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Friction-dampers for rehabilitation of Ecole Polyvalente at Sorel, Quebec

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ABSTRACT

An innovative structural system, which combines the strength and stiffness of a braced frame and high energy dissipation capacity of the friction-dampers, has been adopted to rehabilitate the school buildings damaged during the 1988 Saguenay earthquake. The existing structure, built in 1967, lacked in lateral resistance and ductility requirements of the new building code. The introduction of supplemental damping provided by the friction-dampers reduced the force level and eliminated the necessity of dependence on the ductility of structure. Nonlinear time-history dynamic analysis was chosen to determine the seismic response of the structure. The conventional method of retrofitting with concrete shearwalls involved extensive foundation work which was very expensive and time consuming. The new method of retrofitting, while significantly lower in initial cost of construction, offers greater savings in the life cycle cost as damage to the building and its contents is minimized. The retrofitting work was completed in a record time during the summer vacation of 1990.

INTRODUCTION

On November 25, 1988 an earthquake of magnitude 6.2 on the Richter scale occured in the Saguenay region approximately 36 km south of Chicoutimi, close to the northern boundary of Parc Laurentides in the province of Quebec (Mitchell et al. 1989). The focal depth was 28 km. The peak horizontal and vertical accelerations at the Chicoutimi station were 13.1% and 10.2% of gravity with a frequency content of 13.3 Hz and 18.2 Hz respectively. The earthquake was felt over an extremely large area, as far south as New York and as far west as Toronto. The seismologists of the Geological Survey of Canada have warned that an earthquake worse than the above could well occur in the St. Lawerence valley before the end of the century.

After the earthquake, some minor structural and non-structural damage was noticed in the school buildings. The school authorities, La Commission Scolaire de Sorel, retained the services of Les Consultants Dessau Inc. to investigate the extent of damage and to suggest strengthening measures to rehabilitate the buildings. The existing three building complexes are of precast concrete construction and were built in 1967. Based on the detailed site inspection and analytical studies, the structural engineers concluded that:

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1. The lateral earthquake resistance of the structures is not adequate and that it is only relying on the resistance of unreinforced masonry infilling which is highly vulnerable to damage.
2. The precast concrete frame structure lacks ductility - an essential prerequisite for the survival of structures during a major earthquake.
3. The roof elements are not properly tied to offer adequate diaphragm action for the transfer of lateral inertial forces to the shear resisting arrangement.
4. The damages are repairable but the structure must be strengthened to meet the requirements of the latest National Building Code of Canada.

The structural engineers studied two alternative schemes to rehabilitate the structures. These were: a) a conventional method of strengthening with cast-in-place concrete shearwalls, and b) an innovative technique of introducing supplemental damping by installing friction-dampers.

The conventional method of introducing concrete shearwalls involved extensive new foundation work. This was very expensive and time consuming. The school authorities could not afford to close the school for a long duration. Also, it was felt that any benefits gained from the stiffening with shearwalls could be negated by the shift of the natural frequency of the structure closer to the resonant frequency content of the ground motion, typically experienced during the Saguenay earthquake.

The innovative technique of introducing supplemental damping in conjunction with appropriate stiffness was considered to be the most effective, practical and a smart hi-tech solution for the seismic upgrading of these buildings. This could be conveniently implemented by incorporating friction-dampers in steel cross-bracings in precast concrete frames and connectors on the vertical joints in precast wall panels. It was possible to stagger the bracings at different storeys to avoid interference with the services and avoid overloading of columns/foundations. Flexibility in the location of braces resulted in better space planning. This was not possible with the use of shearwalls. Finally, the client's criteria of shorter construction time and lower initial construction cost, overwhelmingly decided in the favour of this technique. The use of new technology resulted in a saving of 40% in construction cost and 60% in construction time. The roof diaphragm was strengthened with conventional steel plate bracing under the roof insulation.

This paper will discuss the analysis, design and construction details of the chosen system.

STATE-OF-THE-ART

Based on economic considerations, the building 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 a major portion of the seismic energy is dissipated independently from the primary structure. With the emergence of new techniques like friction-dampers and base-isolation, it has become economically possible to design damage free structures. In September 1985, the State of California has passed an Assembly Resolution 'ACR 55 - Seismic Safety' that all publicly owned buildings must incorporate new seismic technology and existing buildings be retrofitted to increase their earthquake resistance. This resolution is based on the consideration that while the past code philosophy was concerned with the avoidance of collapse of the 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.

Friction-Damped Buildings

Of all the methods available to extract kinetic energy from a moving body, the most widely adopted is undoubtedly the friction brake. It is the most effective, reliable and economical mean to dissipate energy. For centuries, mechanical engineers have successfully used this concept. This concept has been extended to building construction to control their vibratory motion caused by the lateral inertial forces of an earthquake.

