African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 5, Issue 1, 2026
Page No: 292-317
Website: https://aaasjournals.com/index.php/ajapas/index
ISI 2025: 1.126 SJIFactor 2024: 6.752 معامل التأثير العربي: 1.62

Study of Some Factors Affecting the Stability of R.C. Buildings Subjected to Progressive Collapse Loads
(Comparative Study: ACI Method versus GSA and UFC Methods)

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دراسة بعض العوامل المؤثرة على استقرار المباني الخرسانية المسلحة المعرضة لأحمال الانـهيار التدريجي (دراسة مقارنة بين طريقة *ACI* وطرق *GSA* و*UFC*)

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Received: November 23, 2025	Accepted: February 04, 2026	Published: February 15, 2026

Abstract
Progressive collapse of reinforced concrete buildings is defined as a phenomenon initiated by the local failure of one or more structural members, which may propagate and result in the partial or total collapse of the structure. This type of failure is usually caused by loads that are not considered in the original design and are therefore classified as *abnormal loads*. Due to its importance in achieving safer structural systems, this study examines progressive collapse analysis using the **Alternate Load Path (AP) method** and the **Tie Force (TF) method**, both of which are widely applied within linear static analysis frameworks. The analyses are carried out using the advanced structural analysis software **SAP2000**. The ALP method is based on four damage scenarios that assume the removal of a single ground-floor column located at the corner, edge, or interior of the building. The demand-to-capacity ratios of beams adjacent to the removed column are evaluated to assess the likelihood of progressive collapse. When these ratios exceed the limits specified by design codes, additional steel reinforcement is provided to the affected beams to reduce the ratios to acceptable levels and enhance structural robustness. The TF method focuses on strengthening the building by providing various types of structural ties to improve continuity and resistance against progressive collapse. In this study, a generalized design curve was developed and divided into three design regions. When the ratio $LL/DL \leq 0.727$, the GSA design approach is adopted, whereas for $LL/DL \geq 8$, the ACI-based approach is recommended. The effects of column displacement in both directions and the influence of span length on building stability under progressive collapse loading were also investigated.

Keywords: Progressive collapse; Reinforced concrete buildings; Alternate load path method; Tie force method; SAP2000; Design corrected curve.

الملخص
الانهيار التدريجي للمباني الخرسانية هو الظاهرة التي تنجم عن الانهيار المبدئي الأولي لعضو هيكلي واحد في المبنى أو أكثر مما يؤدي إلى فشل كامل للمبنى وعادة نتيجة تحميل لا يعتبر في التصميم، وبالتالي، فإنه يشار إليه على أنه حمل "غير عادي. ونظرا لأهميته للتوصل إلى تصميم أفضل للبناء، وتشمل هذه الدراسة تطبيقات الانهيار التدريجي باستخدام طريقة مسار التحميل البديل وطريقة قوة الربط وسيتم الاستناد على الحلول لكلا الطريقتين إلى برامج هندسي مثل برنامج ساب

2000 المتقدم المستخدم هنا, هما طريقتان شائعتا الاستخدام للتحليل الخطي الاستاتيكيي. وتعتمد طريقة المسار البديل على سيناريو من اربعة حالات يفترض فيها ازالة عمود واحد في الدور الارضي عند الر كن او جانبي المبنى او الوسط. تستخدم نسبة الطلب الى القدرة المحسوبة لكمرات المبنى المجاورة للعمود الملغي لمعرفة ان المبنى سيتعرض للانهيار التدريجي ام لا. واذا حدث ان المبنى سيتعرض للانهيار التدريجي سيضاف تسليح من اسياخ الحديد لهذه الكمرات لتبقى نسبة الطلب الى القدرة في حدود النسبة المحددة في المواصفات لحماية المبنى من احتمالات الانهيار التدريجي . اما طريقة قوة الربط فهي تستخدم مجموعة من الاربطة المختلفة لربط المبنى وتقويته ضد احتمال الانهيار التدريجي المحتمل. تم في هده الدراسة تطوير منحنى التصميم العام ، وقسم إلى ثلاث مناطق للتصميم ، المنطقة التي اعتبرت عند $LL \setminus DL \leq 0.727$ ، في هذه المنطقة تكون طريقة التصميم هي GSA ، ولكن عندما $LL \setminus DL \geq 8$ ، فإن الطريقة المستخدمة في التصميم هو ACI ، كما تمت دراسة تأثير إزاحة العمود في كلا الاتجاهين وكذلك تأثير طول الامتداد على ثبات المبنى عند تعرضه لحمل الانهيار التدريجي.

الكلمات المفتاحية: الانهيار التدريجي للمباني الخرسانية، طريقة قوة الربط، طريقة المسار البديل، ساب 2000 النسخة20, تصميم المنحنى المصحح.

Introduction

Progressive collapse of reinforced concrete buildings results from an initial collapse of one or more of the structural members of the building which may lead to a complete failure of the whole building. Local member failure which starts the collapse of the whole structure may be due to any loading which was not taken into account in the design process; thus, it is often referred to as an “abnormal” load. Abnormal loads are such as fire, gas or any kind of explosions, vehicular impact due to terrorist act or may be due to extreme weather events. Due to the importance of this safety engineering matter many official bodies began to include provisions that result in safeguarding the buildings either new or existing against progressive collapse. Several guidelines were recommended by the American General Services Administration (GSA) for new federal office buildings and major modernization projects of October of 2013 [1]. The American Concrete Institute (ACI) latest codes with its latest code of 2014 recommends many provisions regarding progressive collapse of concrete buildings [2].The American Department of Defense (DOD) through the Unified Building Criteria (UFC) in its issue of June 2013 explained methods of analysis and design of concrete, metallic, wooden and masonry buildings for resisting progressive collapse [3].The American Society of Civil Engineers (ASCE) included in a chapter concerning the general structural integrity for structures [4].some provisions regarding what should be done for buildings safety and stability and for building making them stand the consequences of losing a structural member or more due to progressive collapse. The present study is concerned with this topic due to its importance regarding reaching a better concrete buildings design and to introduce this subject to structural engineers and present its importance and details and for making a study to show its applications in this regard for new or already built buildings [5,6,7].

Material and methods

- The research is broadly divided in two phases; each phase is divided into two tasks. in the first phase, primary studies are conducted to choose the optimum design curve which will be used in second phase to study the effect of maximum span, offset of Colum and the maximum area which can the removed column carry.

A- Study the factor of safety

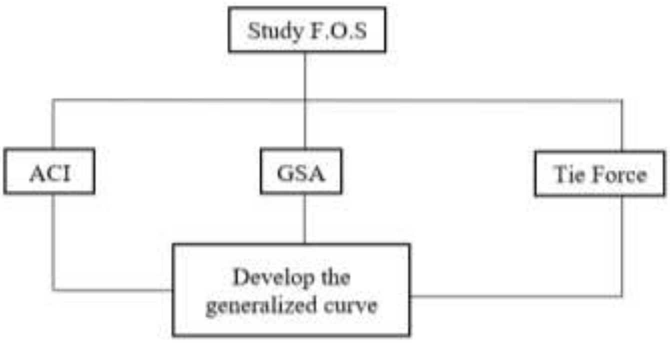

Figure (1) phase one, task 1 and task 2.

B- Study the effect of off-set of the column on the stability of the building

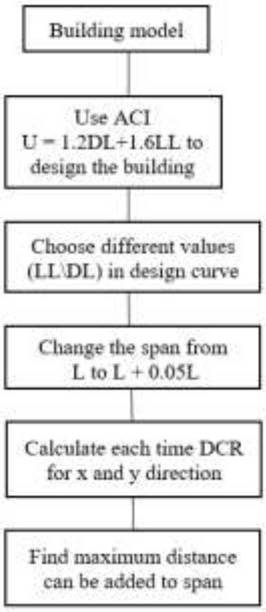

Figure (2) phase 2, task 1

C- Find the maximum collapse area

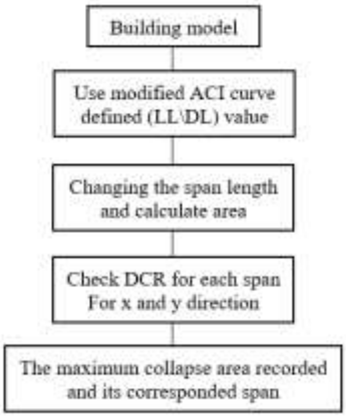

Figure (3) phase 2, task 2.

- **Analysis by Using the Alternate Load Path Method**

For gravity load analysis purposes, the following loads are to be applied to the structure under investigation:

1. Dead load (DL),
2. Live load (LL)

Load combination is considered for design of structural elements, [2].

Loading = 1.2DL + 1.6LL…………….…………….….……..…………. Eq (1)

However, GSA 2003 guidelines have specified the following load case for static analysis procedure:

Loading = 2(DL+0.25LL) ……………….…….…….….……...……………Eq (2)

The coefficient of 2 in the above equation is used to account for the dynamic effect in the static analysis. Figure es (4 , a to c) show the flow charts that explain the procedure for the analysis of any building so as to check and prevent progressive collapse by the alternate load path method.

