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Finding Critical Element in the Progressive Collapse of RC Structures Using Sensitivity Analysis

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Abstract

Failure of some elements in the structure can play triggering role for beginning of collapse progression. The critical element is the structural element that when it fails, leads to progressive collapse. To find the critical element of the structure, sensitivity analysis should be done. But there are not specific structural criteria for using in sensitivity analysis. In this paper following GSA, UFC 4-023-03 and ASCE guidelines, sensitivity analysis has been modified and applied to find the critical element of a major number of reinforced concrete structures. 1080 3D nonlinear pushdown analyses were done and the results showed that the place of the critical elements differs in different stories and different plan shapes of high rise structures. In the structures with high aspect ratio in height, the critical element of the whole structure is located in the story of 2/3 height of the structure. When the aspect ratio of the structure in plan increases, sensitivity of the columns in the long dimension of the structure become closer to each other.

Keywords: Progressive Collapse; Modified Sensitivity Analysis; Critical Element; Reinforced Concrete Structures; High Rise Buildings.

1. Introduction

Local failure is mostly defined as loss of the load carrying capacity of one or more structural elements which are parts of a whole structural load carrying system [1]. After some structural elements failure, the structure should be able to provide an alternative load carrying path that can redistribute the loads of the structure. After redistribution of loads on remaining structural elements, each element will support different new loads. If this new load exceeds the load carrying capacity of any member, it will cause another local failure. Such sequential failures can propagate through a structure. If a structure loses too many members, it may suffer partial or total collapse. Progressive collapse is a failure sequence that relates local damage to large scale collapse in a structure and is defined as “the spread of an initial local failure from element to element, resulting eventually in the collapse of an entire structure or a disproportionately large part of it” [2]. It is estimated that at least 15 to 20% of the total number of building failures are due to progressive collapse [3]. A popular example of such a failure is the Ronan Point building collapse in England [4].

Some researchers studied the progressive collapse with a specific event or reason [5-6]. Kheiroddin and Mehrabi [7] studied the implementation of UFC 4-023-23 to protect structures against progressive failure and analyzed, designed, and investigated two steel buildings, 12 and 20 stories, using the AP method. Considering sudden column loss as a design scenario, Izzuddin et al. [8-9] proposed a framework for progressive collapse assessment of multi-story buildings.

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Leyendecker et al. [10] studied the loading of such phenomenon. The behavior of the structure subjected to progressive collapse was the topic of some researches [11-12]. Al-Salloum et al. [13] studied progressive collapse resistance of a high rise reinforced concrete framed structure. Kheyroddin et al. [20] used nonlinear finite element analysis to propose a new and simple 5-step method to calculate of the dynamic load amplification factor due to sudden column loss within a progressive collapse event in a structure. Mashhadiali and Kheyroddin [21] studied an innovative different structural system subjected to the progressive collapse.

Also design a structure to control the progressive collapse was topic of some researches in recent years [20-25]. Khandelwal et al. [24] studied the progressive collapse resistance of seismically designed steel braced frames with 2D models. Two types of braced systems were considered; special concentrically braced frames and eccentrically braced frames. Some studies have been done to find the most important structural element in progressive collapse [23-27]. Kim et al. [26] studied the sensitivity of design parameters of steel structures to progressive collapse. According to their research strength is the most important design parameter in the moment resisting frame structures while the column yield strength is the most important design parameter in the dual system structures.

Modeling collapse progression, and design a structures against it, is the main aim of some important building codes like GSA 2003 [31], UFC 4-023-03 (2005) [32] and UFC 4-023-03 (2009) [33-35]. The codes and guidelines have suggested that columns are the most important element of a structure in collapse progression, so the main design procedures of these codes are based on column loss scenario. To design or rehabilitate a structure against progressive collapse, the most important part is to find the critical element, i.e. the column that its loss can make the structure collapse more un-proportionately. Hence the main question is that omitting of which column can make the progressive collapse begin. In this paper to find the answer to this question sensitivity analysis has been modified and applied. In UFC 4-023-03 (2009), the progressive collapse design requirements employ three design/analysis approaches [33-35]:

i. Alternate Path method (AP), in which the building must bridge across a removed element.

ii. Enhanced Local Resistance (ELR), in which the shear and flexural capacity of the perimeter columns and walls are increased to provide additional protection by reducing the probability and extent of initial damage.

iii. Tie Forces (TF), which prescribe a tensile force capacity of the floor or roof system, to allow the transfer of load from the damaged portion of the structure to the undamaged portion.

Alternate Path is the most common method for analysis and design. Three analysis procedures are employed in this method:

1. Linear Static procedure (LSP)
2. Nonlinear Static procedure (NSP)
3. Nonlinear Dynamic procedure (NDP)

For each plan location defined for element removal, AP analyses should be performed for:

1. First story above grade
2. Story directly below roof
3. Story at mid-height
4. Story above the location of a column splice or change in column size

In addition to the elevation of the removed column, its location in the plan of the structure is another problem. In these guidelines, the place of removal column is based on threat analysis, which depends on the terrorist attacks not on the structural behavior. UFC 4-023-03 advices to remove external columns near the middle of the short side, near the middle of the long side, and at the corner of the building. Also it recommends removing columns at locations where the plan geometry of the structure changes significantly. Engineering judgment should be used to recognize these critical column locations [33-35]. For a complete risk analysis in a structure against any danger, three analysis are needed: Threat analysis, Impact analysis and Vulnerability analysis [36]. Threat analysis shows the kind, magnitude and place of the danger threatening the structure. Impact analysis shows effect, cost and importance of the collapse. And vulnerability analysis declares the magnitude of the collapse caused by the failure in any kind (e.g. failure of any column in progressive collapse). As it is clear, the location of removal column (suggested in codes) is based on the threat analysis and not based on the behavior of the structure itself (vulnerability analysis). Some researchers have been done on finding the most important element in the structure [24, 26-30]. In each one a procedure has been used, but no procedure in which all steps is clear, reliable and based on an accepted code has been presented. Also in most researches only missing of some of the columns have been checked. In this paper, at first a procedure has been modified according to the reliable codes and has been used for all columns of a structure.

2. Introduction to Modified Sensitivity Analysis (MSA)

Sensitivity analysis is the study of how the uncertainty in an output of a model or system can be apportioned to different sources of uncertainty in its inputs [37]. Frangopol et al. [28], Wada et al. [29-30] studied how much the resistance of a structure would be available after some structural elements were destroyed, and compared it with the resistance in the original state. For instance, Frangopol et al. [28] proposed a relevant index to the redundancy of a structure as the following equation.

$$R = L_{intact} / (L_{intact} - L_{damage}) = \lambda / (\lambda - \lambda^{*}) \tag{1}$$

Where, L_{intact} and λ (or λ_0 in the Equation 2) respectively represent the load carrying capacity and the corresponding collapse load factor of the structure in its original state. Also, L_{damage} and λ^* (or λ_{damage} in the Equation 2) respectively represent the load carrying capacity and the corresponding collapse load factor of the structure in its damaged state. The present study evaluates a decreasing ratio of the vertical load carrying capacity of the structural system before and after the disappearance of a certain member. It is regarded as the sensitivity index to the member's disappearance, denoted as *S.I.*

$$\text{Sensitivity Index: } S.I. = (\lambda_0 - \lambda_{damage})/\lambda_0 \tag{2}$$

The formula above (Equation 2) is equivalent to the reciprocal of the index about the redundancy given by Equation 1 introduced by Frangopol *et al.* [28]. When the vertical load carrying capacity changes a little when a certain member disappears, the corresponding sensitivity index is negligible: $S.I. \cong 0$. Failure of a member like this, does not seriously affect the load carrying capacity of the whole structural system and would be regarded as less important from the standpoint of preserving the load carrying capacity. But on the other hand, when a member with large sensitivity, e.g. $S.I. \cong 1$, disappears, a part of the frame or the whole frame would collapse. Such a member with a high sensitivity index would be regarded as the critical element of the structural system.

That is why finding the critical element of the structure is so important. For this purpose sensitivity analysis has been modified and presented here; in normal pushdown analysis, one point of a structure is pushed down gradually in steps, until some plastic hinges are made in the element (i.e. the element collapses). In every step, the force is recorded and at last a load-displacement diagram is presented.

In the Modified sensitivity analysis (MSA) used in this paper, at first, the whole structure is loaded in gravity direction. This loading is increased step by step until the structure collapses (i.e. plastic hinges are made in some elements and the collapse criteria of the whole structure appears). Ultimate load carried by the structure is called the ultimate load. Then one specific column will be omitted and the structure will be loaded using UFC 4-023-03 (2009) load pattern (i.e. twice the normal load, on the panels related to the removed column and normal loading on the other panels, Figure 1).

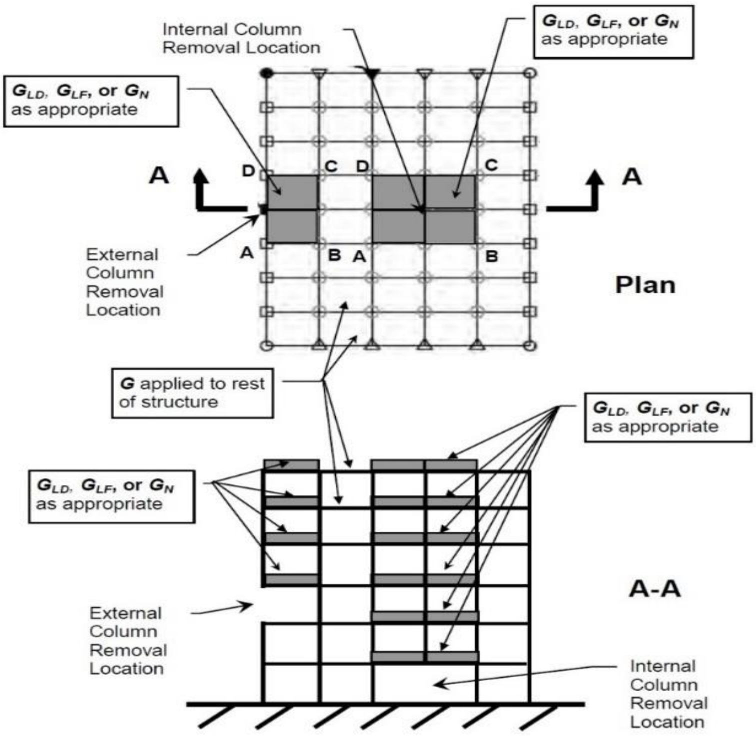

Figure 1. Loads and load locations for column removal based on UFC 4-023-03 (2009) [35]

The whole structure and plastic hinges are monitored in all steps. Two kinds of collapse are considered: local collapse and global collapse. Local collapse is defined as the collapse of panels related to the removed column and global collapse is defined as the collapse of the structure according to GSA (2003) (Figure 2).

