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Performance Based Seismic Design Analysis of Steel Frames for Various types of Bracings

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Abstract – In the recent earthquake, it is observed that losses are increased due to the seismic design of buildings using codal procedure is not able to achieve best performance during earthquake. The Civil Engineering profession has been changing the structural engineering design paradigm from life safety (LS) to Performance Based Seismic Design (PBSD) to tackle catastrophic damage caused by recent earthquakes worldwide. This paper is about the PBSD analysis of steel frame subjected to earthquake loading. Steel is by far the most versatile building material in the world and steel structure has played a major role in construction industry in the last decades. In this a multistoried bare and braced steel frames are analyzed by PBSD procedure in STAAD Pro Advanced following nonlinear static analysis. Frame components (beam, columns, etc.) are progressively adjusted to account for nonlinear elastic–plastic behavior under constant gravity loads and incrementally increasing lateral loads. Capacity curve is obtained for each frame and comparatively studied to decide which type of frame can meet the desired performance level during earthquake. The results of the analysis performed to meet required performance are presented in terms of displacement, shear forces, plastic hinges and capacity curve.

Keywords – Performance Based Seismic Design, Nonlinear Static Analysis, Steel Frames, STAAD Proadvanced, steel structures, bracings, pushover analysis

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1. INTRODUCTION

Reference [1] says that the performance-based design is a more general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard. The performance targets may be a level of stress not to be exceeded, a load, a displacement, a limit state or a target damage state. Reference [2] says recent earthquake caused catastrophic damage in overall world. Steel structures are considered mostly earthquake resistant structure but some significant failures have occurred. Recent earthquake events demonstrate the necessity of change in structural design guidelines. To protect and maintain the economic activity and prosperity of a region, the performance of structure caused by earthquake became a major factor. That's why Civil Engineering profession is updating structural design paradigm of life safety (LS) to the performance bases seismic design (PBSD). Conventional seismic design approaches have the purpose of ensuring life safety (strength and ductility) and regulation of damage (drift limits for serviceability). The design parameters are specified by the stress limits and the strengths of the members determined from the prescribed lateral shear force.

Reference [3] and [4] says there have been different interpretations of what is meant by performance-based design. The most appropriate definition is that performance-based design refers to the methodology in which structural design criteria are expressed in terms of achieving a set of performance objectives.

Reference [9] using an appropriate structural system is critical to good seismic performance of the buildings. While moment frame is the most commonly used lateral load resisting structural system, other structural system is also commonly used such as braced system. A bracing is a system offered to reduce lateral structural deflection. Braced frame virtually eliminates bending factors for the column and girders and thus improve the efficiency of mere rigid frame behavior. Reference [5] already proved that braced frame decreases the displacement of the structure and absorbs more energy during earthquake. But the study does not comment on the effect of the position of the bracing on the structure. Considering this gap, in this study 4 frames are considered one is moment and remaining 3 are braced frame. In that there are three types of bracings X-type, V-type and K-type are externally braced as reference [10] concluded that V type external bracings perform well under lateral loads. [14] Comparative study of four frames is presented in the study to demonstrate which structural design shows best performance under earthquake loadings.

2. METHODOLOGY:

2.1 Finding best bracing model for G+10 building by performing Pushover analysis.

2.2 In Pushover analysis applying push loads in lateral direction and checking the base shear v/s displacement graph after that the analysis is carried out on without bracing model and with various types of bracing model.

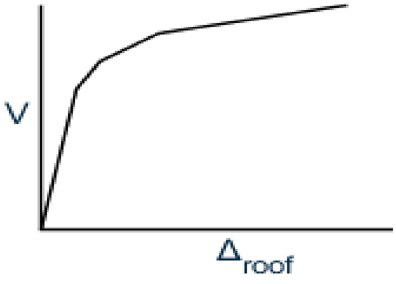
3. NON-LINEAR STATIC ANALYSIS

Non-linear static analysis (Pushover analysis) explained in FEMA 356 and ATC 40. In this method, lateral loads applied in whole-in one shot at a particular point of the structure. In pushover analysis method, structure responses calculated by applying full force or giving target displacement, which is nothing but the 4%, of the height of the structure. Elastic analysis used to determine the lateral seismic forces, which are the reduced to inelastic design force levels by the response modification factor.

