

SEISMIC RESPONSE INVESTIGATION OF SPECIAL TRUSS MOMENT FRAME (STMF) SUBASSEMBLIES UNDER QUASI-STATIC LOADING

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Abstract

A preliminary analytical study of Special Truss Moment Frame (STMF) subassemblies was implemented, using SAP2000, to verify if earthquake induced forces and deformations are resisted when members of a single-panel Vierendeel special segment behave inelastically. The ductile behavior is to be confined only to the special segment, located at the mid-span of floor truss girders, while the remaining members are to behave elastically. The objective of the STMF system is to limit the forces and moments in the members outside the special segment, by the capacity of the special segment. After testing the analytical models with a simplified SAC loading protocol, the force distribution showed that the forces in the members outside the special segment experienced significantly large forces relative to the special segment. Modifications of the conventional STMF design were proposed in which “true” pins were introduced at the chord ends of a two-panel Vierendeel special segment. The analytical testing results showed a significant reduction in axial, shear, and bending moments. If an STMF system is successful in reducing forces and deformations, it will allow buildings to remain inhabitable after an earthquake has occurred. Limiting damage only to the special segments will significantly reduce repair costs compared to conventional building design.

STMF Background and Research Project

Research involving Special Truss Moment Frames (STMF) is of great interest because structures equipped with this system will be able to withstand large seismic events. The idea behind the STMF design is that a “structure can survive an earthquake if sufficient energy dissipation capacity is provided with respect to the energy demand” (Pekcan and Itani, 2007). The STMF system is highlighted by the special segment found at the mid-span of floor truss girders in steel buildings. The special segment can be constructed with or without Vierendeel X-diagonal members. The first STMF system with X-diagonals was developed by Itani and Goel (1991). Due to the excellent behavior of this system, Basha and Goel (1994) developed the STMF system without X-diagonals (Chao and Goel, 2006). For this research project, the STMF system consisted of a single-panel Vierendeel special segment without X-diagonals (fig. 1). The inelastic behavior of the special segment is responsible for resisting forces and deformations induced by earthquake lateral ground motions. The special segment is designed to behave inelastically while the remaining members are to behave elastically. The special segment is designed to withstand large inelastic deformations during seismic events (Pekcan and Itani, 2007). The design of the STMF was carried out using the capacity-design (strong column weak-beam) approach which is “employed to force plastic hinges to form at the beam ends” (Chao and Goel, 2006). The yield mechanism of the STMF system consists of the formation of four plastic hinges at the ends of the

special segment chords. Additionally, STMF systems generally have a higher structural redundancy compared to other systems because of the possible formation of four plastic hinges in the chords of one truss girder (Chao and Goel, 2006). The analytical subassembly models were created using an integrated structural analysis and design software SAP2000 version 11 (CSI, 2007). The purpose of this research paper is to explain the preparation of the analytical modeling and the results obtained from the testing. The findings of the testing will be discussed which will provide insight into its implications. Due to the unexpected results of the conventional STMF design, a modified STMF system was proposed. Real pins were introduced at the chord ends of a two-panel Vierendeel special segment. After testing the modified STMF system, the results improved significantly. Ultimately, the purpose of the analytical modeling was to verify if the STMF characteristics were met. It is to be seen if all inelastic behavior is confined only to the special segment, and see if the forces and moments experienced in the members outside the special segment are limited by the capacity of the special segment.

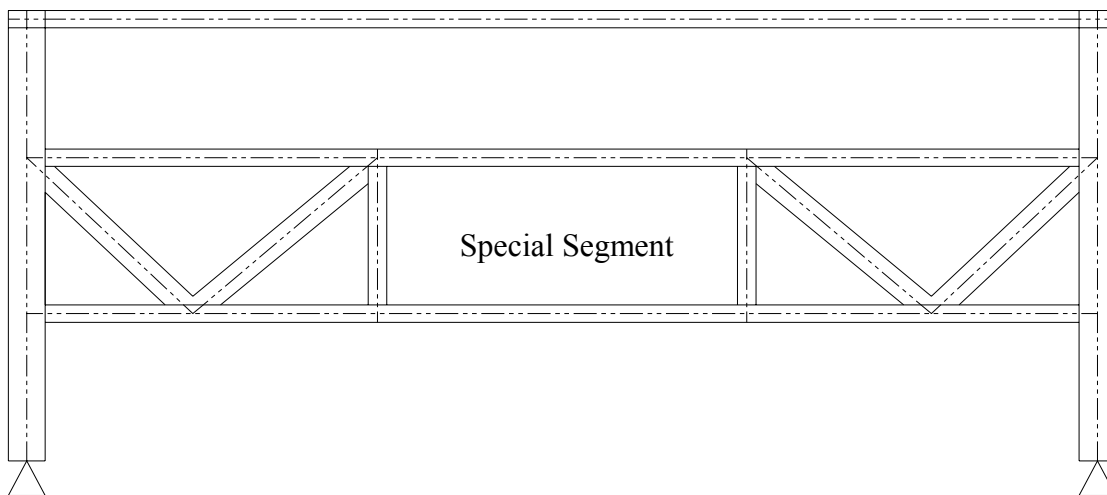


Figure 1: Special Truss Moment Frame (STMF) subassembly with a single-panel Vierendeel special segment.

Significance of Study

Analytical models of the Special Truss Moment Frame (STMF) subassemblies were created during this research project to gain knowledge of the components that make up whole systems. The subassemblies were subjected to lateral push-pull ground motions that are very common during earthquakes. The STMF subassemblies were chosen from a 7-story building that was designed and analyzed by Chao and Goel (2006). The benchmark building was designed by using the Performance-Based Design approach. The steel building is 90 ft by 90 ft in span, and 118 ft in elevation with three 30 ft on-center bays in each direction. Seven subassemblies were modeled for this research project, each consisting for one floor of the building. Each of the seven subassemblies was modeled using SAP2000. Testing subassemblies allows for the observation of damage characteristics under induced ground motions. Be able to see the general trend of the distribution of forces and moments along the STMF. This analytical modeling is part of a preliminary investigation of the STMF system that will lead to experimental testing. Several

STMF systems with various alternative details will be constructed and tested at the University of Nevada, Reno in the near future.

Importance of Research

Structural engineers must find ways to design structures that will survive earthquake ground motion. In this particular case, this research project looked at steel buildings. The Special Truss Moment Frame (STMF) is a relative new type of steel structure system that is “implemented in buildings to help dissipate energy induced by earthquake ground motions” (Chao and Goel, 2006). As noted before, the objective of the system is to resist forces and deformations through ductile behavior (i.e. yield) in the chords of the special segment. The inelastic behavior of the special segment, “limits forces on all elements outside the special segment, to the ultimate capacity of the middle (special) segment, thus enabling them to remain elastic” (Pekcan and Itani, 2007). The purpose of the STMF system is to give buildings a system that will help reduce damage and prevent collapse when earthquakes hit. The drive to design a building with an STMF system is that they will be subjected to controlled damage. Buildings would be repairable because damage would be confined only to the special segment. This is important because repair costs would be significantly reduced compared to conventional building design. The importance of this topic is that many lives would be saved because buildings would stand erect after an earthquake occurs.

