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STEEL PLATE SHEAR WALLS

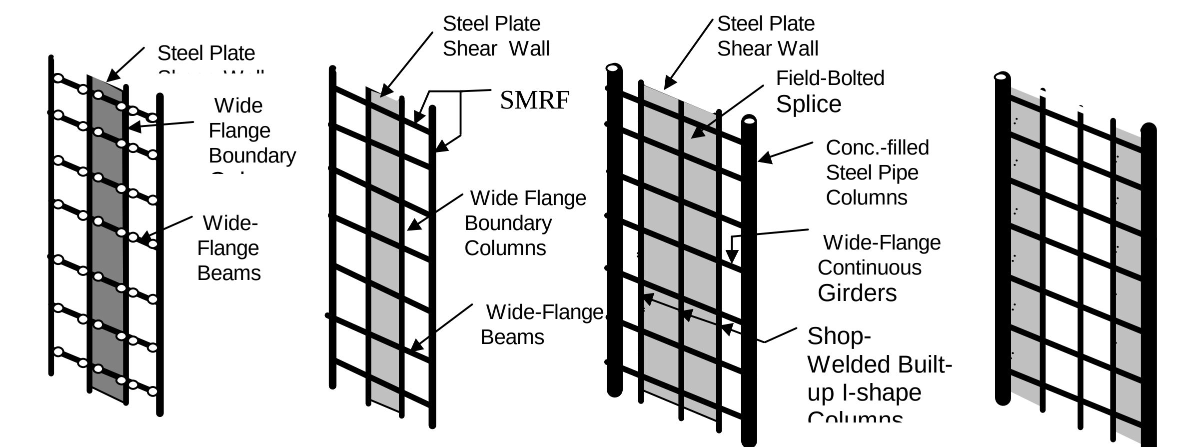
A. ASTANEH-ASL[1]

ABSTRACT

This paper is intended to provide: (a) a summary of the past experimental research on steel plate shear walls with emphasis on research done in North America; (b) a brief summary of state of practice in using steel plate shear walls in highly seismic areas and; (c) a summary of a just-initiated research program at UC-Berkeley to study cyclic behavior of steel plate shear walls and to develop seismic design recommendations. .

INTRODUCTION AND BACKGROUND

The main function of steel plate shear wall is to act as lateral load resisting system and resist horizontal story shear. In general, steel plate shear wall system consists of a steel plate wall, boundary columns and horizontal floor beams. Together, the steel plate wall and boundary columns act as a vertical plate girder. The columns act as flanges of the vertical plate girder and the steel plate wall acts as its web. The horizontal floor beams act, more-or-less, as transverse stiffeners in a plate girder. Figure 1 shows samples of steel plate shear wall systems in use in the United States.



(a) Steel plate shear wall (b) Dual steel plate shear wall system (c) Dual SWMB shear wall system (d) Dual SWMB Shear wall system

(By Skilling, Ward Magnusson, Barkshire)

Figure 1. Two typical steel plate shear wall systems and two innovative systems

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Steel plate shear walls have been used in United States since 1970's when initially they were used for seismic retrofit of low and medium-rise existing hospitals and other structures. These initial shear walls were designed with relatively closely spaced horizontal and vertical stiffeners. The first important structure in California using steel plate shear walls was Sylmar Hospital in northern Los Angeles. Since then, a number of mid-rise and high-rise steel structures with steel plate shear walls have been designed and constructed in west coast of U.S. with high seismicity. A 51-story high-rise is currently at early stages of construction in San Francisco where steel plate shear walls are used as the primary lateral load resisting system.

During the last twenty years, considerable amount of research is conducted in North America as well as in Japan on actual cyclic behavior and analytical modelling of steel plate shear walls. In the following sections, the research done in North America and Japan on steel plate shear walls in recent years, where the results have been in public domain, is summarized.

