ISSN 2229-5518

THE RELIABILITY OF CAPACITY DESIGNED COMPONENTS IN SEISMIC RESISTANT SYSTEMS

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ABSTRACT—After the 1992 devastating earthquake that struck Cairo causing destructive damages ranging from repairable damage to total collapse, significant attention has been paid to evaluate how RC structure perform during and after earthquake. This study investigates the importance of the understanding of the capacity design approach in the design of RC structure building subjected to earthquakes, capacity design principles are recently employed in seismic design codes to help ensure ductile response and energy dissipation in seismic resisting systems using the strong column-weak beam concept. The aim of this study is to create a draft-model code for the Egyptian code on how capacity design can be applied in analysis using the pushover analysis method based on the Performance Based Design procedure. The performance Based Design (PDB) is considered as one of the emerging fields in seismic design which is still in the realm of research and academics. A simple explanation was made for PBD method using the pushover analysis (PA) demonstrating how progressive failure in buildings really occurs, also showing the incapability of the traditional methods in the seismic design, to verdict the behavior of the building during and after earthquake. In this research an example was made through numerical simulations for a 12 storeys height concrete building located in Cairo. The analysis was first performed for the response spectrum analysis to make the design as preliminary level and then Non-linear static analysis (PA) was derived following the ATC procedure to check the building performance, using ETABS 2017.

Index Terms—Earthquake, Energy dissipation, Pushover Analysis, Performance based design, Plastic hinges, performance point, Etabs.

1 INTRODUCTION

The traditional methods of seismic design commonly known in the design a building under earthquake such as Force Based Design (FBD) considered as the preliminary design that deals with the structure in its linear state behavior neglecting the non-linear state that can occur in case of large earthquakes, to make sure that the structural members (i.e., beams and columns) are designed so that the structure can absorb the full impact without collapse beyond its limit state and up to its ductile state. **Force-Based Design (FBD)** (fig.1.1) is based on the traditional force-based design procedure to judge the performance of the structure,

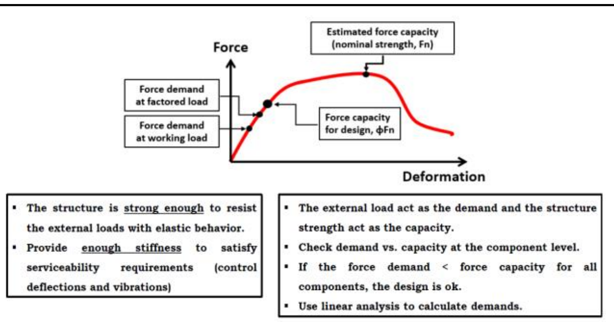

Fig.1.1. Force-Based Design (FBD)

the parameters that matters in this method are strength (to resist the outer loads that affects the building, and Stiffness for serviceability requirements like deformation ad vibrations). In this method we determine a point called "Force capacity "known as the maximum force that the building can resist which depends on nominal strength (Fn), so based on the nominal strength the building capacity is determined, while the Force demand is the actual force that affects the building. If the demand force < reduced force capacity then the design is safe. For large earthquakes with non-linear behavior, **Displacement Based Seismic Design (DBSD)** (Moehle, 1992 and priestley *et al.*, 2007 and Benedetti *et al.*, 2008) (fig.1.2.) method is used, it allows the building to perform large inelastic deformation behavior with specific accepted amount (Deformation capacity), which is determined based on the amount of cracks and inelasticity. If Demand deformation< deformation capacity then the building is safe. This is exactly the method adopted in the response spectrum and equivalent static method, where the only parameter to checked is the storey drift of the building which is so insufficient to judge the behavior of the building. This method had been developed to overcome the disadvantages of the other comparable traditional method especially the FBD.

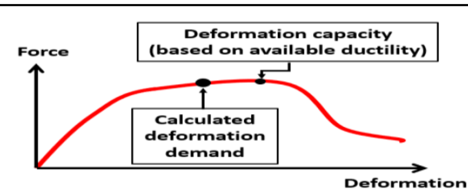

Fig.1.2. Displacement-Based Design.

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While in the event of an earthquake the seismic force resisting system are expected to yield and sustain large inelastic deformation so they can absorb the earthquake's energy and dissipate another part to soften the response of the structure. In order to assure the ductility of the structure we need to provide the plastic mechanism in the structure. Applying the traditional methods mentioned above (FBD and DBSD) on large earthquakes will cause the design of huge uneconomic structural systems to assure the linearity state, so starting from here, it was derived method of design that would help create an economic structure with high ductility level to absorb part of the earthquake and dissipate the rest all over the structure in form of cracks. This approach is called capacity design and is now stated in so many codes through the Performance Based Design using the Pushover analysis to allow the building to perform high deformation and energy dissipation.

Performance Based Design (PBD)(fig.1.3.) was then derived to study the behavior and the performance of the building during and after the effect of earthquake.

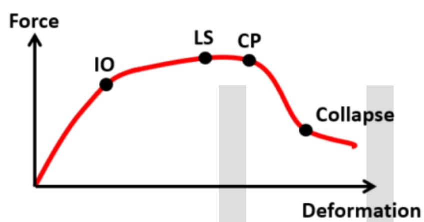

Fig.1.3. Performance Based Design

In this method we do have 3 deformation capacity, each point of these 3 points indicates the performance level of the building (IO-LS-CP) (fig.1.4.)