Objectives

The task of this research project is to verify that the Special Truss Moment Frame (STMF) behaves like designed to behave. In the analytical subassembly models, the members of the special segment should experience yielding by the formation of four plastic hinges at the chord ends. The analytical models should confirm that the inelastic behavior is confined only to the special segment, which will ensure that the members outside the special segment remain elastic. The analytical modeling will show the force distribution in the frame elements. The analytical testing will show if the forces and moments experienced by the members outside the special segment are limited by the capacity of the special segment. The STMF system allows detailing for controlled damage in the special segments of open web trusses that replace conventional solid web girders (Pekcan and Itani, 2007). Thus, the STMF system enables the use of simple detailing in the beam-column connections. The connections are the most important part of the frame because they cannot fail under any circumstances, otherwise the experiment would be inaccurate. The possible failure of the connections cannot be captured using SAP2000 but it is assumed that the connections will not fail.

Proving that the system will indeed work well in resisting forces and deformations, will allow implementation in buildings. The STMF system can either be used in the design of new buildings or used to retrofit older buildings. Buildings will be safer, and damage received from earthquakes will be reduced significantly compared to conventional design.

STMF Subassembly Overview

Previous analytical and experimental research has been done by Itani and Goel (1991) and Basha and Goel (1994) at the University of Michigan for the past fifteen years. Their combined research on seismic behavior of the Special Truss Moment Frame (STMF) system has been “incorporated into the AISC Seismic Provisions for Structural Steel Buildings (AISC, 2005)” (Chao & Goel, 2006). Previous experimental tests were conducted by using double angles with a steel plate but displayed limited strength capacity (Chao and Goel, 2006). However, in larger or taller buildings subjected to stronger seismic events, members will demand higher strength capacity. The original idea of using double channels for truss elements was proposed by Chao and Goel (2006). Based on experimental tests, Chao and Goel (2006) concluded that using double channels for truss elements was feasible. From their conclusion, the truss members of the analytical subassembly models consisted of double channels. Columns of the STMF system consisted of various sized wide-flange sections (fig. 2). The dimensions of the benchmark building in Figure 2 are in feet.

The STMF members are made of steel with yield strength of 50 ksi and a Young’s Modulus of 29,000 ksi. The beam elements connected to the columns are composed of double channels with steel plates welded at each web. The addition of the steel plates to the C & MC sections is to further increase the strength capacity of these members. These end chord sections were specifically chosen to carry steel plates because these members are known to carry larger forces and moments than the rest of the frame elements. The member configurations and the member specifications are shown in Figure 3.

The link beam seen in Figure 3 consists of a wide-flange, W14x68, section. The link beam was added to the frame to ensure that the loading applied at the top-left joint would be transferred to the column on the opposite side. In the analytical modeling, the possible buckling of the link beam was not considered.

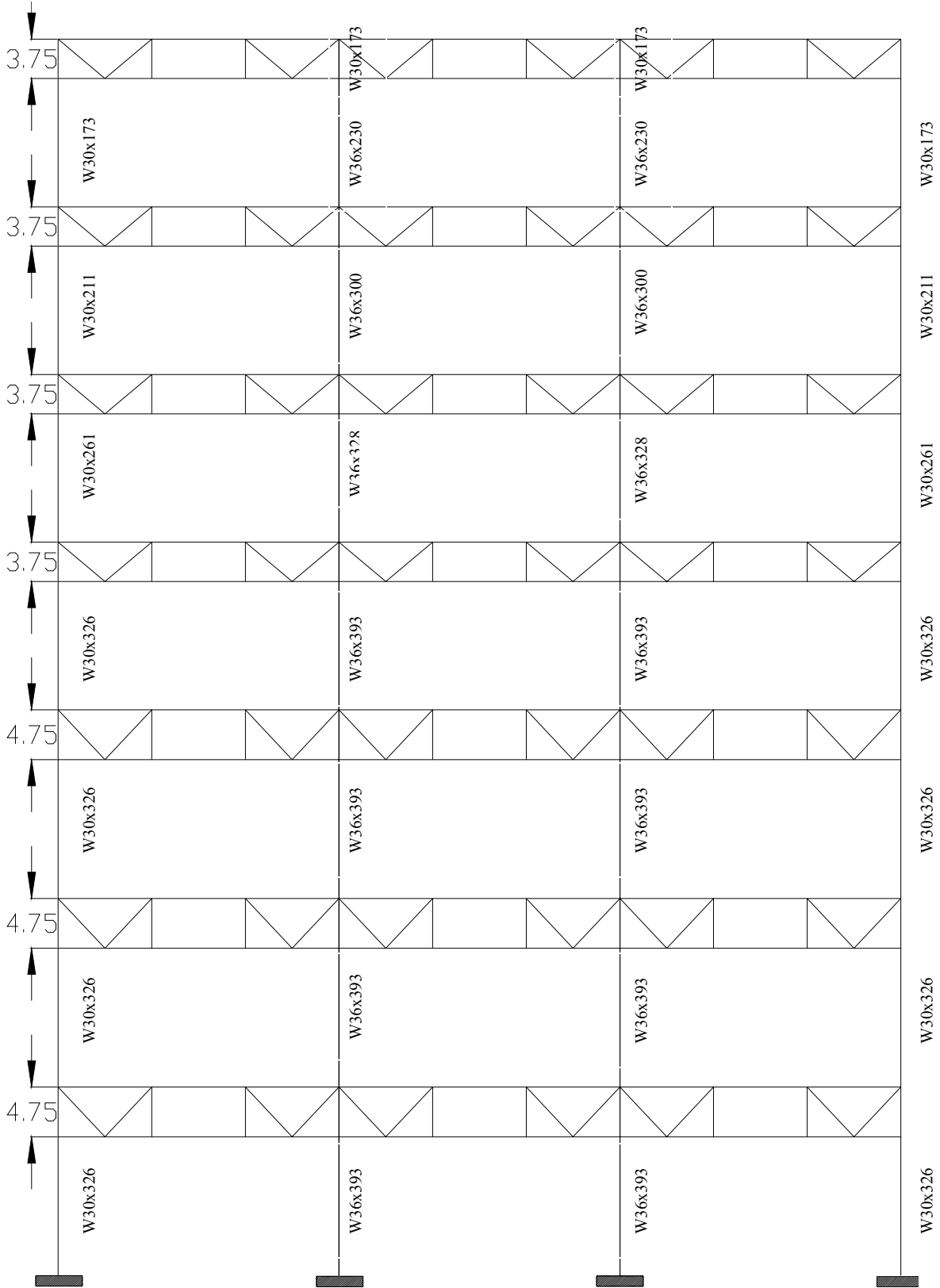
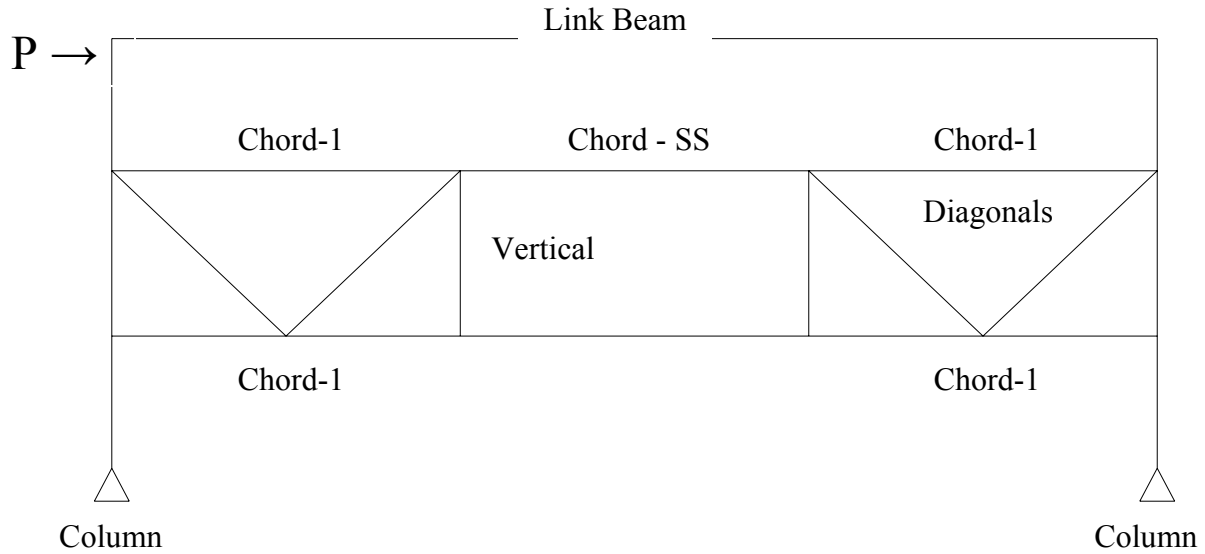


