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Seismic response of a friction-base-isolated house in Montreal

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ABSTRACT

A two storey residential house, incorporating friction-base isolators, has been built in Montreal. Three-dimensional nonlinear time-history dynamic analysis was chosen to determine the seismic response of the structure. Compared to conventional construction, the stresses and accelerations in a friction-base isolated building are dramatically reduced, thereby, the damage to the building and its contents is minimized. The friction-base isolators are simple in construction and need no maintenance, repair or replacement over the life of building. The low cost of friction-base isolators suggests wide application in low-rise construction including residential houses.

INTRODUCTION

During a major earthquake, a large amount of energy is released in rapid ground motion. The amount of energy fed into the structure depends on the relationship between the frequency content of the ground motion and the natural frequency of the building. When the two frequencies are in close proximity, the building resonates and shakes violently. Unfortunately , this is the case in most low-rise to medium height buildings. The amplified accelerations can cause severe damage to the contents of the building even when the structure itself does not suffer any damage. All building codes, including National Building Code of Canada, recognize that it is economically not feasible to reconcile the seismic energy within the elastic capacity of structure. The code philosophy is to design structures to resist moderate earthquakes without significant damage and to resist major earthquakes without structural collapse. In general, reliance for survival is placed on the ductility of the structure to dissipate energy while undergoing inelastic deformations. This assumes permanent damage, after repair costs of which could be economically as significant as the collapse of the structure.

The problems created by the dependence on ductility of the structure can be reduced if the amount of seismic energy getting into the structure can be controlled and a major portion of the energy can be dissipated independently from the primary structure. In low-rise buildings, where overturning moments are not significant, the superstructure is decoupled from the forcing ground motion by providing base isolators. The introduction of supplemental damping in framed buildings is more convenient and economical. With the emergence of new techniques like base-isolation and friction-damping devices, it has become economically feasible to design damage free structures. In September 1985, the State of California passed an Assembly Resolution 'ACR 55 - Seismic Safety' that all publicly owned buildings must incorporate new seismic technology

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like a ficticious truss element, having an elasto-plastic behaviour. Hysteretic behaviour of the friction base-isolator is shown in Fig. 4. The dynamic coefficent of friction of the isolator is 0.2. The effect of 20% accidental eccentricity of mass on the overall seismic response of the building was also studied.

In order to compare the seismic response of the friction-base isolation, analysis were also carried out for this house with a fixed base.

Results of Analysis

1. At earthquake intensity of 0.10g, there is no slippage in the isolator. The friction-base isolated house behaves like a fixed base house.
2. At earthquake intensity of 0.18g, the maximum slippage in the isolator is 3 mm. The accelerations at top of friction-base isolated house and fixed base house are 0.17g and 0.29g respectively - a reduction of 42%. After the earthquake, the permanent offset is 1.5 mm (Fig. 6).
3. At earthquake intensity of 0.33g, the maximum slippage in the isolator is 11mm. The accelerations at top of the friction-base isolated house and fixed base house are 0.21g and 0.55g respectively - a reduction of 62%. After the earthquake, the permanent offset is 4 mm.
4. At earthquake intensity of 0.50g, the maximum slippage in the isolator is 18mm. The accelerations at top of the friction-base isolated house and fixed base house are 0.25g and 0.86g respectively - a reduction of 70% (Fig. 7). After the earthquake, the permanent offset is 7 mm.
5. The effectiveness of friction-base isolation increases with the severity of earthquake (Fig. 6).
6. The friction-base isolated building is not very sensitive to accidental eccentricity.
7. Although there is significant reduction in stresses when compared to fixed base house, it was not possible to save in material cost as standard size materials available in the market are used. However, in larger buildings of 3 storey height or more, the additional cost of isolators will be more than offset by the savings in material cost.

Friction-damped Buildings

Base isolation is not the only technique for protection against earthquakes. Passive energy dissipators provide protection by absorbing earthquake energy while the structure is deforming. Several types of inexpensive friction-damping devices suitable for different construction techniques have been developed by Pall (1980,81,82,84,86,89). These devices are for: large panel precast concrete construction; cast-in-place concrete shearwalls; braced frames; and for connecting precast cladding to frames. Cyclic dynamic laboratory tests have been conducted on specimen devices (Pall 80, Filiatrault 1986). The performance is reliable, repeatable and possesses large rectangular hysteresis loops with negligible fade over several cycles of reversals that can be encountered in successive earthquakes. Much greater quantity of energy can be disposed of in friction than any other method involving the damaging process of yielding of steel. Unlike visco-elastic materials, their performance is not affected by temperature, velocity and stiffness degradation due to aging. Furthermore, these friction-damping devices need no maintenance or replacement over the life of building and are always ready to do their job regardless of how many times they have performed. (Aiken 1988, Baktash 1986, Filiatrault 1986,1988). Shake table studies at the University of British Columbia in Vancouver, the University of California at Berkeley and Imperial College in London have successfully demonstrated the superior seismic performance of friction-damped frames. Friction-damping devices are now finding practical application in new construction as well as retrofitting of existing buildings (Pall 87,91). Their use has resulted in significant savings in the initial cost of construction while the earthquake resistance of the building has increased considerably.