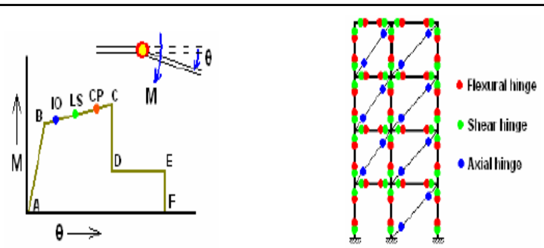

Fig.1.4. Different performance levels of the buildings and formation of plastic hinges

this method is always accompanied by the formation of plastic hinges which reflects the non-elastic behavior of the building and its ability to dissipate the earthquake's energy, the acceptance criteria of these plastic hinges is discussed in details in section 2.

The capacity design approach adopts the concept of strong – weak beam which is based on designing the primary lateral force resisting system for energy dissipation under severe imposed deformation. The critical regions of these members are called plastic hinges that are detailed for inelastic flexural action. While all other structural elements are then protected against failure. In the following example (fig.5a) an admissible plastic hinge mechanism is chosen to sustain the strong column weak beam mechanism, which usually aims to dissipate seismic energy basically in well-confined beam plastic hinge. In the strong column weak beam concept, beams yield first than columns do, therefor columns sway mechanism is avoided in the structure. Fig.1.5 shows a comparison between the behavior of the two frames subjected to the same displacement Δ at the roof level, plastic hinges rotation $\theta 1$ for frame (a) are much smaller than for frame (b) with a rotation of $\theta 2$. Therefor the overall ductility demands in term of the large deflections Δ is way more readily achieved when plastic hinges are applied in all the beams of the building instead of the first floor only.

The formation of the plastic hinges happens when a concrete element is subjected to a long deformation in the post-yield stage and its assumed that the entire deformation takes place at this point, and this formation indicates the ability of the building to dissipate part of the seismic energy that affected the building, its accompanied by the formation of cracks in the weakest parts of the building which represent the connections between the columns and beams as shown in Fig.1.5.

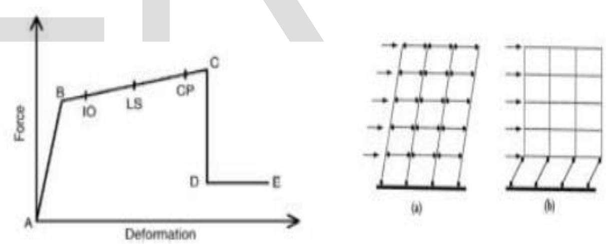

Fig.1.5. Strong column-weak beam mechanism

2 METHODOLOGY

The need of a simple method to predict the non-linear behavior of a structure under large seismic loads has finally seen light in what is now known as Pushover Analysis which

ISSN 2229-5518

helps demonstrate how progressive failure in building occurs. **Pushover analysis** is a non-linear static analysis used to estimate the strength capacity of the structure beyond its elastic limits, it can be performed with guidelines indicated in FEMA356, 440 and ATC40.
This procedure is performed under existing vertical loads (Gravity loads) with gradually increasing assigned lateral loads, Hence, the structural loading magnitude is increased in an incremental order so that the sequence of cracks, yielding, plastic hinges formation and failure modes are detected. It's to be noted that each event and increased applied load the structure loses part of its stiffness. As a result, a plot the roof displacement vs the total base shear of the structure at its center of mass is now obtained to develop the capacity curve of the structure shown in fig.2.1.

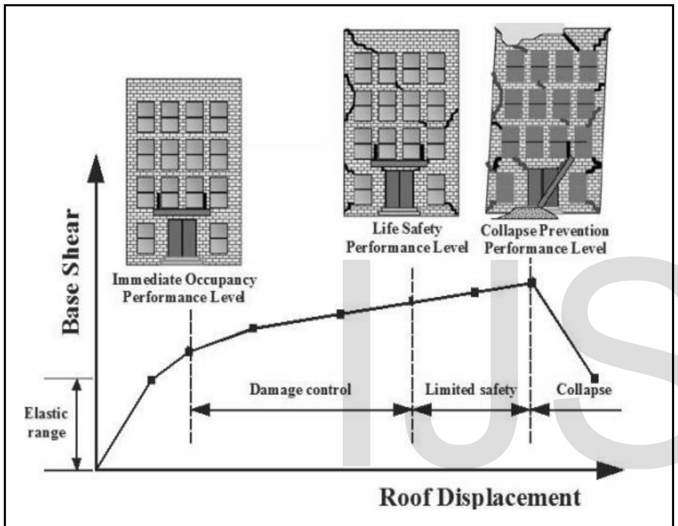

Fig.2.1. Capacity curve with illustration of performance level of the structure

The performance level of the structure is determined after performing a large deformation in the post-yield stage until the formation of plastic hinges used in the PA. Figure 2.2. shows the force deformation behavior in the plastic hinges through five points labelled as following: A, B, C, D and E. Point A represents the origin, B is the yield point, C is the ultimate point while D and E represent the residual displacement capacity and strength. While there are 3 points labelled IO-LS and CP define the acceptance criteria of the plastic hinges as per FEMA and ATC 40.

Immediate Occupancy (IO) is a performance level at which the building performs no damage in the structural elements but few ones in the non-structural elements which can be repaired. Life safety (LS) is a performance level that allows the full damage of non-structural elements with no repair, with few damages in the structural elements that can be repaired as well. Collapse prevention (CP) is the performance level that allows more deformation in the building with more damages in structural without repair but the building will not collapse.

