Nonlinear Pushover Analysis for Steel Beam-Column Connection

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Abstract: This paper presents results of analytical evaluation conducted on beam-column connection using nonlinear static pushover analysis (NSPA) process. The aim of using this technique is to investigate the efficiency of the configuration used in conventional steel beam-column connections. In this research work the beam was subjected to two different applied loads; which are concentrated load and uniform distributed load. Two case scenarios have been studied to check the stability of connections while distributed load increased by a factor of 2.

The beam is connected to the column by a fully penetration weld. Numerous correlations have been investigated such as base shear vs. displacement, displacement vs. time, and base shear vs. time. The numerical result indicated that joint capacity for both cases show the same behavior in the elastic range. However its behavior changes in the plastic range.

The results showed that with increasing (doubled) the applied load on the beam-column connection the base shear and peak displacement do not change. Moreover, for studying the yield point of welded beam-column connection, the model analysis "finite element modeling (FEM) software" was conducted.

Keywords: Beam-Column Connection, Nonlinear Push-Over Analysis, Base Shear, Performance Evaluation

1. Introduction

It is well known that connections are the main join elements in the structural framework in which forces can be safely transferred through these points of connections.

To prevent catastrophic collapse of the structure during a severe load environment, a stable and reliable capacity for energy dissipation should be provided through proper design and detailing of the system, members, and joints. Generally, the strength of steel frames is strongly depends on the behavior of beam-to-column connections (Chen et al., 1996). These connections are particularly used when continuity of the members of the building frame is required to provide more flexural resistance and reduce lateral deflection due to wind loads. In this type of connection both the webs and flanges are connected. In the proposed connection more than 90% of the moment can be transferred with full transfer of shear and other forces.

Since the 1994 Northridge earthquake, extensive research on performance of various connection types has been carried out. The large variations in the load-carrying capacity observed in the experiments are likely due to various yield mechanisms and failure modes. As such, model creation is not a simple process due to large variations of strength and ductility. Particularly, plastic engagement of connection components significantly affects the behavior of connections (Yun et al., 2007).

Since 1989 a greater interest has been shown in the use of connections for building frames (Azizinamini & Radziminski, 1989). The new moment resisting frame connection has encouraged the research community to develop new methods of characterizing connection behavior to carry different types of load (Swanson & Leon, 2001; Tadaharu Nagao, 2004).

Many researchers studied the characteristics of connections using numerical and experimental works. These methods have been widely adopted by researchers, however the key issues the effects of bolting and welding are not fully resolved. In particular, experimental results of many beam –column connection details indicated that the rotational capacity of this type of connection is rather unpredictable (Azizinamini & Radziminski, 1989; Tsai et al., 1995).

The primary goal of the research as indicated is to summarize the analytical modeling results on welded beam-column connections conducted recently using nonlinear static pushover analysis (NSPA) by finite element modeling using ABAQUS software (Abaqus, 2012) through applying concentrated loads and uniform distributed loads.

2. Applications of Pushover Analysis

For professional practicing, a simple analysis tool with less computational effort is desirable. One method that has been gaining ground, as an alternative to time history analysis, is nonlinear static pushover analysis (NSPA) or pushover in FEMA-273 (Council, 1997; Jabbar et al., 2016).

The purpose of the pushover analysis is to evaluate the structural performance by estimating the strength and deformation capacities using static nonlinear analysis and comparing these capacities with the demands at the corresponding performance levels (Thombare et al., 2015) .

The basic procedure of this method is to perform a sequence of static analysis under monotonically increasing loads to stimulate the loading history of the structure during the collapse. The potential of the pushover analysis has been recognized in the last decade. The pushover is expected to provide information of many response characteristics that cannot be obtained from an elastic static or dynamic analysis. The following primary response characteristics are aimed from NSPA:

(a) Estimation of strength and deformation capacities structural system for fundamental mode of vibration.
(b) Location of the critical regions, where the inelastic deformations are expected to be high.
(c) Consequences of strength deterioration of particular elements of the overall structural stability.
(d) The realistic force demands on potentially brittle elements, such as axial force demands on columns, force demands on weld connections, moment demands on beam-to-column connections, shear force demands in deep reinforced concrete spandrel beams, shear force

demands in unreinforced masonry wall piers, etc.