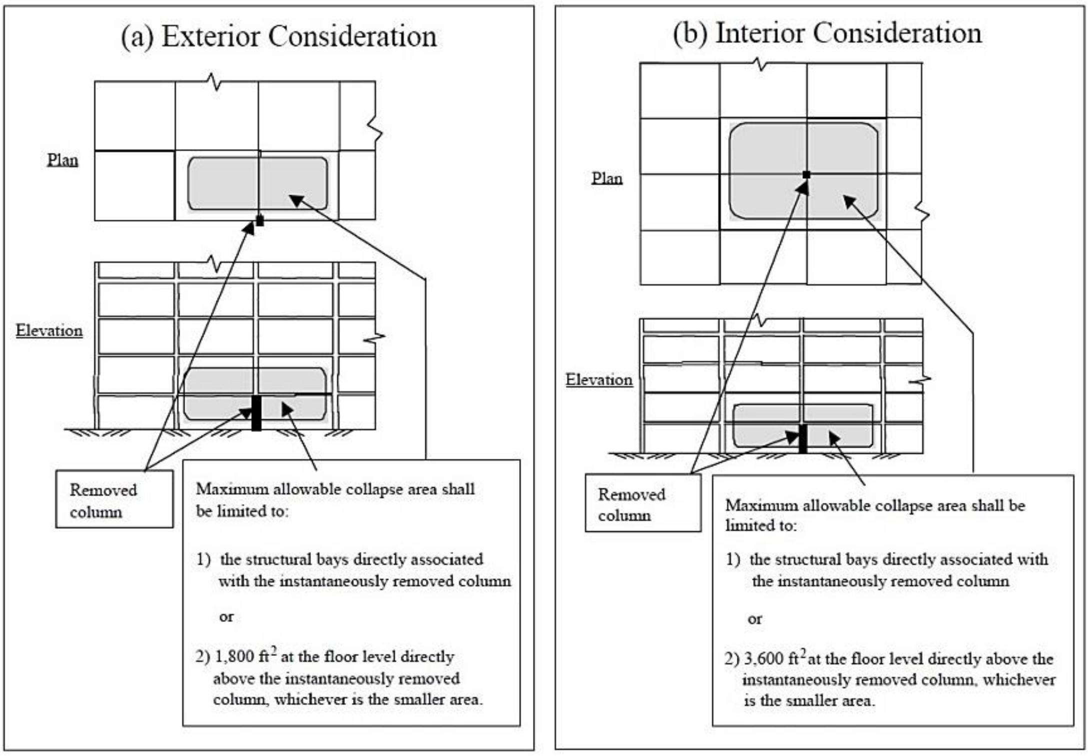

Figure 2. GSA (2003) allowable extent of collapse of column removal [31]

Load of the step in which local collapse occurs is called local damage load and load of the step in which global collapse occurs is called global damage load. Then for both local and global damage conditions, the sensitivity index is calculated using Equation 2. For defining the capacity of elements, reinforced concrete beams and joint requirements of UFC 4-023-03 (2009) should be used; "for new and existing construction, the design strength and rotational capacities of the beams and beam-to-column-to-beam joints shall be determined with the guidance found in ASCE 41 [38] (Figure 3), as modified with the acceptance criteria provided in UFC 4-023-03 (2009)" (Table 1). Advantage of the Modified Sensitivity Analysis (MSA), presented here is that all steps of the MSA are clearly based on reliable codes and completely applicable with commercial programs like SAP2000. Because of the nonlinear analysis, used in MSA, results are more reliable.

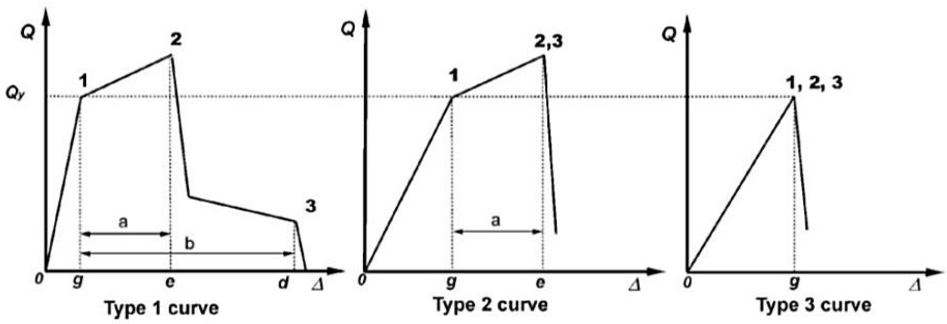

Figure 3. Definition of force-controlled and deformation-controlled actions, in ASCE 41 [37]

Table 1. Examples of deformation-controlled and force-controlled actions, in ASCE 41 [37]

Component	Deformation- Controlled Action	Force- Controlled Action
Moment Frames		
• Beams	Moment (M)	Shear (V)
• Columns	M	Axial load (P), V
• Joints	--	V

Generally for modified sensitivity analysis, some steps should be followed:

1- A uniform load should be applied on all floors of the intact structure, and increased step by step until the structure collapsed. This load is called the ultimate load.

2- One of the columns should be removed, and a uniform load be applied to the whole area of the structure regarding an accepted load pattern such as the UFC 4-023-03.

3- Uniform load of the second step should be increased until disproportionate collapse occurs, around the removed column.

4- Calculation of sensitivity index for all column removal conditions using Equation 2.

Comparison between sensitivity indexes of all columns that shows the elements which the structure is more sensitive to their loss.

As UFC 4-023-03 (2009) uses computer program SAP2000 for modeling progressive collapse in its appendixes, in this study SAP2000 was used to develop 3D finite element models of the structures. Beam elements was modeled as T and L sections and attached to the shell element of the slabs, using 10 nodes in any side of the slabs for connection of beam and shell (slab) elements. T and L sections have been used to include the effect of the slab acting as a flange of beams as recommended by the seismic design codes ASCE 41-06 [39]. For simplicity, the effective flange width on each side of the beam is taken as three times the slab thickness. Recent experimental studies [40 - 41] had shown that, the collapse of RC framed structures is generally governed by the flexural failure mode of beam elements. For the nonlinear analyses, plastic hinge model, as shown in Figure 4, was assigned to beams ends.

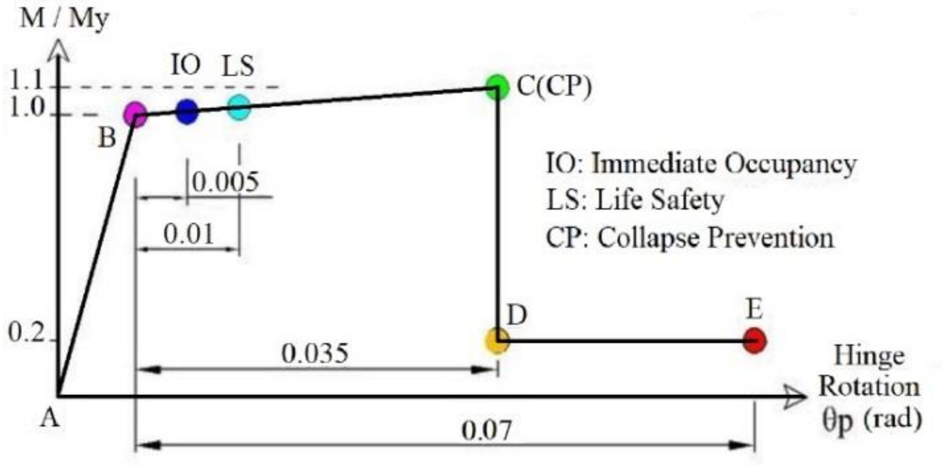

Figure 4. Plastic hinge model assigned to beams ends

These hinges were placed at locations of high stress as recommended by UFC 4-023-03 (2009). Beam elements included plastic hinges at the midspan and ends of the members whereas hinges for the columns were added only at the ends. The properties for the hinges were defined using the built-in hinge assignments for SAP2000. SAP2000 uses the Federal Emergency Management Agency (FEMA) designations for these hinges, specifically Table 5-6 of FEMA 356 for structural steel hinge properties [41]. ASCE 41-13 [42] and the UFC 4-023-03 (2009) recognize these as the standard properties for plastic hinges and reference this table for their own hinge definition procedures.

The maximum allowable rotation in plastic hinges associated to point C on the M vs. θp curve (Figure 4), which corresponds to the “Collapse Prevention” performance level is increased from 0.02 rad. to 0.035 rad. as recommended by the GSA (2003) for RC frames. The slope from point B to C is taken as 10% of the elastic slope for strain hardening; the seismic code ASCE 41-13 [42], indicates that the slope should be taken as a small percentage between 0% and 10%. Point D corresponds to the residual strength ratio of 0.2. Since the GSA (2003) does not specify a value for point E as the failure limit, a value of 0.07 rad. is considered as an average value (0.04 rad.,...,0.10 rad.) given by the UFC 4-023-03 (2009).

3. Modeling and Analysis

In this paper for finding the location of critical element in the structure, four reinforced concrete structures (including two 10-story structures and two 30-story structures) were designed and analyzed using the program SAP2000. The structures with 10 stories height are being categorized as mid-rise structures and the structures with 30 stories height are being categorized as high rise structure [44]. The structures have been designed according to Iranian code of practice for seismic resistant design of buildings (the standard number 2800 – 4^{th} edition) [45], Iranian national codes, number

6, "loading" [46], and Iranian national codes, number 9, "design of RC structures" [47]. The structures are supposed to be as commercial buildings, with RC special moment resisting frames, system of floors is 15 cm thick RC slab. Buildings are located in Tehran, on a soil of type II. Material properties used in the structures for concrete are f_c=250 kg/cm^2 and for reinforcement f_y=4000 kg/cm^2. In all structures, each bay is 5 meters and each floor has 3.5 meters height.

The structures have been named as S10 for the 10-story structure with square plan of 5×5 bays, LR10 for the10-story structure with a long rectangular plan of 5×10 bays, S30 for 30-story the structure with square plan of 5×5 bays and LR30 for the 30-story structure with a long rectangular plan of 5×10 bays. The structures S10 and S30 have 5 bays in both sides and the structures LR10 and LR30 have 5 bays in one side and 10 bays in another side. Geometric properties of the structures are presented in Table 2.

