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PROPOSED SYSTEM FOR REDUCING PROGRESSIVE COLLAPSE POTENTIAL OF STEEL MOMENT RESISTING FRAMES

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ABSTRACT

Progressive collapse may be defined as the spread of an initial local failure from element to element, eventually resulting in the collapse of an entire structure or a disproportionately large part of it. The uncertainty related to lack of knowledge of which columns will be lost during extreme events makes it very complicated to consider all possibilities of column loss scenarios. Progressive collapse is triggered if the surrounding elements are not able to transfer loads that were originally carried by the lost member to other paths. Hence, alternate load paths need to be available in order to prevent collapse of the whole structural system. In this paper, a system composed of tension members is proposed to improve the performance of multi-story steel moment resisting frames upon loss of a column considering a comprehensive study of possible scenarios. The system depends on tension diagonal members to contribute to distributing the load whenever a column is lost. Static and dynamic linear analyses are performed to assess the efficiency of the system under multiple column loss scenarios. More than 450 two-dimensional finite element models are built representing steel moment resisting frames (SMRF) having different number of stories, considering multiple scenarios for column loss in addition to different arrangements for added tension ties. Results focus on impact of the proposed system on reducing the potential of progressive collapse of steel moment resisting frames.

Keywords: Progressive collapse, Alternative path, Collapse reduction.

INTRODUCTION

Progressive Collapse is a phenomenon that compromises the structural integrity of buildings. Its initiation is triggered by different man-made or natural hazards. There are numerous events where progressive collapse took place and resulted in massive casualties in terms of human lives and money. Therefore, many efforts were put to understand its mechanism, find proper ways to simulate, and prevent its occurrence. Powell [1] considered the basic concept of progressive collapse analysis and clarified the load sequence and the difference between applying gravity loads before or after removing a column. Agnew [2], Morone [3] and Habuibullah and Pyle [4] elaborated on how to use commercial program (SAP2000) in order to carry out linear dynamic analyses to study progressive collapse. Sasani et al. [5] considered a different scenario other than those stated in the GSA [6] and UFC [7]. Scenarios included removing four adjacent columns in the ground floor and two beams in the above floor considering an eleven stories reinforced concrete structure. Dhileep et al. [8] showed that due to the complexity of the nonlinear direct numerical integration of the equation of motion, using nonlinear static pushover analysis of structures appears like an adequate solution. Theoretical and numerical procedures for studying progressive collapse phenomenon were studied by Krauthammer et al. [9] and verified by laboratory tests. The two famous accidents of Ronan Point (London 1968) and The World Trade Center (New York City 2001) were considered. Crawford [10] stated that more efforts are needed to improve the retrofit technology and tools to satisfy the requirements resulting from the progressive collapse consideration for structures. Mahmoud et al. [11] investigated progressive collapse of steel moment resisting frames due to seismic loads considering 3-dimensional models. Systems to mitigate progressive collapse after the event of structural member loss gained interest in recent years. Alternate systems in the form of cables, pipes, special connections were investigated by many researchers [12-16]. The current study examines the efficiency of a proposed system composed of tension members that can be used to distribute and create new paths for load in the event of a column loss.

Generally, structural engineers try to consider impact of progressive collapse following guidelines and methods proposed by codes and standards. However, these methods are somehow generic and do not cover all possible scenarios. Moreover, due to complexity of the phenomenon, it is not possible to study all the possible scenarios. Till now, available tools and techniques consume time and effort that are not always available for common practice. In the current study, more than 450 two-dimensional finite element models were built. The considered parameters included the effect of removing each and every column in the considered structure separately. An additional system composed of tension members is proposed to improve the performance of multi-story steel moment resisting frames upon loss of a column. Results were compared while considering the structure with or without the proposed systems to assess the effect of the proposed systems and their benefits.