(e) Verification of the completeness and adequacy of load path, considering all the elements of the structural system, all the connections, the stiff nonstructural elements of significant strength, and the foundation system.

Obviously, these benefits come at the cost of additional analysis effort, associated with incorporating all significant elements, modeling their inelastic load-deformation characteristics, and executing incremental inelastic analysis, preferably with a three-dimensional analytical model.

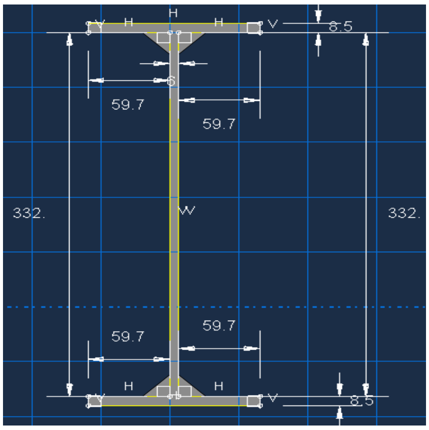
3. Numerical Modeling

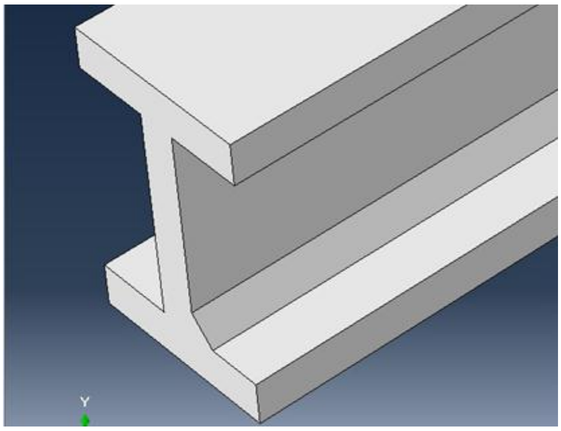
3.1 Preprocessing

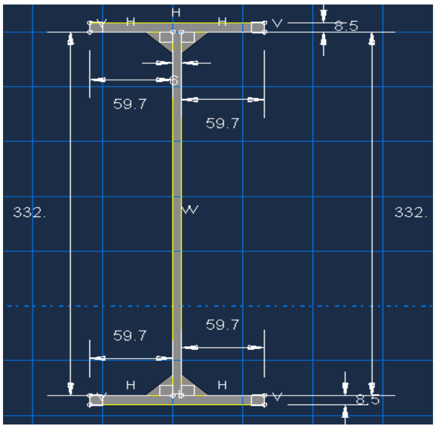
Pre-processing is the initial phase of a finite element analysis program. This phase includes various modules for creating a model, defining material properties, specifying boundary conditions and external loads and meshing the assembly of the model. It is important to uniform the units of dimensions, loading, and stress… etc., since FE planer (ABAQUS) deals with a unifying unit. In this study SI units are used.

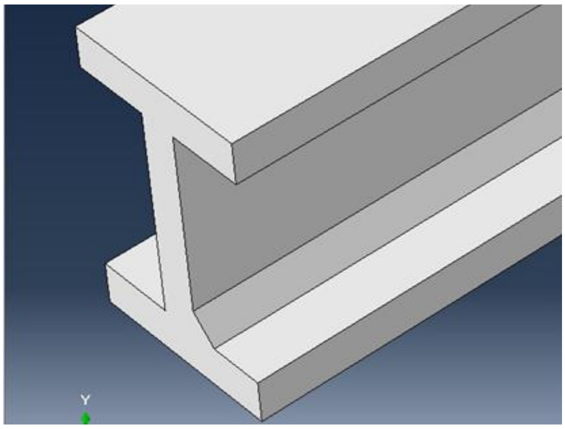
3.2 Module Partitioning

Module partitioning is used to build several sub-models. The aim for this partitioning is to conduct a comprehensive study and determine the parameters affect the stability of beam-column connections. Thereafter, all sub-models have been reassembled again to form the universal model. The model is divided into six parts: column, beam, segment left-top, segment right-top, segment left-middle, and segment right-middle as shown in Figure 1.



