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SEISMIC RESISTANT TRUSS MOMENT FRAMES WITH DUCTILE VIERENDEEL SEGMENT

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ABSTRACT

This paper presents a comprehensive study on Special Truss Moment Frames (STMF) with Vierendeel configuration of the ductile segment. The Vierendeel panel allows greater flexibility and architectural freedom within the special segment when more open space for larger ductwork is needed. During seismic excitations the resulting lateral forces create vertical shear in the special segment which is resisted solely by the chord members. The special segment acts as a ductile "fuse" which dissipates energy through inelastic flexural deformations. An integrated analytical and experimental program was carried out on four one story full scale truss-column subassemblages of STMF with Vierendeel type special segment. The test subassemblages included parameters such as length and location of the special segment as well as different load combinations and loading sequences. Test results showed excellent behavior of the system with stable and "full" hysteretic loops. A rational expression for determining the required overstrength factor to ensure elastic behavior of members outside the special segment under fully yielded and strain hardened chords of the special segment is also developed. Analyses using SNAP-2D, a general purpose computer program, were used to validate the experimental observations. The program was used further to study the behavior of chords of the special segment in the post-yield range and the dynamic response of the system to severe ground motions. The design concept and procedure has been developed and validated by several tests using full size truss-column subassemblages. The system results in increased economy and excellent inelastic seismic response characterized by stable hysteretic behavior, more ductility, and less story drifts, when compared with other conventional framing systems.

KEYWORDS

Truss; seismic; open-web; STMF; Vierendeel.

INTRODUCTION

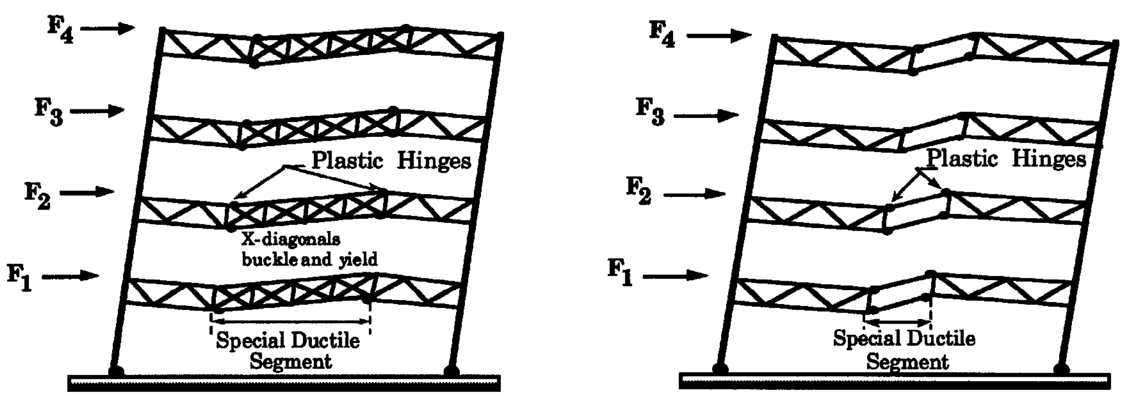
Steel truss moment frames are often used for buildings in seismic regions. This type of framing system is more desirable than solid web framing, primarily for economics of material and flexibility for services running through the girders. The UBC (Uniform Building Code, 1994) currently permits their use as Ordinary Moment Resisting Frames (OMRF) with R_w=*6*, or as Special Moment Resisting Frames (SMRF) with R_w=*12*, provided inelastic activity is kept out of the truss girders. The latter type can be called a "weak column-strong girder" combination, which is not considered very desirable by many engineers. Use of truss girder systems for moment resisting frames has not been popular in Seismic Zones 3 and 4, primarily due to lack of research results concerning them. Also, due to poor observed performance of some truss moment framing structures during the 1985 Mexico City earthquake (Hanson *et al.*, 1986), engineers have been reluctant to use this system in either category in active seismic regions.