Figure 2. The 51-story building with dual steel plate shear wall system
(Designed by Skilling, Ward, Magnusson, Barkshire of Seattle. Rendering courtesy of SWMB)

Although valuable research data on steel plate shear walls are available and steel plate shear walls have been used in a number of important buildings, there is very limited information on seismic design of this system in U.S. seismic design codes. In recent years, Canadian Code (CSA, 1994) has been more active in incorporating seismic design information on steel plate shear wall systems. There is a need for use of available research data and conducting more research in areas that are still unknown, with an aim of developing design office oriented guidelines and eventual incorporation of design guidelines into the code provisions and practice. One of the projects currently underway at UC-Berkeley with these aims is the study of steel plate shear walls (Astaneh-Asl, 2000), later discussed in this paper.

PAST RESEARCH ON STEEL PLATE SHEAR WALLS,

The References section of the paper provides a list of citations to research projects on seismic behavior and design of steel plate shear walls (in English) that could be found in a literature search. In the following, a number of research projects, particularly projects focusing on seismic behaviour are summarized.

Performance of Steel Plate Shear Walls during Past Earthquakes

Buildings with steel plate shear walls have been subjected to actual earthquakes. One of the most important buildings with steel plate shear wall, subjected to a relatively strong earthquake, was the 35-story high-rise in Kobe, Figure 3, which was subjected to the 1995 Kobe earthquake. Researchers in Japan, (Fujitani et al., 1996) have studied seismic performance of this building. The study indicated that the damage was minor and consisted of local buckling of stiffened steel plate shear walls on the 26th story and a permanent roof drift of 225mm in northerly and 35mm in westerly directions. The results of inelastic analyses of this structure reported in Fujitani et al. (1996) indicates that soft stories may have formed at floors between 24th and 28th level of the building. A visual inspection of the structure two weeks after the earthquake did not show any sign of visual damage (Kanada and Astaneh-Asl, 1996).

(1995) (1996)

Figure 3. The 35-story shear wall building in Kobe (in the background) sustained minor damage in 1995 while the City Office building in foreground lost its 3 top floors.
(Photos by A. Astaneh-Asl and M. Kanada, from (Kanada and Astaneh-Asl, 1996)

In seismic areas of the United States, such as in California, steel plate shear walls have been used in seismic retrofit of a number of building structures as well as in design of new structures. One of these buildings is the Sylmar hospital in greater Los Angeles area (Troy and Richard, 1988). The building was built as a replacement for the Olive View Hospital that was so severely damaged during the 1971 San Fernando earthquake that it had to be demolished. The structure of the new Sylmar hospital, Figure 4, consists of a steel structure with concrete shear walls in the lower two stories and steel plate shear walls in the perimeter walls of the upper four floors, Figure 4.

The Sylmar hospital has been instrumented by the California Strong Motion Instrumentation Program (CSMIP). The structure was shaken by the 1987 Whittier earthquake and seven years later by the 1994 Northridge earthquake. Figure 5 shows the data recorded by the CSMIP instruments in this building during the 1994 Northridge earthquake. As the CSMIP data indicate, the accelerations at roof level were more than 2.3g while the ground floor acceleration were about o.66g. The investigation of damage to this building in the aftermath of the 1994 Northridge earthquake, by the author, indicated that there was severe damage to some non-structural elements such as suspended ceilings and sprinkler system resulting in breakage of a number of sprinklers and flooding of some floors. In addition, most TV sets bolted to the wall of the patient rooms had broken the connections to the wall and were thrown to the floor. The non-structural damage was clearly indicator of very high stiffness of this structure, which was also the cause of relatively large amplification of accelerations from ground to roof level. Response of this structure has been studied by Celebi and reported (Celebi, 1997).

