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Abstract. In our recent catastrophes, Progressive collapse become an essential behavior that should be researched widely and to be taken into consideration through the design process. The main vertical loss can be caused by different reasons, either blast due to terrorist attack, failure of columns due to extreme earthquake application, or finally, losing a structural element due to high impact resulted from a vehicle or any other moving object. Losing main vertical element due to extreme earthquake excitation is an important and repeated occurrence, However, it didn't take much attention in progressive collapse recent studies. Unified Facilities Criteria (UFC) and General Services Administration (GSA) guidelines are used to assess the behavior of structures subjected to progressive collapse as a result of the loss of primary vertical support, the structures' types are categorized according to the construction material used such as steel, concrete or timber. Unfortunately, there is no specific guidelines for different structure systems used and subjected to earthquake excitation at the same time. As a result, it is vital to understand the structure behavior including the change in structure system parameter with respect to earthquake excitation. In this paper, an observation on the behavior of a post-tensioned slab system due to the failure of main structure element during earthquake excitation is adopted. A numerical analysis is carried out on a typical ten story reinforced concrete post-tensioned flat slab structure (designed according to the (ACI 318- 14) subjected to primary vertical element loss (corner column, edge column and internal column) due to seismic activity. The case study is assessed following the guidelines of the UFC. Extreme Loading for Structures (ELS) software, based on the Applied Element Method, is used for non-linear dynamic analysis of the structure. A time history analysis of the earthquake is applied along with the column removal scenarios. Observations are recorded for the failed and un-failed cases. Column rotations and stress contours are demonstrated for different scenarios and compared to the UFC guidelines. Tendon prestressing losses are calculated with other parameters to assess the post-tensioned flat slab behavior due to column loss.

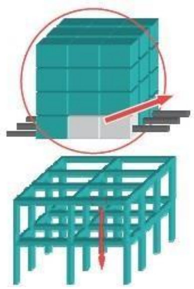
INTRODUCTION

Different parties applied many design requirements and guidelines to reduce the potential of progressive collapse for new and existing facilities. Two design approaches are considered by The Unified Facilities Criteria (UFC) [1] which are; The direct design approach includes alternate load path method (ALPM) and specific local resistance method (SLRM). According to FEMA 356 [2] nonlinear dynamic (ND) methods is recommended for seismic analysis and design of structures. However, in the research field the effects of multi hazards on structure's response didn't get much wide attention or applications. The study of the progressive collapse is handled on two different levels; the component level and system level. Some analytical modeling and validation for high rise buildings are developed, through fiber-beam-element model and multi-layer shell element model, to expand the simulation research approach in this field [3,4]. Unfortunately, building resistance against multi hazards are examined on a small range. Some Experimental tests are conducted to a to a Small-scale PT flat plate system by applying gravity loading, cyclic loading and fire to a Small-scale to evaluate its behavior due to multi hazards. The flexural and shear failure are evaluated experimentally on a small-scale PT slab column connection subjected to gravity and pseudostatic loading [5,6]. An ordinary moment frame's structure is studied by subjecting it to a column removal due to seismic loading. Elshaer et al [7] and Somayyeh Karimiyan [8] concluded that column removal due to seismic loading is more critical for progressive collapse than under gravity load, and the slab contribution plays an important role in resisting structure resistance by the catenary action effect. Kaiya Bian et al [9], studied typical ten-story reinforced concrete frame by applying three harmonic waves, and observed the system's behavior and failure mode that took place severely in the free vibration mode rather than the strong earthquake excitation duration.

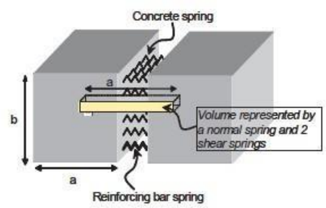
In this paper, progressive collapse assessment of post-tensioned flat slab structure is studied and observed in accordance to the UFC regulations. The adopted structure case study is 10-story reinforced concrete building designed according to the (ACI 318-14) [10]. Non-structural elements are assumed to be neglected in this study. The structure is investigated using the alternative path method defined by the UFC [1].

METHODOLOGY Applied Element Method (AEM)

The Applied Element Method is an innovative modeling method adopting the concept of discrete cracking, Tagel-Din and Meguro [11-13]. In Applied Element Method (AEM), the structures are modelled as an assembly of relatively small elements, made by dividing of the structure virtually, as shown in Figure 1.a.[14] The elements are connected together along their surfaces through a set of normal and shear springs. The springs are responsible for transfer of normal and shear stresses, respectively, from one element to another. Springs represent stresses and deformations of a certain volume as shown in Figure 1.b.