Several types of inexpensive friction-damping devices suitable for different construction techniques have been developed by Pall (1980,81,82,84,89,91). The devices are for: large panel precast concrete construction; cast-in-place concrete shearwalls; braced frames, friction base-isolators for low-rise buildings; and for connecting precast cladding to frames. Cyclic dynamic laboratory tests have been conducted on specimen devices (Pall 80, Filiatrault 86). 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 or cracking of concrete. 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.

Friction-dampers are designed not to slip under normal service loads, wind storms or moderate earthquakes. During a major earthquake, the dampers slip at a predetermined load, before yielding occurs in the other structural elements. This allows the building to remain elastic or at least the yielding is delayed to be available during catastophic conditions. Another interesting feature of friction-damped buildings is that their natural period varies with the amplitude of vibration, i.e. the severity of earthquake. Hence the phenomenon of resonance or quasi-resonance is avoided. Parametric studies have shown that optimum slip load of the structure is independent of the character of future earthquakes and is rather a structural property. Also, within a variation of ±20% of the optimum slip load, the response is not significantly affected.

In 1985, a large scale 3-storey friction-damped braced frame was tested on a shake table at the University of British columbia, Vancouver (Filiatrault 1986). The response of the friction damped braced frame was much superior to that of moment-resisting frame and braced frame. Even an earthquake record with a peak acceleration of 0.9g did not cause any damage to friction-damped braced frame, while the other two frames suffered large permanent deformations. In 1987, a 9-storey three bay frame, equipped with friction-dampers, was tested on a shake table at the Earthquake Engineering Research Center of the University of California at Berkeley (Aiken 1988). All members of friction-damped frame remained elastic for 0.84g acceleration - maximum capacity of the shake table, while the moment-resisting frame would have yielded at about 0.3g acceleration. In 1988, a single storey friction-damped frame was tested on a shake table at the Imperial college in London. Here again, the performance of the friction-damped braced frame was superior to the conventional moment-resisting frame.

Other researchers have investigated the seismic response of friction damped frames and reported on the superior performance of friction-damped frames (Austin 1985, Baktash 1986, Filiatrault 1986, 1988, Aiken 1988). In Montreal, a 10-storey Concordia University library building has been recently completed (Pall 1987). Use of steel bracing in concrete frames has eliminated the need for expensive shearwalls and the use of friction-dampers has eliminated the need of dependence on the ductility of structural components. Use of this system has resulted in a net saving of 1.5% of the total building cost while its earthquake resistance and damage control potential has significantly increased.

Description of the Structure

The school complex consists of three blocks of buildings interconnected to each other. A typical plan view of the buildings at the first floor is shown in Fig. 1. Block-A is of two storey height and Blocks-B & C are of three storey height above the basement. Front view of the Block-A is shown in Fig. 2. Total covered area of the three buildings is approximately 40,000 m. sq. The structural frames are made up of precast concrete columns or wall panel units and beams tied together with welded connections. The columns or wall panel units are of full height of the building. The floor over the basement is of cast-in-place concrete. The upper floor and roof units are of prestressed precast concrete single or multiple T units. Floor units have a concrete overlay of 75mm thickness. Roofing units have standard insulation with tar and gravel finish. Floor and roofing units are placed on the concrete beams and tied with welded connections. These units are also tied to each other with welded connections at 3-4 m spacing. However, site inspections revealed that the connections at the roof are inadequate to offer diaphragm action. All partition walls in corridors, class rooms and around staircases are of unreinforced hollow concrete or terracotta masonry "stack-block" construction.

The location of friction-dampers at the first floor are shown in Fig. 1. The typical details of friction-damper for steel cross-bracing are shown in Fig. 3. Epoxy grouted anchor bolts were used to connect the steel bracings and wall connectors to the precast concrete units.

Nonlinear Time-History Dynamic Analysis

Non-linear time-history dynamic analysis was carried out by using the computer program DRAIN-2D, 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. 4). This earthquake record forms the basis of the NBC response spectrum. For Sorel, the peak ground accelerations of this earthquake record were scaled to 0.18g. The integration time step was 0.002 second.

Viscous damping of 5% of critical was assumed in the initial elastic stage to account for the presence of non-structural elements. Hysteretic damping due to inelastic action of structural elements and slipping of friction-damped connections is automatically taken into account by the program. Interaction between axial forces and moments for columns and P-Δ effect were taken into account by including geometric stiffness based on axial force under static loads.

Actual capacities of the precast concrete beam/column or panel connections and masonry infill panels were included in the analysis. The infill panels are assumed to have shear stiffness only. Cracking of masonry within repairable limits was considered acceptable. The ratio of strain at complete failure to strain at yield was taken to be 5. On the failure of the infill, the forces being resisted by the element immediately prior to failure are transfered to the structure as a shock loading. Strength and stiffness are reduced to zero after the failure.

