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Seismic Capacity Assessment of Existing RC Building by Using Pushover Analysis

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Abstract

The infrastructure, existing in Sudan, is mostly not structured or designed to resist seismic forces accordingly. The study investigated the seismic damage of a 5 storey existing reinforced concrete building in Khartoum, Sudan. Three performance levels were considered in the study, which included immediate occupancy, life safety, and collapse prevention. The gravity push was carried out using force control method and lateral push with displacement control, using SAP2000. Pushover analysis produces push curve, consisting of capacity spectrum, demand spectrum, and performance point. It showed the performance level of building components along with maximum base shear carrying capacity. It has been observed that demand curve intersected the capacity curve between the points B and C at the X direction that is life safety level; and between the points B and C at the Y direction that is life safety and collapse prevention level. Therefore, some building elements are needed to be strengthened.

Keywords: Pushover Analysis; Demand Curve; Capacity Curve; Plastic Hinge; SAP2000; Performance Point; Sudan.

1. Introduction

Sudan has different tectonic and geological formations. Currently, the infrastructure existing in Sudan is mostly not structured or designed to resist seismic forces. Limited work has been conducted, concerning seismic hazard assessment [1]. Up till now, there is no seismic design code in Sudan. The most common type of existing buildings in Sudan is the reinforced concrete (RC) building. Most of these buildings were built in last 50 years and designed to face gravity loads. They were designed in accordance to British Standard Code (BSI) (BS 8110, 1997). These buildings are currently in use for offices and shops and have a reinforced concrete frame structural system. Therefore, the study aimed to examine the safety assessment of existing multistory building. For this purpose, a pushover analysis was carried out.

Capacity curve, which is a load-deformation plot, is the output of pushover analysis. As, pushover analysis is a non-linear static analysis; the load-deformation curve can be obtained from SAP2000. This software was used to perform non-linear static pushover analysis. The SAP2000 static pushover analysis capabilities, which are fully integrated into the program, allowed quick and easy implementation of pushover procedures. These have been prescribed in ATC-40 [2] and FEMA 273 [3] documents for two and three-dimensional buildings. SAP2000 recommends P-M-M hinges for columns and M3 hinges for beams and described in FEMA [3].

Sudan is not free from earthquakes as it has experienced many earthquakes during the recent history [1, 4]. Moreover, a great attention is received by the evaluation of seismic performance of the existing buildings in Sudan. In Sudan, it is a common practice not to consider the effects of earthquake in the building designing [4]. Therefore, the study has contributed to examine the seismic damage of 5 storey existing reinforced concrete building, which was designed

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according to the British standards. SAP2000 has served as the source to obtain load-deformation curve. It allowed easy access and implementation of pushover techniques, suggested in the documents of ATC-40 and FEMA 273.

Majority of the buildings in Sudan are not designed for seismic forces. It is important to study their responses under seismic conditions and to evaluate seismic retrofit schemes. Hence, pushover analysis is gaining much importance for the strengthening and evaluation of existing structures. An effective risk assessment measure is to identify the most vulnerable building that may undergo damage if an earthquake occurs. A sample buildings set was selected to reflect existing construction practices, including regular buildings; such as, residential buildings, hospitals, offices and school buildings. The lateral loads, performed for those buildings through equivalent static method following the rules, were given in the regulations for earthquake resistant design of building in Egypt 1988 (ESEE) [5]. These regulations have been prepared by the Egyptian Society for Earthquake Engineering (ESEE). Moreover, this procedure used a simple estimate of structures' fundamental period and the anticipated maximum ground acceleration to determine a maximum base shear. Horizontal loading equivalent to this shear is then distributed in prescribed manner throughout the height of building to allow a static analysis of the structure. Thus, it is said that this method is rather simple and rapid for better analysis.

2. Methodology

The pushover analysis used in this study has gained much popularity as it is an efficient tool for evaluating the existing and new building structures. This type of analysis provides adequate information on seismic that are executed through the design ground motion based on the structural system and its components. The present study has performed pushover analysis through imperiling a building structure to monotonically increasing pattern of lateral loads. This pattern represents the inertial forces that are experienced by the structure as it is subjected to ground shaking. It has been shown that nonlinear force displacement relationship is evaluated using pushover analysis. The main steps followed in this study using pushover analysis are as follows;

- Defining plastic hingers
- Defining control nodes
- Development of pushover curve to evaluate force distributions
- Estimating displacement demand
- Evaluating the performance level

3. Pushover Analysis

The pushover analysis of a structure is a static non-linear analysis under permanent vertical loads and gradually increasing lateral loads. The purpose of pushover analysis is to evaluate the expected performance of structural systems by estimating performance of a structural system. It can be done to estimate the strength and deformation demands in design by means of static inelastic analysis and comparing these demands to available capacities at the performance levels of interest.