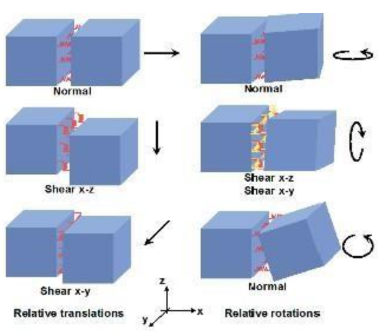
a- Element Generation for AEM

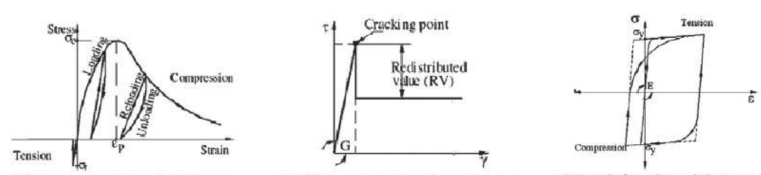


b- Spring distribution and area of influence of each pair of springs

FIGURE 1. Modelling of structure to AEM .[14]

Each single element has 6 degrees of freedom; 3 for translations and 3 for rotations. Relative translational or rotational motion between two neighboring elements cause stresses in the springs located at their common face as shown in Figure 2. These connecting springs represent stresses, strains and connectivity between elements. Two neighboring separated once the springs connecting them are ruptured.

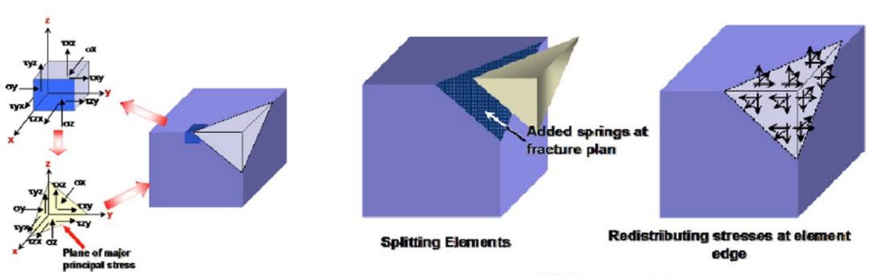




(A) concrete under axial stresses (B) Concrete under shear stresses (C) Reinf. under axial stresses

FIGURE 2. Stresses in springs due to relative displacements .[14]

FIGURE 3. Constitutive models adopted in AEM for concrete and steel. .[14]



(A) Cracking (B) Post-cracking

FIGURE 4. AEM cracking & post-cracking criterion. [14]

Fully nonlinear path-dependent constitutive models for reinforced concrete are adopted in the AEM as shown in Figure 3. For concrete in compression, an elasto-plastic and fracture model is adopted, Maekawa [14]. When concrete is subjected to tension, a linear stress strain relationship is adopted until cracking of the concrete springs, where the stresses then drop to zero. The residual stresses are then redistributed in the next loading step by applying the redistributed force values in the reverse direction. For concrete springs, the relationship between shear stress and shear strain is assumed to remain linear until the cracking of concrete. Then, the shear stresses drop as shown in Figure 3. The level of drop of shear stresses depends on the aggregate interlock and friction at the crack surface. For reinforcement springs, the tangent stiffness of reinforcement is calculated based on the strain from the reinforcement spring, loading status (either loading or unloading) and the previous history of steel spring which controls the Bauschinger's effect, as presented by Ristic [15]. Separated elements may collide with other elements where new springs are generated at the contact points of the collided elements. When the tensile principal stresses reach concrete cracking strength, the concrete assumed to be cracked as shown in Figure 4a. The crack propagation direction depends on the cracking direction with respect to the element faces, where if the direction of crack parallel to the face of the element then the crack will propagate in the same direction. It is numerically complicated to predict the crack propagation direction when the crack is inclined as shown in Figure 4b. Two ways are used to solve such a problem; the first solution is to divide the element into two smaller elements while the second solution is the redistribution of unbalanced stresses across element faces. To transfer shear stresses, the first solution should be adopted while in the fact it is too complicated. The accuracy of the second solution is less compared to the first one, but it can be increased by reducing element size. One of the main advanced features adopted in the ELS is that the element contact is automatically detected whether it's time or location. Elements separation and contact are automatically detected and accurately modeled. Figure 5 illustrates the different types of contacts that may occur during analysis.