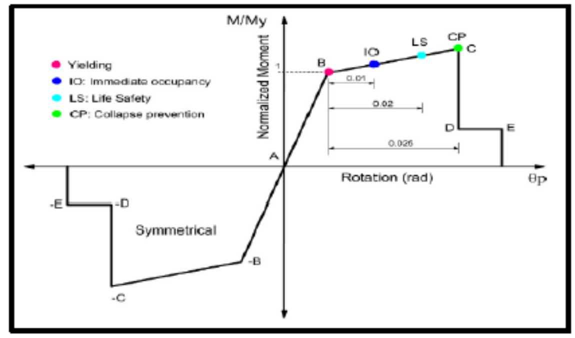

Fig.2.2 Formation of plastic hinges.

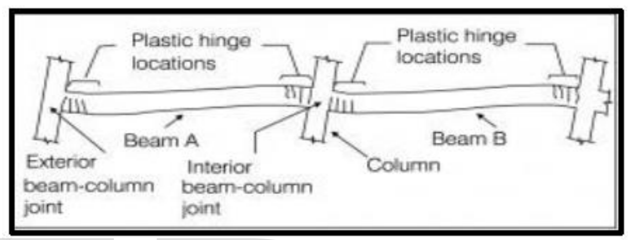

Fig.2.3 Formation of plastic hinges in real connection between column and beam

Both the ATC 40 and FEMA 356 documents presents similar performed-based engineering methods that depends on the non-linear static analysis in the prediction of the structural demands. The only difference lies in the technique used to calculate the global inelastic displacement demand (performance point, target displacement) for a giving ground motion.

- Capacity Spectrum Method (CSM)-ATC 40

It converts the capacity curve (the base shear vs roof displacement) to the capacity spectrum curve which is the acceleration displacement response spectra (ADRS) plotted below in fig.2.4 as illustration of the basic concept.
This process mainly merges the Vb vs Δroof top with the response spectrum curve, which is possible due to a relation connecting Vb, Δroof top and T. First the Vb vs Δroof top must be transformed to what is called spectral acceleration (Sa) vs spectral displacement (Sd) as Fig2.4. Refer to (ATC-40, VOL.1, P-8.9) for detailed equations.

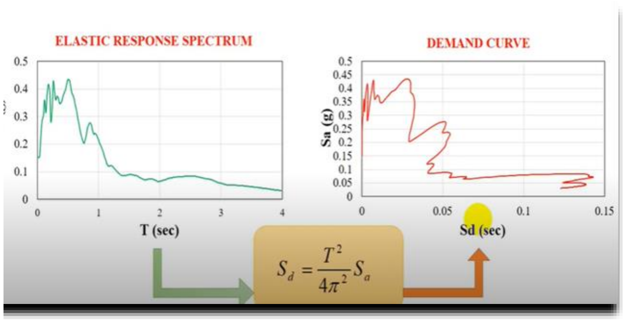

Fig.2.4. Formation of demand curve Transformation of the response spectrum curve into demand curve.

As well as the transformation of the pushover curve to the capacity curve as following in Fig.2.5.

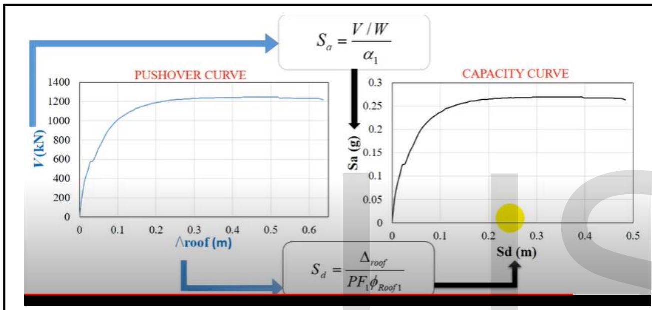

Fig.2.5. Formation of the capacity curve by transformation of the pushover curve into capacity curve.

The intersection of demand curve Fig.2.4. with capacity curve Fig.2.5. is the formation of the performance point showed in Fig.2.6.

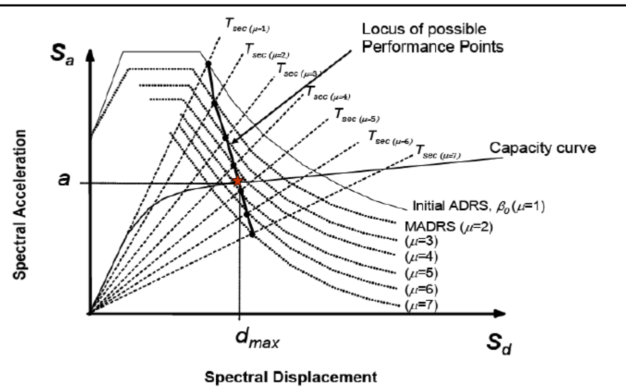

Fig.2.6. Intersection of the demand curve with the capacity curve

- Displacement Coefficient Method (DCM)-FEMA356

It has the same start as the CSM which are the pushover curve and the response spectrum curve as shown in Fig.2.8. It uses a bilinear approximation of the actual push-over curve. Fig.2.7. shows a bilinear basic concept.

