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Seismic Performance of Building with Haunched Beams by Simplified Non-Linear Static Analysis (NSA)

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Md. Foisal Haque

MSc Student, Dept. of Civil Engineering (Structural), Dhaka University of Engineering & Technology, Gazipur 1707, Bangladesh.

Corresponding Author's Email: mfh.civil@gmail.com

Abstract

Haunch mechanism of beam influences on the building performance under seismic loading. Displacement coefficient method expresses better performance of haunch than capacity spectrum method. Actually, evaluation of overall performance of a building is very complex because many primary and secondary components are involved with it. However, in this paper, seismic performance of 12-storied building with haunched beams is evaluated by displacement controlled non-linear static analysis (NSA) by using ETABS. Two variable parameters effect on overall performance of building and individual performance of haunched beams. These are haunch thickness and ratio of haunch length to beam length. These parameters control minimum base shear, plastic hinge rotation and plastic hinge moment. For all case, minimum value obtains for 6 inch of haunch thickness at haunch to beam length ratio of 0.2 except performance point target displacement. Minimum target displacement is very close to 12 inch for 10 inch thickness of haunch at haunch to beam length ratio of 0.3. In this research, plastic hinge response satisfies acceptance criteria, which ensures safety of building under seismic loading

Keywords: Haunched Beams; Non-Linear; Performance; Seismic; 12-Storied Building.

1. Introduction

Generally, reinforced concrete haunched beams are used for the construction of bridges, cantilever retaining wall, flyovers, low-rise buildings etc. (Colunga, 1994; Alberto et al., 2015 and Hou et al., 2015). Building with haunched beams is the modern technique to increase performance against seismic loading. These beams increase lateral resisting capacity, shear capacity, stiffness and ductility behaviors of structures and it reduces drift and weight of structures (Jolly and Vijayan, 2016; and Colunga, 1994). Mainly, non-prismatic mechanism of haunched beam controls structural behaviors (Brown, 1984). Therefore, it resists heavy earthquake (Mayer, 1979) because it carries sufficient structural capacity than other beams. Sometimes, haunched beams are used in retrofit purpose (Calderon et al., 1988) for expecting exclusive structural behaviors. Generally, seismic performance of haunched beam depends on two variables such as haunch length and parabolic variation of haunch (Alberto et al., 2015). Numerically, several authors (Colunga, 1994; Alberto et al., 2015; Nampalli and Sangave, 2015; Penelis and Papanikolaou, 2010; and Rahman et al., 2012) have been evaluated performance of haunched beams under seismic loading by non-linear static analysis (NSA). The vital issue of haunched beam has controlled shear failure under seismic loading (Hou et al., 2015 and Alberto et al., 2015). Experimentally (Hou et al., 2015), seismic performance of haunched beams have been evaluated by artificial cyclic loading. However, haunched beam shows better performance than prismatic beam under seismic loading based on past studies.

In the present research, seismic performance of haunched beam is evaluated by finite element method by using ETABS. Simplified non-linear static analysis (NSA) evaluates acceptance criteria of 12-storied building. NSA method is simplified because there have not addressed following items such as staged construction, large displacements effect, anisotropy etc. Traditional NSA expresses these issues. For neglect complexity, material non-linearity and small P-Delta effect are considered for analysis. Overall structural response depends upon the following parameters such as target displacement, base shear, plastic hinge rotation and plastic hinge moment. Behaviors of these parameters are evaluated by NSA. Haunched beam protects joint from shear failure during spectral seismic shaking. Variations of haunch thicknesses and relative lengths control acceptance criteria and overall structural response. Various codes (BNBC 2021 and ACI 318-14) have not clearly addressed suitable thickness and relative length of haunch. These limitations of codes contrast with the present research. In this study predicts suitable thickness of haunch and relative length based on acceptance criteria and structural performance under seismic loading. These parameters are related with the target displacement, base shear and behaviors of plastic hinges. Therefore, these haunch parameters have optimized contrast between codes and this research.

