FPS the high magnitude of the restoring force feeds additional energy into the structure for high intensity excitations whereas in case of PF system there is no additional energy fed into the structure due to the absence of the restoring force.

The curved sliding surface provides the restoring force by gravity and the isolator period represents the magnitude of this force. The total isolator force governs the isolator performance. For lesser restoring force or higher frictional force, the FPS isolator acts similar to a PF system and the frictional force primarily governs the behaviour. The relative values of these two forces depend upon the extent to which the structure slides. So, it is quite clear that for large sliding displacements as in case of a high intensity earthquake and a lower coefficient of friction, the restoring force component feeds more energy into the structure.

III. MULTIPLE DEGREE OF FREEDOM STRUCTURE

In this paper it is intended to study various aspects of the behaviour of a MDOF structure isolated by FPS system subjected to earthquake ground motion. The effect of various parameters influencing the response is studied.

In this section the effectiveness of FPS system on response of MDOF structures subjected to earthquake excitations has been considered. The NS component of El Centro 1940 earthquake has been chosen for the study and time history analysis is carried out for a five storey shear structure. The model of the example shear building is shown in Figure 11. The structure is represented as a lumped mass model with equal masses of 60080 kg and equal storey stiffness of 112600 kN/m. The results are compared with the same with the same structure isolated with PF system. The FPS used has a time period of 2.0s (R = 1m).

3.1 Time History Response

The time history plots for response quantities are shown in Figure 12. The response quantities of interest are acceleration of the top storey and sliding displacement. In the case of FPS the force transmitted to the superstructure is directly proportional to the isolator displacements. For example, the base shear transmitted in FPS is higher when the sliding displacement is more. The accelerations in the case of FPS is little higher than that of PF system. From Figure 12, it is observed that for FPS the sliding displacements increase, which is due to the fact that the effective isolator force in FPS can act either as restoring force or driving force depending on the direction of motion.

3.2 Modal Contributions

In this section the response contributions in different modes are discussed for the example system. If modes of the superstructure are considered in the analysis then the complex modal analysis is required to be carried out for an order of However, the analysis is carried out for normal modes in the case of non-sliding phase.

It is observed that the first mode of the isolated structure predominantly consists of the displacement at the isolator level whereas the first mode of the fixed base structure is dominated by the displacement in the structure. The deformation in the structure in the first mode of the isolated structure is negligible. The second mode in the isolated structure is dominated by the deformation in the structure. These two modes have a significant contribution in the overall behaviour of the structure and the isolator. So the first two modes of the isolated structure are usually found sufficient for the assessment of the various response quantities. In the isolated structure the first mode is virtually a rigid-body mode corresponding to the isolator displacement and the second mode is due to the deformation in the structure. So, the response of a MDOF structure primarily depends on the first two modes. However it should be noted that the total response consists of successive non-sliding and sliding phases and the effective participation of higher modes may be significant.

IV. RESULT DISCUSSION

Though FPS has several advantages but it cannot serve as a suitable isolator, for structures under a variety of dynamic loads. Any isolator for the structure has to serve two basic purposes:

1. It has to be stiff enough under ambient vibrations and minor earthquakes
2. It should provide a fail-safe mechanism under extreme earthquake loading conditions

FPS has a constant time period and a linearly varying restoring force. The high stiffness required under normal working conditions can be provided, by decreasing the radius of curvature. But this may affect the performance of the isolator under medium and high intensity excitations as high amount of restoring force induces additional energy into the structure. So the basic purpose of isolating the structure may not be served. On the other hand, the radius can be increased so that the isolator performs well under higher level of excitations. Again, a too low stiffness will affect the performance of the isolator under normal working conditions. In fact the isolator may act similar to a PF system at low level of excitations also, leading to unacceptable sliding and residual displacements. So, FPS isolator can perform at its best under a minor range of excitations for which it has been designed

In case of a PF system, lower value of coefficient of friction will lead to lower response and correspondingly with higher sliding displacements. But this is not necessarily possible in the case of FPS system. This is because the force transmitted to the structure in the case of FPS is the sum of frictional and restoring force. The restoring force will govern the response for a lower frictional force. If the frictional force is less, it leads to higher sliding displacements and hence higher restoring force. This feeds more energy in the structure and increases the response. Limitations of the FPS can be summarized as follows:

1. A properly designed FPS can perform well only under a small range of excitations
2. If the response is to be fairly independent of frequency if frequency content and amplitude of excitation for a wide range of excitations, the radius of the isolator has to be quite large and this may affect the stability under normal working conditions
3. A low level of coefficient of friction may not be beneficial to FPS and hence the low friction isolating capability cannot be used effectively

On the other hand the PF system has the major advantage that the behaviour of structures isolated by PF system is independent of the frequency and amplitude of base excitation. The PF system acts like an isolator for all levels ground excitation. The PF system is always detuned with the ground motion giving a very satisfactory performance under a variety of base excitations. But this has a major disadvantage of large sliding and residual displacement.

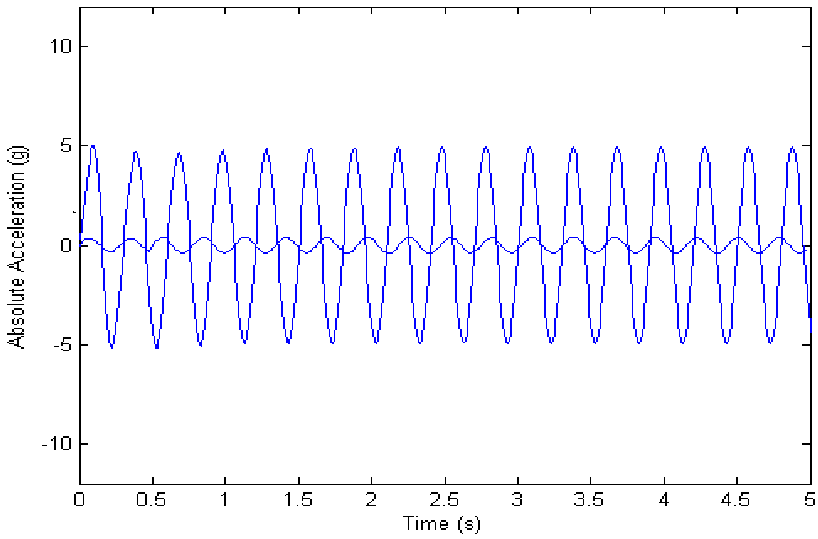


Figure 1 Absolute Acceleration for FPS isolated SDOF system subjected to harmonic acceleration

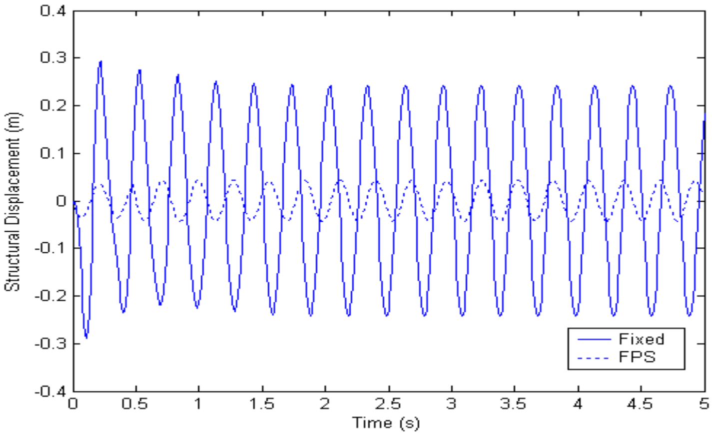


Figure 2 Structural displacement for FPS isolated SDOF system subjected to harmonic excitation

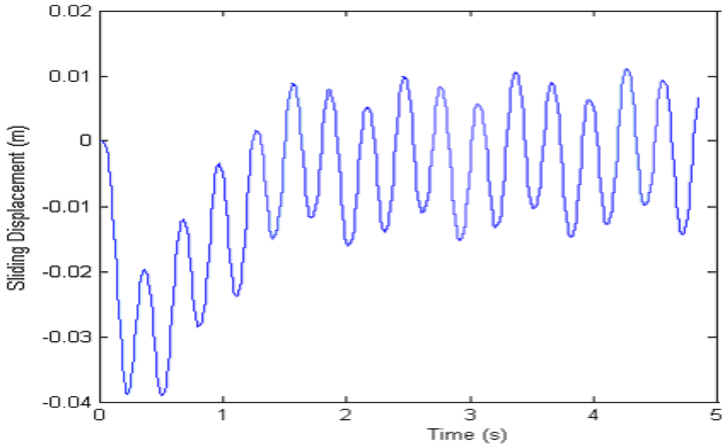


Figure 3 Sliding displacement for FPS isolated SDOF system subjected to harmonic excitation

