# BUILDING DAMPING BY COULOMB FRICTION

by

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## SYNOPSIS

Infill wall panels made of concrete segments prestressed together are presented as a nondestructive means of consuming vibrational energy in structures. The panels conform to building frame distortion like a deck of cards distorting in shear, consuming energy through Coulomb friction along the slip surfaces. Interfloor Coulomb forces are determined for two buildings to approximate maximum response during the El Centro earthquake of the same buildings with 20% viscous damping. Coulomb forces chosen for lowest stories are 6%-8% of a structure's weight. Residual displacements after the earthquake are small, but extra loading on frame members at joints is significant.

## INTRODUCTION

Building vibration amplitudes due to wind or earthquake can be significantly reduced if a large part of the kinetic energy of the structure relative to the ground can be dissipated in each cycle as the building vibrates. A building with 20% critical viscous damping, which dissipates 92% of its energy in one cycle of free vibration, might experience earthquake induced vibrations only 1/2 as large as one with 2% damping, which dissipates only 22% of its energy per cycle. Unless some type of dissipation mechanism is present, during a strong earthquake amplitudes increase to the point where the material of the structure becomes nonlinear, and energy is dissipated through processes which gradually destroy the structural elements.

This paper presents the concept of non-loadbearing prestressed concrete wall panels to dissipate energy through Coulomb friction, while the elements of the structural frame remain linear during the design earthquake. A technique for digitally computing the response of Coulomb damped multistory buildings is outlined and response maxima of a 4-story and an 8-story Coulomb damped structure during the El Centro earthquake are compared with maxima of 20% viscous damped structures.

## PRESTRESSED SEGMENTED WALLS

A segmented prestressed wall is shown activated by building frame distortion in Figure 1(a). Figure 1(b) shows the forces required for activation. Theoretically the lateral force to cause slipping of a panel is

$$FC = \frac{\mu \times PST}{1 - \mu\, h/l},$$

where $\mu$ is the coefficient of friction, PST is the prestressing force in the panel, and h and l are panel dimensions. The panels should fit snugly at all times within the frame opening, touching only at the corners, but not be subject to vertical load other than the force PST. Figure 1(c)

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shows how the panels cause extra load in the frame. Upon reversal of relative velocity the forces of the panels on the frame act along the opposite diagonal.

## DIGITAL COMPUTING TECHNIQUE

To compute the time history of the behavior of buildings with Coulomb dampers, a step-by-step technique based on an assumed linear variation of acceleration across the time step was used (1). The technique requires a knowledge of all forces acting on the masses other than those linearly related to displacement or velocity, therefore with Coulomb friction it was necessary to iterate across the time steps as described below. To decide on the size of the time step and also to check the step-by-step code, computed responses of undamped structures were compared with responses computed by an exact method (2). The stiffness matrix was formed for each framework by permitting joint displacements and rotations, but no axial deformations of beams or columns, then reduced to one degree of freedom for each floor. Masses were lumped at the floors. For the undamped 8-story building under El Centro excitation, a time step as small as 0.005 sec. was necessary to yield maximum responses within 2% of maxima computed by the exact method.

Coulomb friction is a passive phenomenon not linearly related to relative displacement or velocity. The actual friction force FP can assume any value between positive FC and negative FC, and can in theory change instantly from one value to another. The force FP equals FC times the sign of the relative velocity of the masses, but if they are at relative rest FP depends on the magnitude and sign of the active force tending to cause relative motion. To model this phenomenon, an active force $FA_i$ for the panel below the ith floor, tending to move the ith floor relative to the floor below was defined as:

$$FA_i = FS_i + FP_{i+1} - M_i \times (\ddot{y} + \ddot{u}_{i-1}) ,$$

where $FS_i$ is the spring force on floor mass $M_i$ caused by the distorted shape of the framework (the framework was assumed elastic and the panels rigid except on the slip surface), $FP_{i+1}$ is the horizontal force in the panel above the floor, $\ddot{y}$ is ground acceleration, and $\ddot{u}_{i-1}$ is acceleration of the floor below, all quantities positive to the right.