A comprehensive experimental and analytical investigation has been carried out at The University of Michigan since 1988 in order to study the seismic behavior of truss moment framing system. The results from the initial phase of the research program led to development of Special Truss Moment Frame (STMF). The new concept utilizes ductile trusses in a "strong column-weak girder" combination which is preferred by most engineers. The system was originally developed with X-diagonal web members in the special ductile truss segment. It has been shown to be very economical and possesses excellent ductility and stable hysteretic behavior which result in superior response to severe earthquake ground motions when compared with other conventional framing systems which showed rather poor hysteretic behavior with large abrupt drops in strength and stiffness caused by buckling and early fractures of diagonal web members of the truss girders. However, when X-diagonal web members are used in the special segment the available space may be somewhat restricted. In such cases, a fully open Vierendeel type special segment is more attractive to designers.

In a recently completed study (Basha and Goel, 1994) the concept of STMF was extended to fully open Vierendeel type special ductile segment in the middle half of the of truss girders. Such open panels allow greater flexibility and architectural freedom within the special segments when more open space for larger ductwork is needed. In this case, the chord members provide all the needed strength and energy dissipation by formation of plastic hinges at the ends of the special segment. The primary objective of this paper is to present the design concept and evaluate the seismic response of STMF with Vierendeel special segment.

CONCEPT OF STMF

Special Truss Moment Frame (STMF) is a steel structural system in which during a severe earthquake all inelastic deformations are limited to occur in a specially designed portion of the truss girders, called the special (ductile) segment, while rest of the structure essentially behave elastically. The ductile segment is strategically placed in a portion of the truss span. The most logical place is near the mid span where gravity load shears are generally small. The design concept of STMF uses a limit state (plastic) design approach and ensures ductile behavior of the truss girders with "full" and stable hysteretic loops. Hence, STMF are designed using $R_w = 12$, as in Special Moment Resisting Frames (SMRF).



X-Diagonal Configuration of Special Segment — Vierendeel Configuration of Special Segment

Fig. 1. Yield mechanism of STMF.

As the system is subjected to seismic excitations, the resulting lateral forces create vertical shear in the special segment, which is resisted by X-diagonals, if exist, and chord members of the special segment. The special segment acts as a ductile "fuse" which dissipates energy through inelastic flexural deformations of the plastic hinges in chords of the special segment, and buckling and yielding of X-diagonals if exist. This will be the yield mechanism of the frame, with plastic hinges also forming at the bases of the columns if they are fixed. The application of this concept in a moment frame is illustrated in Fig. 1. In order for this yield mechanism to develop it is essential that outside segments of the trusses, and the columns possess strength greater than that required to resist the ultimate strength of the special yielding segments in combination with appropriate gravity loads. Therefore, it is essential that adequate overstrength factors be used to account for probable yield strength and stain hardening of the yielding members in the special segments at maximum expected deformations.

DESIGN CRITERIA OF STMF WITH VIERENDEEL SPECIAL SEGMENT

Special Segment

The design of STMF begins by determining the required vertical shear in the special segment due to the two load combinations:

(a) $1.2D + 1.6L$ (Elastic Behavior)

(b) $1.2D + 0.5L + 1.5E$ (Mechanism)

Under the first load combination which involves gravity loads alone, all members of the truss girder as well as columns must remain elastic. Chords of the special segment are not allowed to experience any inelastic deformations under this load combination. Under the second load combination which involves gravity and earthquake loads, yielding in chords of the special segment may occur, i.e., a yield mechanism of the frame is permitted. Shear force in the special segment due to this load combination may reach the design shear strength of the special segment. Chords of the special segment are then designed for the governing vertical shear from these two load combinations. The special segment must satisfy the following:

(a) $V_u \geq Required\ Shear$ (for the special segment)

(b) $b/t \leq 52/\sqrt{F_y}$ (for angles of the chords)

(c) $P_u/\varphi_t P_y \leq 0.4$ (for chords of the special segment)

Members Outside the Special Segment

According to the design philosophy of STMF, members outside the special segment, including columns, must remain elastic while supporting the ultimate shear strength of the special segment with an adequate overstrength factor, ξ. They should be designed to satisfy the requirements of the following load cases:

(a) $1.2D + 1.6L$ (Elastic)

(b) $1.2D + 0.5L + V_l$ (Mechanism)

