BASE STOREY DESIGN FOR ASEISMIC ISOLATED STEEL BUILDINGS

by

B.B. Barwig and S.F. Stiemer
University of British Columbia

ABSTRACT

Recent research indicates that base-isolation design of buildings reduces earthquake excitation to an acceptable level, without an increase of structural acceleration. This paper presents the results of the experimental investigations of various schemes for steel buildings with base isolation.

A scaled down steel building was used for the shaking table tests, which were conducted in the Earthquake Simulator Laboratory of the University of British Columbia. The base storey design was altered while the dynamic response of the building was recorded. The base isolation consisted of steel roller bearings with parallel ductile steel energy absorbers to limit excessive displacements and to provide the wind restraint.

The variation in the base storey design aimed at the saving of the blind base-storey or double foundation. The experimental tests showed ways of better design methods, and analytical studies are following to optimize them.

It could be verified that uncoupling of buildings from the earthquake ground motion is relatively simple to achieve. However a base isolation system requires a certain restraint against minor horizontal loads, like wind loads, which can be done by mechanical fuses. A new type of solid state energy absorbers was used in the described tests. The newly proposed base storey is substantially different from conventional solutions and results in a less expensive although safer design.

INTRODUCTION

The concept of reducing seismic loading on buildings and structures by isolation from excitation or reduction of its effects is not new. The earliest proposal was to decouple the structures from the ground by a sliding system [1]. Continuous research projects persued various systems designed to reduce seismic loading on structures.

Some techniques presently used or being investigated include base isolation systems, integrated damping devices like asymmetric bracing, and other methods using both frequency separation and energy absorption.

In the case of frequency separation devices, moveable masses [2] can be used to prevent dangerous resonances. Also disengaging joints [3] have been studied which achieve reduction in the stiffness of the structures.

Increasing the overall damping of a structure can also reduce the effects of earthquake excitations. It has been suggested to improve the overall damping by introduction of friction devices at the joints [4] or elasto-plastic elements [5] in the support members.

A flexible first storey concept, where the whole first storey behaves as an elasto-plastic system and allows large deflections without transmitting the earthquake energy into the higher stories, produces stability problems due to the interaction of the vertical load and the large lateral displacements and thus has been shown as impracticable.

The base-isolation system uncouples the structure from the earthquake excitation and reduces the structure's lateral stiffness so that its first natural frequency is well below of most typical earthquake frequencies.

However, not all these techniques are without drawbacks. Usually the additional devices which alter frequency response or damping characteristics are expensive or make the design and construction more complex and need maintenance. The main problems of conventional base isolation systems are not only the extra costs of a blind base-storey or double foundation to separate the structure base and foundation, but the possibility of excessive displacements between structure and ground. The most recent experimental investigations on base isolations [6] have shown that with a combination of rubber bearings and energy dissipators, the displacements at the base level can be reduced to an acceptable level without significant increase in structural acceleration. Steel buildings seem to be better suited for base isolation because an implementing of the isolation elements is relatively simple to design.

One of the main goals in the reported research project was to eliminate the additional blind base-storey. The base-isolation system proposed by the authors consists of steel roller bearings with newly developed ductile energy absorbers in parallel to limit excessive displacements and to provide wind restraint. The steel roller bearings provide the means of stable lateral displacement with unlimited durability without maintenance or function control.

The eliminating of the blind base-storey requires less bracing to the main columns due to a reduced base shear and different moment distribution over the height. This results in additional savings of structural steel.

SHAKING TABLE

The experiments reported in this paper were carried out on the earthquake simulator table, at the University of British Columbia in the Civil Engineering Department. The table has the floor dimensions of 3m x 3m and the capacity to apply seismic ground excitations to structures up to 17.5 tons with a maximum acceleration of 2.5g (24 m/sec^2) horizontally and a displacement of 130 mm peak to peak.