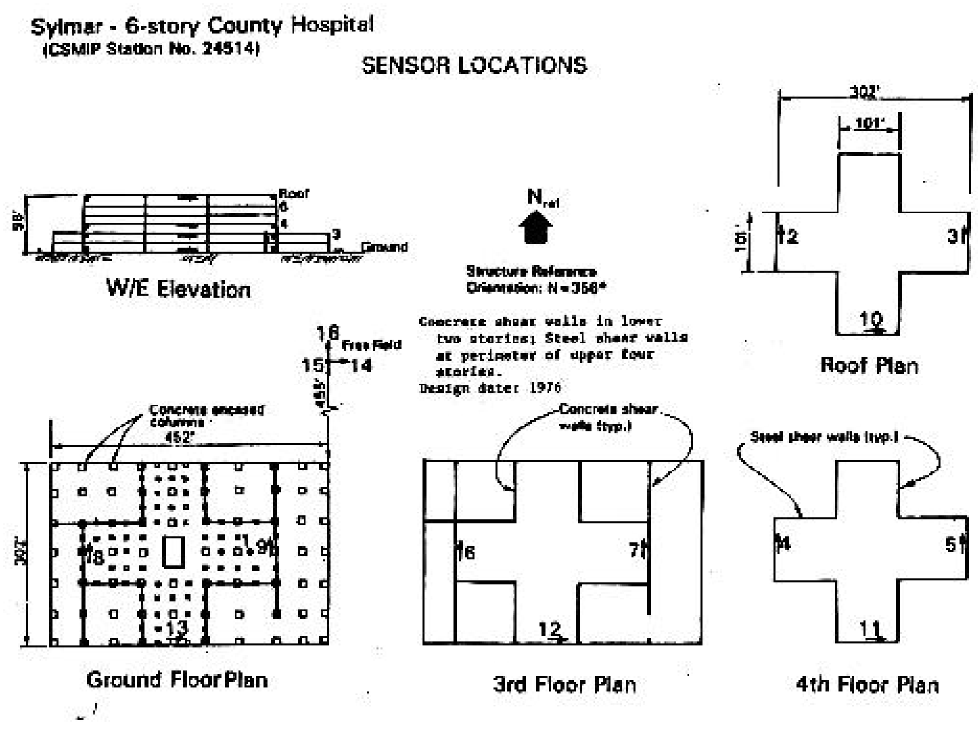

Figure 4. Plan views and elevation of instrumented Sylmar hospital in Los Angeles (CSMIP, 1994)