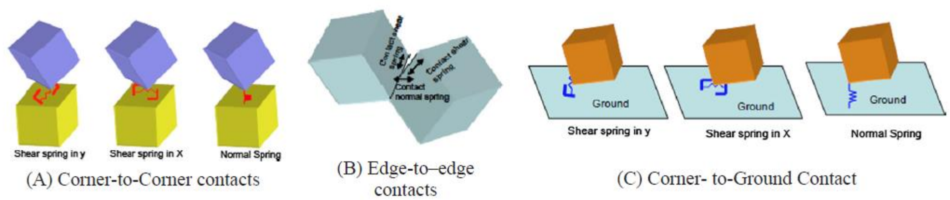


FIGURE 5 AEM different types of contact. [14]

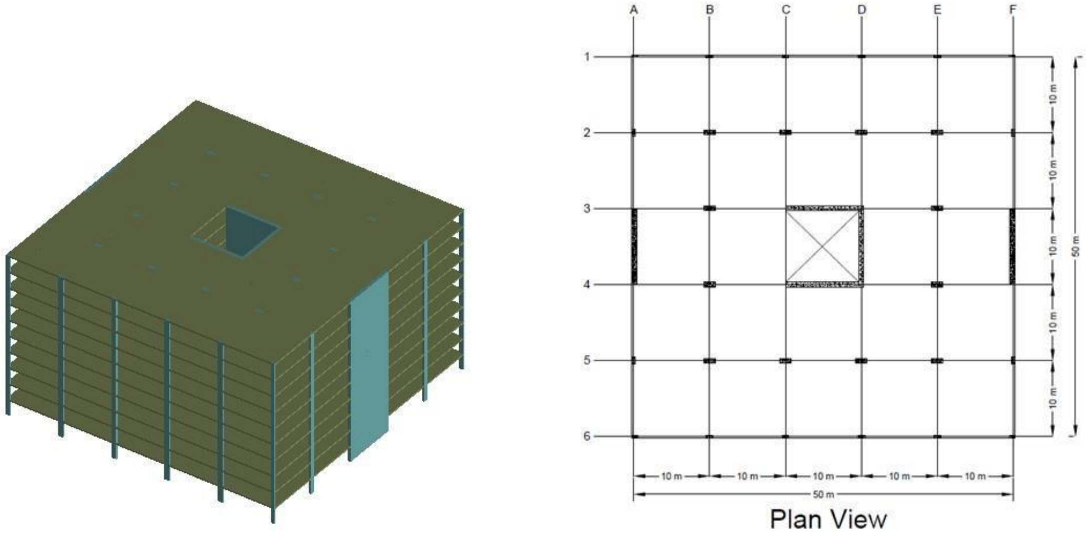
A program validation adopting this method is done by M. Ehab and M. Maxi [15], where an experimental study is adopted from Weng et al. [16] and numerically modeled using ELS software. Three one-third scaled specimens are modeled and detailed using the ELS. A mesh sensitivity is conducted to choose the most suitable mesh in simulating the chosen specimen. Three one-third scaled tested specimens are identified as Full Restrained (FR), full restrain-seismic (FR-S) and Partially Restrained (PR). The RFT detailing is defined in details in ELS models. Experimental and ELS numerical model and results showed a good agreement, as a result, ELS can be verified to show the exact failure and crack pattern and can be replaced by physical laboratory.

Due to the limitation of investigating the structure's collapse experimentally in a real full scale laboratory, ELS is the most optimum solution to make this testing virtually without the experimental limitations and risks.

THE CASE STUDY Structure Details

The structure is symmetrical with five equal bays, of 10 meters long, in each direction. All floors are three meter in height. A reinforced concrete core is located in the center of the structure at the elevators and staircase locations to resist seismic loads according to ACI 318-14 [10], in addition to two shear walls placed at two edges of the structure as shown in Figure 6.

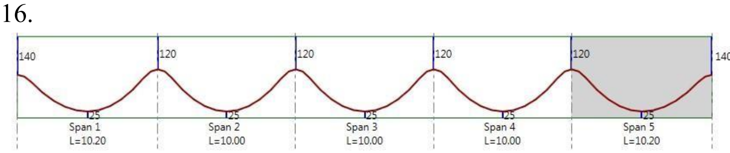
The slab is post-tensioned flat slab with thickness of 280 mm reinforced with pre-stressing tendons spaced at 1.25 meters in both directions distributed among the slab, with bottom mesh reinforcement of Φ16 @ 200mm and top mesh reinforcement of Φ12 @200mm. Column reinforcement is arranged uniformly along column sides. The reinforcement is 44Φ32, 26Φ25 and 14Φ18 for interior, edge and corner column respectively. Column stirrups are taken 5Ø10/m'. For Core and shear wall reinforcement, Φ25 with spacing 78 mm is distributed uniformly along the wall length, and a concentration in the corners of 28 Φ32 is placed.



