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SEISMIC RESPONSE OF SLIDING ISOLATED SOFT STORY BUILDING USING VELOCITY DEPENDENT FRICTION MODEL

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ABSTRACT

The effectiveness of sliding isolation systems for aseismic design has been established in recent past. Their design requires accurate prediction of hysteretic behavior of sliding surfaces using Coulomb friction, in which the coefficient of friction is constant. However, it is revealed by Yester researchers from experimental investigations that sliding materials show complex behavior of friction force, in both sliding and transition phases, which include the non-linear relationship between friction and sliding velocity. Buildings with soft stories at ground level are more vulnerable to seismic excitation. This paper has emphasized the influence of velocity-dependent friction behavior in the sliding isolation system using the Teflon steel interface to mitigate the seismic response of a soft-story building. The presence of soft-story increases the vulnerability towards the earthquake by producing large drift at the soft story level, which can be effectively reduced by using a Sliding isolation system. It concludes based on the results of time history and response spectra analysis that, by using the velocity-dependent friction model, it gives less seismic response than the Coulomb friction model, which has a constant coefficient of friction. Therefore, Coulomb's constant-coefficient friction model may underestimate the usefulness of pure friction sliding isolation systems.

KEYWORDS: Seismic Response; Pure Friction; Friction Model; Soft-Story Building; Sliding Base Isolation

INTRODUCTION

Most of the buildings having stiffness irregularities across the floor were severely damaged under strong seismic ground motion. The soft-story creates stiffness irregularity and is one of the main reasons for the building collapse during a moderate to severe earthquakes. Most vulnerable to damage and collapse from earthquake excitation in moderate to severe seismic regions are soft-story buildings, because of excessive drift in the first story combined with the P-Δ effect on the yielded column makes the building collapse during earthquakes [Fintel and Khan (1)]. The main cause for the soft-story building to be more susceptible to an earthquake is the localization of seismic forces where there is a reduction in stiffness which is at the soft story [Dye and Oretaa (2)]. The lateral strength of a building comes from the stiffness of the shear wall, columns, and bracing, hence low strength in the soft-story causing the failure occurs especially during the earthquakes [Hejazil et al. (3)]. Since there is no provision in code for calculation of earthquake forces for soft-story building, considering it as an ordinary RC framed building leads to an underestimation of base shear, which made a soft-story building vulnerable to earthquake [Haque and Amanat (4)]. The soft-story building shows poor performance during the earthquake demanding large drift demand for ground story columns [Banerjee et al. (5)].

The vulnerability of soft-story towards earthquake demands the incorporation of seismic mitigation techniques. Different types of seismic mitigation techniques including the base isolation system turn out to be the most effective technique [Kelly (6)]. Different types of isolation devices including laminated rubber bearing, pure friction system, friction pendulum system sliding resilient-friction base isolation system, variable frequency pendulum isolator have been developed and used practically for seismic design of buildings [Kelly (6); Mostaghel and Tanbakuchi (7); Mokha et al. (8); Su et al. (9); Pranesh and Sinha (10)].

Sliding isolation with a low coefficient of friction makes it possible to have a base isolation system of higher natural frequencies, which increases the range of effectiveness of the isolation system [Higashino et al. (11)]. The sliding system has the additional advantage of energy dissipation through friction, which reduces the energy transmitted to the superstructure [Mostaghel and Tanbakuchi (7); and Constantinou et al. (12)]. Analysis of a five-story building with the soft ground story with an isolation system shows that seismic isolation can be used as a viable mitigation technique for such buildings, not just only for the regular, uniformly stiff buildings, where the efficiency of isolation system depend on the flexibility of the soft-story [Pinarbasi et al. (13)].

Single degree freedom system with sliding isolation system subjected to the harmonic ground motion was analyzed considering the Coulomb friction model [Mostaghel et al. (14) and Westermo and Udwadia (15)]. A similar system, considering different values of coefficient of friction which remains constant with the velocity was analyzed, concluding at low friction coefficient acceleration response does not vary with frequency [Mostaghel and Tanbakuchi (7)]. A fictitious spring concept was developed to solve the discontinuity arises due to the sliding and non-sling phase in the sliding isolation system considering a constant coefficient of friction in the analysis [Yang et al (16)]. The effects of considering three components of earthquake excitation on pure friction base-isolated 3D structure was analyzed, where the frictional forces developed assumed to have Coulomb frictional characteristics [Shakib and Fuladgar (17)]. The influence of the nonlinear modeling of a fiction based isolation system and the dynamic characteristics of a superstructure on the total system's dynamic response were analyzed. The nonlinearity of the isolation system arises due to the discontinuity behavior of friction, which represented by the Coulomb friction model [Suy et al. (18)]. The derivation of important seismic responses of a 2D sliding isolated structure subjected to harmonic motions and the dependency of responses on the frequency ratio, mass ratio, and amplitude ground acceleration were studied using the Coulomb friction model [Hu and Nakashima (19)]. With extensive experiment data, a mathematical model was developed on the behavior of friction for the Teflon-steel interface by Constantinou et al. [12]. That model was idealized by different parameters including minimum and maximum values of the coefficient of sliding friction, the ratio of the coefficient of sliding friction at the non-sliding phase to sliding phase at the initiation of sliding, dependence of friction coefficient with velocity. However, many researchers have simulated the sliding behavior to evaluate the seismic response of buildings considering the Coulomb's friction model and very limited researchers have considered the dependency of sliding velocity. But those have not come out with appropriate influence of the velocity dependency friction model due to their limitation on simulation strategy.

Studies on the effect of velocity-dependent friction models over Coulomb's friction model in the seismic analysis of the sliding isolation system is limited. This paper attempts to bridge the gap in previous research work. An example four-story soft-story building, with a sliding isolation system, is investigated in this work. Here, following features have been evaluated such as (i) Response of sliding isolated soft-story buildings considering both Coulomb's and velocity dependency friction model, (ii) Influence on response behavior and friction model at the different coefficient of friction, and (iii) Importance of infill wall stiffness on response behavior of sliding isolated structures.

DIFFERENT FRICTION MODELS

Friction models have been considered in this investigation to evaluate the response of sliding isolated soft-story buildings are as follows:

1. Coulomb's Friction Model: Model FM1

This is the most frequently used model because of its simplicity to solve the equation of motion as shown in Figure 1(a). In this model, the coefficient of friction kept constant for both non-sliding and sliding phase and the friction force is expressed as

$$F_s = F_d = \mu_{\max} F_N \operatorname{sgn}(v) \tag{1}$$

where F_N is the normal load on the sliding surface, F_s is the frictional resistance at the non-sliding stage, $F_d = F$ is the frictional resistance at the sliding stage, $\mu_{\max}$ is the maximum coefficient of friction which same for both non-sliding and sliding stages ($\mu_s = \mu_d = \mu_{\max}$), v is relative sliding velocity, and $sgn(v)$

is the signum function that assumes a value of +1 for positive sliding velocity and –1 for negative sliding velocity. This signum function determines the direction of sliding.

2. Realistic Friction Model (Velocity dependent friction model): Model FM2

It is observed from the experimental investigation of Constantinou et al. [12] that the coefficient of friction varies with the sliding velocity dispelling the consideration in the FM1 model. In their observation, the value of the friction force is varying exponentially with sliding velocity. The friction force during sliding, F obeys the following exponential law:

$$F = [F_{max} - (F_{max} - F_{min})e^{(-a|v|)}]sgn(v) \tag{2}$$

$$F_{min} = \mu_{min}F_N \ and \ F_{max} = \mu_{max}F_N \tag{3}$$

where, F_N is the normal force on sliding surface, F is frictional resistance at the sliding stage, v is sliding velocity and μ_{max} & μ_{min} are maximum & minimum coefficient of friction. Furthermore, a is a constant for given bearing pressure and roughness condition of the interface. The friction force variation for Model FM2 is shown in Figure 1(b).

From the friction models, it can be observed that, in model FM1, the coefficient of static friction and sliding or kinetic friction have a constant value. In model FM2, the coefficient of friction changes exponentially from lower bound limit to upper bound. The equation of motion of the structure using model FM2 is dependent on sliding velocity and its direction. From the different friction models, it is also seen that the structure response is linear during the sliding stage for the FM1 friction model. However, the exponential function in model FM2 makes sliding response nonlinear.