3.1. Static Nonlinear Analysis Using FEM Software

SAP2000 nonlinear version offers strong and significant characteristics for the nonlinear static pushover analysis. Both 2D and 3D structures can be analyzed as pushover analysis on SAP2000 nonlinear version [6]. The nonlinear modelling uses different ways of modelling the structure to obtain the capacity curve of the structure; although, the concentrated plasticity is the only choice in nonlinear modelling [6]. The nonlinear behavior of the frame members was determined by particular hinges; and the structural capacity drop occurred for the hinges.

After performing analysis, certain points were achieved ranging from A to E as shown in Figure 1. Point A shows the unloaded state; point B shows yielding state of an element; point C represents nominal strength; and co-ordinate of point C represents displacement axis. It shows deformation at which significant amount of strength degradation occurs. The part from C to D in the figure shows the starting failure and the strength of the element to resist lateral forces that were unreliable after point C. The portion D to E on the curve shows that only the gravity loads are sustained by the frame elements. After point E, the structure has no more capacity to sustain gravity loads [7]. Performance point and location of hinges in various stages can be obtained from pushover curve as shown in Figure 1. The range AB is elastic range; B to IO is the range of immediate occupancy; IO to LS is the range of life safety; and LS to CP is the range of collapse prevention. If all the hinges are within the CP limit, then the structure is said to be safe. However, depending upon the importance of structure after IO range may also need to be retrofitted.

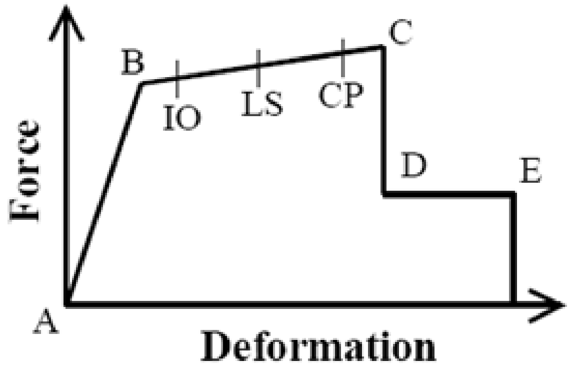

Figure 1. Force-deformation for pushover hinge [6]

3.2. Limitations of the Adopted Procedure (Pushover Analysis)

There are many reasons for supporting the use of inelastic pushover analysis for predicting demand; since in several cases, it may provide quite relevant information than a dynamic or an elastic static analysis. The push-over analysis is likely to show significant nonlinear behavior and important structural damage at the displacement level [8]. Pushover analyses are quite useful, but it has following limitations:

- Due to the higher modes of vibrations, the indication of failure mechanism is an important issue as the accuracy of pushover result is affected.
- Target displacements are very difficult to be estimated.
- As the earthquake gets severe, the inertia forces distribution changes; while in pushover analyses they are assumed to be constant during an earthquake.

3.3. Building Performance Levels

The performance levels as per FEMA (FEMA, 1997) and ATC 40 [2] are (Figure 2):

- Immediate occupancy IO: Damage is relatively limited; the structure retains a significant portion of its original stiffness and strength.
- Life safety level LS: Substantial damage has occurred to the structure, and it may have lost a significant amount of its original stiffness. However, a substantial margin remains for additional lateral deformation before collapse would occur.
- Collapse prevention CP: The building has experienced extreme damage at this level. If laterally deformed beyond this point; the structure can experience instability and collapse. Depending upon the importance of structure, the hinges after IO range may also need to be retrofitted.

