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Non-Linear Behavior of Reinforced Concrete Frame Structure with Vertical Irregularities

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ABSTRACT- Various structural factors that contribute to damage during an earthquake are vertical irregularities, irregularities in strength and stiffness, mass irregularities, torsional irregularities, and so on. Over the past decade, performance-based design (PBD) procedures have become one of the most critical areas in earthquake engineering. The pushover procedure is divided into two parts; the first is the displacement target for the erected building. The target is the estimated displacement of the top of the building when exposed to the design earthquake excitation. Then a pushover analysis is carried out on the building until the top removal is equal to the target displacement. Second is the type of controlled force in which the total amount of force acting is estimated and applied to the structure, and analysis is carried out.

The various performance levels for a building are expressed in terms of the base shear carried versus the roof displacement. If all the plastic hinges formed are within the CP limit, the structure is said to be safe. On the other hand, if the plastic hinge formed exceeds the CP limit, the structure is said to have collapsed. This paper proposes a 2D reinforced concrete frame with three models with variations of vertical irregularity. This paper aims to see the nonlinear behavior of reinforced concrete frames with vertical irregularities through the pushover method using SAP2000 software. Furthermore, the analysis results show that the skeleton is susceptible to increasing vertical irregularity. As the vertical irregularity increases, the percentage of the plastic hinge crossing the boundary increases. The analysis results also show that model 2 has better behavior.

KEYWORDS- Pushover, Reinforced, Concrete, Frame

I. INTRODUCTION

An earthquake is a natural phenomenon associated with violent shaking of the ground. The significant strain energy released during an earthquake travels as seismic waves in all directions through the earth's layers that are reflected and refracted at each interface. Structural damage from an earthquake depends on the materials that make up the structure, the type of earthquake waves (movement) that affect the structure, and the soil on which the structure is built. Thus the dynamic loading on the structure during an earthquake is not an external load but an inertial effect due to the movement of the support. Various structural factors that contribute to damage during an earthquake are vertical irregularities, irregularities in strength and stiffness, mass irregularities, torsional irregularities, and so on. In high-rise buildings, damage due to earthquake ground motion generally begins at the location of structural weaknesses in the structure.

This weakness can sometimes be caused by discontinuities in stiffness, strength, or mass between adjacent stories. Such discontinuities between levels are often associated with sudden variations in the frame's geometry with increasing height [1]–[3]. Many examples of building failures in past earthquakes due to these vertical discontinuities [4]–[6]. Irregular configuration, both in plans and in elevation, is often recognized as one of the main causes of building failure in past earthquakes. Figure 1 shows irregular buildings, and the collapse of irregular buildings due to the earthquake in Islamabad [7]–[10]. Therefore, studying the structural behavior of structures with irregularities is essential.

Figure 1: Irregular building the collapse of irregular buildings due to the earthquake in Islamabad

Static non-linear procedures or pushover analysis [11]–[14] are increasingly used to determine seismic demand estimates for building structures, as structures exhibit non-linear behavior during earthquakes. In earthquake-resistant design, structures are generally designed for lower seismic forces and are allowed to experience a non-linear response due to severe ground motion. Therefore, non-linear static analysis (pushover) [15]–[22] has become popular in recent years and is used to determine parameters such as initial stiffness, yield load, yield displacement, maximum base shear, and maximum displacement. Damage status measures the performance of a building under a certain earthquake level. The form of damage is expressed as a performance level. For the building, the performance level is measured by the inelastic shift of the roof. The use of non-linear analysis is unavoidable to observe whether the structure meets the desired performance or not.

Over the past decade, performance-based design (PBD) procedures [23]–[27] have become one of the most critical areas in earthquake engineering. The pushover procedure consists of; the first displacement target for the erected building. The target is the estimated displacement of the top of the building when exposed to the design earthquake excitation. Then a pushover analysis is carried out on the building until the top removal is equal to the target displacement. Second, the controlled force type in which the total amount of acting force is estimated and applied to the structure and analysis is carried out [28]. Pushover analysis is an approximate method in which the structure is subjected to a monotonically increasing lateral force with an unalterable height distribution until the target displacement is reached [29]. In this analysis method, a building model is subjected to lateral loads, and the intensity of lateral loads is increased slowly. This process is continued until the controlled displacement at the top of the building reaches a certain level of deformation, or the structure becomes unstable.