Results of Analysis

1. The existing structure could not withstand peak ground accelerations of 5% of gravity.
2. The slip load of the dampers was governed by the safe load carrying capacity of the precast units, connections and foundations. The slip load for dampers in cross-bracings and panel connectors varried between 225-355 kN and 30-55kN respectively depending on the location.

3. A total of 64 dampers in cross-bracings and 388 panel connectors were required in all the three buildings to provide the desired energy dissipation.
4. The time-histories of deflection at the roof of a three-storey building are shown in Fig. 5. Maximum deflection was 15mm. The storey drift did not exceed 6mm in any building.
5. Typical time-histories of dampers at the first storey are shown in Fig. 6.
6. The introduction of supplemental damping by the friction-dampers reduced the forces in the structure. Strengthening of the existing members or foundations was not necessary.

CONCLUSIONS

The use of friction-dampers has shown to provide a practical, economic and effective new approach to rehabilitate the existing buildings to resist future earthquakes. The use of new technology resulted in significant savings in the initial construction cost and construction time.

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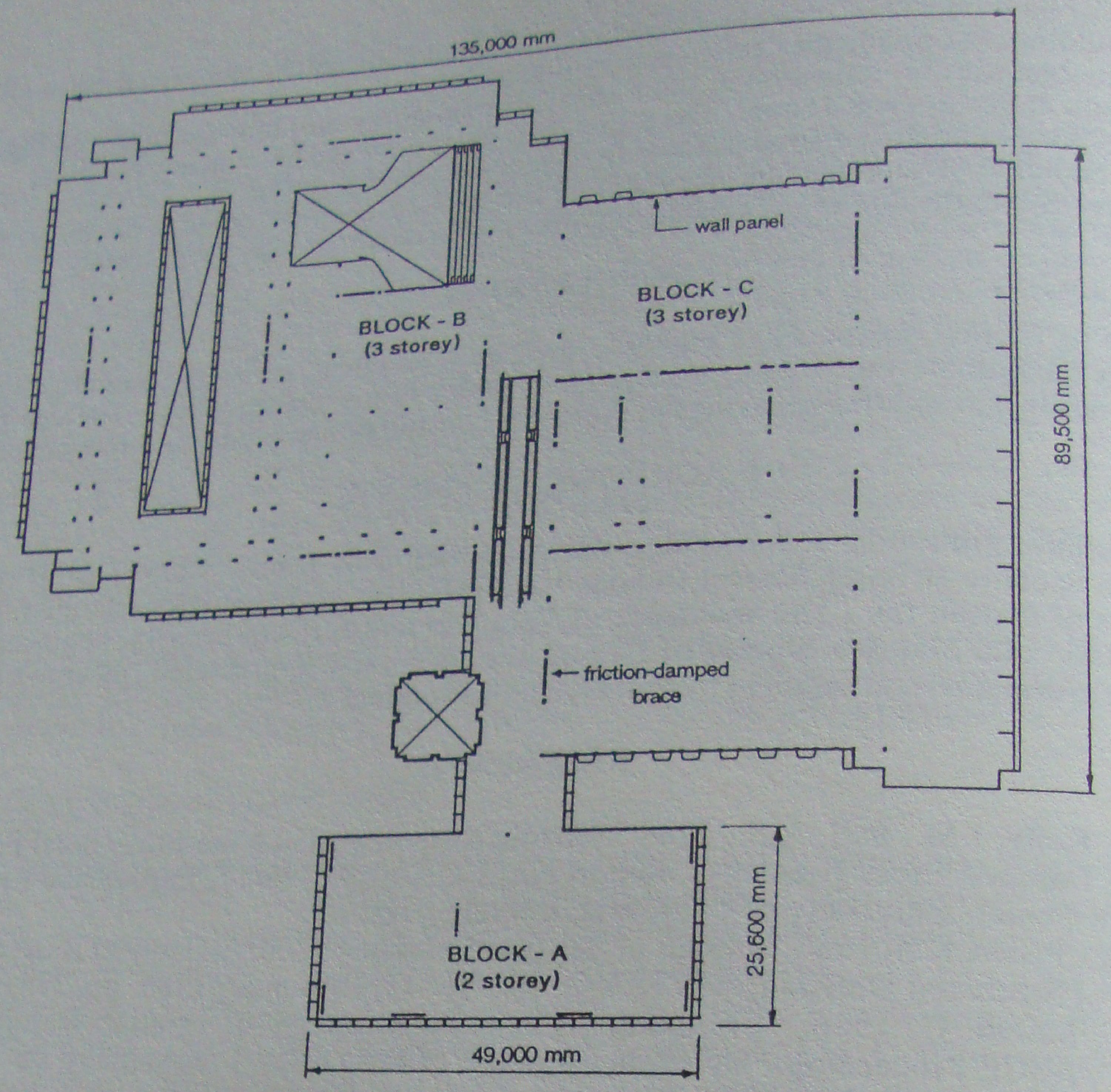