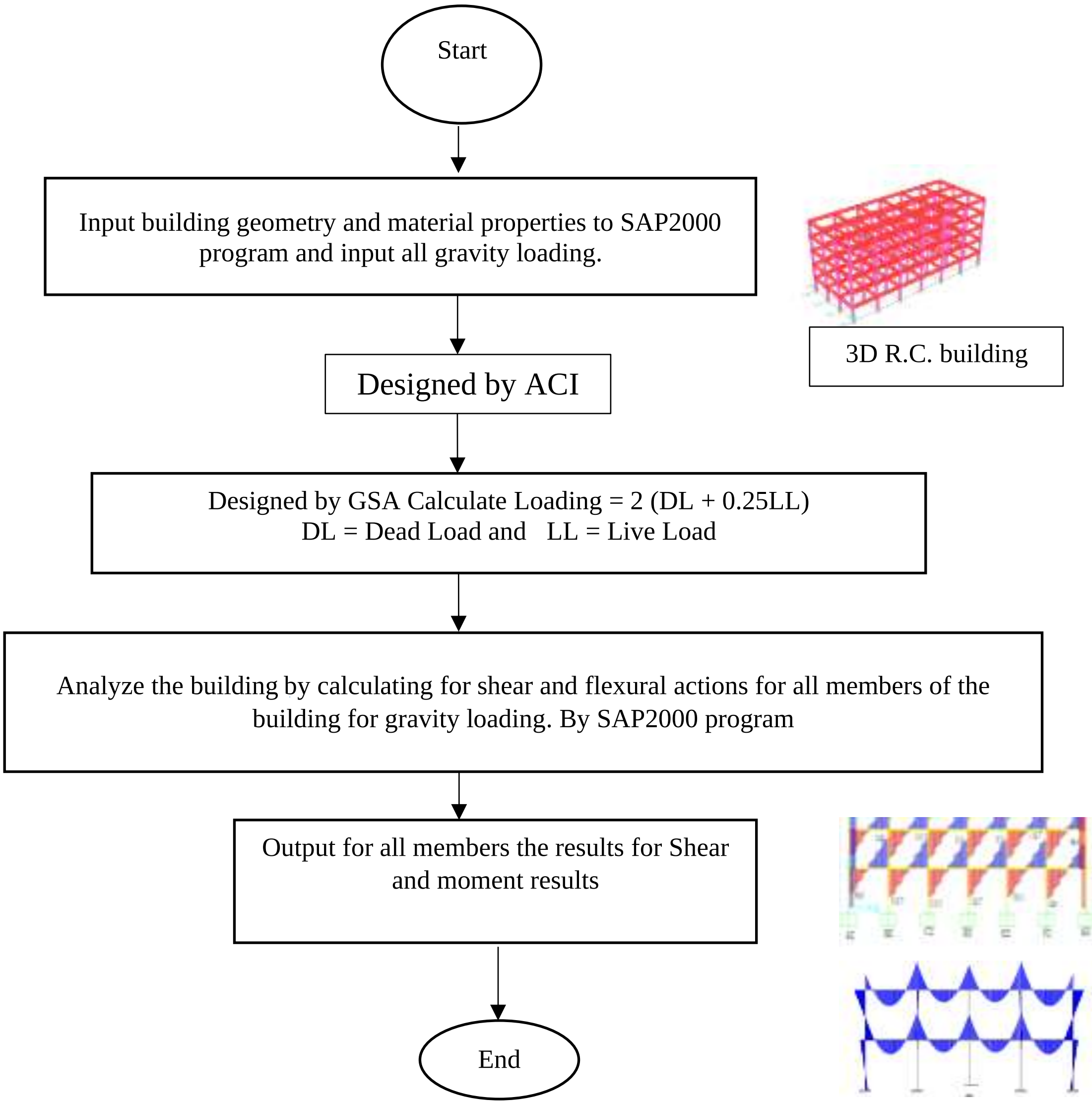

Figure (4a) Flow chart showing the steps for the analysis of the building for gravity loading for finding shear and bending results to calculate the capacity of the members of the building for calculating DCR values by using ACI and GSA methods.

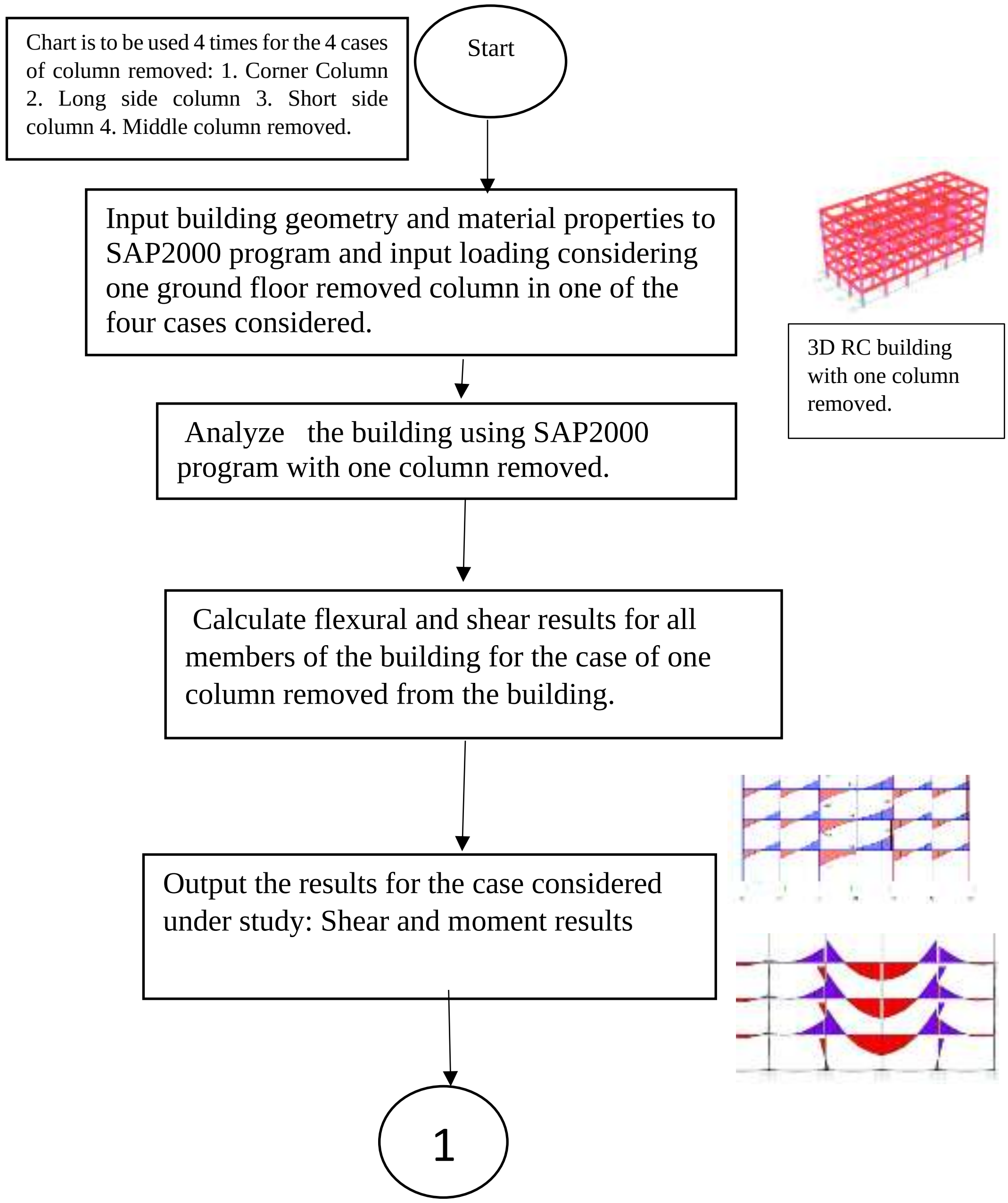

Figure (4b) Flow chart showing the steps for the analysis of the building when removing a corner column or a side column along long and short direction or a middle column in the building for calculating the demand of the members in each case of removing a column scenario value by using GSA method**.**

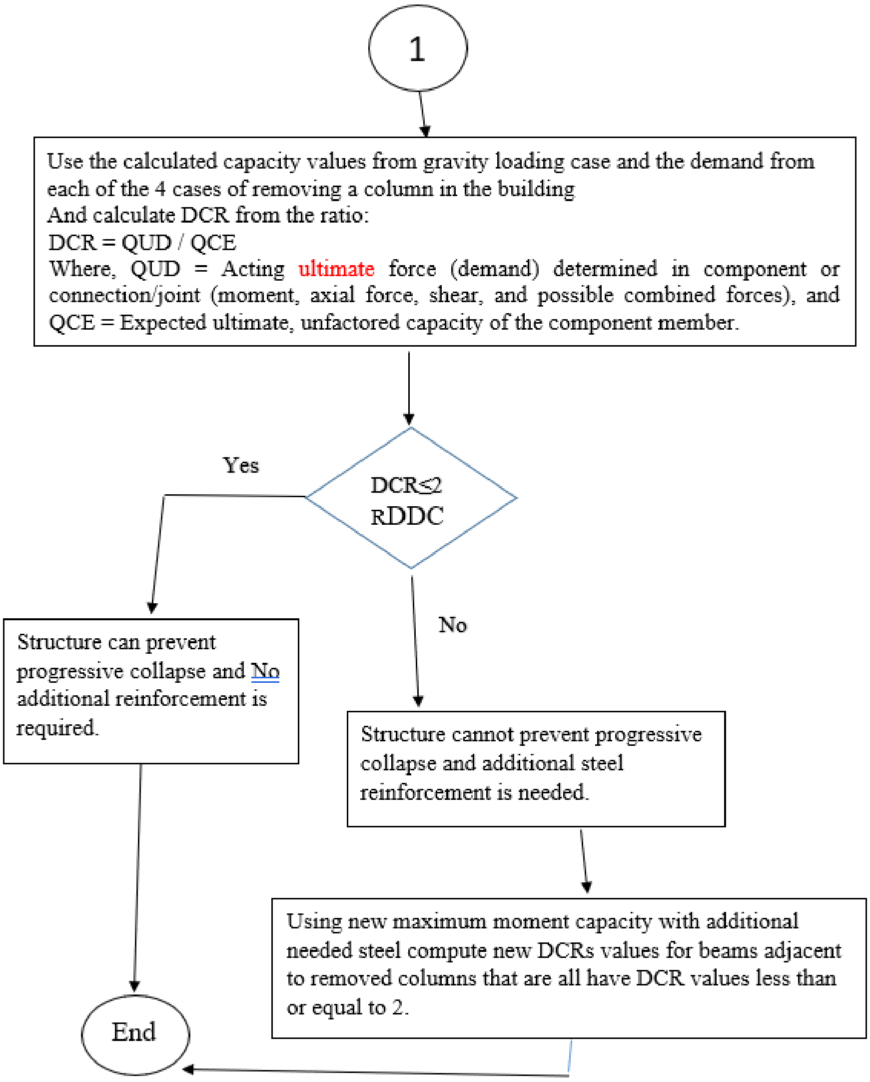

Figure (4c) Flow chart showing the steps for the determination of the DCR values necessary for checking all the cases of removing a column in the building to find out if the building reached the GSA limit for consideration of progressive collapse using the alternate load path.