METHODOLOGY

2D models were built using SAP2000 [17] finite element program. Models were built following same geometry, section sizes, and material (S235, F_y = 235 MPa) reported by Gerasimidis et al. [18]. The considered structures are regular with a constant floor height of 3 m. All models have 4 bays with a uniform width of 5 m. Spacing between frames is 7 m. Pinned column bases are considered for all models. Meanwhile, all beams are rigidly connected to columns as shown in Fig. 1. The parametric study included analysis considering all possible scenarios for single column loss across all axes (A, B, and C) and all floors. Both linear static and linear dynamic analyses were performed considering the basic models in addition to the models including two cases for the proposed system leading to around 450 models.

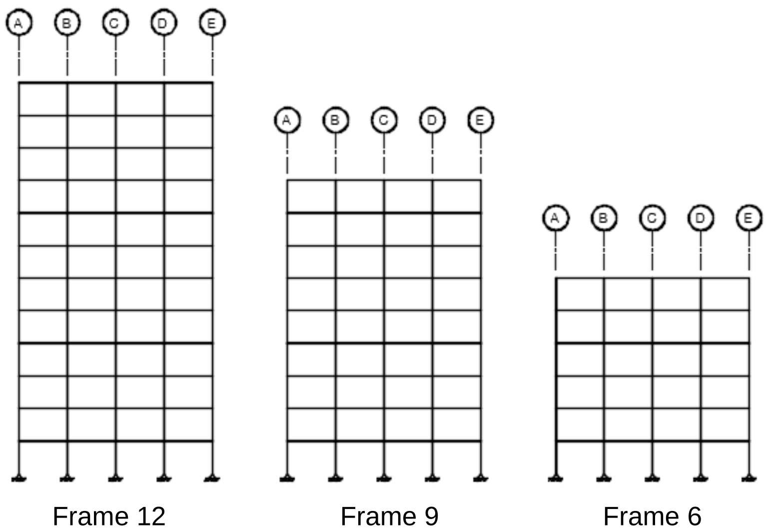

Fig. 1: Profiles of Frames having 6, 9, and 12 floors

For linear static analysis, the used case of loading is: 2.0*(1.2DL+0.5LL) as per DOD [7]. The factor (2.0) is to simulate the load amplification due to sudden loss of column. This amplified load is only applied over the bays adjacent to the removed member. For linear dynamic analysis, the used case of loading is: 1.2DL+0.5LL. The equivalent damping is considered equal to 0.5% through the analysis. In addition, column Loss is almost instant and is simulated by short interval of time (0.1 second) as per Morone [3], Fig. 2. Models are analyzed in two stages. During the initial stage, all columns are present. Afterwards, one column is removed, and a point load is assigned considering the time function shown in Fig. 2. Focus will be given to extracting the demand capacity ratio (DCR) for beams and columns is determined for both the linear static and linear dynamic analyses.

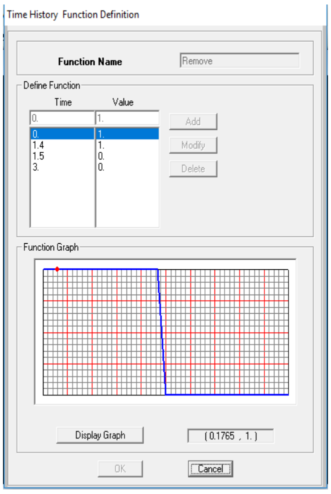

Fig. 2: Function Simulating Column Loss

VERIFICATION OF MODELS

Gerasimidis et al. [18] reported the ratio $M_{PBa}/M_{analysisBa}$ for both analysis methods: elastic limit analysis and limit analysis. Knowing plastic moment of each beam, and by dividing it by the ratio $M_{PBa}/M_{analysisBa}$ given by Gerasimidis et al. [18], it is possible to conclude the resulted moment in the beam above the removed column ($M_{analysis\ Ba}$) for both analysis methods. The concluded results were compared to the results extracted from analyses in the current study. The linear static solution was compared to the elastic limit analysis by Gerasimidis et al. [18]. Meanwhile, the linear dynamic solution was compared to the limit analysis for the same study. Results are shown in Figs. 3 through 5 and show good agreement.