2. Description of Finite Element (FE) Model

Finite element method is more accurate than others numerical methods. In the present study, finite element model are performed by ETABS. In the present model in ETABS, beams and columns are modelled as a 2-noded line element and slabs are modelled as a 4-noded quadrilateral shell element. Numerical solution of such elements are performed by Gauss integration rules. 12-storied, square size reinforced concrete building is considered for analysis. The main reason of consider square size building has to obtain similar structural response of two orthogonal directions in a plane. The height of the building has more than two times of length of building. These length, width and height are considered to form this building in low-rise category. Haunch structural response effects on the building response. Therefore, variations of haunch parameters are considered for analysis and building dimension, height and numbers are constant. Normally, haunched beams are provided in larger span. For low-rise building, larger span varies from 21 feet to 30 feet (Colunga, 1994). In this reason, two different length of beams are considered for getting variable structural response. In addition, two different square and rectangular sizes span represent various acceptance criteria when seismic shaking occurs. Plan and 3D mesh view of building are represented by Figure 1 and Figure 2.

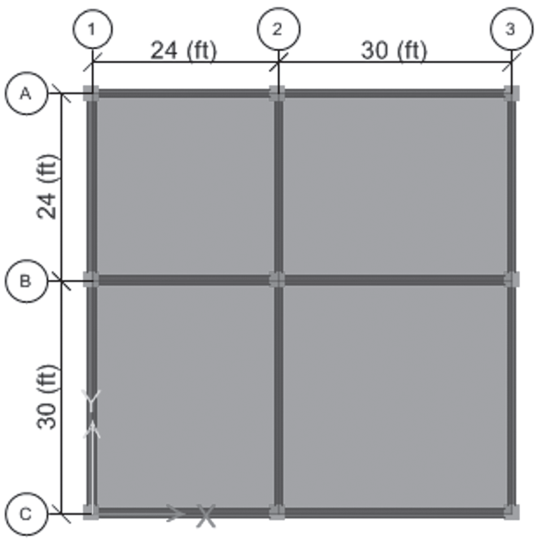

Figure 1: Plane of FE model

Figure 2: 3D mesh view of FE model

2.1 Geometric Properties

In plan and 3D represent three types of structural elements such as columns, beams and slabs. All columns are same in size. Depth and width of column are 24 inch and 24 inch. All beams are haunch and width is 12 inch. At support, depths are 24 inch, 26 inch and 28 inch. At the end of haunch portion, depth and width of haunch beam are 18 inch and 12 inch. Prismatic beam starts from the end of haunch portion. Two lengths of haunched beams are 24 feet and 30 feet. Thickness of slab is 6 inch. Each storey height is 10 feet.

2.2 Connections and Boundary Conditions

All connections are moment connections and rigid diaphragm is considered for analysis. Fixed boundary condition is considered for analysis and it is provided at the bottom of all columns. Embedded length of building is considered to be 5 feet.

2.3 Material Properties

Beams, columns and slabs are considered to be isotropic elements. Poission's ratio of concrete and steel are 0.20 and 0.30. All members of this building are made by stone chips, 28-days cylindrical compressive strength of concrete is 4000 psi and yield strength of steel is 60000 psi. Normal weight concrete is considered for analysis. Coefficient of thermal expansion of concrete and steel are 5.5×10^{-6} and 6.5×10^{-6}.

2.4 Information of Haunch Section

Haunch beam consists of constant width but it thickness and length are variable. Figure 3 represents longitudinal section of haunched beam. Whole beam is separated by two parts such as haunch portion and normal portion of beam. Thickness of normal portion of beam is represented by h_1. Variable thickness and length of haunch portion are expressed by h_y and l_x.

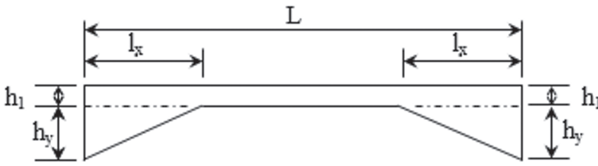

Figure 3: Longitudinal section of haunch beam

2.5 Methodology of Loadings

Two different types of loads are provided in the present model such as gravity load and seismic load. Gravity load consists of dead and live load. Dead loads are self-weight of structure, superimposed line loads on beams, superimposed surface loads on slabs and floor finishes. Superimposed load on beams is considered to be 0.5 k/ft. Floor finish and extra load on slab are 25 psf and 100 psf. Live load is considered to be 125 psf. Seismic load is directly proportional to the full gravity loads and 25 percent live load. Full live load is taken for analysis. Some factors are influenced to the seismic force, which are zone coefficient, structure importance coefficient, soil type, fundamental time period of building and response modification factor. Seismic analysis is performed based on Bangladesh National Building Code (BNBC 2021). For analysis, the value of seismic zone coefficient, structure importance coefficient and response modification factor are 0.20, 1.00 and 5.0. Soil type is considered to be "SC" for analysis. In addition, building is considered to intermediate moment resisting frame.