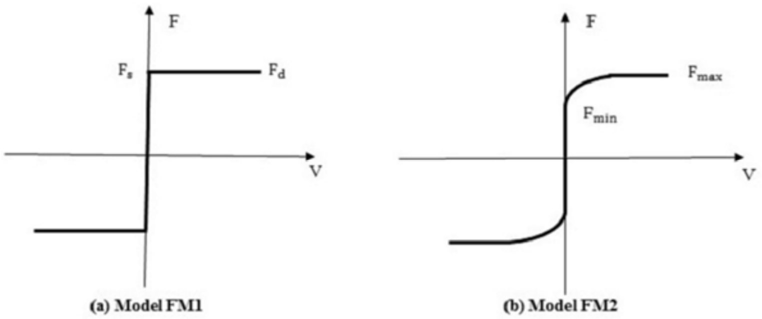

Fig. 1 Friction force variation with sliding velocity for different friction models (a) Coulomb's Friction Model (Model FM1) and (b) Realistic Friction Model (Model FM2)

NUMERICAL EXAMPLE

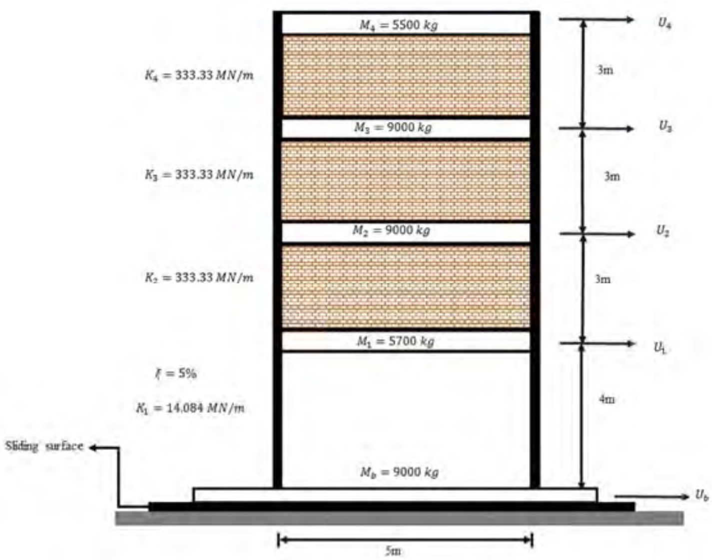

Fig. 2 Schematic sketch of four-story isolated structure with sliding isolator [Agrawal and Shrikhande (22)]

Example four-story shear frame building subjected to earthquake ground motion having different configurations as shown in Figures 2-3 are considered for the investigation. The damping ratio of the example building system has been taken as 5 percent of critical damping.

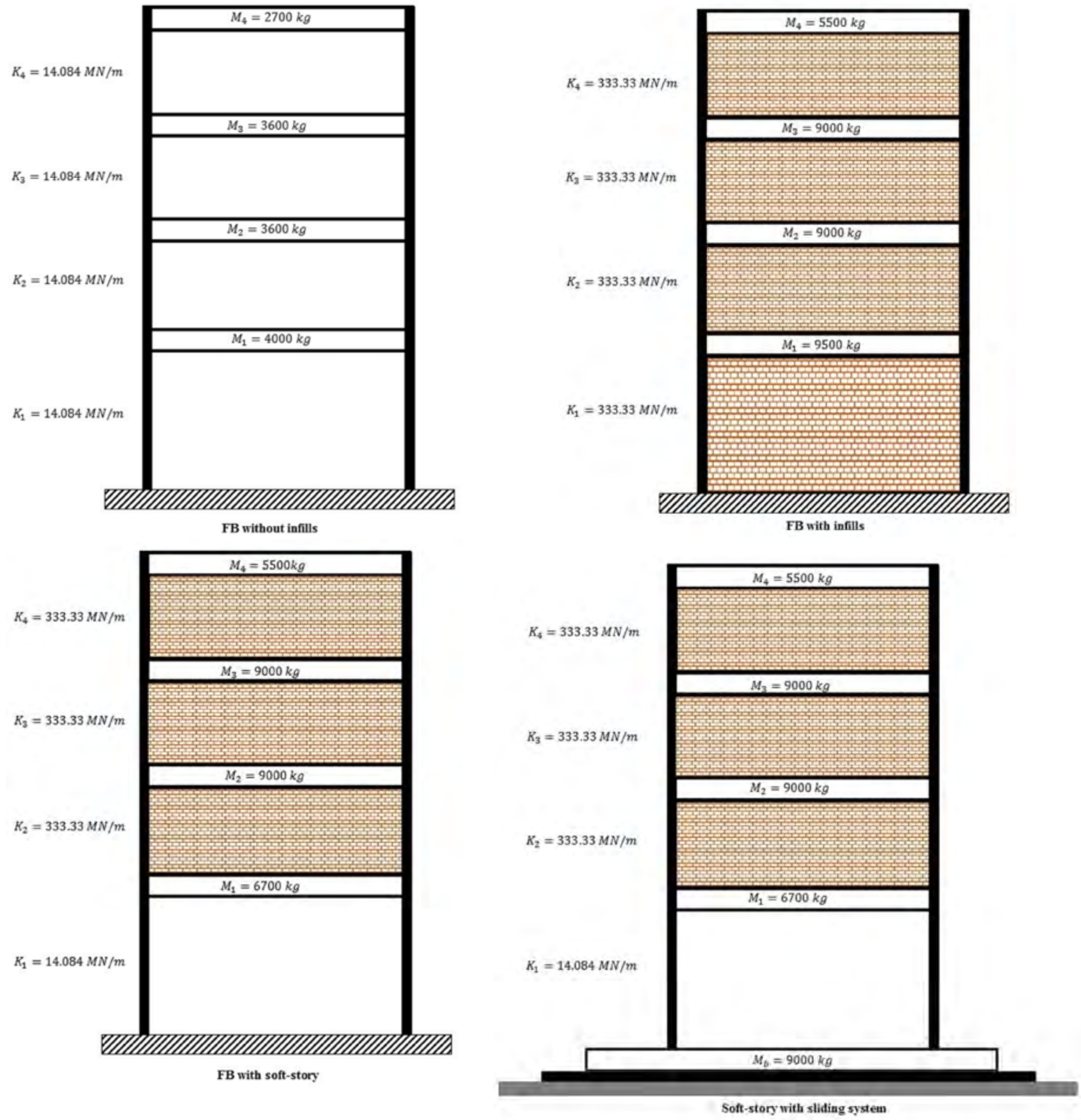

Fig. 3 Schematic diagram for structures considered in the analysis

MATHEMATICAL FORMULATION AND SOLUTION PROCEDURE

The mathematical formulation of an example soft-story building with a sliding isolation system shown in Figure 2 is presented in this section. The vibration of the structure under earthquake consists of two phases: (1) non-sliding when the sliding friction resistance provided by isolators is not overcome by the interface force at the base and the structure behaves as conventional fixed-base structure, and (2) sliding phase when frictional resistance is overcoming and the relative motion takes place at the sliding surface takes place. The overall response of the structure consists of a succession of sliding and non-sliding phases following one another. When the interface force at the isolator level is less than the frictional resisting force the structure behaves as a fixed structure and the system is considered as N DOF system, when the above condition is not satisfied, the structure starts to slide, the degree of freedom (DOF) corresponding to the base mass also becomes active, and the system is considered as N+1 DOF system.

The governing equation of motions for both non-sliding (Equation 4) and sliding phase (Equation 5) are mentioned as below:

$$\mathbf{M}_f\ddot{\mathbf{u}}_f + \mathbf{C}_f\dot{\mathbf{u}}_f + \mathbf{K}_f\mathbf{u}_f = -\mathbf{M}_f\mathbf{r}_f\ddot{u}_g \tag{4}$$

$$\mathbf{M}_s\ddot{\mathbf{u}}_s + \mathbf{C}_s\dot{\mathbf{u}}_s + \mathbf{K}_s\mathbf{u}_s = -\mathbf{M}_s\mathbf{r}_s\ddot{u}_g - \mathbf{r}_s F \tag{5}$$

The system matrices during the sliding phase can be expressed as:

$$\mathbf{M}_s = \begin{bmatrix} \mathbf{M}_f & \mathbf{M}_f\mathbf{r}_f \\ \left[\mathbf{M}_f\mathbf{r}_f\right]^T & m_t \end{bmatrix}, \mathbf{C}_s = \begin{bmatrix} \mathbf{C}_f & 0 \\ 0 & 0 \end{bmatrix}, \mathbf{K}_s = \begin{bmatrix} \mathbf{K}_f & 0 \\ 0 & 0 \end{bmatrix}, \mathbf{u}_s = \begin{Bmatrix} \mathbf{u}_f \\ u_b \end{Bmatrix}, \quad \mathbf{r}_s = \begin{Bmatrix} \mathbf{0} \\ 1 \end{Bmatrix} \tag{6}$$