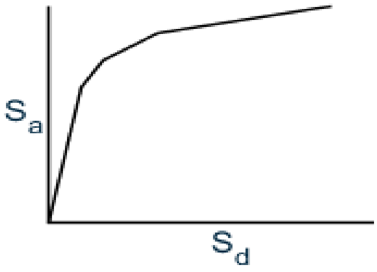
Structural frames considered are analyzed in STAAD Pro advanced by nonlinear static analysis, popularly known as pushover analysis which is one type of PBSD. Reference [6] was that the nonlinear seismic analysis is used in structural Engineering profession to design steel frames for moderate to strong earthquakes. Reference [7] was that the linear procedures maintain the traditional use of a linear stress-strain relationship but incorporate material acceptance criteria to permit better consideration for probable non-linear characteristics of seismic response. The non-linear static procedure, often called “pushover analysis,” uses simplified nonlinear techniques to estimate seismic structural deformations. As per FEMA 356 reference [7], a pushover analysis is a static nonlinear way of estimating seismic structural deformations using a simplified, non-linear technique. Earthquake engineering research is progressing rapidly to consider the nature of buildings that have been exposed to powerful earthquakes. Pushover analysis is done to be able to predict such behavior. The overall capacity of a structure depends on the strength and deformation capacities of the structure's individual components. Reference [11] was to evaluate capacities beyond the elastic limit some form of nonlinear analysis is needed, such as Pushover Analysis. It is a modern performance based seismic design (PBSD) for analytically achieving a structural design that will work reliably under one or more seismic conditions in a specified manner. There are two nonlinear procedures using pushover methods: a. Capacity Spectrum Method b. Displacement Coefficient Method. In this analysis particularly Capacity Spectrum Method is used.

A. Capacity Spectrum Method

Reference [12] was the Capacity Spectrum Method's goal is to establish suitable demand and capacity spectra for the system and to determine its intersection point. During this process, performance of each structural component is also evaluated. The spectrum of capacity is obtained by converting the base shear versus the spectrum of roof displacement into a spectral acceleration versus the spectral displacement as shown in Fig 1(a). The intersection between a corresponding demand curve and the capacity curve is called the performance point. Capacity curve, in terms of base shear and roof displacement, is converted to capacity spectrum, which is a representation of the capacity curve in Acceleration Displacement Response Spectra (ADRS) format (i.e., Sa versus Sd) as shown in Fig 1(b). This curve is obtained by redrawing the design earthquake response spectra as a curve of spectral acceleration v/s spectral displacement as shown in Fig 1(c).



(a)



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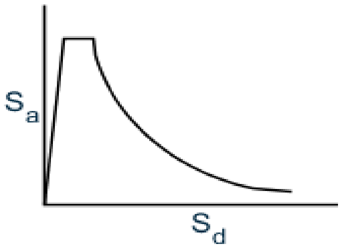


(c)

Fig.1. Curves in capacity spectrum method: (a) Roof deflection, Δroof, plotted versus base shear, V; (b) Spectral displacement, Sd plotted versus spectral acceleration, Sa; (c) Response spectrum

B. Performance Level

It is important to choose performance standards which are ac acceptable to all parties concerned. Reference [7] was that, there are three performance levels now being considered for the seismic risk assessment of steel structures. They are collapse prevention (CP), life safety (LS) and immediate occupancy (IO) of structure. Collapse prevention reflects a level of performance of significant structural damage which can cause collapse. Clearly at this level of damage a building will be unusable. Life safety is a state of significant structural damage; certain component of structure can collapse, and structure must be repaired before reoccupation. The quality of IO efficiency is distinguished by a structure that is essentially undamaged, so the structure can be instantly used. Reference

[13] was to know the performance of the building we need to know the performance point (PP). Performance point indicates the damage state for which building is to be designed. The displacement at PP is the target displacement also called design displacement.

If <, it implies IO building.

> &<, LS building.

> &<, CP building.

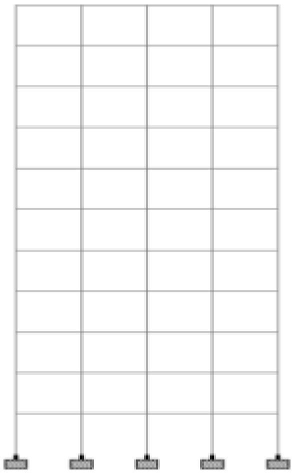
C. Structural Modeling:

Three structural steel frames of G+10 storey

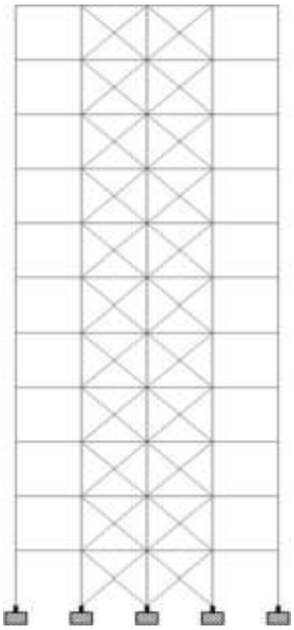
(i) moment frame shown in fig 2 (a)

(ii) braced frame with external concentric diagonal bracing (bracing section –ISMC100) and

(iii) braced frame with different types of bracing (bracing section –ISMC100) are considered for the study with same geometry of beam and column as shown in fig 2 (b), (c) and (d) respectively.



(a)



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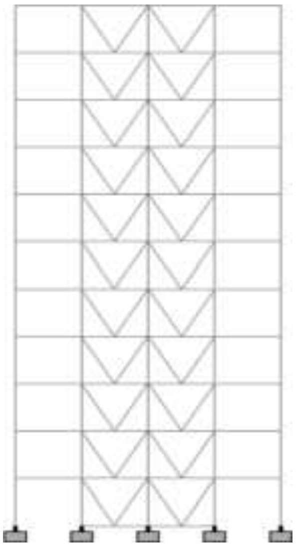
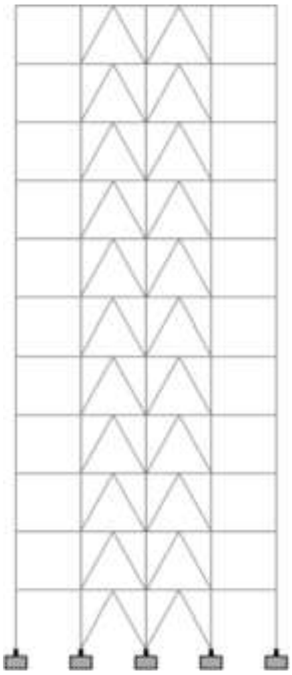


(c)



(d)

Fig.2 G+10 Frame Models (a)Frame Without bracing (b) Frame with X type bracing (c)Frame with V type bracing (d) Frame with K type bracing

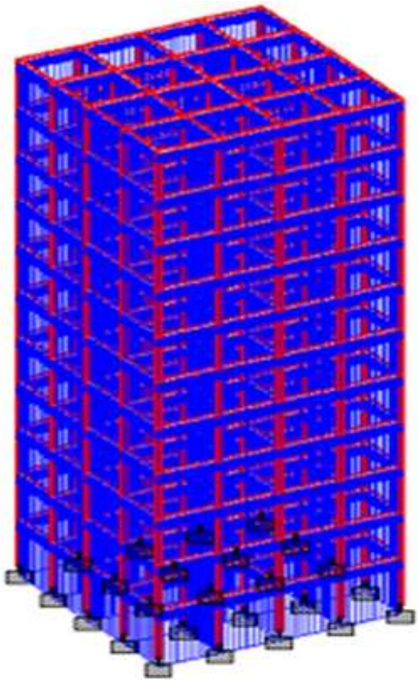


Fig.3. Gravity Loading on Structural Steel Frame for Pushover Analysis

Table 1 shows frame geometry for all four structural steel frames and Table 2 shows the cross-sectional details of beam and columns used in all four frames. While assigning steel sections to column and beam, strong column weak beam concept is taken into consideration. The properties of steel used for the construction of 10-Storey braced frame are; modulus of elasticity is 205 KN/mm2; Poison's ratio is 300E-3; Density is 7833.41kg/m^3

Table- I: Geometry of Existing G+10 Storey Steel Frame

Floor	Height (m)	Length (m)	Width (m)
Ground Floor	3.00	12.00	12.00
1st Floor	3.00	12.00	12.00
2nd Floor	3.00	12.00	12.00
3rd Floor	3.00	12.00	12.00
4th Floor	3.00	12.00	12.00
5th Floor	3.00	12.00	12.00
6th Floor	3.00	12.00	12.00
7th Floor	3.00	12.00	12.00
8tht Floor	3.00	12.00	12.00
9th Floor	3.00	12.00	12.00
10th Floor	3.00	12.00	12.00

Table- II: Size of Steel Cross Section Details for Existing G+10 Storey Braced Steel Frame