The maximum vertical shear in the special segment due to lateral loads, V_l, is obtained as follows:

$$V_{ss} = \mp V_l + V_g \Rightarrow V_l = \pm V_{ss} + V_g = \pm \xi V_u + V_g \quad (1)$$

where, V_{ss} is maximum vertical shear in the special segment under combined gravity and lateral loads and V_u is vertical shear in the special segment when mechanism is formed in the Vierendeel panel. It should be noted that:

- V_{ss} is constant since it depends on maximum deformation in the special segment. It can be +ve or -ve depending on direction of lateral forces applied.
- V_u is constant for given gravity load case. Different gravity load cases result in different values of V_g and consequently different V_l.

EXPERIMENTAL PROGRAM

A four story building using STMF with Vierendeel special segment was selected for this study. The building has plan dimensions of 196 ft by 84 ft, and a story height of 13 ft for all four stories. The building is divided into three bays in the transverse direction and seven bays in the longitudinal direction forming equally spaced frames of 28 f in both directions as shown in Fig. 2. Secondary steel joists spanning the longitudinal direction between the longitudinal frames are simply supported by the transverse frames.

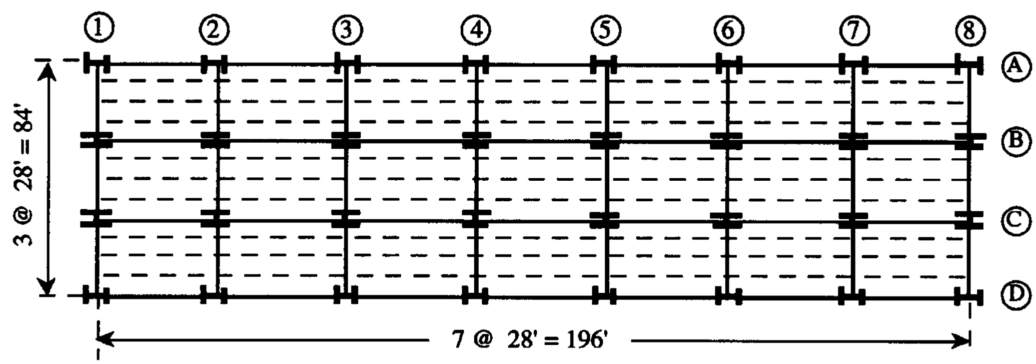


Fig. 2. Plan view of the study building.

The two perimeter moment resisting longitudinal frames (A and D) resist lateral forces and provide lateral stability of the entire building in that direction. These frames are primarily lateral resisting frames with relatively little gravity loads which may be neglected for simplicity. The interior frames (B and C) support only gravity loads for their tributary areas. All frames spanning the short direction of the building (1 through 8) are moment resisting frames which resist lateral forces and support gravity loads as well.

The experimental program was carried out in two phases in which four one-story full scale truss-column subassemblages of STMF with Vierendeel type special segment were tested. The test subassemblages included parameters such as length and location of the special segment, width-to-thickness ratio of chords in the special segment, as well as different load combinations and loading sequences. Boundaries of the subassemblages were chosen to simulate assumed inflexion points (modeled by pins) at mid height of columns of the prototype multistory frame. Each subassemblage is made of two columns, the truss girder specimen, and a rigid link beam. Lateral load was applied at the upper end of one of the columns by means of a hydraulic actuator. The link beam is used to transfer lateral loads to the other column.

Phase 1

In the first phase of the program, frames spanning the longitudinal direction (A and D) of the building were studied (Basha and Goel, 1995). As explained earlier, gravity loads on these frames are small and were neglected in this phase for simplicity. The special (ductile) segment was chosen in the middle of the truss girder. These frames were designed based on the design concept of STMF, presented earlier in this paper, to withstand seismic lateral forces which were calculated to comply with the UBC-94 provisions. The overstrength factor, ξ, was assumed equal to 1.5. Figure 3 shows a typical load-deformation response of STMF subassemblage tested in this phase, due to lateral loading sequence shown in Fig. 4.

