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Effect of Plastic Hinge Properties in Pushover Analysis of Reinforced Concrete Plane Frames

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Abstract - The four-bay, five-story Reinforced Concrete (RC) frame with two-dimensional beams and a column moment frame system that is vulnerable to Mosul, Iraq's seismic activity is examined. A plastic hinge symbolizes the member yielding failure mode in columns and beams. Utilizing SAP2000 software (V.16), the pushover study was carried out to confirm the code's fundamental goal of life safety performance under seismic events. By combining the seismic hazard with the inelastic structural analysis, one may determine the anticipated seismic performance of a structure. An essential outcome of pushover analysis for both brittle (force-controlled) and ductile (deformation-controlled) actions of the plastic hinge behavior is the base shear vs structure's tip displacement curve. The pushover analysis, using a variety of alternatives for the plastic hinge behavior, showed that the plastic hinge formed because of its brittle nature placed it in the more severe category. All of the plastic hinges created in the beams as a result of brittle behavior are placed in the risky branch ("Collapse Prevention CP") of the plastic hinge acceptance criterion. This necessitates increasing the shear strength of the beams.

Keywords: Building frame, Plastic hinge, Pushover analysis, Ductility, Reinforced concrete, Seismic performance.

I. INTRODUCTION

The prescriptive approaches of building regulations are often the foundation for the design of civil engineering construction. In the static scenario, these structures typically experience low loads and the behavior of elastic structures. However, during a powerful earthquake, a structure could actually experience stresses that exceed its elastic limit. Building regulations don't cover how a structure is supposed to work as a whole when it's subjected to strong forces, even though they can give a good idea of how well individual parts of a structure actually work. Engineering for Seismic Performance, which blends earthquake risk evaluation and structural analysis that is inelastic to determine the expected structural performance during earthquakes is becoming more practicable [1,2]. One method to predict how a structure would react to a strong earthquake is to use nonlinear time history analysis. Such analysis is not considered practical (PBSE), which usually necessitates nonlinear static analysis, also known as pushover analysis, because it generates so much data. Furthermore, new building regulations like IBC 2021 (" International Building Code") [3] and FEMA 356-2000 and FEMA 440-2005 ("the Federal Emergency Management Agency") [4, 5] favor more precise approaches (such as "pushover analysis") over conventional linear-elastic methods for a more detailed analysis. Many academics have made conclusions in recent years regarding how to improve, maximize, and building seismic design that takes into account control performance. Combining the failure path and probability of occurrence for plastic hinges to reinforce columns and beams, BAI JiuLin1 and OU Jin Ping [6] found that it is a practical technique to increase the frame structure's capacity for earthquakes. Three existing structures that were previously designed in accordance with Indian norms were examined by Vijayakumar A. and Venkatesh Babu D. L. [7]. They came to the conclusion that the seismic performance of these structures was insufficient, and they recommended that before restoration work began, it was important to check the buildings' ultimate capability to calculate the strengthening volume. The ductility parameter, which is important for estimating the structural systems of buildings made to withstand earthquake forces [8,9], shows how well a structure can spread energy, which makes less of an impact on its elasticity. The design seismic forces decrease as the ductility increases.

The expected building's inelastic response to lateral static loads that are delivered directly to the building frame's joints and are equivalent to projected seismic loads is evaluated in the current study.

II. PUSHOVER ANALYSIS

A static pushover analysis, nonlinear process that gradually increases the structural loading in accordance with a predetermined load pattern. Static pushover analysis, a useful and effective technique for performance-based design, is an

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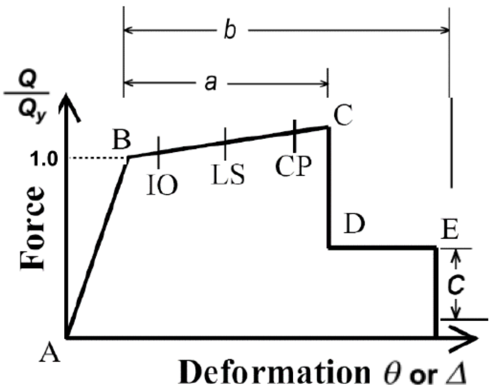
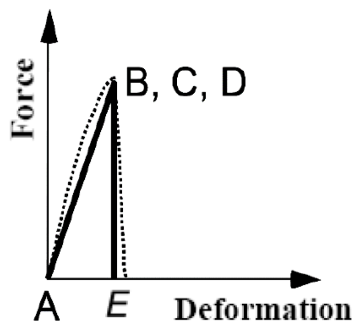
effort by the structural engineering profession to evaluate the true strength of the structure.