- **Analysis by Using the Tie Force Method**

This method is based on tying the members of the building using horizontal and vertical ties by adding steel reinforcement. Floor horizontal ties are expected to be used for supporting columns load above the missing column in the building. Figure (5) shows the needed horizontal and vertical ties in the structure [8,9]. Tie Forces are used for the whole structure and Enhanced Local Resistance for the corner and penultimate columns. The importance of progressive collapse as a major concern has led to addition of explicit requirements regarding the redundancy of the structures in seismic codes throughout the world, Application of this concept is to be made for a building when a single column is removed and the floor starts to collapse, the catenary action of the cable prevents the collapse and transfers the load of the floor to neighboring columns and rest of the structures. Since cables are used in every floor, the loads of all floors above the removed column will be transferred to the adjacent columns.

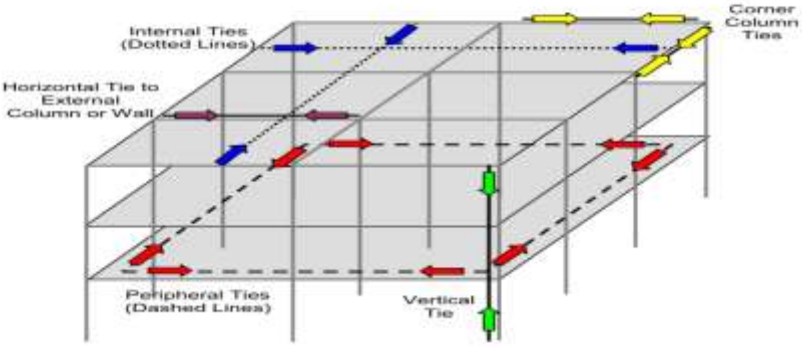

Figure (5) Tie forces in a frame structure for Accidental Actions [9].

In the theory of catenary action, it is assumed that vertical load is carried by the plastic moment and the axial force of a horizontal member after significant deflection of the member, see Figure (6).

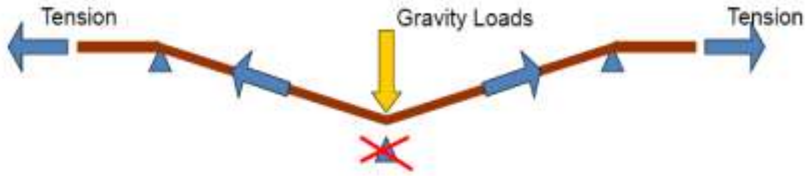

Figure (6) Catenary action [9].

- **Longitudinal and Transverse ties**

The required transverse and longitudinal tie resistance provision is made

through the use of floor and roof system [10].

The Tie Strength Fi in kN/m required in the transverse of longitudinal direction is:

Fi= 3 WF L1……………..………………..…………………………………Eq (3)

Where: WF = Floor load is determined by (1.2D+0.5L) in kN/m^2 and

L1 = Greater of the distances between the centers of the columns.

- **Peripheral ties:**

The peripheral ties are placed within one meter of the edge of a floor or roof and hence, the required development or anchor at corners, re-entrant corners or construction changes is provided.

Fp (in kN), the required peripheral tie strength, is calculated as

Fp = 6 (WF) L. Lp……………….………………………………………… Eq (4)

Where: WF = Floor load, determined per (1.2DL + 0.5LL) in kN / m^2,

L1 = Greater of the distances between the centers of the columns, and Lp = 0.91m

Results and discussion

Three methods of design will be presented here. namely ACI, GSA and UFC methods comparison between these methods with respect to the factor of safety also is presented here, Choosing reinforced building model subjected to collapse load phenomena be design by these methods and analyzed by using SAP2000V20 is given also in this part.

- **The Comparative Study ACI Method Versus GSA And UFC Methods.**

The factor of safety (F.O.S) to any method of design is defined as the ration of factor load to unfactor load.

A- ACI (American concrete institute) method

Referring to Figure (7) which representing the relation between the F.O.S and (LL\DL) for three methods one can conclude from these curves the method UFC is giving the lower bound of the F.O.S and GSA give the upper bound of F.O.S up to (LL\DL) = 0.727 (this is the point of intersection of F.O.S of ACI with F.O.S of GSA).

The rest of the relation are given in APPENDEX A

After this point (LL\DL) = 0.727, the ACI method representing the upper bound of F.O.S.

It should note from the graph that UFC method (F.O.S) when LL\DL = 0 is considers with ACI F.O.S method, the UFC method (F.O.S) when LL\DL become large is considers with GSA F.O.S method.

The rest of the relation are given in APPENDEX A Table (A-1),(B-2) and Figure (A),(B).

$$F.O.S = \frac{(1.2\ DL + 1.6LL)}{(DL + LL)} \quad \text{Eq(5)}$$

Divide Eq (5) by DL

$$F.O.S\ \frac{(1.2 + (1.6LL\backslash DL))}{(1 + (LL\backslash DL))} \quad \text{Eq(6)}$$

If live load is taken zero which practical impossible the F.O.S = 1.2

And also, if (live load \ Dead load) is taken 1000 (which also un practical value) substitute in Eq (6) lead to F.O.S = 1.6

Which means that F.O.S of ACI is between [1.2-1.6]

B- GSA (General Services Administration) method

$$F.O.S = \frac{(2\ DL + 0.5LL)}{(DL + LL)} \quad \text{Eq(7)}$$

Divide Eq (2.3) by DL

$$F.O.S = \frac{(2 + (0.5LL\backslash DL))}{(1 + (LL\backslash DL))} \quad \text{Eq(8)}$$

If we assume there is no live load than the F.O.S = 2.
And if live load is taken 1000 then the F.O.S is 0.50, so a F.O.S of GSA is confined between [2 - 0.5].

C- UFC (Unified Building Criteria) method

$$F.O.S = \frac{(1.2DL + 0.5LL)}{(DL + LL)} \quad \text{Eq (9)}$$

Divide by dead load (DL) Eq (9) will lead to

$$F.O.S = \frac{(1.2 + (0.5LL\backslash DL))}{(1 + (LL\backslash DL))}$$

If live load is taken zero then
F.O.S = 1.2

If live load is taken 1000 the F.O.S will be 0.50, so F.O.S of UFC method is between [1.2 - 0.50].

D- Compression between these methods with respect to (F.O.S)

Referring to Figure (7) which representing the relation between the F.O.S and (LL\DL) for three methods one can conclude from these curves the method UFC is giving the lower bound of the F.O.S and GSA give the upper bound of F.O.S up to (LL\DL) = 0.727 (this is the point of intersection of F.O.S of ACI with F.O.S of GSA).

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The rest of the relation are given in APPENDEX A Table (A-1)(B-1) and figure (A) , (B).

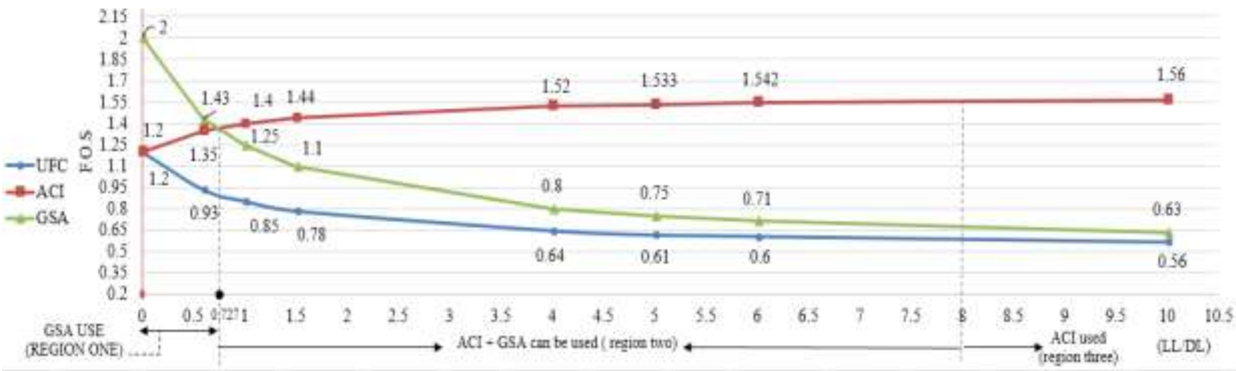

Figure (7) the relation between F.O.S and (LL\DL) for ACI, GSA and UFC methods.

- **BUILDIND MODEL**

The building is consisted from six bayes in x direction and three bayes in y direction, the total length in x direction is A, and total length in y direction is B. The panel length in x direction and y direction are La and Lb respectively as shown in figure (8). The model is designed first by using ACI code and subjected to arbitrary gravity dead and live load with load combination = 1.2DL + 1.6 LL only and the panel dimension was taken 4*5 m2. The results of design are given in following table (1) and illustrated in the following figure and steel details given by Figure (9)

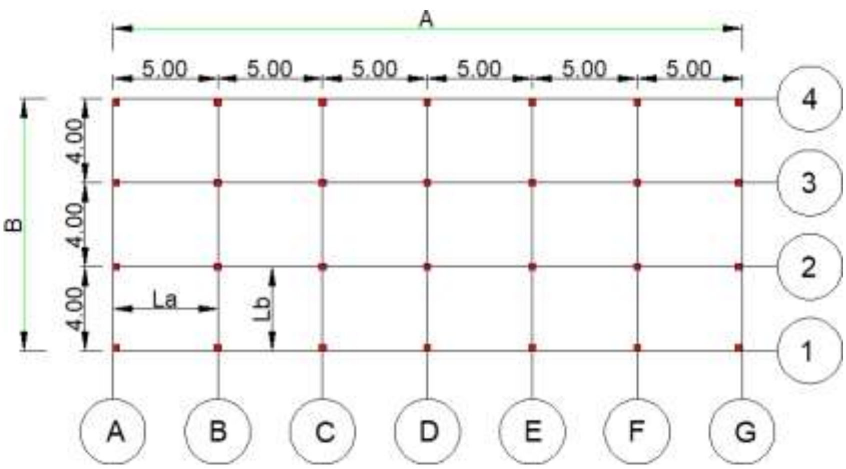

Figure (8) Plan of the R. C. Building Model.