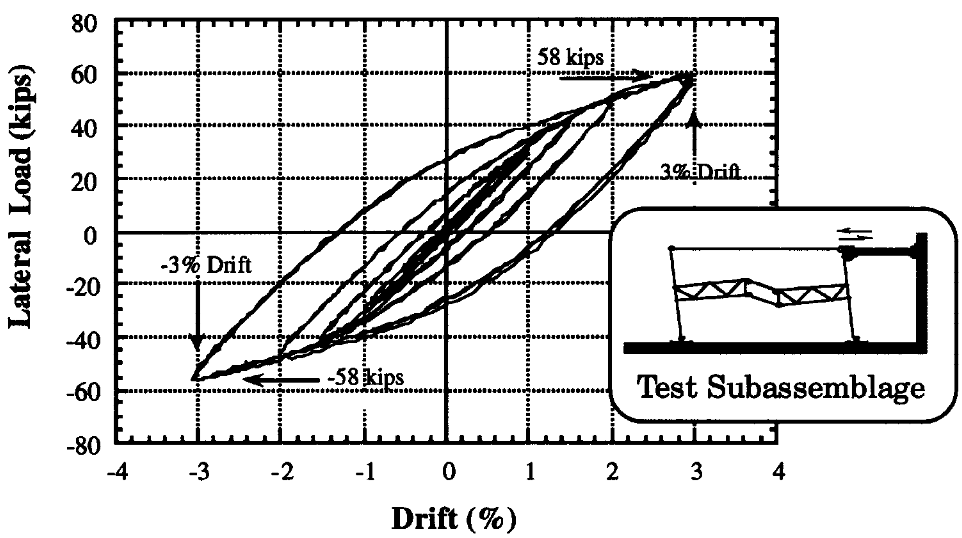


Fig. 3. Hysteretic response of STMF under lateral loads alone.

The hysteretic response of STMF subassemblages was excellent, characterized by "full" and stable loops as shown in Fig. 3. The yield mechanism was as expected with plastic hinges at ends of chords of the special segment, whereas all other members outside the special segment remained elastic. The overstrength factor computed from the test was equal to 1.6, slightly larger than the assumed factor.

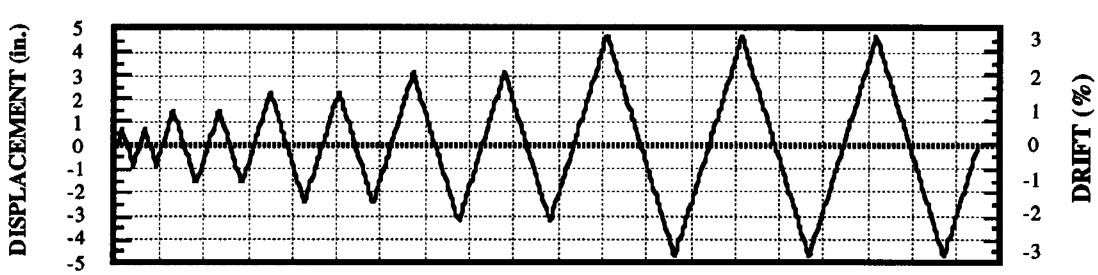


Fig. 4. Loading sequence.

Phase 2

In the second phase, the focus is on frames spanning in the short direction (1 through 8). These frames were subjected to equivalent earthquake lateral forces in addition to concentrated gravity loads transferred by the secondary steel joists at quarter points of truss girders. Since gravity loads are not permitted within special segments, it was decided to off center the special segment as shown in Fig. 5. For test purposes, the three gravity loads were substituted by an equivalent one gravity load applied at mid span. The one point gravity load was chosen in such a way as to equate the resulting vertical shear in the special segment to that of the three point loads. Gravity load was applied at mid length of the specimen through a flexible steel cable connected to a second hydraulic actuator placed horizontally on the floor of the laboratory. Two full-scale subassemblages representing these frames were tested, Fig. 5 shows a typical interior frame in the short direction, and the test subassemblage used.