Model	Storey/ Floor	Column Exterior	Beam Exterior
G+10-Storey	1	ISHB300	ISLB450
	2	ISHB300	ISLB450
	3	ISHB300	ISLB450
	4	ISHB300	ISLB450
	5	ISHB300	ISLB450
	6	ISHB300	ISLB450
	7	ISHB300	ISLB450
	8	ISHB300	ISLB450
	9	ISHB300	ISLB450
	10	ISHB300	ISLB450
	11	ISHB300	ISLB450

On each frame respective self-weight and live load of 2.5kN/m assigned as shown in fig 3. Self-weight and live loads assigned under the gravity load conditions to perform the pushover analysis in STAAD Pro. advanced. In fig 3 red color of entire structure shows the self-weight of structure and green colored arrows in downward direction shows the gravity load of 3Kn/m acting in global Y direction.

4. PERFORMING PUSHOVER ANALYSIS

Pushover analysis on each structural steel frame of G+10 storey is performed in STAAD Pro. advanced. Following steps were done while performing non-linear static analysis.

Defining Type of Frame: While performing pushover analysis in STAAD Pro. Advanced firstly type of the frame should defined. For the first frame, frame type is defined as moment frame and for second and third frame, frame type is braced frame.

Geometric Non-linearity: Some structural damage is allowed during strong earthquake shaking in normal buildings, even though no collapse must be ensured. This implies that nonlinearity will arise in the overall response of building. Hence the geometric non linearity is considered while analyzing the all three steel frames. Convergence of geometric non linearity is taken as 0.254mm and the numbers of iterations performed for geometric nonlinearity are 50.

Defining Loads: Loads are defined under gravity loading case. Gravity loads include dead loads and (typically) most live loads. Live load of 3kN/m is given to each steel frame as shown is earlier fig 3.

Defining Loading Pattern: In this step base shear is defined up till which pushover analysis will be performed. Defined base shear is more than the designed base shear. Here design base shear is 933.33KN and it is calculated by using dynamic response spectrum analysis in STAAD Pro and the defined base shear is more than this. Because design base shear excludes nonlinear effect. When the structure undergoes a strong earthquake, the actual base shear may be very high compared to the base shear design. To distribute base shear vertically method 3 section 3.3.3.2.3 of FEMA 356 reference[8] is used. Incremental value of base shear is taken as 5kN for multiple steps output result. Number of push loads defined are 250.

Defining Spectrum Details: Critical damping of 5.00% is assigned to all three frames. Site class category considered is D of FEMA 356 section 1.6.1.4.1 i.e. hard rock with average shear wave velocity, vs > 5,000 ft/sec is considered as per the location of structure to generate demand spectrum.

Defining acceptance criteria: Reference [8] used to define performance parameters in which all elements are considered as primary elements. Hence performance points are as shown on curves of figure 4. IO is the deformation at which permanent, visible damage occurred in the experiment but not greater than 0.67 times the deformation limit for LS. LS is 0.75 the deformation at point 2 on the curves. CP is the deformation at point 2 on the curves but not greater than 0.75 times the deformation at point 3.

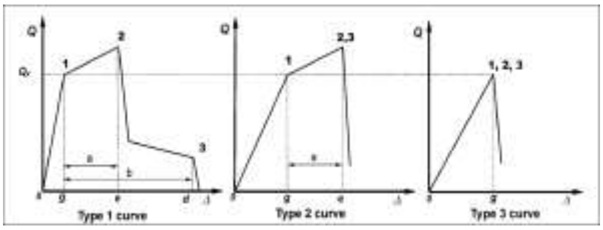
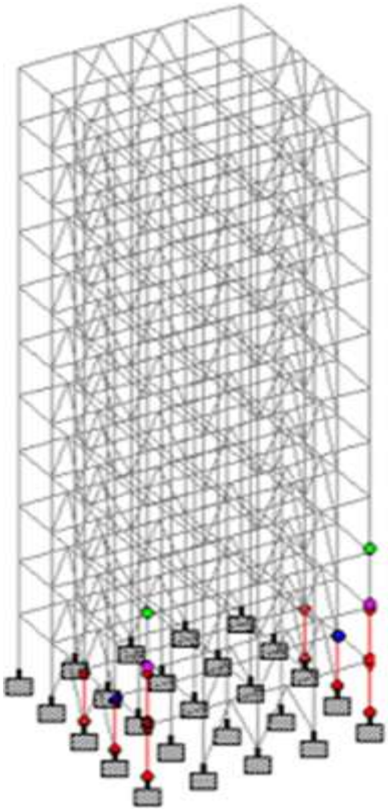


