Upgrading the seismic performance of soft first story frame structures by isolators with multiple sliding surfaces

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**ABSTRACT:** Soft story failure was one of the most observed failures through many earthquakes in the past. In this study, the seismic performance of soft first story frame structures is upgraded by installing a recently developed multiple-slider bearing on the top of the middle columns and rubber bearing at the top of edge columns. The multiple-slider bearing is a simple sliding device consisting of one horizontal and two inclined plane sliding surfaces at both ends set in series. These three surfaces based on PTFE and highly polished stainless steel interface. The main purpose to develop such a device was the need for a seismic bearing that is simple, and effective in reducing the horizontal displacement with a low cost in order to be implemented in multi-span continuous bridges. The idea and concept are extended to be applied in frame structures, specifically in upgrading the seismic performance of soft-first-story frame structures. The proposed system also offers a feasible solution for seismic retrofit of existing buildings with soft stories. A five-story reinforced concrete shear frame with a soft first story is considered to demonstrate the efficiency of the proposed isolation system in reducing the ductility demand and damage in the structure while maintaining at the same time the superstructure above the bearings to behave nearly in the elastic range. Comparative study with the conventional system is also performed. The results show the effectiveness of the multiple-slider bearing in minimizing the damage from earthquake and preserving the soft first story from excessive large ductility demand due to its unique geometry.

1 **INTRODUCTION**

Despite structures with soft first story are inherently vulnerable to collapse during earthquakes, it is still in demand especially in urban areas. Soft first story offers for architects an attractive model by allowing a sense of floating and bright spaces. The famous architect Le Corbusier was one of the pioneers who utilizes the idea of soft first story by lifted the structure off the ground, supporting it by pilotis (or piers), establishing the leading principle of the modern architecture: the "pilotis-story" (Mezzi 2006). The soft first story might be functionally or commercially desirable by providing parking spaces, allowing for a grand entrance or ballrooms as in hotels and permitting a desirable continuous windows for display for stores located in first story. In addition, such building help in raising the inhabitants space of a building above typical storm surge levels in hurricane-prone areas.

In the twenties and thirties, researches started adopting ductility design concept allowing the formation of plastic hinges within the structure which generates an energy absorbing mechanism that increases the flexibility of structure and reduces the damage of earthquake. Based on this idea, some structural engineers introduced the concept of flexible first story (Martel 1929, Bednarski 1935, Green, 1935, Jacobsen 1938). Later on, this idea was modified leading to the concept of shock-absorbing soft story method (Fintel and Khan 1969). However, this attempt to reduce forces on structure by allowing the first story columns to yield during an earthquake is no longer an appealing idea for structural engineers due to the excessive drifts in the first story coupled with P-∆ effects on the yielded columns increasing
the risk to develop a collapse mechanism known as soft story failure. This mode of failure was observed clearly during many earthquakes in the past such as in the 1995 Kobe earthquake. Many of reinforced concrete buildings were severely damaged and most of them were buildings with a soft story (Yoshimura 1997).

Another modification to soft first story was proposed by introducing additional energy dissipation capacity in order to reduce drift and providing a mechanism to reduce P-Δ effects (Chen and Constantinou 1990). In this system Teflon sliders are placed at top of some of the first story columns while the remaining first story columns are designed with reduced yield strength and for ductile behavior in order to accommodate large drifts. A similar concept was also proposed but the difference is that the first story shear walls are fitted with Teflon sliders (Mo and Chang 1995). A further extension of the concept was proposed similar to the above philosophy but additional steel dampers to increase the energy dissipation mechanism during earthquakes (Iqbal 2006).

In this paper, another approach to enhance the seismic performance of soft first story frame structures is proposed. The first soft story is upgraded by installing on the top of first story columns a newly developed multiple-slider bearing consisting of multiple sliding plane surfaces, one horizontal and two inclined surfaces, to effectively protect the first story columns from damage by reducing its ductility demand and maintaining at the same time the superstructure to behave nearly in the elastic range with controlled bearing displacement. The proposed system also offers a feasible solution for seismic retrofit of existing buildings with soft stories in area where clearance between adjacent building is limited. First of all, the concept and principles of operation of the bearing are introduced. The proposed system is then described and its efficiency is illustrated using five-story reinforced concrete shear frame with soft first story. The seismic behaviour of the proposed system subjected to seismic excitation is captured and studied. Comparative study with conventional system is also performed. In addition, comparison with various isolation systems such as rubber bearing interface and resilient sliding isolation is carried out.

2 MULTIPLE SLIDER BEARING

Recently in Japan, the uplifting slide bearing (Photo 1) is developed primarily to be used for upgrading the seismic performance of multi-span continuous bridges, and is installed on the top of the middle piers (Igarashi et al 2010a to 2010d). The main purpose to develop such a device was the need for a seismic isolation device that is simple, and effective in reducing the horizontal displacement with low a cost in order to be implemented in multi-span continuous bridges to replace the conventional rubber bearings.

