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Investigation of the Effect of Geometric Parameters on Behavior of Special Truss Moment Frames

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Abstract - *One of the laterally resistant structural system is special truss moment frame (STMF). This system is similar to other conventional moment frames, but the difference is in using truss beams instead of beams with prismatic cross-section. Since the truss beams depth is usually high, they are more resistant to bending moment compared to other beams. When the forces are applied laterally, the high strength of truss beams in bending can cause plastic hinge in the columns, which is undesirable; because it can cause instability in the structure. In order to prevent the formation of plastic hinge in the beams, a zone in the middle of the truss beams is considered which is called a special segment. The members of this special segment are responsible for yielding to lateral loads and prevent the spread of plastic hinges to other structural members. In other words, the special segment acts like a fuse and prevents the failure of other structural members. In this paper, the geometric parameters of truss beam in the special segment and its effects on the overall behavior of structures have been investigated. The geometric variables considered in this research are the length of special segment, the depth of truss beam, the number of vertical members in the special segment; these variables are in the ranges determined by ASIC Code. The results of nonlinear static analysis showed that structure's behavior is more sensitive to changes in the length of the special segment than other factors, and variation in the length of special segment can have significant effects on its strength, rigidity and ductility of the structure.*

***Key Words*: Special Truss Moment Frame (STMF), Pushover, Ductility, Vierendeel**

1. INTRODUCTION

Buildings require adequate lateral structural systems to resist against lateral loads. There are various systems available to utilize in buildings. Moment frame is one of the most suitable structural systems for dealing with lateral forces. Due to its relatively fixed connection between beams and column, this system has a significant lateral rigidity in addition to transferring gravity forces. These frames can be used for various buildings with different uses. But sometimes, due to some architectural requirements, large spaces in buildings are required. In this case, if moment frames are used, the depth of beam will be increased. Increasing the depth of the beams increases their stiffness which under lateral forces allows plastic hinges to form in the columns before beams. In other words, in moment frames, the strong beam-weak column phenomenon occurs, which is undesirable. One of the solutions in such conditions is using truss elements. Trusses are one of the beneficial and effective structural elements used in variety of structures [1-6]. They are used in various kind of structures from road sign structures to double layer barrel vaults as stadiums' roof. For buildings aspects, one of the practical usages of truss is utilizing special truss in moment frames (STMF) which also provides the lateral load resistance system for buildings. The special truss moment frame system is nearly a new system in structural engineering field and due to its special advantages and benefits, has gained high popularity in recent years. These structural systems are more economical and lighter than frames made from built-up girders. In addition, the open web of these trusses provides suitable conditions for embedding and passing pipes, air conditioner canals and other utilities. In addition to the advantages mentioned, in these structures, details of connecting beam to column are simpler.

In this type of moment frames which use truss beams, although the depth of the beams is deep, due to the presence of special segment in the truss beam, plastic hinges cannot form in the columns. As a result, the columns always maintain their elastic behaviors and thus ensure the stability of the structure during an earthquake. Special segment could be designed in to main method. It can include diagonal X-shaped bracing members or it can be in the form of an open rectangular condition which is called Vierendeel. In moment frames with special truss beams, the zone for plastic deformation and energy absorption is in the middle of the beam. In this zone, the shear force resulting from the vertical load is small, and by placing weaker member of the diagonal or removing these members, this segment will be susceptible to non-elastic deformation and absorbing earthquake energy; therefore, these systems provide an adequate mechanism against earthquake. In these systems, yield mechanism consists of a combination of submitting all members of special truss beam area as well as forming a plastic hinge at the foot of the columns. Figure 1 shows the yield mechanism in these structural systems. Because of the formation of four plastic hinges in the edges, STMFs are generally more undetermined than other systems; in particular, when an X-shaped member is used in the special segment, the level of indeterminacy increases.