Figure 1. Plan View of School Complex

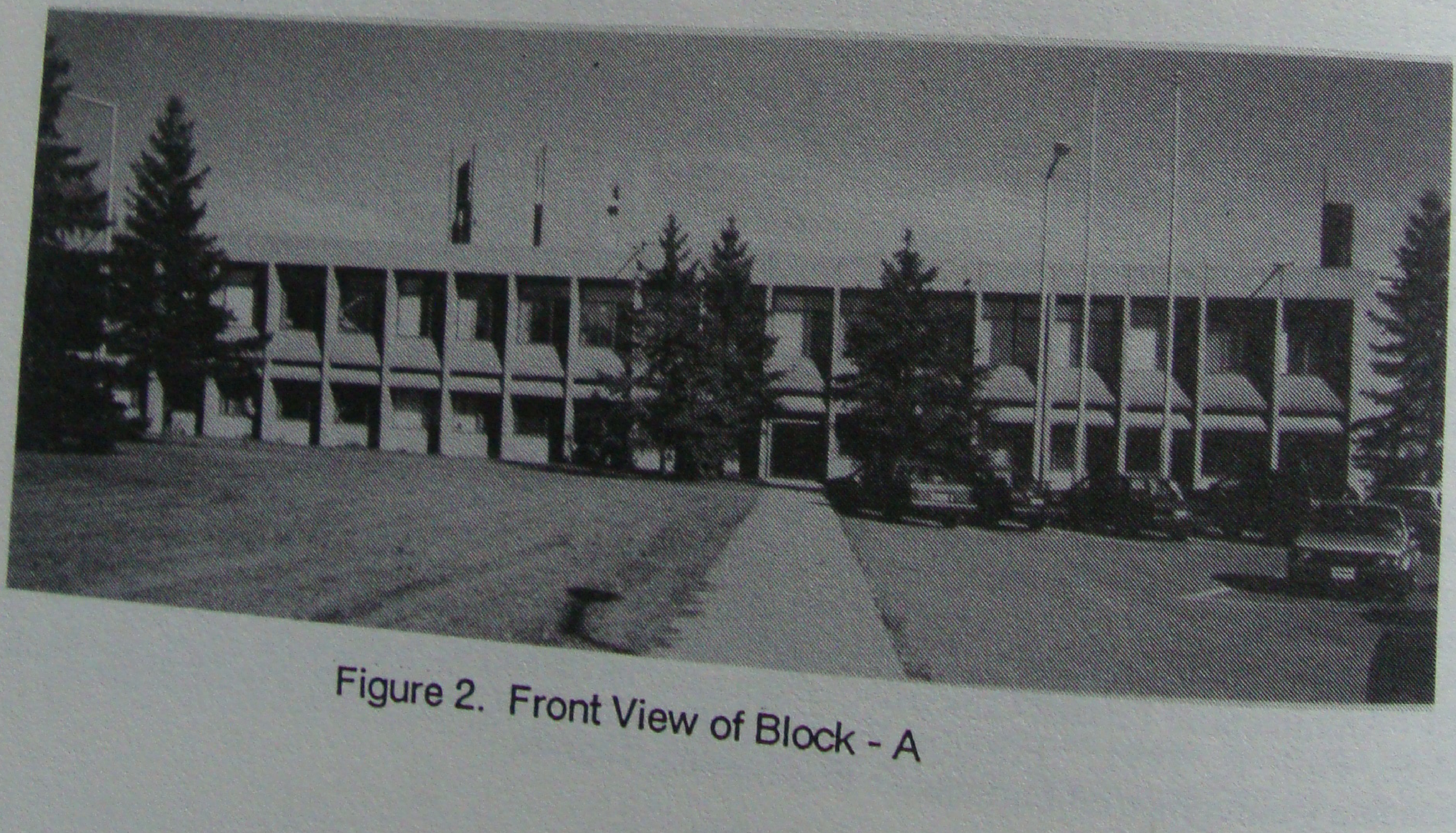