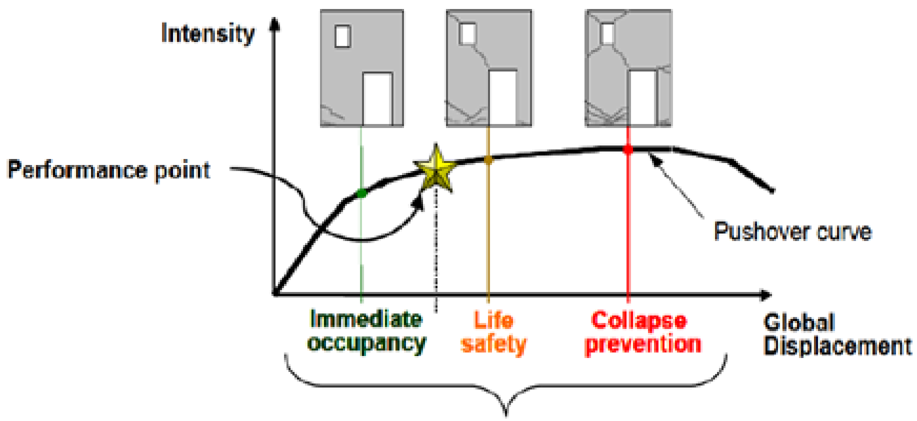

Figure 2. Performance levels described by a pushover curve [8]

4. Case study

4.1. Building Description

The building, studied in the case analysis, was a ٥ storey reinforced concrete building, for offices and shops use. The slab thickness was 20 cm; column section was 25 × 45 cm; and the beam section was 25 × 50 cm. The height of each level was 3.2m; the building was located in the Sudan in seismic zone 1. The building was designed according to British Standard Code (BSI) (BS 8110, 1997). The structure members were made of in-situ reinforced concrete. The overall plan dimension was 11.7 × 6.7. Height of the building was 16 m. Figures 3 has provided the typical floor plan, Figure 4 has illustrated the plan for ground floor; whereas, Figure 5 has provide detailed information on the architectural layout of the building by featuring the x-x section.

