A Case Study: Progressive Collapse Analysis of Existing RC Buildings Using Linear Procedure

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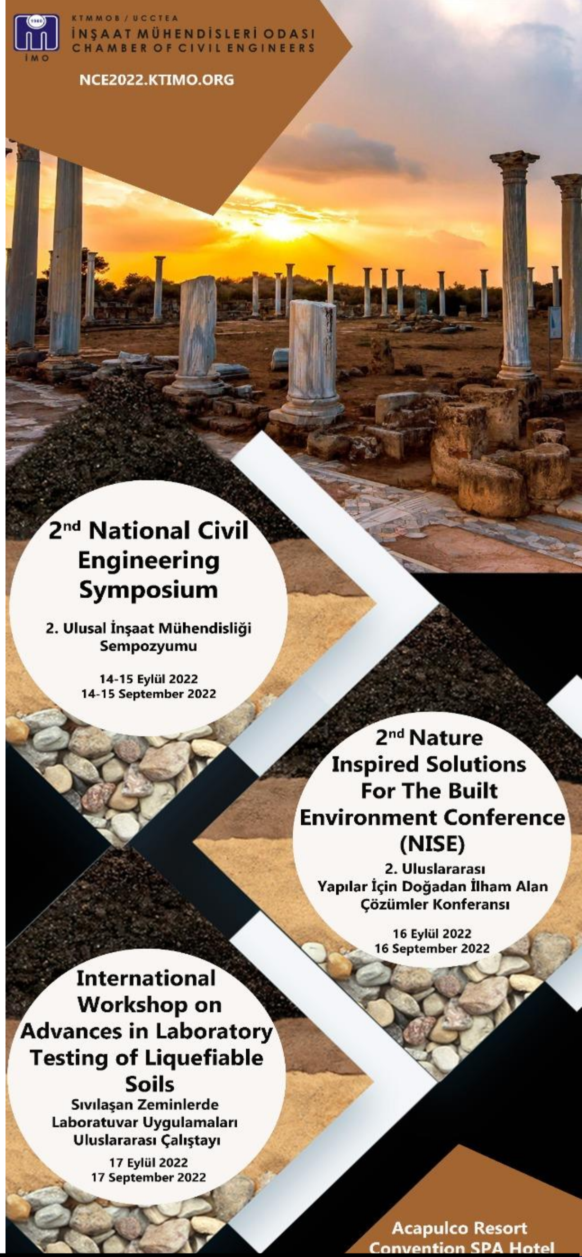
Ahmed Zaid Shams-AL, *"Progressive Collapse Analysis of Four Existing Reinforced Concrete Buildings Using Linear Procedure"*, Jan 2012, MSc Thesis, EMU.



Progressive Collapse?

Progressive Collapse may happen due to design / construction errors, fire, impact, gas explosion, and terrorist attacks

LOCAL DAMAGE - PARTIAL COLLAPSE:

- When buildings are exposed to unexpected loads, one or more of the load-carrying elements (bearing-walls or columns) may lose their capacity and hence the loads get redistributed.
- Every load redistribution causes the failure of other structural elements, until a new equilibrium state is reached. This may lead to **local damage** or **partial collapse** of a building.

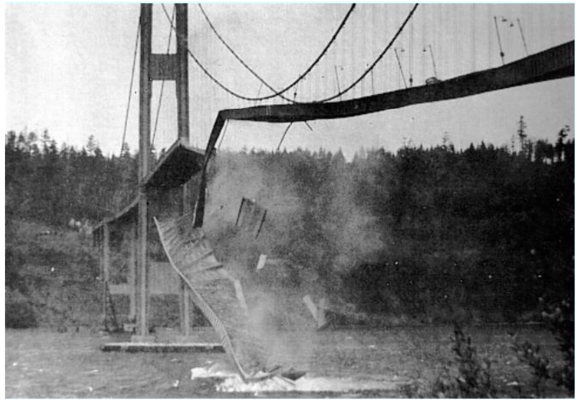
TOTAL COLLAPSE:

- Following partial collapse, if the structure has **ductile design**, then ***Alternate Load Paths*** **(ALP)** start to transmit the gravity load from the failed elements to the neighboring members until reaching an equilibrium status.
- Otherwise, a **global collapse** for the structure could happen which leads to a serious threat to public safety and property.

Typology of Progressive Collapse


1. **Pancake-type Collapse –** earthquake 10 story building – Islamabad, 2005. World Trade Centre Buildings – blast and fire, 2001.

2. **Domino-type Collapse –** ice accumulation. Overhead Transmission Line Towers– Germany, 2005



3. **Zipper-type Collapse –** wind induced vibration - Tacoma Narrows Bridge– USA, 1940

4. **Section-type Collapse –** when an element of a beam in bending or a bar under axial tension element undergoes a cut, the internal forces from this area are transmitted to the remaining cross-section.
5. **Instability-type Collapse -** occurred due to small imperfections or transverse loading, e.g. the failure of a bracing element can trigger the whole system to collapse.
6. **Mixed-type Collapse –** Mixture of the other types of collapse

Progressive Collapse Examples

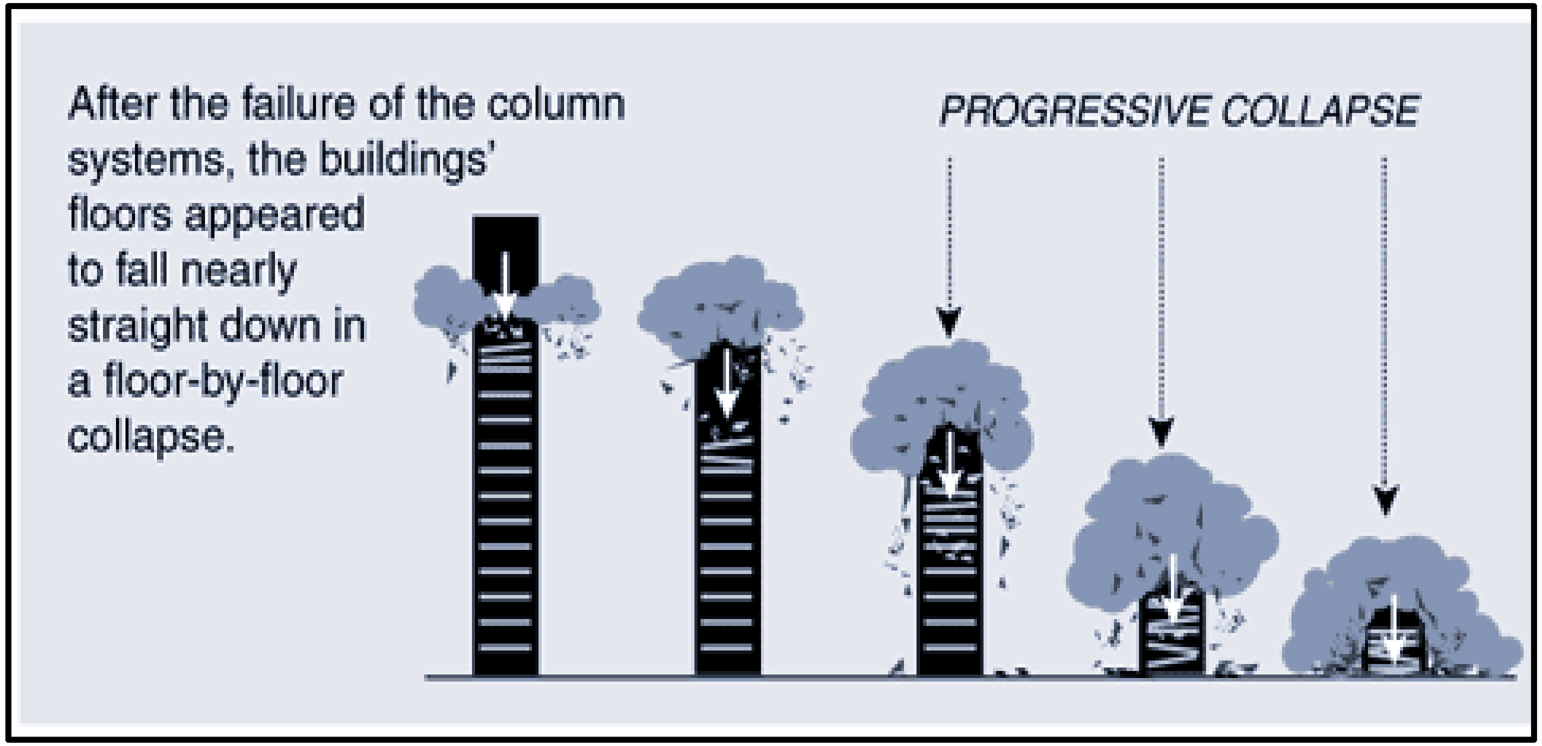


Figure 1. World Trade Center Towers [26,29] New York, USA. 2001, terrorist attack by two hijacked commercial airliners hitting the two towers.