In the above equations, $\mathbf{M}_f$, $\mathbf{M}_s$, $\mathbf{C}_f$, $\mathbf{C}_s$, and $\mathbf{K}_f$, $\mathbf{K}_s$ are the mass, damping and stiffness matrices of the structure during non-sliding and sliding phase, $\mathbf{u}_f$ is relative displacements of the structure with respect to the base, $\mathbf{r}_f$ is the force influence vector of the fixed base structure, u_b is the constant sliding displacement of the base, u_g is the ground displacement. The friction force at the sliding surface is characterized as F and their expressions for different friction models are presented in Equations (1-3). The inequality which ensures the system to be in non-sliding phase can be expressed as

$$\left| \left(\sum_{i=1}^{N} m_i(\ddot{u}_i + \ddot{u}_g) + m_b\ddot{u}_g \right) \right| < F_s \tag{7}$$

where F_s is the maximum frictional resistance at the non-sliding stage. When the inequality in the Equation (7) is not satisfied the structure enters into the sliding phase. The direction of sliding is governed by the signum function. For a multi-degree-of-freedom system, the direction of base sliding can be expressed as:

$$\text{sgn}(\dot{u}_b) = -\frac{\left[\left(\sum_{i=1}^{N} m_i(\ddot{u}_i + \ddot{u}_g) + m_b\ddot{u}_g \right) \right]}{\left| \left(\sum_{i=1}^{N} m_i(\ddot{u}_i + \ddot{u}_g) + m_b\ddot{u}_g \right) \right|} \tag{8}$$

The building may enter to the non-sliding phase or may change the direction of sliding or have a momentary halt and continue in the same direction if the sliding velocity during motion becomes zero. The motion status can be evaluated by using Equation (7) and then solving the appropriate equations of non-sliding or sliding phase during the next time-step. Since a particular phase of response may be arbitrarily short, the response at the end of the previous phase greatly influences the overall response of the building. The response evaluation is therefore extremely sensitive to accurate estimation of the initial conditions at the start of any phase of the response. During the numerical simulations, the determination of transition point with the accuracy of 10^{-10} seconds is found to be adequate. The response at the non-sliding phase can be determined using the step-by-step piecewise exact integration technique. In the sliding phase, standard numerical techniques such as Newmark average acceleration method can be used for the Coulomb Friction model. For the sliding phase with the realistic friction model, the equation of motion can be solved by using a method of solving systems of non-linear simultaneous equations [Aluffi-Pentini et al. (20)]. Solution of non-linear simultaneous equations at sliding phase takes significant amount of computation time in comparison to Coulomb's friction model. The solution at any phase uses the response at the end of the previous phase as the initial value. At the start of a non-sliding phase, the base acceleration and base velocity are zero, and the base displacement has a constant value depending on the extent of sliding in the previous phase. With this technique both Coulomb's friction and realistic friction models are properly simulated by capturing the transition phase accurately and presented in Figure 4. The numerical solution of the above simulation technique is carried out using the FORTRAN 77 programming language [Patro and Sinha (21)].

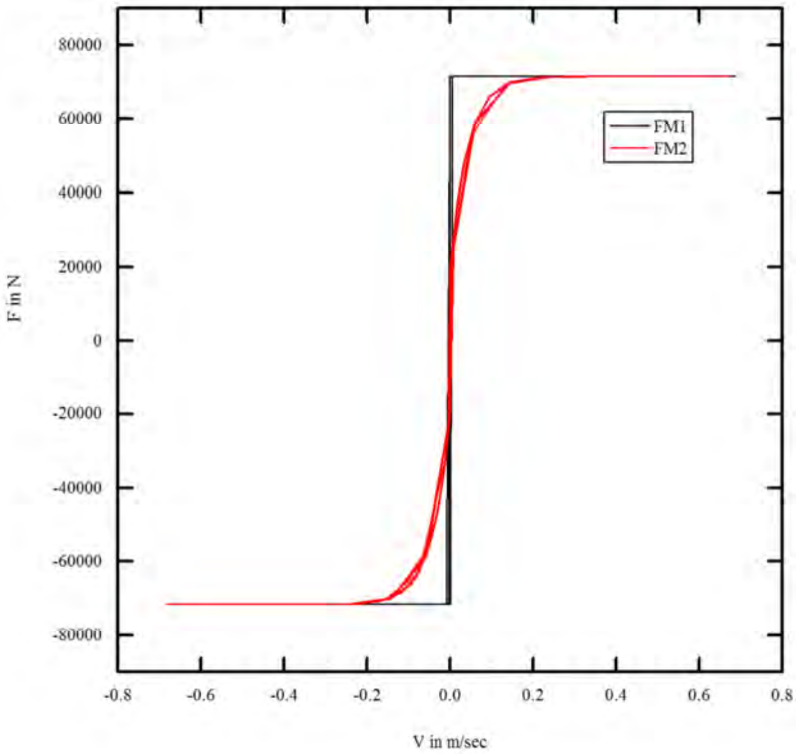

Fig. 4 Variation of frictional force over sliding velocity from simulation algorithm: FM1 – Coulomb's friction model, FM2 – Realistic friction model

RESPONSE ANALYSIS

The time history response for example four-story shear frame building such as (i) fixed-base with-out infill wall, (ii) fixed base with infill wall, (iii) fixed base soft story, (iv) soft story with sliding isolation system as shown in Figures 2-3 subjected to El Centro earthquake ground motion are considered for the investigation. PGA of El Centro 1940 NS ground motion is 0.348 g. The typical sliding surface is considered from an experimental investigation of Constantinou et al. [12] for unfilled Teflon bearing having a constant coefficient of friction of 0.1193 for Coulomb friction model (FM1) and a varying coefficient of friction from a minimum value of 0.026 to a maximum value of 0.1193 for Realistic friction model (FM2). Exponential coefficient (a) and breakaway factor (B) are considered as 0.01524 sec/m and 2.2 respectively. The breakaway factor is the ratio between the sliding coefficient at the non-sliding stage to sliding coefficient at the initiation of sliding. The influence of velocity-dependent friction model on the response of sliding isolated soft-story building and importance in consideration of infill wall stiffness on response behavior are discussed. The time history and peak responses such as absolute top floor acceleration, base shear, and floor displacement at soft story level of concern building configurations are conferred.

1 Time History Responses

The typical time-history response of absolute top floor acceleration, first-floor displacement, and base shear is shown in Figures 5-7. The primary objective of base isolation is to diminish the peak responses, but it is also important to simulate friction behavior accurately for appropriate response prediction of the sliding isolation system. The investigation of maximum responses such as acceleration, displacement, story drift [23] at each floor of example buildings enables one to study the effectiveness of sliding isolation, consideration of different friction models, and the importance of stiffness irregularity. Peak responses of the above parameters are shown in Figure 8.

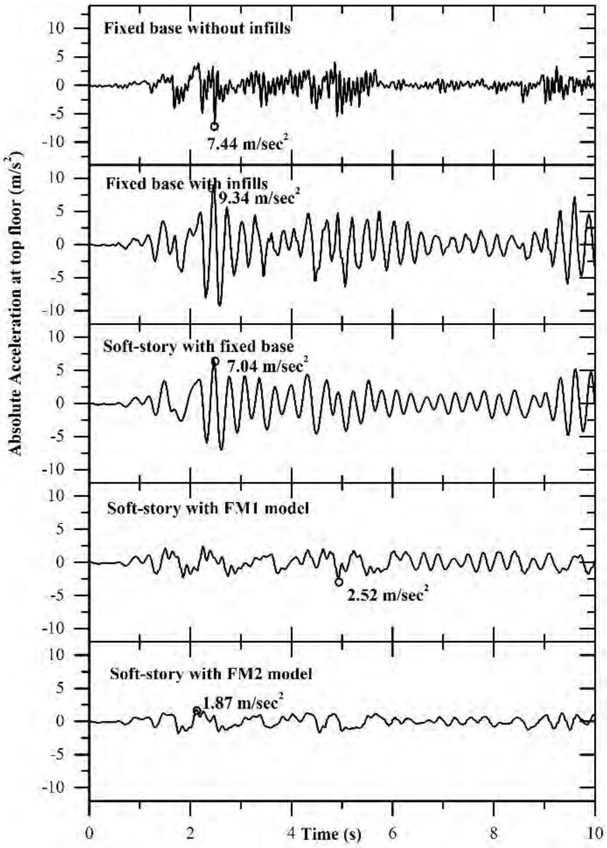

Fig. 5 Top floor acceleration time history responses of example structure subjected to El Centro (1940) ground motions (PGA = 0.348 g)