Table (1) output parameters of the 5 Story model and Column sectional and steel details**.**

Materials	Concrete compression resistance Reinforcing yield stress			fc'=35 MPa fy= 500 MPa	Reinforcement (mm)	
Dimensions	Column			400 x 400 mm2	8ø18	
	Beams			400 x 600 mm2	8ø14	
	walls width			d = 200 mm	/	
	Floor slabs			t = 150 mm	/	
Identification	**B mm**	**D mm**	**Cover mm**	**Main steel**	**Diameter of ties mm**	**Spacing of ties mm**
Column	400	400	40	8ø18	8	300

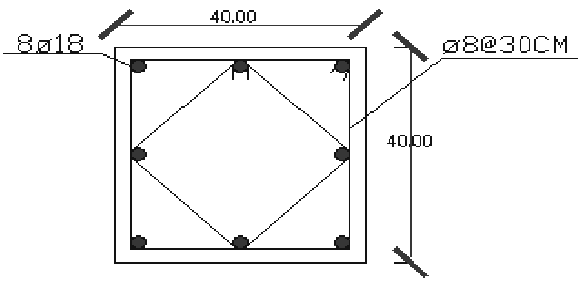

Figure (9) Column sectional and steel details**.**

- **Development of Upper Bound Design Curve Containing These Three Methods.**

From curve in figure (7) one can see that the tie force method give the lower bound demand curve and has no intersection to the other curves., The GSA design method give the upper bound for design from zero (LL\DL) up to (LL\DL) = 0.727, where the ACI give the upper bound for design starting from (LL\DL) = 0.727 up to ∞. In order to develop the common design curve, one has to study the two methods ACI and GSA methods, by using the same building model and at each value point of ((LL\DL). The building was analysis and design by both methods, then the factor of safety of ACI was increased to be higher than the F.O.S of GSA, then the building was checked again for demand stability index for both direction x and y. This process was repeated until the building is reached its stability state after removing the critical column and the result is shown in Figure (10) and tables(2), (3) It was observed from the result the DCRy greater than DCRx as shown in figure (11) that because the rigidity of the building in y direction is less than in x direction.

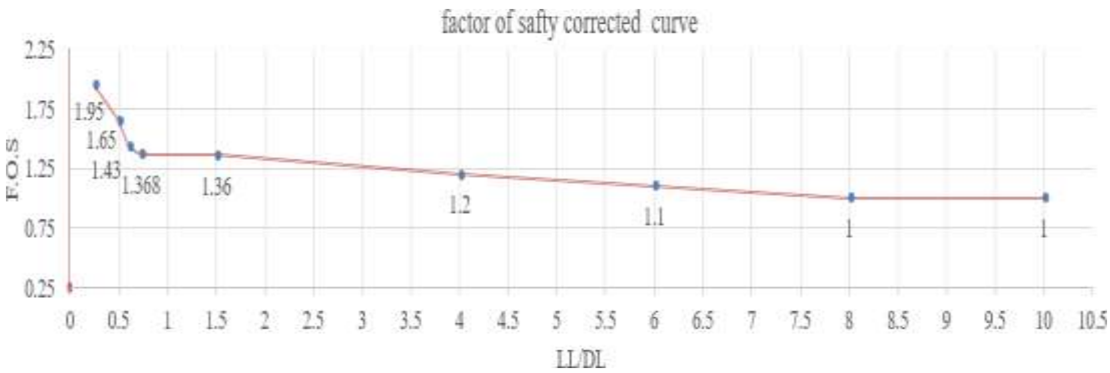

Figure (10) safety curve for using ACI.

Table (2) DCR Values for flexure in y and x direction before removing the column

(LL\DL)	LOAD COM. (ACI)	LOAD COM. (GSA)	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.7 (1.2D+1.6L)	2DL+0.5LL	156.35	326.87	350.08	2.09	2.23
0.50	1.5 (1.2D+1.6L)	2DL+0.5LL	175.4	348.53	372.5	1.98	2.12
0.60	1.43 (1.2D+1.6L)	2DL+0.5LL	196.78	368.6	392.6	1.87	1.99
0.727	1.368 (1.2D+1.6L)	2DL+0.5LL	219.56	387.9	411.9	1.76	1.87
1.50	1(1.2D+1.6L)	2DL+0.5LL	122.5	324.9	348.8	2.65	2.84
4	1(1.2D+1.6L)	2DL+0.5LL	153.2	322.8	346.8	2.10	2.26
6	1(1.2D+1.6L)	2DL+0.5LL	160.15	318.9	342.9	1.99	2.14
8	1(1.2D+1.6L)	2DL+0.5LL	169.2	318.9	342.9	1.88	2.00
10	1(1.2D+1.6L)	2DL+0.5LL	191.05	326.08	350.03	1.706	1.83

Table (3) DCR Values in y and x direction for case after removing column A1 and using the corrected F.O.S

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	179.35	326.87	350.08	1.82	1.95
0.50	1.65(1.2D+1.6L)	2DL+0.5LL	193	348.53	372.5	1.80	1.93
0.60	1.43(1.2D+1.6L)	2DL+0.5LL	196.78	368.6	392.6	1.87	1.99
0.727	1.368(1.2D+1.6L)	2DL+0.5LL	219.56	387.9	411.9	1.76	1.87
1.50	1.36 (1.2D+1.6L)	2DL+0.5LL	167.22	324.9	348.8	1.94	2.08
4	1.2(1.2D+1.6L)	2DL+0.5LL	183.7	322.8	346.8	1.75	1.88
6	1.1(1.2D+1.6L)	2DL+0.5LL	176.11	318.9	342.9	1.81	1.94
8	1(1.2D+1.6L)	2DL+0.5LL	169.2	318.9	342.9	1.88	2.00
10	1(1.2D+1.6L)	2DL+0.5LL	191.05	326.08	350.03	1.706	1.83

SEE APPENDEX B

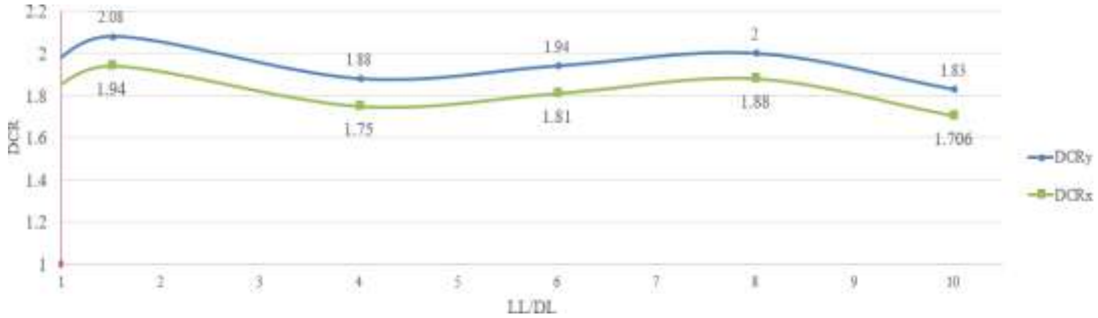

Figure (11) DCRs values carve in x and y directions (table 2.3)

In order to develop the general design curve, for all values of (LL\DL) the curve shown figure (10) was modified as shown in figure (12)

Figure (12) modified ACI design curve to overcome GSA and UFC methods.

The multiple values of ά, β, γ shown in this curve are taken as

$$\acute{\alpha}= 2.255 -1.22(\frac{LL}{DL})$$

$$\beta= 1.4 – 0.05 (\frac{LL}{DL})$$

$$\gamma = 1$$

This new multiple load design curve can be use by design engineer to product the ACI gravity multiple load factors in order the building will be capable to resist the progressive collapse phenomenon and no need to design the building by using GSA or UFC methods.

The application of using this curve in the design is as follow:
The ratio of live to dead load for the design building should be assumed say (LL\DL) = 0.5 then the region of design is known (region one)

ά = 2.255-1.22(0.5) = 1.645

The ACI gravity design factor is 1.645 (1.2DL+1.6LL) = (1.974DL+2.632LL)
Which means the ACI loads factor has be increased 64.5% in order to avoid progressive collapse for the design this building.

- **Application of The Development of ACI Modified Load Design**

  To factors will be studied:

  a- The effect of the off-set of the column on the stability of the building when it is exposed to progressive collapse loads.

  b- The effect of the changing the panel dimension on the stability of the building.

  These two factors where studied by using modified ACI design curve and check by using GSA method.

a- The effect of the off-set of the column on the stability of the building.

This was studied by finding DCR for the critical columns (corner and middle column) in both direction (x, y) for each value of (LL\DL).

The results indicate that the building was stable in x&y direction up to maximum off-set of the column 10% of the total panel span length in the same direction, shown figure (13)

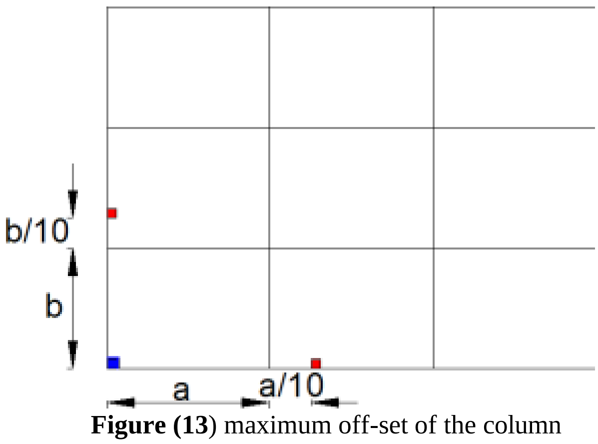

Figure (13) maximum off-set of the column

b- The effect of changing the panel dimension

when the panel dimension is increased in both direction then the collapse area for removed column will increase, the probability of the progressive collapse of the building will also increase many previous researchers have different views for assessment of the damage with respect to the cause , the disproportionate damage with respect of the panel dimension is addressed in this study by using the (LL\DL) ratio equal to 0.25 and choosing the panel dimension (a\b) =1 , (5*5, 6*6 7*7) m2 , and stability of the most critical columns (corner and middle) are studied by calculating DCR in both directions, the results are given in table (4)

Table (4) DCRs Values in y and x direction

(LL\DL)	SPAN (m2)	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY	Aa(mm2) ACI	Aa(mm2) GSA	(%) INCREAE RATIO
0.25	5*5	217.6	421.15	423.3	1.93	1.94	820	930	13.4
	6*6	362	668.07	671.09	1.84	1.85	1420	1590	11.97
	7*7	548	997.6	1001.4	1.82	1.82	2221	2498	12.4