Progressive Collapse Examples

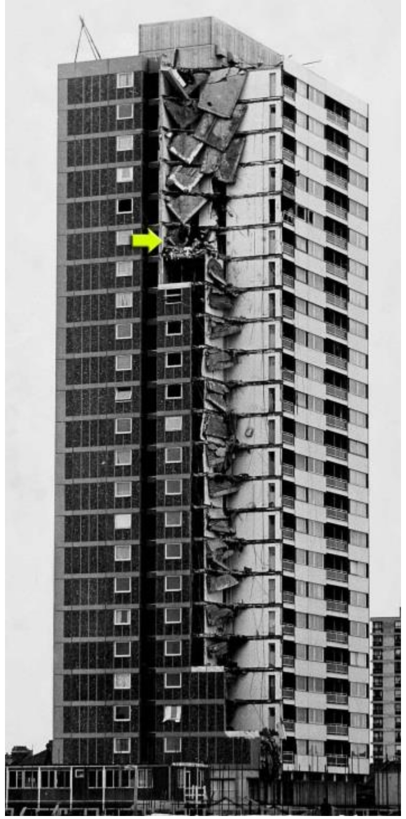
Figure 2. **The Windsor Tower**, Madrid, Spain [12]. **2005**, intensive fire.

Figure 3. **Khobar Towers** Bombing, Dhahran, Saudi Arabia [11]. **1996**, terrorist attack.

Figure 4. **The 2000 Commonwealth Ave. Tower** in Boston, United States [10]. **1971**, lack of shoring and low concrete strength.

Most of the reported PC events have resulted in large number of casualties besides the enormous loss in the property.

Progressive Collapse Examples



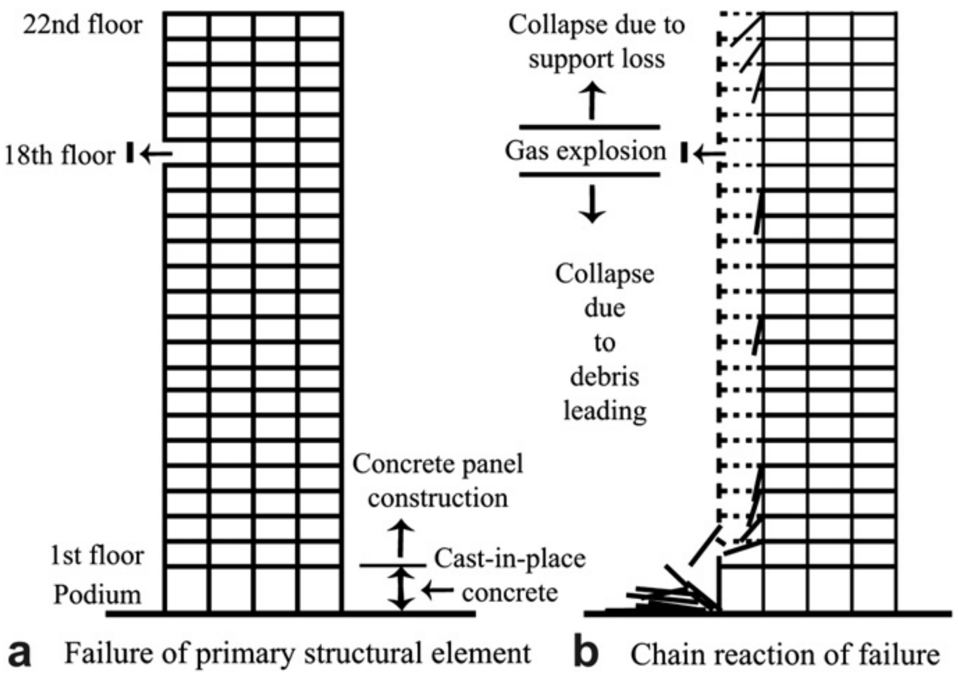


Figure 5. Progressive Collapse of the **Ronan Point Apartment**, London, UK [13,18]. **1968**, gas explosion.

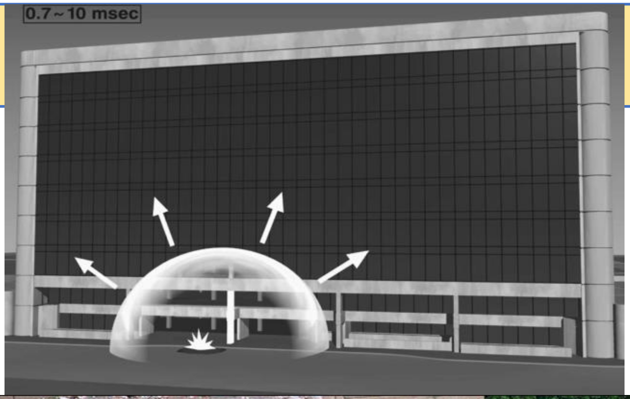


Figure 6. Isometric view showing location of blast for **Alfred P. Murrah Federal Building** [21, 23], Oklahoma, USA. **1995** terrorist attach

How To Prevent Progressive Collapse

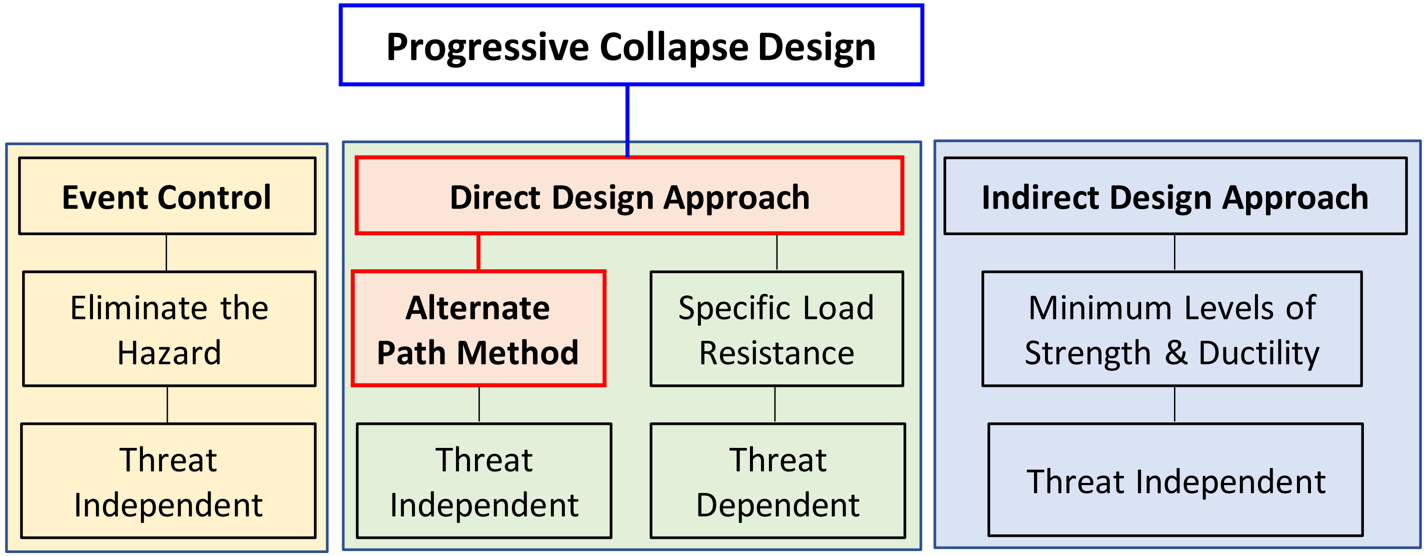
- The designer should increase the **structural redundancy**.
- What matters **is NOT** the initial damage to the primary load-bearing elements.
- What matters **is** the resulting sudden changes to the building's geometry and load-paths.

- Many nations have modified their design codes to include the **PC** phenomenon.
- In USA, the **General Services Administration** (GSA 2003) and the **Department of Defense** (**DoD - UFC 4-23-03**) have published specific guidelines for **PC** analysis and designs for the structures.

Analysis – Design Procedures for Progressive Collapse

PC Analysis Procedures

1. **Linear Static Procedure** (LSP) –
   - ✓ Most frequently used: due to being quick, simple, and economic analysis approach
   - ✓ More widely used: to assess the PC potential in low and mid-rise <u>regular structures</u> (≤ 10 floors)
   - ✓ An <u>amplification factor</u> is applied to the load combination to account for the dynamic influence
2. **Linear Dynamic Procedure** (LDP)
3. **Nonlinear Static Procedure** (NSP)
4. **Nonlinear Dynamic Procedure** (NDP)



Not very popular method

Distinct processes in the design and assessment of *<u>new and existing facilities</u>* to the PC potential. Design provisions are addressed in many design codes, standards and guidelines, **ASCE, GSA, DoD**

DoD: “Design of Buildings to Resist Progressive Collapse”, 2010

The **DoD Unified Facilities Criteria (UFC 4-23-03)** guideline

a) was prepared for the design of the military facilities with three or more stories that necessitate **PC** considerations.

b) provides a thorough explanation for PC design and assessment for new and existing buildings constructed by

- reinforced concrete
- steel structures
- masonry
- wood
- cold-formed steel structures.