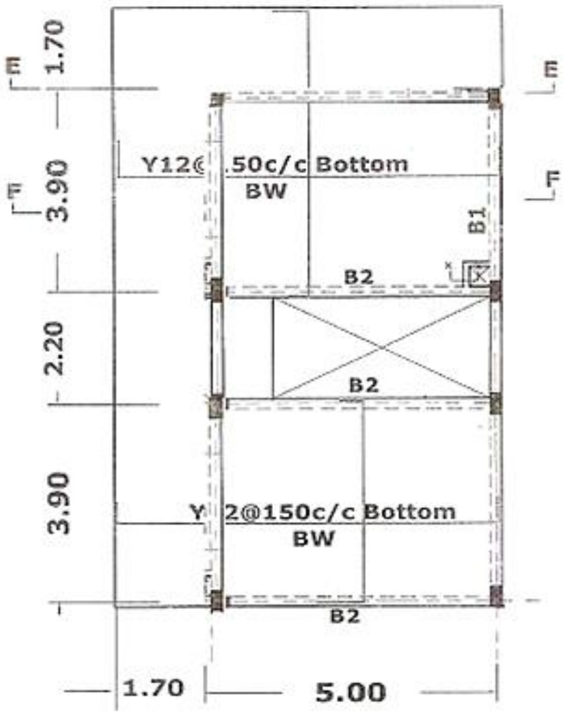

Figure 3. Typical floor plan

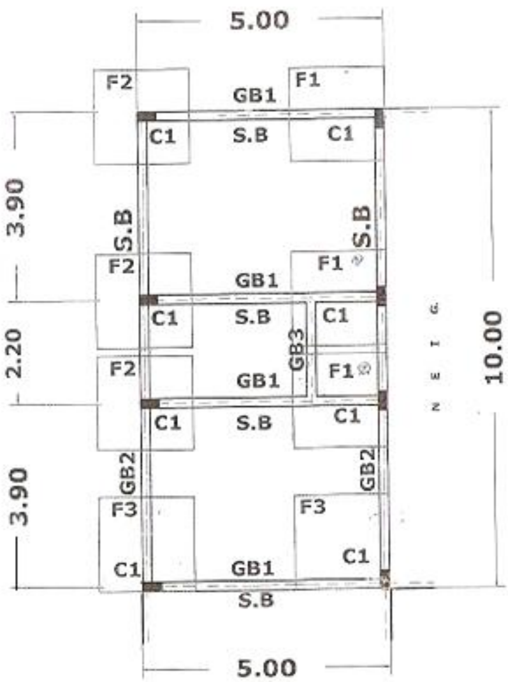

Figure 4. Ground floor plan

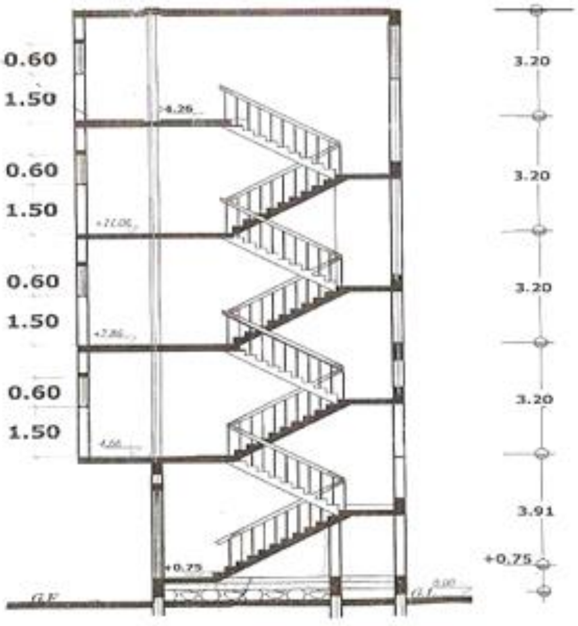

Figure 5. Section x-x

4.2. Structural Modelling

Numerical models for the case have been prepared using SAP2000 version 14 (Computers and Structures) The beam and column elements were modelled as nonlinear frame elements with lumped plasticity by defining plastic hinges at both ends of beams and columns. While, slabs were modelled as shell elements. In this study, the seismic performance of the considered offices and shops' building has been evaluated using the nonlinear static analysis procedure (pushover analysis). Figure 6 shows the 3-D model for the five-story building.

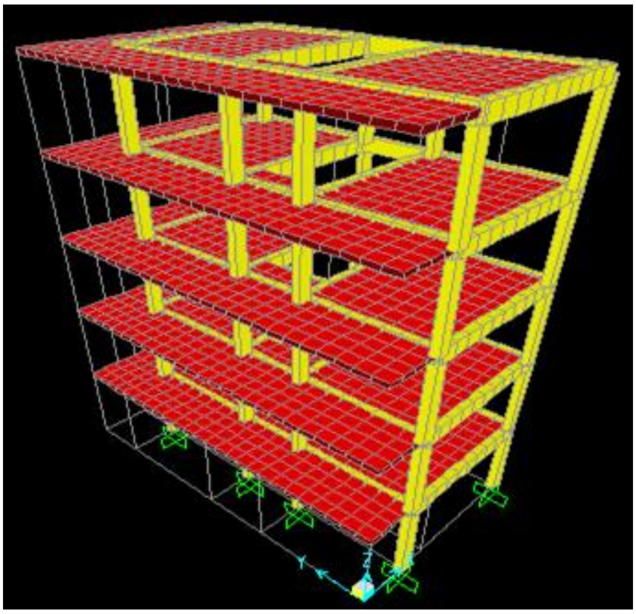

Figure 6. 3D-view of the building

4.3. Calculation of Design Seismic Force by Static Analysis Method According to ESEE 1988 (Egyptian Society for Earthquake Engineering)

The design seismic force at each floor is shown in Table 1.

Table 1. Lateral load distribution with height

Storey level	Wi (KN)	Hi (m)	Wihi	Wihi/sum Wihi	V (base shear) (KN)	Lateral Force	
						X	Y
5	1240	16	19840	0.33	165	55	55
4	1240	12.8	15872	0.27	165	44	44
3	1240	9.6	11904	0.20	165	33	33
2	1240	6.4	7936	0.13	165	22	22
1	1240	3.2	3968	0.07	165	11	11
Sum	6200		59520			165	

5. Results and Discussion

Results of the pushover analysis for the 5 stories building are presented in Figures 7 to 14 (pushover curves, in each of the 2 main directions). Plastic hinges formation started with beam ends and base columns of lower stories, then propagated to upper stories and continues with yielding of interior intermediate columns in the upper stories. Figure 7 shows the pushover curve for model in X direction. For the same storey, figure 8 has illustrated the pushover curve for the model in Y direction.