The table is welded aluminum construction with a grid of threaded steel inserts for attaching test specimens onto the table. The table and test specimen are supported by 4 vertical legs with universal joints at each end to ensure quasi-linear horizontal motion. Horizontal rotation is prevented by three hydrostatic bearings on the sides of the table. The hydraulic system (MTS) can be controlled by an oscillator (K&H) or directly by a computer (PDP-11/04) in a form of a digitized record of an earthquake. A wide choice of 144 different earthquake records are currently accessible.

TEST MODEL

Frame

The frame represents a steel frame building at a geometric scale of 1:3 (Fig. 1). The overall dimensions of the frames are 3.0m x 1.4m in plan and 3.9m in height. There are four separate pieces to the frame which are bolted together: the two side frames and their interconnecting beams, the first storey columns and the base beams, which are attached to the shaking table. In the initial reference test series the columns are bolted to the base beams while in subsequent tests the base isolation system with energy absorbers is assembled between the column bases and these base beams. The side frames, which are parallel to the direction of the excitation, represent a moment resisting construction. In the opposite direction perpendicular to the excitation, the building is bolted. Three of the four floors are loaded with four concrete blocks 300 kg each. The total weight of the frame including concrete blocks is 7300 kg.

The new version of the base storey of the frame, which was prepared for the experimental tests (Fig. 6), is a direct result of the change of bending moment distribution in the base storey columns (Fig. 5) after the base isolation is implemented. The column sizes can be reduced for buildings in regions where earthquake loads are governing. A bracing of the pin-ended columns might only be necessary where energy absorbers or centering springs are attached to. A tapered column might be advantageous, too. These design optimizations will be the subject of the continuing tests and analyses.

Base Isolation

The base isolation pads are installed in each of the first storey columns. Energy absorbers are incorporated in the four outer columns only. The base isolation pads consist of lower bearing plate, linear roller bearings, upper bearing plate, and a thin top layer of rubber. The linear roller bearings allow large displacements without danger of instabilities like in the case of rubber bearings. The rubber layer used in our tests are only incorporated to enhance the quality of measurements and will be omitted in the final design. (Fig. 2.)

The new energy absorbers are mild steel strips bent into a special shape close to a semi-cycle. These are attached to the floor beams and to column bases parallel to the isolation pads. The energy absorbers are designed to withstand possible wind forces only and have a hysteretic load-displacement behaviour (Fig. 3).

In order to ensure that the frame returns to the original position after the energy dissipators have yielded, there are small centering springs installed. These springs are attached to two interior columns. Earlier test have shown that only very little force is needed to achieve a return to the centre position after an earthquake.

INSTRUMENTATION

There are seven accelerometers monitoring the accelerations of the frame and table. Four are attached to the cross-beams, monitoring the accelerations at each storey level. Two accelerometers are monitoring the base acceleration at the feet of the columns. One accelerometer is attached to the table. The range of the cross-beam accelerometers are $\pm 20g$, the accelerometers on the first storey columns $\pm 2.5g$ and the table accelerometer $\pm 50g$. All the accelerometers except the table accelerometer are a strain-gauge types. The accelerometer on the table is a servo accelerometer.

There are two LVDTs attached to the first storey columns, to measure the relative displacements between table and structure base.

DATA ACQUISITION AND REDUCTION

The data acquisition and processing system is based on a Digital PDP11/04 mini-computer with RT11 operating software system and two RX01 disc drives.

The analog signals of the accelerometers and LVDT are fed to amplifiers and to a 16 channel multi-plexed a/d-converter. Data are stored directly on magnetic discs for further reduction and manipulation. A HDLC data link to the main campus computer (Amdahl) enables the users to conduct extensive computations with a wide variety of programs at the convenience of a main frame system.

NATURAL FREQUENCIES

The first two natural frequencies associated with the unloaded shaking table, are 16 Hz and 33 Hz. When the table is loaded, these frequencies are reduced due to the added mass. In our case of a structure with 7300 kg it results in natural frequencies at 9.5 hz and 17 Hz respectively.