Aspect ratio is defined as the ratio of one structural dimension to another dimension [43]. So the aspect ratio in plan (ARp) is the ratio of the long dimension of the structure plan to its short dimension, and aspect ratio in height (ARh) is the ratio of the height of the structure to its shorter dimension of plan in height. In all structures, each bay is 5 meters and each floor has 3.5 meters height. The aspect ratio in plan (ARp) and the aspect ratio in height (ARh) for all the structures are as follows:

Table 2. Structural aspect ratios

Name of the Structure	Length of the Structure (m)	Width of the Structure (m)	Height of the Structure (m)	ARp	ARh
S10	25	25	35	1.0	1.4
LR10	50	25	35	2.0	1.4
S30	25	25	105	1.0	4.2
LR30	50	25	105	2.0	4.2

When a column is omitted, the structure is named as for example LR30-A2@28 that refers to the long rectangular 30-story structure in which the column in axis A and 2 is omitted at the story 28. For more information, see Figure 5 and 6.

The models are shown in Figure 5. In this figure the prototype models (the model with no column omitted) and two studied model (with one column omitted) are shown. The place of omitted column is marked using a red cross and an arrow.

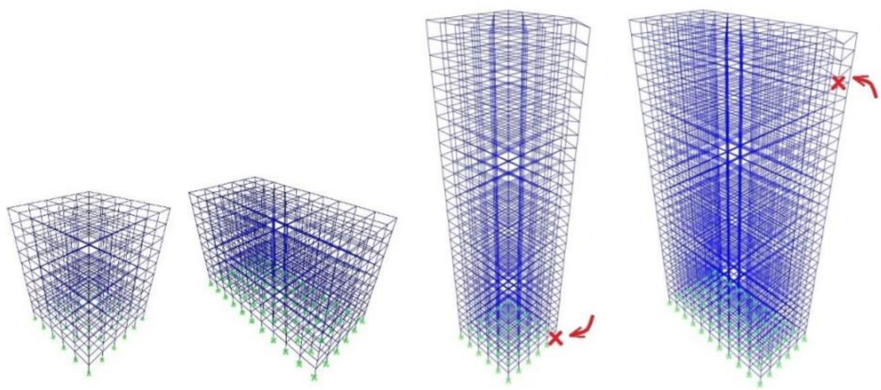

Figure 5. The 30-story structures modeled and analyzed

Naming the axis of columns in the structure plans are shown in Figure 6. For example the column B2 refers to the column which is mutual between the axis B and axis 2 in X and Y directions, respectively. Or the column D3 refers to the column which is mutual between the axis D and axis 3 in X and Y directions, respectively.

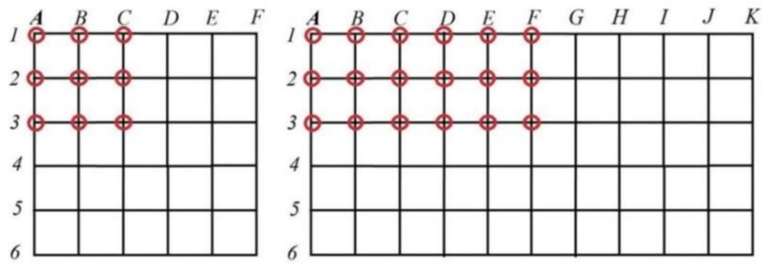

Figure 6. Plan of the structures and naming of axis in X and Y directions for S10, S30, LR20 and LR30

In the first step, a uniform load is applied on all floors and increased step by step until the structure collapsed. It should be noted that according to Figure 1 in some panels the uniform load has been multiplied following UFC 4-023-03. The criterion of collapse was the same as the criteria of GSA2003. The ultimate load for all the intact structures are presented in Table 3.

In the second step, one of the columns was removed (Figure 5), and a uniform load was applied to the whole area of the structure except the panels that the removed column is related to them. For these panels, twice the uniform load was applied (as the pattern showed in Figure 1).

Table 3. The ultimate load of the structures (uniform load)

Name of the Structure	The ultimate uniform load (kg/m^2)
S10	1960
LR10	1975
S30	2105
LR30	2160

The load was increased gradually until panels related to the removed column collapsed, i.e. all beams settled on this column collapsed. The criteria of the collapse of beams are the same as the criteria of ASCE 41 (Figure 3), and UFC 4-023-03 (2009) (Table 1). This load which has caused local collapse is called the local collapse load.

Figure 7 shows schematic views of local collapse of the structure; red signed beam shoes the beams that if they collapse, cause local collapse. The yellow circle shows the panels that if collapses, causes local collapse. As it is seen, for local collapse, in four beams, plastic hinges should be created.

The local collapse is very important when some sensitive instruments or facilities have been located in these areas.

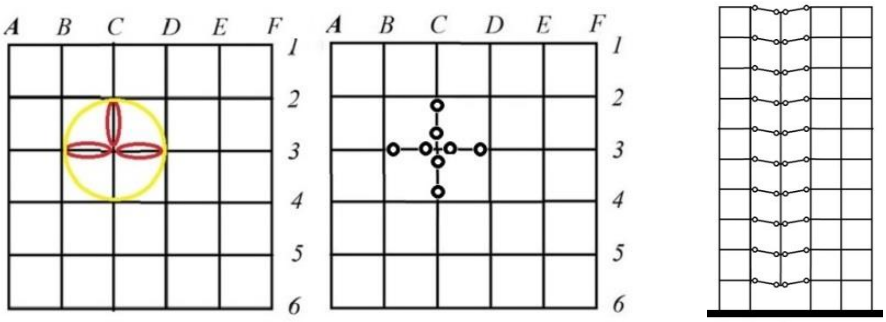

Figure 7. The schematic view of local collapse and creation of plastic hinges in structural plan and height

First plastic hinges show up at upper story where the column has been omitted. Then beams in the upper stories begin to experience plastic hinges.

In the third step, uniform load of the second step is increased until disproportionate collapse occurs, around the removed column. The criteria of global collapse is the same as the criteria of GSA2003 (Figure 2) with respect to the criteria of the collapse of beams in ASCE 41 (Figure 3), and UFC 4-023-03 2009 (Table 1). This load which has caused global collapse of the structure is called the global collapse load.

In this study, the second and third steps have been done for all columns and all floors for both structures. 4080 3D nonlinear pushdown analysis had to be done, but because of the eccentricity of structures 1080 3D nonlinear pushdown analyses were done. Number of analysis needed for each structure is presented in Table 4.

Table 4. Number of analysis needed for each structure

Name of the Structure	Number of needed analysis	Number of done analysis
S10	360	90
LR10	660	180
S30	1080	270
LR30	1980	540

Figure 8 shows the deformation of the structure at the final step of local and global collapse of the model LR10-E1@01.

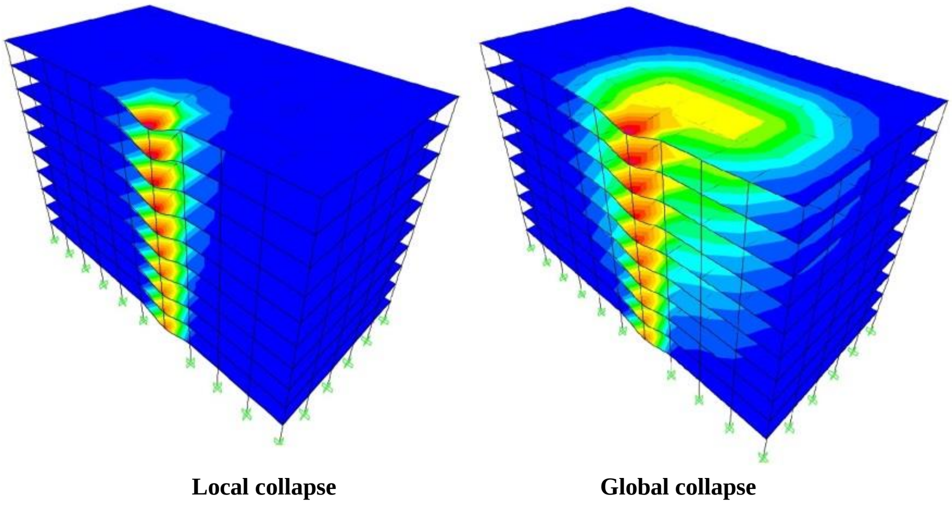

Figure 8. Deformation of the structure in local and global collapse of the model LR10-E1@01

The forth step contains the calculation of sensitivity index for all column removal conditions.

At the end step a comparison between sensitivity indexes of all columns, leads to clarify the elements which the structure is more sensitive to their loss and the most sensitive one called the critical element.

4. Results and Discussions

Doing 1080 3D nonlinear pushdown analyses, the load-displacement diagrams have been drawn. Figure 9 to 11 show the load-displacement diagrams for omitting columns in 1st, 15th and 30th floor of the structure S30, respectively. It can be observed that for the corner column and the column adjacent to it, the area under the diagram is more than the others. For example the area under the diagram for column A1 is 20% more than the area under the diagram for column C3 in S30 at first floor. The area under the diagram for column A1 is 50% more than the area under the diagram for column C3 in S30 at the 15th floor. The area under the diagram for column A1 is 40% more than the area under the diagram for column C3 in S30 at 30th floor. This is because of the effects of mode shape of the structures on the design of beams. In high rise structures for the beams related to the corner columns, and the corner columns themselves, the effects of shear lag and torsion in the whole structure (because of the accidental eccentricity of the structure) lead to a bigger section and reinforcement. As the whole structure must be designed as special moment resisting frames, the connections of these beams contribute to the ductility of the whole structure.