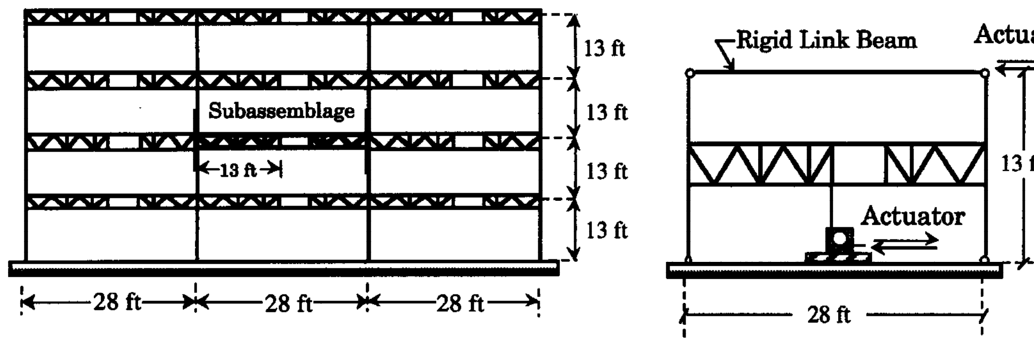


Fig. 5. Typical interior frame of the study building and test subassemblage.

The building was designed based on the design concept of STMF presented earlier in this paper to withstand gravity loads as well as seismic lateral forces. The overstrength factor for the first specimen was assumed equal to 1.5. However, at 1.5% drift the computed overstrength factor was already equal to 1.5. The assumed overstrength factor in this case was inadequate, since imposed lateral drifts of the subassemblage were supposed to continue up to 3%. It was then decided to unload the gravity load and continue the test under lateral loads alone.

OVERSTRENGTH FACTOR, ξ

Inherent with the design philosophy of STMF a reasonable upper bound estimate is needed for vertical shear and/or end moments that can be developed in members of special segments. Consequently, a mathematical expression to determine the required overstrength factor was developed (Basha and Goel, 1994). Its value primarily depends on length and moment of inertia of chords of the special segment, maximum vertical and rotational deformations at ends of chords of the special segment, as well as strain hardening and yield strength of material of the chords. ξ is determined from the following expressions:

$$M_{max} = (\Delta/h) \cdot ((L-L_s)/L_s^2) \cdot 6EI_x \cdot \eta + (1-\eta) \cdot M_n \geq M_n \tag{2}$$

$$\xi = M_{max}/M_n \tag{3}$$

where Δ/h is the story drift, L is span length of the truss girder, L_s is length of chord of the special segment between the two plastic hinges formed at its ends (90% of length of the special segment), M_n is the nominal bending strength of chords of the special segment, and η is ratio of the post-yield slope to the elastic slope of the bi-linear moment-deflection model of chords of the special segment. Correlation of experimental results with analyses using SNAP-2D computer program (Firmansjah and Goel, 1992) - a program for elastic and inelastic, static and dynamic analyses of 2D-structures - showed that the moment-deformation bi-linear model generally used in the analysis of beam-column elements (with 5% post-yield slope) is inadequate for chords of the special segment. This is due to the fact that the model was derived based on past tests of beam-column subassemblages which were conducted under conditions of much lower moment gradient than is typical of chords of special segments in STMF. A moment-deformation bi-linear model with 10% post-yield slope was found more acceptable for chords of special segments in STMF. In order to account for actual strength of material over nominal values in calculating the maximum bending moment in chords of the special segment, η is taken 15% instead of 10%. Thus, for 3% drift, (2) becomes,

$$M_{max} = 0.027EI\{(L-L_s)/L_s^2\} + 0.85M_n \geq M_n \qquad (4)$$

A similar expression was also developed (Basha and Goel, 1996) for STMF with X-diagonal configuration of special segments,

$$M_{max} = 3.4M_n/L_s + 0.11EI\{(L-L_s)/L_s^3\} + 1.25(P_{st} + 0.3P_{sc})\sin\alpha \qquad (5)$$

where P_{st} and P_{sc} are the yield and buckling strength of X-diagonals, and a is the angle which X-diagonals make with the horizontal.

The developed expression given in (4) was used in the design of the second subassemblage tested in phase II of this experimental program. The subassemblage was subjected to lateral loads applied in a quasi-static manner in the presence of gravity loads at the middle of the truss girder as explained earlier. The loading sequence is shown in Fig. 6. After completing the prescribed loading sequence additional cycles of 2% drift were applied until the truss girder lost most of its strength.

