BASE ISOLATION FROM EARTHQUAKE HAZARDS
AN IDEA WHOSE TIME HAS COME!

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Summary

An isolation concept is presented that uses simple principles of nature to reliably absorb the energy of an earthquake with bilinear force-deflection devices at the foundation of each building, thereby providing positive protection against the inelastic rotations that cause building damage. This concept should reduce the initial cost of building construction, avoid the high cost for repairing or replacing damaged buildings after an earthquake, and increase safety for both building occupants and pedestrians on the street below.

History

Of the several isolation concepts that have been presented since 1906, many are flawed. In large part the flaws stem from one common factor, the isolation devices themselves are load-bearing members. This flaw was immediately apparent when Fintel and Khan presented their soft-first-story concept after the failures during the Caracas and Skopje earthquakes of the early 1960s. Clearly the P - effect on long flexible columns could not be tolerated. Witness the numerous buildings that have recently experienced column failure in the first story, such as Olive View Hospital in the 1971 San Fernando earthquake and the more recent failure of the Government Services Building at El Centro on October 15, 1979.

Other isolation concepts, such as the Japanese work on rocker bearings and Professor Kelly's work on reinforced rubber pads, have devices that are more stable than the long flexible columns. However these isolation devices still lack wide acceptance. A principle reason for this is because the isolation devices are load-bearing members. In addition, both concepts have the weakness of using rupture pins or plugs that are intended to hold the building rigidly in place during a windstorm and then rupture suddenly whenever a major earthquake introduces a predetermined level of force at the base. The uncontrolled rupture of the frangible pin will always introduce a major shock load whose impact on the structure cannot be predicted and, once ruptured, leaves only the soft spring remaining to resist earthquake and wind induced forces.

This paper introduces an isolation technique that does not include weak or flexible columns and does not include frangible materials that would impart any shock loading into buildings. Instead, base isolation devices are presented that provide a continual control over the maximum horizontal base shear that could possibly be imparted to a building by even the largest earthquake. Base isolation may be the breakthrough that enables man to construct buildings that:

- Behave like any other building during a major windstorm or a modest earthquake,
- Permit a smooth relative displacement between the building and the ground (i.e., foundation) during moderate or major earthquakes, and

o Have a limiting horizontal base shear during a major earthquake, which base shear is established by the designer so that the columns and beams of the superstructure do not bend into the inelastic range. This feature provides many benefits, such as a reduced cost for initial construction and reduced damage after a major earthquake as well as an order-of-magnitude increase in safety for both building occupants and pedestrians on the street below.

Where Do We Go From Here?

The base isolation approach is simplicity itself. In order to overcome the inherent dangers of soft load-carrying supports at the base of the structure, the concept substitutes stainless steel ball bearing clusters between stainless steel base plates (as shown on Figures 1 and 2), similar to those used reliably for decades in rotating machinery such as turbines. This provides absolute insurance against collapse of the "laterally soft" interface and at the same time reduces the lateral stiffness of the building-to-ground interface to nearly zero (=0.001 to 0.002). With stainless steel ball bearings alone separating the building foundation from the superstructure, the ground could theoretically vibrate horizontally during an earthquake without introducing significant lateral force into the building.

Ball bearing clusters alone are obviously not a complete solution. The building must still be tied to its foundation in a manner that will not impart discomfort to occupants during a windstorm. Something must replace the rupture pin and its inherent dangers of both shock loading and a sudden loss of force that leaves the building without a strong horizontal tie to its foundation. The risk to life and property makes it imperative that relative movement between the foundation and the superstructure be controlled in a positive manner, having provision for fail-safe operation. In addition, the structure must not slip nor sway excessively in the strongest windstorm that could be expected to occur with a given degree of frequency.

These conditions require a form of control whereby the design professional can assign a reliable, bilinear force-deflection characteristic to the interface between the foundation and the superstructure. This bilinear characteristic can then serve to provide the shear transfer during a major earthquake by establishing a predetermined upper limit to the base shear that can be imparted to the superstructure by its foundation during such an earthquake.