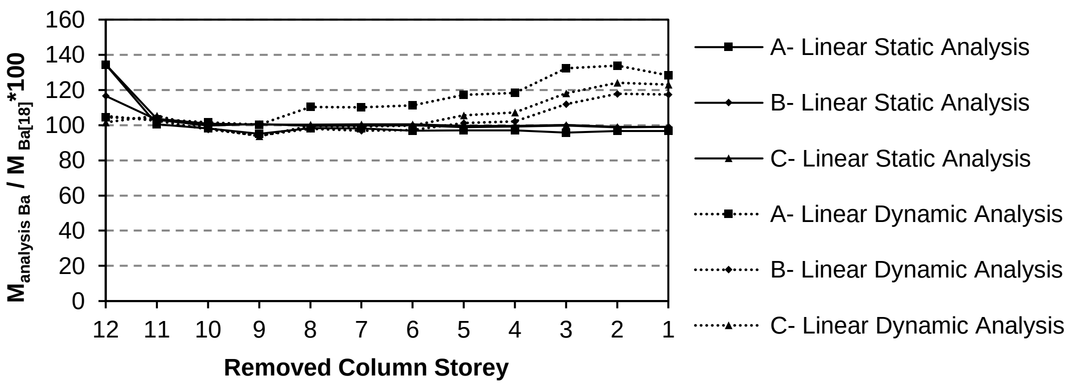

Fig. 3. Verification Results against Gerasimidis et al. [18] for Frame 12

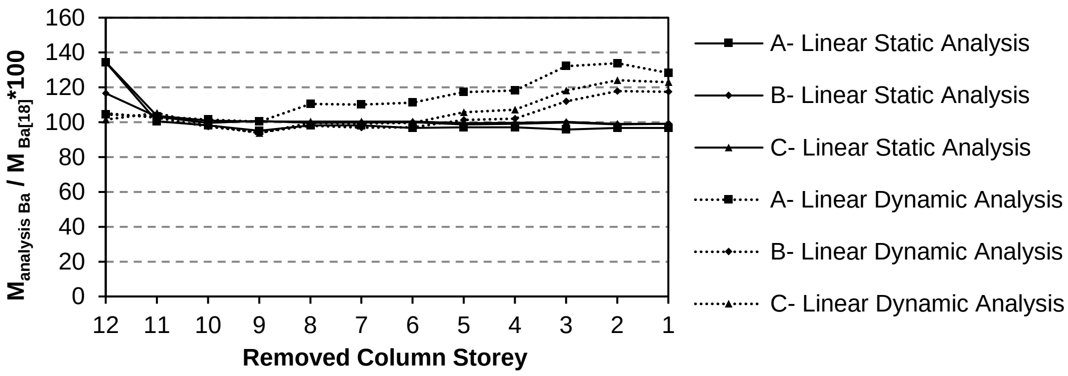

Fig. 4. Verification Results against Gerasimidis et al. [18] for Frame 9

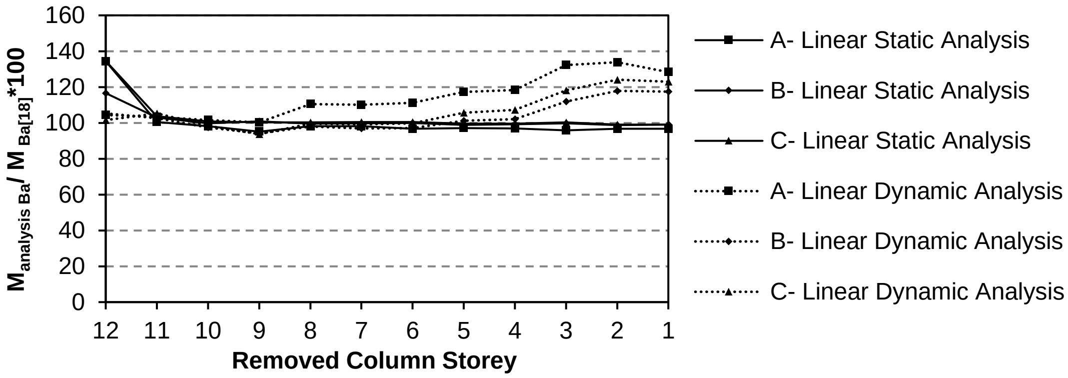

Fig. 5. Verification Results against Gerasimidis et al. [18] for Frame 6

MODELING NEW PROPOSED SYSTEM

Upon verification, the parametric study runs were initiated while considering the proposed system. Tension members are added to re-distribute forces upon different progressive collapse scenarios. The proposed system is assumed to work only when columns are lost. This means that those members will not carry any forces and will not affect the global stiffness of the structure during the normal operation life. The shape and location of the new system is shown in Fig. 6. All the tension members are defined as cylindrical frame elements having diameter equal to 100 mm and releases at both ends. The tension members have a yield strength of 520 MPa. The tension members are added in two cases: at the top floor only (1T) and at the top and middle floors (2T).

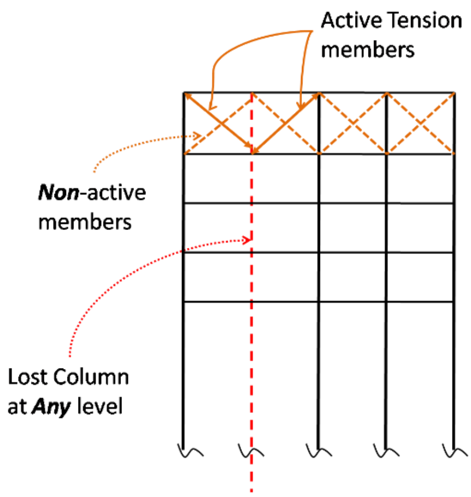

Fig. 6. Proposed System

RESULTS AND DISCUSSION

Buildings considered on this study are regular. Accordingly, Linear Static Procedure (LSP) is valid, even if the demand capacity ratio (DCR) exceeded 2.0 As per DOD [7]. The acceptance criteria considered in the current study will follow Table (9-4) available in ASCE/SEI 41–1312 [19]. All the beams in the models have compact sections. SAP2000 [17] check module was used to evaluate the interaction equations as per AISC 360-0513 [20]. Then, the stress ratio of each frame and for each case was plotted. Focus will be given to internal forces at the