In 1991, a study on the seismic behavior of special moment frames with truss beam, both analytically and laboratory was conducted by Itani et al, in University of Michigan, USA, [7]. A four-story moment frame with truss beam was designed according to the requirements of specified by uniform building code, UBC1988 [8], for moment frames with regular ductility. Furthermore, three laboratory samples built in an actual size and were studied under cyclic load. The results showed that the samples produced have very weak cyclic behavior, which is due to buckling and rapid deterioration of the members of the truss. Also, more than 70% of the initial rigidity and system resistance are eliminated in the early cycles, which confirm non-ductile behavior of the structural system. In addition, the nonlinear dynamic response showed that this system has weak response to severe seismic motions, and this response coincides with relatively high drift ratio between floors and also non-elastic deformation of the columns and web members of truss.

In later efforts to improve the behavior of truss beams in moment frames, in 1992 the first STMF system with X-shaped diagonal bracing members in the special segment was developed by Itani and Goel, [9]. They used capacity-based design method to design this system. In this method the design of STMF starts from designing the special segment. Then, the other members are designed in a way to remain elastic under the shear forces created by yielding the members of the special segment in the middle of the beam. A comparison between STMF and frame with a traditional truss beam showed that the STMF system has better performance than the conventional frame trusses in terms of energy absorption capacity, the drift of floors and cyclic behavior. In 1996, Basha and Goel developed another type of special segment, due to proper behavior of STMF system, which were corroborated with analytical and laboratory studies,[10]. In their model, Vierendeel region was used, which does not have diagonal members.

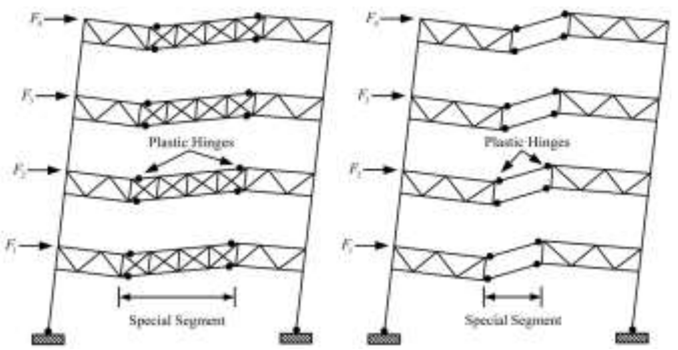


Fig- 1 Deformation of STMF under lateral forces

Basha presented a mathematical model for the expected final shear capacity of the special segment. Subsequent experiments on this particular type of truss beam showed that no deterioration was observed in the hysteresis cycle, and all non-elastic behavior of the beam was limited to the special segment; as a result, the possibility of failure and destruction in other members, such as beam to column, will be eliminated.

In 1997, Ireland used STMF system in a seismic zone with medium to low danger, but possibility of wind was a major factor in this design. He compared this system with other traditional systems available in that place. The results showed that STMF system has a highly desirable performance compared to other systems, [11].

In 1998, Aslani studied the seismicity of the STMF system under the combination of gravity and lateral loads, [12]. The results of this study indicate that this system which was designed to combine certain loads has the ability to perform properly in high seismic movements. In addition, the overall behavior of the structure with concrete block roof (which does not show any dual function) was also investigated. Based on experimental and nonlinear dynamic analysis, he suggested neglecting the effect of combined performance in nonlinear dynamic analysis. Aslani also examined the reparability of the STMF system by testing a repaired sample. The results confirmed that the STMF system could be restored to its initial state with minimum cost; so that the modified repaired system shows a similar behavior to the intact sample.

In 2006, Goel and Chao studied the moment and cyclic behavior of the members made from double channel beam, [13]. They provided suitable detail for connecting the horizontal edges of the special segment adjacent to the vertical members. This detail guarantees the yield act in the horizontal chords of the special segment. They also conducted an analytical study to develop a performance-based plastic design for the STMF system.

In 2008, Peckan et al used certain elements such as Buckling Restrained Braces (BRB) as Energy Dissipation Devices (EDD) in the special segment of the STMF system, [14]. Based on their proposed model, the structure became lighter and the cost of construction decreased.

In 2014, Kim and Park studied a progressive collapse in the STMF system, [15]. They designed a variety of analytical models with different span length, number of floors and length of the special area, and studied them under static and dynamic analysis. The static analysis results showed that in the models, due to the sudden removal of columns plastic hinge is only formed in the special segment, and other members continue to show elastic behavior. While in dynamic analysis the sudden removal of columns causes a progressive deterioration due to complete destruction and damage of the members in the special segment.