2.6 Analysis Procedure

Deformation controlled iterative non-linear static analysis (NSA) is performed for evaluation of seismic performance of building and haunched beams. In NSA, scale factor and P-Delta effect are included. Scale factor expresses seismic coefficient and non-iterative mass based P-Delta effect is considered for analysis. Displacement control point is at roof. Minimum and maximum number of saved steps are considered to be 10 and 100. NSA continues until convergence achieved. Moment-rotation and isotropic hysteresis types plastic hinge is considered for NSA. For satisfy acceptance criteria, plastic rotation values of immediate occupancy (IO), life safety (LS) and collapse prevention are 0.01, 0.025 and 0.05. Plastic hinges are provided in beams and columns. Beams contain only flexural plastic hinge and columns contain flexure-shear plastic hinge. Hinges are provided at near of beam-column joints.

Firstly, linear static analysis is performed for dead, live and seismic loads and secondly, non-linear static analysis is performed for dead load, live load and pushover cases.

3. Interpretation of Results and Discussions

Performance point is found to be intersection of capacity curve and bi-linear demand curve, which is also known as point of target displacement. Damping, short term spectral acceleration factor, spectral acceleration of 1s and long term transition period are considered to be 5 percent, 0.2s, 1s and 8s, which are influenced on the target displacements. Thickness of haunch and relative length are impacted on the capacity curve as well as performance point. Variable thicknesses of haunch are considered to be 6 inch, 8 inch and 10 inch. Similarly, relative lengths are taken as 0.20, 0.25 and 0.30. Relative length expresses the ratio of haunch to beam length.

3.1 Output of Non-Linear Curves

Performance point is represented by Figure 4 when haunch thickness and relative length are 6 inch and 0.20. This point expresses X-direction performance as per plan of building. In this case, target displacement is 14 inch and base shear is 485 kip. Bi-linear force-displacement and capacity curve represent similar results upto 2.7 inch roof displacement. This portion represents linear behavior.

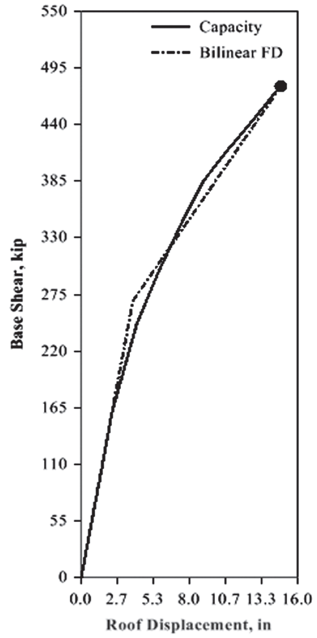

Figure 4: Representation of performance point for X-direction of building plan

3.2 Behaviors of Plastic Hinges

In this paper, plastic hinge rotation depends on the variations of haunch thickness and relative length. Most of the cases, rotations of plastic hinges are stand within acceptance level of immediate occupancy (IO) and life safety (LS). Acceptance criteria due to plastic hinge rotation is represented by Table 1. Maximum plastic hinge rotations are observed at two different locations of beams such as B7 for X-direction and B6 for Y-direction. These rotations are found for the variations of haunch thicknesses and relative lengths. Except two cases, acceptance level has reached life safety (LS) level when thickness of haunch and relative length are 6 inch and 0.30. Figure 5 represents plastic hinge rotation at haunch thickness of 6 inch and relative length of 0.20. Also, locations of B7 and B6 in building plan are represented by Figure 6.