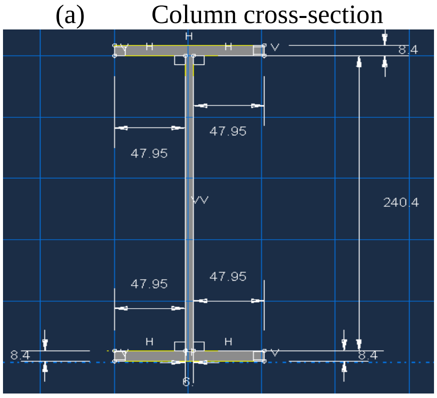




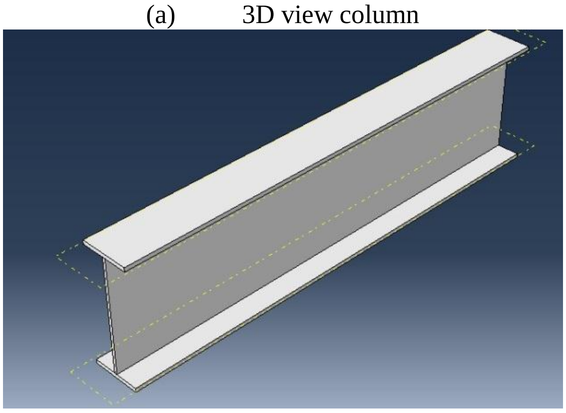


(a) Column cross-section

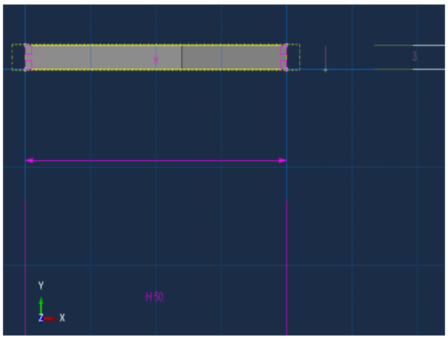
(a) 3D view column



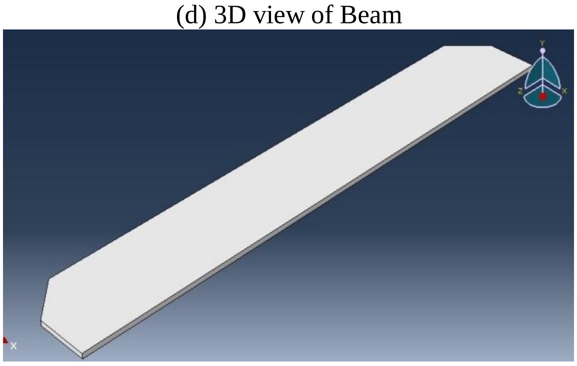
(c) Beam cross-section



(d) 3D view of Beam



(e) Segment cross-section



(f) 3D view of Segment

Figure 1: Model Parts

3.3 Geometric properties

The model consists of a beam and a column which are connected by fully penetration weld connection as shown in Figure 2. The beam and the column are universal British section. Beam and column sections are UB 254x102x25 and UB 356x127x33 respectively. **Error! Reference source not found.** shows the section properties of beam and column. The joint has been strengthened by a plate of 3mm thickness which is used in two positions as illustrated Figure 2.

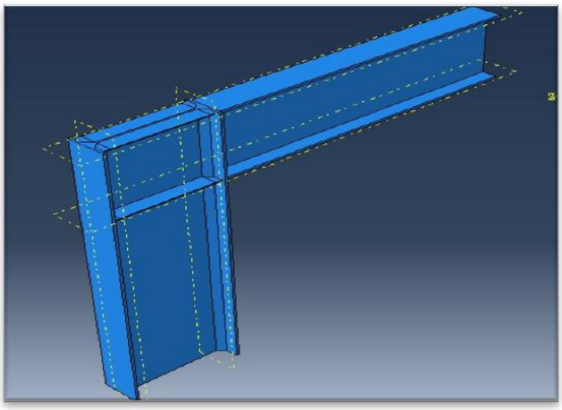


Figure 2: 3D Model

Designation	Mass per m	Depth of Section	Width of Section	Thickness of		Root Radius	Depth between fillets	Area of Section	Second moment area		Radius of Gyration		Section (elastic) Modulus		Plastic Modulus	
				Web	Flange				Axis X - X	Axis Y - Y	Axis X - X	Axis Y – Y	Axis X - X	Axis Y - Y	Axis X - X	Axis Y - Y
	M	h	b	s	t	r	d	A	Ix	Iy	rx	Ry	zx	zy	Sx	Sy
	Kg/m	mm	mm	mm	mm	mm	mm	Cm^2	Cm^4	Cm^4	cm	Cm	cm^3	cm^3	cm^3	cm^3
254 x 102 x 25	25.2	257.2	101.9	6	8.4	7.6	225.2	32	3415	149	10.3	2.15	266	29.2	306	46
356 x 127 x 33	33.1	349	125.4	6	8.5	10.2	311.6	42.1	8249	280	14	2.58	473	44.7	543	70.3

3.4 Material Properties

Table 1 represents material properties of steel section for both beam and column.