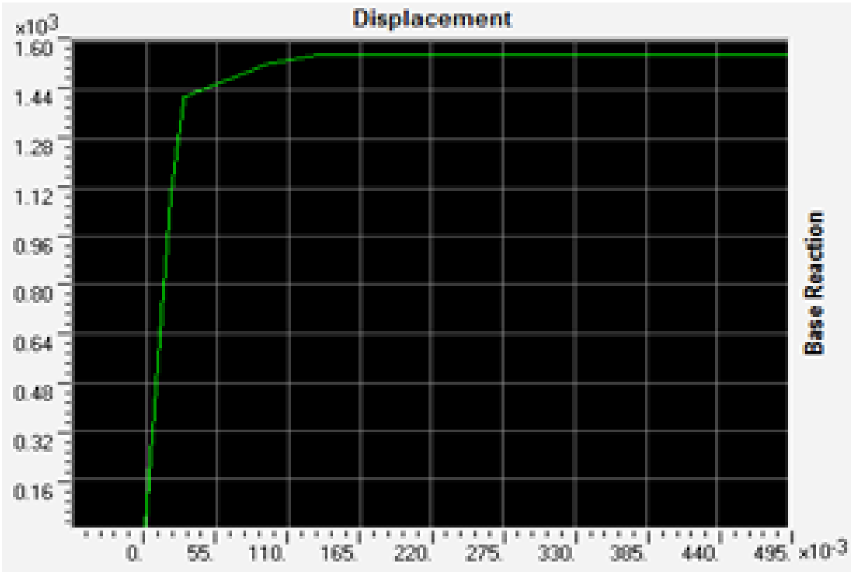

Figure 7. Pushover curve for model in x direction

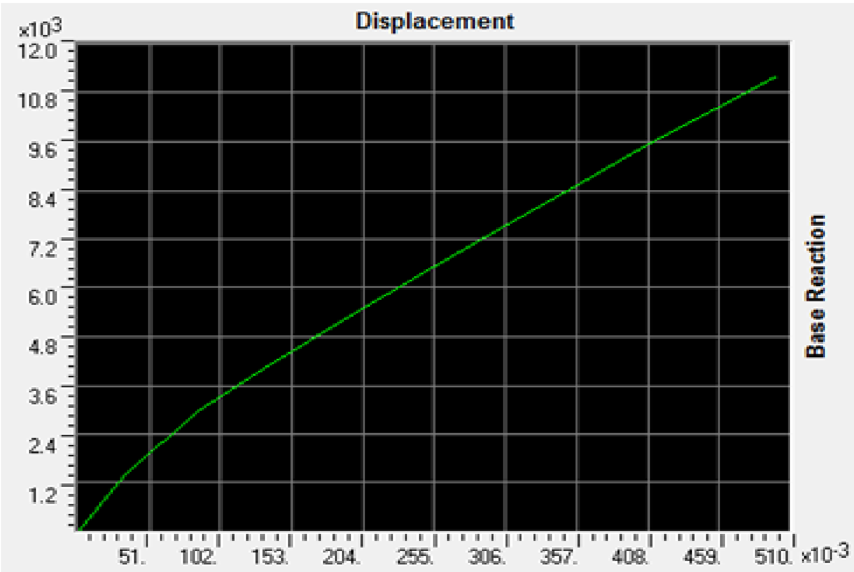

Figure 8. Pushover curve for model in Y direction

Pushover capacity curve and performance point at the X direction have been depicted in Figure 9. Figure 10 has shown the hinges for the concerned model in X direction. Specifically, Figure 10 has illustrated the analysis at its 4th step. Step 5 of the pushover analysis for making hinges in X direction has been illustrated in Figure 11.