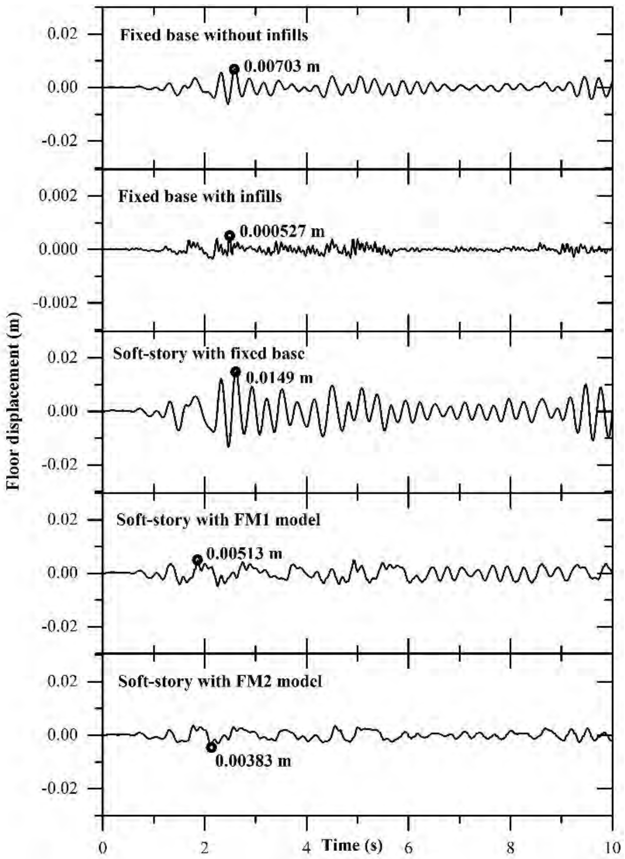

Fig. 6 First floor displacement time history responses of example structure subjected to El Centro (1940) ground motions (PGA = 0.348 g)

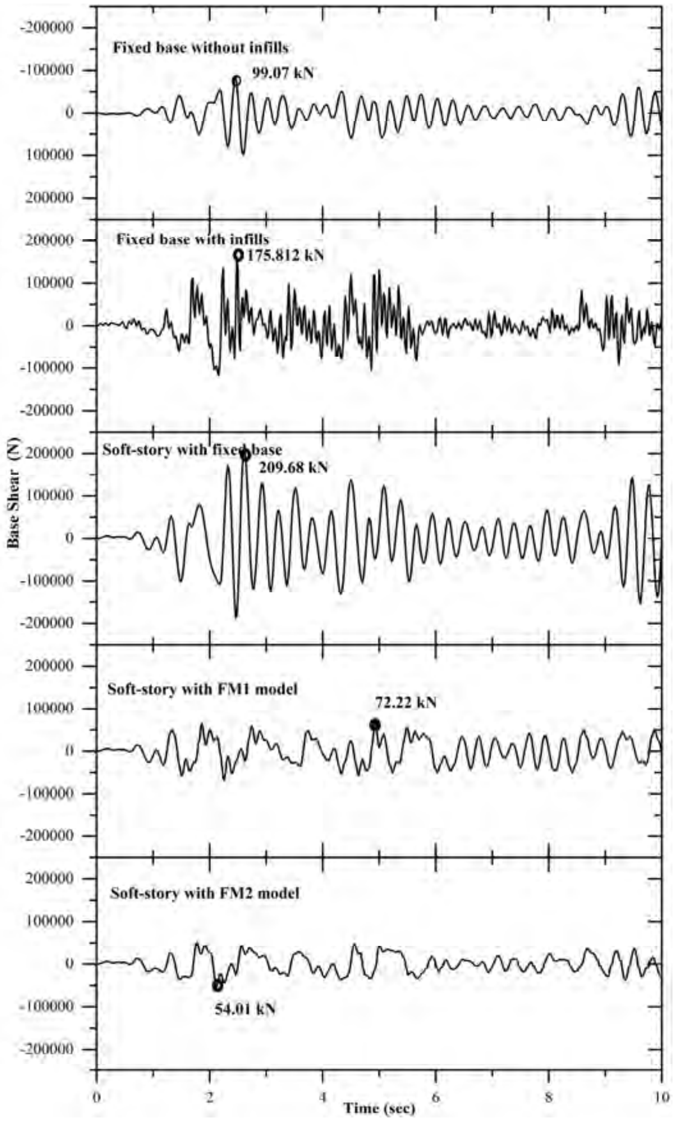

Fig. 7 Base shear time history responses of example structure subjected to El Centro (1940) ground motions (PGA = 0.348 g)

Figure 5 depicts the increase in absolute acceleration at the top story by 5.68 % and 32.67 % for a fixed base with-out and with infills walls respectively as compared to soft-story building with a fixed base. There is a reduction in the acceleration of 64.21 % and 73.44 % for the sliding isolation system with FM1 and FM2 models respectively as a compared soft-story fixed base. With this, a realistic friction model evaluates acceleration response 25.8 % less than Coulomb's friction model at the top story. Figure 6 shows the decrease in first-floor displacement by 52.82 % and 96.46 % for a fixed base without and with infills compared to the soft story with a fixed base. As compared to the soft story with a fixed base, the floor displacement reduced by 65.57 % and 72.3 % for the sliding isolation system with FM1 and FM2 models respectively. The realistic friction model calculates first-floor displacement 25.34 % less than model FM1. Figure 7 demonstrates the reduction in base shear by 52.75 % and 16.15 % in the fixed base without and with infills respectively as compared to the soft story with a fixed base. Sliding isolation system with FM1 and FM2 model show a reduction in base shear of 65.56 % and 74.24 % respectively as compared to the soft story with a fixed base. The realistic friction model predicts base shear 25.21 % less than model FM1 as like other response parameters.

Figure 8 shows the peak response quantities of each floor. There is a decrease in absolute acceleration on the 3rd floor by 8.38 % without infill and increase the same at 29.68 % with infills walls as compared to soft-story building with a fixed base. However, the acceleration decreases by 27.58 % without infill wall and minor variation with infill wall in comparison to the soft story fixed base on the 2nd floor. Further, there is a decrease in acceleration by 48.67 % and 26.17 % without and with infill wall at first floor in comparison to the soft story with a fixed base respectively. As compare to the soft story with fixed base, soft-story with

FM1 and FM2 model show a reduction of acceleration response 66.91 % and 75 % for 4th floor, 65.37 % and 74.28 % for 3rd floor, 64.63 % and 73.72 % for 2nd floor and 64.35 % and 73.55 % for the first floor respectively.

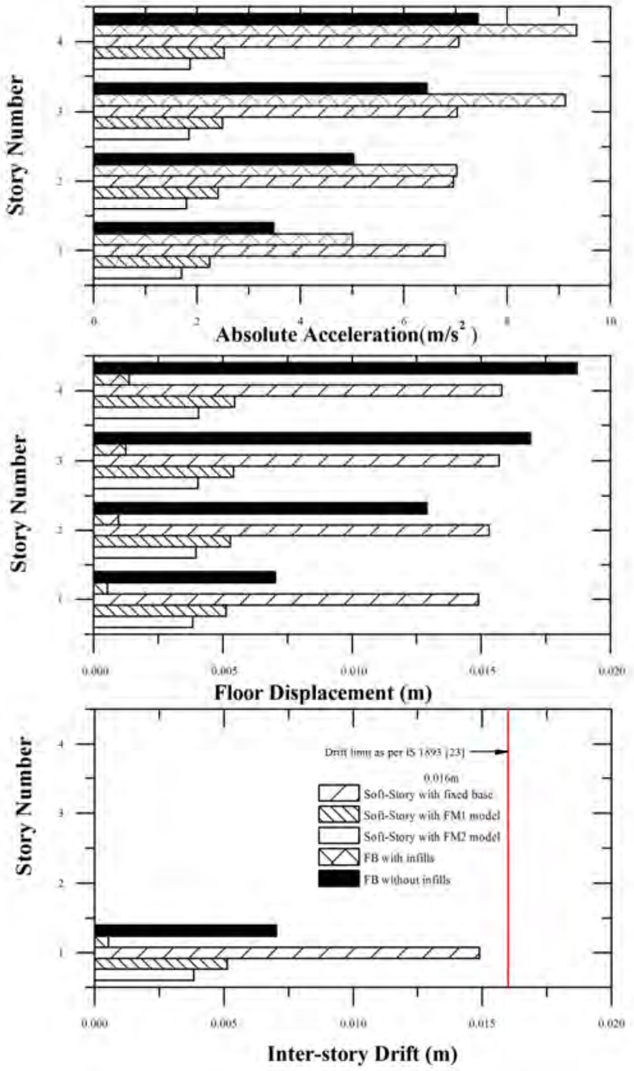

Fig. 8 Peak responses of example structure subjected to El Centro (1940) ground motions (PGA = 0.348 g)