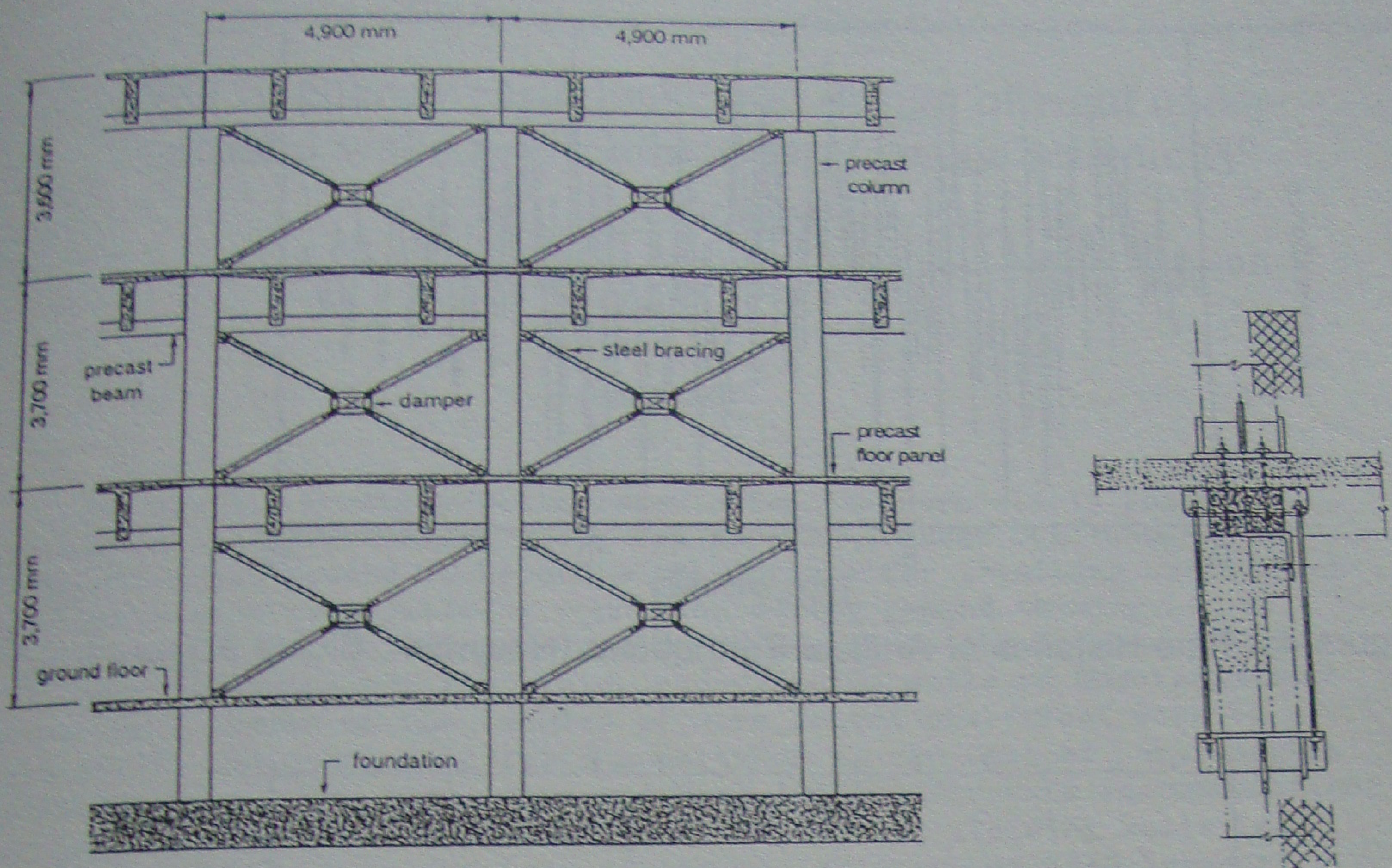
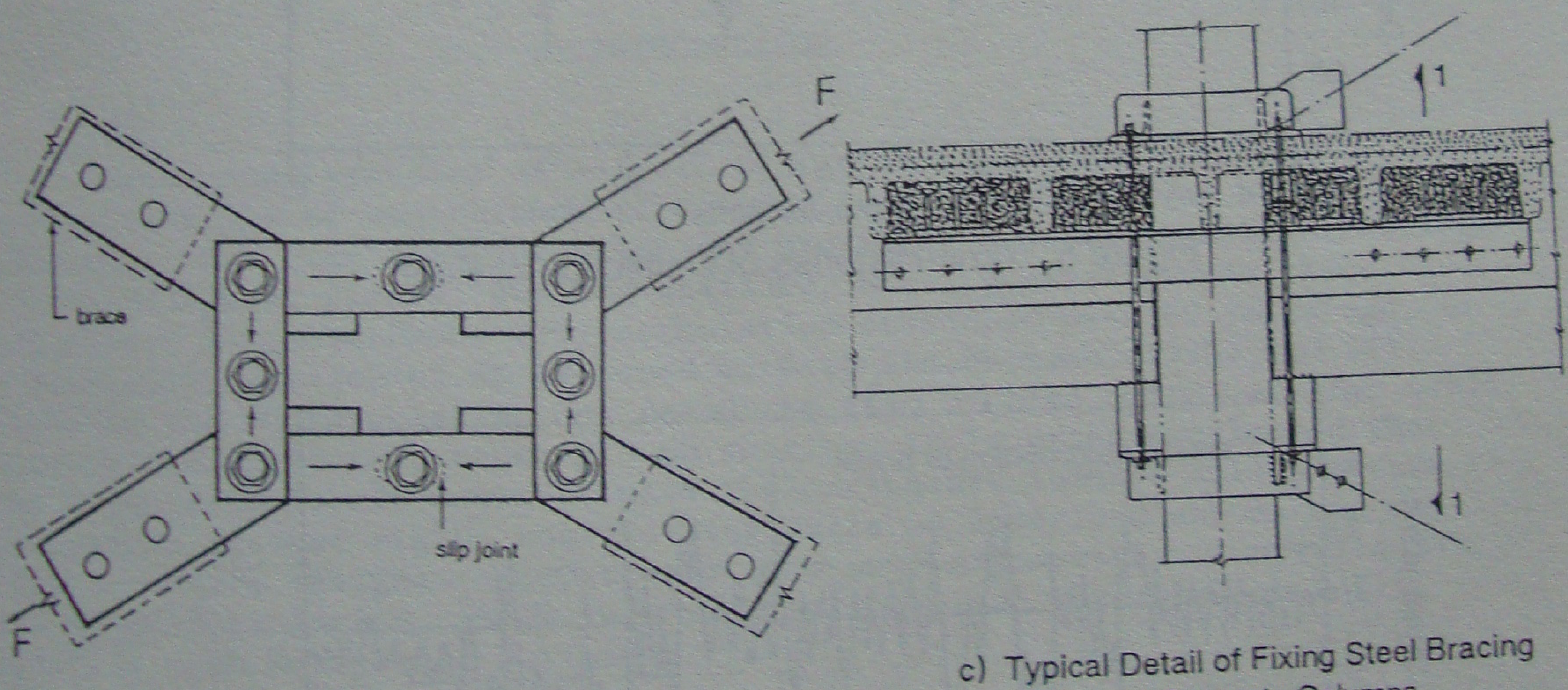