It's clear from these result that the maximum panel dimension can be used without changing the proposed load factor is (5*5) m2 which has the maximum collapse area., The collapse area calculated as circle the collapse area = 66.7m2 when consider as parabolic formula78.54≈80 m2 for interior column and for exterior column the collapse area 19.6m2 and collapse area is equal 16.8m2 when consider as parabolic as illustrated in figure (14)

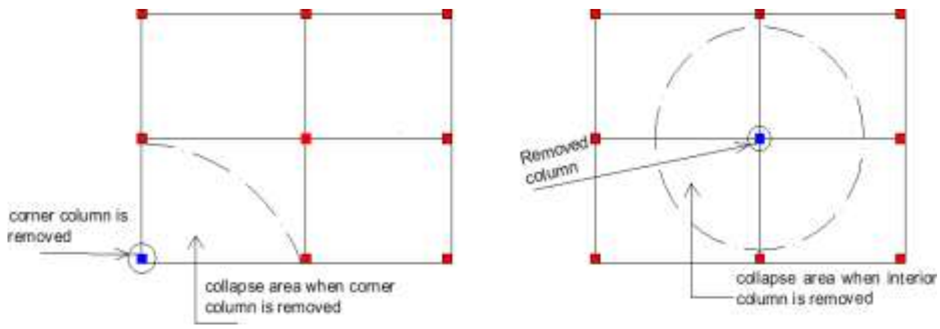

Figure (14) maximum allowable collapse area

The average collapse areas are 72m2 and 18m2 for interior and corner column respectively. The comparison of the reached collapse area with these given in the international codes (is given in table (5) and in found in good agreement in most of international standard maximum limits.

Table (5) the maximum collapse area in various standard

Code	Maximum area
EURO CODE	100 m2
UK Regulation	70 m2
U.S(DOD)	(70 ≈ 140) m2
U.S GSA	(170 ≈ 330) m2
Canadian Regulation	One bay
In this study	72 m2

If the factor of safety of ACI (proposed one) is increased up to 2.2, which means the load combination of ACI will be U = 2.64DL+3.52LL.

The design of the building by using this load combination and panel dimension (6*6, 7*7) m2 , will lead to an average maximum collapse areas 142 m2 & 36 m2 for interior & corner columns respectively, the found result is given in table (4), so the recommended panel dimension is (5*5) m2 which will lead to economical and safe building. As an example of checking the accuracy of the developed ACI – design curve.

F.O.S measurement on design curve which meet (LL\DL) = 2.5, for check by:

β= 1.4 – 0.05(LL\DL)

β= 1.4 – 0.05(2.5) = 1..275 =1.28 see figure (15)

Figure (15) modified ACI design curve to overcome GSA and UFC methods

Conclusion

The objective of this research divided in two phases to answer some main equations, which were raised from extensive literature review given in this thesis.

The first phase of this study is to investigate the effect of factor of safety of the proposed methods of design, and to identify which method of design should be used and its range of applicability.

The second phase of this study was to evaluate the effect of off-set of columns, and the effect of changing the span length in both direction on stability of the building when it is subjected to progressive collapse load.

1. SUMMARY

1.1. PHASE 1

The focus of this research presented in this phase was to investigate whether the ACI design method can be used to design the reinforced concrete building to resist the progressive collapse load without redesigned by using GSA method or tie force method. In this phase of research, studies where conducted in two stages where each stage was divided in to several tasks, each of which has been this covered in detail in scope of work of this thesis.

1.1.1. Stage One

This stage defined, the factor of safety of each method of design and analysis in an attempt to identified parameter that may lead to identify the efficiency of each method.

Task 1

In this task, the range of applicability of each method in the design was studied. The found results indicated that the GSA method is suitable to be applied in the design when (LL\DL) ≤ 0.727, and ACI is most suitable method in design when (LL\DL) ≥ 8

Task 2

As result of the task1 suggests that the general design curve can be reached, by increasing the factor of safety of ACI in the region, where GSA has factor of safety greater than ACI, and the final curve is reached and divided into three regions.

Region one is which represent by the equation 2.25-1.22(LL/DL), while the region two which has equation 1.404 – 0.05(LL/DL), and finally the third region is doment by ACI method and the equation is straight line parallel to (LL\DL) axis.

1.1.2. Stage Two

In this stage the investigating of factors which effecting the accuracy of each method of design is presented in these tasks.

Task 1

The effect of off-set of the column in both directions were studied in this task. The results indicated the maximum off-set of the column should not be more than 10% of span in both directions.

Task 2

In this task the maximum allowable collapse area or the maximum span length in both direction x and y was investigated and the results indicated when instantaneously removed vertical member in the floor, the maximum area allowable to keep the system of building safe from progressive collapse is 72 m2.

2. OVER ALL CONCLUSIONS FORM THIS RESEARCH

Based on the present study of progressive collapse with the application on symmetrical reinforced concrete buildings of different spans and heights using an advanced computer program of SAP2000 the following main conclusions can be introduced:

1. The present subject matter is of prime importance to safe guard reinforced concrete buildings against progressive collapse. Engineers should be concerned with this aspect and should be aware with including this effect in their future design and building rehabilitation of existing structures. Codes of practice are available now for this consideration.
2. Three regions of design where reached the region one and three were partly doment by GSA & ACI respectively.
3. The modified ACI load factor was developed which can be used to calculate the multiple load factor to the gravity load factor given by ACI, when live load to dead load is known, then any building can be safety designed by using the new ACI load factor, and no need to design the building by using GSA method of Tie Force Method.
4. The effect of off-set of the columns were also studied in both directions, and the result indicated that the maximum allowable off-set of the column is 10% of the span length in both direction x and y.
5. The maximum span length or the maximum area to be carried by the column in progressive collapse load was about 72 m2 for the removed column, this value was very close to those values given by international standard.
6. The alternate load path method has the advantage of finding the needed amount of steel to satisfy the progressive collapse requirements by finding the DCR values and using the GSA limits while the tie force method has no such facility.
7. The tie force method requires less work as compared to the five computer runs required in the alternate load path method for finding the moment and shear capacities of the building and the moment and shear in the four column removal cases for the demand so as to determine the DCR values in each case.
8. Since DCR values for shearing force in the present work are less than 2 in all the cases studied, shear reinforcement was considered adequate as it meets the requirements by the GSA criteria in all cases studied.

3. RECOMMENDED FURTHRE RESEARCH TOPICS

For future work in this aspect of research on progressive collapse analysis and design the following points of interest may be recommended:

1. The present work is dealing with symmetrical reinforced concrete buildings which constitutes most of the reinforced concrete buildings but it may of interest to study unsymmetrical buildings which are of interest in some cases like the cases of asymmetrical reinforced concrete buildings.
2. The present study is mainly concerned with the effect of progressive collapse on reinforced concrete buildings located in areas not affected by wind or seismic activity but future work may regard other locations where such dynamic effects may be needed in combination with progressive collapse effects as in areas of windy and seismic sites.
3. Experimental work on laboratory models that represent symmetrical and asymmetrical buildings that may be subjected to progressive collapse is of interest as a means of following and justifying the GSA provisions. The research work may be done in the laboratory for assigned stages of the alternate load path method. Cases of using gravity loading alone or with combination with any lateral loading subjected to the models and stages of gravity loading with all building columns present or stages of losing a column at the corner or at each of the two sides or middle column of the building. The results will be of great interest in knowing the behavior of such models under these conditions of different loading and in case of comparison with analytical work. Beam and slab reinforcements effect may be added to the models to find out how this will enhance the response of these models when losing a ground floor column in the assigned locations specified by the GSA provisions and mentioned above.
4. Investigation of the failure of a column or columns on floors other than the ground floor, for example in the

story of the middle levels and under the ceiling may be studied although they are not required by the present GSA or UFC provisions.

5. More investigation is needed for different values of (a\b) and different building system (flat slab, flat plat …etc

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Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that they have no conflict of interest.

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APPINDEX A

The factor of safety (F.O.S) Between ACI and GSA will be found and compared with the live load on the dead load, it was calculated through Eq 1 and Eq 2, and then drew curve between them as shown in figure(A) will be found. shown table that in (A-1).

ACI code =1.2DL+1.6LL

Factor of safety ACI code = $\frac{1.2+1.6(LL\backslash DL)}{1+(LL\backslash DL)}$ …………………………………. Eq (1)

GSA code = 2(DL+0.25LL)

Factor of safety GSA = $\frac{2 + 0.5(LL\backslash DL)}{1+(LL\backslash DL)}$…………………………………........... Eq (2)

The overlap point was found and found when the live load on the dead load (LL\DL) = 0.727, and the factor of safety (F.O.S) was = 1.36 shown in the following relationship:

Over lab point:

$$\frac{1.2+1.6(LL\backslash DL)}{1+(LL\backslash DL)} = \frac{2+0.5\ (LL\backslash DL)}{1+(LL\backslash DL)}$$

1.1 (LL\DL) = 0.80
(LL\DL) = 0.727

The factor of safety (F.O.S) between ACI and UFC will be found and compared with the live load on the dead load, it was calculated through Eq 3 and Eq 4, shown table shows that (B-1) and then drew curve between them as shown in chart (B) and after that found curves between ACI, GSA and UFC as shown in figure (C)

ACI code =1.2DL+1.6LL

- Factor of safety ACI code = $\frac{1.2+1.6(LL\backslash DL)}{1+(LL\backslash DL)}$…………………………………………Eq (3)

UFC code = 2(DL+0.25LL)

- Factor of safety UFC = $\frac{1.2 + 0.5(LL\backslash DL)}{1+(LL\backslash DL)}$…………………………………….……… Eq (4)

Table (A-1) F.O.S for ACI and GSA

(LL\DL)	F.O.S ACI	F.O.S GSA
0	1.20	2
0.25	1.28	1.70
0.50	1.33	1.5
0.727	1.368	1.368
0.75	1.37	1.35
1	1.40	1.25
1.25	1.42	1.16
1.50	1.44	1.10
1.75	1.45	0.961
2	1.466	1.00
2.25	1.477	0.961
2.5	1.485	0.928
2.75	1.493	0.9
3.00	1.50	0.87
3.25	1.505	0.852
3.50	1.51	0.83
3.75	1.515	0.815
4	1.52	0.80
4.25	1.523	0.785
4.5	1.527	0.77
4.75	1.53	0.76
5	1.533	0.75