Objective

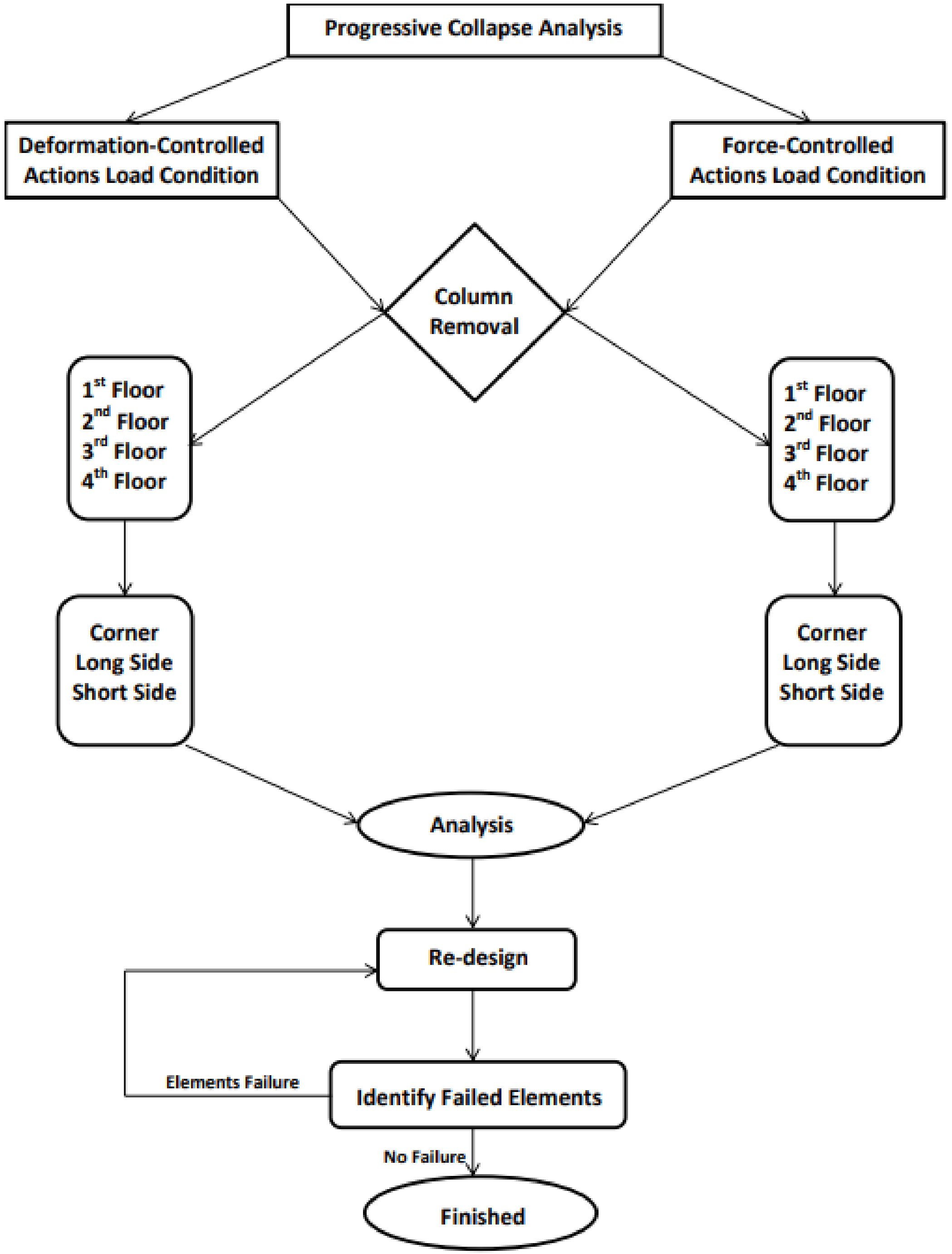
DoD - UFC 4-23-03 Alternate Load Path method is based on **"sudden column loss".** Removal of column from

- middle of the short side
- middle of the long side
- corner of the building

So far **it is not clear** which one of theses three cases is the most significant and what is the influence of the building height.

Main objective is to assess the **PC** potential in four existing low to mid-rise RC buildings to investigate

- which **column removal** case is more critical
- what is the influence of **building height**.



Methodology

- **DoD, UFC 4-023-03** guideline with **Alternate Path Method** (APM) was used to analyze and re-design the buildings
- **2 four-story** and **2 eight-story** existing apartment buildings in *Famagusta, Northern Cyprus* were selected to fulfill the **structural regularity** required by UFC guideline.
- Buildings were constructed between the years **1992 and 2004** according to **Turkish Standards**.
- The structural system is a conventional (**non-ductile**) RC frame.
- 3D computer models of each building was prepared, designed and **LSP** was carried out by using **SAP2000** program.
- Analysis results for four buildings were compared. The failed members were identified and re-designed.

Case Study Building Details

Building No	No of Storeys	Width x-direction (m)	Length y-direction (m)
1	4	15.55	17.60
2	4	15.30	16.00
3	8	15.20	17.80
4	8	15.00	15.30

Dimensions and Reinforcement of the Cross Sections for the Buildings

Building 1 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	10@15cm
Column	35X50	12ϕ14	10@15cm
Column	35X75	16ϕ14	10@15cm
Column	50X25	10ϕ14	10@15cm
Column	60X30	12ϕ14	10@15cm
Column	70X30	14ϕ14	10@15cm
Column	D50	10ϕ16	10@12cm
Beam	25X50	10ϕ14	10@12cm

Building 3 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X70	12ϕ14	10@15cm
Column	25X80	14ϕ14	10@15cm
Column	25X105	16ϕ14	10@15cm
Column	25X110	16ϕ14	10@15cm
Column	30X75	14ϕ14	10@15cm
Column	30X90	16ϕ14	10@15cm
Column	30X105	16ϕ14	10@15cm
Column	40X70	14ϕ14	10@15cm
Column	80X25	14ϕ14	10@15cm
Column	100X25	16ϕ14	10@15cm
Beam	25X60	10ϕ14	10@12cm

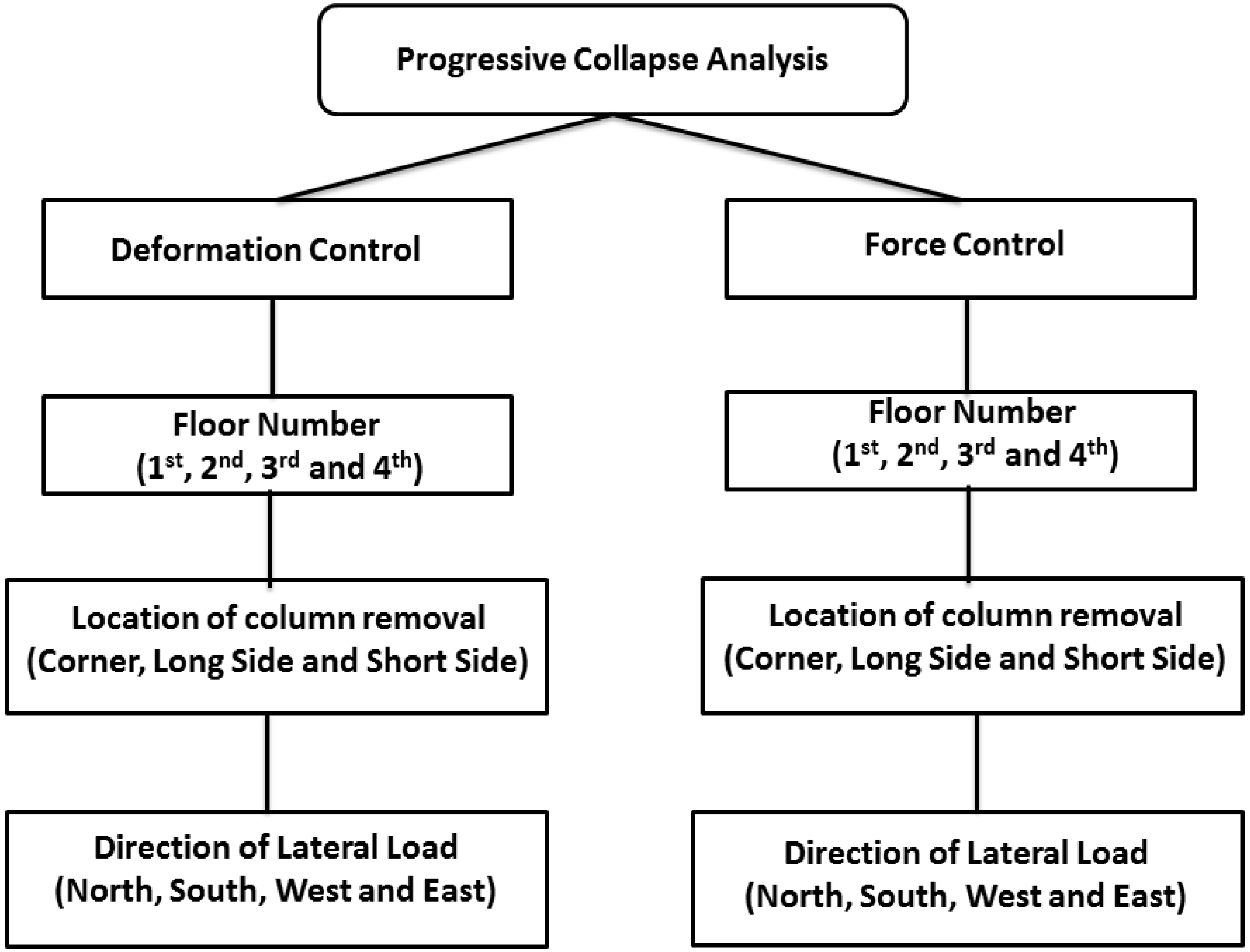
Building 2 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	8@12cm
Column	25X60	10ϕ14	8@12cm
Column	25X70	12ϕ14	8@12cm
Column	30X135	24ϕ14	8@12cm
Column	60X25	10ϕ14	8@12cm
Column	70X25	12ϕ14	8@12cm
Beam	25X50	10ϕ14	8@10cm

