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Developments in the Design of Steel Buildings for Earthquake

Progrès dans la conception de bâtiments antisismiques en acier

Neue Entwicklungen in der Konstruktion von erdbebensicheren Stahlbauten

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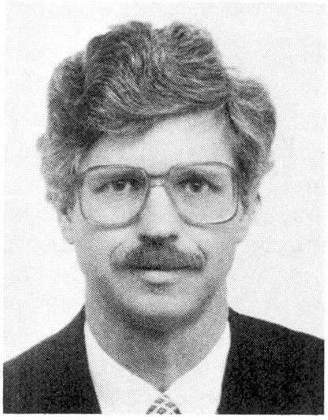

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SUMMARY

This paper describes new steel structural systems being used in the United States to resist earthquake forces and some improvements to, and innovative uses of, older systems. Included systems are: braced frames, eccentrically braced frames, steel plate shear walls, and steel plate and concrete composite shear walls.

RÉSUMÉ

Cet article décrit de nouveaux systèmes structuraux en acier, actuellement utilisés aux Etats Unis, qui résistent aux forces provoquées par les séismes, ainsi que quelques améliorations des systèmes traditionnels: cadres contreventés, cadres contreventés excentriquement, murs de refend muni d'une tôle résistante au cisaillement et murs de refend composites en tôle et béton.

ZUSAMMENFASSUNG

Dieser Vortrag beschreibt ein neues erdbebensicheres Stahlbausystem, das in den Vereinigten Staaten angewandt wird und zeigt einige Verbesserungen und Neuerungen älterer Systeme auf. Behandelt werden folgende Systeme: versteifte Rahmen, exzentrisch versteifte Rahmen, Stahlplatten-Schubwände und Schubwände aus dem Verbund von Beton mit Stahlplatten.

1. INTRODUCTION

Design of buildings to resist earthquakes requires design for cyclic loads the magnitude and dynamic characteristics of which are not determinate. This indeterminacy is due to the compounding of uncertainties in the earthquakes themselves with those of the soil and geology and the building characteristics. Certainly, there is, and has been, considerable study undertaken to decrease the level of uncertainty in all of the above factors and this work is valid and continues to improve our knowledge.

For the majority of building designs, it is not practical, nor warranted, to engage in a complete dynamic study in order to produce a design which will provide for competent earthquake performance. Earthquake codes in the United States dating from 1927 have been based on "equivalent static methods" wherein a certain percentage of a building's weight is applied as a static horizontal force distributed over the building height in some fashion. Using these loads, member forces are determined by analysis and members are designed elastically. The earliest of these codes used very simple formulas and relatively low forces. Gradually as our knowledge has improved through research, we have arrived at more and more sophisticated formulas. The present formula, being used in most of the United States (contained in the Uniform Building Code), includes considerations of locality, soil conditions, building period of vibration, framing system type, and importance of the facility. The seismic lateral forces obtained from the code formula are recognized to be considerably lower than those to which the building may in reality be subjected (probably 1/3 to 1/6 of what may occur in a very major quake). It is nonetheless felt that properly executed designs utilizing these forces will produce competent earthquake resistant structures, and for the most part, such has been demonstrated in recent earthquakes.

What is the key to this performance by apparently "underdesigned" structures? It is primarily the post-elastic behavior of the materials and systems. Given materials able to provide large inelastic strains without failure, and systems which preclude instability and brittle connection fracture, large amounts of earthquake input energy can be dissipated by local yielding of the structure, without failure.

Structural steel is, of course, the most outstanding structural material available to meet the requirements of seismic design. The purpose of this paper is to describe some of its newer innovative uses in seismic design of buildings in the United States.

Historically, since our codes were developed, the most commonly used earthquake resisting building sytems for major structures have been moment resisting frames of steel and concrete, concrete shear walls, and steel braced frames for light buildings. Somewhat more recently steel perimeter frames which act as large tubes have been popular for tall buildings of appropriate shape. In recent years several factors have contributed to development and use of new and innovative seismic resisting systems. These factors, all of which ultimately relate to the system economics, include:

- Code imposed limits on building lateral deflections.
- A trend in certain building types to more open and flexible space planning (i.e., more widely spaced columns, movable partitions and higher bays).

- Code imposed higher seismic loads especially for special buildings such as hospitals, public safety structures and large public assembly buildings.

- The extensive seismic upgrading of old, heavy structures of masonry and concrete inspired by government and institutional programs and by tax incentives and preservation requirements for private developments.