Pushover analysis modeling parameters, acceptance criteria, and techniques have been created and are described in the ATC-40, FEMA-356, and ASCE 41-13 [10,4,11] papers. These documents also detail the steps taken throughout the analysis to determine the degree of frame member failure. The member's inelastic behavior is regulated by either deformation-controlled (ductile action) or force-controlled (brittle action), as depicted in Figure (1), during the pushover analysis [12].



(i) Deformation-controlled option (Ductile Behavior)



(ii) Force-controlled option (Brittle Behavior)

Figure 1: Schematic depictions illustrating inelastic idealized Force-deformation relationships

Tables (6-7) and (6-7) of the ASCE41-13 [11] display the parameters' values (a, b, and c) for columns and beams. These factors are influenced by the section's characteristics, including the steel ratio in the tension and compression fibers, the design shear strength, the balanced steel ratio for the section, the concrete's compressive strength, the design axial load, and the cross section area.

The ratio of the yield moment to the curvature and associated moments makes up the moment-curvature relation for a member section. Once a hinge occurs there, this relationship has an impact on how that segment behaves. The section designer found in the SAP2000 program can be used to obtain all the values required to define the M- Øp relation. Based on Berry et al. and Paulay and Priestley [13], the plastic hinge length needed for these computations.

III. ACCEPTANCE CRITERIA (Performance Level)

The performance standard or acceptance criteria for the plastic hinges that were close to the joints is determined by three points denoted by the letters LS, IO, and CP (at the ends of columns and beams). Life Safety, Immediate Occupancy, and Collapse Prevention are each abbreviated as LS, IO, and CP, respectively. Several other characteristics specified in the ATC-40 specifications, as well as the type of member, affect the values assigned to each of these locations. The structural performance values of the concrete frames are shown in Table (1) [10].

Table 1: Description of performance levels of the concrete frame [10]

Elements	Type	Structural Performance Levels		
		Collapse Prevention S-5	Life Safety S-3	Immediate Occupancy S-1
Concrete Frames	Primary	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (< 1/8" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks < 1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
	Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints < 1/16" width.
	Drift[2]	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent

IV. NONLINEAR HINGE PROPERTY

In this study, the nonlinear hinge properties are calculated based on the models stored in SAP2000 package [14] that are:

4.1 The Interaction Surface between Axial Load and Moment (P-M)

A reinforced concrete segment's load capacity of a column or beam becomes inelastic and forms a hinge are determined by the P-M interaction surface. According to the ACI code (2019) [15], the P-M interaction surface was computed for a specific section shape, material, and reinforcement.

4.2 *M- θp* (Moment-Plastic Rotation) Relationship

Plastic rotation and related moments expressed as a ratio of yield moment make up the M-p relation for a member section. Once a hinge occurs there, this relationship has an impact on how that segment behaves. Using the FEMA recommendations in Table [4], it is possible to obtain all the values needed to define *M- θp* relationships.

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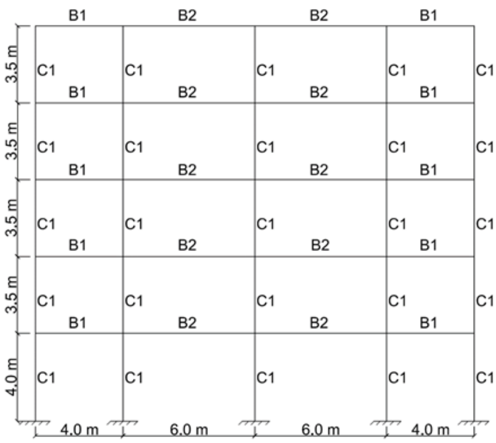
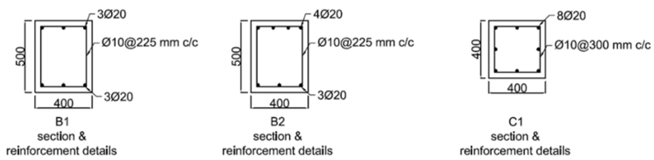
V. NUMERICAL APPLICATIONAND STRUCTURAL CAPACITY RESULTS