To overcome this problem, Kim and Park provided a closed form formula to obtain the horizontal chords in the special segment based on the concept of energy balance. Finally, the initial models were redesigned and it was observed that progressive deterioration does not occur in redesigned models and plastic hinge is limited in the special segment.

In 2014, Heidari and Qareh Baghi examined the role of energy absorber elements in truss moment frame, [16]. So, they used Buckling Restrained Braces (BRB) as horizontal members attached to the column. Their results indicated that the proposed structure exhibited proper seismic performance in using EDD with these frames.

Simon Chao et al tested the performance of special truss moment frame with double-channel chord member under cyclic loading condition, [17]. The test results revealed acceptable performance of channel sections as horizontal chords.

In this paper, the effect of geometrical features of special segment in general behavior of STMF is investigated. The geometric variables considered in this research are the length of the special segment, depth of truss beam, number of vertical members in the special segment and the height of frames.

2. Numerical Models

In this research, a typical building is considered with a plan shown in figure 2. This building is designed for 5-story and 10-story buildings. In the 5-story structure, the STMF frames are assumed in two axes of A and D according to figure 3 and in 10-story models, all frames in the X- direction is considered as STMF system. The Vierendeel special segments are considered for all truss beams of the STMF systems.

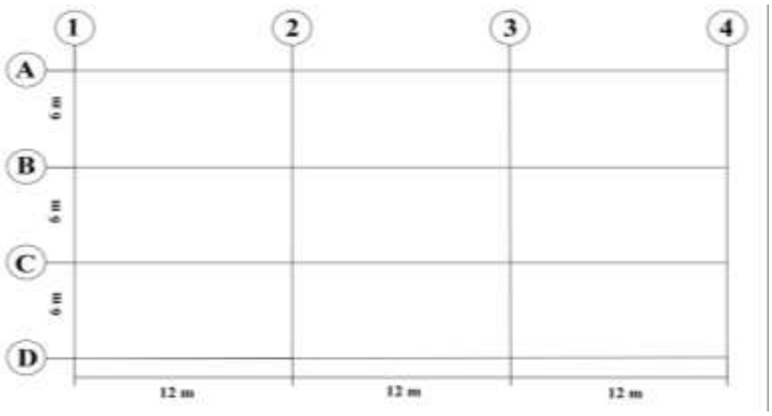


Fig- 2 Plan view of building

To design the structure, a distributed dead load of 500 kg/m2 is assumed for all floors and roof. Also, live load for floors and roof is assumed to be 350 kg/m2 and 150 kg/m2 respectively. Response modification factor (R) is considered 7 according to ASCE code,[18]. All models in this section are designed according to performance-based plastic design method. In this study, the effects of the following parameters are considered as geometric variables in Vierendeel truss beams:

1) Increase in the length of the special segment in truss beams with 1, 2 and 3 Vierendeel panels

2) Increase in the number of Vierendeel panels, in a constant length of the special segment