The traditional seismic force resisting systems previously listed, while still appropriate and in use for many structures, frequently have liabilities in responding to one or more of the above factors. For example, for large open bay structures, moment frames are frequently uneconomical due to the large members required to limit lateral drift. Concrete shear walls, while excellent for limiting drift in low and midrise structures, have severe architectural liabilities for many structures and, due to high forming costs in the U.S., are frequently uneconomical. Steel braced frames, as currently being designed, while also excellent for limiting drift, have questionable post-elastic performance particularly when used in large heavy structures. Research and design innovations, frequently sponsored by steel industry organizations, have led to the use of new steel systems and to improvements in conventional systems to meet the challenges presented, these include:

- Improved design concepts for concentrically braced frames;

- Steel eccentrically braced frames;

- Steel plate shear walls;

- Steel plate and concrete composite shear walls.

2. DEVELOPMENTS IN CONCENTRICALLY BRACED FRAMES:

Concentrically braced frames (vertical trusses) have been found to be economical systems of lateral bracing for low to moderate height buildings of relatively light weight, and in the United States this has been their predominant use until about the last 10 years.

Use of these frames for larger and heavier structures has become more prevalent largely due to their inherent lateral stiffness to meet the new drift limitations and their economy and convenience as a seismic resisting system in rehabilitation of existing concrete and masonry structures.

It has been recognized for some time that these systems have inherent liabilities in the post-elastic range, since the majority of yielding and therefore energy absorbing capability is concentrated in the brace elements which alternate between tension and compression. The tension yield of the brace results in decreased compression capacity and stiffness of the brace with each successive cycle, leading to continually increasing deflections and possible eventual failure.

The above noted-weakness of this system was previously accounted for in the Uniform Building Code in a rather arbitrary fashion by requiring that members and connections of braced frames be designed for forces 25% larger than those obtained from the code seismic analysis. While perhaps qualitatively correct, quantitatively this increase had no rational basis.

Because of the increased use of braced frames in larger, heavier and more important structures, it was felt that improved design requirements were needed. Recent synthesis and interpretation of research by the Research

Committee of the Structural Engineers Association of Northern California, by an ad hoc committee on Synthesis of Steel Research for Code Development sponsored by the Structural Steel Educational Council, and by the Steel Subcommittee of the Seismology Committee of the Structural Engineers Association of California has led to what is, in my opinion, a more rational approach.

The current approach, which is under study for adoption in the codes is expected to include a reduced capacity for braces based on study of cyclic load test data for compression members. The result is anticipated to be reduction of normally used capacities of long slender braces (length divided by radius of gyration in the range of 120) of 1/2 or more. Shorter braces will suffer lesser reductions. Also included in the revised codes will be required improvements in brace connection details which will greatly decrease the probability of brittle connection failure. These improvements will increase the safety of concentrically braced frame systems and possibly foster even wider use of them.

3. ECCENTRICALLY BRACED FRAMES

The eccentrically braced frame is unquestionably the most popular and intriguing of the new systems, because it combines the stiffness advantages of the braced frame with post elastic performance, comparable in its ability to dissipate energy, to the ductile steel moment frame. An eccentrically braced frame has been defined as "a braced frame in which at least one end of each brace frames only into a beam and in such a way that at least one stable ductile link is formed in each beam". If one thinks of framed lateral force resisting systems as a continuum between the extremes of the moment frame, which depends primarily on bending and shear resistance of the frame elements, to the normal braced frame which depends primarily on the axial strength of diagonal members, the eccentrically braced frame would represent the entire array between the extremes. The degree of reliance of the system on bending and shear, versus its reliance on brace axial forces, is primarily a matter of frame aspect ratios.

Although eccentrically braced frames have been used for years somewhat accidentally, the actual rational development of the system for use in resisting earthquakes has been relatively recent. This development is largely due to the work of Egor Popov at the University of California at Berkeley and his various collaborators.

The system performs, as suggested above, as a hybrid between frame action and braced frame action. The bracing provides excellent stiffness useful in limiting building lateral deformations, while the link beam element is designed as a "fuse" to limit the force in the braces and thus prevent non-ductile type failures such as tension failure of the brace connection or buckling of the brace. The action of the link, particularly when it is designed to yield in shear before it yields in bending, is a particularly effective energy dissipator. A feeling for this energy dissipation can be obtained by examining Fig. 1, which is representative of the type of open, stable hysteresis loops observed by Popov in testing of properly designed shear links.

The design of an eccentrically braced frame system is predicated on the following:

- The link beam should be capable of large inelastic vertical deformations (on the order of 10% of its length) through a number of cycles without buckling or tearing failure.