To establish this degree of control, a relatively simple device has been developed to permit both an accurate and reliable control of the bilinear force-deflection characteristic. This predetermined lateral force -- at which the control devices cause the superstructure to lag behind the ground motions and introduce relative displacement between the two -- has been termed the causative force.

Since the control devices must be designed to experience relative displacements of up to a few inches, it is imperative that they be divorced from the structural members that support the gravity loads of the structure. It is for this reason that the control device are shown to be separated from the weight supporting members of the superstructure (i., e., the columns and walls). This bilinear force-deflection characteristic relieves the superstructure of any need to distort beyond the yield point of its beams and columns in order to dissipate energy.

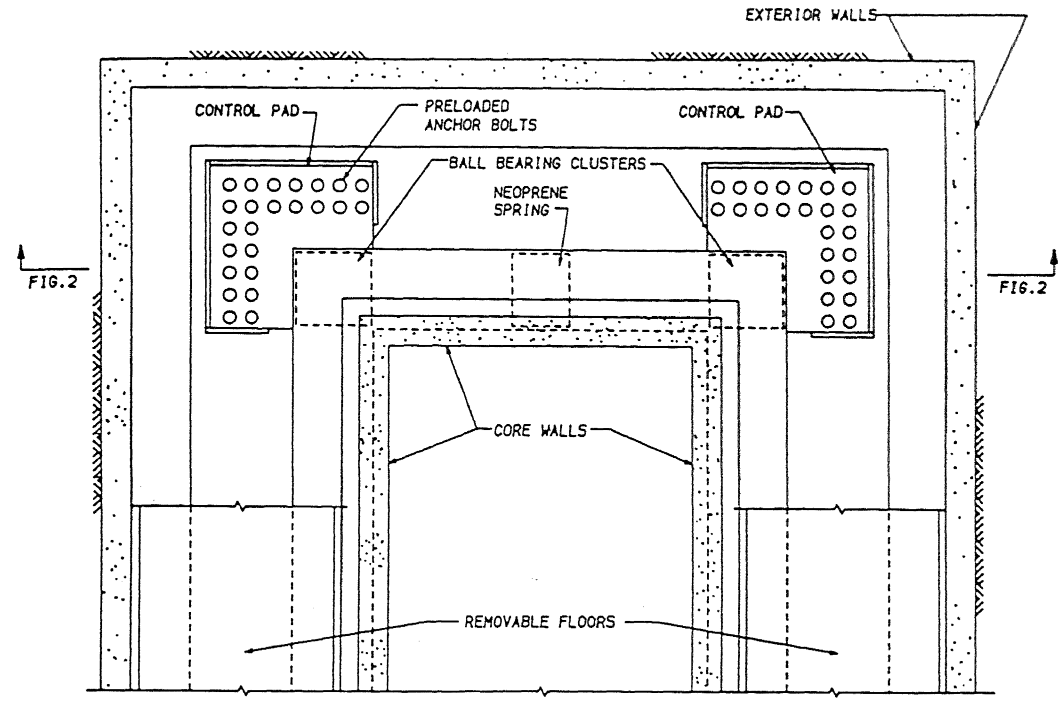

FIGURE 1 - SECTIONAL PLAN OF THE BASEMENT FLOOR LEVEL AT ONE END OF A CONCRETE CORE WALL STRUCTURE

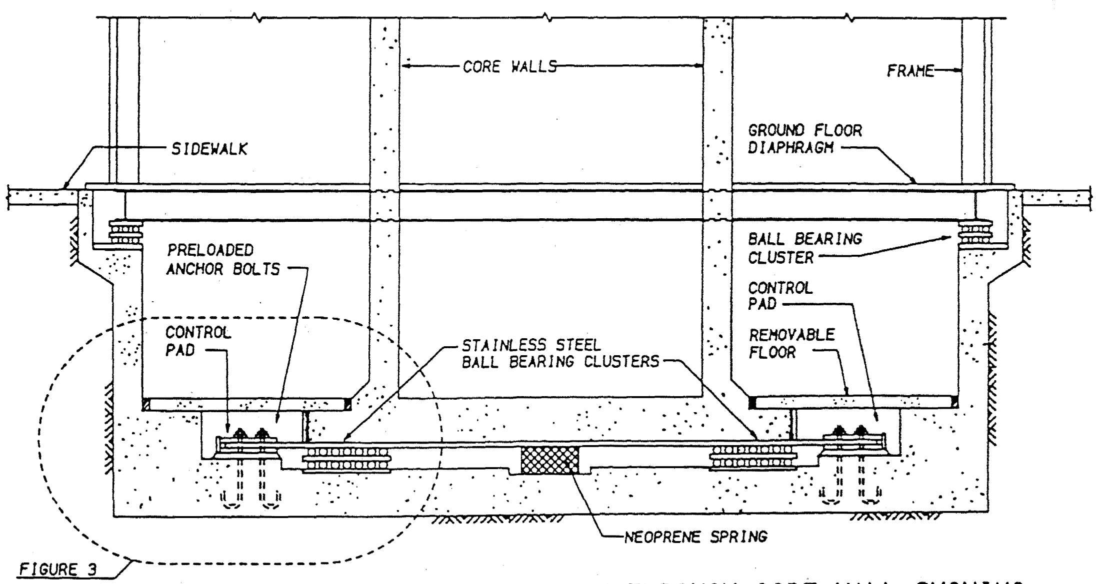

FIGURE 2 - SECTIONAL ELEVATION THROUGH CORE WALL SHOWING SHOWING CONTROL PADS AND BALL BEARING CLUSTERS

Control Pads

The control devices are shown on Figures 1, 2, and 3 in one of many possible configurations. First the lateral shear transfer capacity is reduced to a negligible value by the insertion of stainless steel ball bearings under all weight supporting members at the interface between the superstructure and the foundation. The lateral force resistance is then replaced by control pads that intertie the superstructure and the foundation in a controlled manner.

The control pads are used to permit the designer to accurately establish the causative force. This force must, of course, be related to the total base shear to be expected during an infrequently recurring windstorm. Recent work permits a reliable statistical evaluation of the frequency of recurrence of major windstorms throughout the world, accounting for the effects of surface friction, height, drag forces, and the spatial distribution of gusts.

It follows that the design of the isolation devices involves a statistical analysis of the wind forces acting and their recurrence interval, to establish a minimum value for the causative force. But this is not to imply that the minimum value will necessarily prove to be optimum in the dynamic analysis for earthquake motions, it may be more. It is just such a dynamic analysis that will be employed to establish both the optimum causative force and the minimum relative displacement to be experienced between the superstructure and its foundation.