3) Increase in the depth of the truss beam

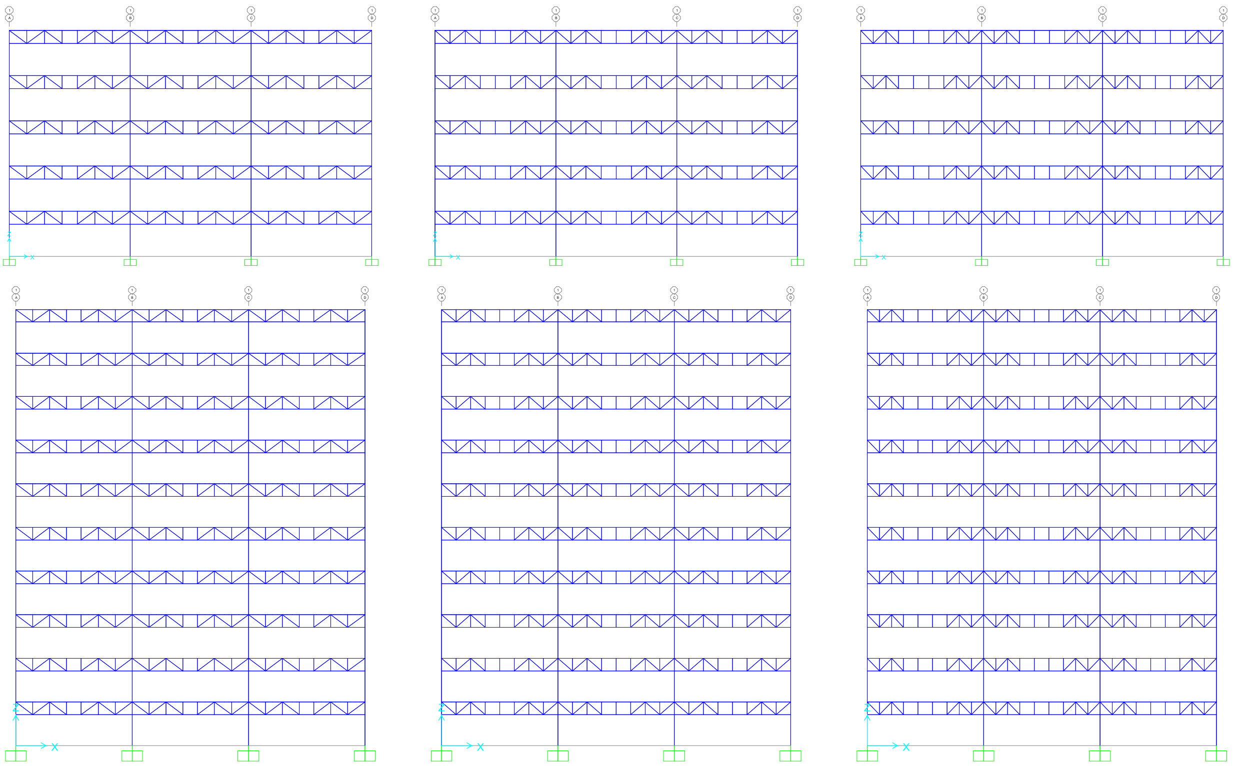
According to Goel et al.[13], the most suitable section for horizontal edges of truss beams is double channel beam. For this purpose, in this study channel beam cross sections based on AISC-2016 standard is utilized for designing the chord members and also vertical elements adjacent to the special segment, [19]. For diagonal and vertical members outside the special segment, double angle profiles were used and for columns, IPB sections were used. In 10-story models, these sections were used in pairs for interior columns.

For each of the 5-story and 10-story models, nine analytical models are considered, in which the length of the special segment gradually and over different models increases. According to AISC-2016 requirements, the length of the special segment ratio to the length of the beam should be in the range of 0.1 to 0.5. On the other hand, the length of each panel in the special segment ratio to the depth of truss beam should be between 0.67and 1.5. In this study, truss beams with one, two and three panels were considered in the special segment. Table 1 shows the label of each designed model. Naming of the models in this table is in the form of Ls-X-P-XX, in which 'X' denotes the length of the special segment and 'XX' represents the number of Vierendeel panels in the truss beam.

Table-1 Property of designed models

Model	Number of panels in special segment	Ls* (m)	Lsp** (m)	Lsp/D
Ls-1.50-P-1	1	1.50	1.50	1.2
Ls-1.75-P-1	1	1.75	1.75	1.3
Ls-2.00-P-1	1	2.00	2.00	1.5
Ls-3.00-P-2	2	3.00	1.50	1.2
Ls-3.50-P-2	2	3.50	1.75	1.3
Ls-4.00-P-2	2	4.00	2.00	1.5
Ls-4.50-P-3	3	4.50	1.50	1.2
Ls-5.25-P-3	3	5.25	1.75	1.3
Ls-6.00-P-3	3	6.00	2.00	1.5

* Ls: the length of the special segment
** Lsp: the length of the panel in special segment



Ls-1.50-P-1 Ls-3.00-P-2 Ls-4.50-P-3

Fig- 4 Numerical models for 1,2 and 3 panel STMF system for 5-story and 10-strory structures

3. Pushover Analysis

In order to anticipate the actual behavior of numerical models, they need to be analyzed using finite element methods. These methods are one of the powerful analytical methods which are able to simulate various material in various fields from geosynthetics analysis of pavement to electromagnetic problems,[20]. After designing the models, they were analyzed by nonlinear static (pushover) method. For this type of analysis a reversed-triangular load is considered in lateral direction. By increasing the load step by step, the lateral displacement of roof is recorded in each step. The resultant diagram provides capacity or pushover curve for each model. Figures 5 and 6 compare the capacity curve of 5-story and 10-story models, respectively. According to these diagrams, in both 5-story and 10-story models, by increasing the length of special segment the capacity and stiffness of the models decrease.