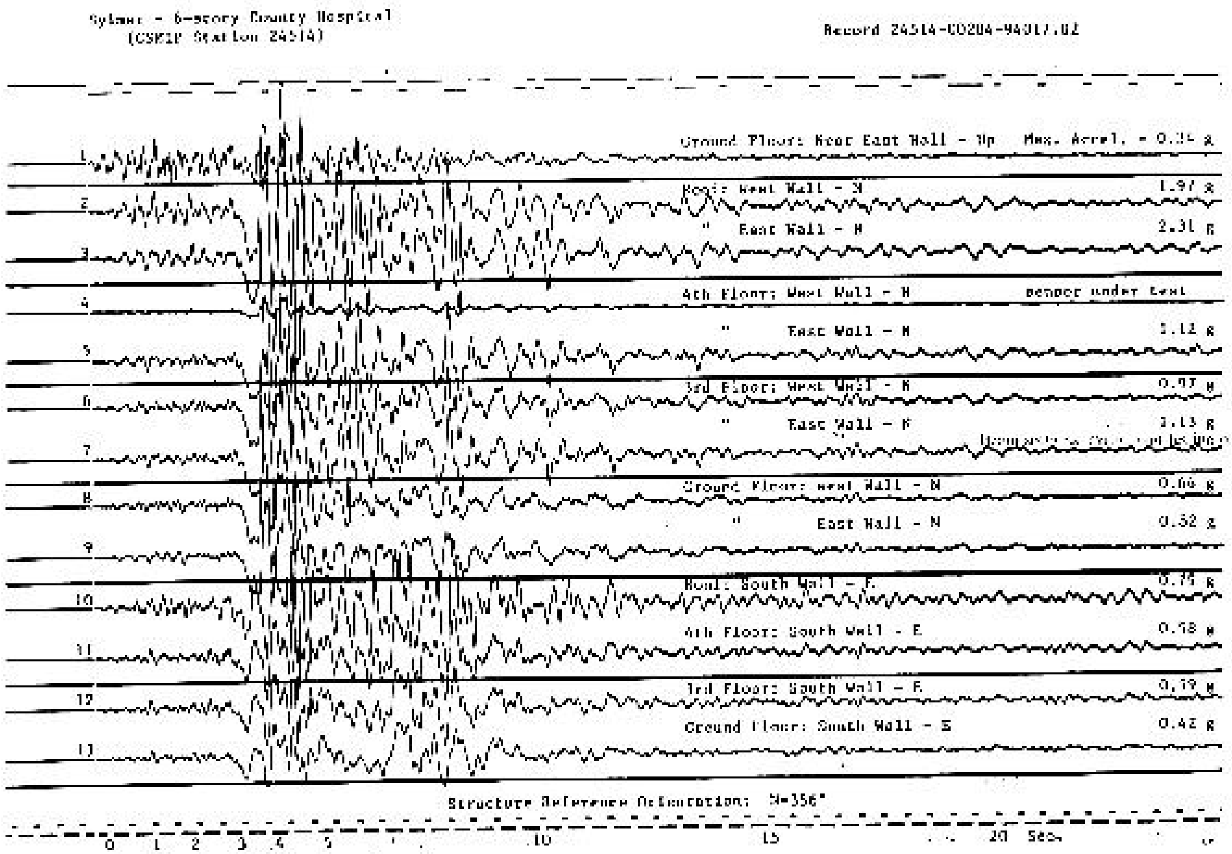

Figure 5. Records obtained from instruments in Sylmar hospital
(CSMIP Records)

Seismic Behavior of Steel Shear Walls in Laboratories

Actual behavior of steel shear walls has been studied in the laboratories by a number of researchers in the US, Japan, Canada and UK. The research conducted in Canada by Thorburn et al (1983) was the first significant work on steel plate shear walls. The studies continued by Kulak (1985) and his research associates (Timler and Kulak, 1987), (Kulak, 1991), (Driver et al., 1996), included cyclic testing of steel shear walls as well as development of relatively simple truss bar models of the shear wall. These studies have resulted in valuable information on seismic behavior, modeling, design as well as code provisions on steel plate shear walls.

Recently Rezaii et al. (2000) and Rezaii (1999) have conducted a number of cyclic and shaking table tests of steel plate shear walls. The cyclic test consisted of subjecting two single story and one four-story single bay steel plate shear wall specimens, Figure 6, to a sequence of low, moderate and severe cyclic loading. The frames in the specimens were moment frames resulting in a "dual" structural system. The single story specimens experienced significant inelastic deformations up to ductility of six. The researchers concluded that the two one story specimens demonstrated that the infill steel plates significantly reduced demand on the moment-resisting frame by producing redundant diagonal story braces that alleviated the demand on the beam-to-column connections. In the 4-storey specimen, a maximum displacement ductility of 1.5 was achieved prior to a global instability failure, propagated by yielding of the columns. The specimen proved to be somewhat more flexible than the one-story specimens. Full details of the cyclic tests can be found in Lubell (1997) and Rezaii (1999).

Figure 6. One-story and four-story specimens (Rezaii, Ventura and Prion, 2000)
(Photos courtesy of Prof. C. Ventura.)