and existing buildings be retrofitted to increase their earthquake resistance. This resolution is based on the consideration that while the past building code philosophy was only concerned with the avoidance of collapse of structure, the modern buildings have expensive finishes and contain extremely sensitive and costly equipment which must be protected. The National Building Code of Canada 1990, Clause 83 of Commentary-J of the Supplement, allows the use of new technology.

In 1988, a residential house incorporating friction-base isolators was built in Montreal. This paper discusses the results of the analytical studies and describes the construction details of its practical application.

STATE-OF-THE-ART

The concept of base isolation is not new. Mechanical engineers have used this concept for centuries to isolate the transmission of vibration of machinery to the foundation or vice-versa. In recent years, the use of base isolation system as a mean of aseismic design of structures has attracted considerable attention. The reviews on its historical and recent developments have been extensively provided by Kelly 1986, Tarics 1987 and Buckle 1990. Now, the concept of base isolation has matured into a practical reality and is taking its place as a viable alternative to conventional fixed base seismic resistant construction. In the past decade about 40 base isolated buildings have been built or retrofitted in the U.S and Japan. The most commonly used isolators are of laminated rubber bearings with or without lead core. Friction type base isolators have been used by Electricite de France in nuclear power plants (Vaidya, Plichon 1986). All base isolators have certain features in common. These are: horizontal flexibility, energy dissipation capacity. The purpose of the horizontal flexibility is to shift the natural frequency of the structure to a lower value and away from the energy containing frequencies of the earthquake. However, low flexibility could result in excessive displacements relative to ground. Energy absorbing capacity reduces both base displacement and the transmission of the seismic energy to the building. The isolators should also have some rigidity against wind and low earthquakes.

Friction-Base Isolators

In low-rise structures, where overturning moments are not significant, the friction-base isolators are located horizontally between the foundation and the superstructure to partly isolate it from the forcing ground motion (Pall 1981 ii, 1986). Ideally, frictionless joints will allow the foundation to move without exerting any force on the building, but the displacements of the building relative to ground will be very large. A friction force is therefore required, sufficient to react to wind and small earthquakes. During a severe earthquake, the magnitude of lateral force that the building can experience is limited to the slip load. The slip load or the coefficient of friction is so selected that the stresses in the materials do not exceed the permissible stresses of the materials and that the relative displacements are limited to an acceptable value of say 25 mm. In friction-base isolated buildings, the displacement at the end of an earthquake is a permanent offset as there is no restoring force. In order to provide restraint on the total movement during catastrophic conditions, increasing resistance to sliding is provided by the ramp shape in steel plates or by providing an elastic pad at the end of travel (Fig. 3). The slippage of device acts like a safety valve to limit the forces exerted and as a damper to limit the amplitude of vibration. Another interesting feature of the friction-base isolated building is that the natural period of the structure varies with the amplitude of vibration i.e. the severity of earthquake. Hence the phenomenon of resonance is difficult to establish. Some of the many technical and economic advantages of friction-base isolators are:

1. Friction-base isolators provide high damping by dissipating energy in friction during slippage.

2. The relative displacement of rubber pad base isolators is in the order of 150-180 mm. This involves expensive detailing of service connections. In friction-base isolators, the maximum displacements are less than 25 mm.
3. Rubber pad base isolators have a natural period of about 2 seconds. Hence, these are suitable for regions with high frequency ground motions. In case of earthquakes similar to 1985 Mexico earthquake (0.5 Hz.), the buildings with rubber pad base isolators would have resonated and damaged. Friction-base isolators are suitable for any type of future earthquake.
4. The cost of rubber pad base isolators is high and thus has so far found application only in government buildings of national or historic importance. The low cost of friction-base isolators is very appealing and it is therefore possible to extend the benefits of this concept to all low-rise construction including residential houses.

Description of the Friction-Base Isolated House in Montreal

The residential house is located in the Dollard-des-Ormeaux, a suburb of Montreal. The house has two storeys above grade and one basement below grade. It is about 20 m x 15 m in plan and has a total living area of about 700 m^2 including the basement. The basement walls are of reinforced concrete upto the ground floor. The superstructure is of typical Canadian construction of wood stud wall framing with brick veneer. The front view of the house is shown in Fig. 1. The superstructure is actually floating over the foundation/basement wall. A continuous white line, just below the brick masonry, is a strip of flashing on the outside of the isolation joint to protect against rain or moisture penetrating the jont.