Table 1: Beam and column Material Properties

Properties	Quantity
Density	7.85 E9 kg/m^3
Young Modules	210000 MPa
Poisson ratio	0.3
Yield Stress	370 MPa
Failure Stress	460 MPa
Plastic strain at yield	0
Plastic strain at Failure	0.25

3.5 Connection

Structural welding is a process by which parts are to be connected heated and fused, with supplementary molten metal at the joint. A relatively small depth of material will become molten, and upon cooling, the structural steel and weld metal will act as one continuous part where they are joined as displayed in Figure 3.

In ABAQUS modelling, fully constrained contact behavior is defined using tie constraints. A tie constraint provides a simple way to bond surfaces together permanently. Easy mesh transitioning, and surface-based constraint using a master-slave formulation. The constraint prevents slave nodes from separating or sliding relative to the master surface. ABAQUS tie connection has been used to link beam and column together. Tie rotational degree of freedoms are used, if applicable, to allow the connection to have a possibility of rotation in default value.

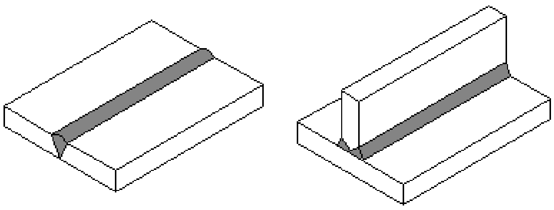
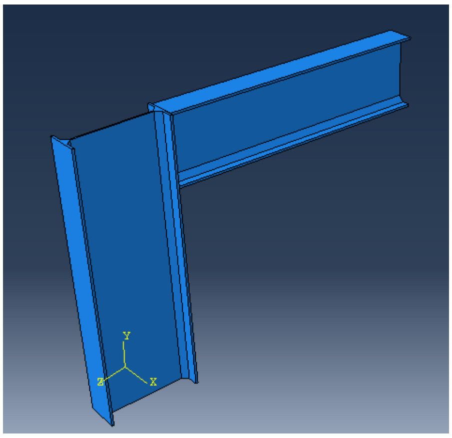


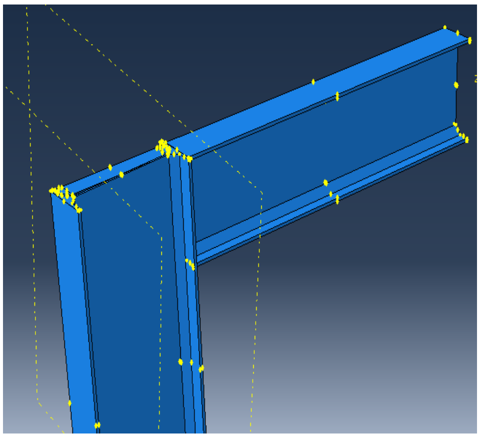
Figure 3: 3D Weld Connection

3.6 Assembly

In this module, all the parts created earlier can be put together (assembly) to get the required complete model. After doing this we can apply the necessary constraints and loads on the assembly (see Figure 4).