5.1 Case 1

As a numerical case, a four-bay, five-story reinforced concrete regular frame with (150 mm) slab thickness was used, as shown in Figure (2) with section details. At 28 days, concrete has a strength of (f'c) = 28.0 N/mm^2 for beams and (f'c) = 45.0 N/mm^2 for columns, whereas steel has a yielding strength of (fy) = 420 N/mm^2. No structural or geometrical anomalies [16], presumed to be in Mosul City, and classified as a "D" site (the ASCE7-13) [11]. Similar information about the P-M interaction for column hinges is shown in Figure (3). The building frame is modeled using two nodes of frame components (each end has three degrees of freedom) and the aforementioned geometric and structural data using the computer program SAP2000 (V.16) [14].



(a) Building Frame with key codes



(b) Sections details

Figure 2: Building Frame and Sections

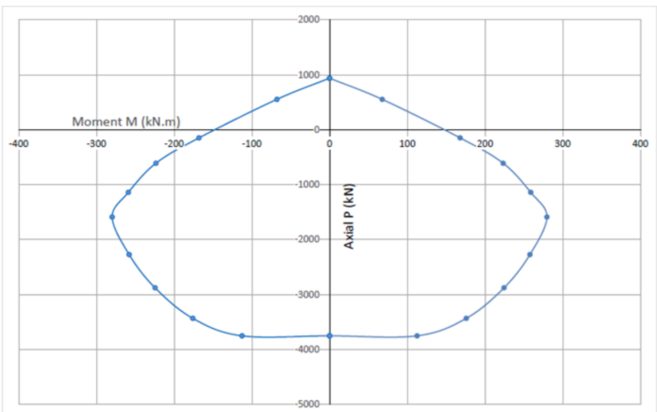


Figure 3: Interaction diagram for the columns of frame (C1 sections)

The process of the ATC-40 Capacity-Spectrum Method [10] begins with the development of the force-deformation relationship for a structure. Following that, the results are shown using the ADRS ("Acceleration-Displacement Response Spectrum") framework, as illustrated in Figure (4). The link between base shear and roof displacement is simply converted utilizing the dynamic characteristics of the system to produce what is referred to as a capacity spectrum for the structure.

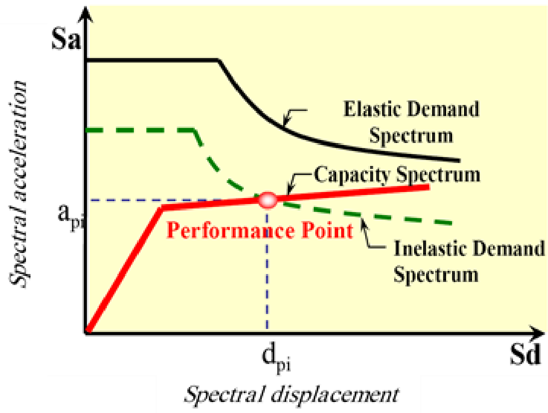


Figure 4: Set the performance point

The acceleration-displacement response spectrum (ADRS) format of the seismic ground motion indicated for the current investigation is also transformed, and the resulting data is referred to as a demand spectrum with flexibility (typically with a 5% dampening of the structure).

Additionally, effective damping, which differs the inelastic demand spectrum from the elastic demand spectrum, is used to present the inelastic structure behavior underneath a particular ground motion. The energy dissipation of the structure's hysteretic behavior is taken into consideration when calculating the effective damping, which also incorporates equivalent viscous damping [10] and intrinsic damping in the structure as shown in Figure (5).