A total of 15 friction-base isolators are provided all along the outer basement wall. The location of the isolators is shown in plan in Fig. 2. The cross-section of the wall shows the location of friction-base isolators. The reinforced concrete wall above the isolators is a continuous tie-beam. The floor acts as a rigid diaphragm and is bolted to the tie-beam. The interior columns have pinned connection at the top and bottom and can rotate to accomodate a displacement of 25 mm. During construction, to avoid blowing of the tie beam and light weight wooden shell structure in wind storms, 6 low yielding anchor bars of 10 mm diameter were provided at the corners. These anchor bars are redundant after the outside masonry veneer is constructed. These bars will yield during a major earthquake and allow the base isolators to slide.

The cost of 15 friction-base isolators was only \$8000. Patented (Pall 1980) friction-base isolators were designed and supplied by Pall Dynamics Limited.

Nonlinear Time-History Dynamic Analysis

Three-dimensional nonlinear time-history dynamic analysis was carried out by using the computer program DRAIN-TABS, developed at the University of California, Berkeley. This program consists of series of subroutines that carry out a step by step integration of the dynamic equilibrium equations using a constant acceleration within any time step. As future earthquakes may be erratic in nature, an artificial earthquake record generated to match the design spectrum of Newmark-Blume-Kapur, which is an average of many earthquake records, has been used (Fig.5). This earthquake record forms the basis of the NBC response spectrum. For Montreal, the ground accelerations of this earthquake record were scaled to 0.18g. Analysis were also carried out for intensities of 0.10g, 0.33g and 0.5g accelerations. The integration time step was 0.005 second. Analysis were done for the earthquake acting in directions x, y and 45 degrees axis.

The superstructure is assumed to be rigid elastic. Nonlinearity is assumed in the friction-base isolator only. Viscous damping of 3% of critical was assumed in the initial elastic stage to account for presence of non-structural elements. Hysteretic damping due to slipping of friction base-isolator is automatically taken into account by the program. Friction-base isolator is modelled

CONCLUSIONS

The use of friction-base isolators have shown to provide a practical, economic and effective new approach to design low-rise buildings to resist future earthquakes. Whereas the use of base isolation has so far been limited to only government buildings of national or historic importance, the low cost of friction-base isolators suggest their wide application for all low-rise buildings including residential houses.

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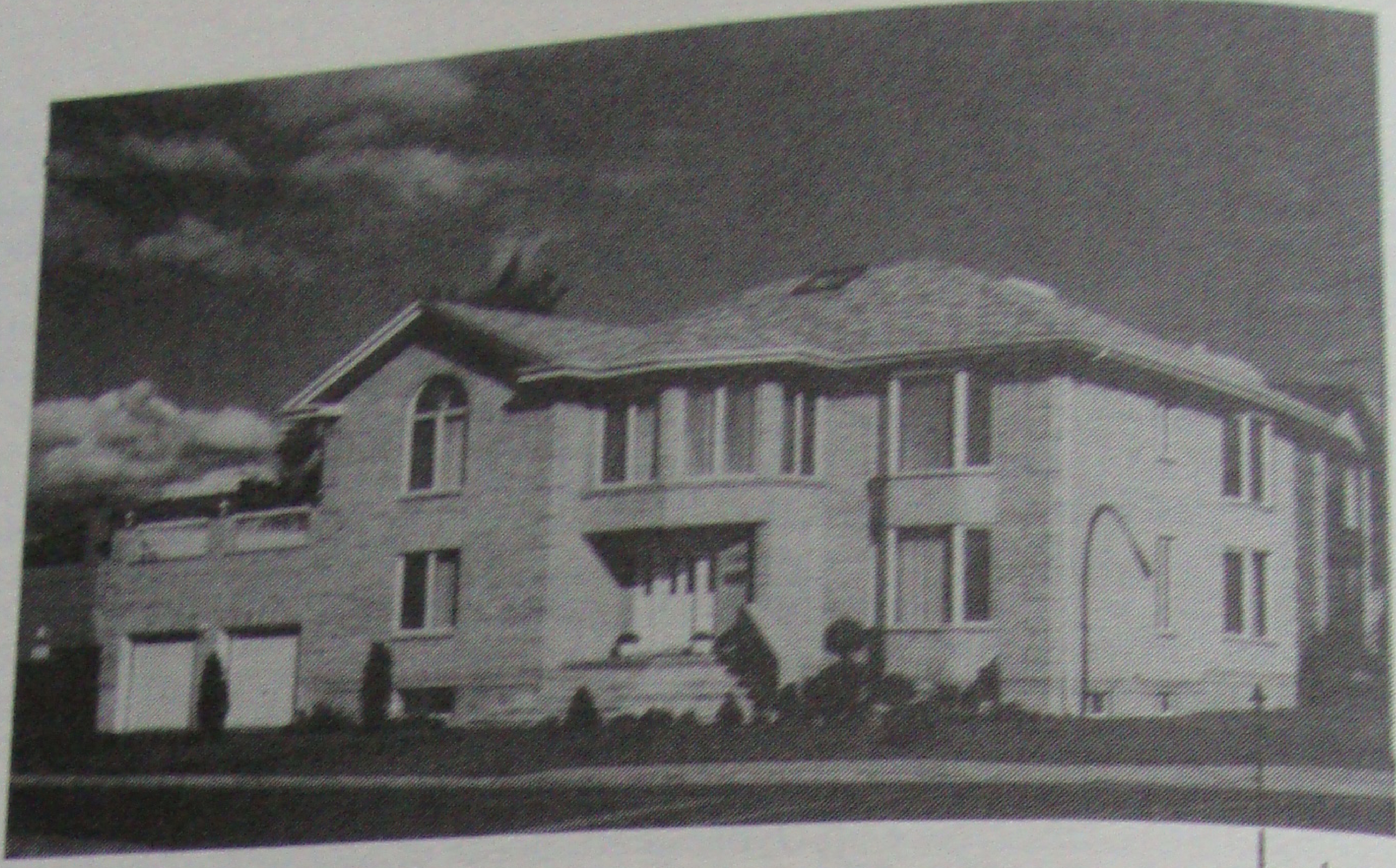