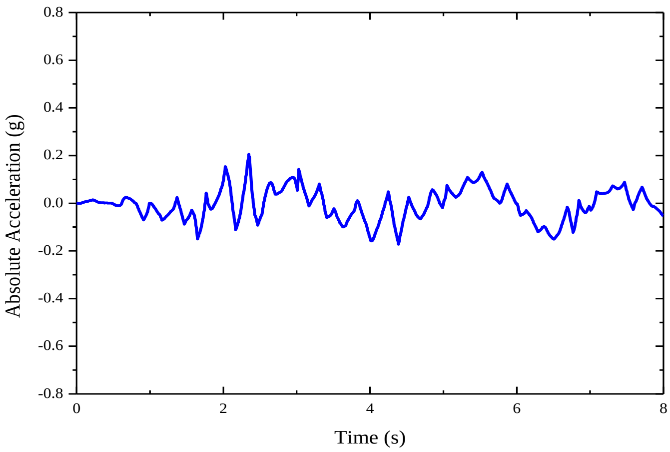


Figure 4 Absolute Acceleration for FPS isolated SDOF system subjected to El Centro (1940)

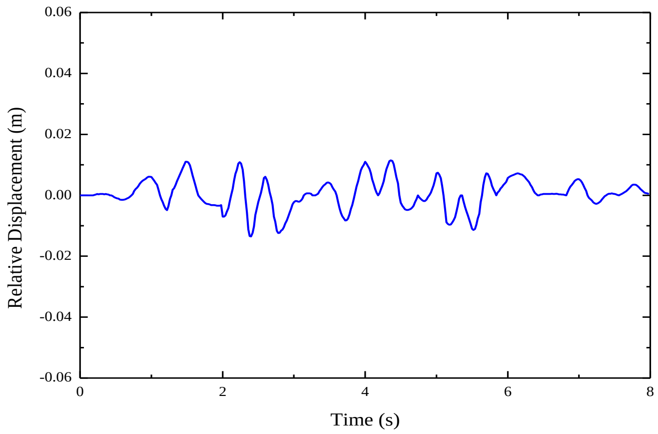


Figure 5 Relative displacement for FPS isolated SDOF subjected to El Centro (1940)

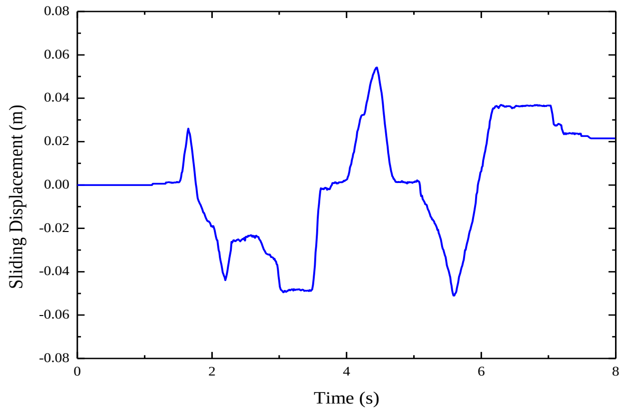


Figure 6 Sliding displacement for FPS isolated SDOF subjected to El Centro (1940)