following locations: beam above lost column (M_{Ba}); beam above the beam above the lost column (M_{Baa}); beam adjacent to the beam above the lost column (M_{Badj}); column(s) adjacent to lost column (MCadj, P_{Cadj}); column(s) above column(s) adjacent lost column (M_{Caadj}, P_{Caadj}); and tension members of the proposed system adjacent to/connected with the location of the lost column. Fig. 7 shows a summary of the reported results. Focus in the current study will be given to the beam above the lost column and the column adjacent to it.

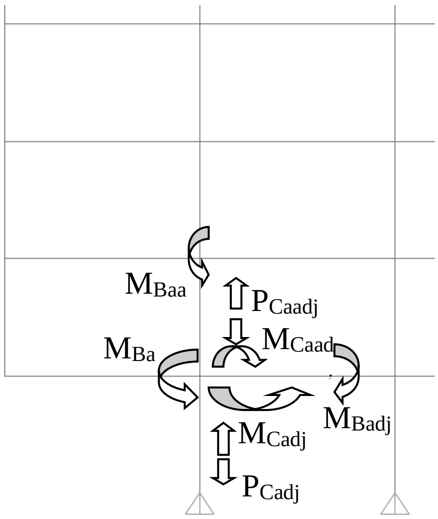

Fig. 7. Reported Results in the Current Study

Beam above Lost Column (B_a):

By using tension members (One Row or Two Rows), the moment in this beam dropped. The effect of the tension members depends on the location of the lost column with respect to the tension members System. This effect is reflected in Fig. 8. and Fig. 9. As can be seen, the reduction in beam moments gradually increase and the value of the reduction gets closer to the tension members system location. This means that the contribution of the proposed system, in supporting the beam above the lost column, increases when the failure happens closer to it. In case of using one row of tension members, one reduction is observed. On the other hand, two reduction locations appear in the event of using two systems of tension members. In addition, the values of moments in beams due to the loss of columns at floors 1 through 5 are less than the values of moments in beams due to the loss of columns at the same floors when one row of tension members is used. This is attributed to the fact that, in this case, upper and intermediate Systems are working together, compared to (1T) case where the upper level was functioning alone.