After performing the above steps, the target displacement is calculated according to proposed method of FEMA356 and the actual pushover curve is simplified to bilinear curve. Utilizing achieved bilinear curve the parameters such as effective stiffness (Ke), Yield Displacement (dy), yield strength (Vy), target displacement (δt), ultimate strength (Vu), displacement ductility (μ), strength reduction factor (Rμ) and response modification coefficient (Rw), are calculated. Table 2 and 3, respectively, shows above mentioned parameters for each of the 5-story and 10-story models. In this study the Uang method and Mirand method is used to calculate the strength reduction factor (Rμ) and response modification coefficient (Rw) respectively,[21], [22]. Since there are many coefficients involved in calculating the overstrength factor which determining these coefficient require laboratory studies, the overstrength factor is considered 3 for all frames according to ASCE standard suggestion. Furthermore, given the fact that Z/S ratio obtained from the design is approximately equal to 1.2, the value of 1.5 has been used as the allowable stress factor.

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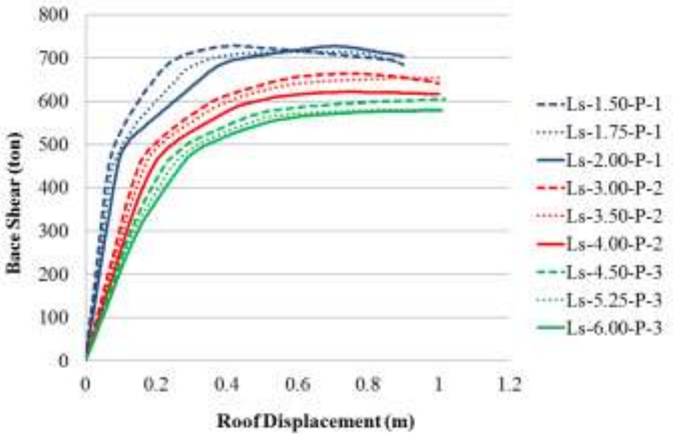

Fig-5 pushover curves for 5-story models

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According to Figures 7, the increase in the length of the special segment reduces stiffness and, as a result, increase the fundamental period of structural vibration. In models with one and two panels, for both 5-story and 10-story frames, yield displacement (dy) increases with the increase in the special segment's length. While in 5-story models with three panels, this amount is increases for longer special segment models. This makes it possible to increase the ductility (μ), by increasing the length of the special segment, which ultimately increases the response modification coefficient. Unlike the 5-story models with three panels, in 10-story models with three panels, by increasing the length of the special segment, yield displacement (dy) slightly decreases. As result, in the models with three panels for 10-story structures, with an increase in the length of the special segment, ductility (μ) slightly decreases, which ultimately cause reduction in the response modification coefficient, as shown in figure 7-e. On the other hand, the ultimate displacement (target displacement) is increasing for all models.