Almost parallel to Canadian studies, in the United States, Elgaaly and his research associates, (Caccese et al, 1993), (Elgaaly and Caccese, 1993), conducted a number of studies of steel plate shear walls including cyclic tests of small scale steel frames infilled with steel plate shear walls. The studies also included valuable analytical research and resulted in development of analytical models of hysteresis behavior of steel plate shear walls

In United Kingdom, Roberts and his research team (Sabouri-Ghomi and Roberts, 1992), (Roberts, 1995) have reported results of 16 tests of steel shear panels diagonally loaded. An analytical model of the hysteresis behavior of the shear panel also was developed in the study.

In Japan, a number of valuable studies on steel plate shear walls have also been conducted and steel shear walls have been used in a number of modern steel structures. Sugii and Yamada (1996) have reported results of tests on 14 steel plate shear walls. Their studies, in all specimens shows pinching of hysteresis loops due to buckling of compression field. Torii et al (1996) have studied application of "low-yield" steel walls in high-rises.
In recent years, there have been significant research and development efforts in Japan to use low-yield steel in shear walls to control seismic response. Such efforts have led to design and construction of a number of structures using this system (Yamaguchi et al, 1998). From the published data, it appears that this system is very promising and more research and development in this field is needed.

CURRENT RESEARCH ON STEEL SHEAR WALLS AT UC-BERKELEY

Currently there are two parallel research projects conducted at the University of California, Berkeley on shear walls. One is on composite shear walls (Astaneh-Asl, 1998-2000) and the other is on steel plate shear walls (Astaneh-Asl, 2000-20001). The project on composite shear walls is sponsored by the National Science Foundation and is part of the US-Japan Cooperative Research Program on Composite and Hybrid Structures. The main objective of the research project on composite shear walls is to study and conduct cyclic tests of composite shear walls system consisting of steel columns, steel girders and steel plate shear walls with concrete wall attached to the steel plate by shear studs. More information on composite shear wall project can be found elsewhere and this project will not be discussed further here.

The project on steel plate shear wall systems is to conduct cyclic tests of two 1/2-scale, 3-story, specimens of shear walls, Figure 7, and to develop design recommendations and analytical models for the tested system.

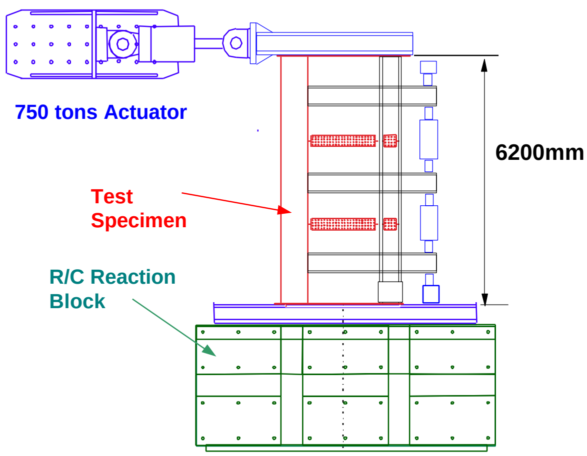

Figure 7. Test set-up and a steel plate shear wall specimen in it, (Astaneh-Asl, 2000).

Objectives of Steel Shear Wall Tests:

1. To establish cyclic behavior of steel plate shear walls, shown in Figure 7, including their stiffness, buckling strength, tension field strength, failure modes and ductility under cyclic event.
2. To test performance of the mid-height construction bolted splice in the walls.

Specimens

The specimens are realistic ½-scale representative of the actual shear walls used in buildings. A total of two specimens will be tested. The specimens will be half-scale realistic representatives of the steel shear wall systems used in high-rise structures. Currently (February 2000), the specimens are being fabricated for testing in March-April 2000.

DESIGN ISSUES ON STEEL PLATE SHEAR WALLS

Currently, there several issues on seismic design of steel plate shear walls that need to be addressed by design codes. These issues relate to seismic design of the systems as well as their components. In order to conduct a rational design, more information is needed to establish forcedisplacement response of the steel plate shear wall systems. Such information can lead to development of performance based design guidelines and code provisions. Also, information needs to be developed for use of current force-based codes. Such information includes proper R-factors for steel plate shear wall systems when they are used as the only lateral load-resisting system or as part of a dual system along with special moment-resisting frames.