Building 4 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X60	10ϕ14	8@15cm
Column	25X105	14ϕ14	8@15cm
Column	50X25	8ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	120X25	16ϕ14	8@15cm
Beam	25X50	10ϕ14	8@12cm

Analytical Approach of Study



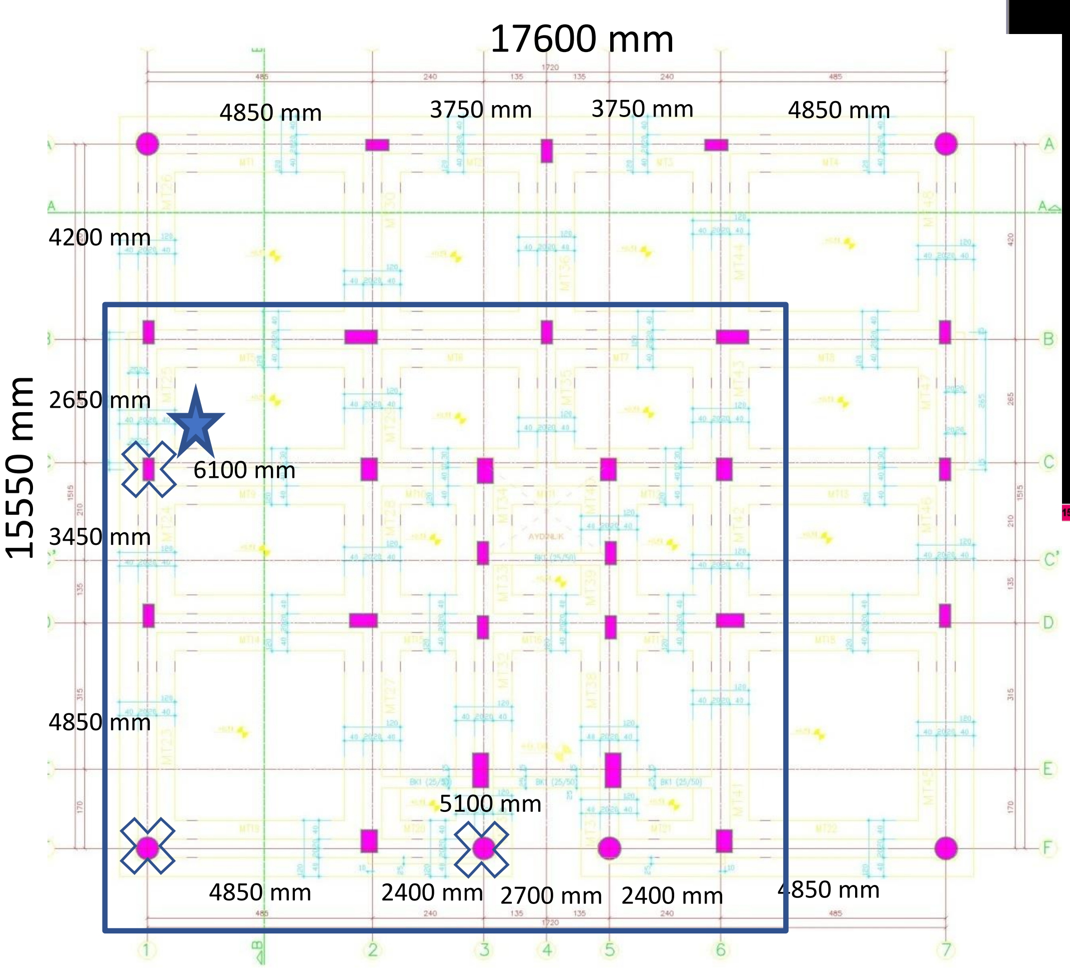
1. Complete the modeling and analysis of each building
2. Identify failed members
3. Categorize failed members with respect to their actions, floor number, location of the column removal, direction of the notional lateral loads applied to each face of the structure

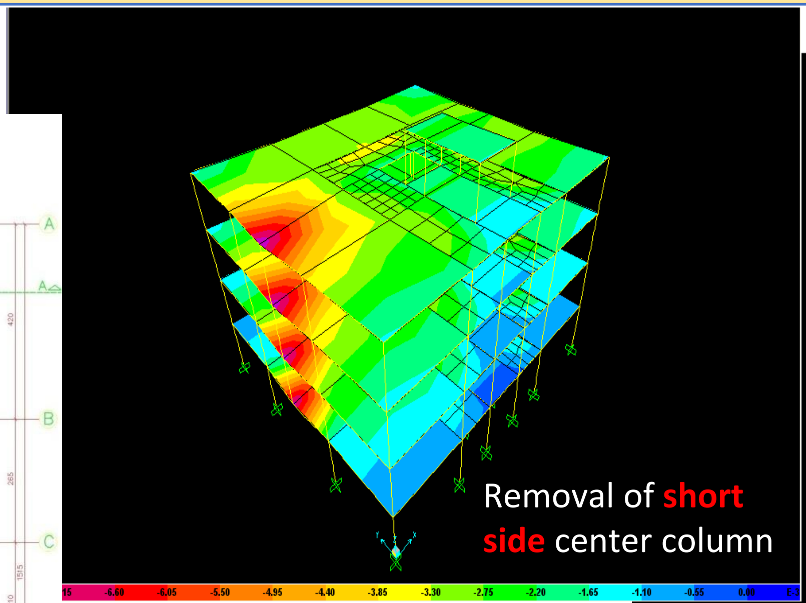
- Remove 3 columns from each story (first, top and middle)
- 4 story bld. - 12 columns removed from all story's
- 8 story bld. - 12 columns removed from 1st, 4th, 5th, 8th story's

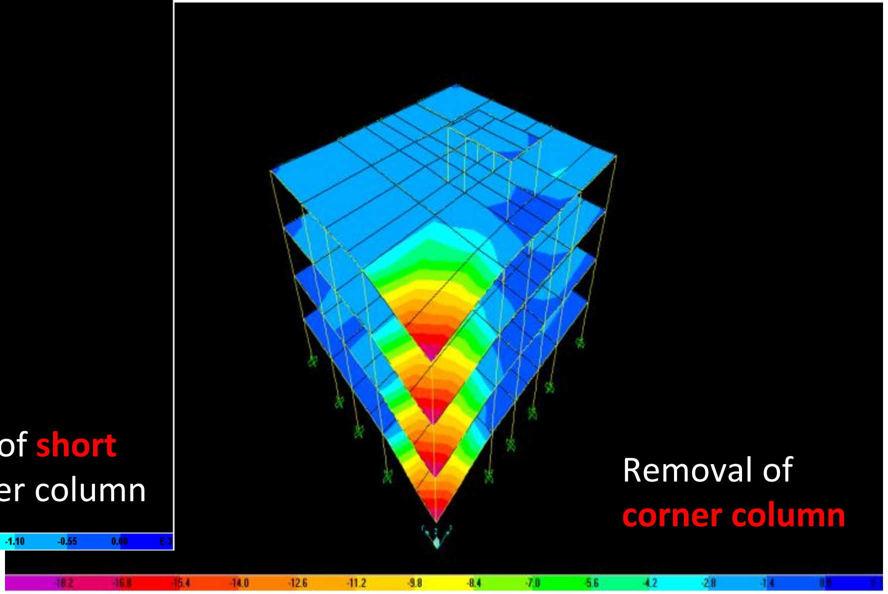
for **deformation-controlled** and **force-controlled actions**

Hence each apartment was **analyzed** and **re-designed** for **96 times** to cover all required scenarios