Figure 2: Column members of benchmark building



Floor	Chord-SS	Chord-1	Vertical	Diagonal	L (in.)
7	MC10x22	MC10x22 (1 in. plate)	MC10x22	MC9x25.4	7.25
6	C12x25	C12x25 (1 in. plate)	C12x25	MC9x25.4	9.25
5	C12x30	C12x30 (1 in. plate)	C12x30	MC9x25.4	9.25
4	MC12x31	MC12x31 (1.5 in. plate)	MC12x31	MC9x25.4	9.25
3	MC12x31	MC12x31 (1.5 in. plate)	MC12x31	MC9x25.4	9.25
2	MC12x35	MC12x35 (1.5 in. plate)	MC12x35	MC9x25.4	9.25
1	MC12x35	MC12x35 (1.5 in. plate)	MC12x35	MC9x25.4	9.25

¹All sections are double channels.

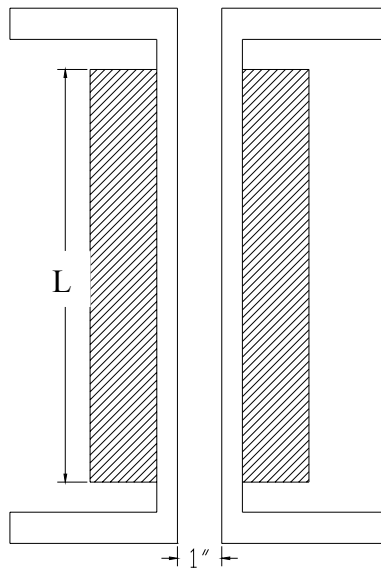


Figure 3: Member specification for STMF subassemblies.

Research Process

The lateral ground motions of earthquakes are responsible for causing the most damage to structures. Structural engineers must strengthen the lateral load capacity because earthquake induced lateral loads exceed the design capacity against wind loads. Therefore the assigned loads to the analytical subassemblies were lateral loads. The Special Truss Moment Frame (STMF) subassemblies were subjected to a displacement-controlled unit-load in the top-left joint of the frame (fig. 3). A push-pull loading protocol was used to simulate the motion of an earthquake.

The STMF subassemblies were loaded with a basic loading protocol that is similar to the SAC (Seismic Analysis Code) loading protocol. The original SAC loading protocol was developed as a result of a “series of non-linear analyses of hypothetical steel moment frame structures subjected to a range of seismic inputs” (SAC). The basic loading protocol implemented in the analytical models is a very simplified version of the SAC loading protocol. This basic loading protocol consisted of eleven (11) nonlinear static pushover analyses cases that simulate earthquake ground motion (fig. 4). The basic loading protocol consisted of step-wise increasing deformation cycles. The objective of the loading analyses cases was to capture the first and subsequent yielding that may occur in the frame elements. Another alternative could have been to use the entire loading cycles of the SAC loading protocol. The reason for using the simplified loading protocol was because SAP2000 cannot account for accumulated damage caused by push-pull ground motions. Therefore, including all the different loading stages would be unnecessary because of the limited capabilities of the software. By simply implementing the basic loading protocol into our analysis cases, we were able to model the STMF characteristics.

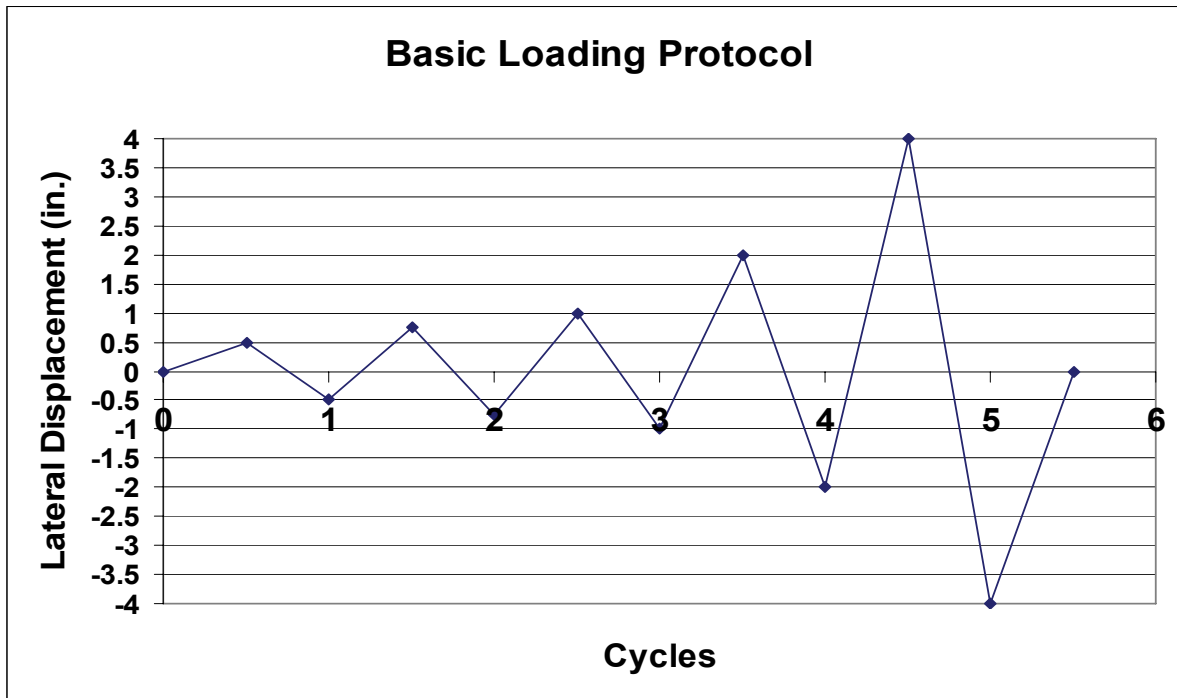


Figure 4: Basic loading protocol with eleven nonlinear static-pushover analyses cases.

In the analytical models, nonlinear rigid-plastic moment hinges with P-M yield interaction surfaces were added to each subassembly to capture the possible yielding of members. The hinges were added to the ends of every member because it was not certain where the plastic hinges would form.

Under SAP2000 hinge properties, hinges were created for every member size. Every member of the frame was assigned interacting axial load-moment (about z-axis) hinges. The inputted moment rotation data included strain hardening in the elements. The scale factor for rotation was assigned to 0.01. The axial load-displacement relationship was chosen as being proportional to moment rotation. To input the data points for the interaction curve data, P-M (axial force-moment) curves were created in Microsoft Excel for every member size. First, the yield load capacity, P_y was calculated by using the relationship:

$$P_y = F_y * A, \quad \text{(eqn 1)}$$

where A is the cross-sectional area of the combined section, and F_y is the yield strength.