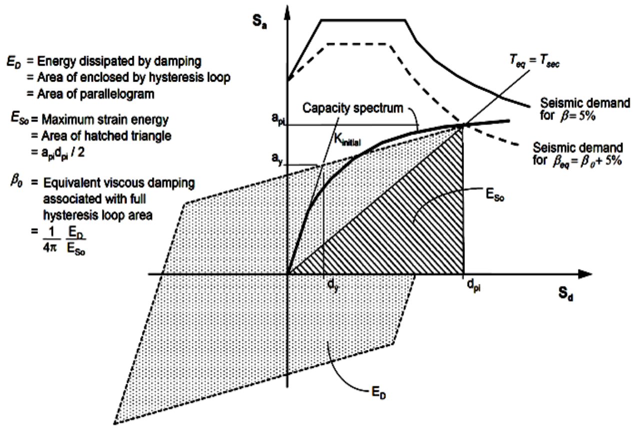


Figure 5: Graphical representation of the Capacity-Spectrum Method, as present in ATC-40 [10]

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The performance point, which is indicated by the intersection of the capacity spectrum and the inelastic demand spectrum in Figure (4), can be found by performing iterative calculations as described in ATC-40 [10]. The maximum displacement ductility ratio, ($\mu=\Delta max/\Delta yield$), and the nonlinear SDOF oscillator's effective period is determined by using the vibration's initial period. The related values for the performance point, which measures how well the building frame withstands earthquakes, are provided in Table (2) and displayed in Figure (6).

Table 2: Characteristics of performance point of the frame according to ATC-40 capacity spectrum approach

Effective Damping (β_{eff})	Effective Period (T_{eff}) Sec.	Spectral Acceleration (S_a) g	Spectral Displacement (S_d) cm	Base Shear (V) kN	Displacement at roof (Δ_{roof}) cm
0.051	0.545	1.1	8.23	770.3	10.4

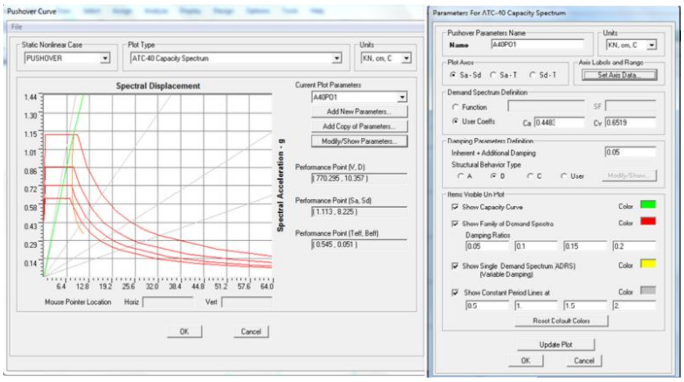

Figure 6: Demand spectrum, capacity spectrum, and parameters of ATC-40 method

In this study, the five-story building frame's seismic response was evaluated in a typical earthquake zone with seismic coefficients Ca = 0.4483 and Cv = 0.6519 ("Soil Type D"), according to Figure (6). Preferably, the initial analysis for the dead plus live loads is followed by the pushover study of seismic forces.

There were two hinges added to the ends of each element (columns and beams). The ultimate bending moment was created in the beams throughout the study, and the behavior of the hinges constructed in the columns was governed by the interaction curves of the axial force-bending moment (P-M).

The plastic hinge patterns at various loading stages are shown in Figure (7) together with the various control options that influence the plastic hinge's behavior throughout the investigation. Additionally, the figure depicts their condition using the relevant colors. All of the plastic hinges built into the beams are situated in the branch of the plastic hinge acceptance criteria connected to their flexural action that is harmful (collapse prevention CP) [17], while the plastic hinges related to their other action are damaged.

5.2 Case 2

In case 2, the same material properties and definition as in case 1 are applied. Equations for the interplay of axial load and bending moment (P-M) for columns and the bending moment only [M] equations for beams were included when the hinge for the columns and beams is modeled.