The 4th floor peak displacement increases by 18.35 % for without infill wall whereas it significantly reduces by 91.26 % for considering infill wall as compared to Soft story with a fixed base as shown in Figure 8. Similar behavior was also seen for the 3rd floor. However, for the 1st and 2nd floor, there is a reduction of 15.68 % and 52.82 % respectively considering without infill and reduction of 93.95 % and 96.46 % respectively considering with infill wall as compared to soft story fixed base. As compare to the soft story with fixed base, soft-story with FM1 and FM2 model show a reduction in displacement response of 65.51 % and 74.24 % for 4th floor, 65.64 % and 74.26 % for 3rd floor, 65.63 % and 74.11 % for 2nd floor and 65.57 % and 74.29 % for the first floor respectively. There is a significant increase in the inter-story drift on the first floor of soft-story with a fixed base by 52.82 % and 96.46 % in comparison to without and with infill wall respectively. Compare to the soft story with a fixed base, the sliding isolated soft-story with FM1 and FM2 model show a reduction of 65.57 % and 74.29 % inter-story drift for the 1st floor respectively.

The time history and peak response results clearly show the significant influence of fixed base soft-story building for different response characteristics in comparison to the with and without infill walls. These demonstrate the requirement of a sliding isolation system to minimize the response of a fixed base soft-story building.

It is worth mentioning from the above results that realistic friction model (FM2 model) predicts all the peak responses such as acceleration, displacement, and inter-story drift 25 % less than model FM1 at all the floors. This indicates that Coulomb's friction model having a constant coefficient of friction at the sliding and non-sliding phase does not simulate the behavior of friction accurately. Model FM1, provides higher frictional resistance to overcome the non-sliding state in contrast to model FM2 as shown in Figure 4. It is in general understanding that sliding state shall dissipate energy in terms of frictional work done which helps out as reduction of structural responses in sliding isolated structures. Higher frictional resistance of model FM1 doesn't allow the system to slide and restricts the simulation of sliding phenomena. Model FM2 which is less frictional resistance at non-sliding state allows the system to keep on slide state for more time. Further, the increase of the sliding coefficient of friction exponentially with the sliding velocity at transition state from non-sliding to sliding turns to be more frictional work done leads to more response reduction of model FM2 in comparison to model FM1. Thus the importance of appropriate simulation of sliding isolation cannot be ignored.

2. Effect of Different Friction Parameters

Table 1: Different friction parameters [Constantinou et al. (12)]

Types of Teflon interface	μ_{max}	D_f	a (sec/m)	B
UF-1	0.1193	0.0927	0.01524	2.2
UF-2	0.0870	0.0695	0.01524	2.3
UF-3	0.0703	0.0552	0.02032	3.7
UF-4	0.0572	0.0485	0.01270	4.3
UF-5	0.1420	0.1181	0.01143	3.0
UF-6	0.1050	0.0878	0.01778	4.4
UF-7	0.0820	0.0530	0.01397	1.5
UF-8	0.0550	0.0439	0.01143	3.2
15 % GF-1	0.1461	0.1060	0.01524	2.1
15 % GF-2	0.1008	0.0580	0.01397	1.4
15 % GF-3	0.0849	0.0417	0.01524	1.3
15 % GF-4	0.0527	0.0312	0.01778	2.2
25 % GF-1	0.1320	0.0766	0.01651	1.4
25 % GF-2	0.1120	0.0633	0.01651	1.4
25 % GF-3	0.0960	0.0520	0.00813	1.5
25 % GF-4	0.0589	0.0270	0.02286	1.8

Note: UF = unfilled Teflon; 15GF = 15 % glass-filled Teflon; 25GF = 25 % glass-filled Teflon
$D_f = \mu_{max} - \mu_{min}$
a: constant for exponential function
B = Breakaway factor = $\dfrac{coefficient\ of\ friction\ at\ non\text{-}sliding\ stage}{coefficient\ of\ Sliding\ friction\ at\ initiation\ of\ sliding\ stage}$

The importance of a realistic friction model cannot be ignored as discussed above. Mokha et al. [8] have carried out various tests on the Steel-Teflon interface. They have measured the values of the coefficient of friction at a different range of bearing pressure (6.9 to 44.9 N/mm^2) and sliding velocity (0.0025 to 0.5 m/s). Teflon interface has consisted of unfilled Teflon (UF), glass-filled Teflon at a mix of 15 % (15GF), and 25 % (25GF). They have induced sliding in the direction of both parallel and perpendicular to lay. It was also seen that the coefficient of friction before the initiation of sliding (static state) was significantly higher than the sliding coefficient of friction and their ratio was termed as a breakaway factor. Once sliding starts, the coefficient of friction increases with sliding velocity up to a certain value of velocity and then onwards that remains constant as shown in Figure 4. The friction parameters such as maximum coefficient of friction (μ_{max}), the difference of max and minimum coefficient of friction (D_f), constant for exponential function (a), breakaway factor (B) used in this investigation for a different type of Teflon-steel interface are taken from Constantinou et al. [12] and presented in Table 1. UF1-4: unfilled Teflon interface, 15GF1-4 Teflon filled with 15 % glass, and 25GF1-4: Teflon filled with 25 % glass represent at bearing pressure of 6.9, 13.8, 20.7 and 44.9 N/mm^2 respectively. The parameters of Teflon type UF5-8 in Table 1 were recorded when sliding was induced during the test in the direction perpendicular to lay and at bearing pressure of 6.9, 13.8, 20.7, and 44.9 N/mm^2 respectively. However, other Teflon-steel interfaces (UF1-4, 15GF1-4, 25GF1-4) are from the direction parallel to lay. Frictional parameters in Table 1 such as μ_{max},

D_f, a, and B represent the condition of the surface at different Steel-Teflon interfaces and are used in friction models (FM1 and FM2) during the solution of the equation of motion.

The peak values of top floor acceleration, first-floor displacement, base shear, sliding displacement, and residual base displacement responses of the sliding isolated soft-story building considering different friction parameters are shown in Figures 9-13. The influences of different friction parameters are also summarized in Table 2.

It can observe that the reduction in all the responses such as top floor acceleration, floor displacement at soft story level and base shear, on an average are 64.24 % for FM1 model, 73.94 % for FM2 model when unfilled Teflon bearing UF-1 is on the sliding surface, 72.37 % for FM1 and 78.85 % for FM2 when UF-2 is on the sliding surface, 76.39 % for FM1 and 80.76 % for FM2 when UF-3 is on the sliding surface, and 79.99 % for FM1 and 85.85 % for FM2 when UF-4 is on the sliding surface, as compared to soft-story with a fixed base. Similarly, all these response reductions can be observed in 15 % GF Teflon bearing. The reduction in all the above-mentioned responses are 60.42 % for the FM1 model whereas 70.70 % for FM2 model when glass-filled Teflon bearing 15 % GF-1 is taken on the sliding surface, 69.57 % for FM1 and 75.45 % for FM2 when 15 % GF-2 is on sliding surfaces, 72.87 % for FM1 and 77.03 % for FM2 when 15 % GF-3 is on the sliding surface, 79.61 % for FM1 and 85.03 % for FM2 when 15 % GF-4 is on sliding surfaces as compared to the soft story with a fixed base. For 25 % GF Teflon bearing the reduction in these responses is 62.14 % for FM1 model whereas 70.50 % for FM2 model as compared to soft-story with the fixed base when glass-filled Teflon bearing 25 % GF-1 is taken on the sliding surface. These reductions in response are also observed as 67.13 % for FM1 and 72.95 % for FM2 when 25 % GF-2, 70.46 % for FM1 and 78.09 % for FM2 when 25 % GF-3 and 79.46 % for FM1 and 81.88 % FM2 when 25 % GF-4. The reduction in these responses is 61.24 % for the FM1 model whereas this reduction is 73.87 % for the FM2 model as compared to soft-story with the fixed base when unfilled Teflon bearing UF-5 is taken as a sliding surface. A similar reduction is responses are also observed as 68.61 % for FM1 and 75.47 % for FM2 when UF-6, 73.59 % for FM1, and 79.27 % for FM2 when UF-7 and 80.67 % for FM1 and 86.48 % for FM2 when UF-8 sliding surface as compared to soft-story with a fixed base. It is interesting to note from Figure 12 that the maximum sliding displacement consistently decreases in model FM2 compared to FM1 model at different friction parameters. Similarly, a significant reduction in residual base displacement has also been observed in Figure 13 at model FM2 compared to FM1 model. Higher frictional resistance of model FM1 at the non-sliding phase doesn't allow the system to slide and restricts the accurate simulation of sliding displacement. Model FM2 which is less frictional resistance at non-sliding state allows the system to keep on slide state for more time and helps in the reduction of the sliding and residual base displacement.