Secondly, the yield (plastic) moment capacity, M_y , was calculated using:

$$M_y = F_y * Z_{xx}, \quad \text{(eqn 2)}$$

where Z_{xx} is the combined section plastic modulus about the major axis.

The P-M curves were developed by using an interaction equation developed by Chen and Han (1988) (Chao & Goel, 2006).

$$(P/P_y)^\alpha + (M/M_y)^\beta = 1.0, \quad \text{(eqn 3)}$$

where P is the axial force, M is the bending moment, P_y is the yield load capacity at $M = 0$, and M_y is the yield moment at $P = 0$.

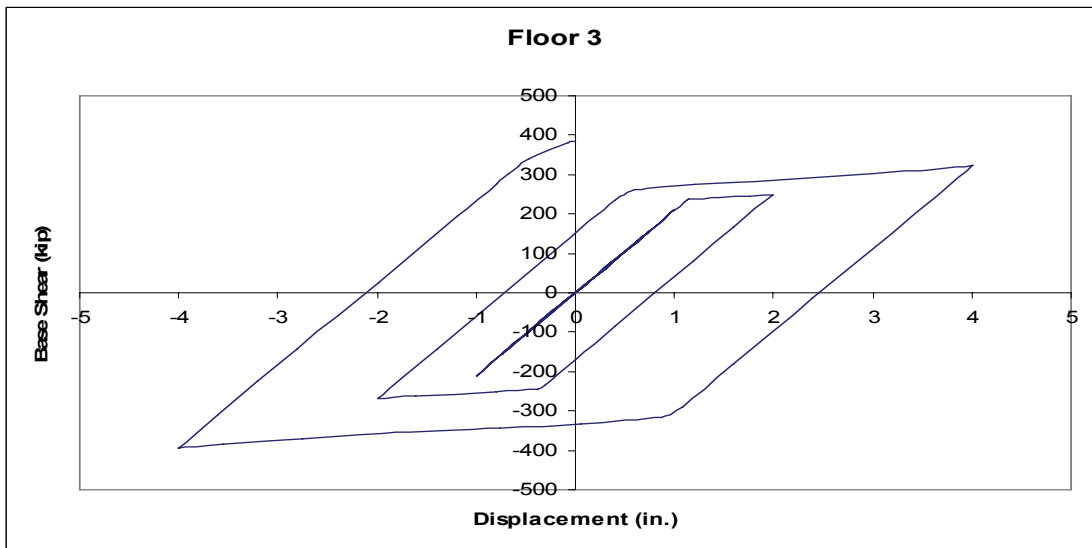
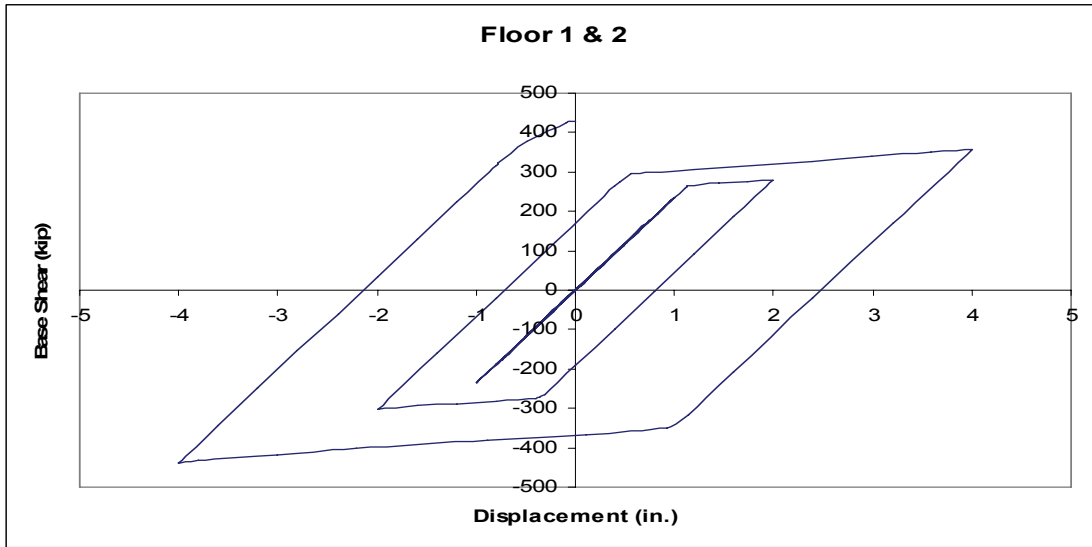
In the analytical models, suggested minimum values by Perform-2D, were used for the coefficients α and β , where $\alpha = 1.5$ and $\beta = 1.1$ (Chao and Goel, 2006). For $\alpha = 1.0$ and $\beta = 1.0$ the profile would be linear. In this study done by Chen and Han (1988), double channel (back-to-back) sections were assumed to have P-M relations as for wide-flange sections. Ultimately, eqn 3 describes the ellipse of a P-M interacting curve. Thirdly, the different values for P were calculated by multiplying P_y times $P_{\text{normalized}}$. Lastly, eqn 3 was used to solve for the moment, M .