An active force was computed for each floor at the beginning (FA) and at the end (FAT) of each time step. For the first iteration the forces in the panels at the end of the interval were assumed equal to the forces at the start of the interval (FPT = FP). If the average active force on a floor over the interval was less than the force FC necessary to cause slipping, and if the computation showed that during the interval the velocity of the floor changed sign relative to the floor below, or the relative velocity changed from zero to a nonzero value, it was decided that during the interval the ith floor was locked to the floor below. This decision was based on the passive nature of Coulomb friction: an active force FA less in absolute value than FC cannot reverse a relative velocity nor start from rest a mass already at rest relative to the mass below. If the floors were found to be locked together at the end of an interval, the actual friction force FPT in a panel was set equal to FC if $|FAT| \geq FC$, or was set equal to FAT if $|FAT| \leq FC$, signs corresponding to the direction of impending relative motion. Accelerations at the end of the interval were computed from Newton's second law of motion.

Because the values of the FPT forces at the end of each time step must be known but usually cannot be predicted, it is necessary to iterate, using the previously determined FPT forces as the basis for the next trial. If no FPT force changed by more than 0.002 FC from the previous iteration, the calculation across an interval was accepted, but if convergence was not reached in 10 trials, the values after 10 trials were accepted. The fraction of calculations not converging depends on the size of the time step, the natural periods of the building, and the nature of the ground excitation. With the 8-story structure, .005 sec. time step, approximately 10% of the calculations did not converge. At 0.0025 sec., approximately 4% did not converge, and at 0.00125 sec., approximately 2% did not converge.

A more correct computational scheme would determine the exact instants, within the time steps, at which relative velocities of adjacent masses changed sign or changed between zero and nonzero values. This was not attempted here. Two tests performed on the accuracy of the computational scheme used were 1) to lock all but one story with large FC forces and to observe the decay of free vibrations, and 2) to recompute earthquake response with a reduced time step. Free vibrational decay of the SDF system agreed well with theory, and maximum earthquake responses at time steps one half as large changed in most cases by less than one percent. An energy balance, in which the difference between running totals of energy input and energy dissipated was compared with the sum of instantaneous kinetic and elastically stored energy, was satisfactory.

## COULOMB AND VISCOUS DAMPING COMPARED

Figure (2) shows 8 stories of a building which has appeared in the literature (3). The top 4 stories were also studied separately as a 4-story building. Response of the buildings to the El Centro earthquake was computed with 1) 20% viscous damping in all modes, using modal superposition, and 2) Coulomb damping of the proper magnitude to yield approximately the same maximum amplitudes, using the digital technique described. The Coulomb force FC in each story was arbitrarily made proportional to the sum of the masses above it so that under increasing ground acceleration all panels would start to slip at the same instant. Maximum top story shears (sum of shears in the columns only) and maximum accelerations in the Coulomb damped buildings are somewhat greater than in the viscous damped buildings. Other combinations of Coulomb damper values can, of course, be used to reduce these maxima.

In the 8-story frame the Coulomb force in the ground story is about 50% of the maximum story shear, which means that if the panel is located in the center bay, column shear at the beam-column joint is increased by about 75%. Beam shears at the joints are also increased significantly by the presence of the panels.

Residual displacement of the top floor of the 4-story frame after 18 seconds of earthquake was 0.1 inch; maximum possible residual displacement with the Coulomb dampers shown is 0.5 inch. For the 8-story frame, the maximum residual displacement is 1.1 inches. Because Coulomb dampers absorb energy only as the first power of vibration amplitude (viscous dampers absorb energy as the square of the amplitude), at amplitudes larger than the design amplitude Coulomb dampers appear less effective, and at smaller amplitudes more effective. When ground excitation was doubled in intensity, response of the Coulomb damped structures roughly tripled, corresponding to about 5% viscous damping. Greater effectiveness at smaller amplitudes is shown by the fact that the Coulomb damped structures did not begin to move until more than one second of the earthquake had occurred.

## CONCLUSIONS

The prestressed wall panels described here act like bracing across one diagonal of the openings in a building frame. The force in the bracing, limited by the Coulomb slip force, opposes relative velocity of the floors, not relative displacement. Digital computer studies have so far indicated that not unreasonably large Coulomb forces are required to limit maximum responses during a strong earthquake to the same maxima achieved with 20% viscous damping. Further investigation seems justified.

Practical questions which must be answered regarding this technique of energy dissipation include: Can the prestressing force be maintained constant over the years and during an earthquake? Will a soft spring be necessary in series with the prestressing tendons? Will the coefficient of friction remain reasonably constant during an earthquake? Can the required close fit of the panels into the frame openings be attained and maintained? How can the extra shear forces at the joints of beams and columns be economically resisted? Is the entire concept economical when compared with other methods of design? Are there other forms of dissipation mechanisms more practical, e.g., crossed diagonal braces containing Coulomb slip joints? These questions cannot be answered by analytical or digital computer studies alone, but only by constructing panels within frames and testing them.