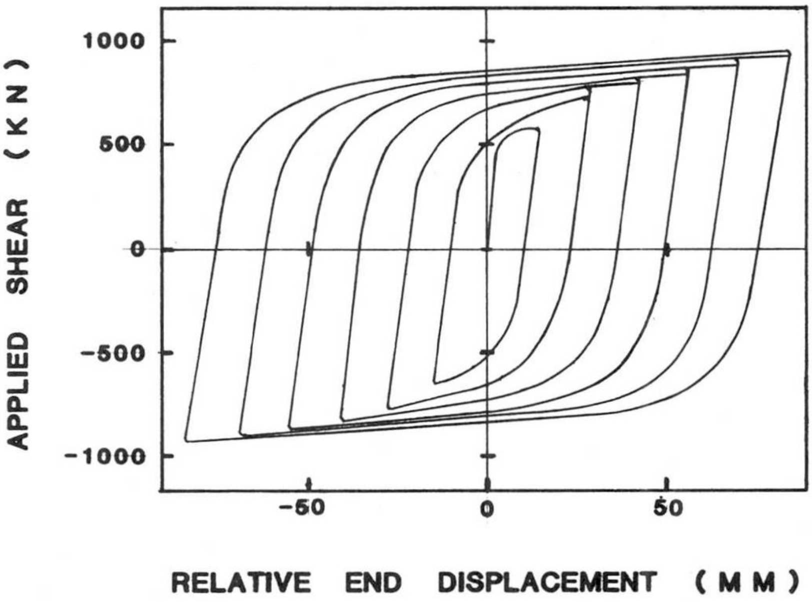

Fig. 1

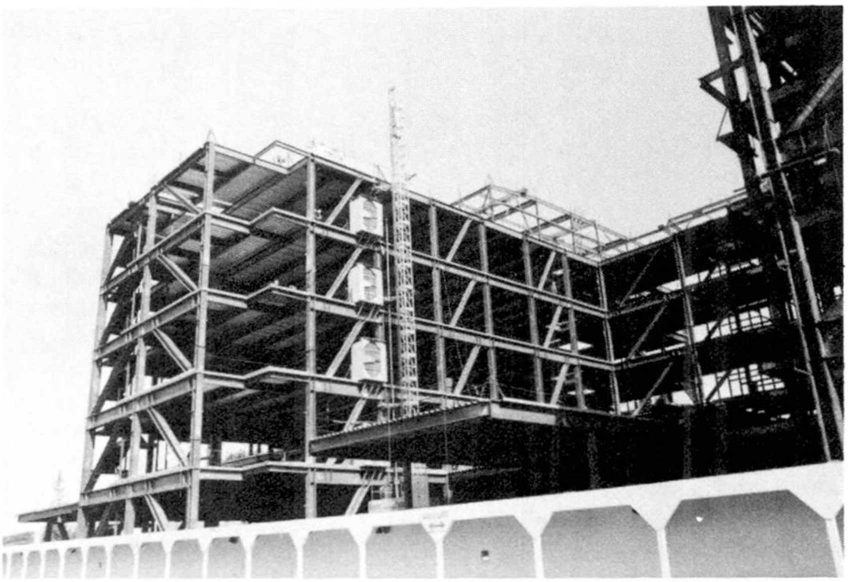

Fig. 2 Eccentrically Braced Frame Hospital

- The strength of the brace and its connection should exceed by a comfortable margin the yield capacity of the link beam.
- Columns and other elements of the system should be capable of resisting elastically the forces occurring at yield of the link beam.

Once the link beam yields, it acts as a fuse to protect the balance of the system from further increases of loading (except for secondary effects such as strain hardening).

Specifics of the design of this system and the research leading to the design procedure are beyond the scope of this presentation. An extensive list of references on the subject is included at the end of this paper.

As suggested above, this system is highly advantageous when there is need for high ductility and energy absorption coupled with high lateral stiffness.

Photographs of a hospital structure employing an eccentrically braced frame system, designed by our office, are included herein. The structure and use are fully described in References [1] and [10].