5.25	1.536	0.74
5.50	1.538	0.73
5.75	1.54	0.72
6.00	1.542	0.714
8	1.55	0.66
10	1.563	0.63

Table (B-1) F.O.S for ACI and UFC

(LL\DL)	F.O.S ACI	F.O.S UFC
0	1.20	1.20
0.25	1.28	1.70
0.60	1.35	0.93
1	1.40	0.85
1.50	1.44	0.78
4	1.52	0.64
5	1.533	0.61
6	1.542	0.60
10	1.56	0.56

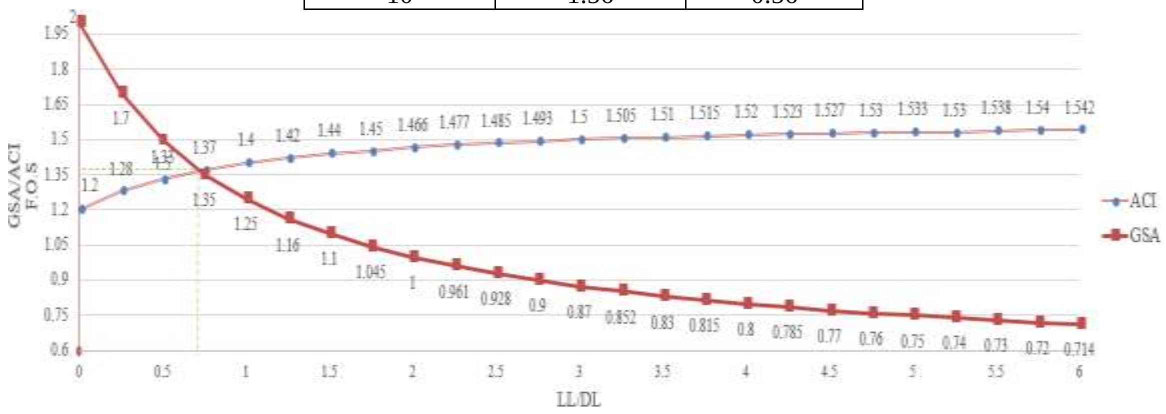


Figure (A) F.O.S values between GSA and ACI

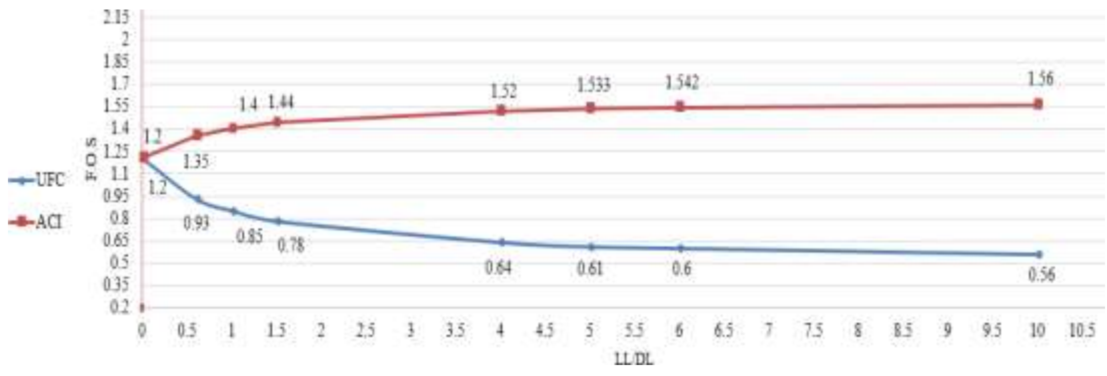


Figure (B) F.O.S values between ACI and UFC

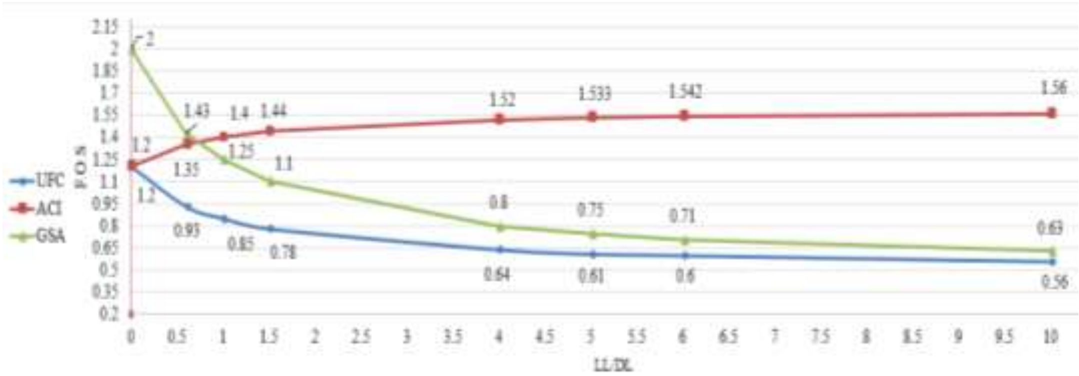


Figure (C) F.O.S values between ACI, GSA and UFC

The DCR values in both directions are within the permissible limits for example take case (LL\DL) = 0.25, as shown in the table 1

Table1 DCR Values in y and x direction for case of removing column D2

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	179.35	297.69	340.4	1.65	1.89

For Analysis by Using the Tie Force Method the required tie strength results are determined from WF = 1.2DL + 0.5LL and the data for tie force calculations and take many cases of (LL\DL) and the resulting reinforcement are summarized are given in table 2

Table (2) Tie Forces results for the five stories R. C. building for ratio (LL\DL) cases

(LL\DL)	Tie type	Location	Length m	Wf, kN/m²	F KN/m	As req, mm²/m
0.25	Longitudinal long /L	Distributed	5.00	9.62	145.8	311
	Transverse short /L	Distributed	4.00	9.62	116.6	248
	Tie type	**Location**	**Length m**	**wF, kN/m²**	**FKN**	**As req, mm²**
	Peripheral	Longitudinal	5.00	9.62	265.3	566
	Peripheral	Transverse	4.00	9.62	212.2	452.8
(LL\DL)	**Tie type**	**Location**	**Length m**	**Wf, kN/m²**	**F KN/m**	**As req, mm²/m**
0.6	Longitudinal long length	Distributed	5.00	13.32	199.8	426.2
	Transverse short length	Distributed	4.00	13.32	159.84	341
	Tie type	**Location**	**Length m**	**wF, kN/m²**	**FKN**	**As req, mm²**
	Peripheral	Longitudinal	5.00	13.32	363.6	775.7
	Peripheral	Transverse	4.00	13.32	290.9	620.6
(LL\DL)	**Tie type**	**Location**	**Length m**	**Wf, kN/m²**	**F KN/m**	**As req, mm²/m**
1.50	Longitudinal long length	Distributed	5.00	10.17	152.5	325.3
	Transverse short length	Distributed	4.00	10.17	122	260.3
	Tie type	**Location**	**Length m**	**wF, kN/m²**	**FKN**	**As req, mm²**
	Peripheral	Longitudinal	5.00	10.17	277.6	592.3
	Peripheral	Transverse	4.00	10.17	222.1	473.8

(LL\DL)	Tie type	Location	Length m	Wf, kN/m^2	F KN/m	As req, mm^2/m
4	Longitudinal long length	Distributed	5.00	10.72	160.8	343
	Transverse short length	Distributed	4.00	10.72	128.6	274.4
	Tie type	**Location**	**Length m**	**Wf, kN/m^2**	**F KN/m**	**As req, mm^2/m**
	Peripheral	Longitudinal	5.00	10.72	292.6	624.3
	Peripheral	Transverse	4.00	10.72	234.12	499.4
(LL\DL)	**Tie type**	Distributed	**Length m**	**Wf, kN/m^2**	**F KN/m**	**As req, mm^2/m**
6	Longitudinal long length	Distributed	5.00	10.62	159.3	339.8
	Transverse short length	**Location**	4.00	10.62	127.44	271.87
	Tie type	Longitudinal	**Length m**	**Wf, kN/m^2**	**F KN/m**	**As req, mm^2/m**
	Peripheral	Transverse	5.00	10.62	289.9	618.5
	Peripheral	Distributed	4.00	10.62	231.94	494.8

Where : $As(mm2) = \frac{F*10^3}{0.75*(1.25)Fy}$

It is estimated that the weight of additional reinforcement for first floor for 5- story building for use alternate path (AP) and tie force (TF) putted comparative with many cases **(LL\DL)** are given in Table (3). and in Figure (1) explain relation weight of additional reinforcement between them.

A relationship was found the reduction coefficient between the (AP, TF) methods in the additional reinforcement required to prevent progressive collapse and ratio (LL\DL), as shown in Figure (2).

Table (3): comparative of additional reinforcement to prevent progressive collapse between (AP) and (TF).