As for the design of the components, the first step in design of steel plate shear walls, like any other structural component, is to identify failure modes. The failure modes of a typical steel plate shear wall (Astaneh-Asl, 2000) are:

a. Compressive buckling of the steel plate along the diagonal compression field,
b. Slippage of bolts connecting the wall plate to fin-plates on the boundary columns and beams,
c. Tension yielding of the steel plate along the diagonal tension field,
d. Tension fracture of wall plate along the diagonal tension field,
e. Bending failure of boundary beams or their connections,
f. Failure of the connections of the wall to boundary columns and beams,
g. Compression failure of boundary columns,
h. Tension fracture of the boundary columns,,
i. Failure of base plates of boundary columns in compression or in uplift; and,
j. Failure of foundations of the wall.

To obtain a desirable and ductile performance, these failure modes can be listed with respect to their desirability. This hierarchical order of failure modes is shown in Figure 8

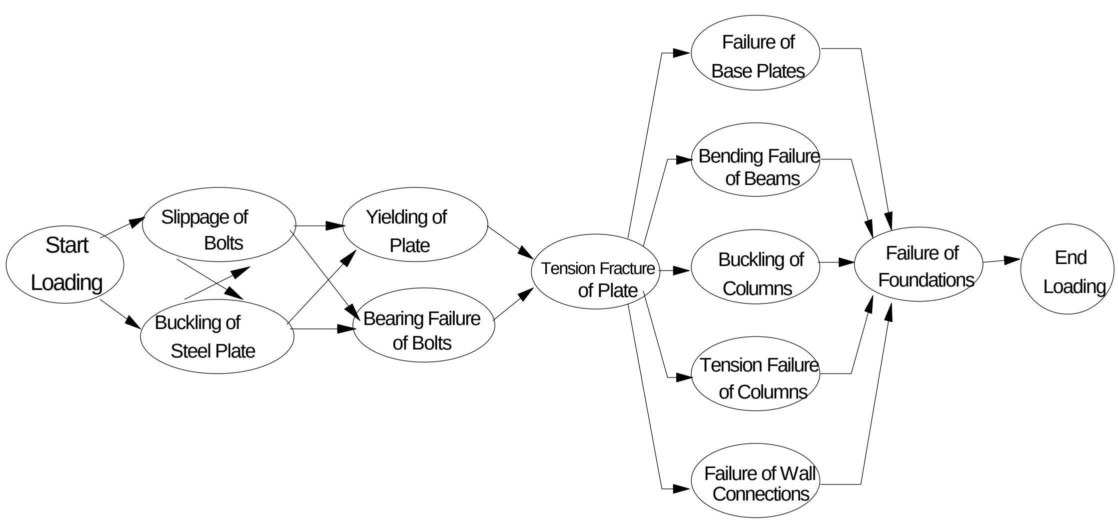

Figure 8. Major failure modes of typical steel plate shear walls

The slippage of the boundary bolts should not be considered a consequential failure mode. In fact, such slippage provides a mechanism of energy dissipation through friction and introduces some beneficial “semi-rigidity” to the structure. The buckling of plate in unstiffened steel plate shear walls is not considered detrimental in performance and has no significant effect on the ultimate shear strength and overall performance of the wall. If buckling of the wall, which will result in out-of-plane deformations, is creating serviceability problems, then stiffened shear walls should be used to delay buckling of the wall and to reduce out-of-plane deformations due to buckling. Of course, such stiffened walls are expected to be more expensive to fabricate. The yielding of diagonal tension field is the best mechanism of failure and should be established as the governing failure mode in seismic design. The fracture in tension or buckling in compression of boundary columns should be avoided in design since such failures can have serious stability consequences as well as very high cost of post earthquake repairs.