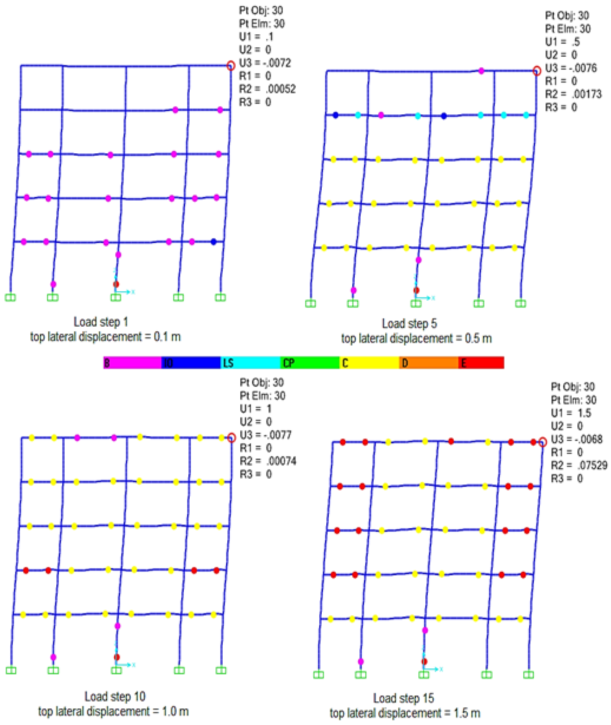

Figure 7: Plastic hinge patterns at different load steps

The SAP2000 section designer was used to calculate the moment curvature relation. The moment-curvature relationship of the frame sections is shown in Table (3). To simulate the moment-curvature behavior of plastic hinge development, the following two equations were utilized in the current work to calculate the plastic hinge length:

1- Berry formulation [16]:

$$L_p = 0.05\times L + 0.008\times f_y \times d_b \times \sqrt{f\grave{c}_m} \quad (1)$$

Where:

L_p = Plastic hinge length (m), L = Member length (m), f_y = Longitudinal reinforcement yield stress (MPa), $f\grave{c}_m$ = Concrete cylinder compressive strength (MPa). d_b = Diameter of longitudinal bars (mm).

2- Paulay and Priestley formulation [16]:

$$L_p = 0.08 \times Z + 0.022\times d_b \times f_y \quad (2)$$

Where:

Z : Distance from critical section to point of contra-flexure.

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Figure (8-a) depicts the hinge pattern for a frame whose hinge length was determined by equation (1), and Figure (8-b) depicts the hinge pattern for a frame whose hinge length was determined by equation (2).

Table 3: Moment-Curvature relation for (B1, B2 & C1) sections

B1 Section		B2 Section		C1 Section	
M (kN.m)	φ (rad.)	M (kN.m)	φ (rad.)	M (kN.m)	φ (rad.)
183.568	0.0845	183.228	0.0839	160.368	0.0715
131.376	0.006135	131.09	0.006107	116.898	0.008664
0	0	0	0	0	0
-131.376	-0.00613	-170.603	-0.00638	-116.898	-0.00866
-183.568	-0.0845	-235.761	-0.0754	-160.368	-0.0715

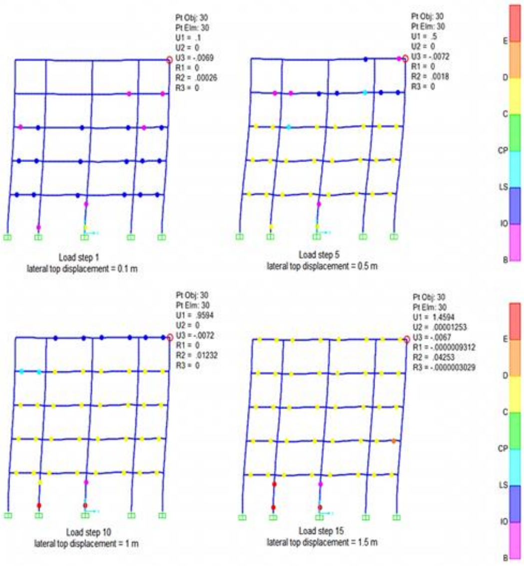

Figure 8-a: Plastic hinge patterns at different load steps Berry equation for hinge length calculation

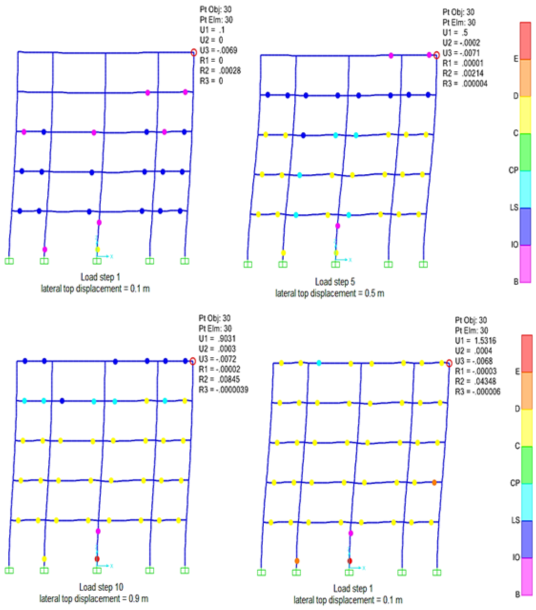

Figure 8-b: Plastic hinge patterns at different load steps Paulay and Priestley Equation for hinge length calculation