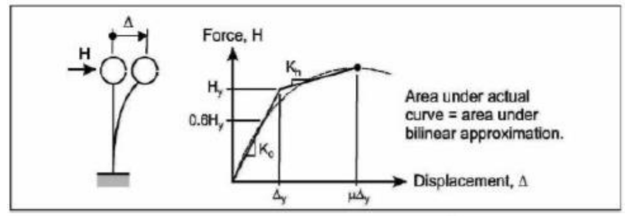

Fig.2.7. Formation of demand curve Transformation of the response spectrum curve into demand curve.

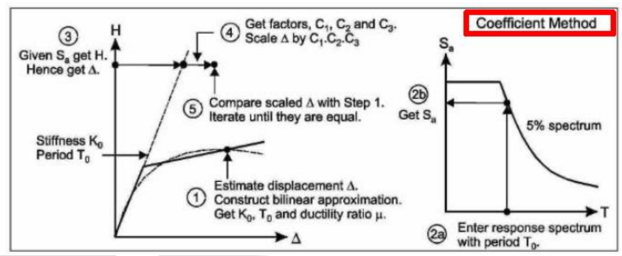

Fig.2.8. Formation of demand curve Transformation of the response spectrum curve into demand curve.

The strong-column weak beam behavior was applied in this research using the PA as following steps from fig.2.9. a to 2.9.e.

A-create a 3D non-linear computer static analysis by assigning plastic hinges as follows:

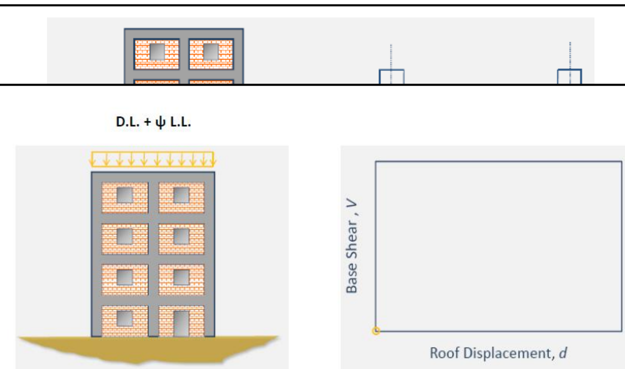

Fig.2.9. b. shows the gravity load to be applied

b-Apply gravity load (Total Dead load+0.25 LL) as following:

c-Apply lateral loads to the structure with different levels, starting by level 1 the building remained almost static as following:

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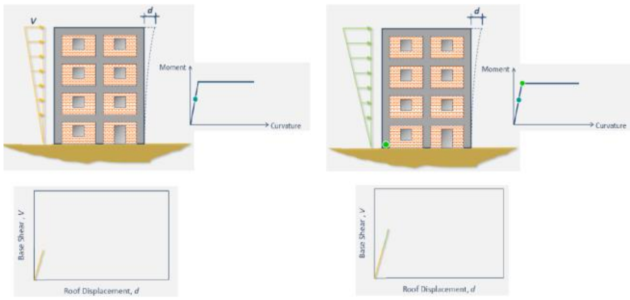

Fig.2.9. c. shows the low level of lateral load effect

d-Apply lateral loads to the structure with level 2 that refer to a moderate level, Plastic hinges took place in the building but it is still in the collapse prevention state as following:

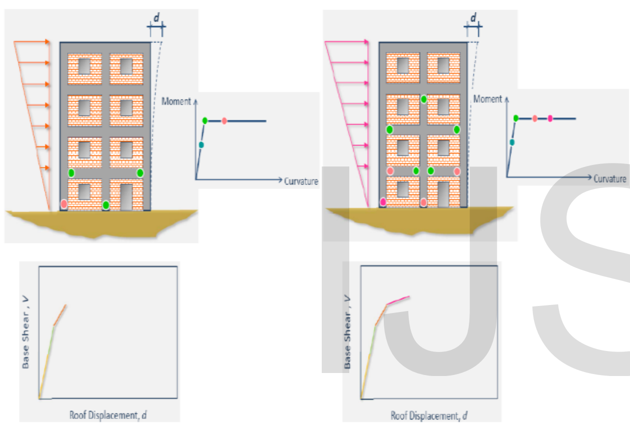

Fig.2.1. d. shows the medium level of lateral load effect

e-Apply lateral loads to the structure with level 3 that refer to a large earthquake level, Plastic hinges took place in the building in collapse area, showing the building that the point of failure will occur in the low point of column at which the total failure of the building occurs as following:

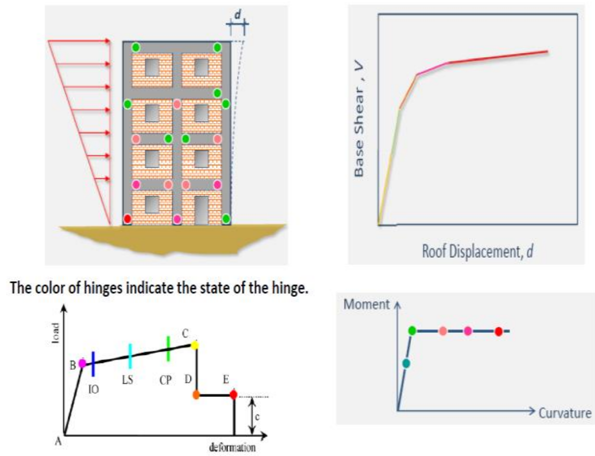

Fig.2.1. e. shows the high level of lateral load effect

3 EXPERIMENTAL PROCEDURE

In this research the analysis is made on two steps over a multistorey RC frame of a 12 storey for residential use, first step the preliminary one, which consists of the design of the structure using Response spectrum analysis, in the second and main step of analysis was made using the non-linear static pushover analysis following the ATC 40 procedures to judge the performance of the framed building.