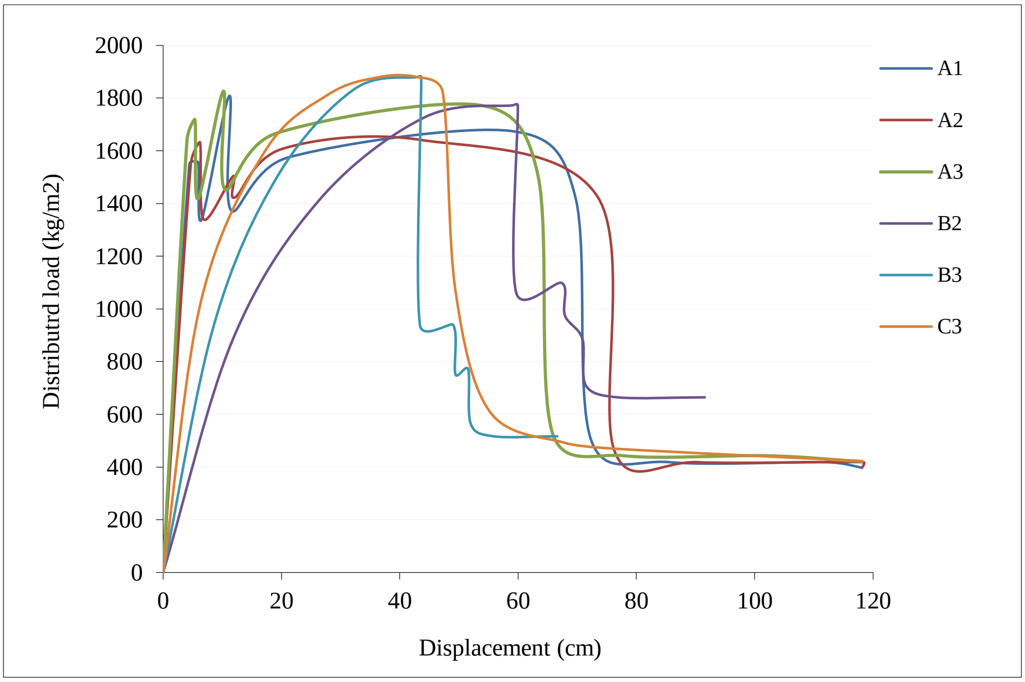

Figure 9. Load-displacement diagram for different column loss of S30 at 1st floor

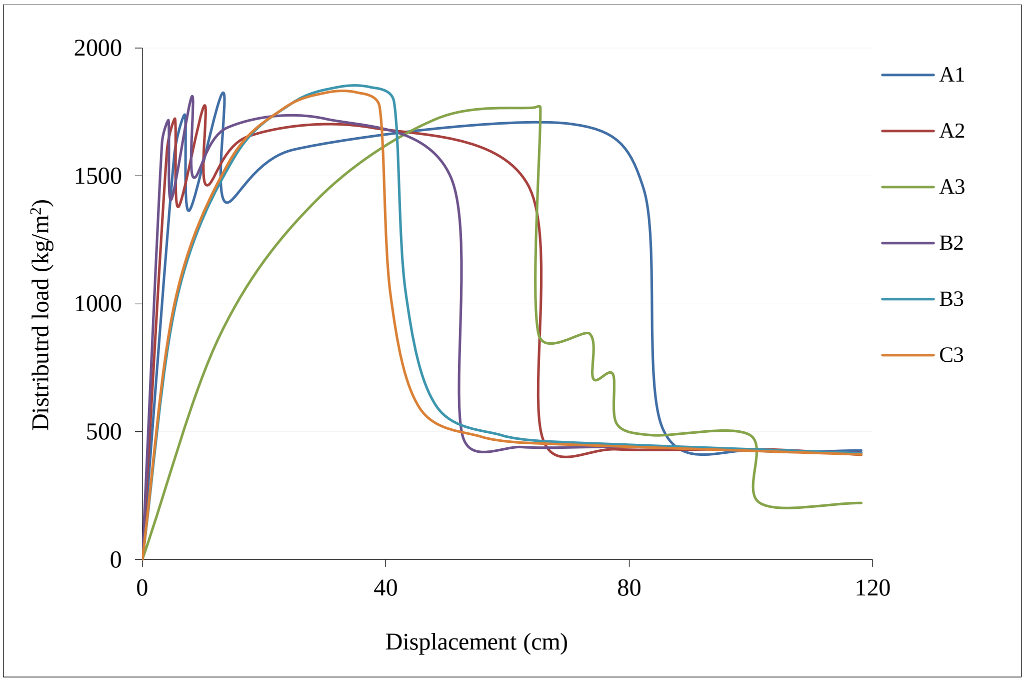

Figure 10. Load-displacement diagram for different column loss of S30 at 15th floor

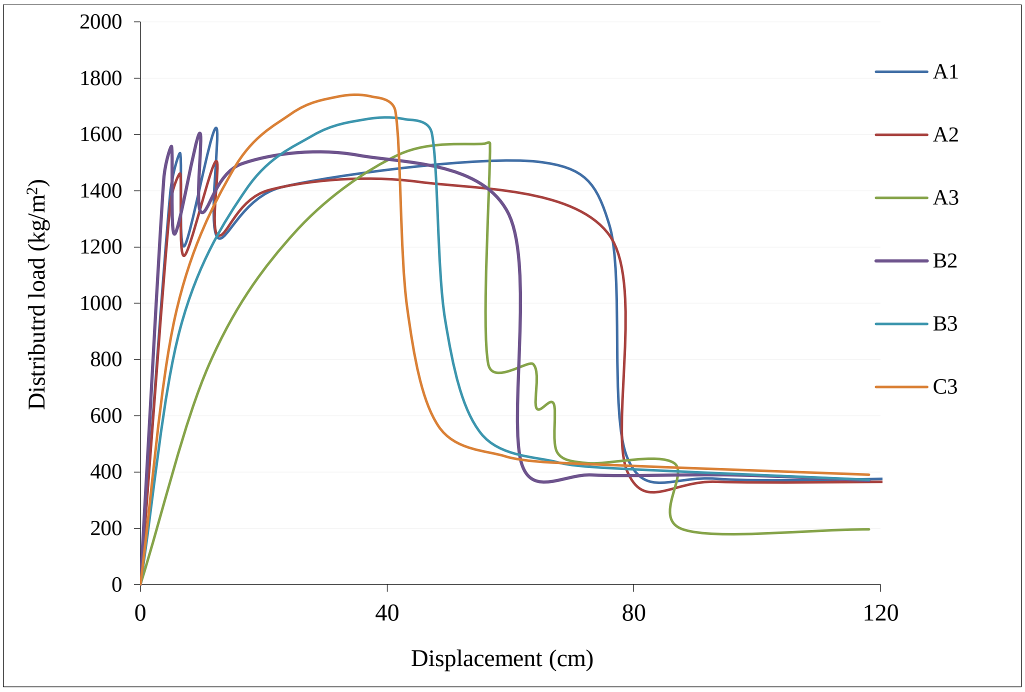

Figure 11. Load-displacement diagram for different column loss of S30 at 30th floor

The sudden drops in the load-displacement diagrams, as observed in Figure 9 to 11, occur simultaneously with the plastic hinges occur in the first beam that transfers loads of the floor. Final collapse occurs when plastic hinges form in the last beam and also in the slabs. Based on the results of analysis, outer beams of the structure (peripheral beams in the structure plan) are more ductile than inner beams. Hence collapse of the structure subjected to the loss of an inner column is more sudden than collapse of the structure subjected to the loss of a peripheral column. Because of the place of the omitted column, one, two or four slabs are connected to the beams that are connected to the column, which shows the effect of the slabs in the integrity of the whole panel. Also as mentioned before the effective flange width on each side of the beam is taken as three times the slab thickness. Hence it seems to be necessary to pay more attention to the role of the slabs in preventing progressive collapse.

In Figure 12 the load-displacement diagrams for S10-A1@01, LR10-A1@01, S30-A1@01 and LR30-A1@01 is shown. In Figure 13 the load-displacement diagrams for S10-C3@01, LR10-C3@01 S30-C3@01 and LR30-C3@01 is shown.

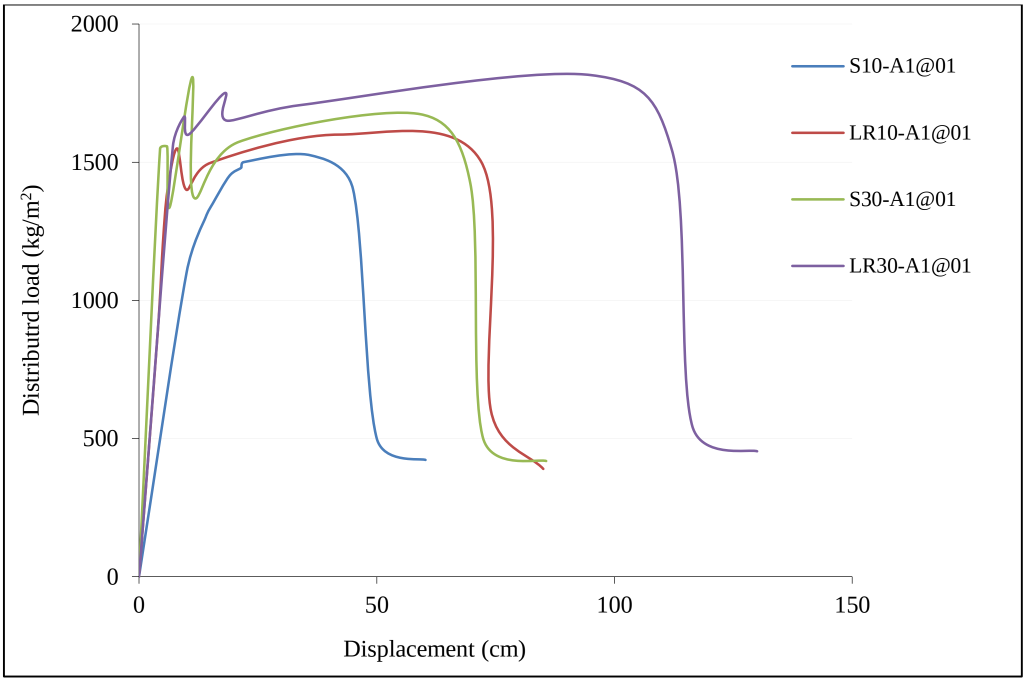

Figure 12. Load-displacement diagram for the corner column in the 1st story

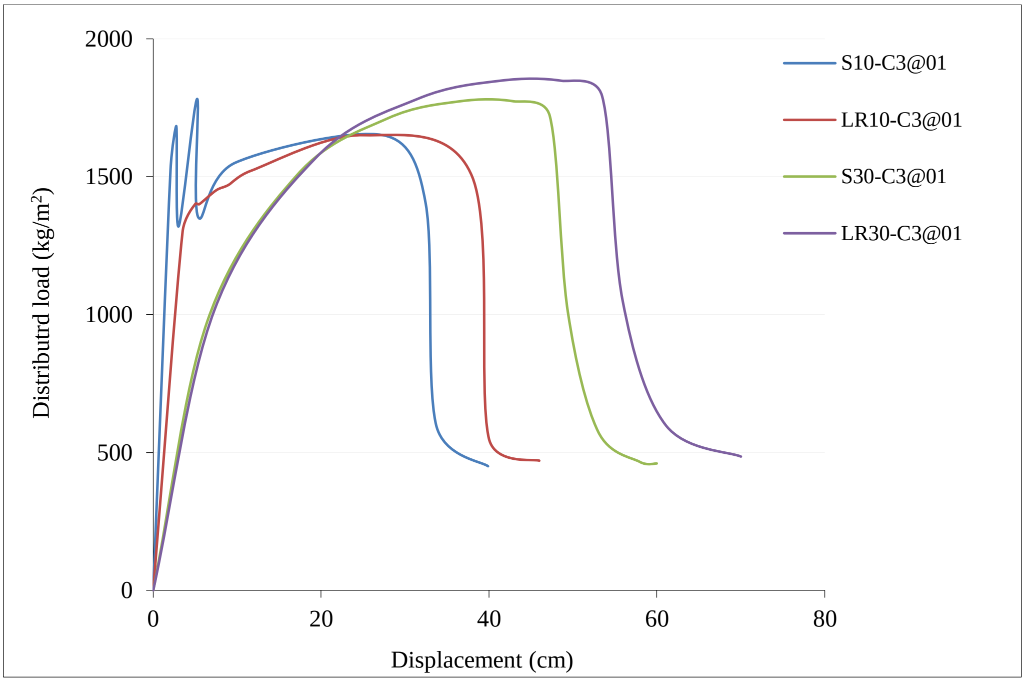

Figure 13. Load-displacement diagram for central column in the 1st story

As it is seen in the Figure 13 and 14, for the structure LR30, area under the diagram is more than for the structure S30 and it is more obvious in the corner column loss.