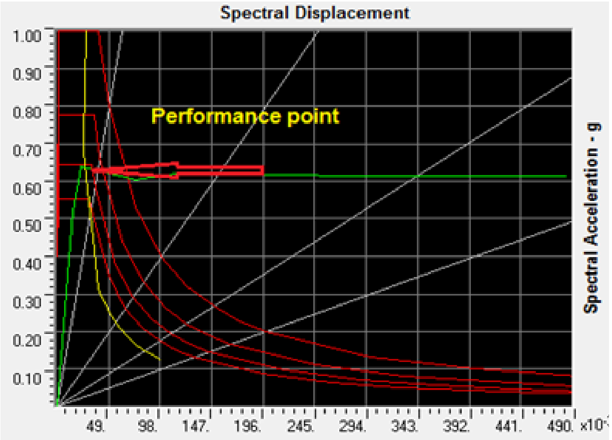

Figure 9. Pushover capacity curve and performance point at X direction

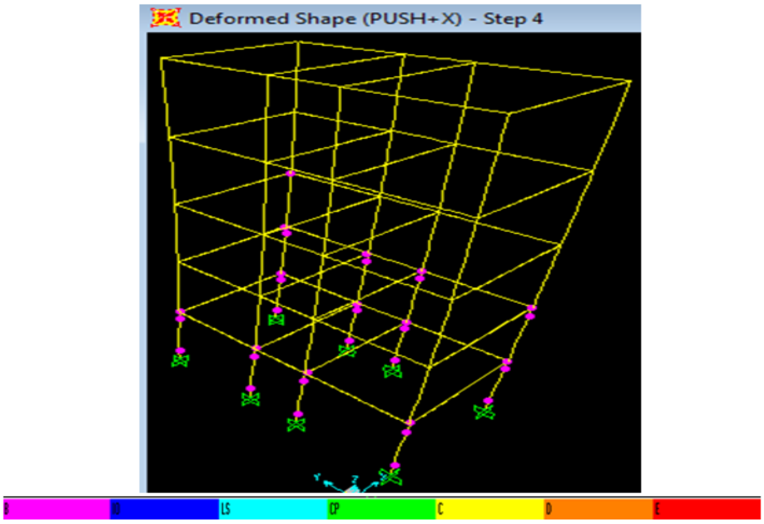

Figure 10. Hinges for model in X Direction-Step 4

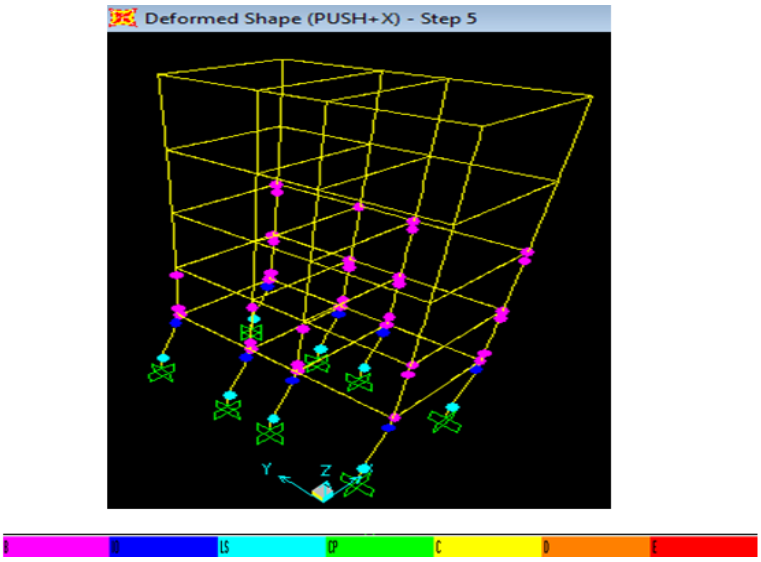

Figure 11. Hinges for model in X Direction-Step 5

Figure 12 has illustrated the pushover capacity curve and performance point at Y direction. In the same context, Figure 13 has shown step 1 of developing hinges for the model in Y direction. Figure 14 has exemplified step 2 of hinges development for model in Y direction.