Create a 3D computer model of 12 storeys with the following criteria:

3.1 Geometry of the building

The building consists of 3 spans and 5 bays of 4 m in each direction to form 4*4 grid of plan area as in Fig.3.2. The height of all floors is typically 3m except the first-floor height is 4m as in Fig,3.1. This building represents a typical building constructed in Cairo. As well as the columns are deducted as the height increases every 3 stories up to the roof of the structure.

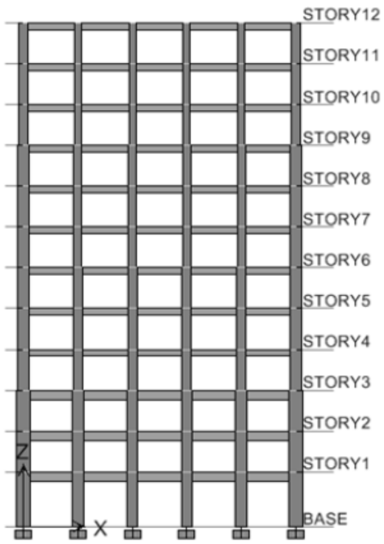

Fig.3.1. Structural Elevation and side view

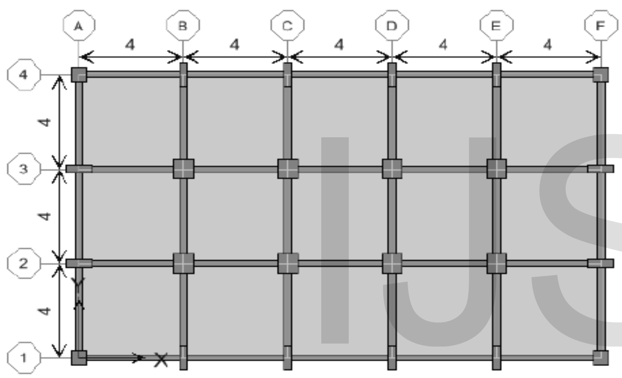

Fig.3.2. Structural Plan

3.2. Material of the building:

Material properties used in the analysis of the building: *Fcu* of 25 N/mm2 after 28-days, *fy*= 360 N/mm2 of high-grade steel, both are used for design and analysis. Specific weight of RC(γc = 25 kN/m3).

3.3. Applied loads:

The loads assigned to the model are categorized as gravity load which includes dead, live and lateral loads. Total dead load including floor cover and portioning elements are taken as 1.5 kN/m2, and 2 kN/m2 respectively. The own weight is calculated by the software program, and according to the Egyptian code the LL must be assigned as 2.5 kN/m2.

Lateral loads are taken as full dead loads+25% of the Live loads (ECP-201, 2008), As well as the seismic characteristics of Cairo are as shown in table 3.2.

Response curve	1	Importance factor	1
Number of floors	12 floors	Building zone	Zone 3
Typical floor height	3m	Damping correction factor	1
Ground floor height	4m	Response modification factor R	5
Typical floor weight	277 ton	Soil type	C
Ground floor weight	277 ton	Ct factor	0.075

Table.3.2. shows the seismic characteristics according to Ch.8 in the Egyptian code of loads

3.3. Design of the building;

Step 1: Response spectrum analysis was made following the Egyptian code of practice, the selected RFT ratios for the beams are within the allowable range, where the maximum and the minimum RFT ratios are 1.25% and 0.3% respectively (ECP-201, 2008). For the non- ductile columns, steel reinforcement ratios have been chosen to satisfy the Egyptian code specifications through which the range allowed for maximum and minimum percentage of steel RFT are 4.0% and 0.8% respectively. The RC building is provided with 0.12 m thick floor slabs and hence was considered as a rigid diaphragm.

Structure element			Storey Number			
			1,2,3	4,5,6	7,8,9	10,11,12
Beam		Cross-section mm2	0.25x0.7	0.25x0.5	0.25x0.5	0.25x0.5
		Reinforcement	4T16	4T16	4T16	4T16
Edge	Columns	Cross-section mm2	0.3X1.00	0.3X1.00	0.3X0.8	0.3X0.7
		Reinforcement	18T16	14T16	12T16	10T16
Inner		Cross-section mm2	0.8X0.8	0.7X0.7	0.6X0.6	0.5X0.5
		Reinforcement	32T16	24T16	20T16	16T16
Corner		Cross-section mm2	0.6X0.6	0.5X0.5	0.4X0.4	0.3X0.3
		Reinforcement	20T16	16T16	12T16	4T16

Table.3.3. shows the dimensioning and reinforcement of the structural elements

4 RESULTS AND DISCUSSION

The etabs software package is used to perform analysis using ground acceleration of intensities of 0.15 and 0.30g in X-direction and Y-direction considering the strong-column weak beam concept to allow ductile failure instead of undesired shear failure that may occur in the strong beam-weak column mechanism.