Sensitivity index of all column losses for all structures are shown in Figure 14 to 21. Figure 14 to 17 show sensitivity index for local collapse (S.I.L.) and Figure 18 to 21 show sensitivity index for global collapse (S.I.G.). Figure 14 and 15 show sensitivity index for local collapse (S.I.L.) in the mid-rise structures.

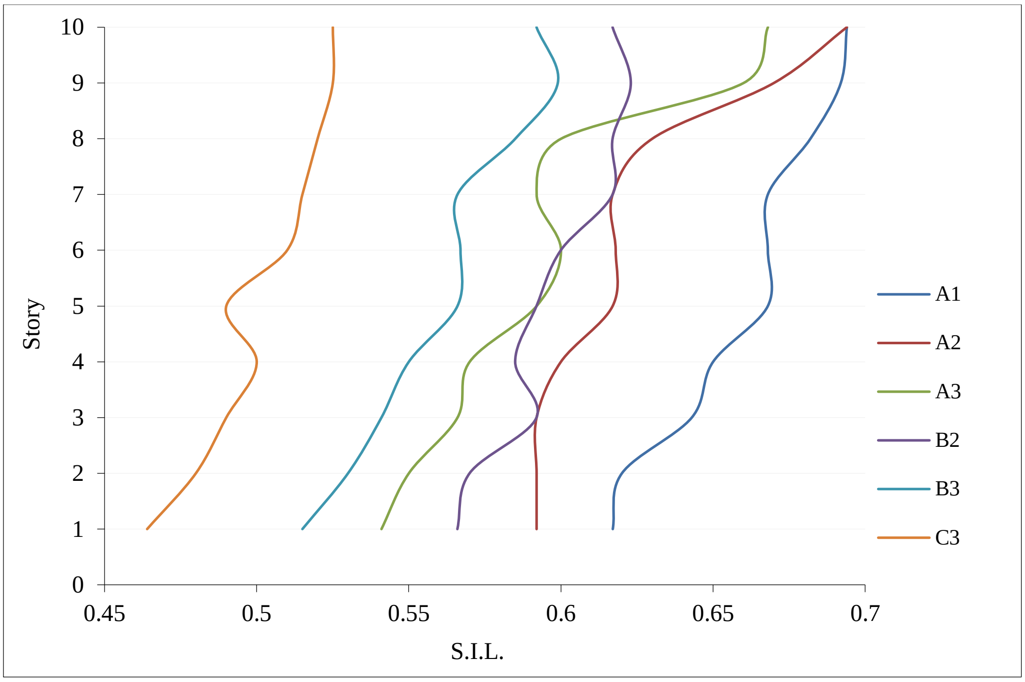

Figure 14. Sensitivity index for local collapse (S.I.L.) of the structure S10

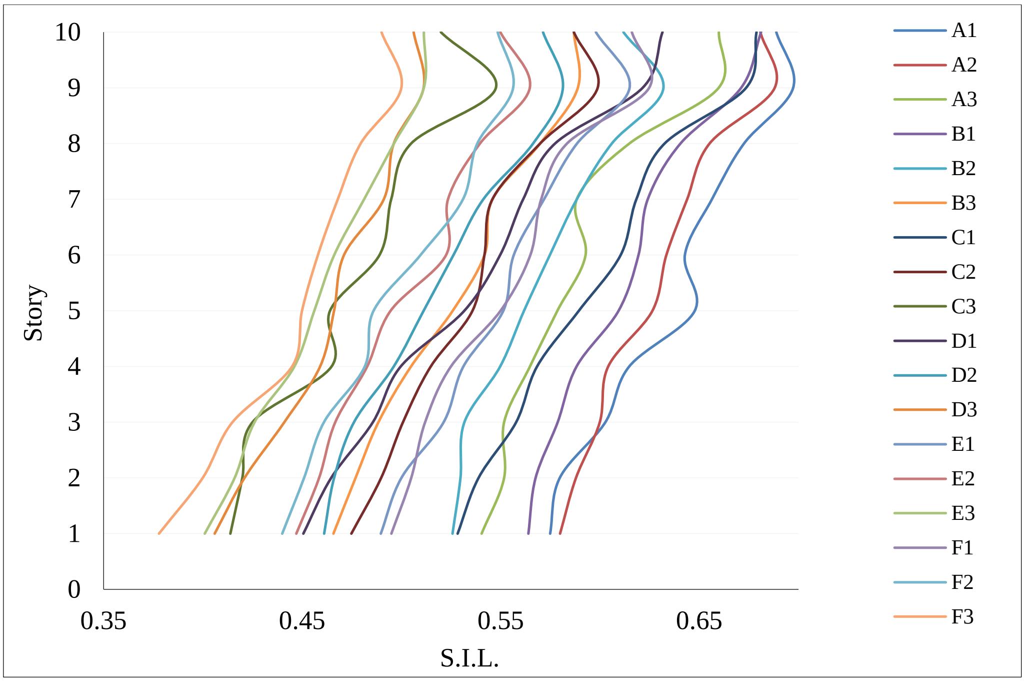

Figure 15. Sensitivity index for local collapse (S.I.L.) of the structure LR10

As observing the sensitivity index for local collapse (S.I.L.), in mid-rise structures, in all stories the corner column (A1) is the most sensitive column for the structure. The columns near the corner column (A2 and B1) are the next one, especially in the short dimension of the structure (column A2) in the structures LR10 and LR30. The column A2 is more sensitive than the column B1 in long rectangular plan. Also the column in the middle of the short dimension (A3) is more sensitive than the columns in the middle of the long dimension (E1 and F1) of the structures LR10 and LR30.

It is observed that when the plan of the structure changes from square to rectangular, the columns on the short dimension of the structure become more sensitive. It is because of bigger aspect ratio of the structure in the short dimensions of the structures (ARh). The aspect ratio for the short dimension of the structures is 1.4, but in long dimension is 0.7 for LR10 and LR30. It was observed that in rectangular plans (LR10 and LR30), as the aspect ratio of the structures in two directions of the plan (X and Y directions) differ, the behavior of the structure differ too. In short dimension, the structure behaves more like a high rise structure and some issues of high rise structural design such as shear lag affects the designation of the structure, especially for corner columns and beams.

All structures with square, long rectangular plan are less sensitive to the loss of inner columns and the column at the center of the structure is the least sensitive one. Hence for a mid-rise structure, the critical elements in local collapse are the corner column in long dimension and the corner column and the column adjacent to it in the short dimension. For the whole structure in local collapse, sensitivity of structure to the column loss increases in height. The critical element of the whole structure is in the story bellow the roof.

Figure 16 and 17 show sensitivity index for local collapse (S.I.L.) in high rise structures.

As observing the sensitivity index for local collapse, in high rise structures, in lower stories the columns near the corner column (A2 and B1) are the most sensitive columns for the structure. This can be because of the effects of shear lag in the design of high rise structures that leads to different situation in design of corner columns. But about 2/3 of the structure height, the place of the sensitive element changes and the corner column (A1) becomes the most sensitive column in upper stories. All structures with square and long rectangular plan are less sensitive to the loss of inner columns.