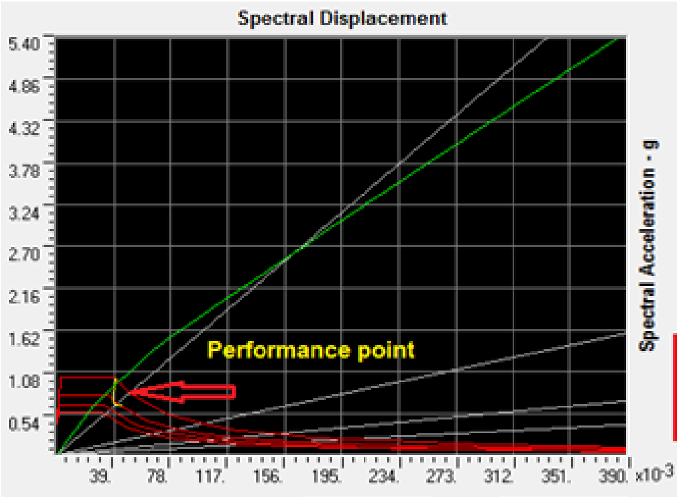

Figure 12. Pushover capacity curve and performance point at Y direction

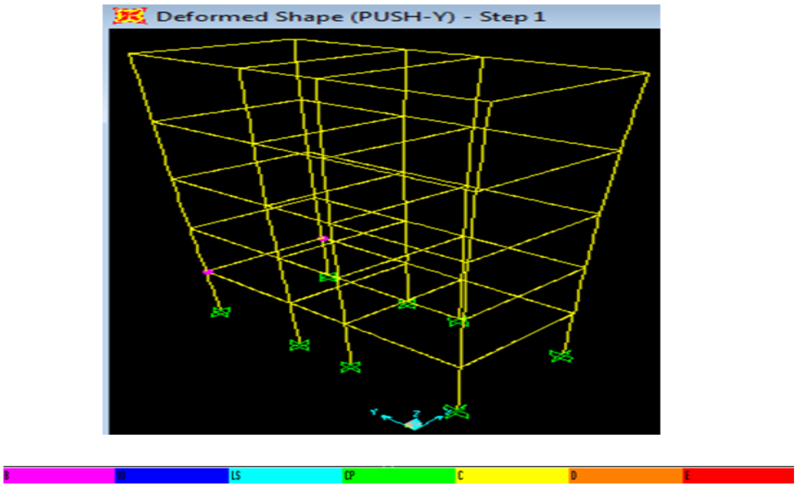

Figure 13. Hinges for model in Y Direction-Step 1

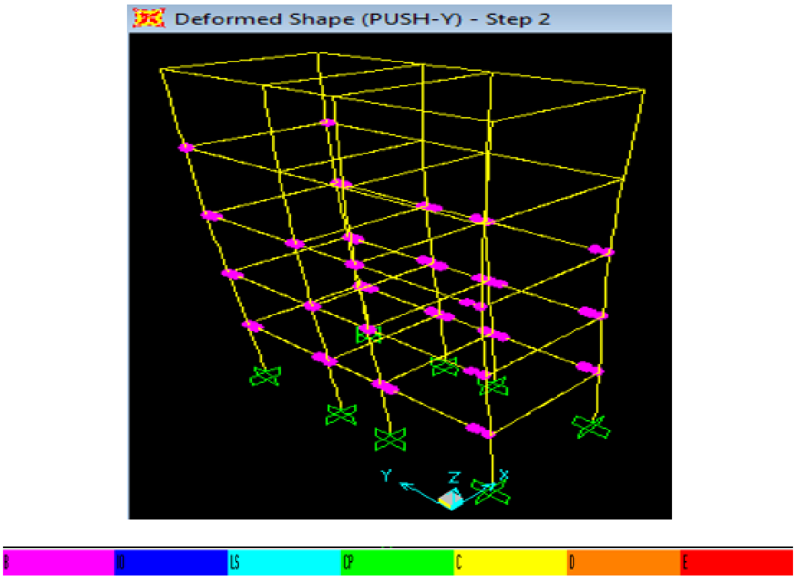

Figure 14. Hinges for model in Y Direction-Step 2

Table 2. Tabular data for pushover curve- X direction

Step	Displacement m	Base Force KN	AtoB	BtoIO	IOtoLS	LStoCP	CPtoC	CtoD	DtoE	BeyondE	Total
0	-0.000622	0	860	0	0	0	0	0	0	0	860
1	0.018818	1094.193	857	3	0	0	0	0	0	0	860
2	0.028967	1410.816	831	29	0	0	0	0	0	0	860
3	0.029451	1418.45	828	32	0	0	0	0	0	0	860
4	0.029965	1422.762	827	33	0	0	0	0	0	0	860
5	0.08502	1513.684	809	35	8	8	0	0	0	0	860
6	0.090651	1521.809	806	38	8	8	0	0	0	0	860
7	0.125343	1552.705	805	39	0	8	0	8	0	0	860
8	0.125347	1552.713	805	39	0	8	0	0	8	0	860
9	0.133849	1557.699	805	38	1	7	0	1	8	0	860
10	0.13385	1557.7	805	38	1	7	0	0	9	0	860