(LL\DL)	weight of Addisonian reinforcement by A.P (Kg)	weight of Addisonian reinforcement by T.F(Kg)
0.60	251	2554
1.50	279	1956
4	561	2063
6	217	2040

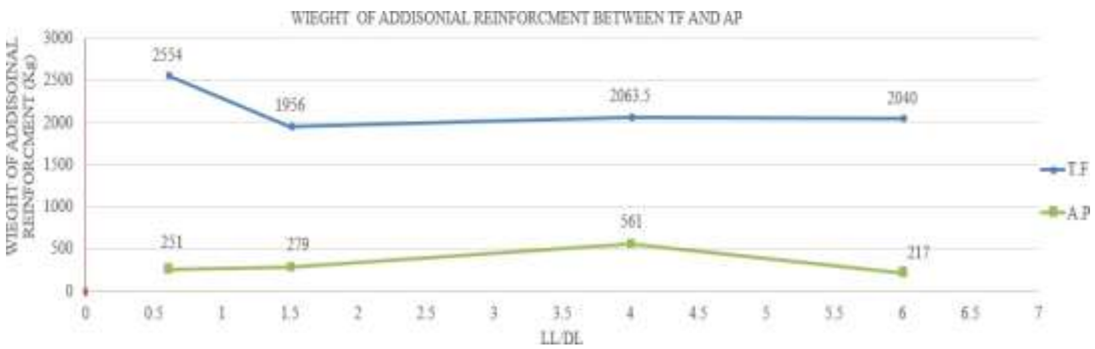


Figure (1) weight of additional reinforcement between TF and AP

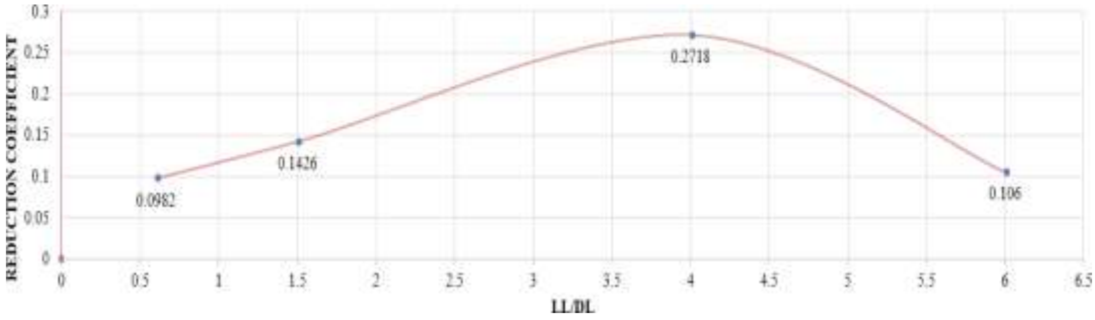


Figure (2) reduction coefficients between the (AP, TF) methods in the additional reinforcement

The model was analysis with La = 5m and Lb = 4m for remove critical corner Colum A1, and it founded the maximum addition in the length of the building in the X and Y direction was 10%, as shown in tables (4),(5) and figure (3) ,(4) below.

Tables (4) DCR Values in y and x direction for case of removing column A1 after additional long direction (La) 10 %

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	218.2	350.6	393.19	1.60	1.80
0.50	1.65 (1.2D+1.6L)	2DL+0.5LL	235.73	374.8	417.95	1.59	1.77
0.727	1.368 (1.2D+1.6L)	2DL+0.5LL	268.7	418.9	462.9	1.56	1.72
1.50	1.36 (1.2D+1.6L)	2DL+0.5LL	203.5	348.4	390.9	1.71	1.86
4	1.2 (1.2D+1.6L)	2DL+0.5LL	225	346.19	388.7	1.53	1.72
6	1.1 (1.2D+1.6L)	2DL+0.5LL	219.5	341.7	384.1	1.55	1.75
8	1(1.2D+1.6L)	2DL+0.5LL	207.2	341.78	384.1	1.65	1.85
9	1(1.2D+1.6L)	2DL+0.5LL	220.66	345.7	388.18	1.56	1.76

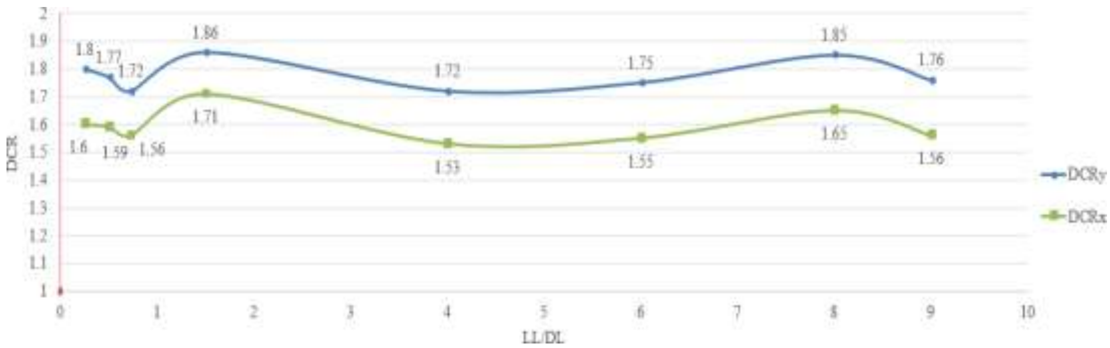


Figure (3) DCRs values carve in x and y directions after add 10% in long direction La

Tables (4)DCR Values in y and x direction for case of removing column A1 after additional short direction (Lb) 10 %

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	183.11	368.91	378.4	2.01	2.06
0.50	1.65 (1.2D+1.6L)	2DL+0.5LL	197.2	393.7	402.8	1.99	2.04
0.727	1.368 (1.2D+1.6L)	2DL+0.5LL	224.5	438.7	447.2	1.95	1.99
1.50	1.36 (1.2D+1.6L)	2DL+0.5LL	175.3	366.6	376.2	2.06	2.09
4	1.2 (1.2D+1.6L)	2DL+0.5LL	188	364.4	374.03	1.93	1.98
6	1.1 (1.2D+1.6L)	2DL+0.5LL	183.4	359.9	369.9	1.96	2.01
8	1.1 (1.2D+1.6L)	2DL+0.5LL	186	359.9	369.5	1.93	1.98
9	1(1.2D+1.6L)	2DL+0.5LL	184.2	363.9	373.5	1.97	2.02

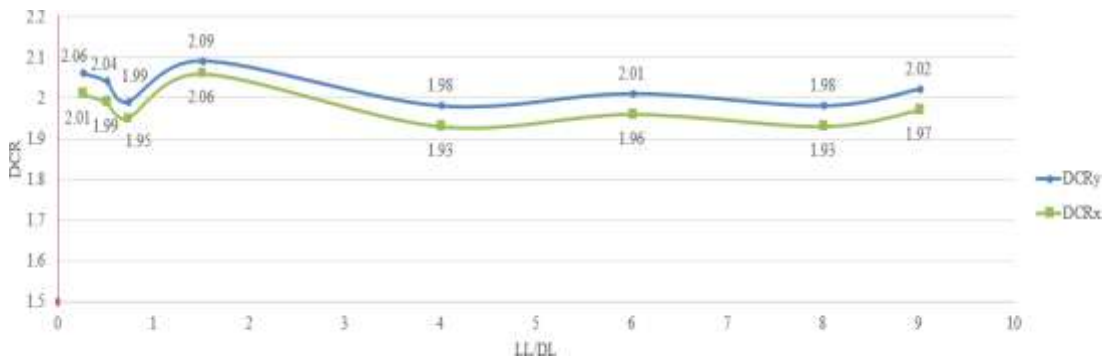


Figure (4) DCRs values carve in x and y directions after add 10% in short direction Lb

THE EFFECTIVE SPANES OF BOTH DIRICTION

In this part we considered (La\Lb)=1 that panel be square , and when studying the corner column removed A1, the DCRs values were in the permissible number shown in table (5) below , but when the critical column removed was the middle D2 The DCRs values were outside the permissible limit, shown in table (6) and therefore here we need to increase the factor of safety until the DCRs values are connected to the permissible limit in both directions.

Table (5) DCR Values in y and x direction for case of removing column A1 after change span in long and short dir. = 6m

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	326	649.7	631.2	1.99	1.93
0.60	1.43 (1.2D+1.6L)	2DL+0.5LL	363.8	746.6	725.4	2.05	1.99
0.727	1.368 (1.2D+1.6L)	2DL+0.5LL	408	791.3	769.04	1.93	1.88
1.50	1.36 (1.2D+1.6L)	2DL+0.5LL	316	645.1	626.8	2.04	1.98
4	1.2 (1.2D+1.6L)	2DL+0.5LL	341.2	640.6	622.3	1.87	1.82

Table (6) DCRs Values in y and x direction for case of removing middle column D2 after change span in long and short dir.=6m

(LL\DL)	LOAD COM. ACI	LOAD COM. GSA	CAPACITY Kn.m	DEMAND IN X DIR	DEMAND IN Y DIR	DCRX	DCRY
0.25	1.95 (1.2D+1.6L)	2DL+0.5LL	326	668.07	671.09	2.04	2.05
0.60	1.43 (1.2D+1.6L)	2DL+0.5LL	363.8	850.17	853.9	2.33	2.34
0.727	1.368 (1.2D+1.6L)	2DL+0.5LL	408	934.3	938.5	2.28	2.3

It is estimated of additional reinforcement for first floor for 5-story building for use ACI and UFC putted comparative with many cases **(LL\DL)** are given in Table (7) below. and in Figure (6) explain relation of additional reinforcement between them.

A relationship was found the reduction coefficient between the (UFC, ACI) in the additional reinforcement required to prevent progressive collapse and ratio (LL\DL), as given in table (8) below and shown in Figure (7).

Table (7): comparative of additional reinforcement to prevent progressive collapse between (UFC) and (ACI).

(LL\DL)	Addisonian reinforcement by ACI (mm2\m)	Addisonian reinforcement by UFC (mm2\m)
0.25	612	559.8
0.727	560	867.9
1.5	612	585.6
6	575	611.6
8	575	623.2

Table (8): Reduction factor coefficient of additional reinforcement to prevent progressive collapse (ACI\UFC).

(LL\DL)	Reduction factor (ACI\UFC)
0.25	**1.09**
0.727	0.64
1.5	1.04
6	0.94
8	0.92

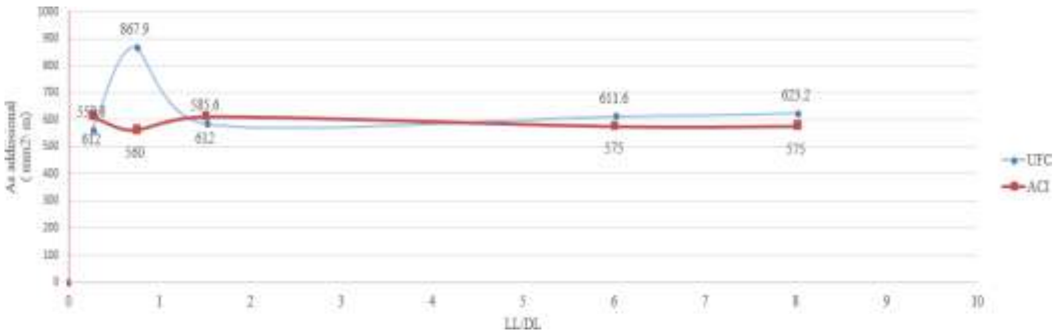


Figure (6) additional reinforcement between UFC and ACI

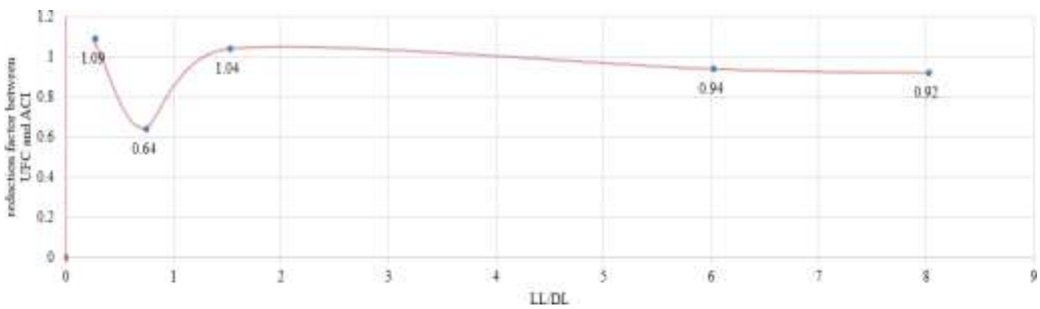


Figure (7) reduction coefficient factor between the (ACI\UFC) in the additional reinforcement

As an example of checking the accuracy of the developed ACI – design curve.