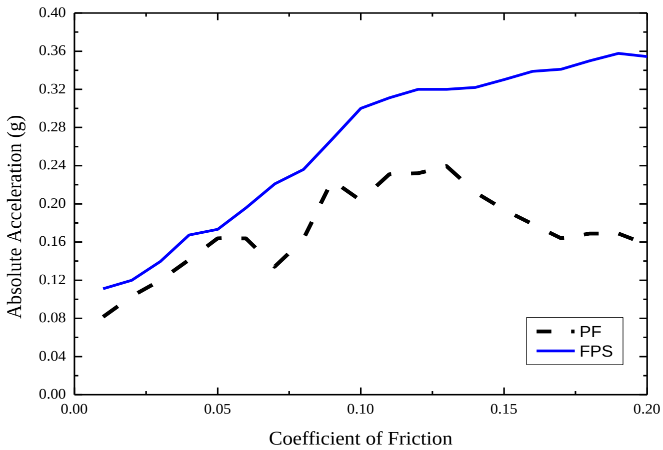


Figure 7 Effect of coefficient of friction on peak acceleration

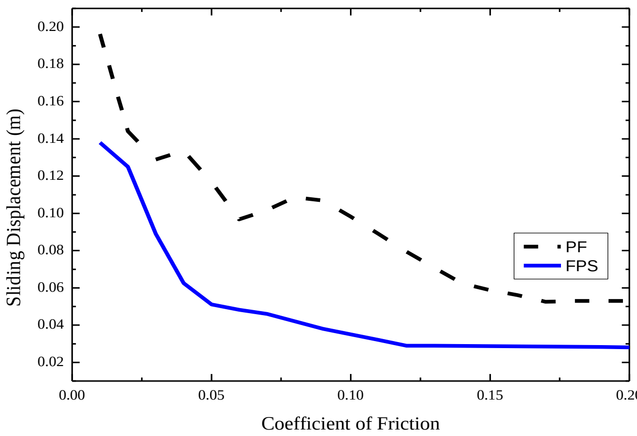


Figure 8 Effect of coefficient of friction on peak sliding displacement

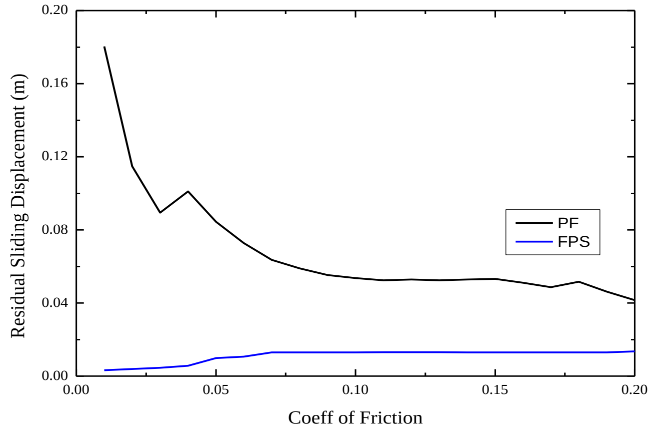


Figure 9 Effect of coefficient of friction on peak residual displacement

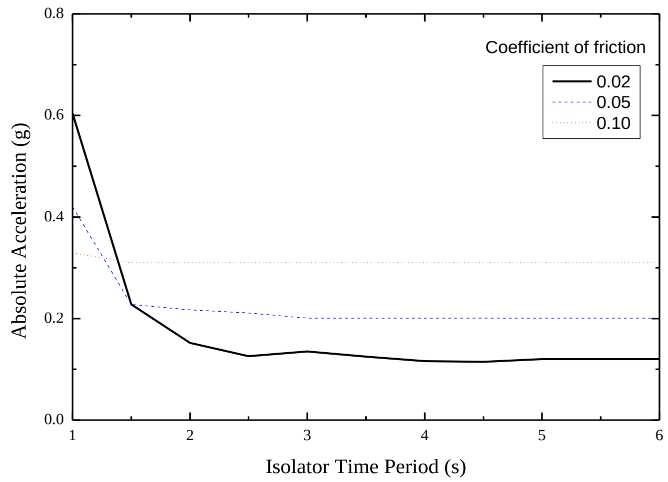


Figure 10 Effect of isolator time period on peak acceleration for FPS

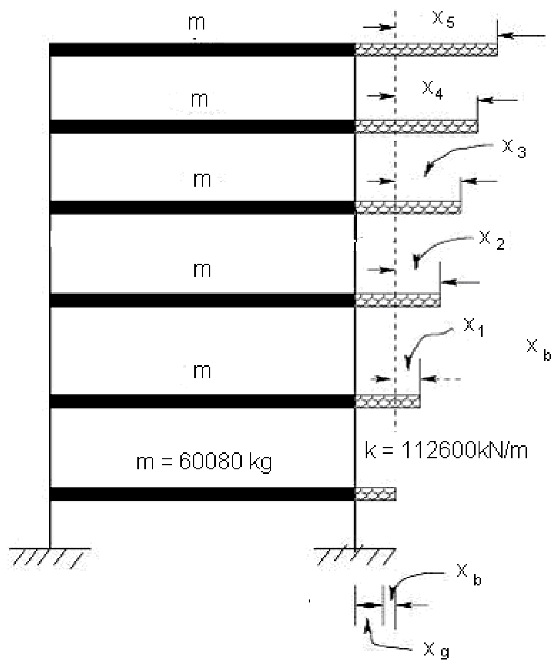
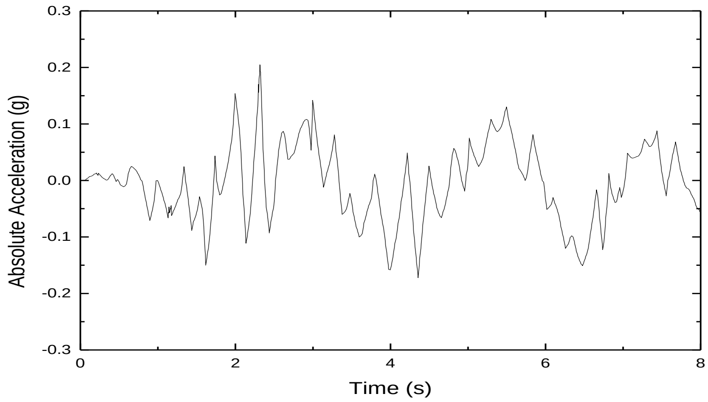
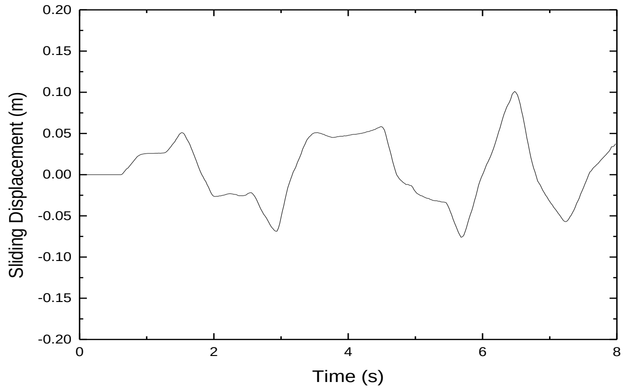


Figure 11 Five storey example shear structure isolated by sliding type isolator



(a) Absolute acceleration



(b) Sliding displacement

Figure 12 Response quantities for five storey shear building subjected to El Centro

V. CONCLUSION

The dynamic behaviour of FPS and PF isolated structures are examined through a parametric study on SDOF structural models. A five storey shear building is also considered for the study to compare the effectiveness of FPS and PF system for MDOF systems also. Friction pendulum system also uses friction in reducing the forces transferred to the structure. It uses its weight as a restoring force. They behave similar to the pure friction system in reducing the forces with an additional advantage of smaller residual displacements. In FPS the restoring force is directly proportional to the sliding displacement; therefore, in case of large sliding displacements the restoring force acts as driving force thus introducing increased energy content of the structure. Thus FPS is not very useful in case of low coefficient of friction and high excitations. Based on the results obtained for the FPS isolated structures, following conclusions can be made:

1. In the FPS system, the restoring force is provided by gravity and is dependent on mass of the structure and geometry of the isolator. This makes the system more reliable than the other restoring force mechanisms like spring, elastic material like rubber

2. The structure can be subjected to a ground motion which has a wide range of frequencies. The behaviour of FPS is fairly independent of frequency content of excitation for low magnitudes of restoring forces.

3. As the isolator time period depends on the geometry of the isolator the calculated time period is quite reliable and can be decided simply by choosing the radius of the isolator. The isolator time period is independent of mass of the structure.

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