For (2T) system, the values of moments on beams due to the loss of columns at floors 6 through 11 are almost same as the values of moments in beams due to the loss of columns at the same floors when (1T) system is used. This is since, between floors 6 and 11, the upper system was functioning alone.

As for the cases where the lost column was at the upper (Last) Floor, there is no reduction in moment in the beam above the upper column (last floor) as the tension members cannot carry any compression force, thus they are not functioning in this case. Accordingly, the upper beam will act as a cantilever.

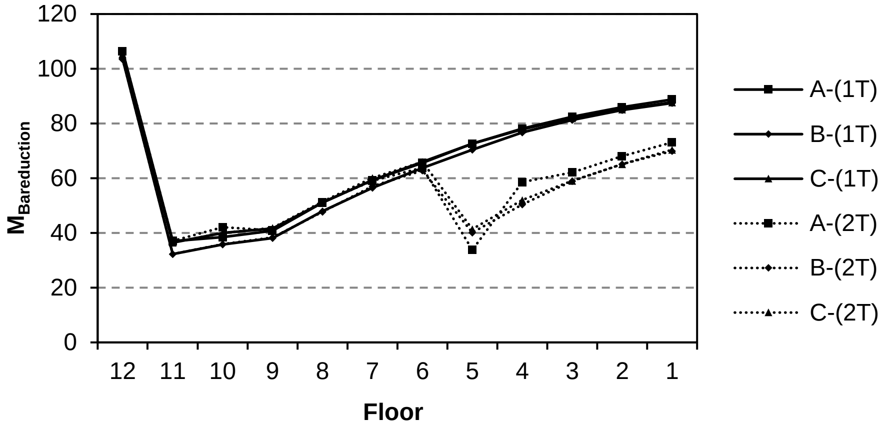

Fig. 8. $M_{Bareduction} = M_{Ba\ with\ T} / M_{Ba\ NoT}$***100**
Linear Static Analysis

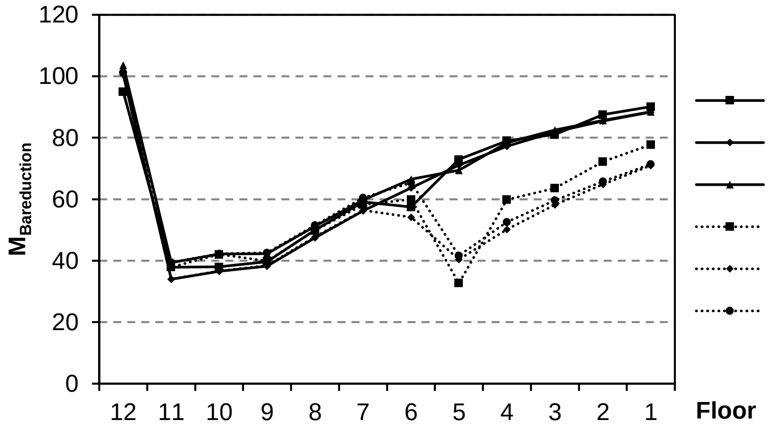

Fig. 9. $M_{Bareduction} = M_{Ba\ with\ T} / M_{BaNo\ T}$***100**
Linear Dynamic Analysis

The Column(s) adjacent to the lost column (C_{adj}):

Reduction in moments transferred to adjacent columns were also observed. Fig.s 10 and 11 shows the reduction due to the use of the proposed system. For (1T) system, the smallest reduction percentage was observed when the failed column is far away from the tension members, and the larger reduction percent is when the failed column is under the tension members. For the cases in between, the values of reduction percent are gradually varying between both extreme values. (2T) system gave similar behavior to that. As for the axial forces in these columns, there is almost no reduction in their values. This is expected since the weight(s) of the floor(s) above the removed column has to be transferred to the ground regardless of having the proposed system, as shown in Fig. 12. and Fig. 13. When the removed column is at the topmost column/floor, no reduction in the moment at these columns is observed since the proposed system is not functioning in overcoming the effect of losing a column.