Building 1: 4-Storey Floor Plan Dimensions: 17.6 m x 15.55 m





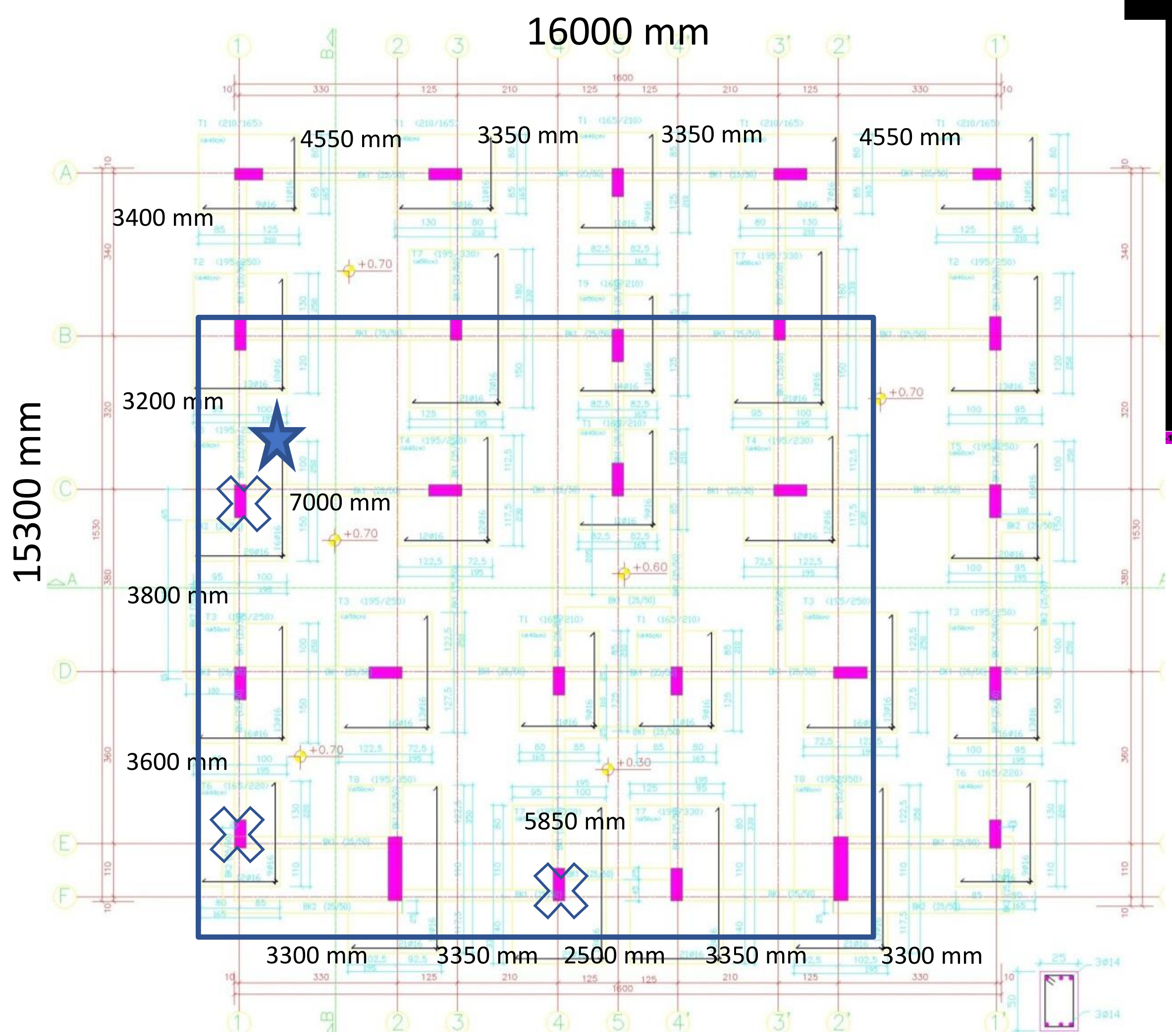


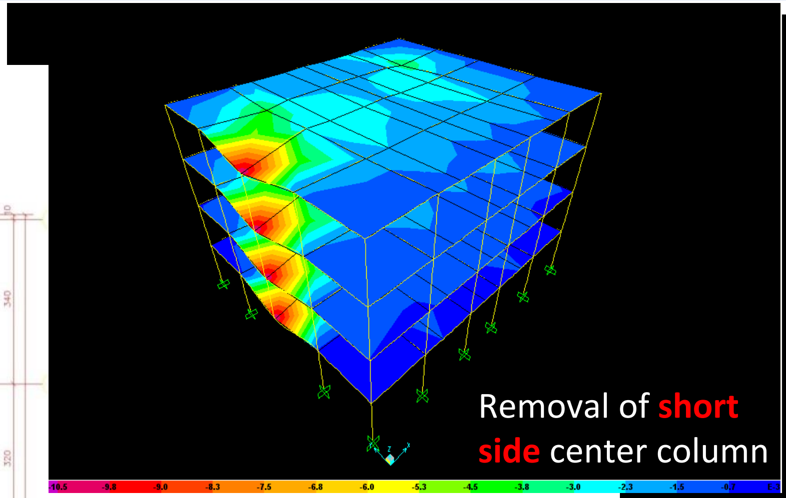
Building 1 - Deformation-controlled Actions

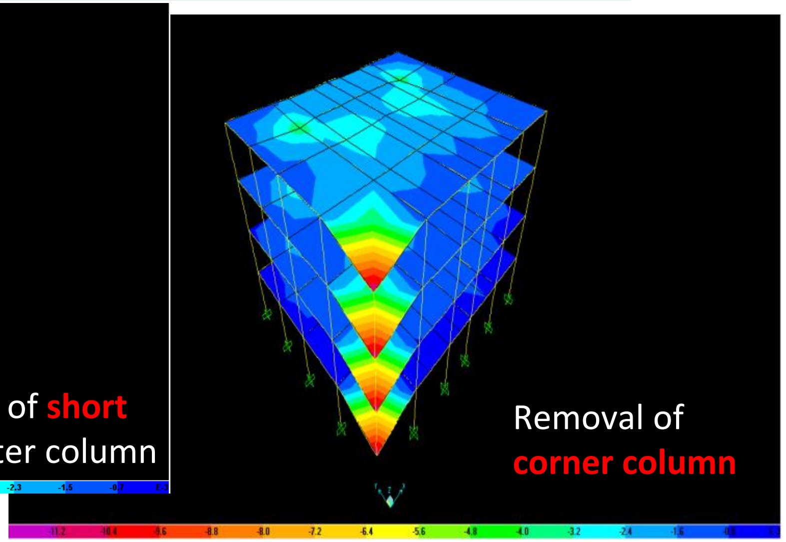
Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	5	0	11	4	0	8	2	0	4	0	0	2
South	5	0	11	4	0	8	2	0	5	0	0	2
West	5	0	13	4	0	8	2	0	4	0	0	2
East	5	0	11	4	0	8	2	0	4	0	0	2

Max. vertical deflection is at the corner of **4th floor**: **Building 1= 7.7 mm**

Building 2: 4-Storey Floor Plan Dimensions: 16.0 m x 15.3 m





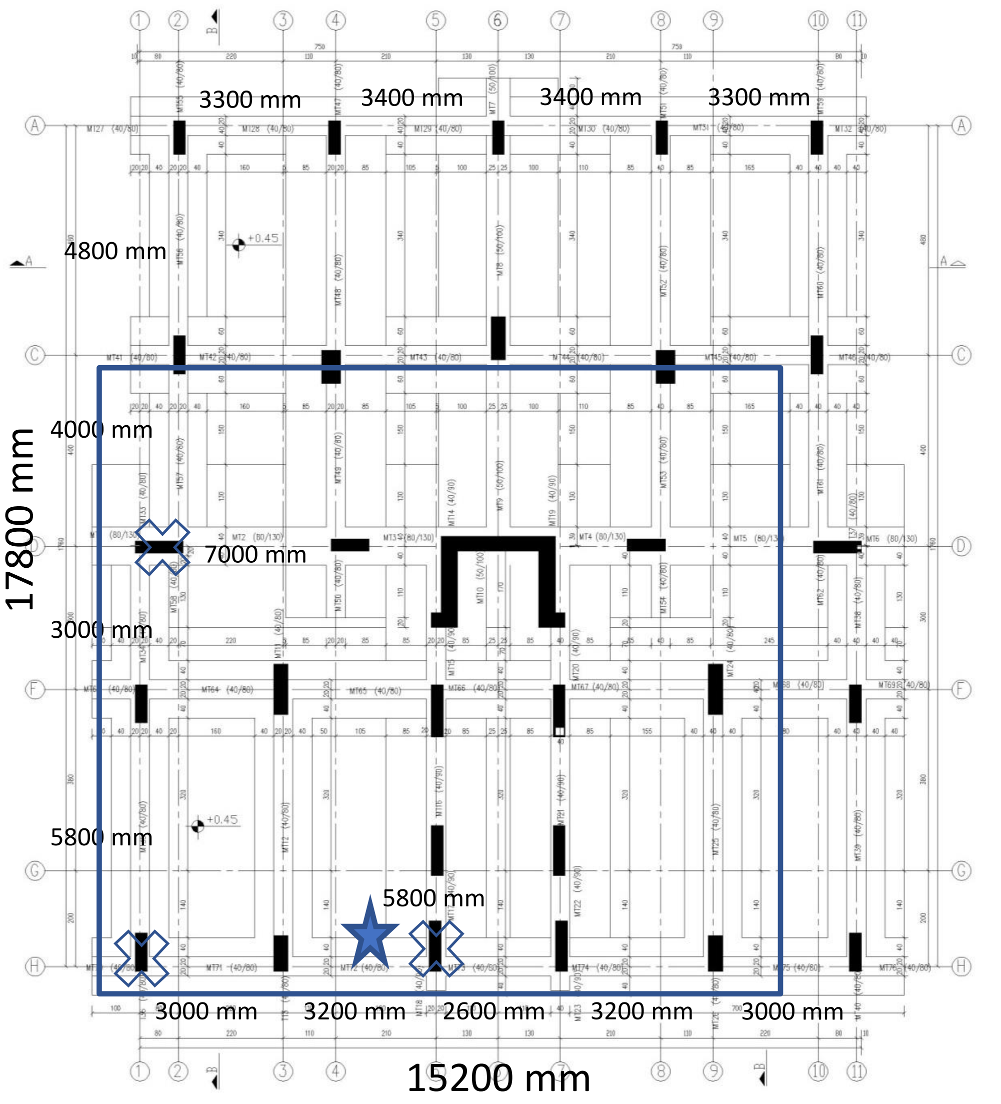


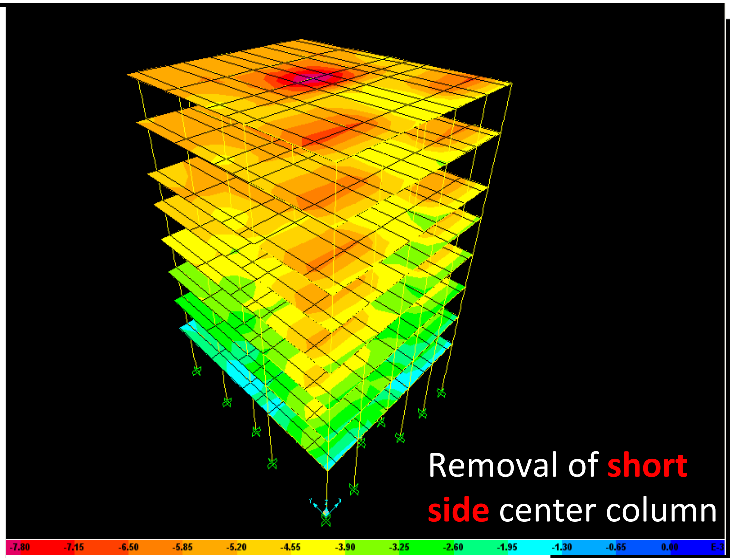
Building 2 - Deformation-controlled Actions