(a) Assembly of beam and column

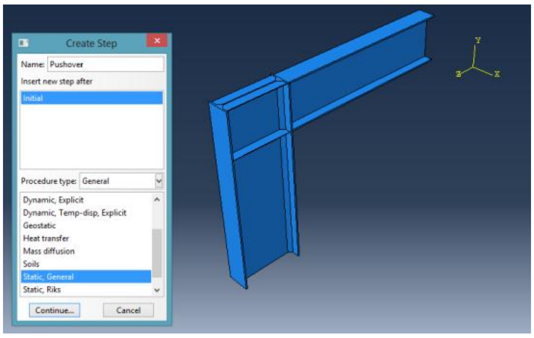


(b) Segment assembling

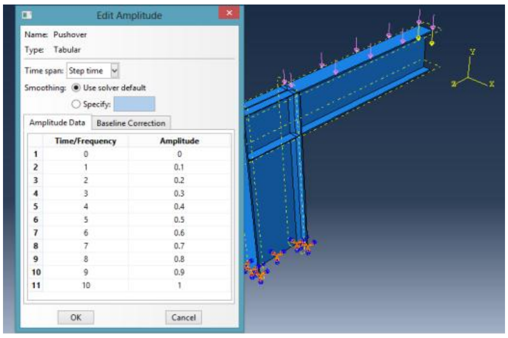
Figure 4: Assembly of parts

3.7 Steps

This module is used to perform many tasks, mainly to create analysis steps and specify output requests. The main steps include: Create steps, time period, incrimination, and amplitude values (see Figure 5).



(c) Create step

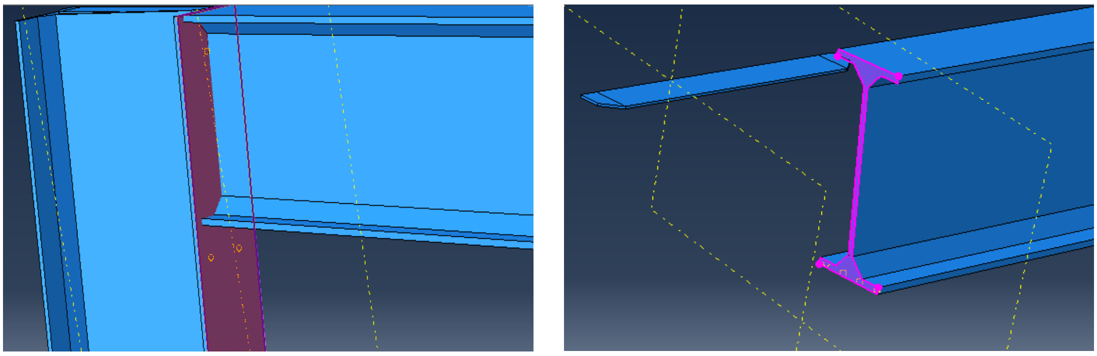


(d) Amplitude configuration

Figure 5: Steps configuration

3.8 Interaction

As the title suggests, this module is used to define various interactions within the model or interactions between regions of the model and its surroundings. The interactions can be mechanical or/and thermal. Analysis constraints can also be applied between regions of the model. The interaction which is used in this analysis is weld connection between beam and column and also between the column and segments as shown in Figure 6.



(e) Select main surface (f) Select slave surface

Figure 6: Interaction process

3.9 Boundary Condition

Load module is used to define and manage various conditions like loads, boundary conditions and predefined fields as shown in Figure 7.

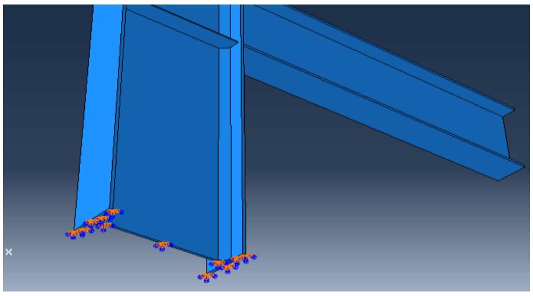


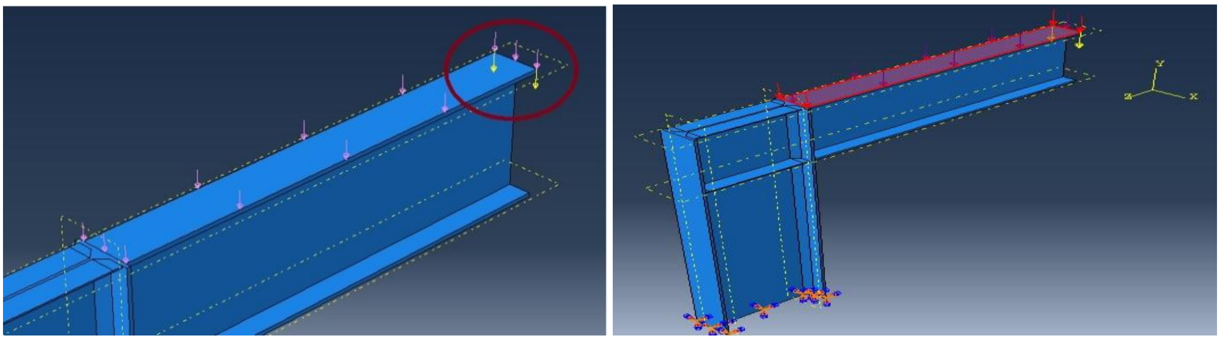
Figure 7: Fix end boundary condition

3.10 Loading

Concentrated load has been applied on the beam edge, and distributed load also applied on whole top beam surface (see Figure 8). However, quantity and type of applied loads can be seen in Table 2.