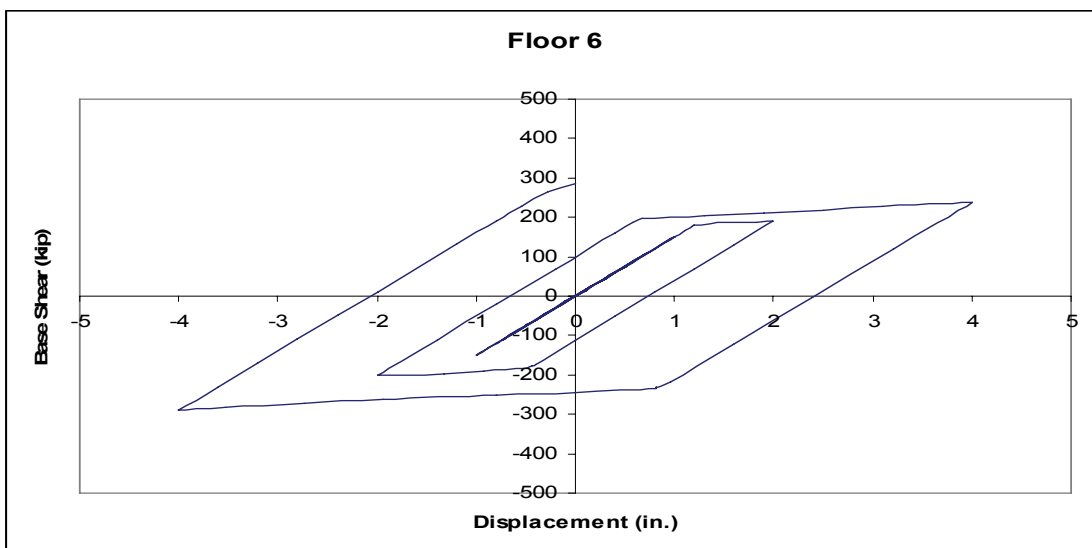
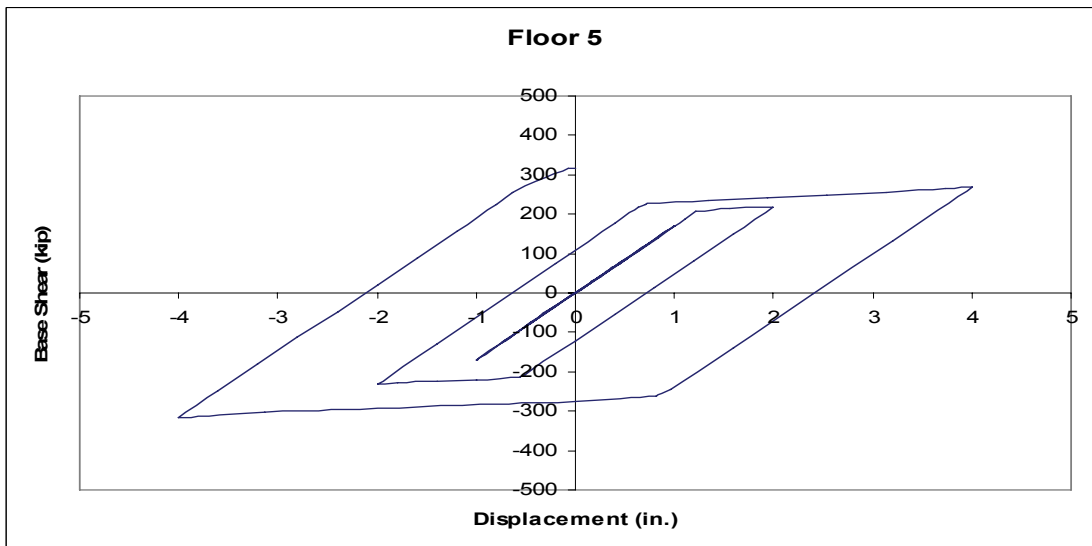
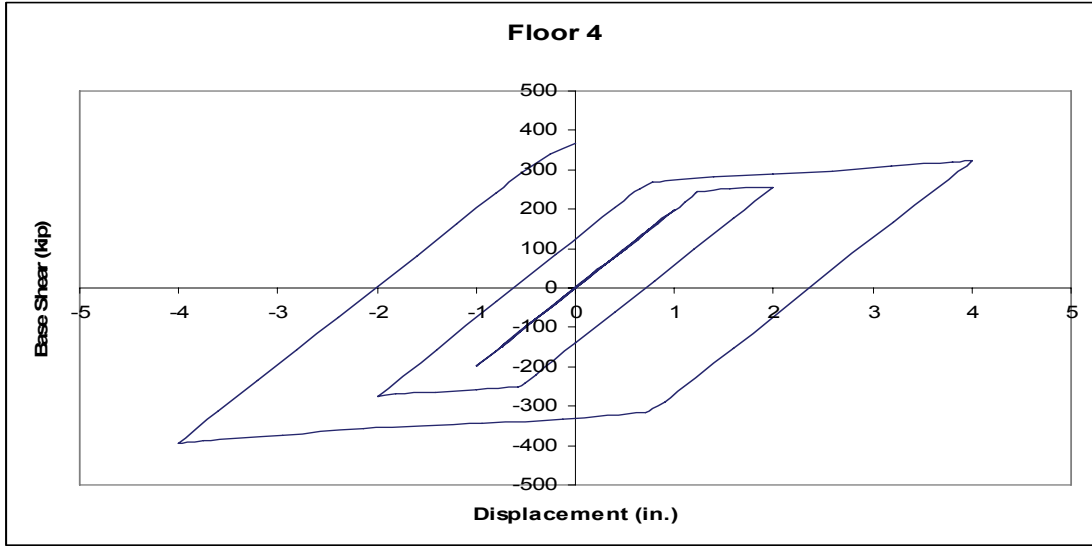
After all seven subassembly models were completed each one was tested by running the cyclic “test” of the basic loading protocol. Keeping in mind, the purpose of the analytical modeling is to verify if plastic hinge formation will occur in the special segment. Also, the analytical modeling of the subassemblies is to verify if the STMF system functions as a resister of forces and deformations when subjected to earthquake ground motions.

Outcomes and Findings

The analysis ran in SAP2000 showed that the characteristics of the Special Truss Moment Frame (STMF) were not captured. Nonetheless, hysteretic loops were created with the collection of data from the analysis. The hysteretic loops display the column base shear versus the lateral displacement applied at the point of action. Seven hysteretic loops were developed, one for each floor of the seven-story benchmark building. It is important to note that the first and second floors displayed the same results because the subassemblies had the same properties. Thus, Figure 5 displays six hysteretic loops, the first plot representing floors 1 and 2. Observations made from the hysteretic loops, shows a trend of diminishing base shear capacity as the floors get higher. Lower floors are designed with larger members because they have to resist

earthquake induced lateral forces plus additional induced loads from upper floors. On the contrary, the upper floors are designed with smaller members because they need to resist smaller forces.





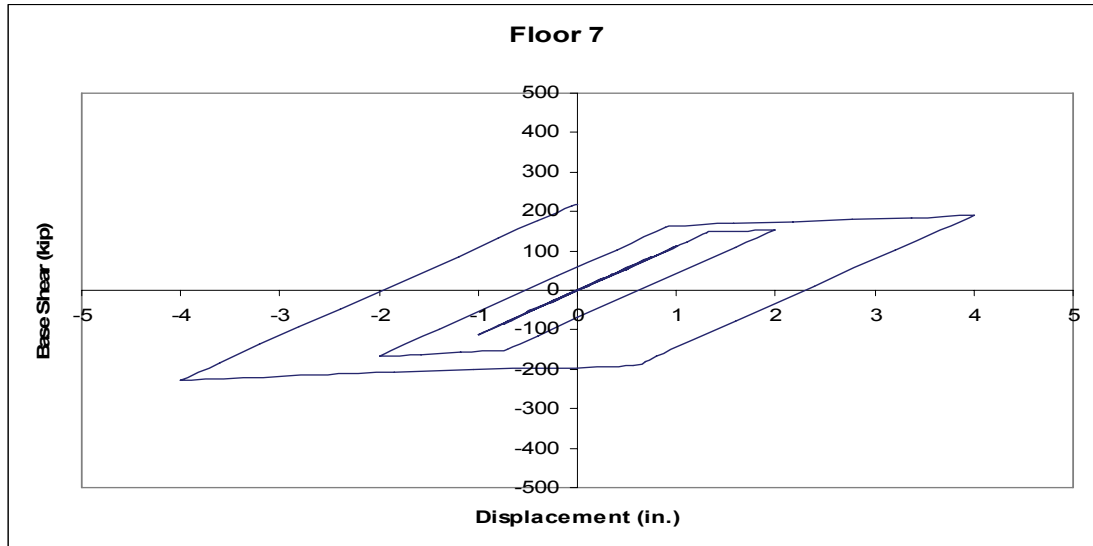


Figure 5: Base shear force versus lateral displacement hysteretic loops

Additionally, the analysis showed that the inelastic behavior was mostly confined to the special segment. Four plastic hinges formed at the ends of the special segment chords as expected, but the verticals formed plastic hinges as well (fig. 6). The STMF system is not designed to have the verticals behave inelastically. This behavior is a cause of concern because the structural integrity of the floor truss girders is jeopardized. If the verticals, along with the special segment members yield, there is nothing from keeping the floor from coming down. It is safe to say that further design and detailing is necessary for these STMF subassemblies. Keeping in mind that Chao and Goel (2006) designed the structure as whole, and did not analyze floor subassemblies. Nonetheless, the analytical modeling showed that the inelastic behavior was, for the most part, confined to the special segment. The controlled damage that the STMF system allows will reduce the amount of structural damage a building will receive during a seismic event.