Modeling of Steel Plate Shear Walls in Analysis

Studies by Thorburn et al (1983) and later by Driver et al (1998) indicated that steel shear wall can be modeled as truss members by using a series of diagonal tension struts positioned at almost 45-degree angles as shown in Figure 9(a). By replacing the shear wall with these struts, the resulting steel structure can be analyzed using currently available computer analysis software, such as SAP2000 Nonlinear and inelastic pushover programs (CSI, 2000).

Rex, Ventura and Prion (2000) recently have proposed a "multi-angle strip model" for steel plate shear walls. Using a non-linear analysis program and the model shown in Figure 9(b), the researchers have shown that the predictions of analyses are reasonable close to the test results.

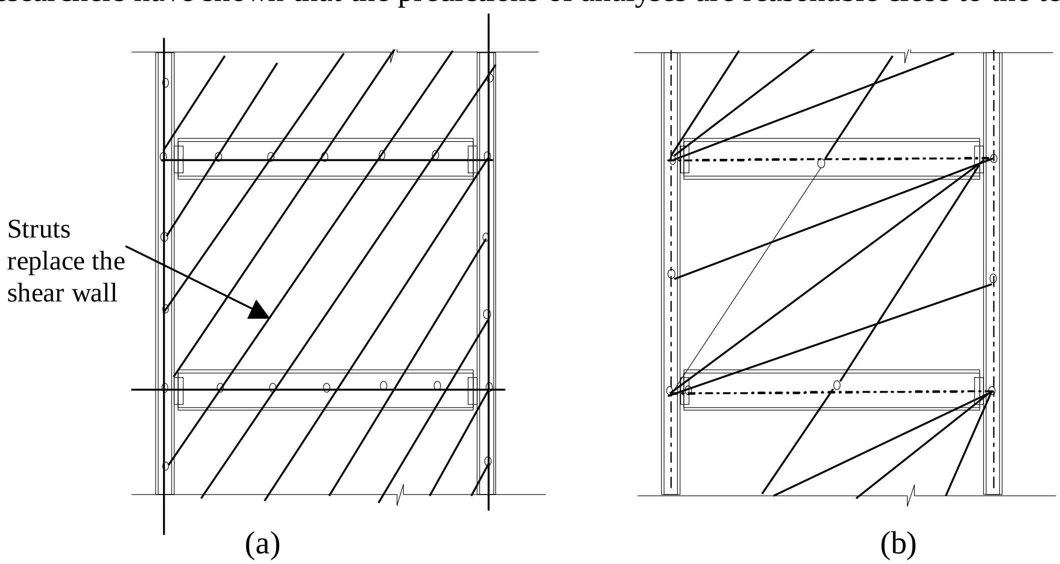

Figure 9. Two proposed strut models: (a) Thorburn et al. (1983) and (b) Rezaii et al. (2000)

Seismic Design Code Issues

Currently, seismic design codes and guidelines in the United States, such as Uniform Building Code (ICBO, 1997) and NEHRP Provisions (FEMA, 1995) have very limited provisions regarding steel plate shear walls. These shear walls can be used within a simply supported frame or can be part of a dual system as shown in Figures 1(a) and 1(b) respectively. In a dual system, the shear wall and its boundary elements are the primary lateral load -resisting system while the entire moment frame after steel plate is removed can be considered the back-up system. For a number of dual systems, the Uniform Building Code (ICBO, 1997) provides specific values of R factor. However, for a dual system of steel moment frame and steel plate shear wall there is no R factor specified. Currently, an R factor of about 7.5 is used for these dual systems. However, considering the available test results and other parameters affecting R factor, it appears that an R-factor of 8.5-9.0 can easily be justified for these systems provided that the back-up moment frame is a special steel moment resisting frame.

ACKNOWLEDGMENTS

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KEYWORDS

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