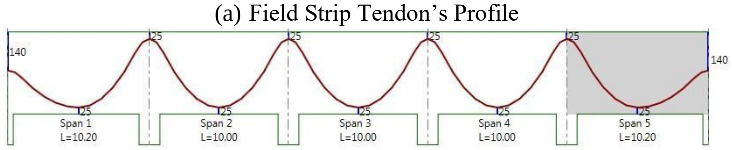
(a) (b)

FIGURE 6. 3D Structure Model in ELS and general Plan view with Dimensions

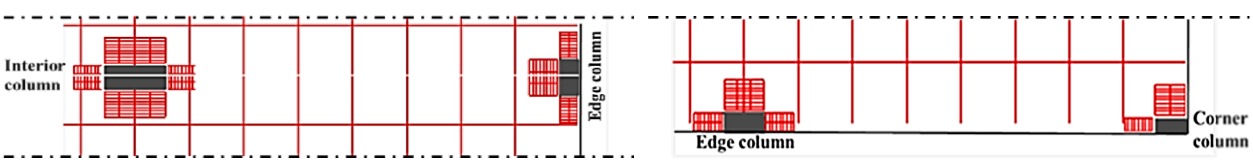
The tendon's profile for different structural segments is shown in Figure 7 (a & b). The structure is designed following the code requirements for structural concrete ACI 318-08 [10]. In addition to the self-weight of the structure, uniformly distributed loads of 2 kN/m^2 are considered for both live loads and finishes, plus 2.5 kN/m^2 for partitions. The structure is designed to follow response spectrum Type-1 with a peak ground acceleration 0.15 g, columns are assumed to be fixed to foundation. The load combination is taken (1.2 D.L. + ½ L.L. + E), where E is the earthquake load, according to the (UFC, 2009) [1], and (ASCE, 2005). A punching check is applied on the post-tensioned slab for gravity and lateral loading. Punching design is required due to lateral loading, stirrups are used and arranged across the punching critical section around the columns as shown in Figure 7(c). closed stirrups of Φ12 at spacing 80 mm is spaced along the critical section hanged by a longitudinal reinforcement of Φ16.



(a) Field Strip Tendon's Profile



(b) Column Strip Tendon's Profile



Column strip at the middle bay Column strip at the edge bay

(c) A typical part of plan showing slab punching reinforcement above column critical sections in the ELS environment

FIGURE 7. Reinforcement details of the structure components.

The time history artificial earthquake adopted, with time duration of 20 seconds, is generated based on response spectrum following the ACI 318-08 regulations, and based on the location and the structural properties, as shown in Figure 6. SeismoArtif software is used to obtain the artificial earthquake used as shown in Figure 8 with peak ground acceleration of 0.146g at 3.45 seconds.

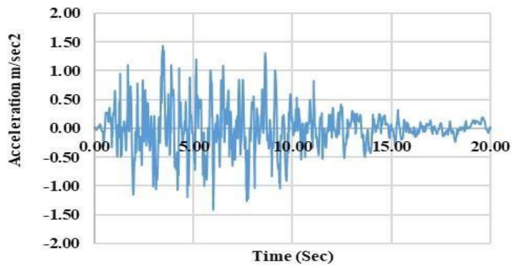


FIGURE 8. the Artificial time -history EQ generated from the SeismoArtif Software

Material properties

The concrete in this study is taken with a compressive strength of 40 MPa, post-tensioned tendons of strands 13 mm and ultimate strength of 1860 MPa and yield strength of 1675 MPa. Main ordinary reinforcement is taken with 360 yield stress.

Analytical approach

For assessing the progressive collapse behavior of post-tensioned flat slab due, to earthquake excitation, multiple column removal is applied following the UFC regulations. The column may be lost due to overstressing or column deficiency during earthquake application. In this paper, corner, edge and interior columns, located at the first floor, are removed one at a time.

STRUCTURAL BEHAVIOR DUE TO COLUMN LOSS

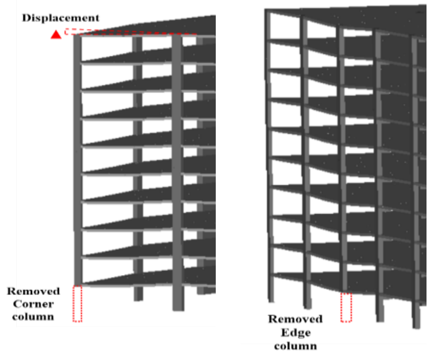
Different structural behaviors are observed after applying the removal of the different vertical supports. Cases of edge and corner column, the structure showed resistance to its removal and for the interior column removal, total collapse encountered.