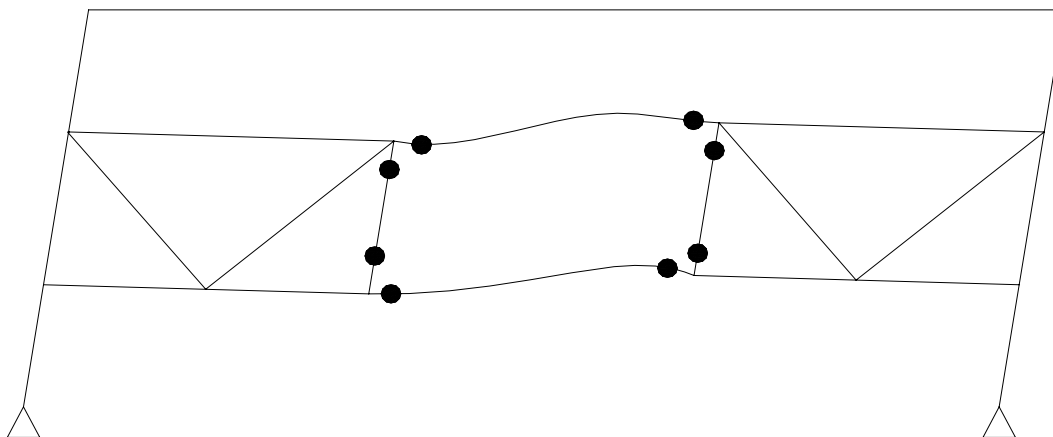


Figure 6: Deformed conventional STMF

The experimental results obtained from Chao and Goel (2006) showed that all inelastic deformations were confined to the special segments. It was concluded that this behavior would eliminate the possibility of damage in the other elements, such as girder-to-column connections.

Even though the inelastic activity was mostly confined to the special segment, minor yielding occurred in the vertical members. Further analyzing data, showed that the tests done on the subassemblages showed no pinching in the hysteretic loops with very stable and ductile behavior (Chao and Goel, 2006). The analysis also showed that the axial forces in the members of the special segment were generally small and recommended that they can be ignored when designing the special segment (Chao and Goel, 2006).

After observing the force distribution in the analytical models, it was evident that the forces and moments were not limited by the capacity of the special segment. In fact, the forces and moments experienced by the members outside the special segment were much greater than in the special segment. It is important to note that both truss girders outside the special segment experienced roughly the same magnitudes in forces and moments. Relatively large moments existed in column section BC and truss sections CE and BF (see fig. 7). As noted earlier, these elements are known to carry larger forces and moments compared to the remaining elements. These large bending moments are a cause of concern because connections might be prone to failure. Further observation showed large axial forces in the truss members. From this observation it was concluded that the large axial forces in the connecting beam-column truss elements, are responsible for the large moments in the column and adjacent truss elements. Based on the observations made from the force distributions, it was evident that the STMF subassemblies did not behave like designed to behave. The members outside the special segment should experience forces lesser than or equal to the forces being experienced by the special segment. Further design and detailing will be needed for these STMF subassemblies. Even though the STMF resulted in unexpected behavior, it still outperforms conventional truss girders as well as solid web beams, in terms of the energy-dissipation capacity, story drifts, and hysteretic behavior” (Chao and Goel, 2006).

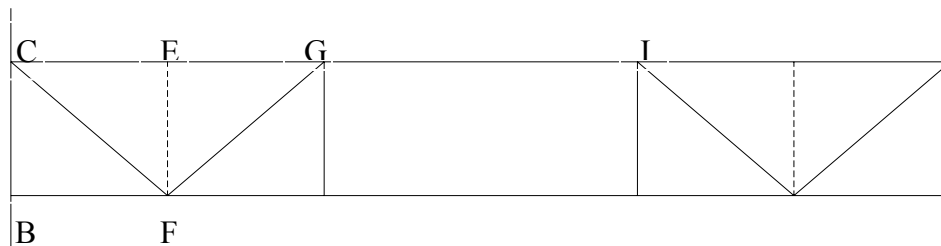


Figure 7: Member designation of conventional STMF

Discussion

The unexpected behavior of the Special Truss Moment Frame (STMF) system presented an opportunity to further design the frame. From observing the axial force distribution in the conventional STMF, it was evident that truss elements were experiencing significantly large forces. It was noted that the reason for such large moments in the frame, was a result of these large tension and compression axial loads. Therefore, if the axial forces are reduced, the bending moments in the frame will be reduced as well. Based on the force distribution obtained from the analytical testing, it was evident that the forces and moments in the members outside the special segment were not limited by the capacity of the special segment. Additionally, large moments existed in the truss and column members, which creates a great deal of concern for the durability

of the connections. It is commonly believed that simple details are adequate for truss-to-column connections in conventional STMF designs. Based on past experiments on STMF assemblies, has shown that significant connection forces may develop and will lead to premature failure in the gusset plates (Pekcan and Itani, 2007). Due to these undesired results, a modified STMF system was proposed to see if the characteristics of an STMF system could be met. One alternative that was further investigated is an STMF system that consists of a two-panel Vierendeel special segment. The modifications would be able to be done because the stability of the structural integrity of the frame would not be jeopardized. In the proposed system, “true” pins were introduced at the ends of the special segment chords (fig. 8). The purpose of modifying the conventional STMF system is to reduce the forces and moments, especially in the members outside the special segment. Also, modifying the STMF design is to ensure that the inelastic behavior will be confined only to the special segment. The STMF alternative should reduce the forces and moments in the members, as well as the gravity loads in the columns. The introduction of real pins at these joints means moment releases in the analytical models. The reduction of forces in the members will allow for the possible selection of smaller/lighter members to use as frame elements.

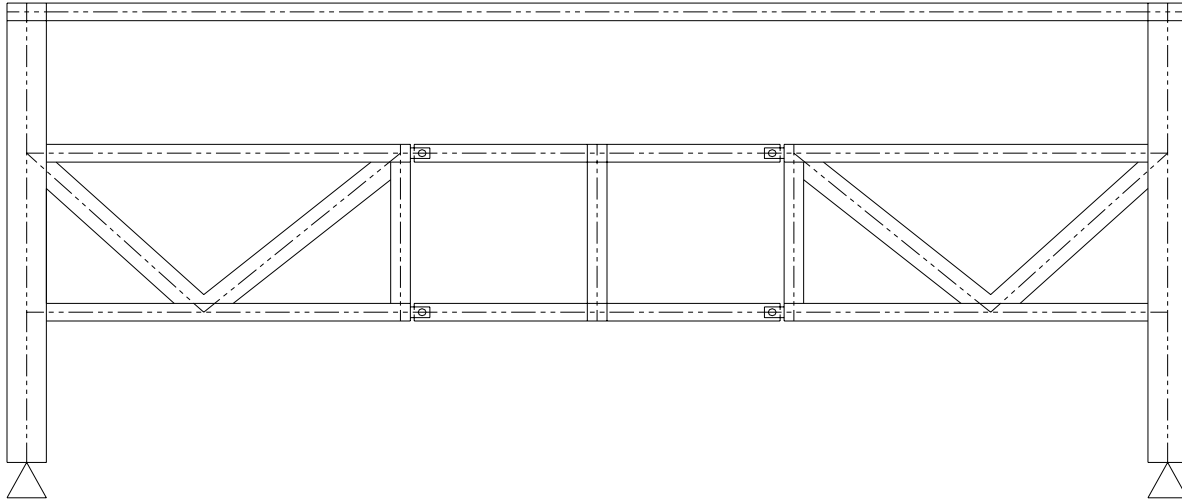


Figure 8: Special Truss Moment Frame (STMF) subassembly with a two-panel Vierendeel special segment.