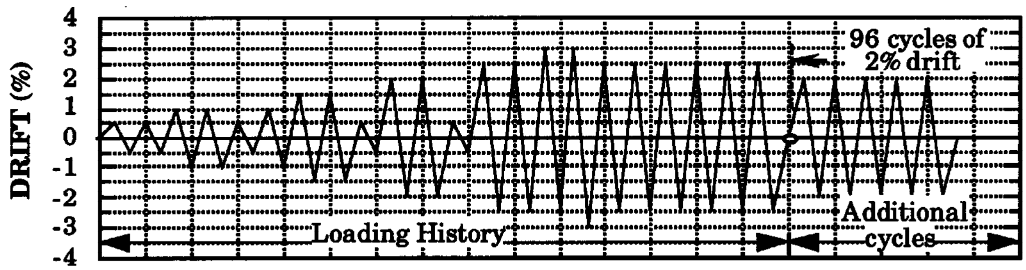


Fig. 6. Loading sequence.

The lateral load-deformation response of the subassemblage is shown in Fig. 7. Due to lack of symmetry (special segment off centered) lateral loads required to attain certain lateral deformations were different than those required for same deformations in the other direction. All inelastic deformations were limited to chords of the special segment. As shown in Fig. 7, hysteretic loops were "full" with no degradation. Also shown is the increase in lateral stiffness of the girder, this was due to the spreading of the inelastic zones at ends of chords of the special segment under larger deformations, i.e., increase in length of plastic hinges, and consequently reducing the effective length of the ductile segment to about 90% at 3% drift. The overstrength factor computed from the test was 2.0 compared to 2.1 as calculated from (3).

After completing the prescribed loading sequence, the specimen was cycled 96 times at 2% drift until fracture was initiated in angles of chords of the special segment. The hysteretic response of this part of loading is shown in Fig. 8.

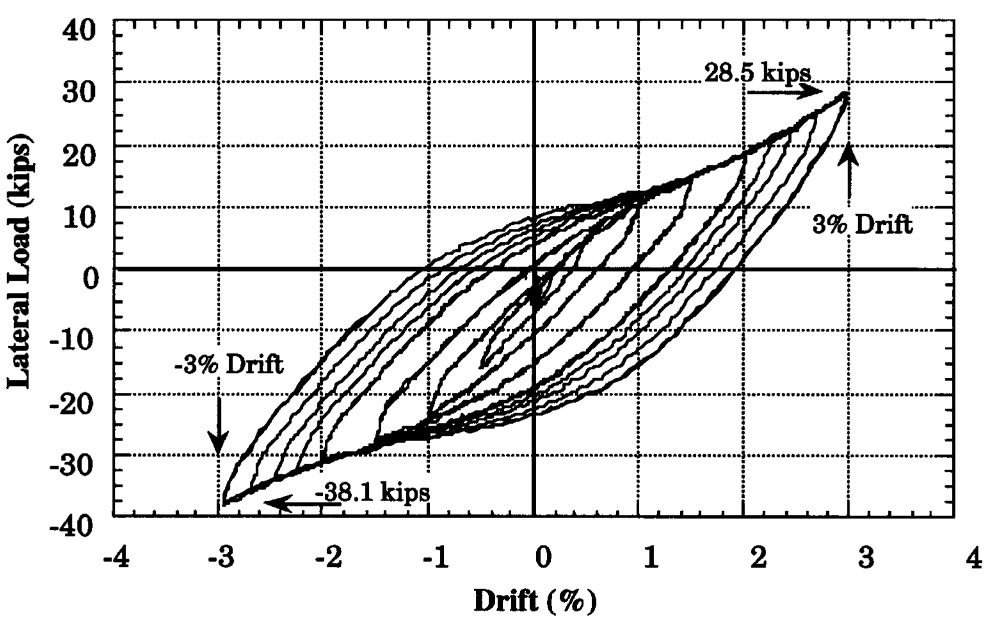


Fig. 7. Hysteretic loops of STMF under combined gravity and lateral loads.