## ACKNOWLEDGMENT

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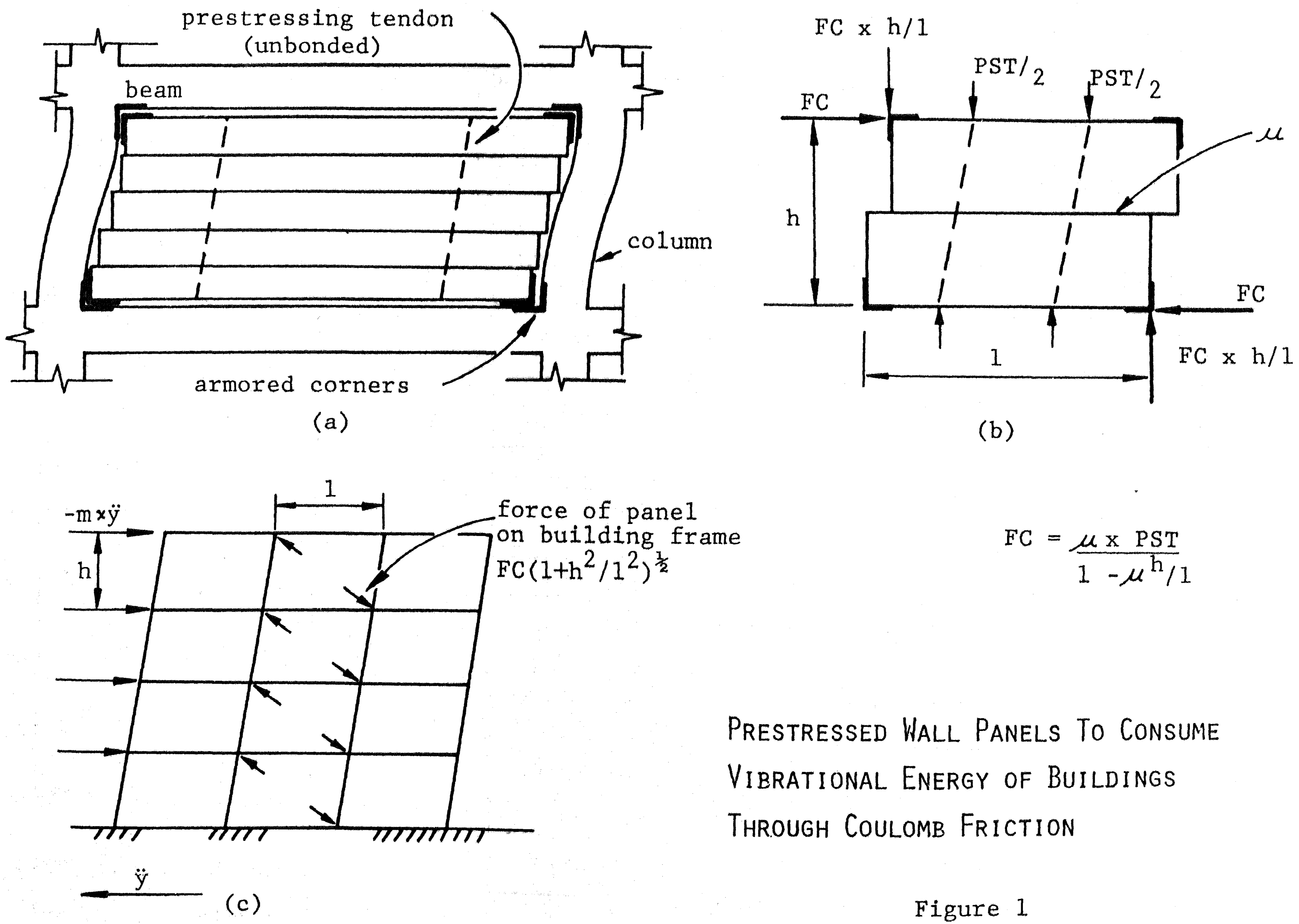
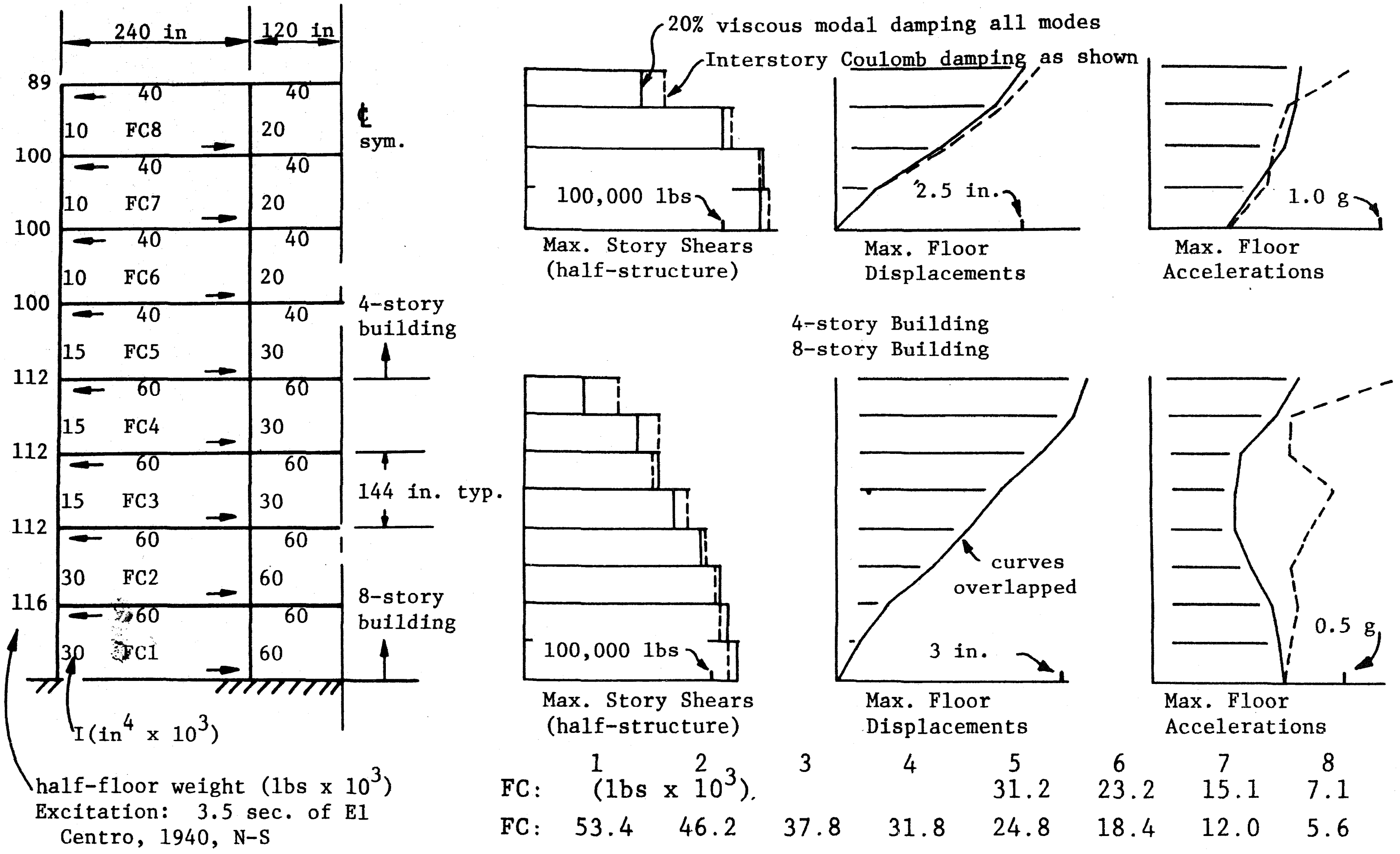


$$FC = \frac{\mu \times PST}{1 - \mu\, ^{h}/_{1}}$$

PRESTRESSED WALL PANELS TO CONSUME VIBRATIONAL ENERGY OF BUILDINGS THROUGH COULOMB FRICTION

Figure 1



|  | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| FC: | (lbs x $10^3$). |  |  |  | 31.2 | 23.2 | 15.1 | 7.1 |
| FC: | 53.4 | 46.2 | 37.8 | 31.8 | 24.8 | 18.4 | 12.0 | 5.6 |

COULOMB AND VISCOUS DAMPING COMPARED IN TWO BUILDINGS

Figure 2