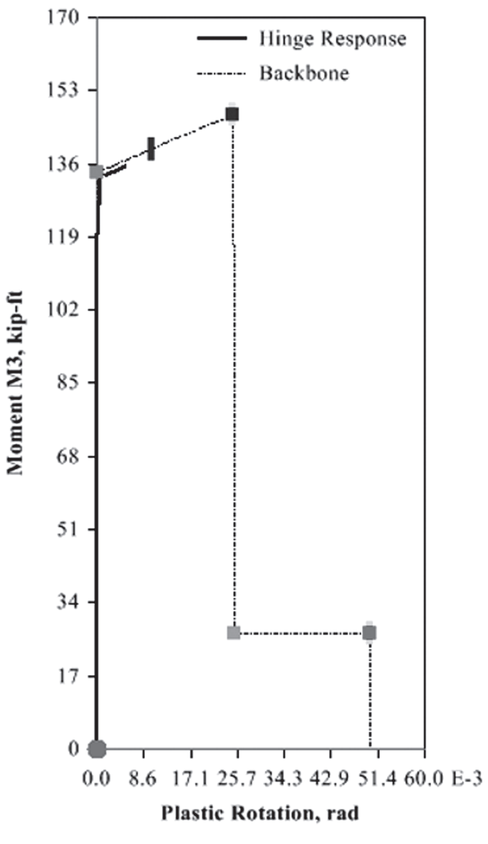

Figure 5: Plastic hinge rotation at B7 location in X-direction

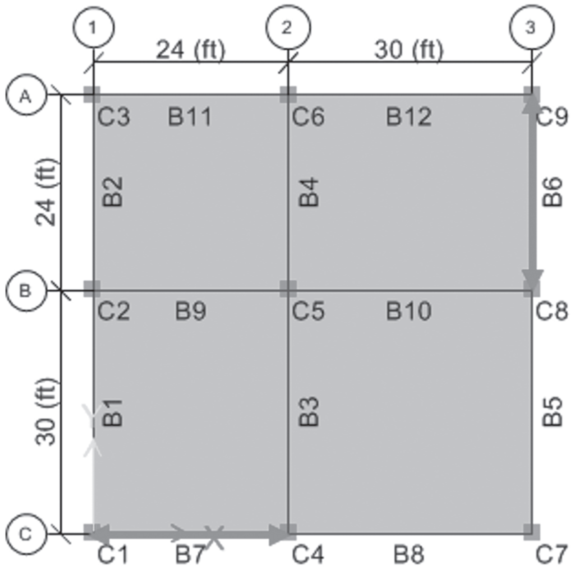

Figure 6: Locations of B7 and B6 in FE model plan

Table 1: Plastic hinge acceptance level status

Haunch thickness, h_y (inch)	Ratio of haunch length to beam length, l_x/L	Hinge status (X-direction; ID: B7; First Floor)	Hinge Status (Y-direction; ID: B6; First Floor)
6	0.20	IO	IO
8	0.20	IO	IO
10	0.20	IO	IO
6	0.25	IO	IO
8	0.25	IO	IO
10	0.25	IO	IO
6	0.30	LS	LS
8	0.30	IO	IO
10	0.30	IO	IO

3.3 Variations of Drifts

Structural stability depends on the variations of drift. Drift varies haunch and non-hunch case. This variation of drift is expressed by Table 2. Fundamental period of this building is greater than 0.7 second. So inter storey drift is 0.004 times of storey height as per code. Drifts are same in two directions because of symmetry. Depth of non-haunch and haunch beam are 18 inch and 24 inch. According to linear static analysis, drift exceeds from code prescribed limiting value for both cases. Top two or three stories, drift stands within code defined limiting value for both cases. Therefore, it is proof of requirement of non-linear analysis.

Table 2: Inter storey drift variations of haunch and non-hunch cases

Storey level	Inter storey drift (ETABS)		Code (BNBC 2021)
	Haunch	Non-Haunch	
1	0.54	0.70	0.48
2	0.74	1.02	0.48
3	0.81	1.14	0.48
4	0.80	1.17	0.48
5	0.77	1.12	0.48
6	0.72	1.06	0.48
7	0.65	0.96	0.48
8	0.59	0.84	0.48
9	0.49	0.72	0.48
10	0.39	0.58	0.48
11	0.29	0.44	0.48
12	0.20	0.32	0.48

After non-linear analysis, drifts are stand within code prescribed limit. Drift decreases within range of 21% to 35% from non-haunch to haunch. Therefore, haunch mechanism controls structural response based on drift performance.