Once the optimum value of the causative force has been established, the control pads can be sized. The desired bilinear force-deflection characteristic is achieved by employing the principle of sliding friction. The control pads provide a stiff intertie between the superstructure and the foundation until stressed to the sliding point (i.e., the causative force), thereafter permitting large relative displacements once sliding has begun.

To employ friction for this purpose requires a material that possesses a coefficient of friction which can be predicted with reliability, for predictability is far more important than the magnitude of the coefficient itself. The most attractive low friction material commercially available at this time is polyterafluoroethylene (TFE), commonly known as reinforced teflon. This material, having the lowest known coefficient of friction of any solid, exhibits the unique property of having a coefficient of friction under static conditions that is nearly equal to that under sliding conditions. This constant friction permits smooth motion, without the highly objectionable start and stop jolting that would occur with most other materials. Glass fiber reinforced TFE pads have a coefficient of friction of between 0.060 and 0.075 under well protected atmospheric conditions, when loaded to less than 2000 psi and having a relative velocity of less than 10 fpm. This coefficient can be expected to double if relative velocities reach 100 fpm.

TFE is easily bondable to steel and is highly resistant to decay, having negligible changes in characteristics with age. Note also that the 2000 psi allowable bearing stress is not defined by the failure level of the material, but rather is selected to prevent mechanical locking of the TFE pads because of indentation at the edges, a problem that can be eliminated entirely by rounding all of the contact edges between friction plates. This bearing value is fully compatible with the 1125 psi bearing stress permitted on a concrete support.

The preloading force required to develop horizontal slippage at a predetermined value of the causative force is readily calculated as the causative force divided by the coefficient of friction. This vertical force on the control bearings can be developed by post-tensioned rods that are anchored in the foundation (as shown on Figure 2). Post-tensioning provides far better control of the causative force than would reliance on the building weight, because building weight varies with usage.