Fig.4. Fig 4 Component force v/s deformation curves from FEMA 356

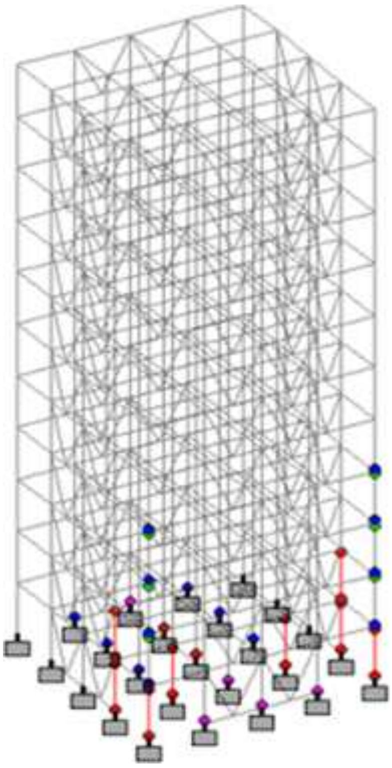
Defining Solution Control: Analysis can be done either by defined base shear or by defined displacement at controlled joint. Here push up to defined base shear approach is used as earlier discussed in step 4 of performing pushover analysis.

Performance Check: Performance of all three G+3 structural steel frame obtained by performing pushover analysis and comparative results of base shear, displacement, capacity curve and plastic hinges are computed to find out the which structure meets the required performance under earthquake loading.

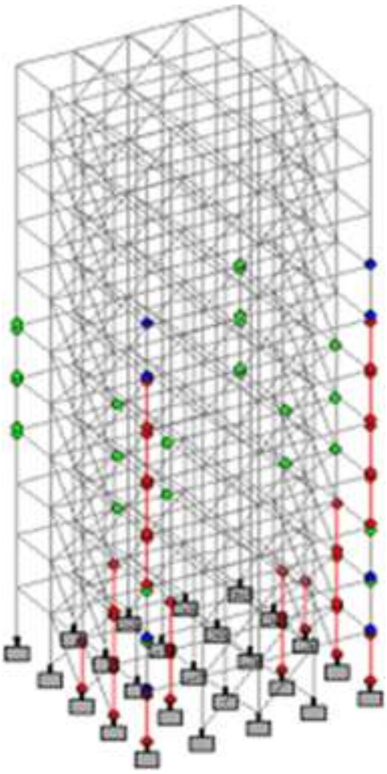
5. RESULT AND DISCUSSION



(a) Members of K Braced Steel Frame in IO-LS Performance Level



(b) Members of V Braced Steel Frame in LS-CP



(c) Members of Moment Steel Frame in CP

Fig. 5

Performance of Moment Frame: After performing pushover analysis on the G+10 storey steel frame, frame performed linearly up to the base shear of 894.09KN then after it started performing nonlinearly as base shear increased. The structure is in IO performance level as green colored plastic hinges developed in it as shown in fig5 then after it started performing nonlinearly as base shear increased.

1. Performance of Externally (X) Braced Frame:

G+10 storey frame with analyzed by static nonlinear process, frame performed linearly up to the base shear 1206.90 KN. When base shear is 3594.83KN column 451 and 455 is in IO performance level as green colored plastic hinges developed in it as shown in fig5 (c). When base shear reached the value 3883.37KN column456 and 460 is in IO – LS performance level as shown in fig 5(c) column 456 and460 reached LS-CP performance level at base shear 3996.61KN and in complete CP level when base shear 4256.04KN as shown in fig 5(c). Bracing provided started failing when base shear 4314.119KN as shown in fig5(c). It is observed that due to external bracings lateral load carrying capacity of structure is increased but displacement is also more which laid to failure of structure. After that base shear redistributed up to the push load stem 49 and the Maximum columns of basement were failed at base shear 4359.818KN. After which entire structure will collapses. Capacity curve obtained for this frame is as shown in fig6.