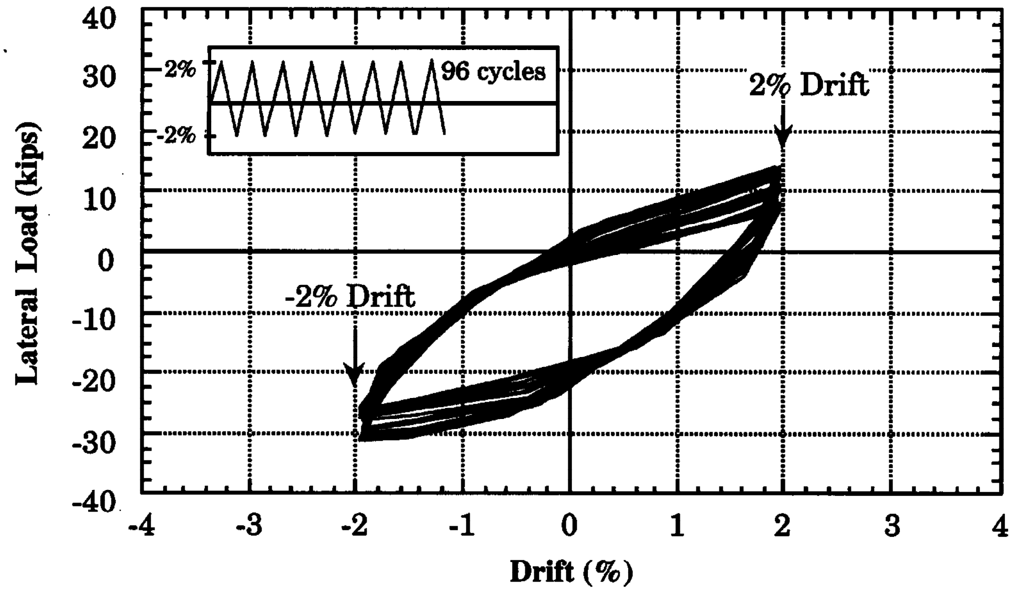


Fig. 8. Hysteretic loops of STMF - additional cycles.

DYNAMIC RESPONSE

The dynamic response of the four story building was also studied using SNAP-2D computer program. The building was subjected to a severe earthquake record (Miyagi-Ken-Oki record scaled to 0.4g PGA). A typical four story one bay frame representing frames in the longitudinal direction of the building (Frames A and D) was analyzed. The relative mid-story displacement responses were monitored, Fig. 9 shows the largest set which corresponds to the second story. The maximum story drift was about 2.9%.

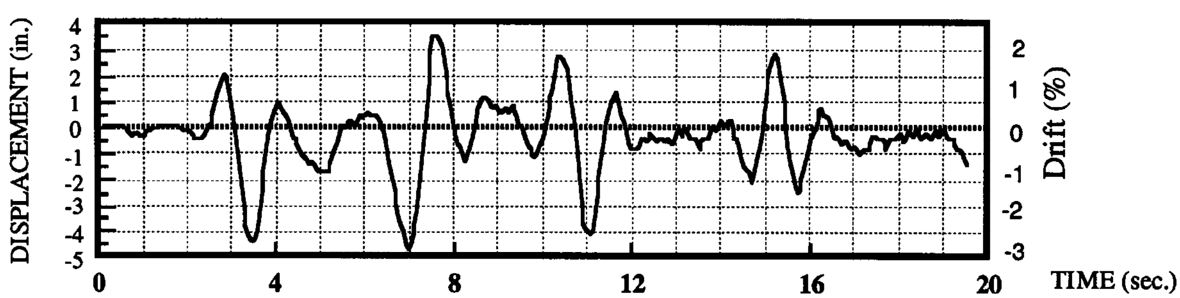


Fig. 9. Maximum relative mid-story displacement response of the four story. frame.

Frames spanning the long direction of the building were previously studied (Itani and Goel, 1990) when designed as conventional truss moment frames (OMRF), solid-web frames (SMRF), and STMF with X-diagonal special segment and the above mentioned framing systems. The system showed excellent response when compared to other framing systems subjected to the same ground motion. It showed better response, characterized by smaller floor displacement and story drifts, in addition to less total weight of steel.