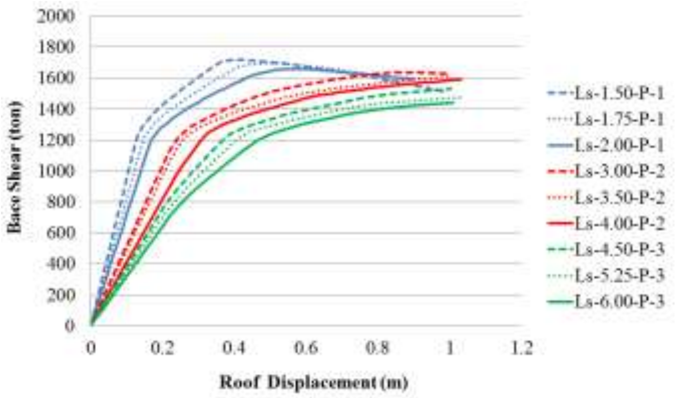


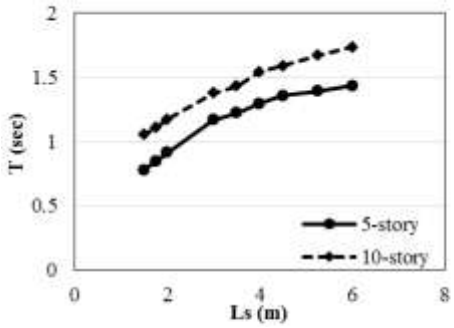
Fig-6 pushover curves for 10-story models

Table 2 results from pushover analysis for 5-story building models

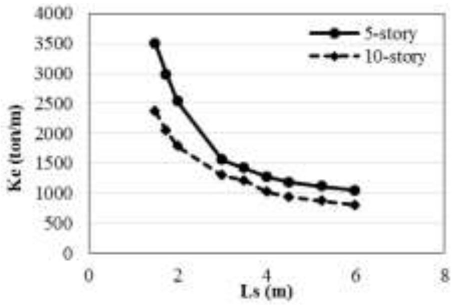
Model	T (sec)	K_e (ton/m)	d_y (m)	V_y (ton)	δ_t (m)	V_u (ton)	μ	R_μ	R_w
Ls-1.50-P-1	0.781	1745.72	0.068	238.05	0.148	299.54	2.171	2.48	11.19
Ls-1.75-P-1	0.846	1492.11	0.077	231.51	0.163	283.81	2.010	2.45	11.04
Ls-2.00-P-1	0.913	1265.63	0.095	240.68	0.181	275.31	1.904	2.22	10.01
Ls-3.00-P-2	1.167	778.84	0.145	227.13	0.242	266.71	1.660	1.89	8.51
Ls-3.50-P-2	1.221	707.77	0.158	224.24	0.257	264.47	1.622	1.83	8.23
Ls-4.00-P-2	1.294	636.96	0.168	214.93	0.274	258.92	1.624	1.82	8.17
Ls-4.50-P-3	1.355	588.89	0.161	189.99	0.290	250.26	1.798	2.02	9.09
Ls-5.25-P-3	1.391	557.90	0.159	177.58	0.303	246.05	1.904	2.14	9.63
Ls-6.00-P-3	1.433	520.87	0.156	162.68	0.311	241.61	1.991	2.23	10.05

Table 3 results from pushover analysis for 10-story building models

Model	T (sec)	K_e (ton/m)	d_y (m)	V_y (ton)	δ_t (m)	V_u (ton)	μ	R_μ	R_w
Ls-1.50-P-1	1.05	590.56	0.13	1262.08	0.21	359.44	1.55	1.76	7.90
Ls-1.75-P-1	1.11	510.18	0.15	1246.96	0.23	350.53	1.47	1.65	7.41
Ls-2.00-P-1	1.17	446.67	0.17	1219.92	0.24	340.29	1.42	1.56	7.04
Ls-3.00-P-2	1.38	322.34	0.22	1160.48	0.30	325.44	1.33	1.42	6.41
Ls-3.50-P-2	1.43	302.89	0.24	1156.72	0.31	321.45	1.29	1.36	6.11
Ls-4.00-P-2	1.54	255.37	0.26	1081.28	0.34	316.98	1.29	1.35	6.09
Ls-4.50-P-3	1.59	235.05	0.22	843.00	0.37	299.73	1.64	1.76	7.93
Ls-5.25-P-3	1.67	217.57	0.23	817.68	0.38	284.05	1.61	1.70	7.67
Ls-6.00-P-3	1.74	199.95	0.25	796.48	0.40	272.10	1.61	1.70	7.65



(a)



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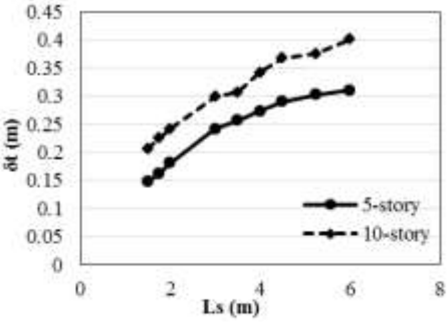