Figure 1. Front View of House

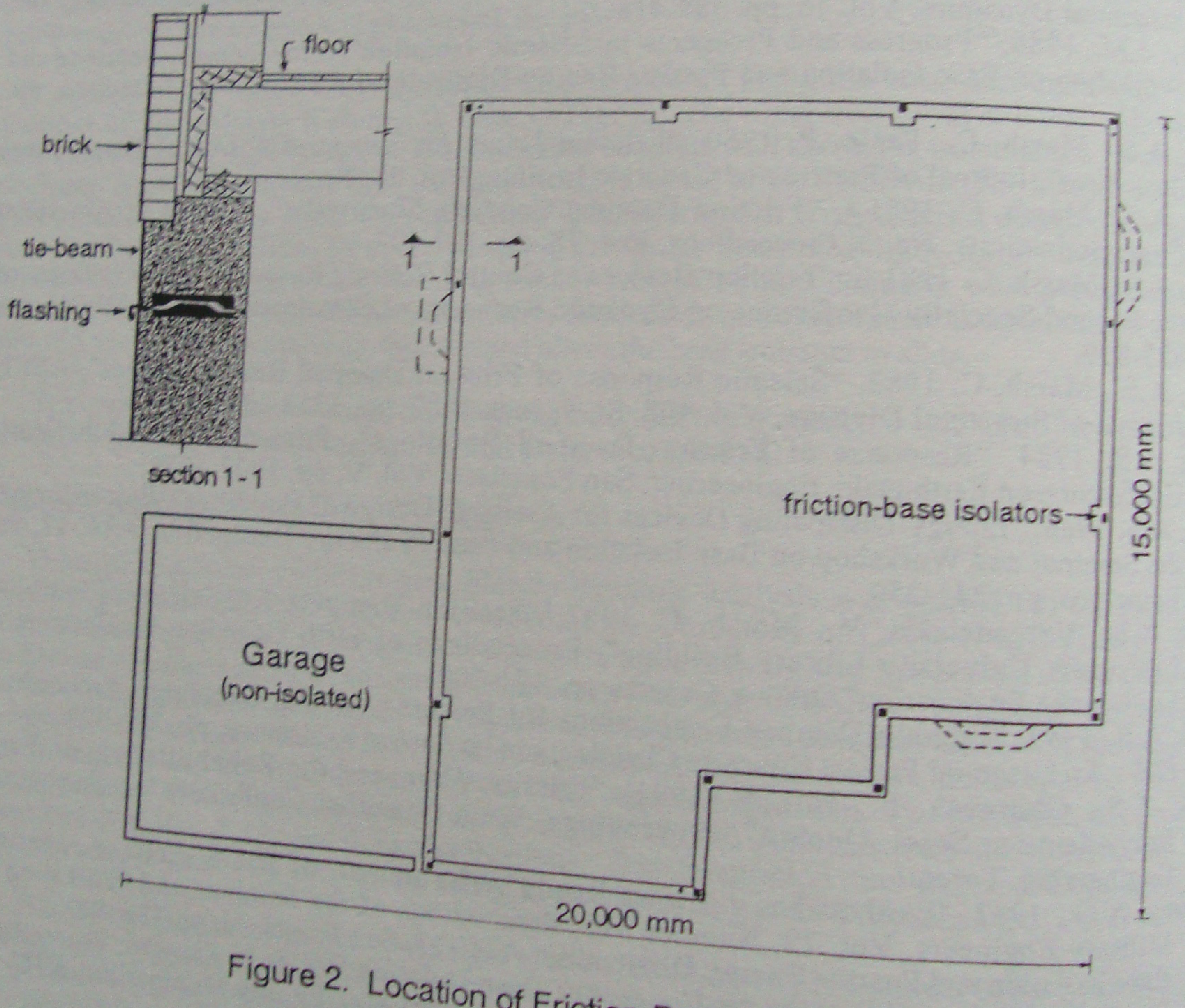
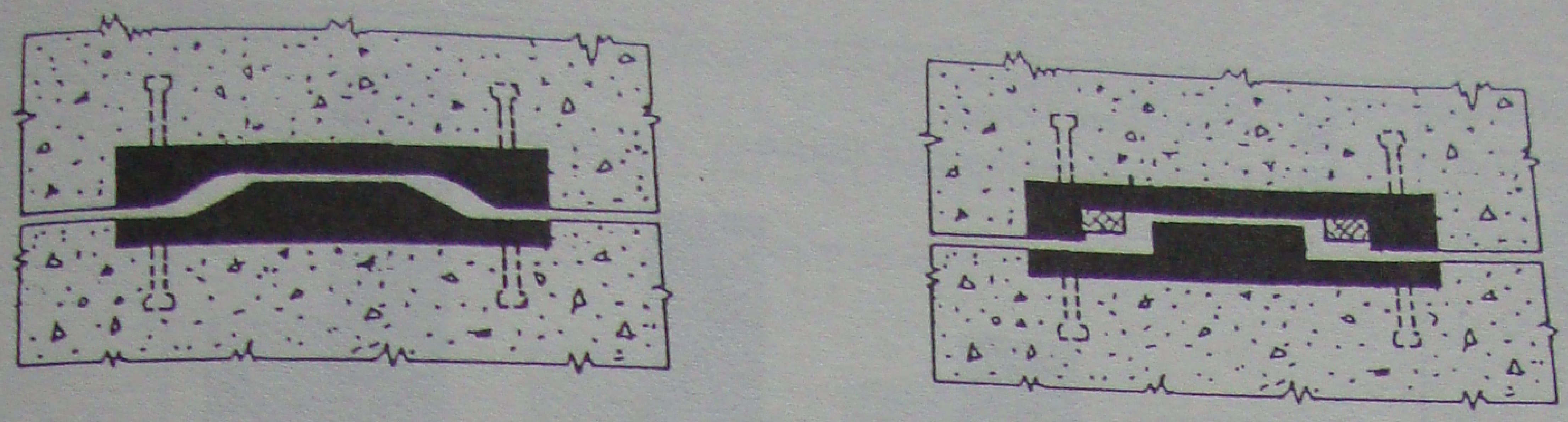