3.4 Behaviors of Target Displacements

Variations of PPTD in X and Y directions are represented by Figure 7 and Figure 8. Performance point target displacements (PPTD) are gradually decreasing with the increment of relative lengths (lx/L) of haunched beams for both directions of FE model plan. Also, PPTD's are decreasing gradually with the increment of haunch beam thickness (HBT). Minimum PPTD is found to be 12 inch in Y-direction, when thickness and relative length of haunch are 10 inch and 0.3. PPTD's of X-direction are higher than Y-direction although plan of the building is symmetric. So, main seismic force resisting direction is X and lateral stiffness of the building is high along this direction. PPTD variations between any of two haunch thicknesses are less than 1 inch for both directions.

Lower difference of PPTD indicates better response of structure. Larger length and thickness of haunch represent lower target displacement and this displacement is lower than allowable displacement of linear analysis. Therefore, structure is safe against lateral deflection under seismic loading and it properly informs adequate lateral stiffness within acceptance level.

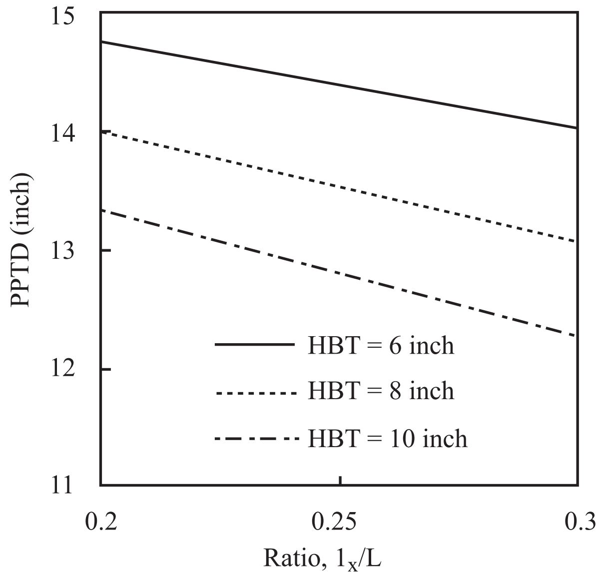

Figure 7: Performance point target displacement (PPTD) variations in X-direction

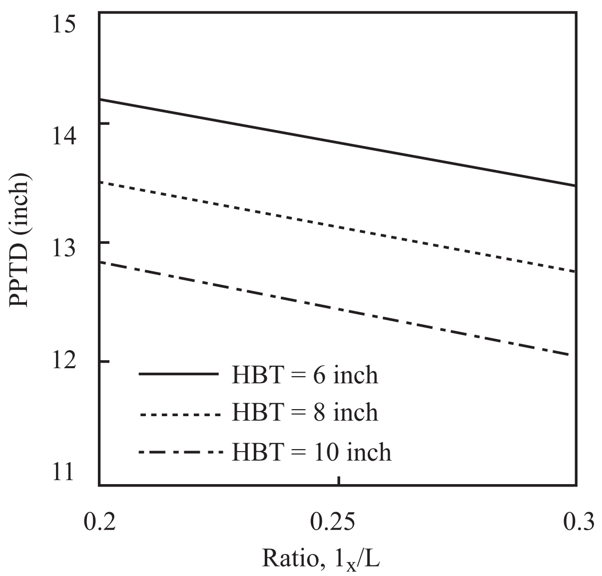

Figure 8: Performance point target displacement (PPTD) variations in Y-direction

3.5 Variations of Base Shear

Base shear variations in X and Y directions are expressed by Figure 9 and Figure 10. Base shears are increasing gradually with the increment of relative lengths (lx/L) of haunch in X and Y directions. On the other hand, increment of base shear is proportional to the increment of thickness of haunch (HBT). Maximum base shear represents minimum target displacement for both directions. Base shear varies 30 kip to 35 kip between any of two consecutive haunch thickness for both directions. Maximum base shear capacity indicates stable condition of structure because minimum performance point target displacement shows in this location. Minimum base shear capacity is 477 kip in X-direction, when haunch thickness and relative length are 6 inch and 0.20.