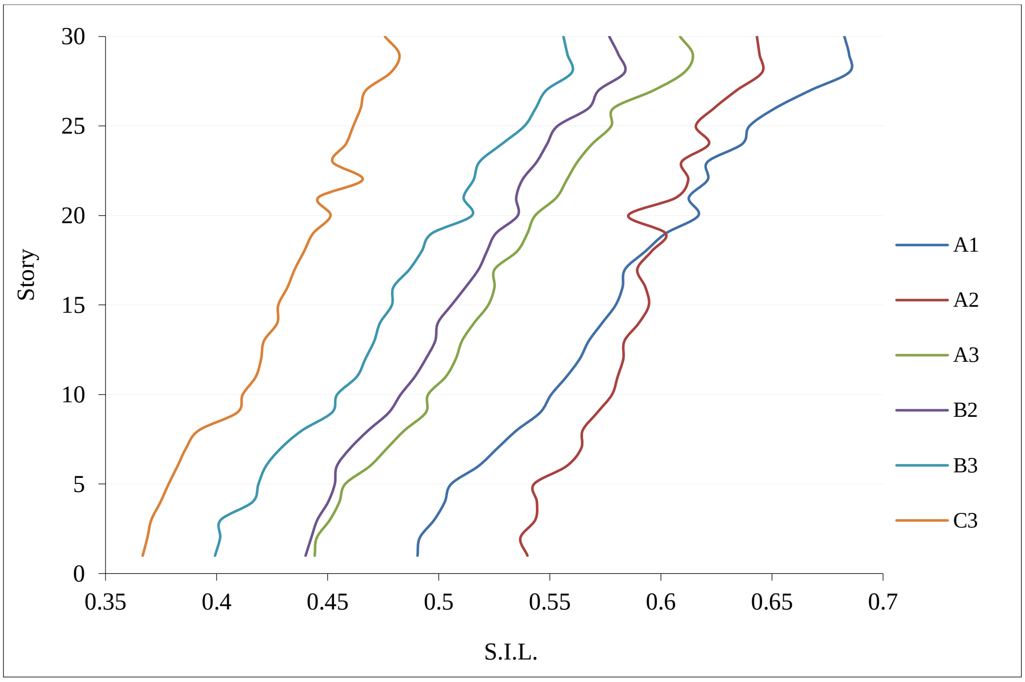

Figure 16. Sensitivity index for local collapse (S.I.L.) of the structure S30

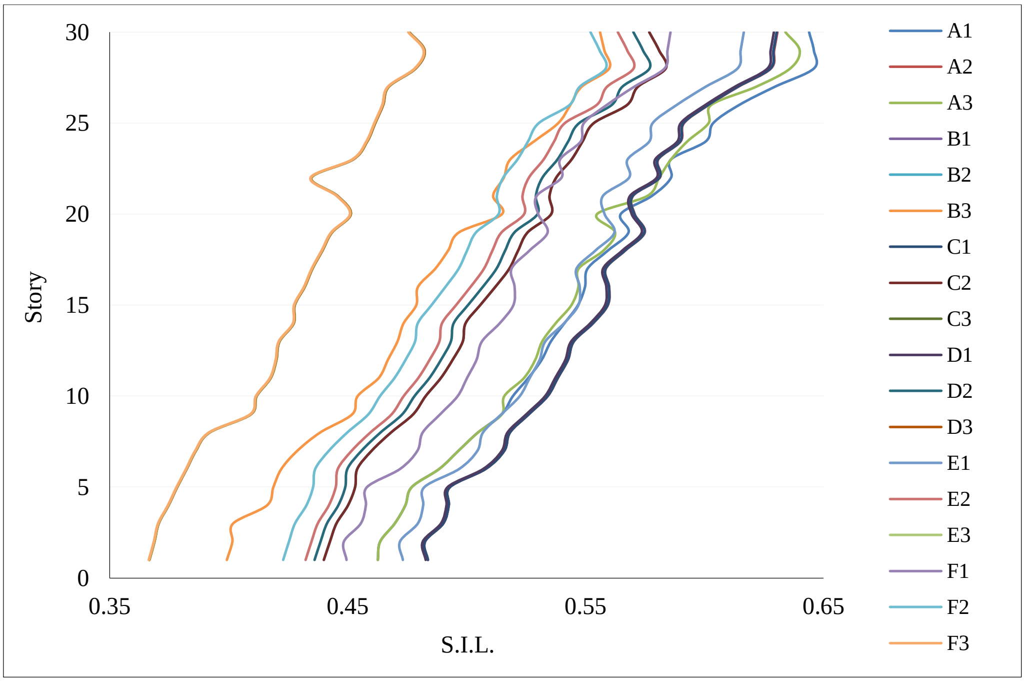

Figure 17. Sensitivity index for local collapse (S.I.L.) of the structure LR30

In long rectangular structures, as the aspect ratio in plan (ARp) changes, the columns on the short edge become more sensitive than the columns on the long edge of the structure.

Hence, for a high rise structure the critical elements in local collapse are the columns near the corner column in lower stories and the corner column in upper stories. For the whole structure in local collapse, sensitivity of structure to the column loss increases in height. The critical element of the whole structure is in the story bellow the roof.

Figure 18 and 19 show sensitivity index for global collapse (S.I.G.) in mid-rise structures.

According to Figure 18 and 19, in mid-rise structures, the sensitivity index for global collapse (S.I.G.) of the corner column (A1) is more than other columns in all stories. The columns near the corner column (A2 and B1) are the next, especially in the short dimension of the structure (column A2). Like the local collapse, in the global collapse, the column A2 is more sensitive than the column B1 in the long rectangular plan. Also the column in the middle of the short dimension (A3) is more sensitive than the columns in the middle of the long dimension (E1 and F1) of the structure. When the plan of the structure changes from square to rectangular, (as the ARp changes) the columns on the short dimension of the structure are more sensitive.

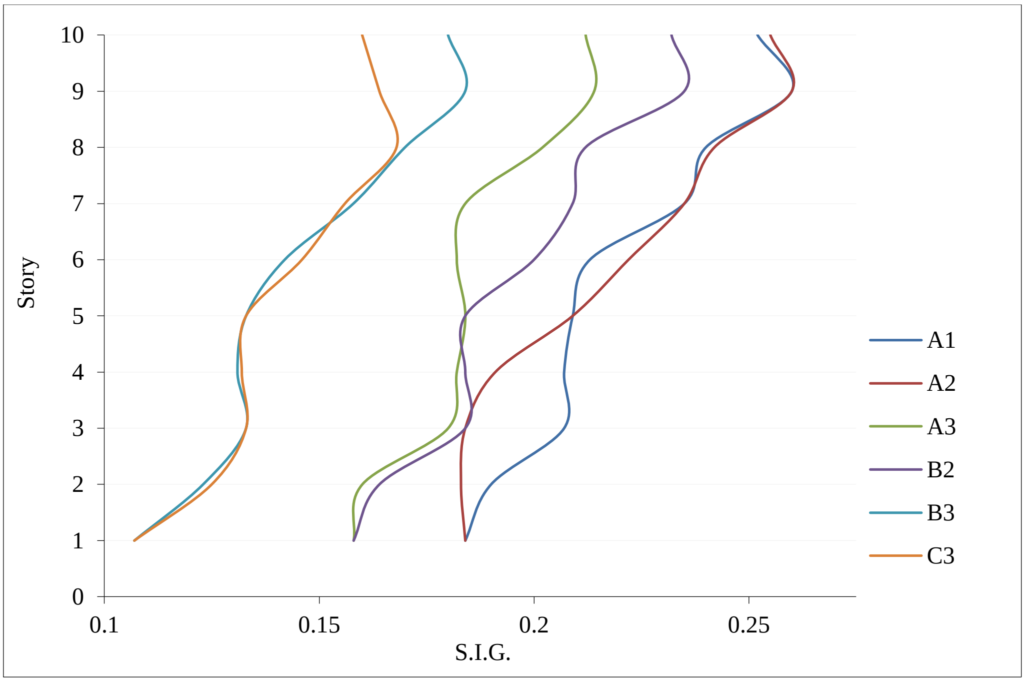

Figure 18. Sensitivity index for global collapse (S.I.G.) of the structure S10

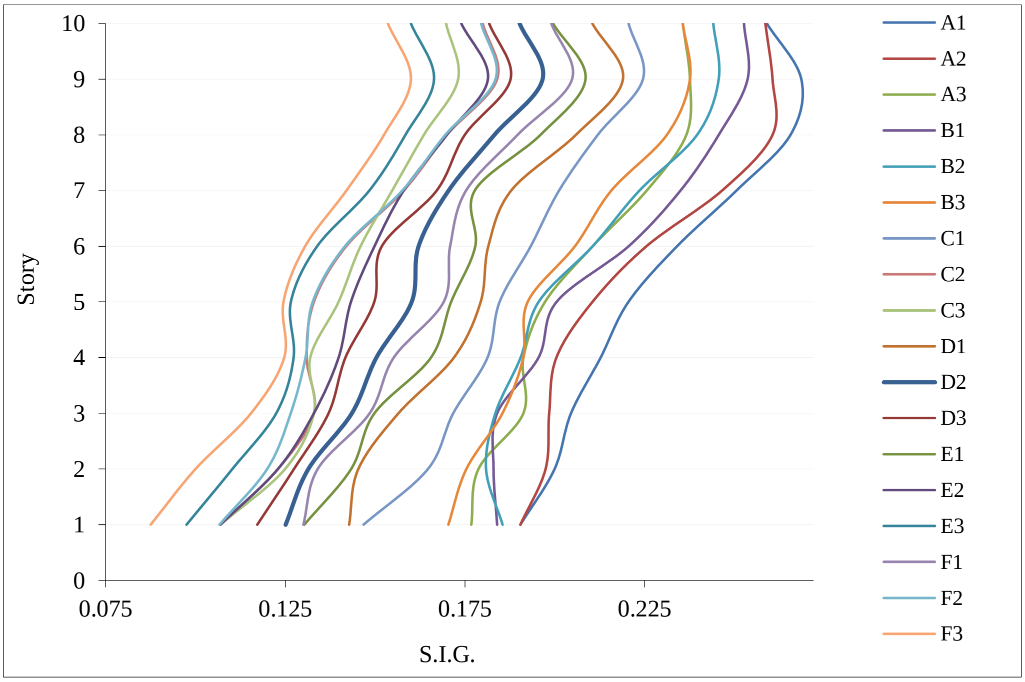

Figure 19. Sensitivity index for global collapse (S.I.G.) of the structure LR10

All structures with square, long rectangular plan are less sensitive to the loss of inner columns and the column at the center of the structure is the least sensitive column.

Hence, for a mid-rise structure the critical elements in global collapse are the corner column in the long dimension, and both the corner column and the column adjacent to it in the short dimension.

For the whole structure in local collapse, sensitivity of the structure to the column loss increases in height. The critical element of the whole structure is in the story bellow the roof. But when the plan of the structure changes from square to long rectangular, for the columns on the short dimension the sensitive column appears in the 8th story. It shows that when the aspect ratio of the structure is increased, the story of the critical element will change.

Figure 20 and 21 show sensitivity index for global collapse (S.I.G.) in high rise structures.

Observing the sensitivity index for global collapse, in high rise structures, in all stories the columns near the corner column (A2 and B1) are the most sensitive columns for the structure. As it was mentioned this can be because of the effects of shear lag in the design of high rise structures. But for the stories 28, 29 and 30 of the structure, the place of the sensitive element changes and the corner column (A1) becomes the most sensitive column. All structures with square and long rectangular plan are less sensitive to the loss of inner columns.