The top and bottom plates (A and C) shown on Figure 3 are rigidly fastened to the foundation and would move with it at all times during an earthquake. The middle plate B is an integral part of the superstructure. It is caused to move with the top and bottom plates until the friction force on both surfaces is exceeded, at which point slippage occurs. All potential contact surfaces are faced with a bonded TFE layer and all contact edges are rounded. The middle plate B transmits lateral forces between the superstructure and the foundation and is extremely stiff and strong in the horizontal direction. This shear connection to the underside of the floating core wall foundation is shown to be continuous across the foundation for greater reliability and stiffness. Because torsional resistance is greatest at the extremities of the building, it is desirable to locate the control pads as far from the center of the building as possible, yet symmetrical about the axes. In this manner all of the control pads can be made to reach the point of incipient slippage simultaneously.

The sequence of constructing the control bearings (see Figure 3) is most important. The side plate G -- which should extend around all four sides of the assemblage -- should be shop welded to the bottom plate. Likewise all TFE surfaces should be positioned and bonded in the shop with a suitable adhesive. Field assembly then would consist of leveling and grouting the bottom plate A (after the building is complete and most settlement of the foundation has occurred), installing the top plate C, preloading anchor bolts F and then welding top plate C to side plates G after several days have passed. Under no circumstance should the top plate be welded to the side plates prior to tensioning the preloading anchor bolts F. This weld should be the final procedure, for it locks the top plate to the bottom plate, thereby preventing any tendency for it to move laterally with the central diaphragm.

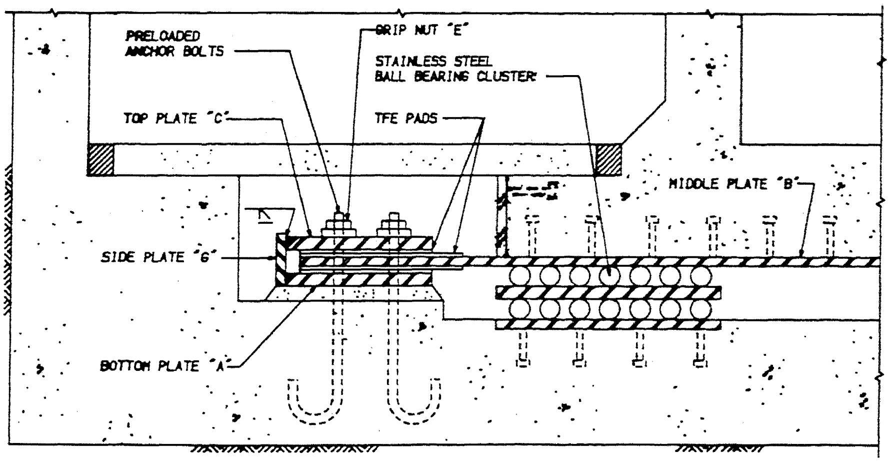

FIGURE 3 - DETAILED CROSS-SECTION OF CONTROL PAD AND BALL BEARING CLUSTER

Mode of Operation

An understanding of the mode of operation of the isolation concept requires a thorough visualization of the relationships between the time-dependent parameters shown typically on Figure 4 for the 1940 El Centro earthquake. The variation of accelerations, velocities, and displacements in an earthquake is not harmonic, hence the variation in amplitude of the acceleration curve is not symmetrical about the base axis of time. Instead, it can be thought of as being weighted towards one direction and then the other in a relatively longer period, small amplitude cycle that is comprised of a series of very short period, high amplitude cycles that are superimposed directly thereon (i.e., higher frequency modes of vibration). Since the velocity at any instant of time is the cumulative area under the acceleration curve, the maximum velocity occurs whenever the long period cycle of acceleration crosses the base axis and begins changing the ground velocity into the opposite direction. Isolated spikes of acceleration that are not representative of the direction of weighting (i.e., the direction of the longer period acceleration) do not necessarily cause a reveral in the direction of the ground velocity, even though they do cross the time axis. It is for this basic reason that the period of the velocity component is much longer than that of the individual acceleration spikes, as shown on Figure 4.