![Photo 1 Uplifting Sliding Shoe (UPSS) Isolator.](image)

In this study, the idea and concept of the multiple-slider bearing, which is developed primary for bridges, are extended to be applied in frame structures, specifically in upgrading the seismic performance of soft-first-story frame structures. The creativity of the device depends essentially on the geometrical configuration of the isolator through the dual interaction between one horizontal and two inclined plane sliding surfaces. These three surfaces based on PTFE and stainless steel (SUS) interface. During normal or low intensity earthquakes, the bearing behaves as a pure friction isolator
with sliding only in horizontal direction. However, during severe earthquakes, sliding will occur on the inclined surface producing displacements in both horizontal and vertical directions, Figure 1.

A proper design of the isolator is accomplished by understanding the sensitivity of selecting the device parameters and their effects in de-amplification of the input motion. The multiple-slider bearing is defined by three main factors: The clearance \( L \) i.e. the horizontal distance prior the sliding along the inclined surface, the inclination angle \( \theta \) and the friction coefficient \( \mu \). The free body diagram for the multiple-slider bearing can be simplified as shown in Figure 2.

2.1 Concept behind peak displacement reduction

The analogy of a dynamic sliding block on an inclined plane has been used to illustrate the effectiveness of the inclined surface in reducing the peak horizontal displacement in comparison with rubber bearing. The motion of a mass on a frictional inclined plane is the interplay of different force types and the characterizing features of the incline surface. If a block mass \( m \) placed on an inclined plane, which is accelerated towards left with a horizontal acceleration \( a_h \), see Figure 3.

The angle of incline is \( \theta \) and friction coefficient is \( \mu \) at the contact surface. Assuming the block mass stays in contact with the inclined surface while moving upslope and the mass is sliding upward, the net horizontal reaction force yields to:

\[
F_x = m a_h \left[ \mu \sin \theta \cos \theta - \cos^2 \theta \right] - g \left[ \sin \theta \cos \theta + \mu \cos^2 \theta \right] \tag{1}
\]

Based on the energy conservation law, the maximum horizontal displacement \( x_{\text{max}} \) can be written as:

\[
x_{\text{max}} = \frac{1}{2} v_0^2 \times \frac{\cos \theta}{g \sin \theta + \mu g \cos \theta - \mu a_h \sin \theta} \tag{2}
\]
where \( v_0 \) is the initial velocity, combining (Eq. 1) and (Eq. 2), \( x_{\text{max}} \) can be expressed as:

\[
x_{\text{max}} = \frac{1}{2} mv_0^2 \times \frac{\cos^2 \theta}{-F_x - ma_h \left[ \cos^2 \theta - \mu \sin \theta \cos \theta + \mu \sin \theta \right]}
\]

In the same manner, the maximum horizontal displacement for the conventional rubber bearing \( x_{r_{\text{max}}} \) assuming the simplest case where the rubber resisting horizontal forces \( (F_r) \) are kept constant can be represented:

\[
x_{r_{\text{max}}} = \frac{1}{2} mv_0^2 \times \frac{1}{-F_x - ma_h}
\]

The above formulation can also be seen as a flat plane when setting \( \theta \) equal to zero in (Eq. 3). This is a useful observation for assessing the reduction effectiveness of the inclination surface. Comparing (Eqs. 3 and 4) reveals that \( x_{\text{max}} \) is always much less than the \( x_{r_{\text{max}}} \) i.e.

\[
\frac{x_{\text{max}}}{x_{r_{\text{max}}}} = \left[ \cos^2 \theta \times \frac{-F_x - ma_h}{-F_x - ma_h \alpha} \right] < 1.0
\]

where \( \alpha = [\cos^2 \theta - \mu \sin \theta \cos \theta + \mu \sin \theta] \) is a constant less than one for any combinations of \( \theta \) and \( \mu \). The optimum value of \( \alpha \) is achieved using smaller inclined angle. Equation (5) implies the effectiveness of inclined surface in reducing the peak horizontal displacement compared to conventional rubber bearing for the same level of horizontal reaction force. The fraction of reduction depending mainly on both factors simultaneously: \( \cos^2 \theta \) and \( \alpha \).

### 2.2 Shaking Table Test

An extensive series of shaking table tests were performed to capture the real dynamic behaviour of multiple-slider bearing with different properties under various types of excitations including both harmonic and earthquake waves. A sample of these excitation waves is selected to compare the displacement time history between analytical and experimental results. In this experiment, a 4.15 m \( \times \) 2.65 m rigid steel frame was supported on two multiple-slider bearing and two rubber bearings, as shown in Figure 4. The total weight of the floor was 107.8 kN. The excitation was carried on only in one horizontal direction. Rubber bearing stiffness was chosen to produce an isolation period of 1.25s with effective damping ratio 4.28%. The specifications used for the isolators were \( \theta = (30^\circ, 15^\circ) \), \( L = (30, 42) \) mm and \( \mu = 0.1 \).