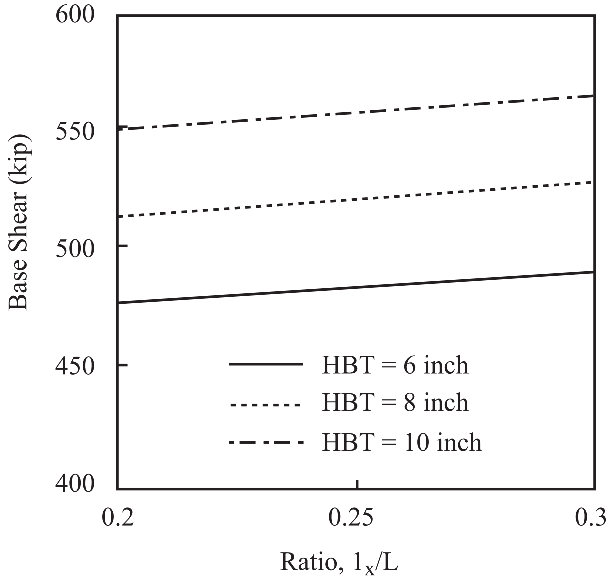

Figure 9: Base shear variations in X-direction

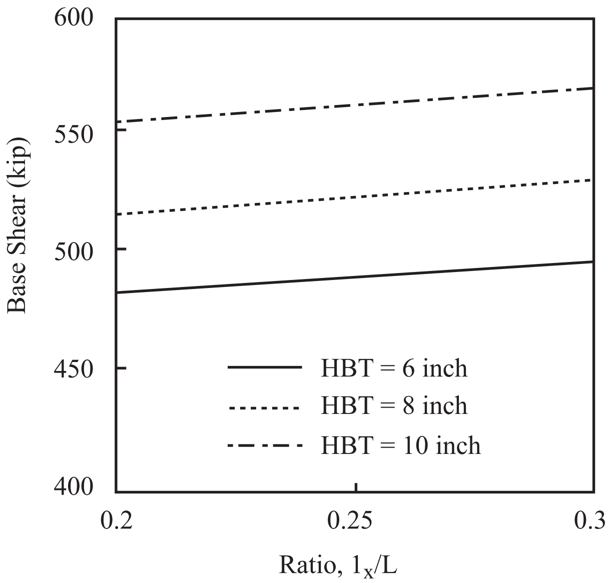

Figure 10: Base shear variations in Y-direction

Variations of base shear is very low with the increment of relative lengths. Therefore, base shear is controlled by the variations of haunch angles as well as haunch thickness because haunch thickness is the function of haunch angle.

3.6 Performance of Plastic Hinge Rotation

Irregular variations of plastic hinge rotation (PHR) are shown in Figure 11 and Figure 12 for X and Y directions respectively. PHR is decreasing first and it is increasing with the increment of relative length (lx/L) for 6 inch thickness of haunch beam (HBT). This phenomena occurs for both directions. PHR's are decreasing with the increment of relative lengths for 8 inch haunch thickness. On the other hand, PHR's are increasing with the increment of relative lengths, when haunch thickness is 10 inch. This mechanism is valid for both directions. Plastic hinge rotations are fluctuated with the variations of haunch thicknesses for both directions. Maximum rotation represents worst condition of haunched beam. In addition, it expresses reduction of lateral force resisting capacity. Minimum PHR is found to be 0.00495 rad for haunch thickness of 6 inch at relative length of 0.20 for X-direction. PHR is same for 6 inch and 8 inch haunch thicknesses along X-direction, when relative length is 0.26. Similarly, PHR is same for 6 inch and 10 inch haunch thicknesses along X-axis for relative length of 0.265. For Y-direction, similar plastic hinge results are shown in four locations and relative lengths of these locations are approximately 0.225, 0.258, 0.260 and 0.274 respectively. In these locations, plastic hinges rotations are not influenced by the variations of haunch thicknesses. Plastic hinges rotation values are lower than the acceptance criteria of immediate occupancy (IO) in both directions. Therefore, structural members are safe against collapse under seismic loading.