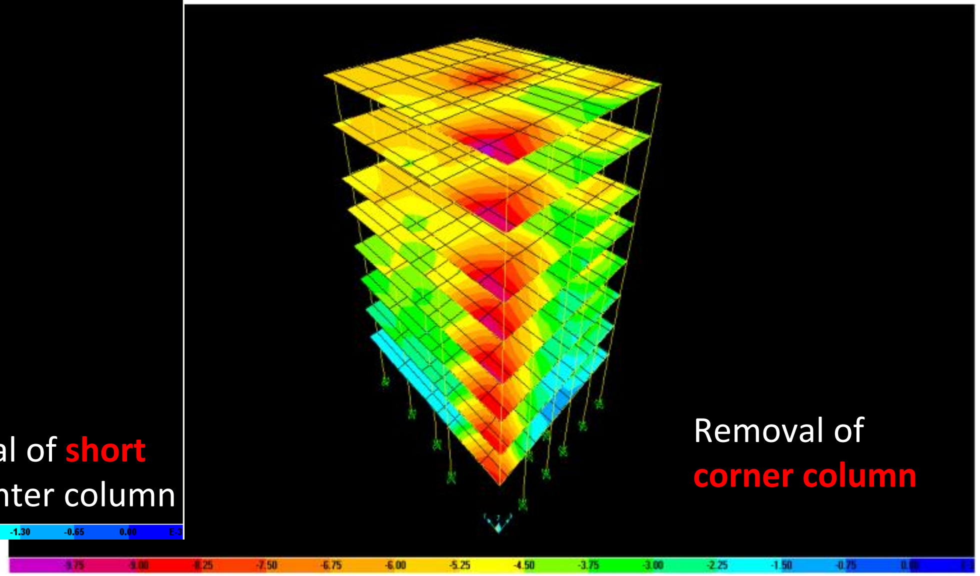
Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	8	7	12	6	2	9	5	1	6	3	0	3
South	8	8	12	6	2	9	4	0	6	2	0	3
West	8	7	12	6	2	9	5	1	6	2	0	4
East	8	7	12	6	2	9	5	0	6	2	0	3

Max. vertical deflection is at the corner of 4^{th} floor: **Building 2= 10.6 mm**

Building 3: 8-Storey Floor Plan Dimensions: 17.8 m x 15.2 m







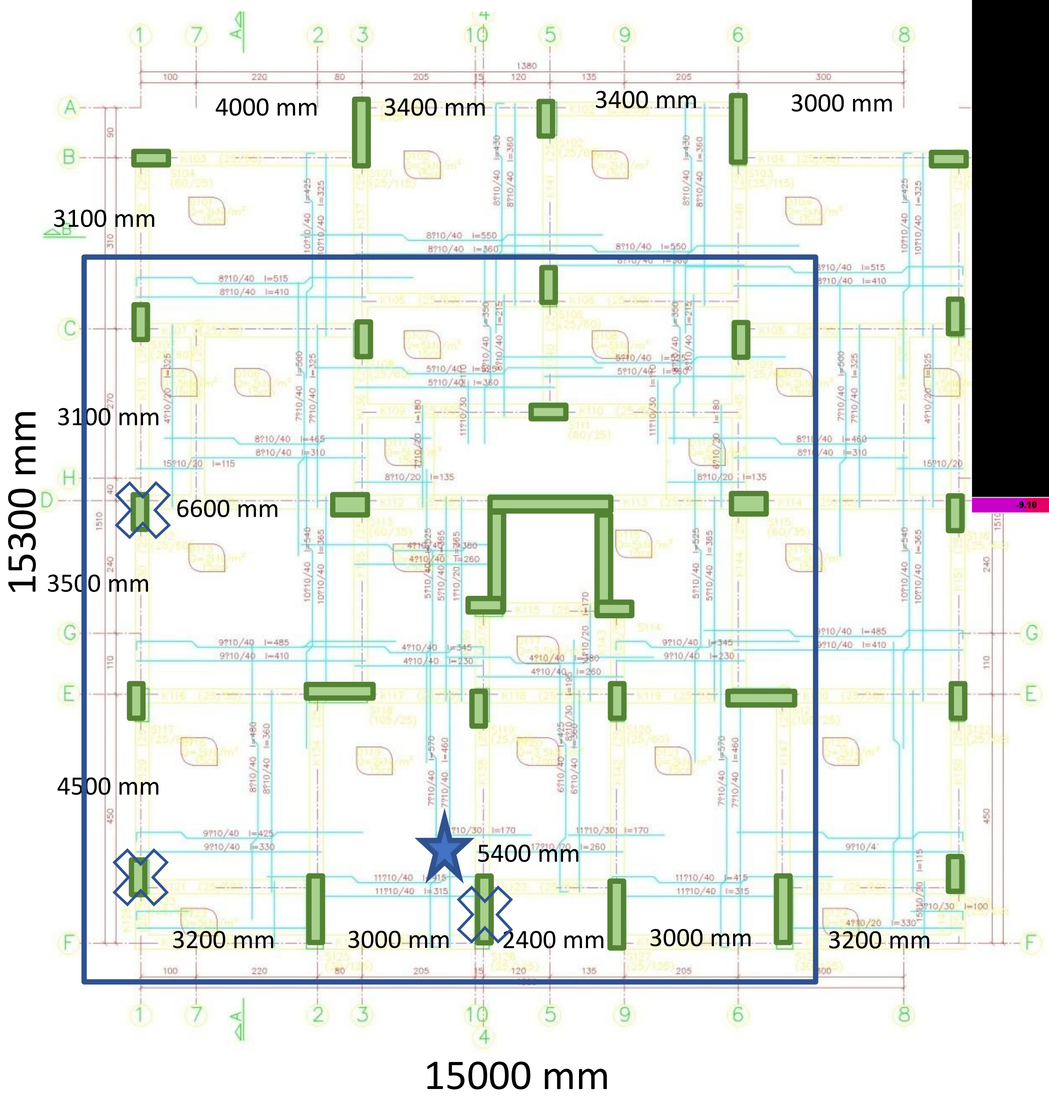
Building 3 - Deformation-controlled Actions

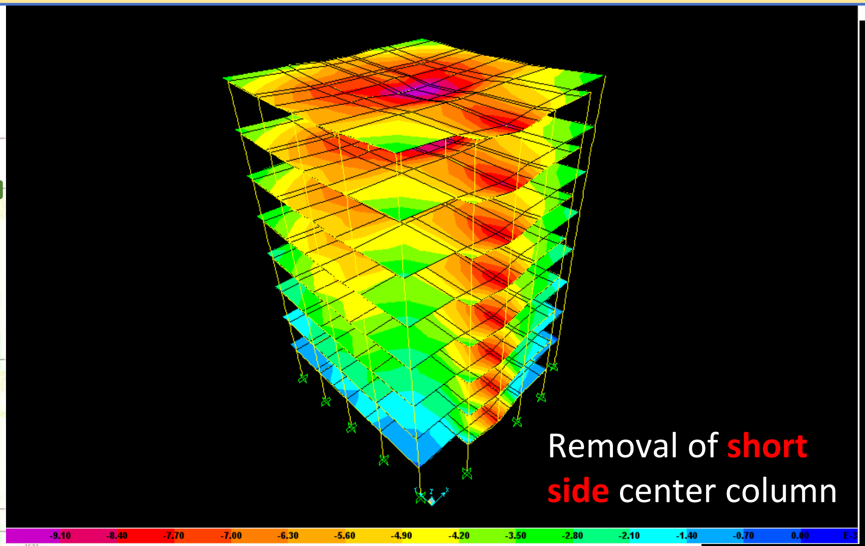
Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	12	11	13	11	11	13	10	10	13	9	9	12
South	12	11	13	11	10	13	10	9	13	9	8	12
West	12	12	13	11	11	13	10	9	13	9	9	12
East	12	11	13	11	11	13	10	9	13	9	9	12