4.1. Performance of the building under 0.15g

The pushover curves due to the application of lateral load in x and y directions are shown in Fig.4.1 As expected the curves starts the loading process with linear behavior followed by non-linearity due to the inelastic actions of beams and columns and their ability to dissipate the energy of the seismic by the sustaining small deformation followed by large ones accompanied by the formation of plastic hinges, hence the formation of cracks. From the analysis it has been deducted that the roof displacement and base-shear in x-direction are 383mm and 7198KN respectively.

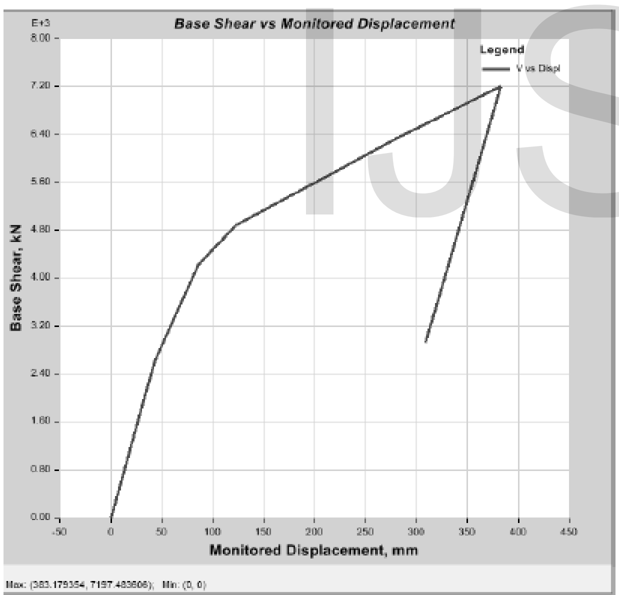

Fig.4.1. Pushover curve in x-direction

The analysis in Y-direction shows roof displacement and base shear of a value of 391mm and 7105 respectively as show in Fig.4.2.

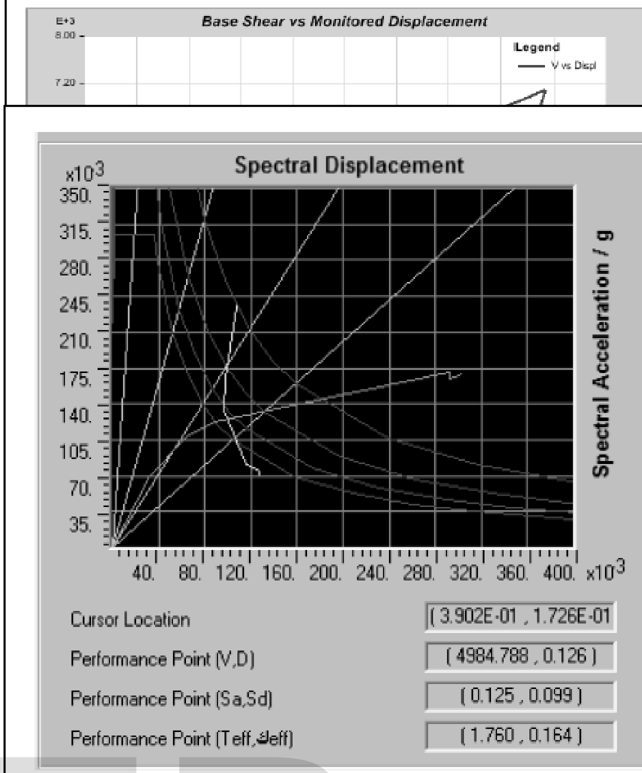

Fig.4. 3..Pushover curve, demand spectrum and performance point under applied acceleration of 0.15g in x-direction

The pushover curves (x andY) and the performance point resulted from the intersection of the demand spectrum curve and the capacity curve are shown in Fig, 4.3.and 4.4.

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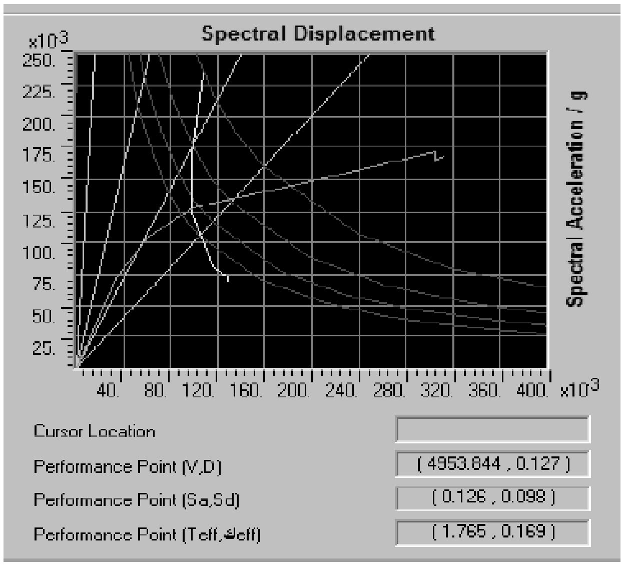

Fig.4.4...Pushover curve, demand spectrum and performance point under applied acceleration of 0.15g in Y-direction

The performance point was found to be associated with roof displacement of 0.125m and a natural period of 1.760sec. Table 4.1. defines the pushover results represented in the base shear, roof displacement and the behavior of plastic hinges.