Table 2: Applied loads

Case	Loads	
	Concentrated (N)	Distributed (N/mm2)
Case 1	20000	50
Case 2	20000	100



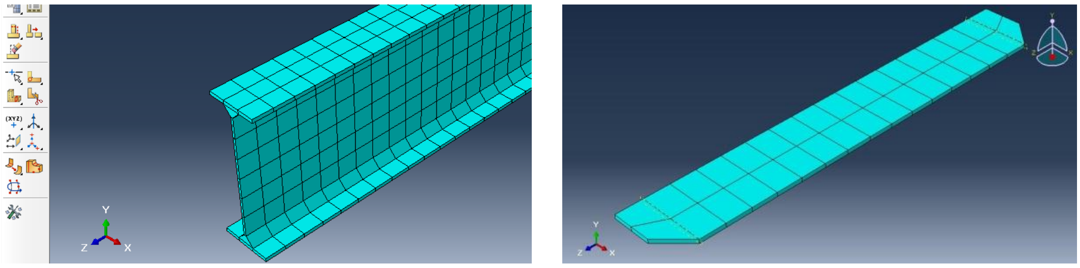
(a) Concentrated load **(b)** Distributed load

Figure 8: load configurations

3.11. Mesh

Mesh is one of the most important modules since accuracy of the results depends on the meshing of the assemblies. This module can be used to generate meshes and even verify them (see

Figure 9).



(a) Colum meshing (b) Segment meshing

Figure 9: Mesh configurations

4. Results and Discussion

ABAQUS (Abaqus, 2012), a general purpose of FE solver is used for numerical analysis. Two dimensional FE planers have been analyzed to plot pushover curve.

4.1. Case 1

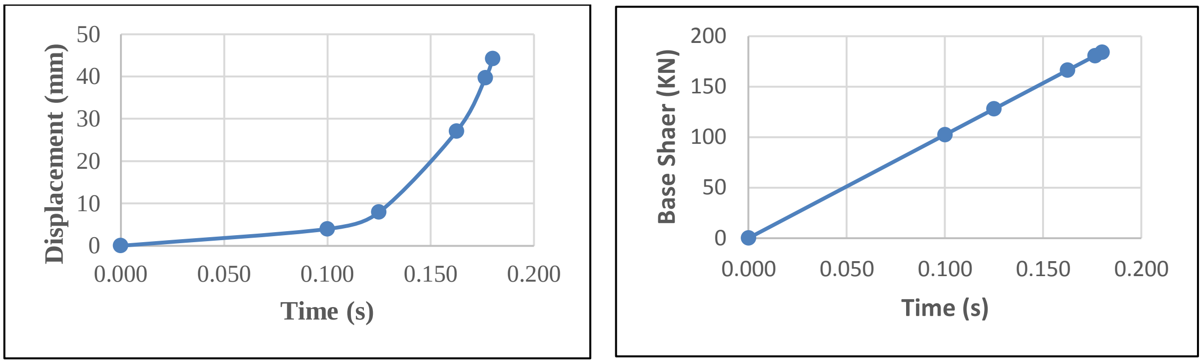
Nonlinear models have been analyzed to plot the requirement of pushover curve graph.

Table 3 shows the increment of base shear and displacement with regard to time. It can be seen that within less than 0.2 second, the peak displacement reached to 44mm.

Figure 10 represents base shear force outcome and displacement VS time. The most critical area subjected to the large stress is the column beam connection. Therefore, this should be taken to the consideration (Figure 11a). It's very obvious that the peak displacement would be occurred at the cantilever beam (Figure 11b). Figure 12 illustrates displacement VS base shear force. The correlation between the base shear and displacement is linear in a range of 4mm, thereafter a non-linear relationship starts till the peak happens.