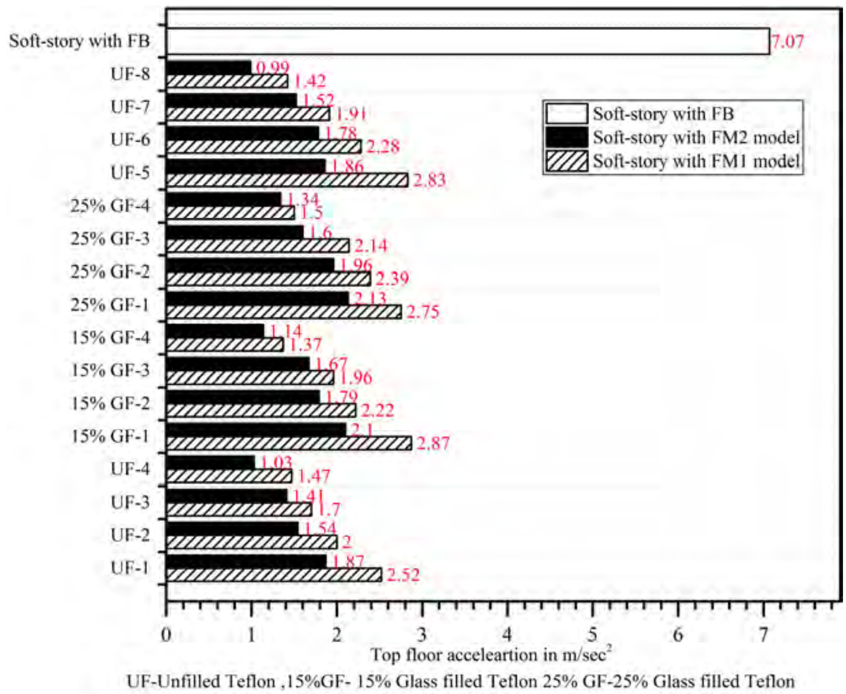

Fig. 9 Peak top floor acceleration of example structure subjected to El Centro (1940) ground motions for different friction parameters

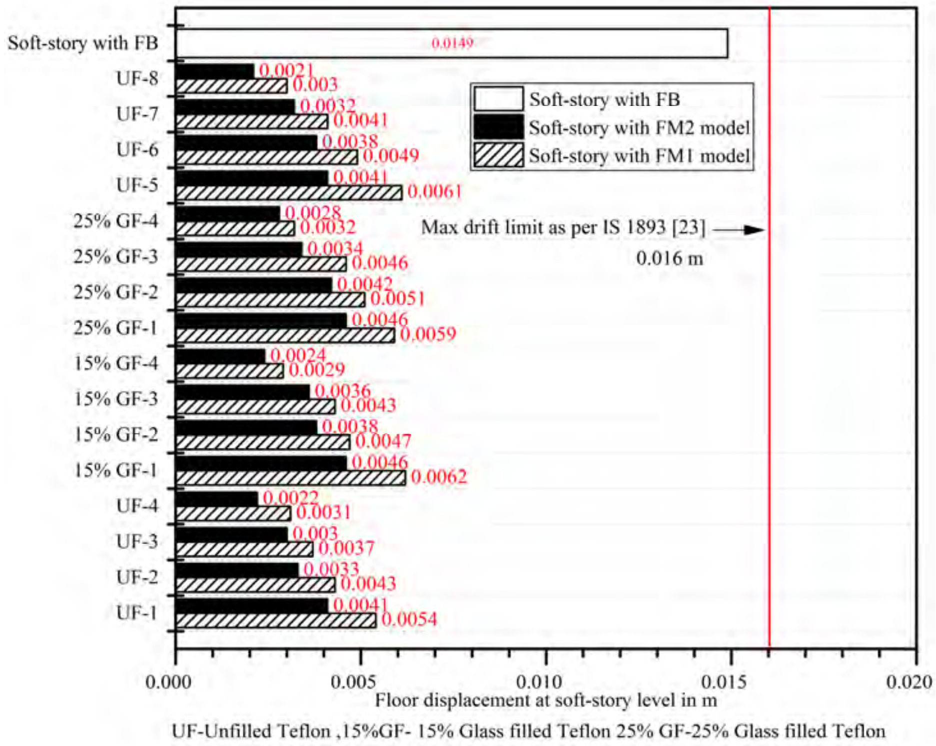

Fig. 10 Peak floor displacement at the soft story of example structure subjected to El Centro (1940) ground motions for different friction parameters

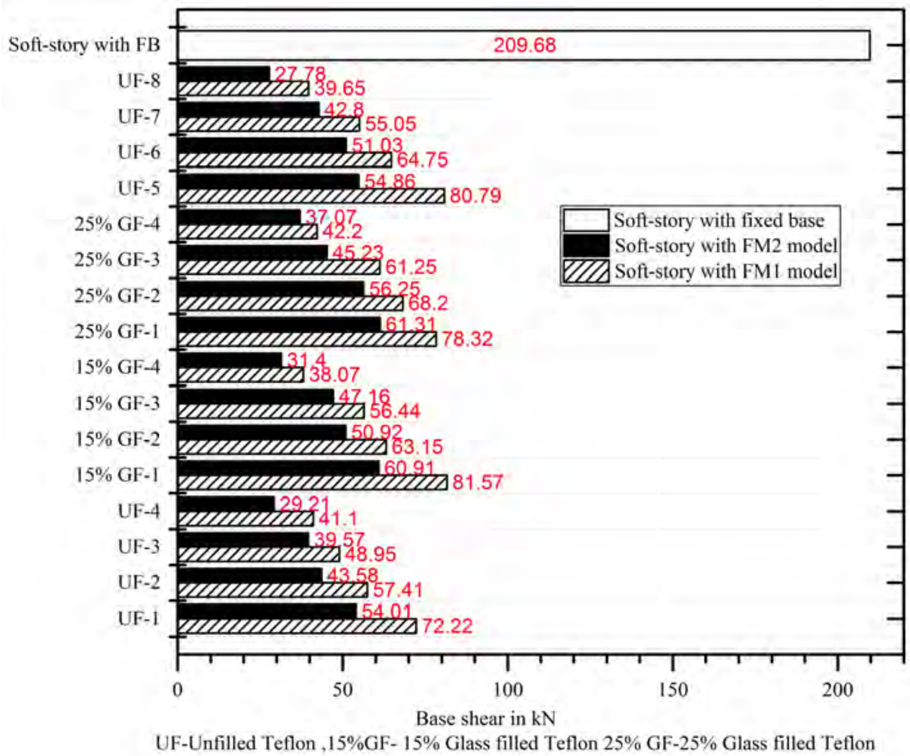

Fig. 11 Peak base shear of example structure subjected to El Centro (1940) ground motions for different friction parameters