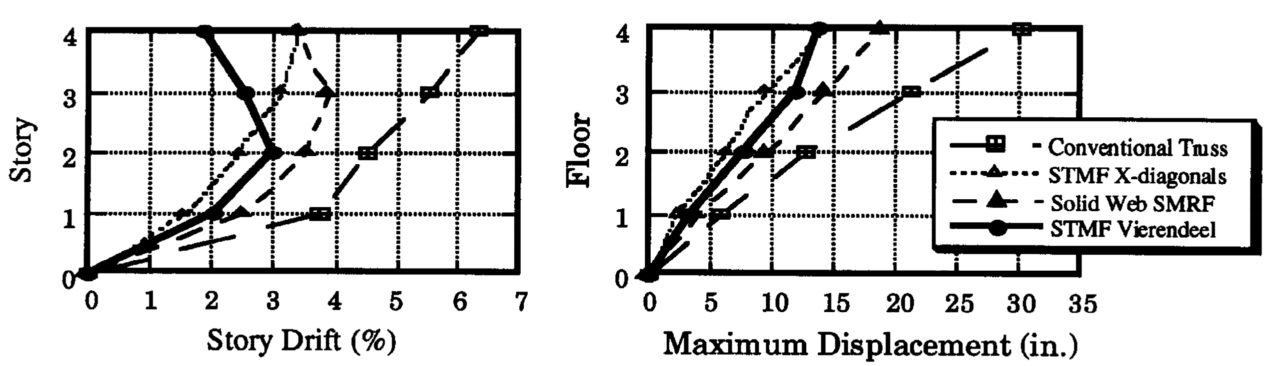


Fig. 10. Comparison between responses of different framing systems.

Dynamic response of the gravity load carrying frames spanning the transverse direction of the building was also studied. A typical interior four story three bay frame representing these frames (Frames 1 through 8) was analyzed. The relative floor displacement responses were monitored, Fig. 11 shows the largest set which corresponds to the second story. Maximum floor drift was 3.3 in.(2.2%). Results at end of the analyses showed no inelastic deformations any where other than chords of the special segment and bases of columns which were necessary to form the expected mechanism.

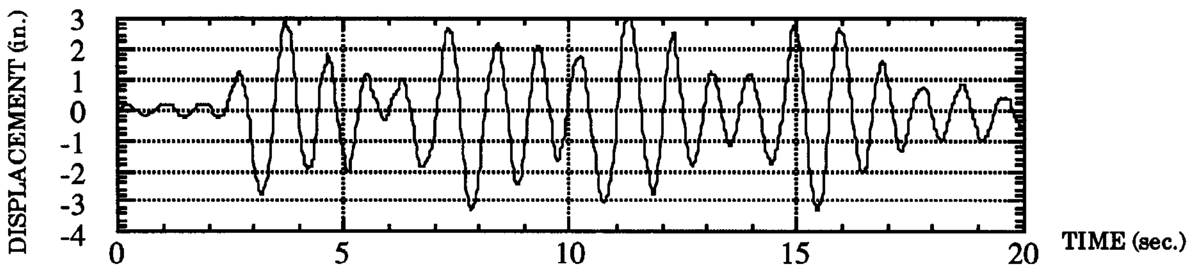


Fig. 11. Maximum relative floor displacement of the three-bay frame.

CONCLUSIONS

The analytical and experimental study demonstrated excellent behavior of STMF with Vierendeel type special segment under lateral loads alone as well as under combined gravity and lateral loads. The design concept and procedure has been developed and validated by several tests using full size truss-column subassemblages. A mathematical expression for determining the required overstrength factor which is used to ensure elastic behavior of members outside the special segment under maximum vertical shear generated by members of the special segment is also developed. The system results in increased economy and excellent inelastic seismic response characterized by stable hysteretic behavior, more ductility, and less story drifts, when compared with other conventional framing systems. Analyses using SNAP-2D computer program, were used to validate the experimental observations. The program was used further to study the behavior of chords of the special segment in the post-yield range and the dynamic response of the system to severe ground motions.

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