Figure 2. Location of Friction-Base Isolators - Plan



a) with ramped surface

b) with rubber cushion

Figure 3. Detail of Friction-Base Isolator

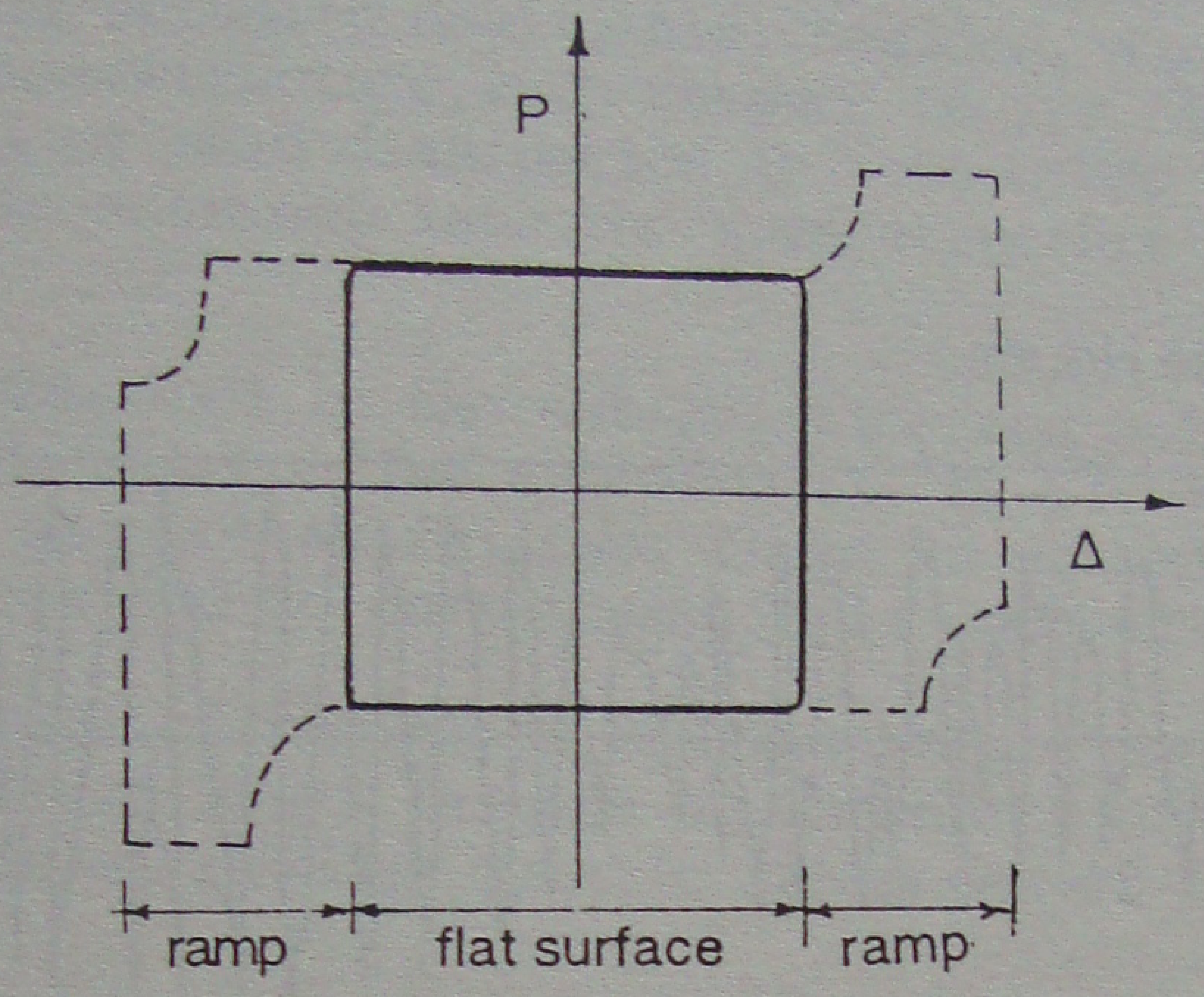


Figure 4. Hysteresis Loop of Friction-Base Isolator (with ramped surface)