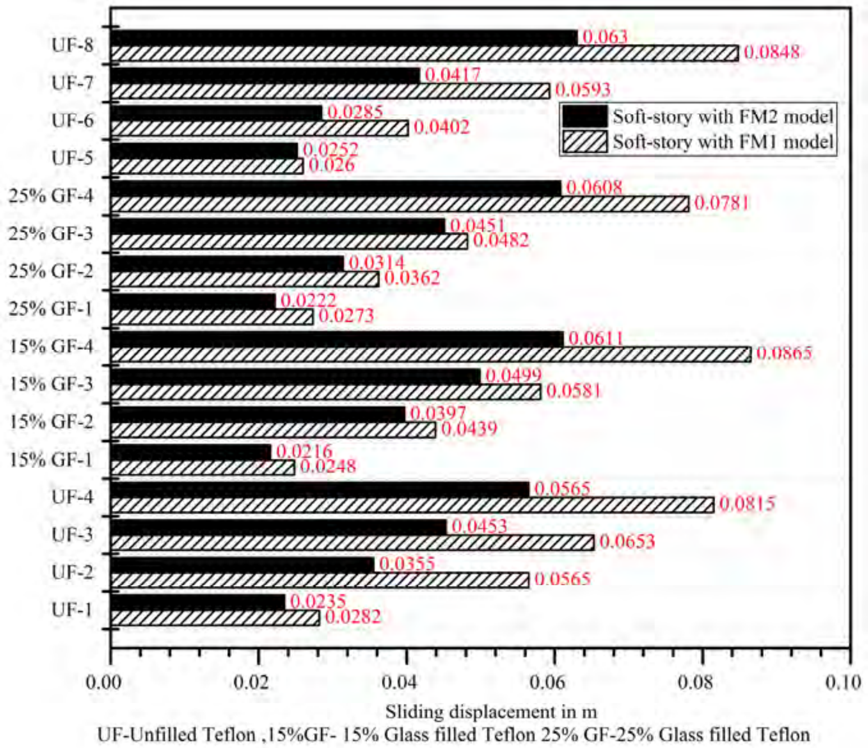

Fig. 12 Peak sliding displacement of example structure subjected to El Centro (1940) ground motions for different friction parameters

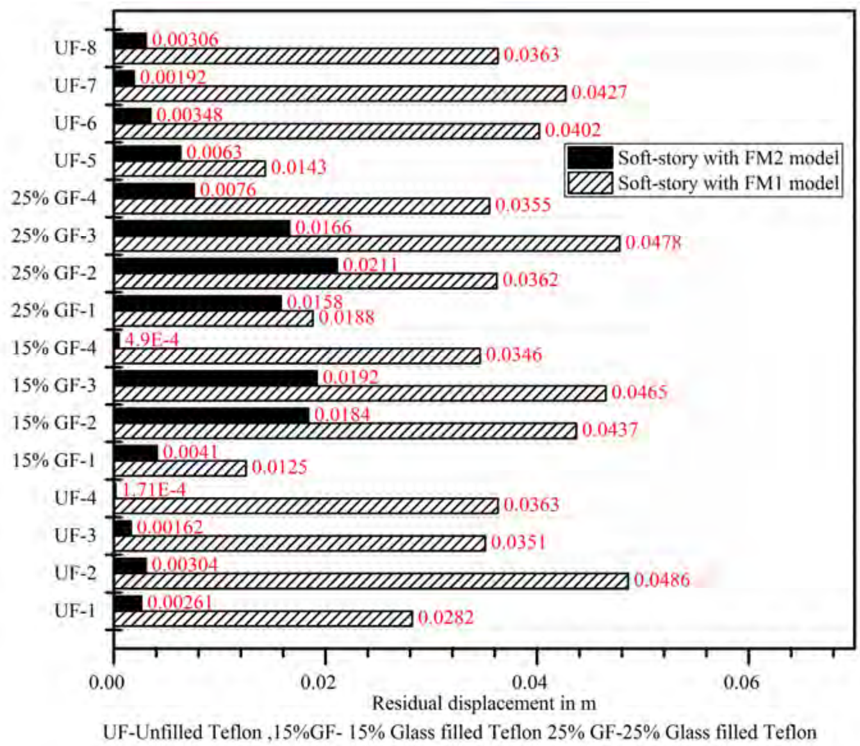

Fig. 13 Residual base displacement of example structure subjected to El Centro (1940) ground motions for different friction parameters

Table 2: Performance of sliding isolated soft-story building at different friction parameters

Type of Teflon interface	% Reduction in Responses of sliding isolated building in comparison to soft-story fixed base at different friction models					
	Top floor acceleration		Base shear		Floor displacement at soft story	
	Model FM1	Model FM2	Model FM1	Model FM2	Model FM1	Model FM2
UF-1	64.35	73.55	65.56	74.22	65.82	74.05
UF-2	71.71	78.22	72.62	79.22	72.78	79.11
UF-3	75.95	80.00	76.65	81.28	76.58	81.01
UF-4	79.21	85.43	80.40	86.06	80.37	86.07
15 % GF-1	59.41	70.30	61.10	70.92	60.75	70.88
15 % GF-2	68.60	74.68	69.88	75.71	70.25	75.95
15 % GF-3	72.77	76.37	73.08	77.51	72.78	77.21
15 % GF-4	80.60	83.87	76.58	86.41	81.64	84.81
25 % GF-1	61.11	69.87	62.65	70.76	62.65	70.88
25 % GF-2	66.20	72.27	67.47	73.17	67.71	73.42
25 % GF-3	69.73	77.36	70.78	78.43	70.88	78.48
25 % GF-4	78.78	81.04	79.87	82.32	79.74	82.27
UF-5	59.97	73.69	62.36	73.88	61.39	74.05
UF-6	67.75	74.82	69.11	75.66	68.98	75.94
UF-7	72.98	78.50	73.74	79.58	74.05	79.74
UF-8	79.91	86.00	81.10	86.75	81.01	86.71

3 Peak responses of Single Degree of Freedom (SDOF) system

A single-story sliding isolated system has been considered for evaluating the influence of the velocity-dependent friction model over Coulomb's friction model. A fixed-base time-period between 0.03-10.0 s has been considered in this investigation. However, a time-period between 0.03-2.0 s (0.5-33 Hz) covers the full range of typical structure time-periods and hence presented in Figures 14-16. The damping ratio of the system is considered as 5 %. SDOF is subjected to 1940 El Centro (NS) ground motions (Peak ground acceleration, PGA = 0.348 g) for 30 seconds. Responses of different intensities of ground motions are simulated by scaling the El Centro ground motions by three different factors. PGA = 0.174 g has been used to simulate the response under a small earthquake with an intensity factor of 0.5. Similarly, PGA = 0.348 g and PGA = 0.698 g have been used to simulate the behavior under moderate and large earthquake respectively by considering the intensity factor of 1.0 and 2.0. The properties of sliding surface used in this investigation such as the maximum coefficient of friction (μ_{max} = 0.1193), difference of max and minimum coefficient of friction (D_f = 0.0927), constant for exponential function (a = 0.01524 sec/m), breakaway factor (B = 2.2) are from Constantinou et al. [12].

Peak top floor absolute acceleration, maximum sliding displacement, and residual base displacement responses of the SDOF system over a different time-period are shown in Figures 14-16. The response spectra indicate that the peaks of the acceleration response are reduced in the FM2 friction model than the FM1 friction model by 17-36 %, which shows the influences of velocity-dependent friction models in the seismic analysis of sliding isolated building. Again, from these plots, it can be observed that within the structural time-period of 2 seconds, the effect of friction models is significant. It is also seen from Figure 14 that for the higher intensity of ground excitation and at higher time-periods, differences in peak acceleration response are not significant between the friction models. The maximum sliding displacement and residual base displacement estimate based on Coulomb friction model FM1 may also have errors resulting in inaccurate responses as shown in Figures 15-16.