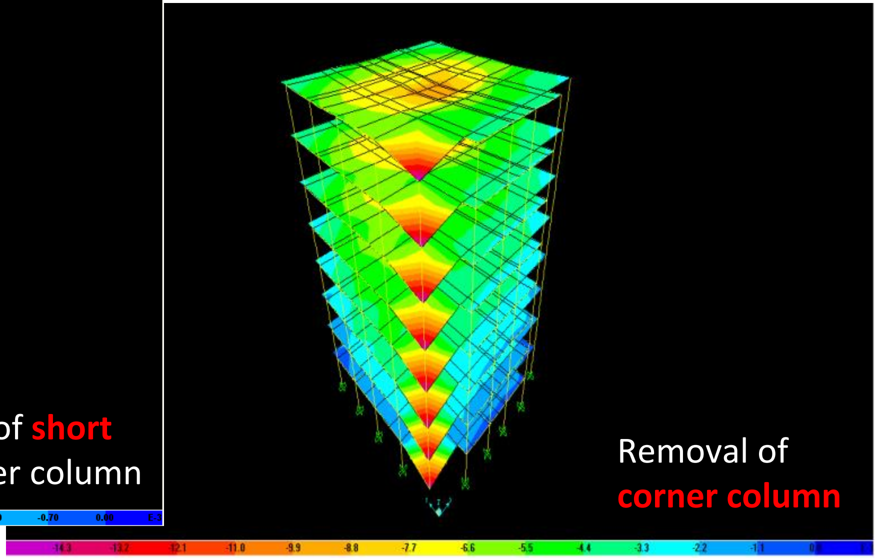
Max. vertical deflection is at the middle of **8th floor = 8.8 mm**

Max. vertical deflection above the removed column **= 3.5 mm**

Building 4: **8-Storey** Floor Plan Dimensions: 15.3 m x 15.0 m







Building 4 - Deformation-controlled Actions

Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	11	20	22	11	14	18	10	14	17	10	10	10
South	12	20	23	10	14	17	10	13	15	10	10	10
West	11	19	22	10	14	18	10	14	15	11	9	11
East	13	22	23	11	17	18	11	15	16	11	10	11

Max. vertical deflection is at the middle of **8th floor = 9.7 mm**

Max. vertical deflection above the removed column **= 8.5 mm**

Building 1 and 2: 4-Storey   Building 3 and 4: 8-Storey

Building 1 - Deformation-controlled Actions

Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	5	0	11	4	0	8	2	0	4	0	0	2
South	5	0	11	4	0	8	2	0	5	0	0	2
West	5	0	13	4	0	8	2	0	4	0	0	2
East	5	0	11	4	0	8	2	0	4	0	0	2

Building 3 - Deformation-controlled Actions

Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	12	11	13	11	11	13	10	10	13	9	9	12
South	12	11	13	11	10	13	10	9	13	9	8	12
West	12	12	13	11	11	13	10	9	13	9	9	12
East	12	11	13	11	11	13	10	9	13	9	9	12

Building 2 - Deformation-controlled Actions

Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	8	7	12	6	2	9	5	1	6	3	0	3
South	8	8	12	6	2	9	4	0	6	2	0	3
West	8	7	12	6	2	9	5	1	6	2	0	4
East	8	7	12	6	2	9	5	0	6	2	0	3

Building 4 - Deformation-controlled Actions

Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	11	20	22	11	14	18	10	14	17	10	10	10
South	12	20	23	10	14	17	10	13	15	10	10	10
West	11	19	22	10	14	18	10	14	15	11	9	11
East	13	22	23	11	17	18	11	15	16	11	10	11

Building 1 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	10@15cm
Column	35X50	12ϕ14	10@15cm
Column	35X75	16ϕ14	10@15cm
Column	50X25	10ϕ14	10@15cm
Column	60X30	12ϕ14	10@15cm
Column	70X30	14ϕ14	10@15cm
Column	D50	10ϕ16	10@12cm
Beam	25X50	10ϕ14	10@12cm

Building 2 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	8@12cm
Column	25X60	10ϕ14	8@12cm
Column	25X70	12ϕ14	8@12cm
Column	30X135	24ϕ14	8@12cm
Column	60X25	10ϕ14	8@12cm
Column	70X25	12ϕ14	8@12cm
Beam	25X50	10ϕ14	8@10cm

Building 3 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X70	12ϕ14	10@15cm
Column	25X80	14ϕ14	10@15cm
Column	25X105	16ϕ14	10@15cm
Column	25X110	16ϕ14	10@15cm
Column	30X75	14ϕ14	10@15cm
Column	30X90	16ϕ14	10@15cm
Column	30X105	16ϕ14	10@15cm
Column	40X70	14ϕ14	10@15cm
Column	80X25	14ϕ14	10@15cm
Column	100X25	16ϕ14	10@15cm
Beam	25X60	10ϕ14	10@12cm

Building 4 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X60	10ϕ14	8@15cm
Column	25X105	14ϕ14	8@15cm
Column	50X25	8ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	120X25	16ϕ14	8@15cm
Beam	25X50	10ϕ14	8@12cm

Building 1 and 2: 4-Storey   Building 3 and 4: 8-Storey

Building 1 - Force-controlled Actions

Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	4	0	9	2	0	6	1	0	4	0	0	2
South	4	0	8	2	0	6	1	0	4	0	0	2
West	4	0	9	2	0	6	1	0	4	0	0	2
East	4	0	9	2	0	6	1	0	4	0	0	2

Building 2 - Force-controlled Actions

Floor Number	First Story			Second Story			Third Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	6	6	7	3	0	7	4	0	5	0	0	3
South	6	5	10	3	0	3	2	0	3	1	0	1
West	6	5	10	3	0	6	3	0	5	1	0	1
East	6	6	8	3	0	6	3	0	4	1	0	1

Building 3 - Force-controlled Actions

Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	1	1	6	0	0	3	0	1	2	0	0	0
South	1	1	6	0	0	3	0	0	2	0	0	0
West	1	1	6	0	1	3	0	0	2	0	0	0
East	1	1	6	0	0	3	0	0	2	0	0	0

Building 4 - Force-controlled Actions

Floor Number	First Story			Fourth Story			Fifth Story			Last Story		
Location / Direction	C	L	S	C	L	S	C	L	S	C	L	S
North	1	6	8	0	2	3	0	1	3	0	0	1
South	0	6	8	1	1	4	0	1	3	0	1	1
West	1	5	7	2	2	5	1	2	4	1	1	2
East	1	8	8	1	3	3	1	2	4	1	1	1

Building 1 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	10@15cm
Column	35X50	12ϕ14	10@15cm
Column	35X75	16ϕ14	10@15cm
Column	50X25	10ϕ14	10@15cm
Column	60X30	12ϕ14	10@15cm
Column	70X30	14ϕ14	10@15cm
Column	D50	10ϕ16	10@12cm
Beam	25X50	10ϕ14	10@12cm

Building 2 – 4 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X50	10ϕ14	8@12cm
Column	25X60	10ϕ14	8@12cm
Column	25X70	12ϕ14	8@12cm
Column	30X135	24ϕ14	8@12cm
Column	60X25	10ϕ14	8@12cm
Column	70X25	12ϕ14	8@12cm
Beam	25X50	10ϕ14	8@10cm

Building 3 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X70	12ϕ14	10@15cm
Column	25X80	14ϕ14	10@15cm
Column	25X105	16ϕ14	10@15cm
Column	25X110	16ϕ14	10@15cm
Column	30X75	14ϕ14	10@15cm
Column	30X90	16ϕ14	10@15cm
Column	30X105	16ϕ14	10@15cm
Column	40X70	14ϕ14	10@15cm
Column	80X25	14ϕ14	10@15cm
Column	100X25	16ϕ14	10@15cm
Beam	25X60	10ϕ14	10@12cm

Building 4 – 8 story

Section	Dimensions (cm)	Reinforcement	
		Longitudinal	Stirrups
Column	25X60	10ϕ14	8@15cm
Column	25X105	14ϕ14	8@15cm
Column	50X25	8ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	60X25	10ϕ14	8@15cm
Column	120X25	16ϕ14	8@15cm
Beam	25X50	10ϕ14	8@12cm

Discussion of Results

1. Load increase factor is higher for Deformation-control actions hence more members failed with larger deflection values. Hence the results of DCA are discussed below

For all the buildings regardless of the type of actions, the number of stories and the direction of the notional loads, the **column removal from the first floor** located at or **near the middle of the short side** of the facility leads to more damage and relatively greater number of failed members in all floors.

- This is particularly valid for **Building 1** where the corner column removal causes the second highest member failure in all floors except 4th floor.

  REASON: Span lengths around the removed short side column is relatively large compared to others
- For **Building 2** similar number of members failed due to corner and short side column removal

  REASON: Span lengths around the removed short side and corner column is relatively large compared to long side
- For **Building 3** relatively similar number of members failed in each floor for all column removal scenarios

  REASON: Span lengths around the removed long side and corner column is relatively large and part of the building has smaller overall dimensions

Discussion of Results

- For **Building 4** column removal from the middle of long and short sides caused relatively higher number of member failures when compared to corner column removal, except for the 8th floor, where all column removal scenarios had similar number of member failures.

  REASON: Span lengths around the removed long and short side column is relatively larger than the ones around corner column.