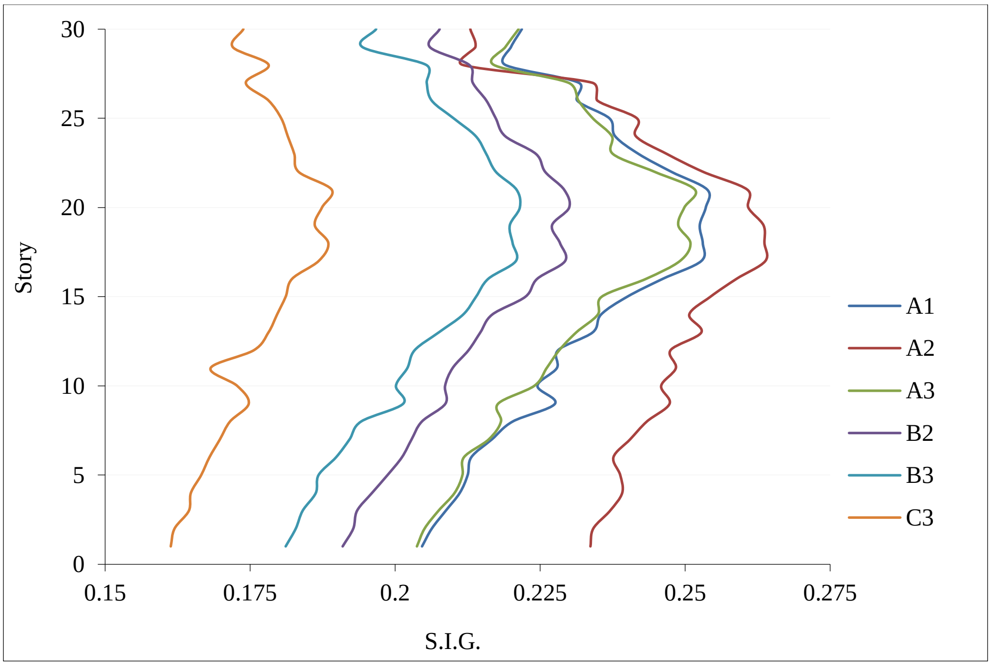

Figure 20. Sensitivity index for global collapse (S.I.G.) of the structure S30

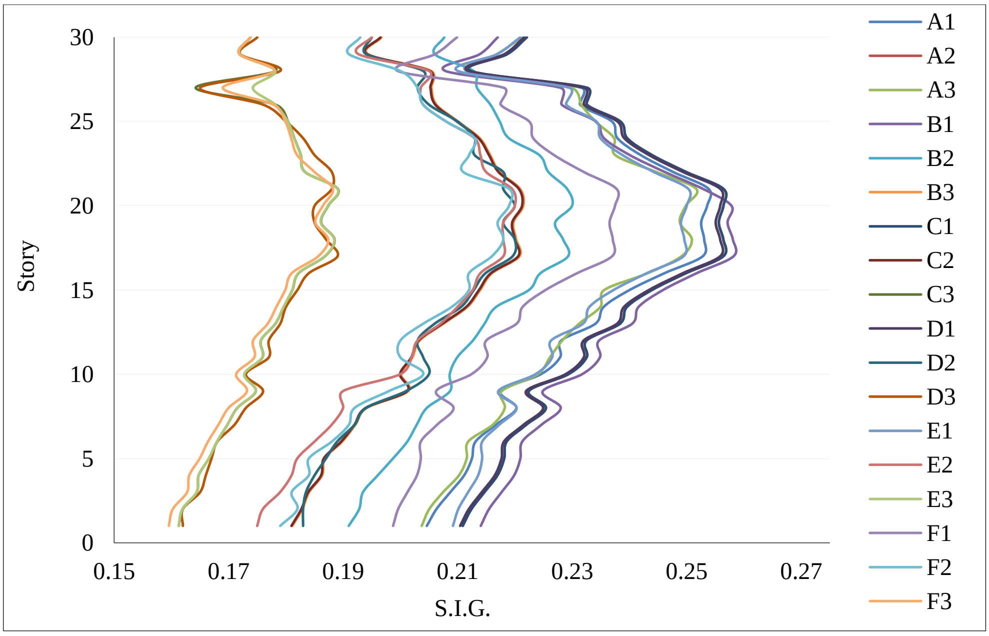

Figure 21. Sensitivity index for global collapse (S.I.G.) of the structure LR30

In long rectangular structures, the columns on the short edge are more sensitive than the columns on the long edge of the structure.

Hence, for a high rise structure, the critical elements in global collapse are the columns near the corner column. For the whole structure in global collapse, sensitivity of the structure to the column loss increases with height until 2/3 height of the structure and decreases after that. The critical element of the whole structure is in the story of 2/3 height of the structure.

In Figure 22 sensitivity index for local collapse (S.I.L) along the height of the structures are presented. Figure 23 shows sensitivity index for global collapse (S.I.G) along the height of the structures. In both Figure 22 and 23, vertical coordinate shows ratio of the height of missing column (z) to the total structural height (H). In both Figure 22 and 23 the diagram is only for the corner column of the structure (A1).

It is notable that all Figure 22 to 27 are dimensionless.

From Figure 22 and 23, it is seen that for local collapse, as the ARh of the structure increases, the height of the critical element is changing from the top of the structure to nine tenths (9/10) of the height of the structure. But for global collapse, the height of the critical element is changing from nearly the top of the structure to two thirds (2/3) of the height of the structure.

For ARp, as it is increasing in the structure, the height of the critical element is changing; about 0.1 when ARh is low and a 0.05 when ARh is more.

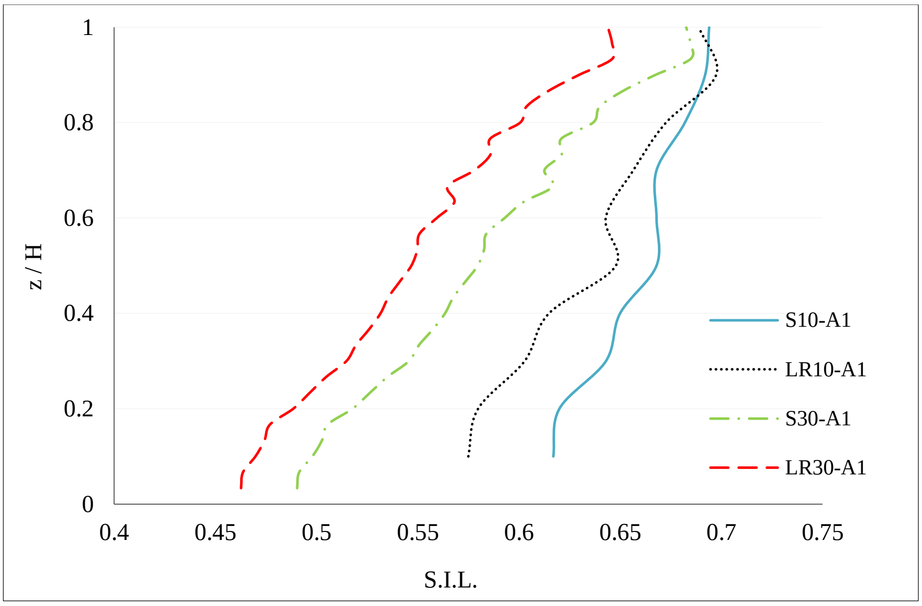

Figure 22. Sensitivity index for local collapse (S.I.L.) along the height of the structures

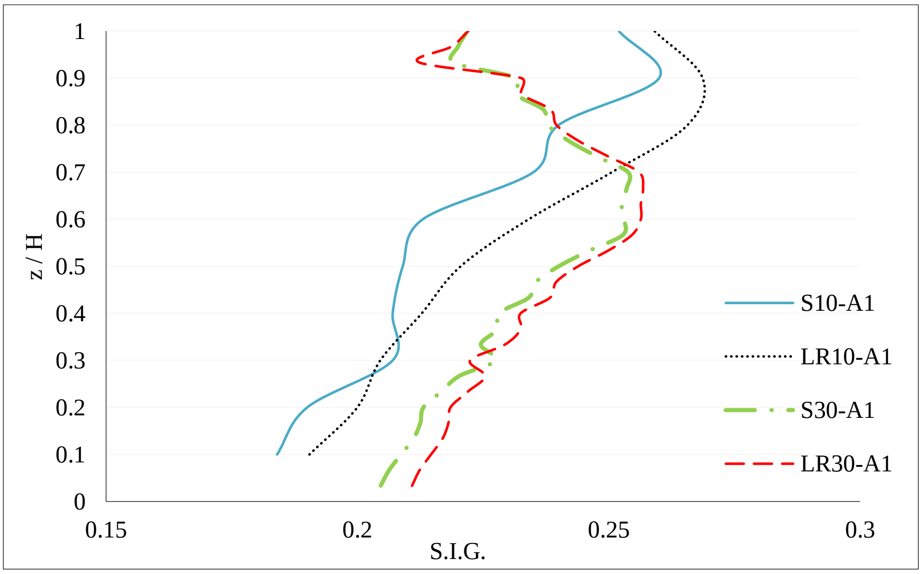

Figure 23. Sensitivity index for global collapse (S.I.G.) along the height of the structures

In Figure 25 and 26 sensitivity index for local collapse (S.I.L.) and sensitivity index for global collapse (S.I.G.) are presented respectively, along the plan of the structures at the first story, for the axis A. In both Figure 25 and 26, horizontal coordinate shows ratio of location of the missing column (*x*) to the total structural width (B).

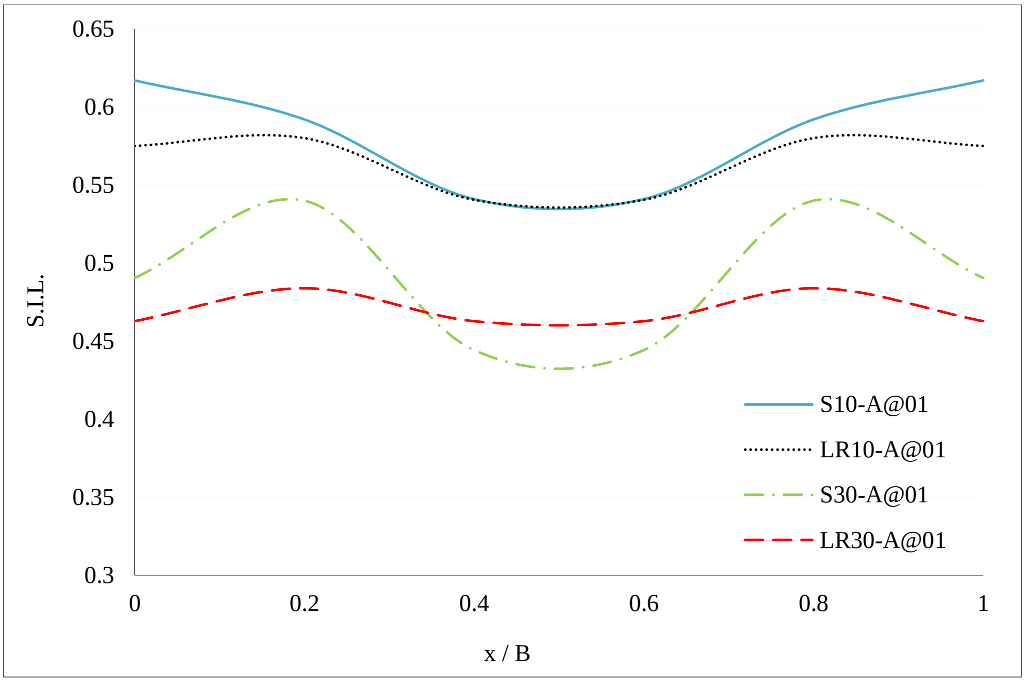

Figure 24. Sensitivity index for local collapse (S.I.L.) along the plan of the structures at the first story, for the axis A