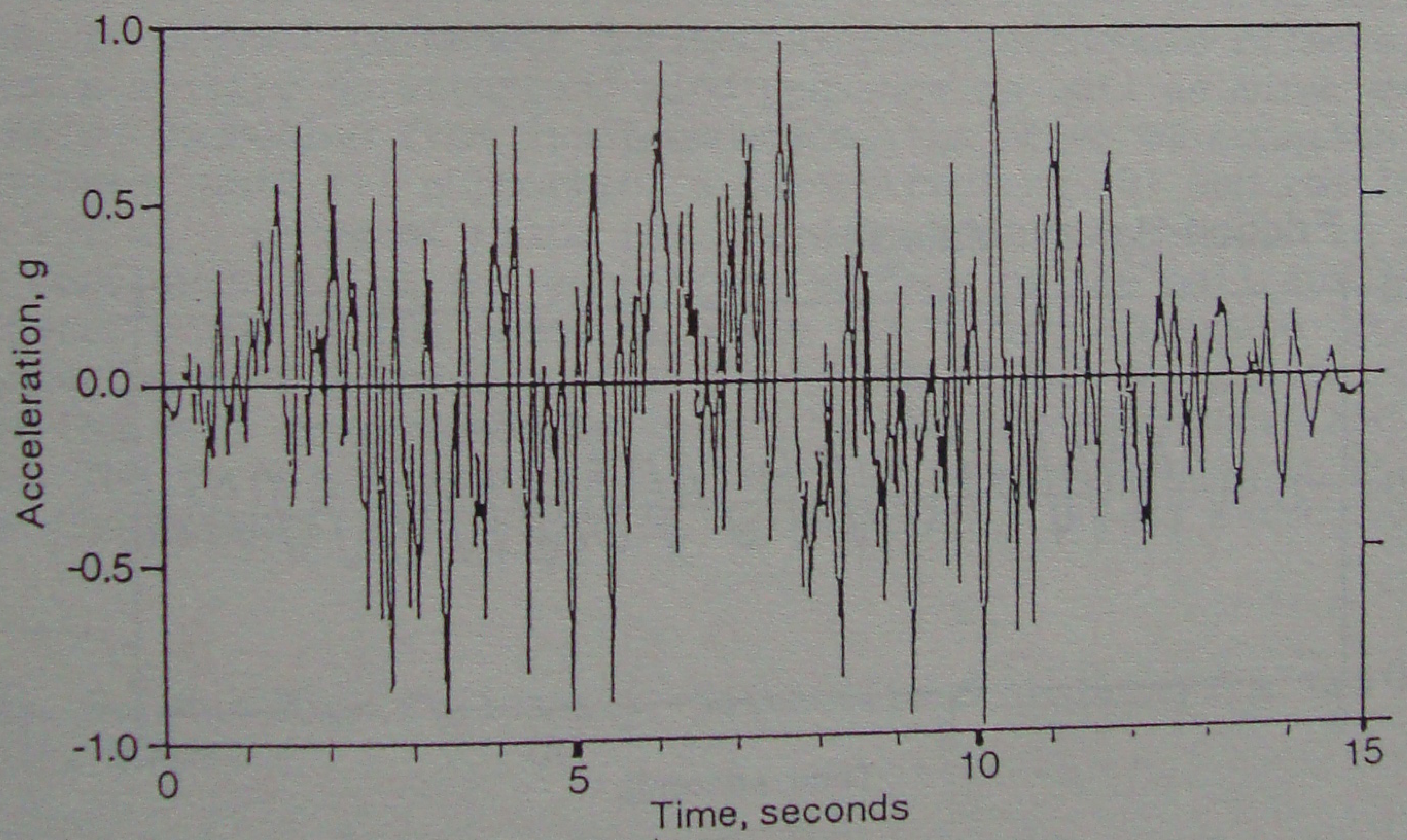


Figure 5. Time-Histories of Artifical Earthquake (Newmark, Blume & Kapur)