Similarly, the displacement is an accumulation of the area under the velocity curve and the same logic applies. The correct picture of the earthquake ground motion is therefore that of a short period (0.2 seconds) excitation or acceleration that causes long period (2 to 6 second) displacements. That is, the ground vibrates rapidly but it moves relatively slowly off in one direction and then back and into the other direction.

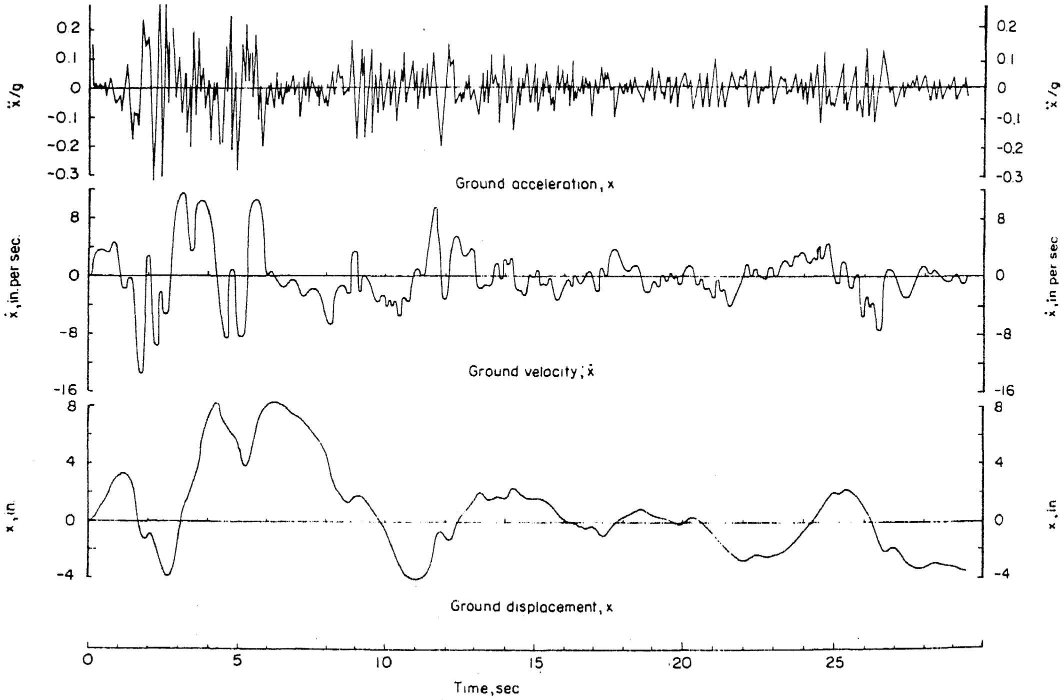

FIGURE 4 - RECORDED GROUND MOTIONS OF THE EL CENTRO EARTHQUAKE

Comprehension of this ground motion and its interaction with an isolated building is crucial to understanding the force balance that exists within the base isolation devices during an earthquake. Neoprene or rubber springs, used to store strain energy at the base of a structure, have an elastic stiffness that creates a resistance to relative displacement whose magnitude is directly proportional to that relative displacement at every instant of time. Hence, whenever the foundation moves off in one direction relative to the superstructure (i.e., after the causative force has been exceeded), the springs act as self-righting mechanisms that increase the force acting on the superstructure and cause it to accelerate in the direction of the relative ground displacement. Since the ground displacement has a much longer period than does the acceleration, these springs have an extended interval of time during which to force the superstructure back towards (but not necessarily to) its original position with respect to the foundation. This distance, $s=f\ (vt,\ at^2)$, would be traversed with a lesser acceleration of the superstructure than that experienced by the rapidly vibrating ground in displacing to this same point. This is because the distance traversed due to the spring induced force is a function of the time interval squared. Hence, even a soft spring can serve as an effective isolation device for limiting relative displacement between the ground and the building.