2. No remarkable difference in the findings when the direction of the notional loads was changed.
3. For combination of gravity and lateral notional loads

   Max. vertical deflection is at the corner of 4th floor, **Building 1= 7.7 mm**

   Building 2= 10.6 mm

   Max. vertical deflection is at the middle of 8th floor, **Building 3 = 8.8 mm**

   Building 4 = 9.7 mm

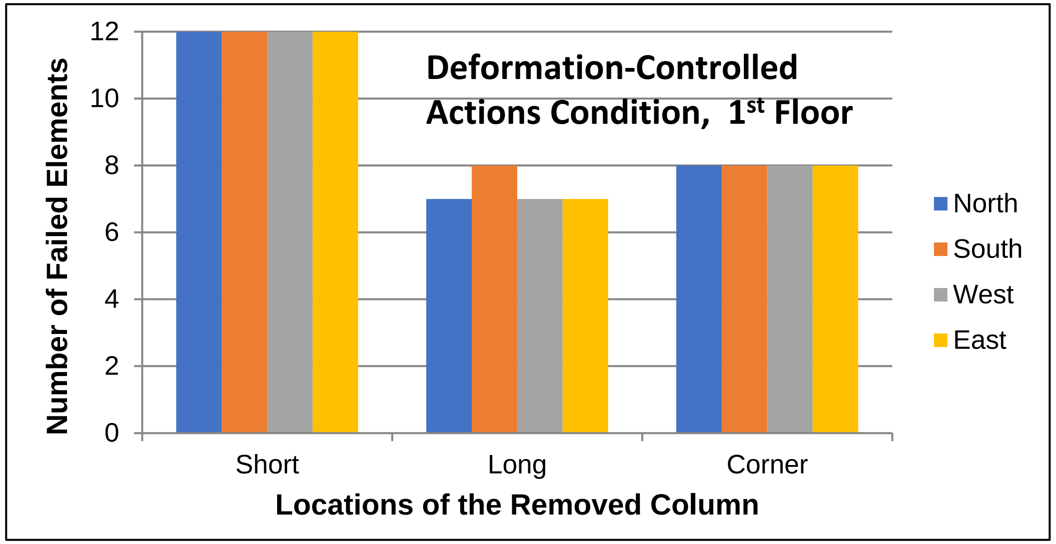
   Max. vertical deflection above the removed column, **Building 3 = 3.5 mm**

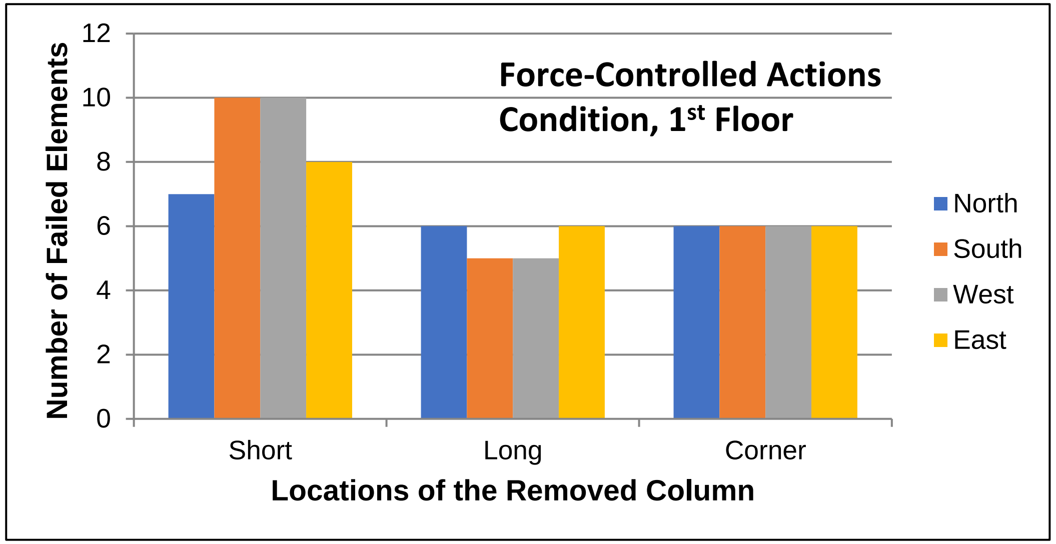
   Building 4 = 8.5 mm

Retrofitting of Building 2: 4-Storey and Building 4: 8-Storey

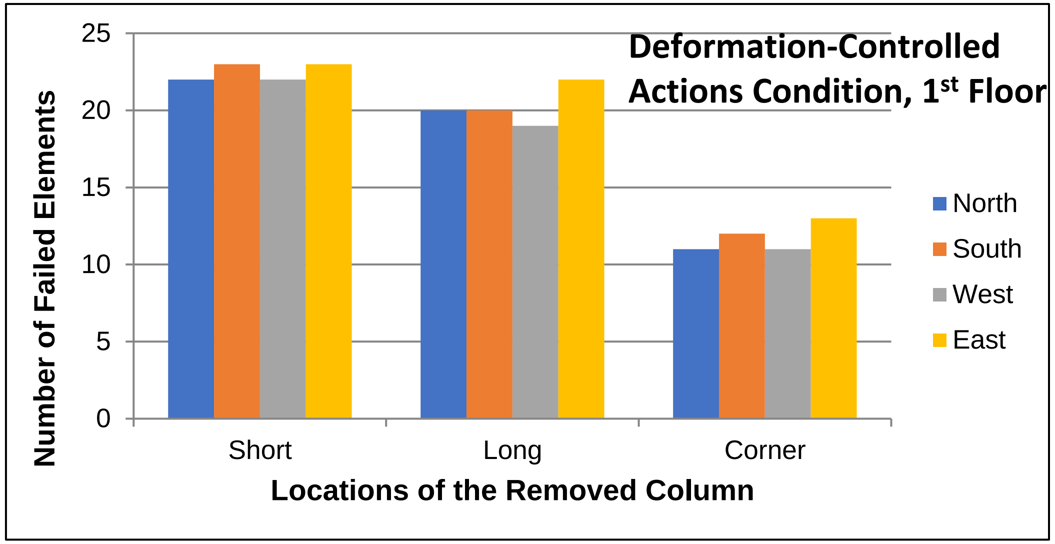
1. After completing the analysis of each structure, the failed elements (beams and columns) were identified.
2. Consequently, the failed members were re-designed with consideration of retrofitting requirements as per ACI 318R-05 design code and UFC 4-023-03 (DoD, 2010).
3. To do this, all the failed components were identified, and then their cross-sections and reinforcement were modified. Iterative analysis and re-design were conducted for each building until all the structural members pass the required checks.

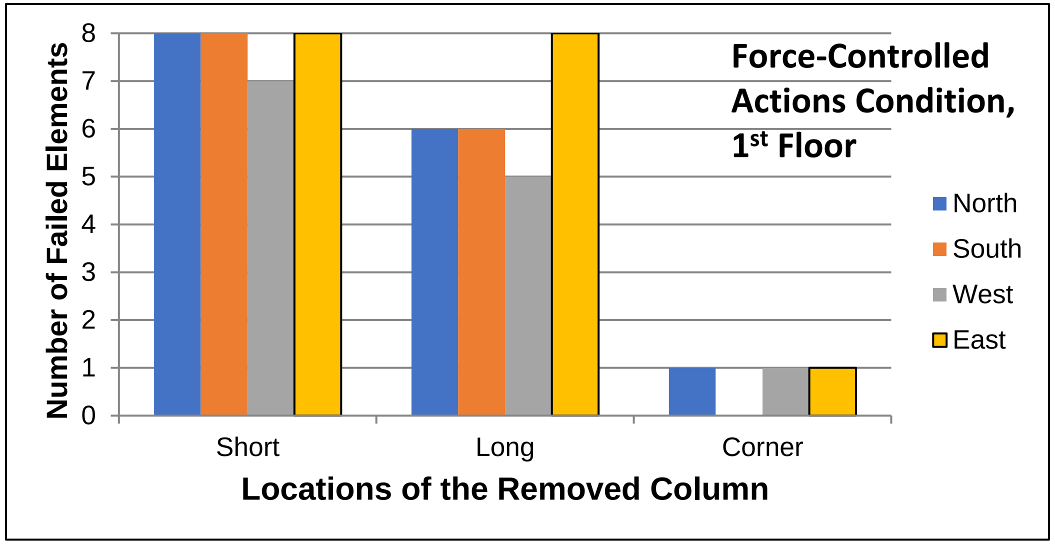
Building 2: 4-Storey





Building 4: 8-Storey





Conclusion

It should be emphasized that these findings and recommendations are only to be employed for the regular structures since this study was carried out for regular buildings.

Conclusion 1: Based on the analysis outcomes of this investigation, the **removal of column from the middle or near the middle of the short side** at the first floor of the building is the worst-case scenario which led to more damage and greater number of failed members.

Recommendation: More study needs to be carried out on this to see whether column located at or near the center of short side is the most critical load carry element in the analysis and design procedures. If do using this approach would simplify this type of comprehensive analysis procedure.

Conclusion 2: The results of the analysis illustrate that the **higher the building the more failure in the structural members**. However, comparing the two eight story buildings **there are differences in number of failed members**.

Recommendation: More study needs to be carried out on different building heights and plans to arrive at more firm conclusions

Conclusion 3: Observations from the results of this study demonstrated that

(a) the eight-story apartment buildings are relatively more critical

(b) the column removed from middle or near the middle of the short side of the building is more significant

to **progressive collapse** event when compared to four-story buildings.

Further Recommendations

1) Economical analysis of the cost of retrofitting such structures against possible PC should be done.
2) Depending on the cost and the risk of buildings for PC, retrofitting can be done at design stage.

Thank you for your attention