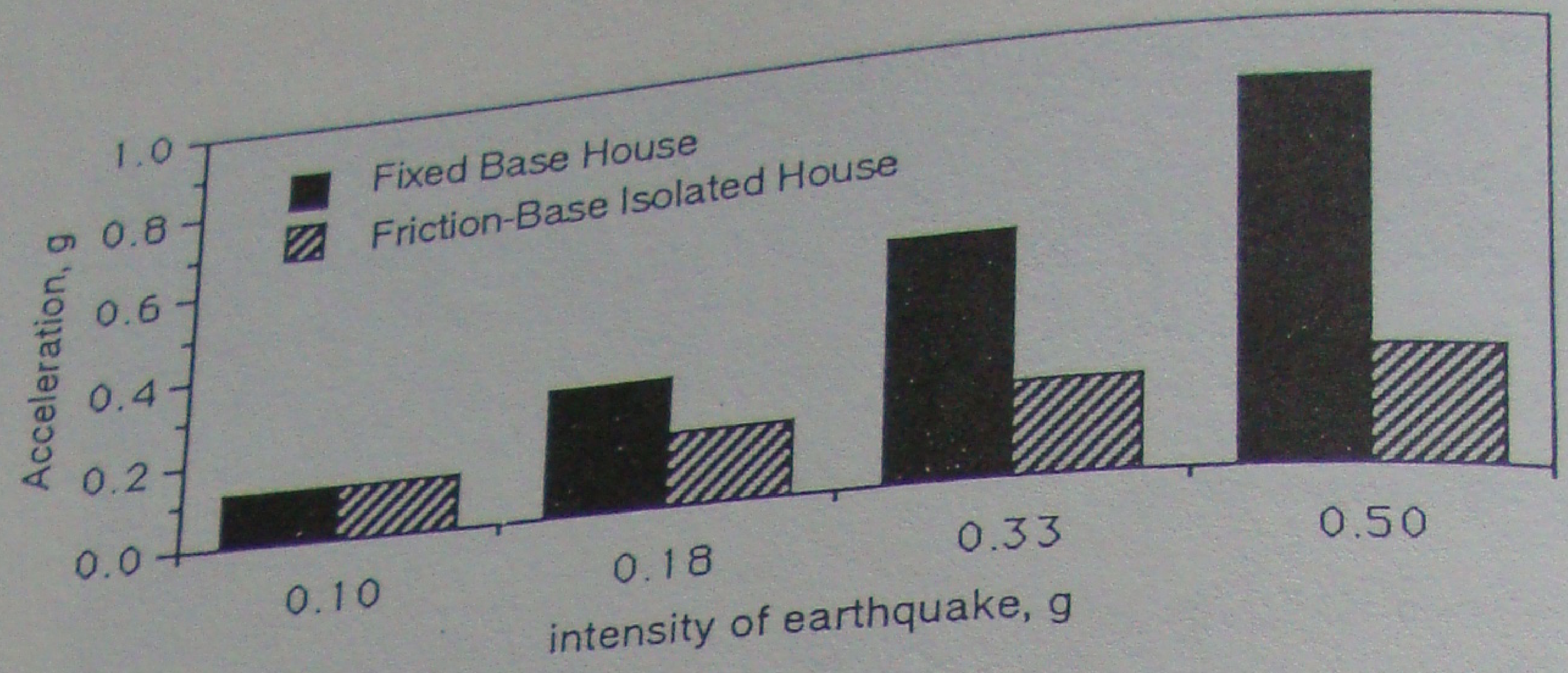


Figure 6. Comparative Seismic Performance