F.O.S measurement on design curve which meet (LL\DL) = 2.5, see figure (8) for check by

β= 1.4 – 0.05(LL\DL)

β= 1.4 – 0.05(2.5) = 1..275

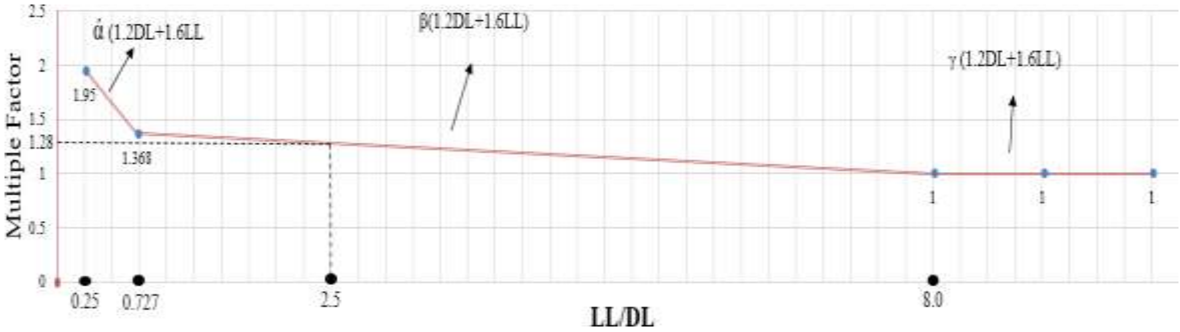
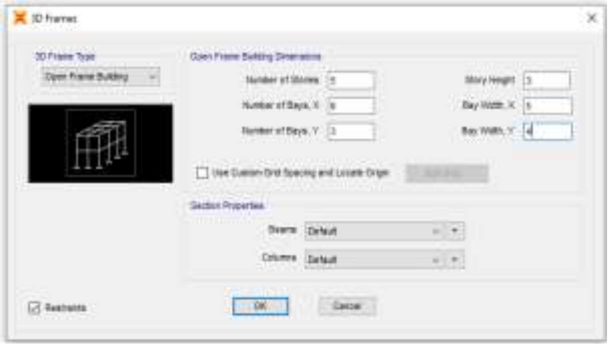


Figure (8) modified ACI design curve to overcome GSA and UFC methods

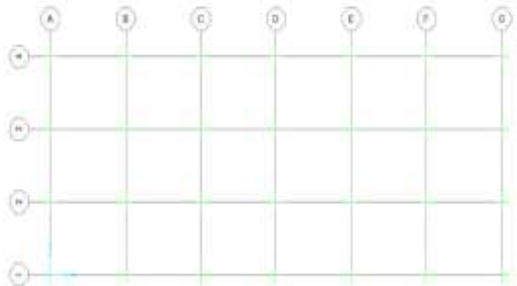
APPENDIX B

Results obtained from SAP2000 software

The geometry of the building is needed for the SAP2000 program and a plan view with marked axes is given :



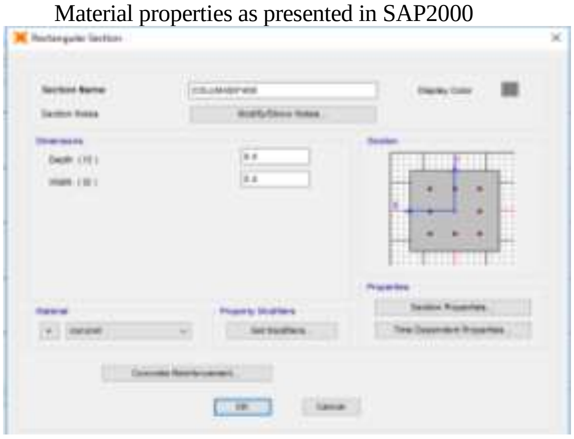
Properties of Building as specified as in SAP2000.



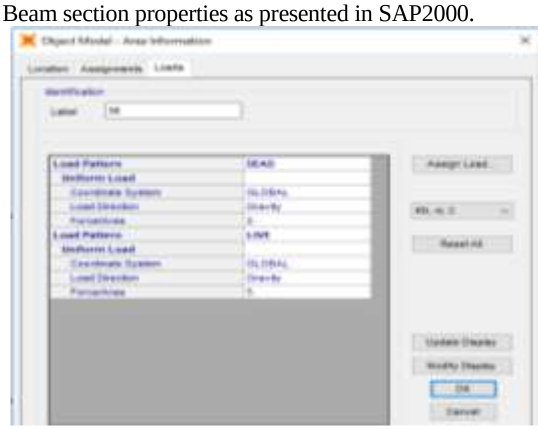
Plan view of the R.C. five story building.

Material properties as presented in SAP2000

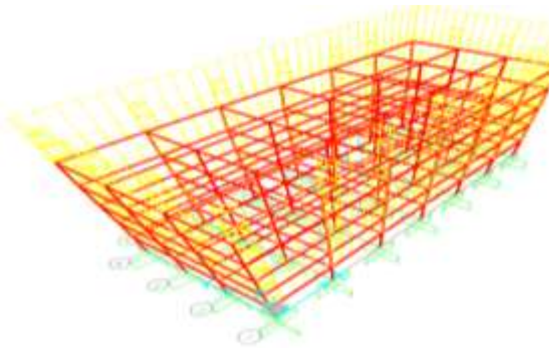
Beam section properties as presented in SAP2000.



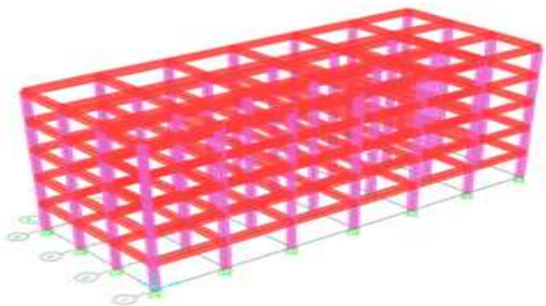
Column section properties as presented in SAP2000.



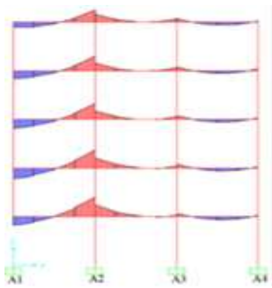
Gravity loading values as presented in SAP2000.



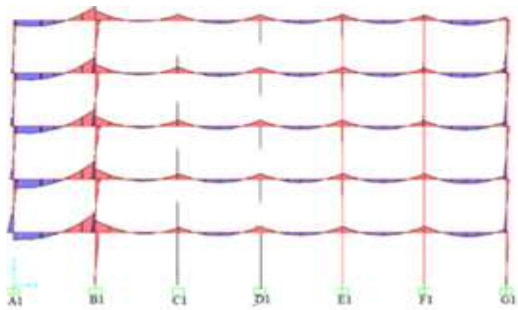
Wall load in 3D dimension of the buildings in SAP2000.



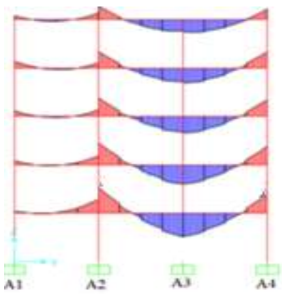
Five Stories 3D R.C. Frame Building.



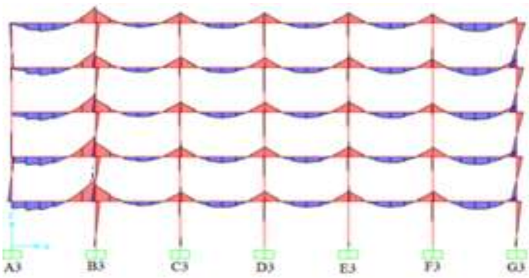
Case of ColumnA1 removal view short direction.



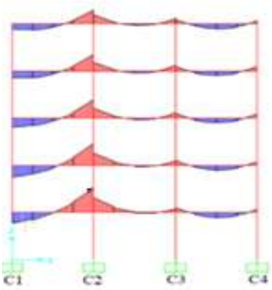
Case of ColumnA1 removal view along direction.



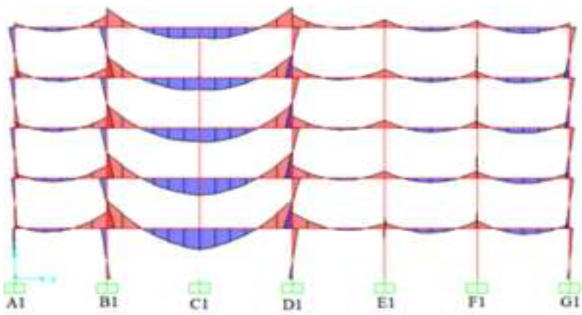
Case of ColumnA3 removal view short direction.



Case of ColumnA3 removal view long direction.



Case of ColumnC1 removal view short direction.



Case of ColumnC1 removal view long direction.

Figure Bending moment due to GSA load combination after removal of columnsA1, A3 an