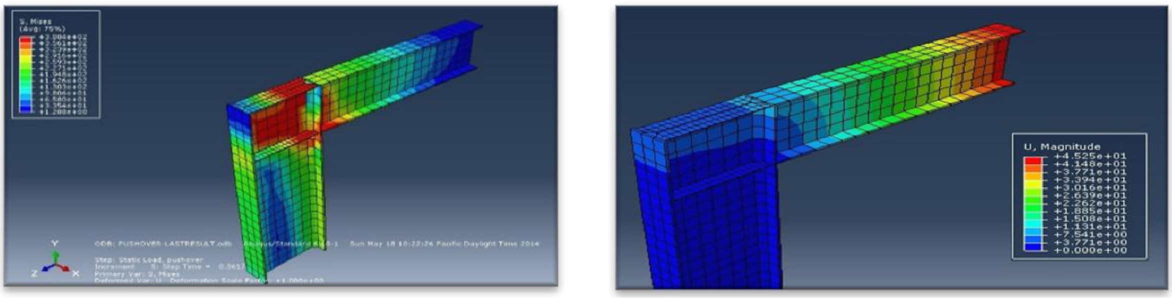
Table 3: Base shear and displacement with time

Time (s)	Case 1	
	Base Shear Force (N)	Displacement (mm)
0.000	0	0
0.100	102	4
0.125	128	8
0.163	166	27
0.177	180	40
0.180	184	44



(c) Displacement Vs. Time **(b)** Resultant Base Shear Force Vs Time

Figure 10: Force and displacement vs time



(a) Stress distribution (b) Displacement distribution

Figure 11: Stress and displacement distribution of beam column connection

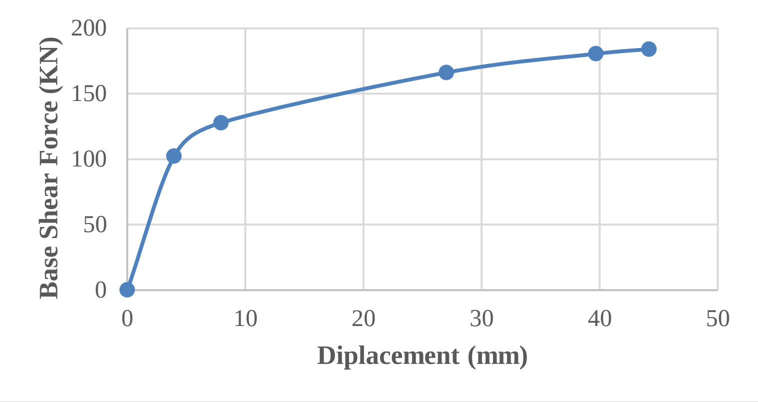


Figure 12: Displacement Vs. base shear force, case 1

4.2. Case 2

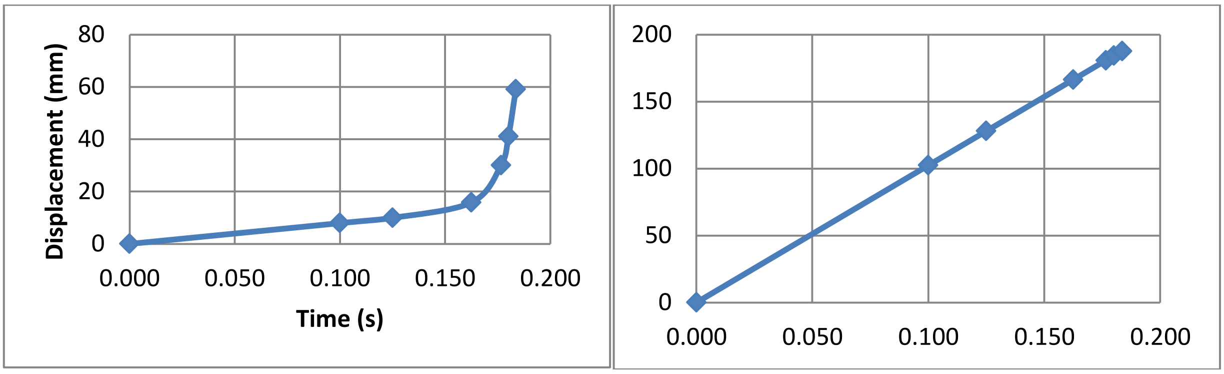
In this case, the beam-column connection was modeled and subjected to concentrated load at the end of the beam of 20000 N and distributed load on the whole surface of the beam of 100 N/mm2. As mentioned previously, the boundary condition for column is considered as fixed support. Table 4 illustrates the effect of the base shear on the peak displacement at the far end of the beam. Concentrated load (less distributed load) can have a larger scale of displacement which is 59mm.The largest displacement happened at the late time of the pushover analysis (