Cases showed resistance to collapse

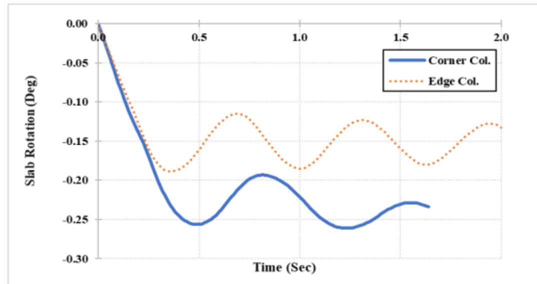
Cases of edge and corner column resisted the collapse due to the involvement of many parameters that contributed in increasing the structure resistance. Some of these parameters are the nature of the post-tensioned flat slab used along with the reinforcement applied for resisting punching failure. In addition to this, the redistribution of forces with respect to the structural arrangement according to the location studied and selected.

Slab rotation

Histories of deflection and slab rotation for the two analysis cases that showed no collapse are presented in Figure 7 and Figure 8 respectively. The maximum slab rotation is found to be 0.25 and 0.18 degrees for corner and edge column removal scenarios respectively. By comparing the values with UFC limits, which is 2.86 degrees, the two cases are found to be safe and satisfying the safety limits against progressive collapse. It is observed that despite the effect of the maximum earthquake acceleration that took place at certain time (3.45sec), it didn't affect the deflection oscillation for the two cases, as a result of reducing the time history in the graph shown due to space limitations.



(a)



(b)

FIGURE 7. structural deformation due to different column removal scenarios

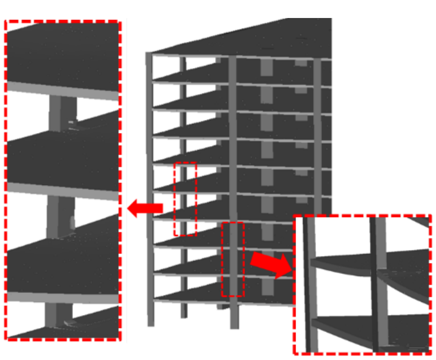
FIGURE 8. Histories of slab rotation in case of corner column removal

Interior Column Cases collapse

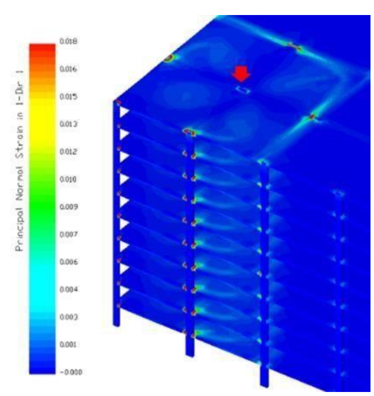
In this Case, the structure suffered a partial collapse of the area directly connected to the removed column in the ground floor. Mainly the failure took place due punching stresses resulted from column shear and the transferred biaxial moments from slab in the corner column adjacent to the removed column, that leads to punching failure in the slab around the column, despite of the punching reinforcement that placed in the initial design, as shown in Figure 9. The post-tensioned slab system could bridge over the interior column removal in the ground floor until the failure initiated at edge column. As a result, a new consideration needs to be added for the punching failure occurrence in multi hazard structures.

CONCLUSION AND FUTURE WORK

The analysis and results illustrated is a part of a full research that will be continued. The AEM is used to evaluate the resistance of reinforced concrete post-tensioned flat slab structure subjected to earthquake loading and assessed through different column scenarios. The post-tensioned slab system proved to resist progressive collapse due to multihazards in the corner and edge column removal scenarios and also creating an alternative load path led to transfer the gravity load safely. Also, the slab rotation limits satisfied the UFC regulations. In case of interior column removal case, post-tensioned slabs helped in minimizing the collapse to be controlled in the parts that are subjected to column loss. However, the punching reinforcement, previously designed and placed, failed to resist the high punching shear stresses and the biaxal moment occurred, as a result of slab collapse. It is concluded that for the interior column removal case, to avoid punching failure, a design consideration needs to be added to increase the resistance towards punching and biaxal moment effect between the column and slab junction. As a continuation of this research, additional column and shear wall removal scenarios will be applied and tested. A clear observation will be done including the prestressing force behavior in the post-tensioned tendons along with a comparison of rotation with respect to all structural components not only slabs.



(a)Punching Failure in the Edge Column



(b)Strain contour concentration around

the columns just before failure

FIGURE 9. Failure initiation and pattern

A comparison will be conducted between progressive collapse assessment under gravity loading, and multi hazard loading (earthquake excitation).

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