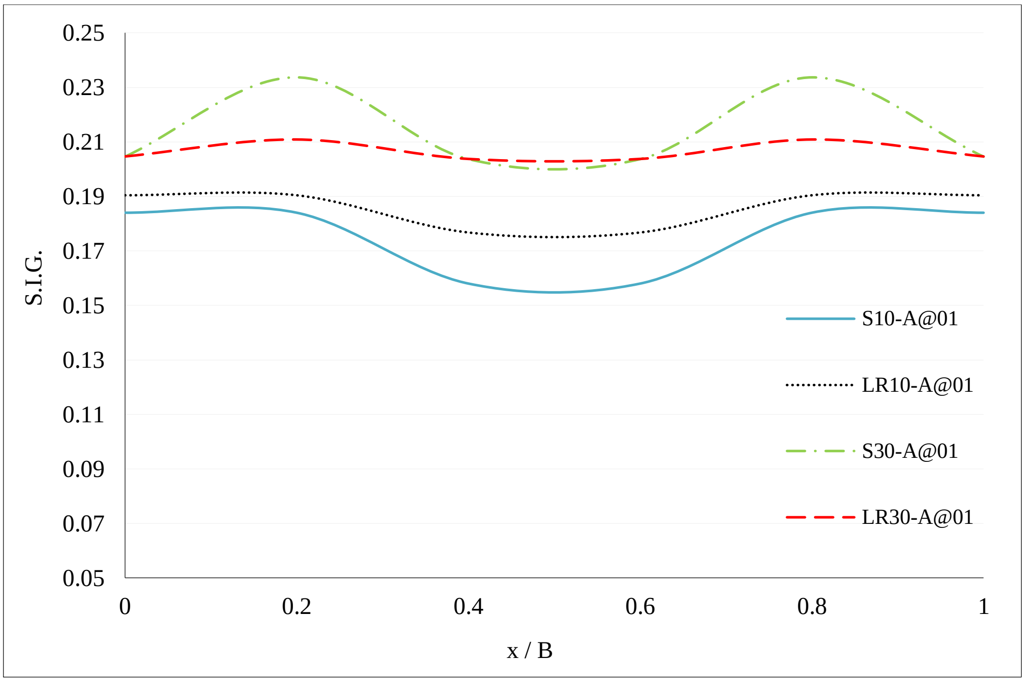

Figure 25. Sensitivity index for global collapse (S.I.G.) along the plan of the structures at the first story, for the axis A

From Figure 26 and 27, it is seen that for local and global collapse, as the ARh of the structure increases, the location of the critical element changes from the edge of the plan of the structure to two tenths (0.2) of the width of the structure (i.e. shorter dimension of the structure). Also, it is clear that when ARh increases, the structure becomes more sensitive to the loss of the columns in the middle of the plan.

When ARp of the structure increases, all columns in the short dimension of the structure become important and the sensitivity of the structure to loss of them becomes like each other.

In Figure 26 and 27 sensitivity index for local collapse (S.I.L.) and sensitivity index for global collapse (S.I.G.) are presented respectively, along the plan of the structures at the first story, for the axis 1. In both Figure 26 and 27, horizontal coordinates shows ratio of the location of the missing column (*y*) to the total structural width (L).

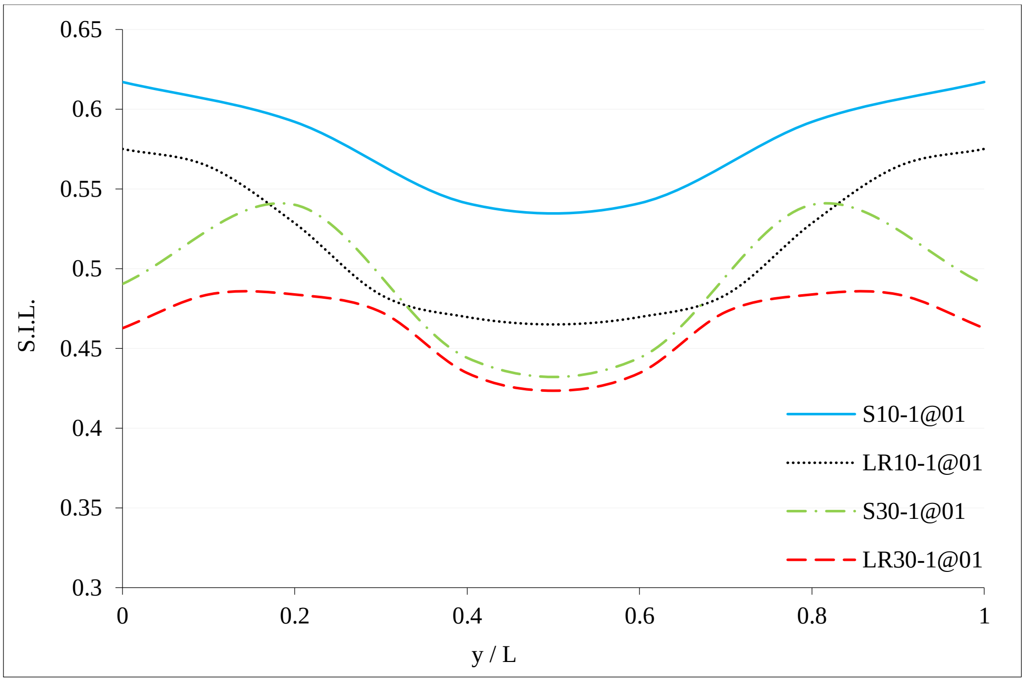

Figure 26. Sensitivity index for local collapse (S.I.L.) along the plan of the structures at the first story, for the axis 1

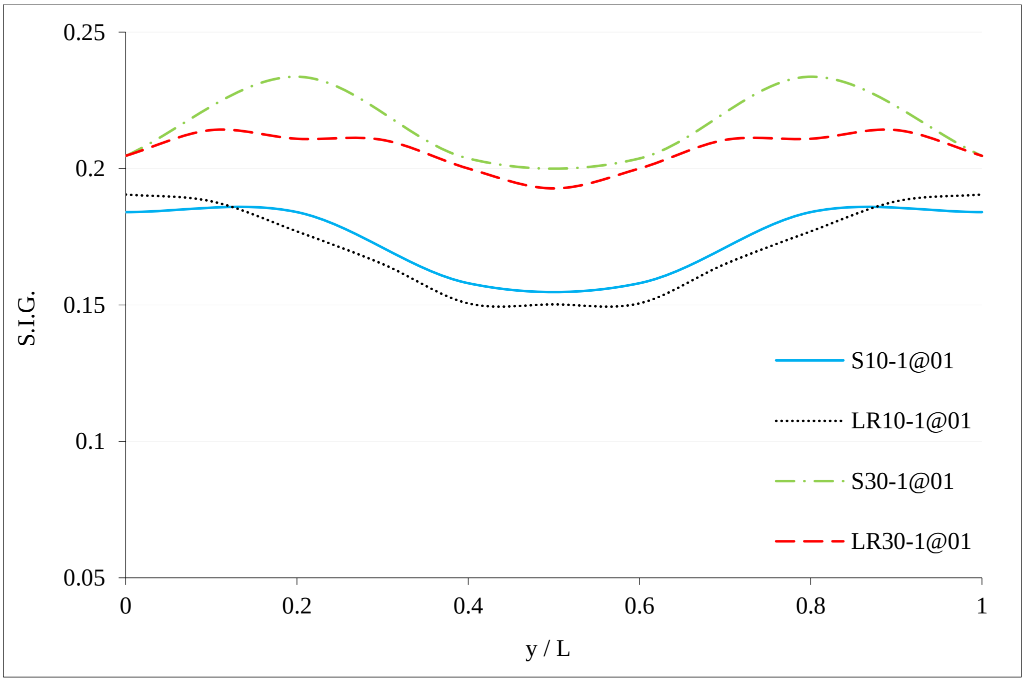

Figure 27. Sensitivity index for local collapse (S.I.L.) along the plan of the structures at the first story, for the axis 1

From Figure 26 and 27, it is seen that for local and global collapse, as the ARh of the structure increases, the location of the critical element changes from the edge of the plan of the structure to one tenth (0.1) of the length of the structure (i.e. the longer dimension of the structure).

When ARp of the structure increases, sensitivity index of the columns in the long dimension of the structure become closer to each other.

5. Conclusion

In this paper, sensitivity analysis was modified and applied to identify the location of the most critical column of high rise RC structures called the critical element. Using this method in two mid-rise structures and two high rise structures and doing 1080 3D nonlinear pushdown analyses, the brief conclusion are presented as follows:

- For the corner column and the columns adjacent to it, the area under the load-displacement diagrams is more than the others. For the long rectangular structure (LR10 and LR30), area under the diagrams is more than for the square structure (S10 and S30), especially the corner column loss.
- In mid-rise structures, the critical elements in local and global collapse are the corner columns.
- In long rectangular, plan the columns near the corner column (especially in the shorter dimension of the structure) are more sensitive.
- In local collapse, sensitivity of structure to the column loss increases in height.
- In mid-rise structures in global collapse, sensitivity of structure to the column loss increases in height. But in the long rectangular plan, for the global collapse, the critical element in the shorter dimension of the structure is in the 8^{th} story of the structure.
- For long rectangular structures, the column at the middle of the short dimension of the structure is more sensitive than the columns at the middle of the long dimension.
- In high rise, structures the critical elements in local collapse are the columns near the corner column in lower stories and the corner column in upper stories.
- For the whole structure in local collapse, sensitivity of structure to the column loss increases in height. In high rise structures, the critical elements in global collapse are the columns near the corner column.
- The ARp has direct effect on the place and height of the critical element.
- In global collapse, the critical element, in the structures with high ARh, is located in the story of 2/3 height of the structure. When ARp of the structure increases, sensitivity index of the columns in the long dimension of the structure become closer to each other.

6. Conflict of interest

The author declares no conflicts of interest.

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