step	Displacement	Base Force	A-B	B-IO	IO-LS	LS-CP	CP-C	C-D	D-E	>E	TOTAL
0	0.0000	0.00	1484	4	0	0	0	0	0	0	1488
1	0.0430	2655.66	1298	190	0	0	0	0	0	0	1488
2	0.0847	4264.26	1218	270	0	0	0	0	0	0	1488
3	0.1135	4853.75	1136	104	148	100	0	0	0	0	1488
4	0.2728	6479.24	1110	92	72	212	0	2	0	0	1488
5	0.3639	7268.23	1108	94	72	210	0	0	4	0	1488
6	0.3639	7036.75	1106	96	72	210	0	0	4	0	1488
7	0.3638	7147.58	1098	104	68	210	0	4	4	0	1488
8	0.3767	7258.92	1098	104	68	200	0	6	12	0	1488

Table.4.1. Pushover results and the behavior of the formed plastic hinges in X-direction

The table illustrates the corresponding base shear and displacements at each step as well as the number of plastic hinges formed at each step of performance level.

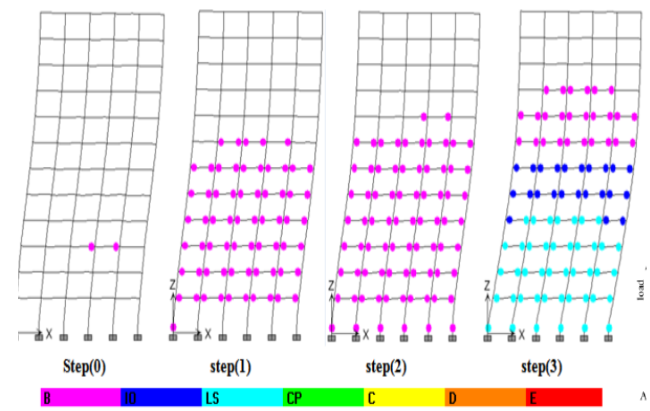

Fig.4.5. History of formation of plastic hinges in x-direction

the performance level of the plastic hinges that took place in the building is judged by Fig.4.6.

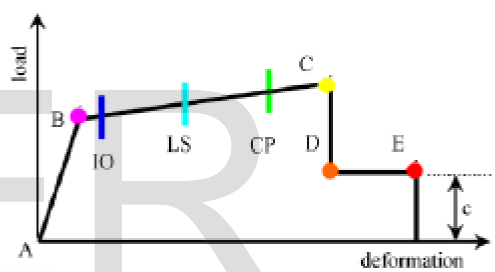

Fig.4.6. Performance level of the structure.

From table 4.1., Fig.4.3. using the performance point recorded roof displacement which equals to 0.126m, by having a look on table 4.1 we can estimate the nearest point to the performance displacement which is found in step 3. Step 3 is now the tool through which I will judge the performance of the building. At step 3, out of 1448 of assigned plastic hinges, 1136 are in the stage of A-B. The remaining assigned hinges are 104,148,100 and 0 are found respectively in B-OI, IO-LS, LS-CP and CP-C stages, hence it's now confirmed that the plastic hinges are forming in the CP zone which as explained in section 2 considered a zone at which happens unrepairable damages for some structural elements but without collapse. The formation of plastic hinges in this is desirable as its forming in the beam (ductile element) and assure the concept of strong column-weak beam and how effective it is in the dissipation of energy of the earthquake.

same thing can be done for the Y-direction with very slight difference in results between X and Y

ISSN 2229-5518

4.2. Performance of the building under 0.3g

Another analysis was made for the same model subjected to PGA of 0.3g which way greater the GA in Cairo, so we can study the behavior of this building under large earthquakes. The pushover curves (x and Y) and the performance point resulted from the intersection of the demand spectrum curve and the capacity curve are shown in Fig, 4.7.and 4.8.

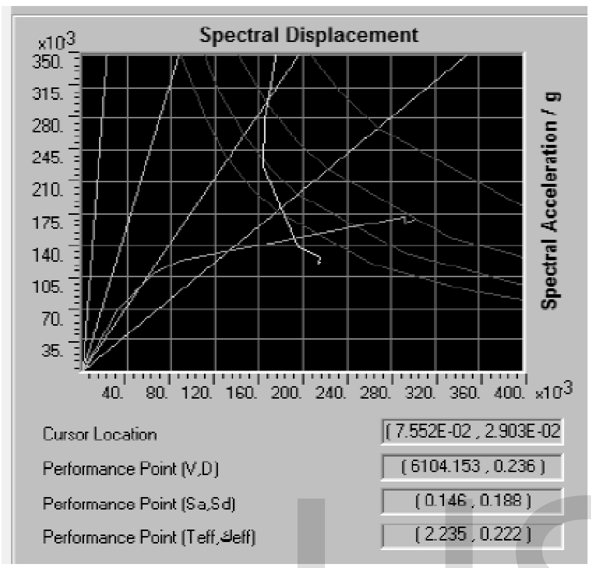

Fig.4.7. Pushover curve, demand spectrum and performance point under applied acceleration of 0.3g in x-direction