The natural frequencies of the loaded frame without base isolation and reference columns were pre-determined by analysis with a plane frame dynamic program and a basic method where the frame is modelled as a cantilever with a mass at the end. Both approaches yielded similar results. The analytical values could be verified by actual measurements. The first two natural frequencies for the loaded frame are 20 Hz and 59 Hz.

In the case of the loaded frame with the base isolation pad only no significant natural frequency could be determined, as expected. Then absorbers were installed starting from a weak version and subsequent absorbers were made stronger in order to determine the affect of different yield strengths of the absorbers.

As expected the introduction of the energy absorbers reinstated natural frequencies as opposed to the isolated system. As the absorbers were made stronger, the first natural frequency was increased but once these absorbers had yielded, the hysteretic action of the absorbers produced damping which caused a drop in the typical natural frequencies of the elastic system.

DAMPING

There were two procedures used to produce a decaying acceleration graph: Pull-back test and a sine-wave excitation. The decay of the free vibrations was measured in each case after the pull-back or shutting off the sine-wave input which frequency was tuned to the expected natural frequency. This procedure provides a direct value of the damping from each natural frequency, the table and the loaded frame. For a critical damping of D < 20% the decay of the acceleration can be used to determine

$$D \approx \frac{\delta}{2\pi} = \left\lfloor \ln\left(\frac{\ddot{x}_n}{\ddot{x}_{n+1}}\right) \right\rfloor \frac{1}{2\pi}$$

where δ = logarithmic decrement
$\ddot{x}$ = acceleration
D = critical damping (in percent)

The value for the rigid frame (no isolation) was 1%-3%, which is a typical value for steel buildings.

In the isolated case with energy absorber, only within the elastic region of the energy absorbers can a damping value be determined with these classical procedures. Once the energy absorbers yield, the system is highly non-linear and the absorbed energy can be determined by load-displacement measurements of the devices.

EXTREME VALUES

During the tests an immediate evaluation of the structural response was made by determining the absolute extreme values of accelerations and displacement for the different earthquake excitations. The measurements were compared for four representative earthquakes (TAFT, EL CENTRO, PACOIMA and PARKFIELD).

CONCLUSION

With the incorporation of the described base isolation system in a steel building the dynamic response, the forces and overturning moments due to earthquake excitation can be drastically reduced by 80-90%, which depends on strength of the energy absorbers and magnitude of the earthquakes. The energy absorbers are designed to resist wind loads of the buildings elastically. Their behaviour in the post-yield region has to be carefully considered to balance maximum accelerations with excessive displacements. Further investigations are underway to develop design rules for this region and to determine the long cycle limits.

The new design of the first storey due to the reduced base shear differs considerably from the conventional design and has various consequences on the design of the remaining building (Fig. 4). Firstly, reduced base shear amounts in lighter columns throughout the whole building. Secondly, the missing, because unnecessary, double foundation does not contribute to increase costs when compared with conventional designs. Thirdly, structural design can be standardized, because due to the base isolation it does no longer matter in what region of earthquake risk the building is erected, only wind forces govern. Furthermore, large interior systems and equipment need no longer to be prevented from dynamic excitation which is crucial for strategical important or dangerous buildings, like hospitals, government buildings, bridges, nuclear power plants, research stations, emergency power supply, etc. These buildings might have their highest value by continued operation during or immediately after an earthquake. The base-isolation system has not only proven its feasibility in laboratory tests and implementing in prototype but is now advanced enough in its design to be economically competitive for steel buildings. In some cases it might be even useful to install base isolation systems in an existing building, e.g. historically valuable buildings or monuments, etc. which were not designed for earthquake loadings.

The base-isolation pads used by the authors seem to have superior properties than older proposals. They are stable, self-centering, have limited displacements and introduce predetermined small accelerations. They are maintenance and control free and of relatively low costs. There are no patents to restrict their use and they can be manufactured or bought off the shelf in many countries. The authors would like to express the hope that this paper contributes to the implementing of base-isolation system in steel buildings and a safer future.