Table (4) shows the value of base shear and top displacement at performance point of ATC-40 approach [10], the results shows that the frame in case 1 (moment- rotation form ASCE41-13 [11]) that the frame needs to (783 kN) base shear to deflect (92 mm) at the performance point, (at this point, the seismic demand equates with the frame capacity), while the frame in case 2-a (moment-curvature was calculated form section properties and plastic hinge length obtained from Berry formulation) shows that the frame needs (652 kN) base shear to deflects (115 mm). So the frame in case 2-b needs to about (600 kN) to deflect (123 mm) at performance point, when Paulay and Priestley equation was used to calculate the hinge length. It is important to remember that the hinge length in case 2-b is larger than the length in case 2-a.

Table 4: Base shear and displacement at performance point by ATC-40 approach

Case	Base shear (kN)	Top displacement (mm)	Effective period (sec.)	Effective damping (unitless)
Case 1	**783.5**	**92.0**	**0.511**	**0.051**
Case 2-a	**652.4**	**115.0**	**0.626**	**0.079**
Case 2-b	**600.5**	**123.0**	**0.674**	**0.075**

The effective duration for cases 1, 2-a, and 2-b was (0.51), (0.63), and (0.67) seconds respectively. This period corresponds to the performance point of the ATC-40 technique [10].For cases 1, 2-a, and 2-b, the effective damping was (0.051, 0.079, and 0.075), respectively. Therefore, there is less energy lost when the hinge length is longer. In the ductile behavior of elements of frame, the amount of energy absorbed by structural elements differs significantly from the brittle behavior of the plastic hinge model by about 27% decreasing due to brittleness, Figure (9) demonstrates the decreasing in the adsorbed energy for different behaviors of plastic hinges after formations.

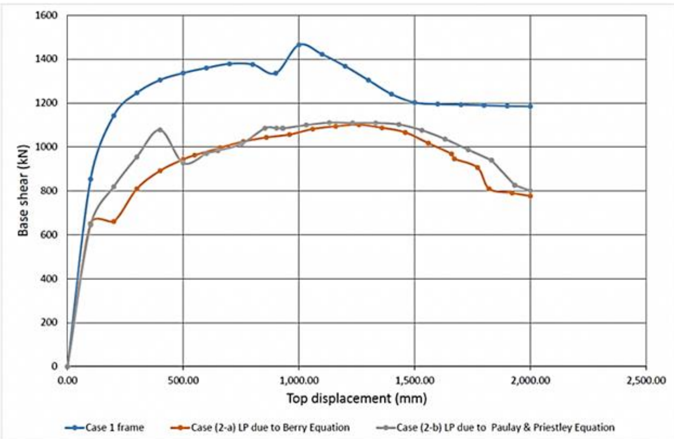

Figure 9: Capacity curve at the tip of frame for different cases of hinge length

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VI. CONCLUSION

An existing reinforced concrete building frame has been evaluated using the nonlinear static (Pushover) analysis, as described by ATC-40, when changing plastic hinge properties of main members of frame. The following are the primary conclusions:

1. Under a moderate seismic load, the nonlinear pushover method was employed to predict probable structural faults in the RC frame. The analysis demonstrated that, with considerable yielding at several beams, the frame can withstand the expected earthquake force for different lengths option of plastic hinges.
2. The structure shows the mechanism of strong column and weak beam during the analysis. Only the beams reveal the order in which the frame components' plastic hinges were made to yield.
3. The Acceptance Criteria for plastic hinges classifies all plastic hinges formed in the beams (for two models of plastic hinge length) as belonging to the hazardous branch ("collapse prevention CP"). This requires action of strengthening the beams.
4. The plastic hinge, which was caused by its brittleness, placed it in the most severe group when numerous alternatives of its length behavior were compared during the pushover investigation.
5. In the case of ductile behavior, the amount of energy absorbed by structural elements differs significantly from the brittle behavior of the plastic hinge model by about 27% decreasing due to brittleness. This behavior extends till the completion of the structural element bearing.

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