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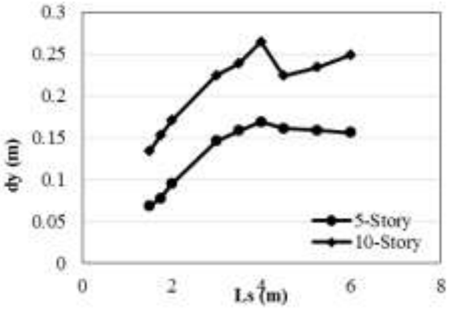

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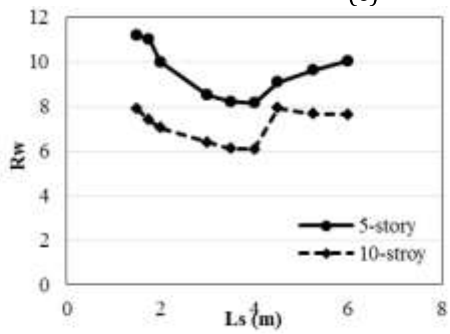
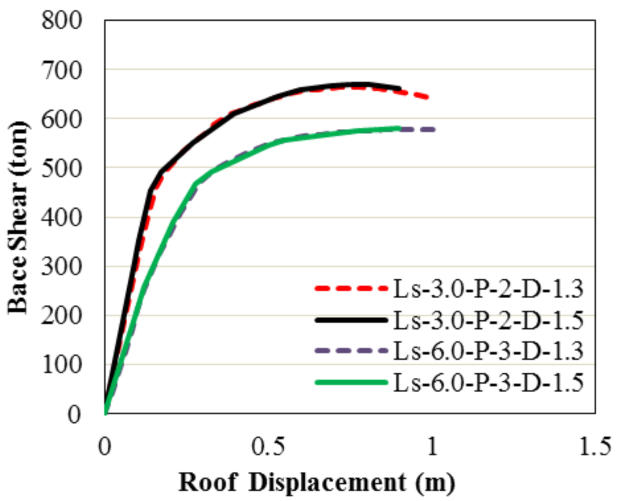


(e)

Fig-7 comparing parameters resulting from pushover analysis (a) fundamental period of vibration (b) effective stiffness (c) ultimate (target) displacement (d) yield displacement (e) response modification coefficient

Given that in the displacement-based plastics design method, the beam's depth does not interfere with design calculations, it is assumed that this parameter does not have much effect on the capacity curve of the structure. To investigate this case, two similar models Ls-3.0-P-2 and Ls-6.0-P-3 but with a depth of 1.5 meters, are modeled for both 5-story and 10-story buildings. Figure 8 shows that with an increase in depth, no significant effect is seen in the behavior of STMF frame. The only advantage of increasing the depth of the truss beam is that axial force decreases in the horizontal chords and as a result, the concentrated force in the connection point.

To investigate the effect of vertical elements in a constant length of special segment, two more models are designed for each 5-story and 10-story structures. In these models number of panels is increased while the length of the special segment is considered constant. According to figure 9 the increase in the number of panels in a constant length of the special segment does not have a profound effect on the capacity of the structure. In other words, increasing the number of panels will cause changes in the behavior of truss moment frame, when the length of special segment is also increased.



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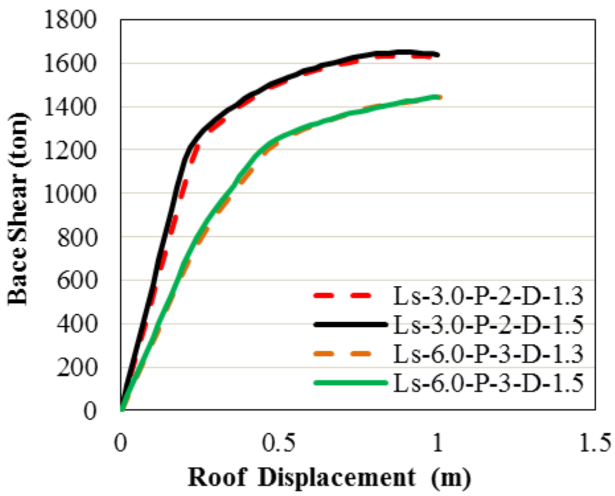