ACKNOWLEDGEMENTS

The described research project was made possible through funding by the Canadian Institute of Steel Construction (CISC) and the University of British Columbia. The local office of the CISC with Mr. B. Garrick and its members supported actively this project. We would like to thank the project coordinator of the CISC, Mr. D. Halliday for his support and Brittain Steel Limited, for its donation of the structural material for the test set-up. The professional work of all members of the technical staff of the Department of Civil Engineering shall be greatly acknowledged. Without all this friendly help these experimental studies could not show the results above at this time.

REFERENCES

[1] Calantarients, J.A.: Improvements In and Connected With Building and Other Works and Appurtenances to Resist the Action of Earthquakes and the Like, Paper No. 325371, Engineering Library, Stanford University, California, 1909.

[2] Matsushita, K. and Izumi, M.: Application of Input Controlling Mechanisms to Structural Design of a Tall Building, Fifth World Conference on Earthquake Engineering, No. 8.

[3] Aizenberg, Y.M. and Chachua, T.L.: Application of Disengaging Joints to Increase Earthquake Resistance of a Tall Building With Stiffening Diaphragms and Core, Seismostoikoe Stroitelsto, 3, 1977.

[4] Kilimnik, L.S.: Design of Frame Buildings With Elastic Friction Joints on High Strength Pins for Seismic Regions, Seismostaike Stroitelsto, 5, 1977.

[5] Mallik, A.K. and Gosh, A.: Improvement of Damping Characteristics of Structural Members With High Damping Elastic Inserts, Journal of Sound and Vibration, 27, March 8, 1973.

[6] Kelly, J., Eidinger, J.M, Derham, D.J.: A Practical Soft Story Earthquake Isolation System, UCB/EERC - Report No. 77/27, Nov. 1977.

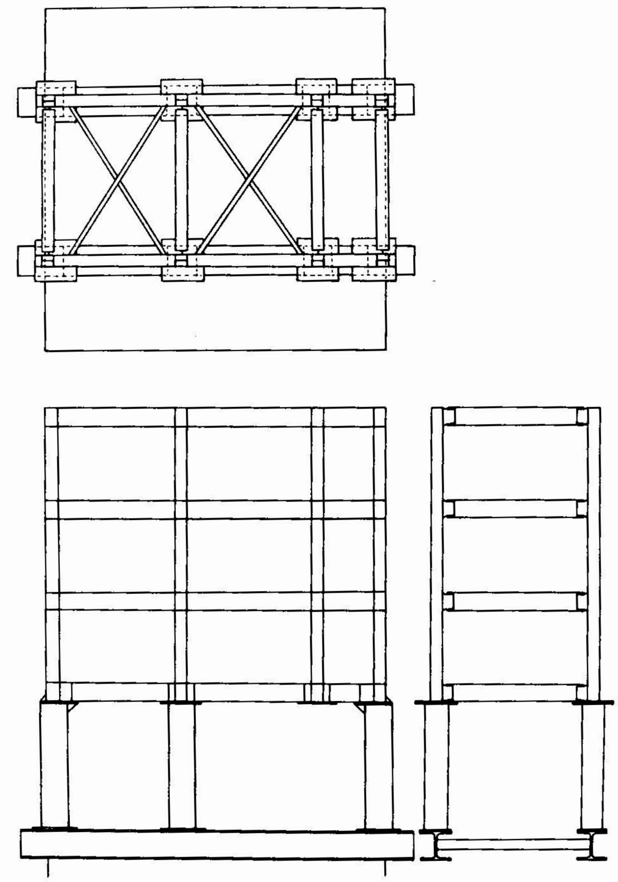
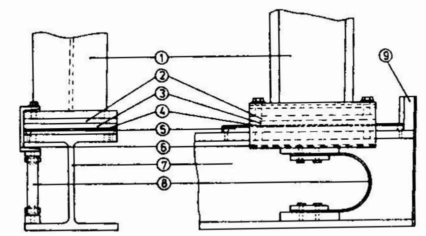


Fig. 1. Steel Frame Model Overview, Deadloads Not Shown, Rigid First Storey for Reference Measurements.