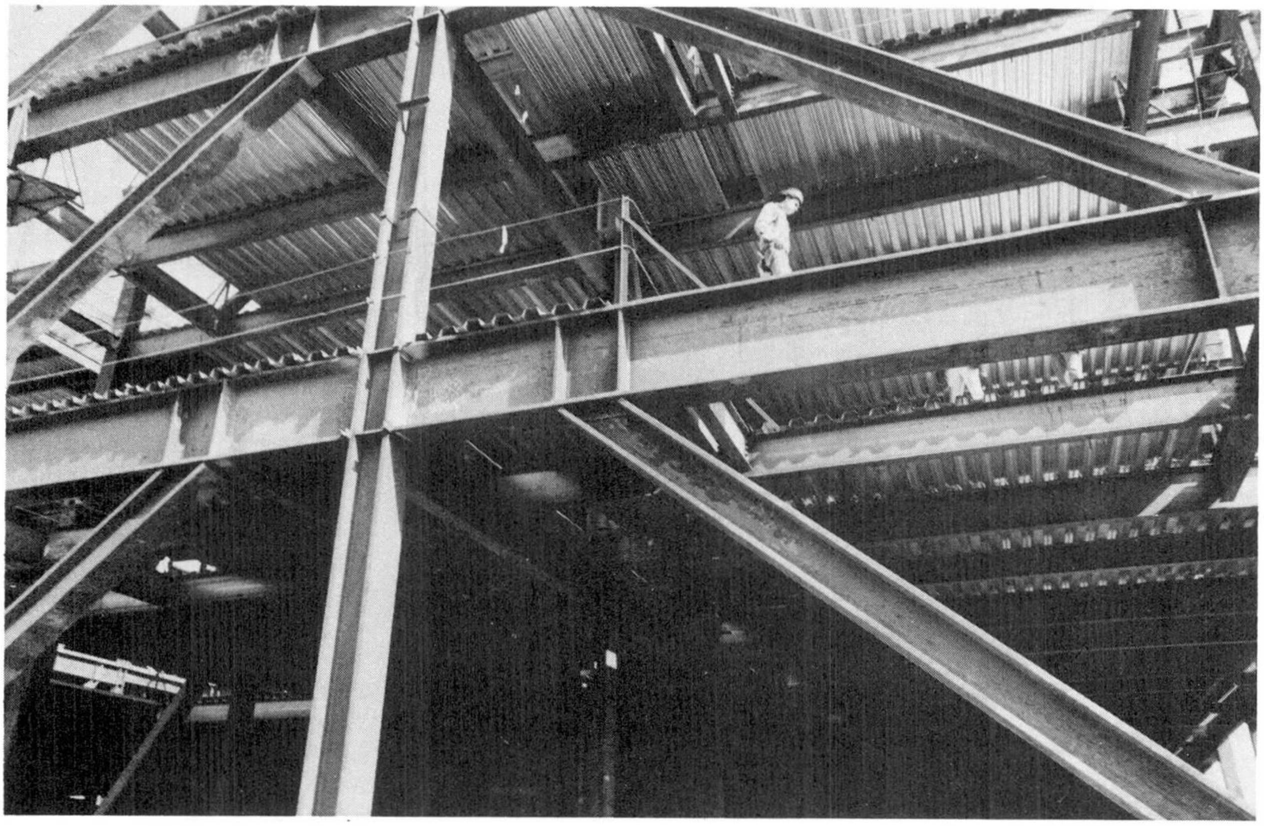

Fig. 3 Eccentric Brace Detail

4. STEEL PLATE SHEAR WALLS

In addition to the use of braced frames to provide seismic bracing for existing heavy and stiff but non-ductile buildings, another novel use of steel has been the steel plate shear wall.

This system has been used in reinforcing an existing hospital building in Charleston, South Carolina where the engineer (URS/John A. Blume and Associates of San Francisco) found that it provided the unique combination of required lateral stiffness and strength with relative ease of erection within a functioning hospital structure.

Each shear wall panel was fabricated in place by field welding a system of plates approximately one meter square and 8 mm in thickness to vertical stiffening ribs made of steel channels approximately 180 mm deep and to horizontal plate stiffeners. The panel size and thickness were determined based on considerations of stiffness and plate buckling and on ease of transportation within the hospital. The panels were attached to existing concrete columns and slabs using drilled-in anchors. A photograph of a typical shear wall panel is included on the next page. Further information on the design of the system can be found in References [2] and [3].

A similar system has also been used in some new structures in both the United States and Japan.

Research on the performance of steel plate shear walls has been reported by Geoffrey Kulak as noted in Ref. [5].

Fig. 4 Steel Plate Shear Wall

5. COMPOSITE STEEL PLATE AND CONCRETE SHEAR WALLS

Another system, which should be mentioned among innovative seismic resistant designs using steel, is the composite steel plate and concrete shear wall system used by H.J. Degenkolb and Associates in designing a 15 story addition for a San Francisco Hospital. This system is fully described in Ref. 4 and will not be repeated in detail herein, except to note the reasons for its use:

- Very high seismic design forces.
- Strict code limitations of lateral deflections (drift).
- Impracticality of moment frames because of member depth, since floor to floor height was limited to match an existing building.
- Extreme thickness required for concrete shear walls (1.2 m at lower levels).
- Difficulty of connections for braced frames under the extreme seismic loadings.

The shear walls consist of steel plates cast into concrete walls. The concrete is held to the steel plates using reinforcing bars through holes in the plates. The concrete is moderately reinforced and is intended to provide lateral stiffness to prevent buckling of the plates and of course will provide considerable dynamic damping to the structure.

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