Figure 2. Front View of Block - A



a) Location of Friction-Damper in Frame

Section 1 - 1



b) Typical Friction-Damper

c) Typical Detail of Fixing Steel Bracing to Precast Concrete Columns

Figure 3. Typical Detail of Friction-Damper in Steel Cross-Bracing

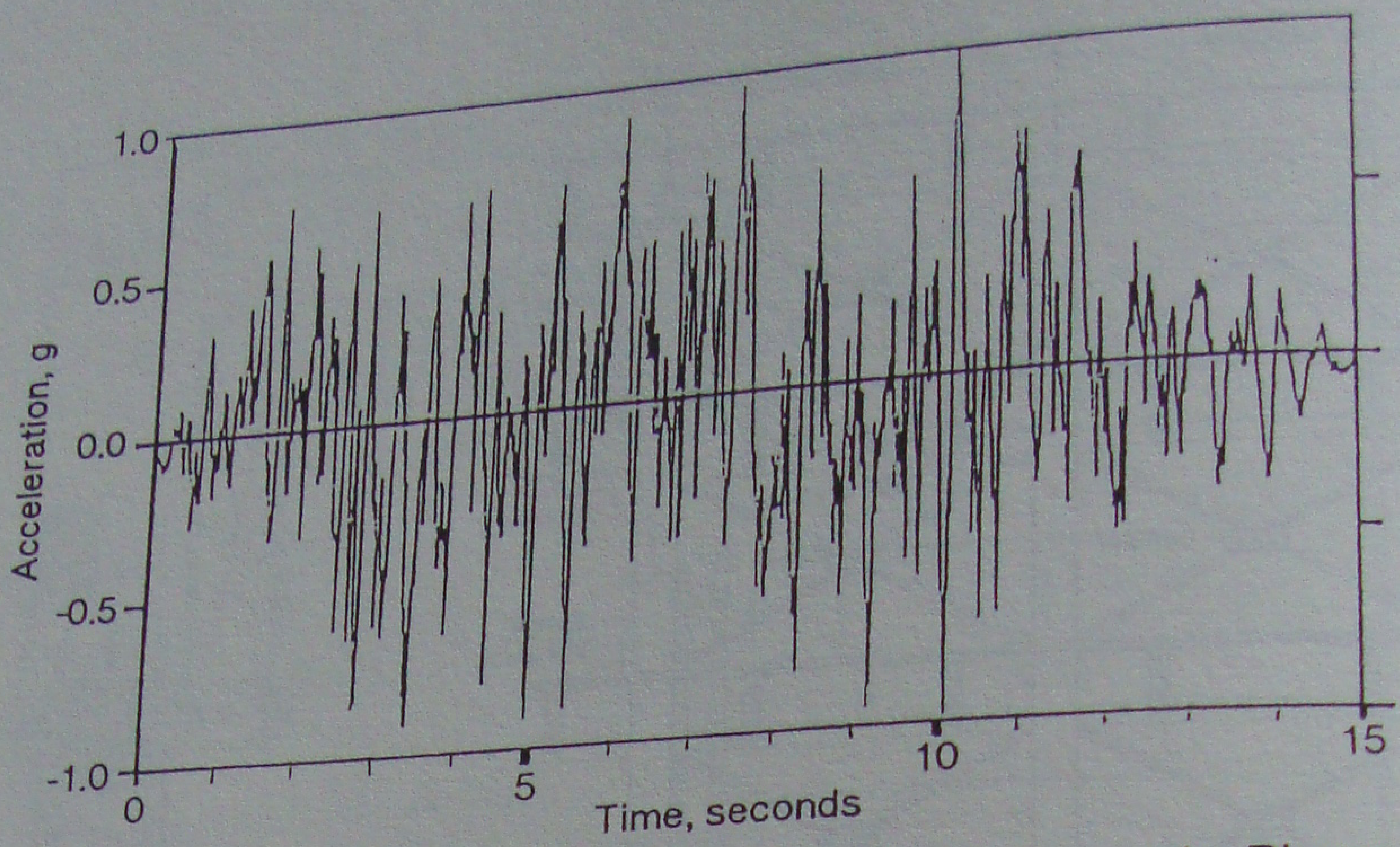


Figure 4. Time-Histories of Artifical Earthquake (Newmark, Blume & Kapur)