1. base column
2. rubber pad
3. upper bearing plate
4. roller bearings
5. lower bearing plate
6. absorber base, building side
7. foundation beam
8. steel ring energy absorber
9. safety pad

Fig. 2. Base Isolation Modul with Components

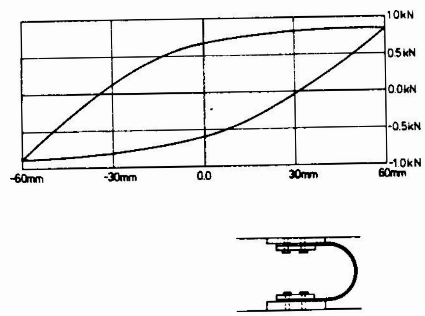


Fig. 3. Typical Load-Displacement Behaviour of Ring-Energy Absorbers.

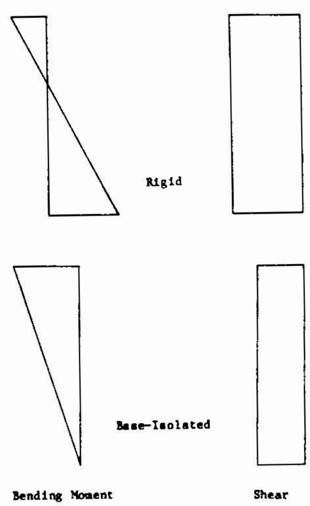


Fig. 4.

Comparison of Shear and Bending Moment Distributions of Base Storey Columns, Rigid and Base-Isolated.

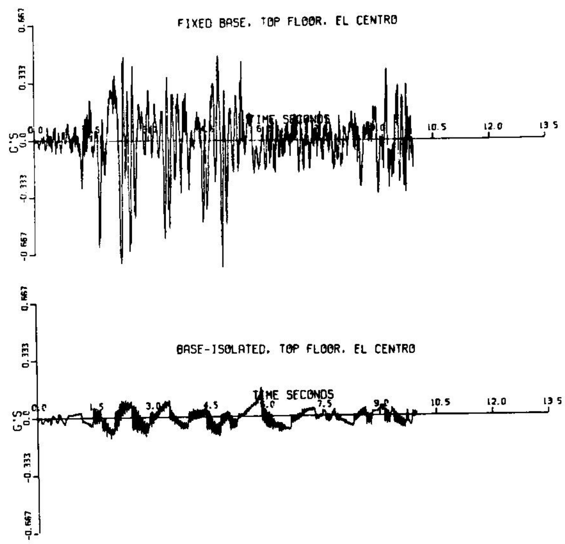


Fig. 5. Comparison of Acceleration Time Histories Between Rigid Frame and Base-Isolated Frame.

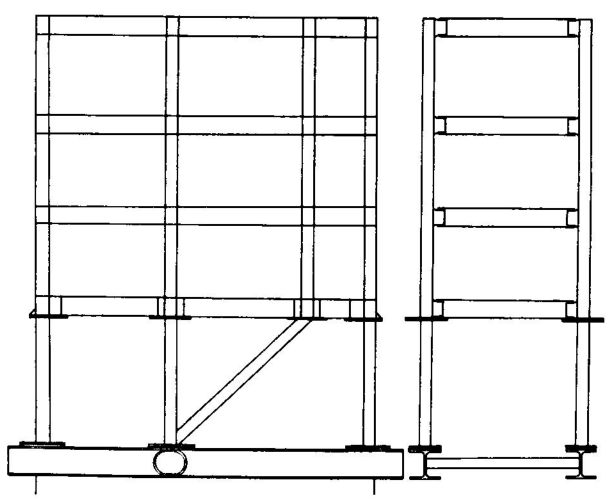


Fig. 6. Steel Frame Model With Modified First Storey, Single Energy Absorber Modul Installed.