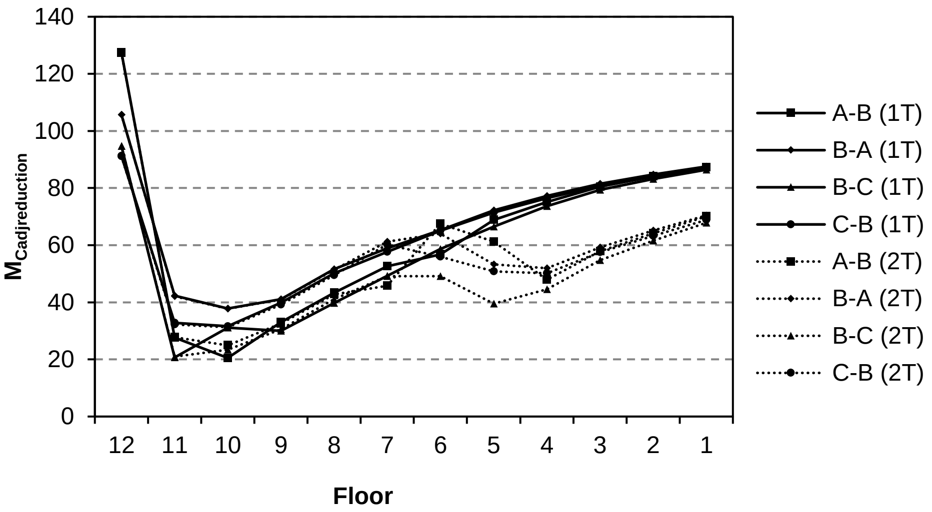

Fig.10. $M_{Cadjreduction} = M_{Cadj\ with\ T} / M_{Cadj\ No\ T}*100$
Linear Static Analysis

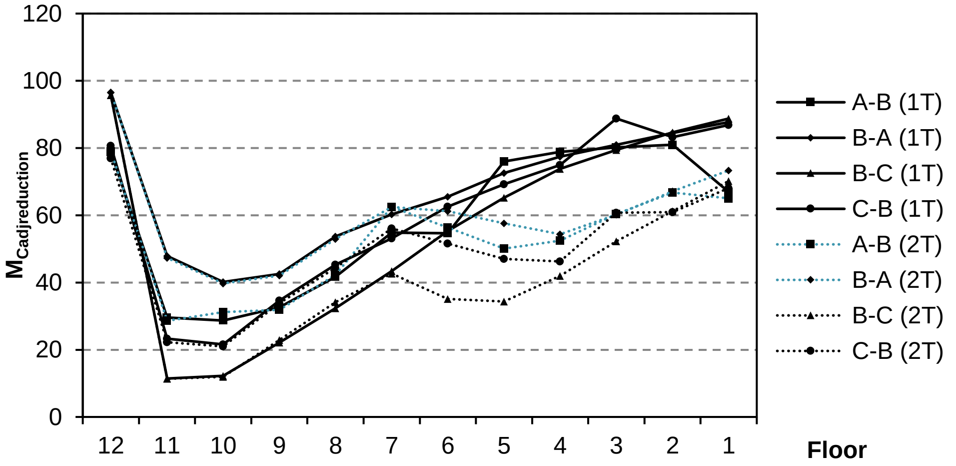

Fig.11. $M_{Cadjreduction} = M_{Cadj\ with\ T} / M_{CadjNo\ T}*100$
Linear Dynamic Analysis