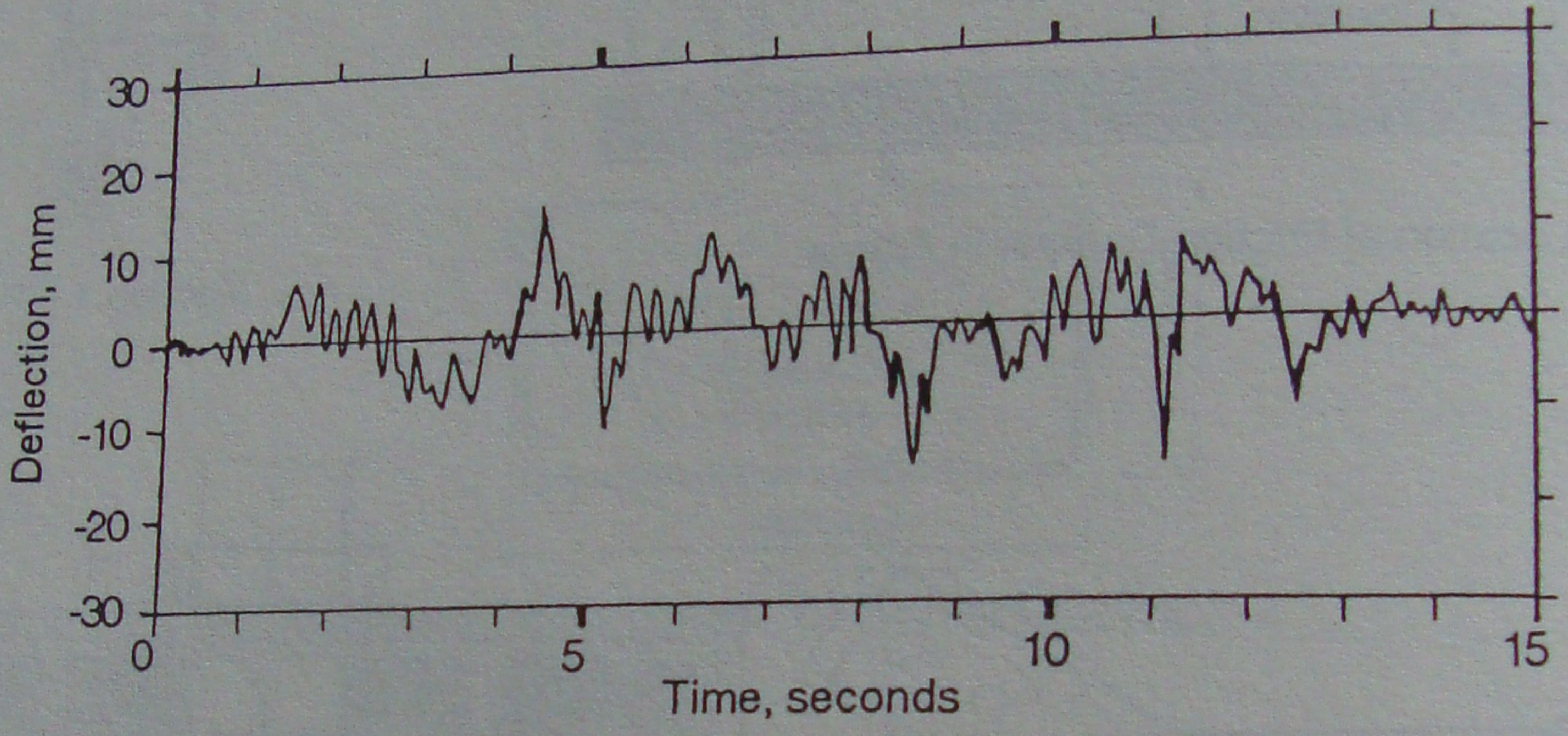


Figure 5. Time-Histories of Deflection at Roof