The pushover curve is the plot drawn between the base shear along the vertical axis and the displacement of the roof along the horizontal axis. The structure's performance point in various stages can be obtained from the pushover curve. Different building performance levels in the base shear carried versus the roof displacement curve, as shown in Figure 2 [30]. A to B is the elastic range, B to IO is the immediate occupancy range, IO to LS is the life safety range, and LS to CP is the collapse prevention range. When the plastic hinge reaches point C on the force transfer curve, the plastic hinge must begin to lower the load [31]. The structure is said to be safe if all the plastic hinges are within the CP limit. On the other hand, if the plastic hinge formed exceeds the CP limit, the structure is said to have collapsed. The point of intersection of the curves is called the performance point.

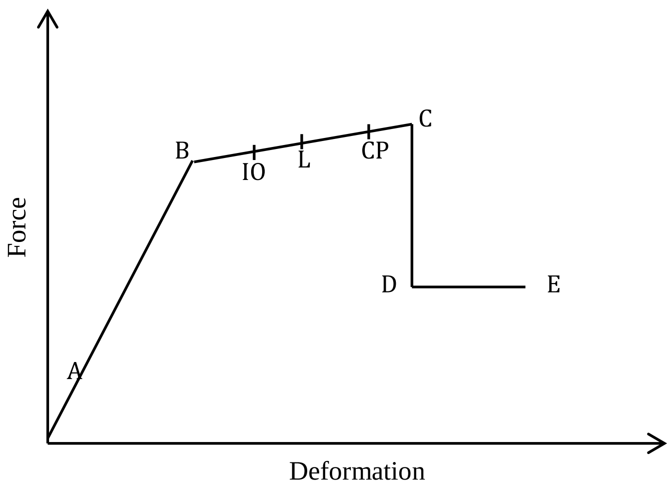


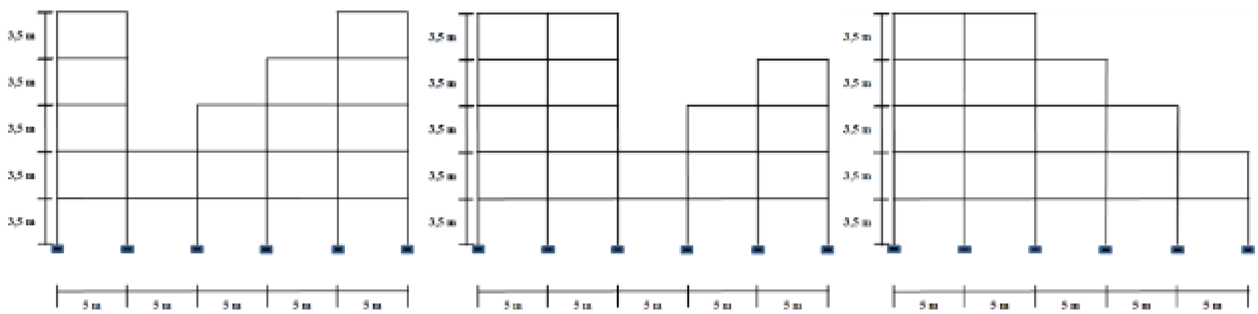
Figure 2: Performance level

The location (coordinates) of this point indicate the level of performance of the structure under the design earthquake load. This case shows the maximum base shear carried by the structure and its ductility characteristics. Non-linear static analysis is not a new development, and its origins can be traced back to the decade of the 70s [32]–[36]. However, the recent performance-based design process has brought pushover non-linear static analysis procedures to the forefront. In the last decade, most of the research has focused on the pushover method's various applications, advantages, and disadvantages. This paper aims to see the non-linear behavior of reinforced concrete frames with vertical irregularities through the pushover method using SAP2000 software.