The control pads cause the superstructure to follow the ground displacement in a similar manner, except that the direction in which the continuously applied causative force acts upon the underside of the superstructure is dependent on the relative velocity, rather than the relative displacement, at every instant of time (i.e., the forcing function is velocity dependent). Since the velocity parameter is a shorter period phenomenon than is displacement (see Figure 4), more frequent reversal can be expected during the duration of the earthquake. The relatively constant magnitude of the causative force causes the superstructure to follow the ground motions at a relatively constant value of both building acceleration and base shear ($F = Ma$). As the velocity is still a longer period phenomenon than is the acceleration, this constant force acts on the base of the building's superstructure for an extended interval of time, to again take advantage of the time squared term in the expression $s=f\ (vt,\ at^2)$.

In essence, the spring control devices and the control pads act to complement one another in smoothing out the sharp vibratory accelerations of the ground. This results in a comparitively gentle motion for the superstructure. The motion is a function of both the causative force and the spring stiffness selected by the designer.

This explains the physical manner in which the isolation technique functions to form a vibration barrier. The isolation devices serve the dual function of controlling the magnitude of the horizontal inertial forces that are transmitted into the superstructure, while at the same time limiting the relative displacement imposed on the interface between the superstructure and its foundation as it rolls on the stainless steel ball bearing clusters. This simplified picture of the equilibrium of forces is only one aspect of the complex ground-structure interaction experienced by the superstructure. The magnitude of these horizontal forces will depend to a large extent on the response of the superstructure to the very long period of the velocity dependent earthquake excitation. The ability of the control pad isolation devices to absorb the total energy that is imparted to them as viscous dampers (i.e., friction dampers) permits the designer to reliably limit the stress levels in the superstructure to the elastic range, for any and all earthquakes.

These effects can best be accounted for in design by performing a dynamic analysis on a mathematical model of the isolated superstructure. Such a general model has been developed, and the test results have proven most gratifying. All indications are that it is possible to maintain a superstructure that has been designed for wind resistance (in accordance with the local building code) within the elastic range throughout the entire duration of a major California earthquake. Only in this manner is it possible to prevent damage to buildings and to enhance the safety of both building occupants and pedestrians.

Conclusion

This paper is intended to demonstrate the logic of the isolation technique so that competent design professionals can assimilate, evaluate, and improve on the design procedure. Ingenuity and revision are required to optimize the solution of every building in accordance with site conditions and usage.

Several design considerations must be resolved before permitting relative motion between the superstructure and the foundation during an earthquake. Suitable details have already been developed to prevent damage to elevators, stairwells, piping, and vent ducts by these motions. Provision for the insertion of hydraulic jacks is necessary if it is desired to return the superstructure to its original position with respect to the foundation, should a residual relative displacement exist following a major earthquake. Fire protective coatings and details for the insertion of hydraulic jacks adjacent to the control pads have been omitted from the illustrations for clarity.

The isolated superstructure can be expected to survive a major earthquake with little or no structural or nonstructural damage. In contrast, the most modern techniques for the design of conventional earthquake resistant structures prevent collapse during a major earthquake by intentionally permitting the structural beams and columns to distort inelastically. The owner of a conventional structure should anticipate extensive non-structural damage together with some serious structural damage because of the large inelast rotational strains that are intended to occur within the superstructure. This enormous financial liability that is borne by owners of multi-story buildings is compounded by the cost of repair or replacement as well as both an extensive loss of revenue during the repair period and any liability to occupants and pedestrians for personal injury.

Application of base isolation techniques to both design and construction will serve to greatly increase the safety of a multistory building during an earthquake. Furthermore, studies show that isolated buildings can be constructed at a lesser initial cost than is now possible with conventional earthquake resistant construction. The lesser initial cost of an isolated structure stems directly from the design procedure. Conventional earthquake resistant superstructures must have an increased level of strength and ductility as defined in local building codes. When these factors are combined, they can add substantially to the cost of such buildings. As it is expected that strengthening of the superstructure for earthquake resistance will not be required for isolated structures, this expenditure need not be made. Isolated buildings should cost no more in California than conventional buildings in New York or Chicago because height limitations will be removed on building materials such as concrete and masonry. The added cost for installing the base isolation devices will not be excessive because these devices involve no new technology and require no unusual skills on the part of the contractors or fabricators.