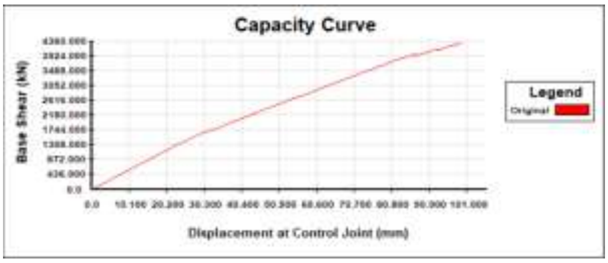


Fig. 6. Capacity Curve of X Braced Frame

2. Performance of Externally (V) Braced Frame:

G+10 storey frame with analyzed by static nonlinear process, frame performed linearly up to the base shear 1206.90 KN. When base shear is 3883.83KN column 451 and 455 is in IO performance level as green colored plastic hinges developed in it as shown in fig5 (b). When base shear reached the value 4061.37KN column 456 and 460 is in IO – LS performance level as shown in fig 5(b) column 456 and 460 reached LS-CP performance level at base shear 4388.61KN and in complete CP level. when base shear 4354.04KN as shown in fig 5(b). Bracing provided started failing when base shear 4354.119KN as shown in fig5(b). It is observed that due to external bracings lateral load carrying capacity of structure is increased but displacement is also more which laid to failure of structure. After that base shear redistributed up to the push load stem 49 and the Maximum columns of basement were failed at base shear 4354.818KN. After which entire structure will collapses. Capacity curve obtained for this frame is as shown in fig.7.

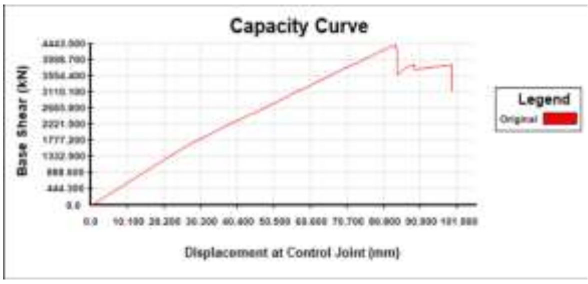


Fig. 7. Capacity Curve of V Braced Frame

3. Performance of Externally (K) Braced Frame:

G+10 storey frame with analyzed by static nonlinear process, frame performed linearly up to the base shear 1206.90 KN. When base shear is 2627.83KN column 451 and 455 is in IO performance level as green colored plastic hinges developed in it as shown in fig5 (a). When base shear reached the value 2756.37KN column 456 and 460 is in IO – LS performance level as shown in fig 5(a) column 456 and 460 reached LS-CP performance level at base shear 2848.61KN and in complete CP level. when base shear 4354.04KN as shown in fig 5(a). Bracing provided started failing when base shear 2961.119KN as shown in fig5(a). It is observed that due to external bracings lateral load carrying capacity of structure is increased but displacement is also more which laid to failure of structure. After that base shear redistributed up to the push load stem 49 and the Maximum columns of basement were failed at base shear 2961.818KN. After which entire structure will collapses. Capacity curve obtained for this frame is as shown in fig.8.

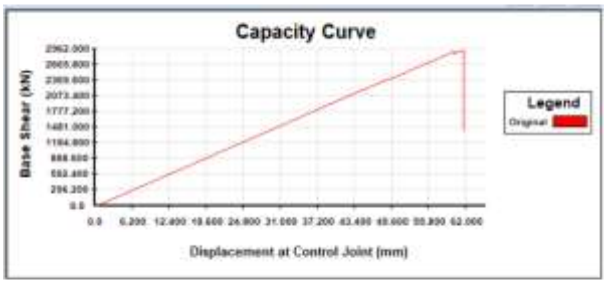


Fig. 8. Capacity Curve of K Braced Frame

6. CONCLUSION

This paper presented and documented performance based seismic analysis for steel frames. The concept of performance based seismic design was successfully implemented by nonlinear static analysis by applying incremental lateral loads on braced and non-braced steel frames. The performance criteria suggested by FEMA 356 can be successfully implemented in PBSD pushover analysis method by using STAAD Pro. Advanced. Maximum members of moment frame reach to Collapse prevention level and ultimately fails under the incremental push loads. This leads the collapse of entire steel frame during the earthquake. The Shear capacity of the structure can be increased by introducing external steel bracings in the structural system. But under the incremental lateral loads bracing also fail. This leads to the maximum members to be in CP level and causes failure of structural members during earthquake. To avoid this different tpes of the bracing can be studied by using pushover analysis by identifying which braced frame is failing after incremental lateral load and which prevents the failure of these members. Such study of bracing saves the structure during earthquake. It is concluded in this paper that such V type braced steel frame increases the shear capacity of structure and performs well, maximum in LS level. No collapse of member is observed in this frame after incremental lateral loads. Pushover analysis is successfully implemented to study nonlinear behavior of structure under earthquake loading.

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