II. METHOD

This paper presents a proposed 2D reinforced concrete frame model with variations of vertical irregularity in Figure 3. The nonlinear pushover static analysis method is used in this paper. Modelling and analysis of 2D reinforced concrete frames with vertical irregularities were performed with the help of SAP 2000 software. SAP 2000 facilitates the plastic hinge properties described in ATC-40 [37], [38]. The nature of automatic plastic hinges, such as PMM, is installed at the end of the column, and the M3 plastic hinge is installed at the end of the beam. Pushover analysis is carried out by considering controlled displacement analysis. The steps of modelling and analysis are presented in the form of a flow chart in Figure 4. Furthermore, the data used for modelling are as follows:

- Number of levels: 5;
- Height between stories: 3.5 m;
- Grade of Concrete: K-325;
- Grade of Steel: Bj-50;
- Column size: 0.4 m x 0.4 m;
- Column reinforcement: default software;
- Beam size: 0.4 m x 0.3 m;
- Super Dead Load: 15 kN/m;
- Live Load: 10 kN/m;
- Lateral load: 200 kN/m.



Model 1 Model 2 Model 3

Figure 3: Proposed model

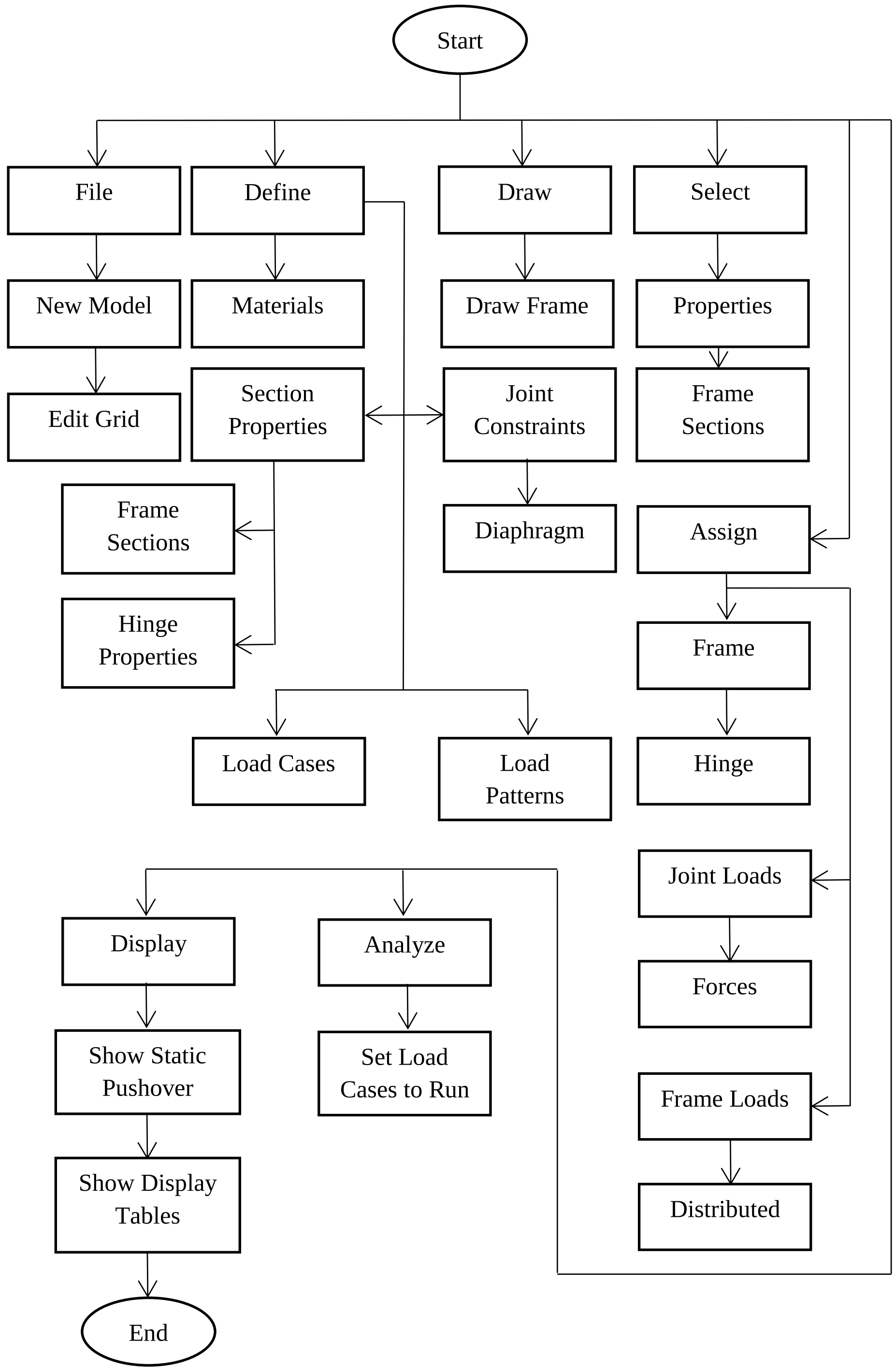
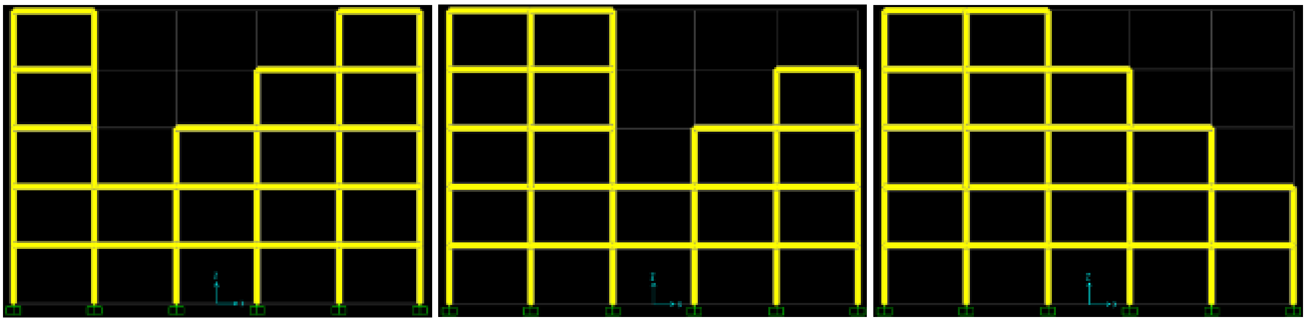