The seven subassemblies (floors 1 through 7) developed from the conventional STMF design, were modified to obtain seven more subassemblies of the proposed STMF system. Once again, each analytical subassembly of the modified STMF design was tested using SAP2000. But this time, the loading protocol that was used to test the modified STMF subassemblies was not the same one used in testing the conventional STMF subassemblies. The loading protocol consisted of a monotonic nonlinear static pushover analysis case. The force applied at the point of action was deformation-controlled from zero to five inches of lateral displacement. This can be done because steel is a material that is not rate-dependent. Not being rate-dependent means that the behavior of steel does not change with the speed of its loading application. Loading the frame slowly or quickly would not make a difference because both cases would exhibit roughly the same results.

After running the analysis in SAP2000, it was evident that all inelastic behavior was confined to the special segment. The vertical that separates the two panels in the special segment was the only member that yielded (fig. 9).

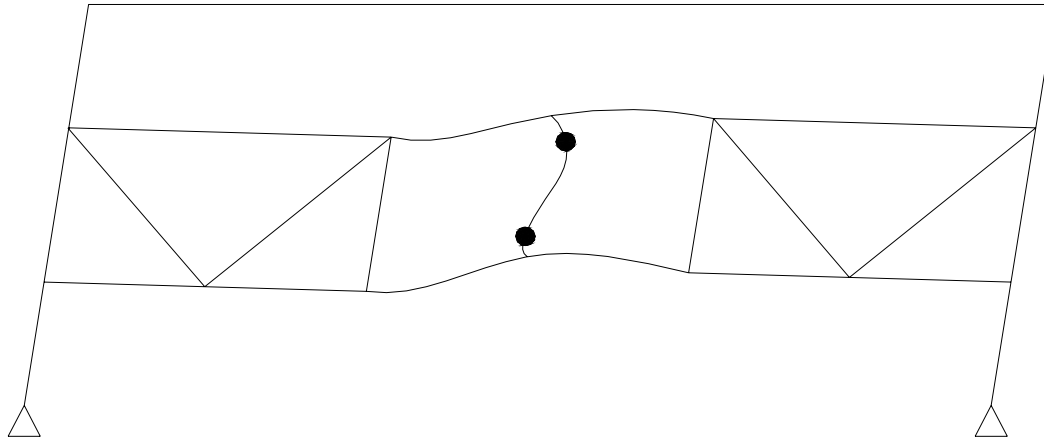


Figure 9: Deformed modified STMF

After observing the force distribution, it was evident that the forces and moments had significantly been reduced compared to the conventional STMF system. The addition of the moment releases caused the forces and moments in the frame elements to reduce. To verify this result, bar charts were created to show the comparison of maximum moments in the conventional and modified STMF systems. Three floors were chosen arbitrarily to be analyzed - floors 1, 4, and 7 - to compare the difference in their maximum moments. Figure 11 shows the comparison of the maximum moments experienced by the top chord GI in the special segment (see fig. 7 and 10). Figure 12 shows the comparison of the maximum moments experienced by the column segment BC. It is evident that the modified STMF design significantly reduced the maximum moments compared to the conventional STMF design. Further observation showed that the axial and shear forces experienced by the modified STMF system were significantly reduced as well, compared to the conventional STMF design.