Table 3. Tabular data for pushover curve - Y direction

Step	Displacement m	BaseForce KN	AtoB	BtoIO	IOtoLS	LStoCP	CPtoC	CtoD	DtoE	BeyondE	Total
0	0.000351	0	860	0	0	0	0	0	0	0	860
1	0.033026	1388.708	858	2	0	0	0	0	0	0	860
2	0.085013	2963.189	800	60	0	0	0	0	0	0	860
3	0.137107	4122.54	759	101	0	0	0	0	0	0	860
4	0.193247	5288.552	732	128	0	0	0	0	0	0	860
5	0.243657	6308.945	704	152	4	0	0	0	0	0	860
6	0.298514	7397.457	684	170	6	0	0	0	0	0	860
7	0.355285	8507.214	664	181	13	2	0	0	0	0	860
8	0.407347	9504.288	635	197	24	4	0	0	0	0	860
9	0.467245	10628.883	605	220	29	2	0	0	4	0	860
10	0.500351	11238.761	585	236	33	2	0	0	4	0	860

Table 4. Pushover curve demand capacity - ATC40 - PUSH-X

Step	Teff	Beff	SdCapacity m	SaCapacity	SdDemand m	SaDemand
0	0.338	0.050	0.000	0.000	0.028	1.000
1	0.338	0.050	0.015	0.522	0.028	1.000
2	0.380	0.123	0.023	0.638	0.026	0.710
3	0.383	0.128	0.023	0.639	0.025	0.697
4	0.388	0.136	0.024	0.638	0.025	0.677
5	0.713	0.324	0.076	0.603	0.040	0.314
6	0.736	0.326	0.082	0.606	0.041	0.304
7	0.858	0.329	0.114	0.622	0.048	0.261
8	0.858	0.329	0.114	0.622	0.048	0.261
9	0.887	0.331	0.122	0.624	0.049	0.253
10	0.887	0.331	0.122	0.624	0.049	0.253

Where, (*Sa*) is pseudo-acceleration, (*Sd*) is spectral displacement and (Teff) is effective period.

Table 5. Pushover curve demand capacity - ATC40 - PUSH-Y

Step	Teff	Beff	SdCapacity m	SaCapacity	SdDemand m	SaDemand
0	0.401	0.050	0.000	0.000	0.040	0.997
1	0.401	0.050	0.026	0.638	0.040	0.997
2	0.444	0.086	0.067	1.364	0.038	0.779
3	0.476	0.105	0.108	1.915	0.039	0.685
4	0.496	0.106	0.151	2.479	0.040	0.656
5	0.507	0.103	0.190	2.979	0.041	0.647
6	0.516	0.100	0.232	3.510	0.042	0.642
7	0.523	0.096	0.275	4.049	0.044	0.640
8	0.528	0.093	0.315	4.538	0.044	0.640
9	0.533	0.090	0.359	5.093	0.045	0.641
10	0.535	0.089	0.384	5.394	0.046	0.641

Where , (Sa) is pseudo-acceleration, (Sd) is spectral displacement and (Teff) is effective period.

6. Conclusion

The present study has aimed to investigate the seismic damage of a 5 storey existing reinforced concrete building in Khartoum, Sudan. Three performance levels including immediate occupancy, life safety, and collapse prevention have been considered. The study has carried out gravity push with displacement control, using SAP2000. Pushover curve and demand curve were obtained by conducting the pushover analysis on building. It has been evaluated through the findings that one needs to decide whether to perform rehabilitation or retrofitting, depending upon the seismic zone of the existing structures. The pushover analysis combined with the performance levels is able to evaluate the seismic damage of buildings for examining the state of structure under the action of an earthquake. Thus, providing information on the damage would be beneficial, which can be sustained by a structure. The results showed that the buildings in Sudan need to be strengthened as the demand curve intersected the capacity curve between the points B and C at the X direction that is life safety level; and between the points B and C at the Y direction that is life safety and collapse prevention level. The study concluded that pushover analysis is preferably used for static nonlinear procedures because of its simplicity. It has been observed that the location of plastic hinges indicated weak zones in a building, which is helpful for re-strengthening the existing buildings. It has been analyzed that the building can be easily stiffened or strengthened by changing member properties and rerunning the analysis.

7. Acknowledgement

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8. Funding

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