Figure 4: Flow chart

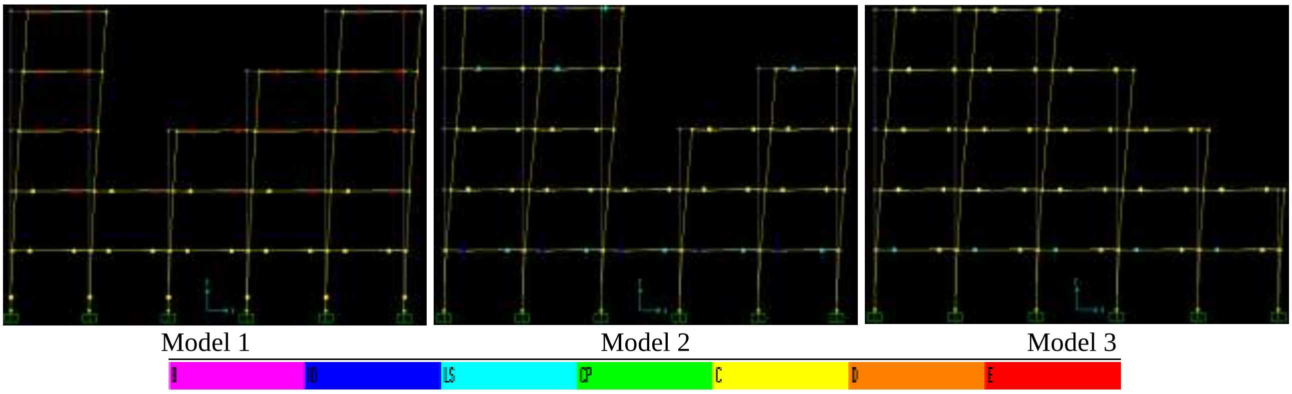
III. RESULTS AND DISCUSSION

Non-linear modelling and analysis of reinforced concrete frames with vertical irregularities using SAP2000 software have been obtained. Figure 5 shows the results of modelling reinforced concrete frames with vertical irregularities. Figure 6 shows the analysis results in the form of performance levels and the maximum deformation in the frame. Figure 7 shows the pushover curve in base shear and displacement. Model 1 shows that the plastic hinge on the column is within the CP limit, but some beams have crossed the CP limit, so the beam will collapse. Models 2 and 3 show that the entire plastic hinge is within the CP limit, so that beams and columns can be said to be safe from collapse.



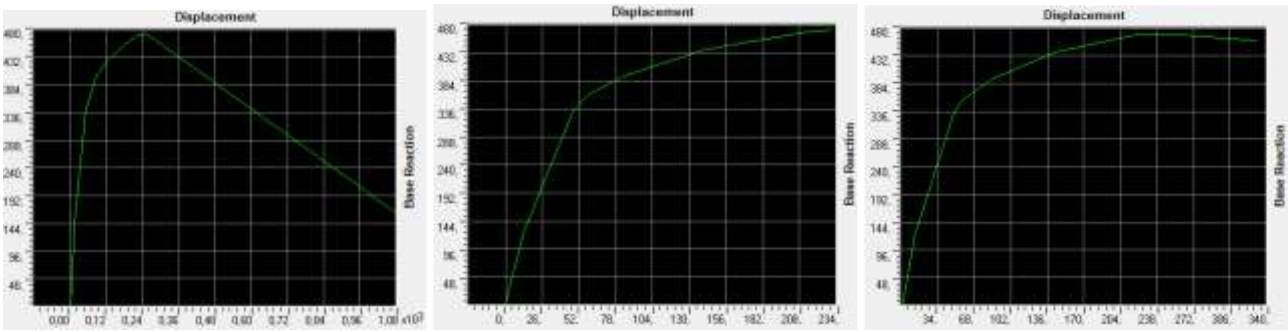
Model 1 Model 2 Model 3

Figure 5: Modelling results



Model 1 Model 2 Model 3

Figure 6: Maximum performance and deformation level



Model 1 Model 2 Model 3

Figure 7: Pushover curve

In Table 1, Table 2, and Table 3, step-by-step analysis results are presented in the form of base shear, displacement, and the formation of plastic hinges in each model. Each beam and column element is fixed with plastic hinges at both ends. So that one beam element represents two plastic hinges, the example in Table 1 for step 10 shows that 12 beam elements have collapsed. Furthermore, Figure 8 compares the pushover curves for each model.

Table 1: Step-by-step analysis of pushover model 1

Step	*Displacement* (m)	*Base shear* (kN)	B	IO	LS	CP	C	D	E	*Be*
0	0,000000	0,000	92	0	0	0	0	0	0	0
1	0,014273	142,656	91	1	0	0	0	0	0	0
2	0,049463	340,445	69	12	11	0	0	0	0	0
3	0,085093	397,587	57	12	23	0	0	0	0	0
4	0,124356	430,300	54	4	34	0	0	0	0	0
5	0,214083	468,683	54	0	11	17	0	10	0	0
6	0,220499	470,365	54	0	10	14	0	14	0	0
7	0,225648	471,264	54	0	9	11	0	18	0	0
8	0,236033	472,368	54	0	7	10	0	21	0	0
9	0,251670	473,120	54	0	6	8	0	24	0	0
10	1,083587	161,512	48	0	0	0	0	21	0	23