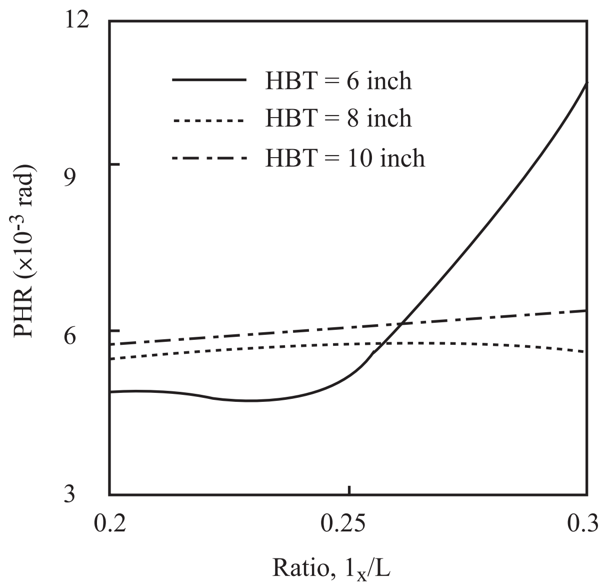

Figure 11: Variations of Plastic hinge rotation (PHR) in X-direction

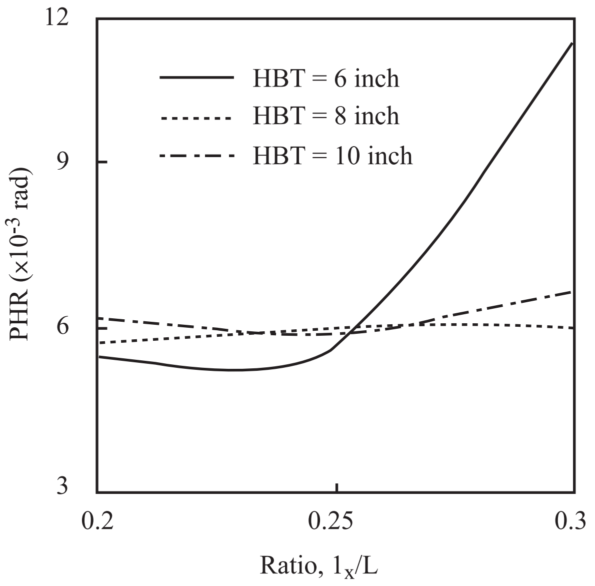

Figure 12: Variations of Plastic hinge rotation (PHR) in Y-direction

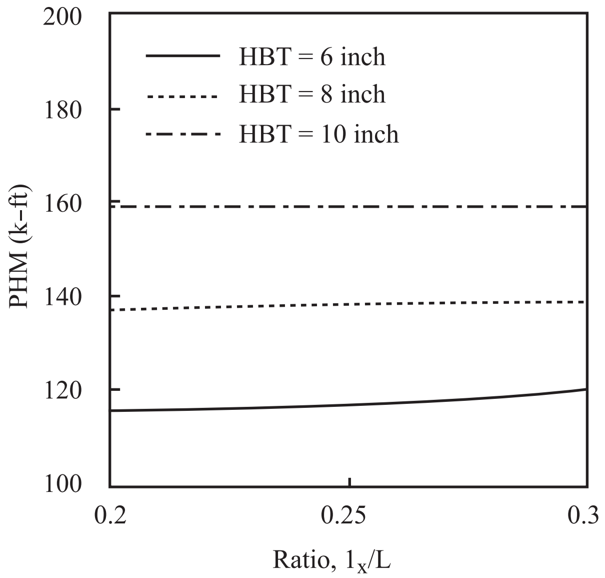

Figure 13: Variations of Plastic hinge moment (PHM) in X-direction

3.7 Performance of Plastic Hinge Moment

Uniform variations of plastic hinge moment (PHM) in X and Y directions are represented by Figure 13 and Figure 14. PHM is not influenced by the variations of relative length (lx/L), when haunch thickness is 10 inch at X-direction. Similarly, it is not influenced by the variations of relative length, when thickness of haunch is 8 inch at Y-direction. Variations of PHM are very small for X-direction, when haunch thicknesses are 6 inch and 8 inch. Similar results are observed for Y-direction, when haunch thicknesses are 6 inch and 10 inch. Variations of PHM in X and Y directions are nearly similar. Minimum PHM occurs at same location of minimum PHR. PHM variations between any two hunch thicknesses are nearly same for both directions. Minimum value of PHM is 115 kip for haunch beam thickness (HBT) of 6 inch at relative length of 0.20 for both directions.