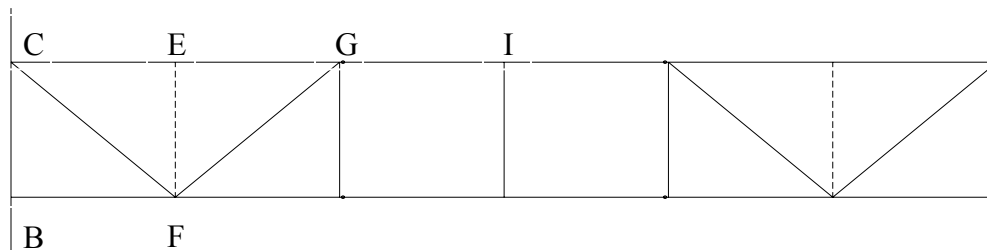


Figure 10: Member designation of modified STMF

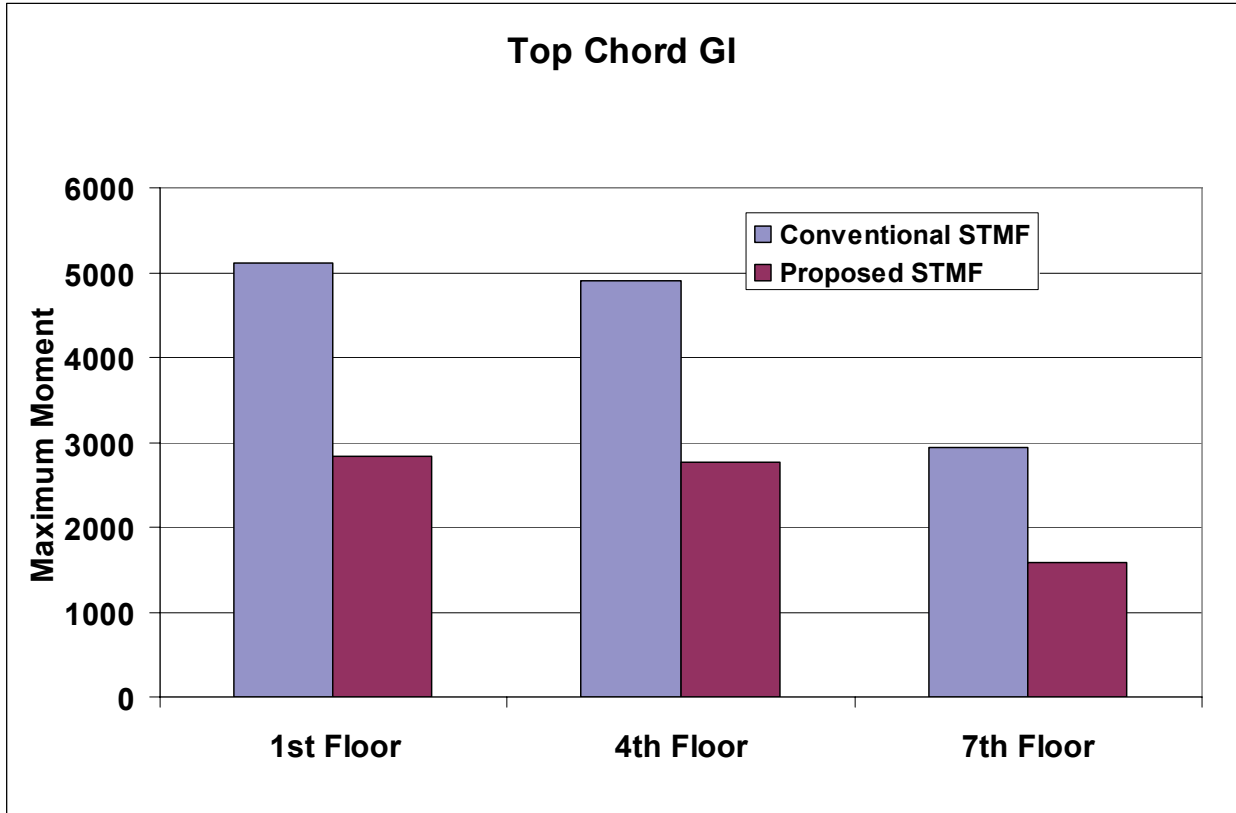


Figure 11: Comparison of maximum moments in top chord GI of the special segment

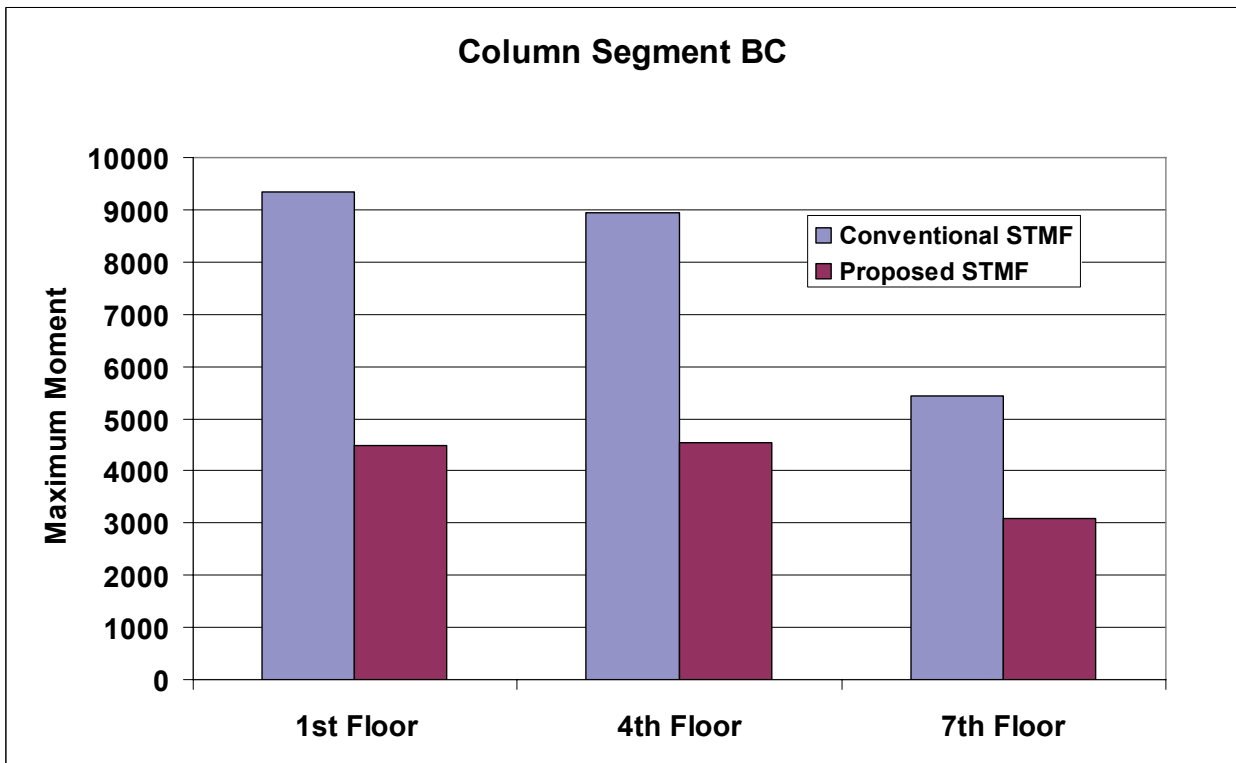


Figure 12: Comparison of maximum moments in column segment BC

By simply observing the force and moment capacity of both STMF designs, does not signal a clear alternative of which system is better. Each design and subsequent behavior has its advantages and disadvantages. The members of the conventional STMF design have a larger strength capacity than the modified STMF design. The conventional design has a large strength capacity but the frame is prone to receiving additional forces and moments. Additional forces and moments would lead to possible yielding of members outside of the special segment. The modified STMF system has a smaller strength capacity but the pin connections would not allow the addition of moments. Thus, the conventional design has a high strength capacity but it is not necessarily the best design because of the possibility of more members yielding. The modified design at first might seem like a bad design because of its smaller strength capacity, but because it has the ability to reject additional induced moments, seems like the best design. It is not safe to say which design would be best.

Conclusions and Possible Future Work

During this preliminary analytical research project, the conventional Special Truss Moment Frame (STMF) system displayed unwanted characteristics, where the proposed STMF system displayed encouraging results. The fact that the vertical members in the conventional STMF design yielded, was a sign of concern. The verticals should not yield because it could lead to failure of the floor girders. Having no vertical support in the floors, would surely result in their collapse. This preliminary analytical investigation recommends that further design and detailing should be conducted. Some possibilities are to upgrade the verticals to larger members in order to ensure that these verticals will not yield.

Proposing a modified STMF system resulted in a desirable outcome because of the achieved STMF characteristics. The testing of the conventional STMF system resulted in unexpected inelastic behavior, and the forces and moments in the members outside the special segment were not limited by the capacity of the special segment. After running the analysis for the modified STMF system, all inelastic behavior was confined to the special segment and the forces and moments in the frame were significantly reduced compared to the conventional STMF design. The axial, shear, and moments were all reduced. It was previously noted that reducing the axial forces in the connecting beam-column truss members would reduce the moments experienced in the columns. The reduction of axial forces was accomplished and as a result, the moments were reduced. The addition of the moment releases in the form of pins resulted in these encouraging results.

This preliminary analytical investigation was important in observing the behavior of the frame components and force distributions. The analytical results will be important because future experimental work will be conducted at the University of Nevada, Reno. Various STMF systems will be tested with various alternative details. The STMF systems that will be built in the laboratory will not follow the design of any of the seven floor subassemblies. As noted before, analytically testing these subassemblies was simply to gain knowledge about the behavior of the components that make up whole systems (i.e. buildings). Quasi-static testing of subassemblies can be used to establish response characteristics of whole systems. For example, in analytical testing of the subassemblies, the inelastic and elastic behavior was captured for both STMF designs. Also, the distribution of forces was observed. This was extremely important because it

lead to the modification of the conventional STMF design to reduce the large forces and moments.

Although testing subassemblies is really productive, a full system modeling is necessary to be able to make conclusive remarks about the benefits of the STMF system as presented in this preliminary investigation. The reason for this future study is that the characteristics of the STMF system may vary from floor to floor in a complete model of a building. Inelastic behavior might be displayed in some floors but might not be in other floors. Basically, it is not certain that all special segments will behave inelastically. Additionally, some floors might experience large (i.e. upper floors) deformations while other floors (i.e. lower floors) might experience small deformations. Therefore, an analytical study looking at the complete system response is recommended. Also, since the forces and moments were reduced in the modified STMF system, a study that would model the complete system response of this modified design would be ideal.

Designing buildings that can dissipate earthquake induced forces and deformations will help diminish the amount of damage that structures would receive. The value of the Special Truss Moment Frame (STMF) system is that buildings will be repairable after a relatively large earthquake, without having to fully replace them. This is important because some buildings cannot afford to have down-time because of their dependence from society. For example, hospitals, schools, etc. cannot afford to be uninhabitable for a finite amount of time because of their importance. Therefore having a building equipped with an STMF system, will ensure that the condition of the structure is inhabitable after an earthquake. Global structural stability and performance will not be compromised if inelastic activity is confined only to special segments (Pekcan and Itani, 2007). Besides this, great interest is to be taken for this system because it can reduce the amount of costs for repair work. Repair costs would be reduced significantly because only the special segments would need to be replaced.

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