Table 2: Step-by-step analysis of pushover model 2

Step	*Displacement* (m)	*Base shear* (kN)	B	IO	LS	CP	C	D	E	*Be*
0	0,000000	0,000	90	0	0	0	0	0	0	0
1	0,012961	127,683	90	0	0	0	0	0	0	0
2	0,047877	333,342	69	11	10	0	0	0	0	0
3	0,058347	360,670	60	18	12	0	0	0	0	0
4	0,086721	395,907	54	12	24	0	0	0	0	0
5	0,140024	438,217	52	3	32	3	0	0	0	0
6	0,212970	468,422	52	0	11	16	0	11	0	0
7	0,215924	469,113	52	0	11	15	0	12	0	0
8	0,217077	469,530	52	0	11	15	0	12	0	0
9	0,222284	470,679	52	0	10	11	0	17	0	0
10	0,228598	471,509	52	0	8	10	0	20	0	0
11	0,232152	471,708	52	0	8	9	0	21	0	0
12	0,232152	471,708	52	0	8	9	0	21	0	0

Table 3: Step-by-step analysis of pushover model 3

Step	*Displacement* (m)	*Base shear* (kN)	B	IO	LS	CP	C	D	E	*Beyond*
0	0,000000	0,000	86	0	0	0	0	0	0	0
1	0,012614	122,025	86	0	0	0	0	0	0	0
2	0,048789	335,975	64	13	9	0	0	0	0	0
3	0,056895	356,861	56	17	13	0	0	0	0	0
4	0,086173	393,973	50	13	23	0	0	0	0	0
5	0,144113	439,423	48	3	31	4	0	0	0	0
6	0,217751	467,884	48	0	12	13	0	13	0	0
7	0,220419	468,347	48	0	12	9	0	17	0	0
8	0,221948	468,469	48	0	10	10	0	18	0	0
9	0,224444	468,815	48	0	9	8	0	21	0	0
10	0,250966	470,202	48	0	7	8	0	23	0	0
11	0,331510	458,339	48	0	0	5	0	33	0	0

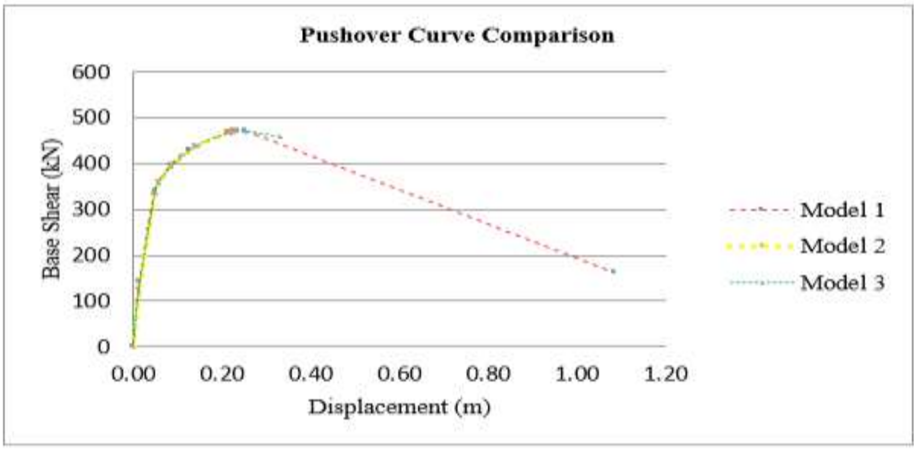


Figure 8: Pushover curve comparison

IV. CONCLUSIONS

The non-linear behavior of reinforced concrete frames with vertical irregularities was obtained using SAP2000 software. The analysis results show that the skeleton is susceptible to increasing vertical irregularity. As the vertical irregularity increases, the percentage of the plastic hinge crossing the boundary increases. The analysis results also show that model 2 has better behavior.

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