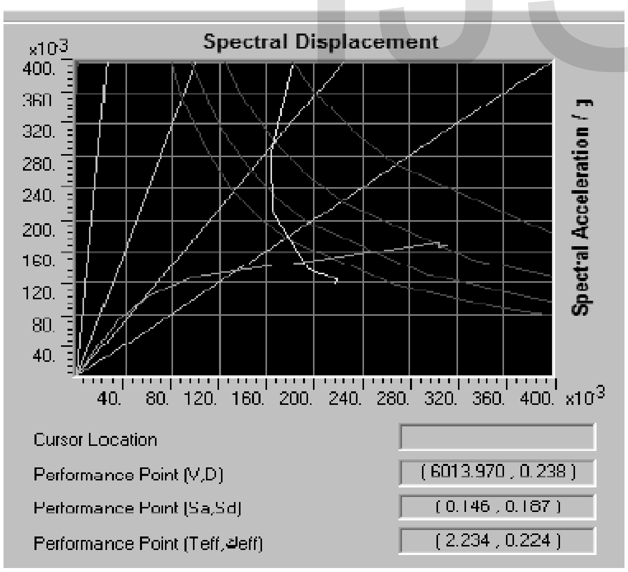

Fig.4.8. Pushover curve, demand spectrum and performance point under applied acceleration of 0.3g in Y-direction

The performance point in this case is associated with roof displacement of 0.236 m. from Table 4.1 and fig.4.7, Step 4 is found to be the nearest to that performance point of value of 0.2728 for the roof displacement. This captured roof displacement at step 4 is higher than the one at the performance point which means that the demand curve intersects with the capacity curve beyond the CP stage, hence the structure performed high deformation beyond the ductility limit which might cause instability and then collapse in the structure.

Its noticed at table 4 that out of 1488 plastic hinges assigned, 1100 were in the A-B stage, 92, 72, 212, 0 and 2 hinges are in B-IO, IO-LS, LS-CP, CP-C and finally C-D respectively.

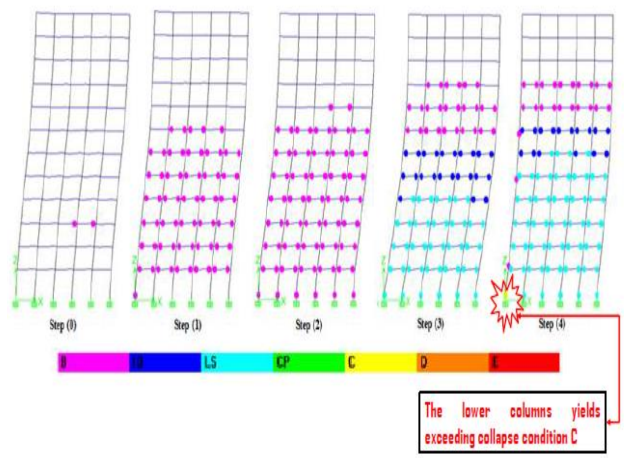

Fig.4.9. History of formation of plastic hinges in x-direction

The performance level of the plastic hinges in fig.4.9. shows undesirable failure occurs in the lower part of the column after yielding and exceeding the collapse condition C.

This is an alert that the cross-section of this column needs to be modified to a greater one that would deform that large deformation, and then the analysis should be made once more to assure the safety of the structure.

5 CONCLUSIONS

The subsequent conclusions were drawn from the analysis of a 12-storey RC framed building, designed following the Egyptian code of practice for loads, considering two different ground acceleration, the first chosen levels fit the seismicity zone of Cairo and the other is of a higher magnitude.

The analysis was derived using ETABS software as a tool in both direction of applications X and Y.

1. By applying the ground acceleration 0.15g which is the same as the seismicity zone of Cairo, the demand curve intersected with the capacity curve almost near the elastic zone, by consequence the formation of plastic hinges occurred away from the critical sections, causing desirable ductility in the beams which helped the building to absorb part of the seismic energy and dissipate the rest by the formation if cacks in safe zones, assuring the concept of strong column-weak beam

which indicates that the proposed model of non-linear analysis has produced satisfactory performance.

2. While exposing the RC framed building to seismic level that exceeds twice the value recommended by the code based on its seismicity, would lead to the intersection between demand curve and capacity curve in the inelastic zone of the building which causes severe cracks and formation of plastic hinges in dangerous level causing the building poor behavior that needs to be strengthened to avoid such undesirable failure.
3. The research showed the importance of the capacity design concept in the seismic design of RC structures, and how it suggests the building to be more ductile, hence being able to resist the lateral loads in the most desirable failure modes to prevent the collapse of the building during large eathquakes energy, through an economic structure that is able to dissipate the energy of earthquake instead of absorbing it as whole.
4. The capacity design concept was introduced in this research, and how to apply it in analysis using the new seismic design methods such as the Performance Based Design method, and the pushover analysis procedure.
5. The aim of this research is shedding light on the new seismic design methods for RC structures like the performance based design, these methods gives a large study of the performance of the structute in its non-linear state during and after-earthquake which is something that should be taken into consideration during the design and while checking the performance of the building.
6. This research showed that the traditional methods of design mentioned in the Egyptian code, can just help in making the design of the structure without checking its performance after the event of an earthquake, ignoring the importance of the ductility of the buiding in dissipating the energy of the seismic.
7. This research has introduced the pushover analysis in its simpliest form, it can be used as guildeline of the basic concept of pushover analysis.

6 RECOMMENDATIONS FOR FURTHER WORK

This research is a recommendation for the Egyptian code of practice to the employment of the capacity design concept as well as the tools that helped realizing this concept like the Performance Based Design. It can be reference for future researches in the understanding of the basic concept of the pushover analysis procedure which is still in the realm of researches till date.

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