(b)

Fig-8 effect of truss beam's depth on behavior of STMF system (a) 5-story building (b) 10-stroy

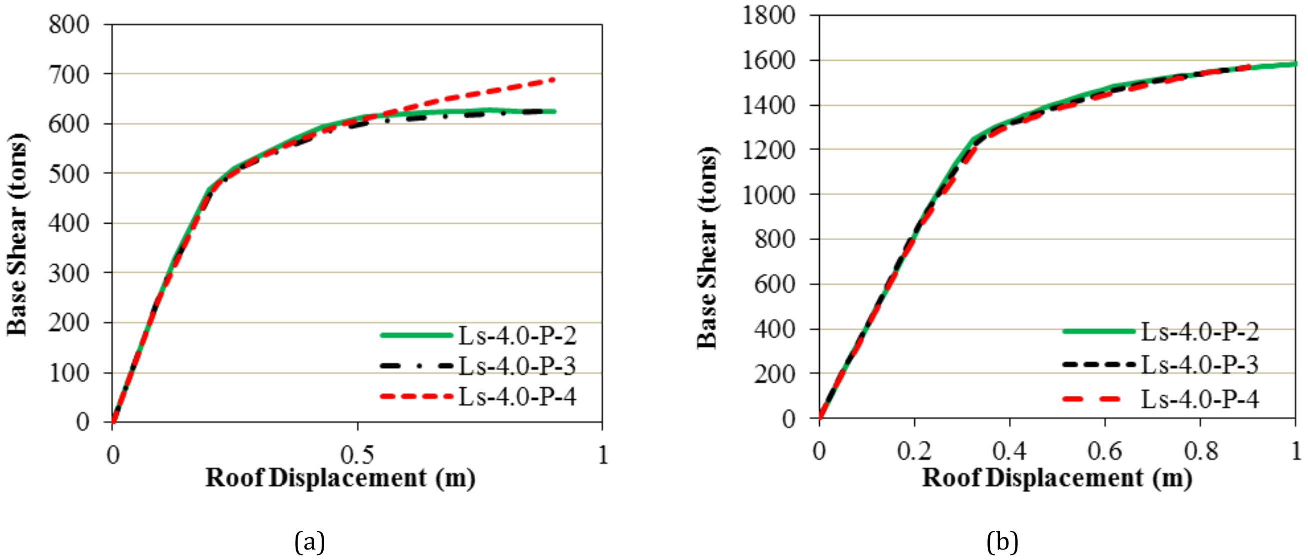

Fig-9 effect of number of Vierendeel panels in constant length of truss beam on the behavior of STMF system (a) 5-story building (b) 10-stroy

4. Conclusions

Considering the three geometric variables for truss beams, the effect of these factors can be expressed as follows:

1. With the increase in the length of the special segment in truss beam, stiffness and maximum structural strength are always reduced. In other words, there is an inverse relation between the length of the special segment with stiffness and system's strength.
2. Increasing the length of the special segment continuously increases the principal period of the structure. In other words, increase in the principal period of structure can be attributed to the reduced stiffness of the structure.
3. According to the diagrams, it is evident that with an increase in the length of the special segment, target displacement increases, which indicates more seismic demand of the structure occurs as the result of an increase in the length of the special segment.
4. An increase in the depth of the truss beam does not have a profound effect on the behavior of truss moment frames. However, more depth can reduce the shear force on the column at the cross-section with beam.
5. An increase in the number of panels in a constant length of the special segment does not change the behavior of the structure. In other words, an increase in the number of panels only reduces the required cross-section surface for the vertical element in the special segment.
6. The response modification coefficient, in one- and two-panel models, decreases with an increase in the length of the special segment. However, in three-panel models of 5-story frames this factor increases with the length of the special segment, but in 10-story frames with three panels, the behavior coefficient decreases with the length of the special segment. In general, the average values obtained for the behavior coefficient for 5 and 10-story buildings are 9.5 and 6.5 respectively. It is concluded that response modification coefficient varies by changing the special segments changes.

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