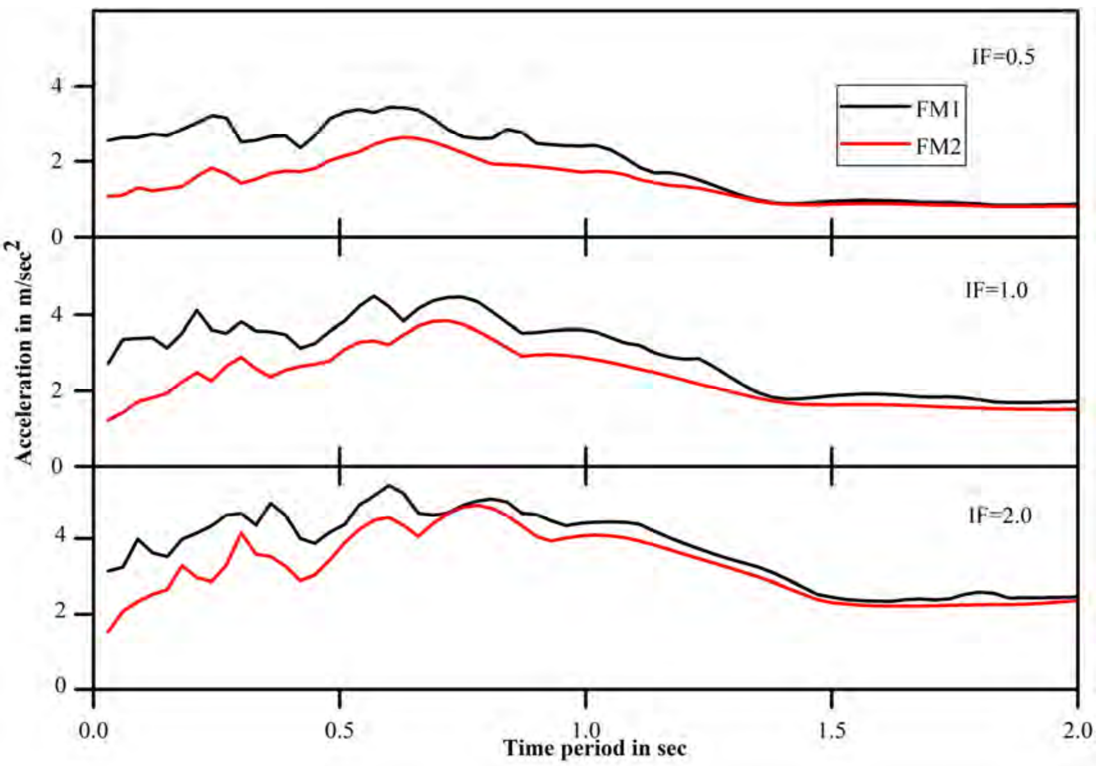

Fig. 14 Acceleration response spectra of top story subjected to El Centro (1940) ground motions (PGA = 0.348 g), (IF = Intensity factor)

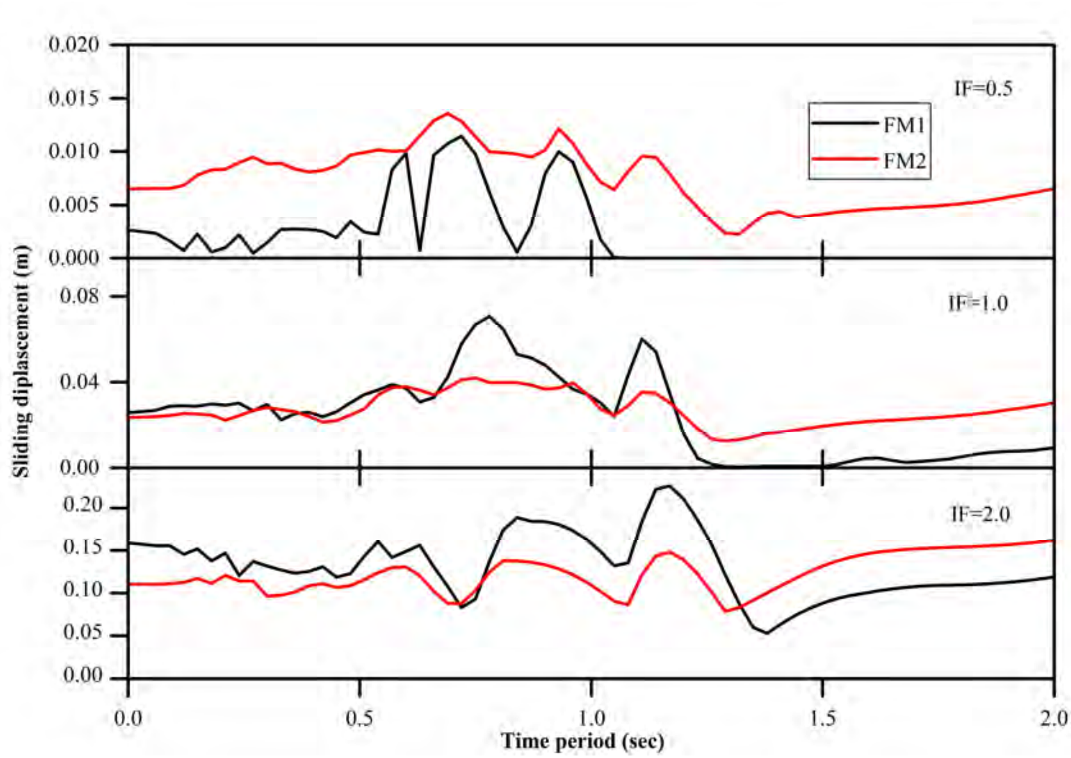

Fig. 15 Sliding displacement spectra subjected to El Centro (1940) ground motions (PGA = 0.348 g), (IF = Intensity factor)

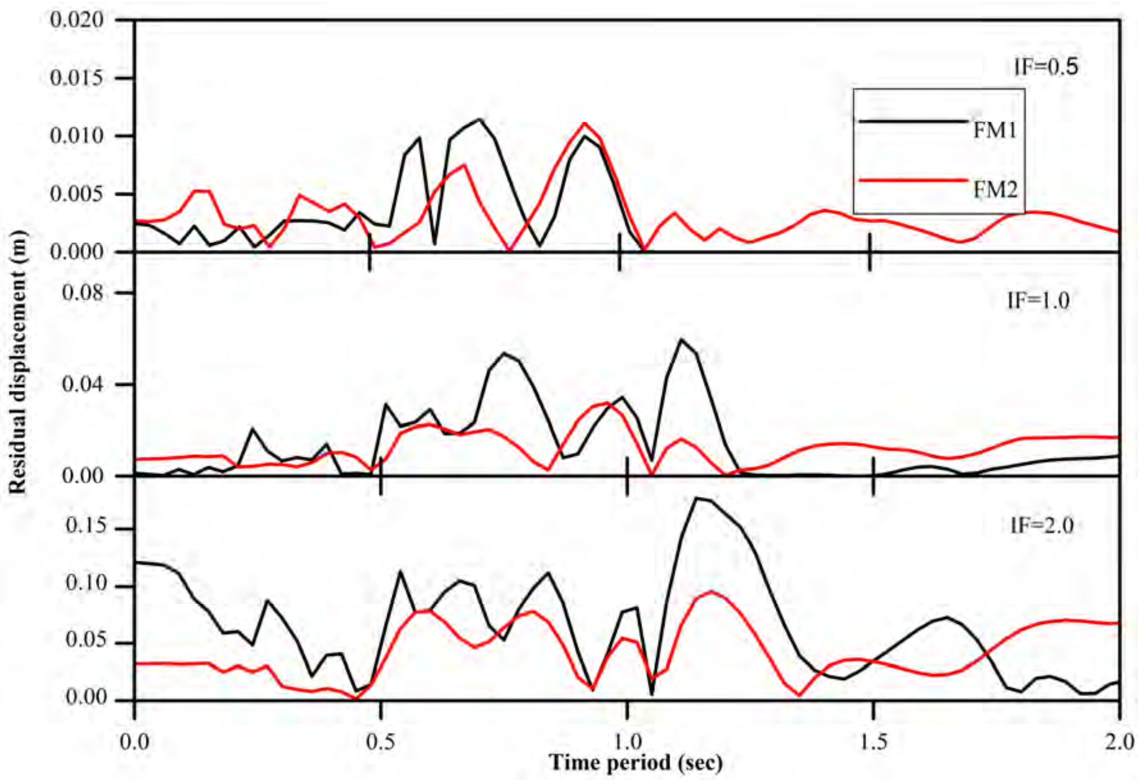

Fig. 16 Residual base displacement subjected to El Centro (1940) ground motions (PGA = 0.348 g), (IF = Intensity factor)

CONCLUSIONS

Based on the investigation presented herein, the following major conclusions can be drawn.

1. The time history and peak response results clearly show the significant influence of fixed base soft-story building for different response characteristics in comparison to the with and without infill walls. These demonstrate the requirement of a sliding isolation system to minimize the response of a fixed base soft-story building.
2. Soft story building equipped with the sliding isolators considering FM1 model and FM2 model in the analysis can reduce about 65 % and 75 % respectively in all the responses such as the inter-story drift, the absolute acceleration, and the base shear in comparison to soft-story building subjected to El Centro ground motions. It is observed that the use of a velocity-dependence friction model in the analysis of soft-story isolated buildings enhances the performance of the isolation system at the cost of computational effort, in comparison to the simple Coulomb friction model.
3. Frictional parameters such as minimum and maximum sliding coefficient of friction, constant for exponential coefficient, and breakaway factor have a great influence on the performance of the realistic friction model, it results that the unfilled Teflon interface gives the better performances for the example system.
4. The influence of the realistic friction model is not significant at higher structural time-periods.
5. This result has great significance in the practical design of sliding isolation systems since the prevalent practice is based on the use of Coulomb's friction to determine the isolation system parameters.

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