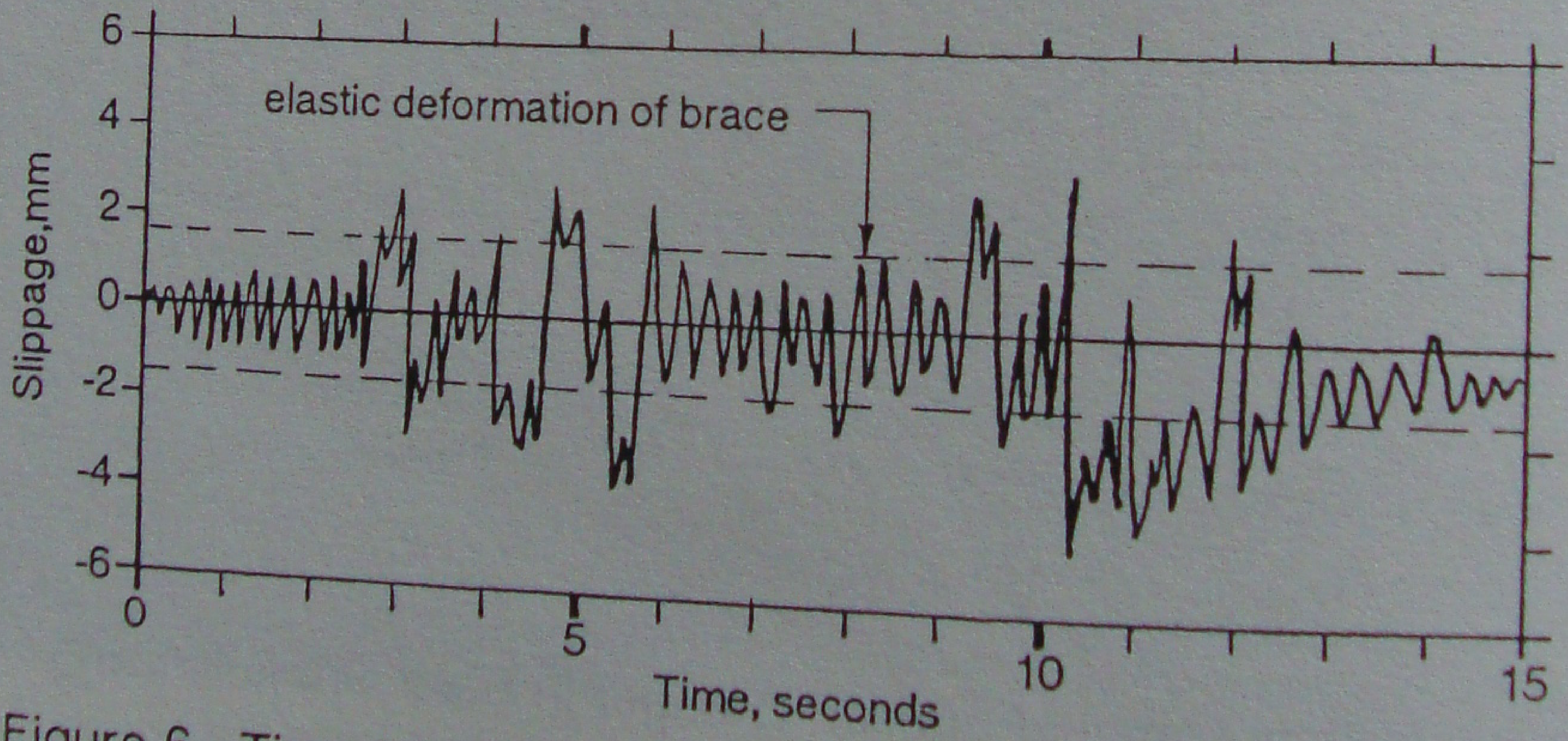


Figure 6. Time-Histories of Slippage in Friction-Damper in Cross-Brace