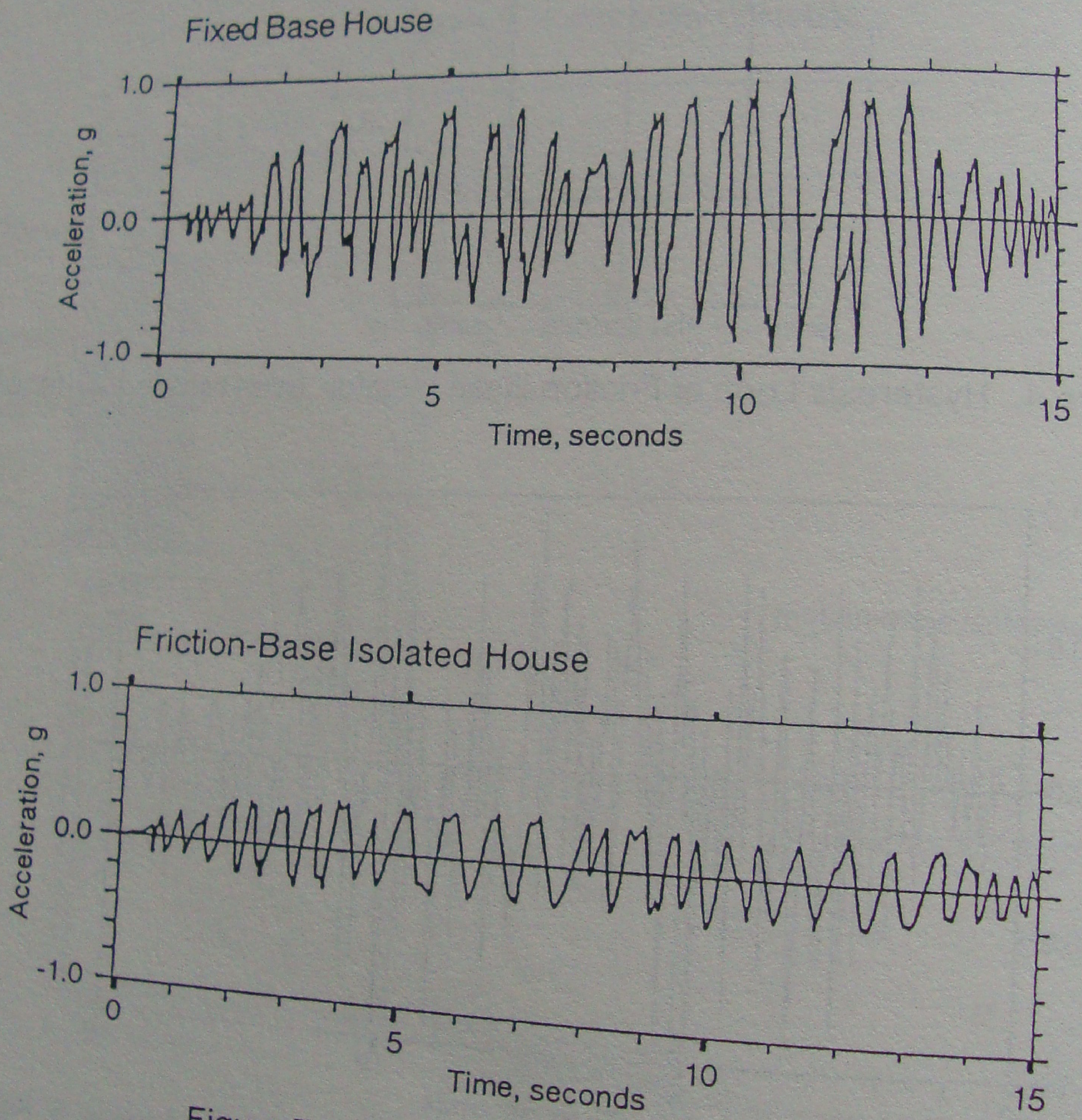


Figure 7. Time-Histories of Accelerations at Top