![Figure 4 Details of test experiment](image)

The response quantities between experimental and analytical results show a good agreement as shown in Figure 5. However, it has been noticed that the dynamic behaviour at the transition between horizontal and inclined surfaces is extremely random and nonlinear. Small shock impulses are formed in some strong excitation motions.
3 PROPOSED SYSTEM

The new proposed system using multiple-slider bearings is implemented in soft-first-story frame structure, as shown in Figure 6. Separation between soft first story columns and the rest of superstructure is incorporated by installing multiple-slider bearings on the top of middle columns and rubber bearings at the top of edge columns. The first story columns are tied together by tie beams to insure stability and enhance the safety.

The need for controlling displacement of the isolators to a minimum level is a vital issue especially in big and crowded cities where buildings are often built closely to each other. This may cause pounding of adjacent buildings due to the insufficient or inadequate separation and can be a serious hazard in
seismically active area. Accommodating such large displacement responses by conventional rubber bearing is costly and may cause instability. Therefore, the geometry of the multiple-slider bearing was chosen to help in mitigating such a problem by preventing the motion to be fully activated in the horizontal direction instead allowing part of the earthquake transmitted energy to be transferred into a gravitational potential energy through the diagonal sliding. Besides the economical reason and the ease of manufacture, the hysteretic behaviour of this device provides more freedom in the process of design. In addition, such geometry has the potential of using different frictional bearing in each plane surface which has been found to add more reduction to the horizontal displacement response especially structures subjected to strong and near-fault ground motions (Fakhouri and Igarashi 2010a and 2010b). The proposed system also offers a feasible solution for seismic retrofitting of existing buildings with soft stories. Commonly, the seismic rehabilitation can be carried out simply by transmitting the load acting on the column temporary to jacks, then column is cut from the top at first story level and the isolation device is inserted and connected to the adjacent structural elements before the removal of the temporary jacks. Nevertheless, more neat and reliable methods without using lifting equipment also exist. The multiple-slider bearing is vertically stiff, minimizing the vertical deflections of columns that occur during bearing installation in retrofit application avoiding damage to architectural finishes in upper stories. It is worth pointing out that the isolator provides an architecturally flexible and aesthetic solution in term of integration into the structural system.

4 NUMERICAL EXAMPLE

A five-story reinforced concrete shear frame with soft first story is considered to demonstrate the efficiency of the proposed isolation system in reducing the ductility demand and damage in the structure. The system is also examined and compared with the conventional frame structure. Table 1 presents the story initial stiffness ($K_i$) and the story yield strength to total weight ($V_y/W$).

<table>
<thead>
<tr>
<th>Story</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_i$ (kN/m)</td>
<td>41,137</td>
<td>154,220</td>
<td>133,500</td>
<td>96,127</td>
<td>60,997</td>
</tr>
<tr>
<td>$V_y/W$</td>
<td>0.1451</td>
<td>0.5344</td>
<td>0.4572</td>
<td>0.3488</td>
<td>0.2084</td>
</tr>
</tbody>
</table>

The fundamental natural period ($T_1$) is equal to 0.56 sec for this frame structure with equal lumped floor masses equal to 45.34 Ton for each story. Rayleigh damping in the structure with damping ratio of 5% for the first two modes is assumed. To account for the continually varying stiffness, the columns are described by the modified Clough bilinear stiffness degrading model. Five percentage post to pre-yielding stiffness ratio and 10% degradation stiffness rate ($\alpha$) are used for column hysteretic model. The ground motions used in simulations is 1995 Kobe JMA record NS component (0.82g). Only unidirectional excitation is considered.

Figure 7 illustrate the ability of the proposed system to reduce both drift and ductility demand in the first story columns without significant changes in upper stories in comparison with the conventional design. The drift and ductility demand were reduced both considerably by 41% when subjected to Kobe earthquake. Figure 8 shows both the force displacement relationship for the multiple-slider bearings placed on the top of first story columns and the force displacement relationship the first story. It is obvious that the presence of such isolation interface controls efficiently the vibration energy of earthquake by an absorption mechanism that tends to transfer the high concentrated energy and stresses from the soft first story columns to the isolation interface. As shown Figure 8, the hysteresis behaviour of first story columns is reduced in terms of force-displacement relationship, indicating a less energy being absorbed by these columns. It can be concluded that the proposed system is a practical cost-effective solution which can be adopted to retrofit existing buildings with soft stories and increase their seismic resistance.
Figure 7 Comparison between conventional design and proposed isolation system (a) max. story drift vs. story height (b) story ductility demand vs. story number.

Figure 8 Hysteresis loop (a) the multiple-slider bearings (b) soft first story.
5 CONCLUSION

Seismic retrofitting of soft-first-story frame structures with by introducing a seismic interface on the top of first story columns proves its efficiency to enhance the structural safety and integrity for such special type of structures. The effectiveness of the multiple-slider bearing in reducing the peak horizontal displacement in comparison with rubber bearing is illustrated in the analogy of dynamic sliding block on an inclined plane. Moreover, the proposed system also offers a feasible solution that is simple and practical to be implemented for seismic retrofitting of existing building with soft stories. The results indicate the ability of the proposed system to reduce significantly the ductility demand and excessive drift for the first story columns.

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