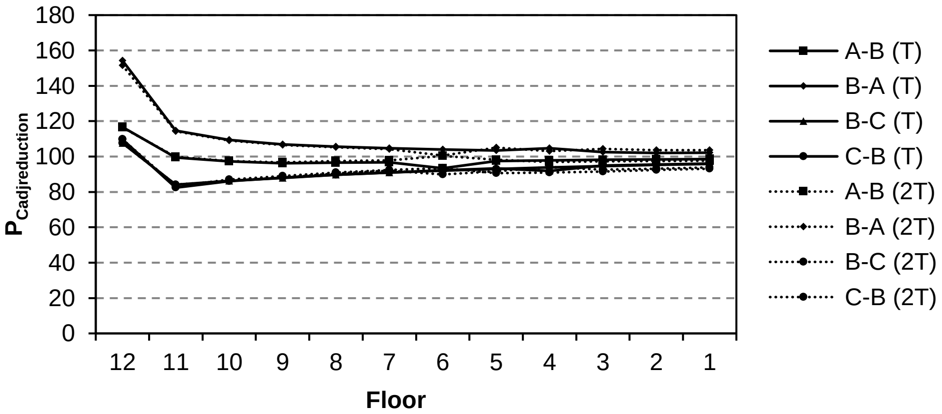

Fig.12. $P_{Cadjreduction} = P_{Cadj\ with\ T} / P_{Cadj\ No\ T}*100$
Linear Static Analysis

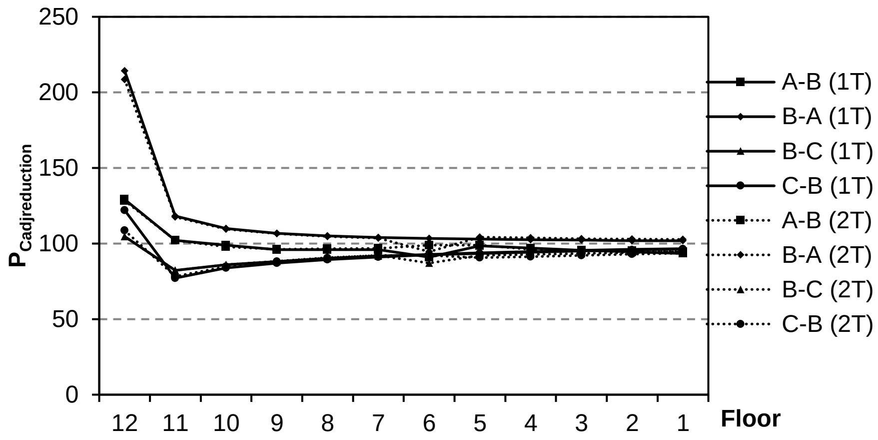

Fig.13. $P_{Cadjreduction} = P_{Cadjwith\ T} / P_{Cadj\ No\ T} * 100$
Linear Dynamic Analysis

A-B: is the effect on Column B due to the loss of Column A.
B-A: is the effect on Column A due to the loss of Column B.
B-C: is the effect on Column C due to the loss of Column B.
C-B: is the effect on Column B due to the loss of Column C.

CONCLUDING REMARKS

The influence of a proposed system to reduce progressive collapse is investigated in the current study. Around 450 runs were performed considering 2-D steel moment frame models with and without the proposed system. Variations in internal forces were examined through static and dynamic linear analyses considering multiple scenarios for column loss in addition to different arrangements for added tension ties. It was found that the proposed system reduces the moment in beams, the moment transferred to columns(s), the moment applied to the connection between beams and columns. However, the reduction percentage depends on the location of the lost column with respect to the proposed system. Meanwhile, the proposed system hardly affected the axial force in columns adjacent to the lost column. The contribution of the proposed structural system(s) is maximum when the lost column is closer to it. Using two systems increase the reduction in the moment in the beams and columns as long as the lost column is located below the two systems. However, when the lost column is above the lower system, the reduction in the moments using any of the two systems (1T or 2T) is almost the same.

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