PHM is controlled by HBT. PHM represents moment capacity at beam column joint. This capacity is lower than the demanding moment of this joint. Therefore, joints are safe against failure under seismic loading. Higher haunch thickness shows maximum moment capacity in both directions. PHM stands within immediate occupancy level of acceptance criteria.

Behaviors of plastic hinges at the specific locations of haunched beam are influenced on the overall performance of the building as well as individual performance of haunched beam. In ETABS, minimum relative locations of plastic hinges from both ends of haunched beam are used to be 0.02. For this reason,

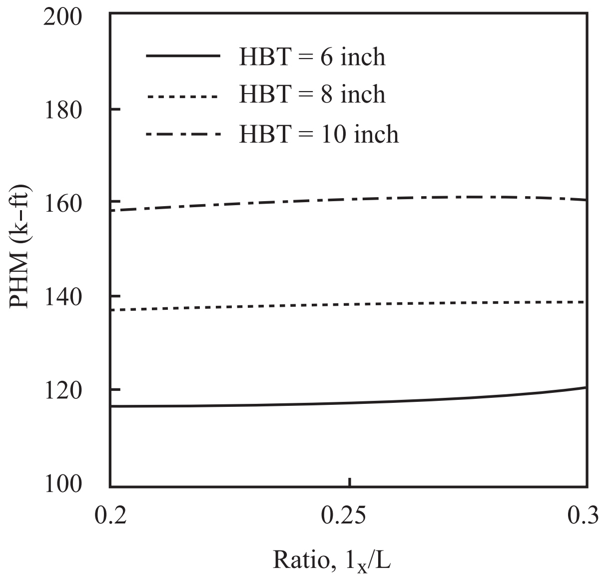

Figure 14: Variations of Plastic hinge moment (PHM) in Y-direction

performance of control node at roof and joints meet the acceptance criteria under seismic loading.

4. Conclusion

Lateral seismic force influences on the individual performance of haunched beam and overall performance of building. Most of the hinges are formed within one to five steps of loading based on output results of pushover analysis. Simplified non-linear static analysis has controlled haunched beams from collapse. In addition, it optimizes the inter storey drift of building under seismic loading. Geometric non-linearity has not influenced on the present study based on traditional non-linear analysis. Mass based load-deflection analysis executes the performance mechanism. In addition, building and individual beams have satisfied acceptance criteria. The main contrast between the present research and codes has not clearly defined haunch parameters. This study tries to overcome such limitations. All members of the building have not reached collapse state although anisotropy and compressibility have not influenced them. In haunch mechanism reduces depth of some portions of beam and it increases structural response under lateral loading. Overall depth of haunch beam complies with the codes prescribed depth although codes have not clearly addressed about the thickness of haunch. Therefore, haunch action of beam satisfies strong column and weak beam theory.

All beams and columns have met immediate occupancy (IO) level of acceptance criteria except one location. This location indicates haunch thickness of 6 inch at relative length of 0.3. Minimum target displacement is 12 inch and all values of target displacements have met acceptance criteria within the seismic performance level. Maximum base shear is captured by minimum displacement of performance point. Monitored displacement of control node is 1.25 times of target displacement. Haunch thickness and relative length of haunch have influenced target displacements. Minimum value of plastic hinge rotation occurs at minimum plastic hinge moment and maximum base shear, which controls minimum displacement of performance point. Haunch decreases drift limit and it increases internal moment resisting capacity of beam. Difference of results of drifts for haunch and non-haunch cases varies from 21% to 35%. Plastic hinge rotation and moment capacity, base shear capacity are increased with the increment of haunch thickness although target displacement has decreased. Therefore, larger thickness of haunch controls structural response as well as acceptance criteria under seismic loading.

In the present study, variations of force-displacement and capacity curves are close each other. These behaviors inform sufficient lateral force resisting capacity of structure. However, structural stability is controlled by haunch thickness and mechanism of plastic hinges. Therefore, haunched beam expresses adequate structural response under seismic loading than conventional prismatic beam.

Acknowledgment

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