Figure 13a). On the other hand a linear correlation between base shear vs. time can be seen obviously (

Figure 13b). Figure 14 shows displacement vs. base shear force. The graph indicates that the effect of distributed load (constant concentrated load) remains as same.

Table 4: Base Shear and displacement for case 2

Time (s)	Case 2	
	Base Shear Force (N)	Displacement (mm)
0.000	0	0
0.100	102	8
0.125	128	10
0.163	166	16
0.177	181	30
0.180	184	41
0.184	188	59



(c) Displacement Vs. Time **(b)** Resultant Base Shear Force Vs Time

Figure 13: Case 2, displacement and base shear force VS time

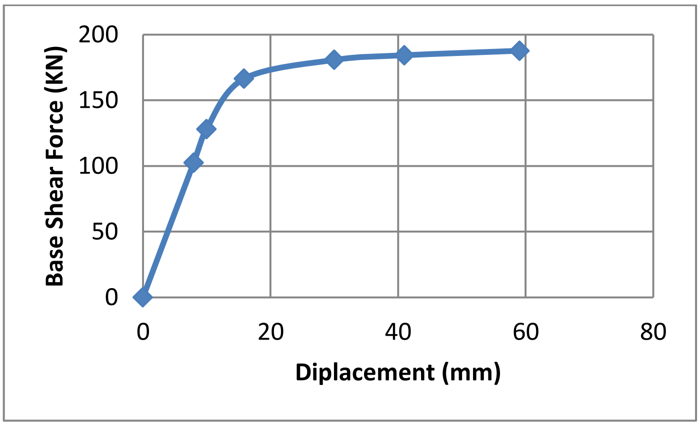


Figure 14: Displacement Vs base shear force, Case 2

4.3. Comparison between Pushover Curves (case 1 Vs case 2)

The predicted load deformation curves for elastic structural elements are analyzed, presented and discussed in this section. All values for the ultimate capacity and maximum deflection of the models are plotted in Table 5 Table 6. Time deflection and load deflection graphs of the cases are plotted in Figure 15 and Figure 16 consecutively. The result indicated that the ultimate deformation under case 1 is about 49 mm and it is smaller than case 2 which is equal to 59 mm. Furthermore, the area under the load–deflection curve is displayed in Table 6, which is reduced by 8% for case 2 in comparison to case 1. However, the deflection increased by 25% when the uniform distributed load was increased from 50 MPa to 100 MPa.

It can be seen that the ductility of the connection in case 1 is greater than 30% if compared to case 2 (see Table 6). In addition, the ultimate loads of case 1 and 2 are 184 KN and 188 KN, respectively. This has been indicated a slight difference of 2% reduction in the ultimate load. Apparently, the uniform distributed load has a slight impact on the ultimate and capacity loads (see Table 5).

Due to distributed load, it's observed that the column beam connection yields at the earlier time in comparison to case 2 in which concentrated load have been applied (Figure 15). It's well recorded that the effect of distributed load in case 2 is sever than the effect of concentrated load in case 1. This means that the beam-column connection has a long service life under case 1loading (Figure 16).

Table 5: Force and deflection comparison between of studied cases

Time (s)	Case 1		Case 2	
	Deflection (mm)	Base Shear Force (N)	Deflection (mm)	Base Shear Force (N)
0.000	0	0	0	0
0.100	4	102	8	102
0.125	8	128	10	128
0.163	27	166	16	166
0.177	40	180	30	181
0.180	44	184	41	184
0.184			59	188

Table 6: Capacity and ductility comparison of studied cases

Case	Load (KN)		Area under curve		Displacement (mm)		Ductility
	Ultimate Load (KN)	Increasing (%)	Capacity	Reduction (%)	At maximum force	At 0.85 from maximum load	
Case 1	184	-	6479	-	44	22	2
Case 2	188	2	5970	8	59	42	1.4

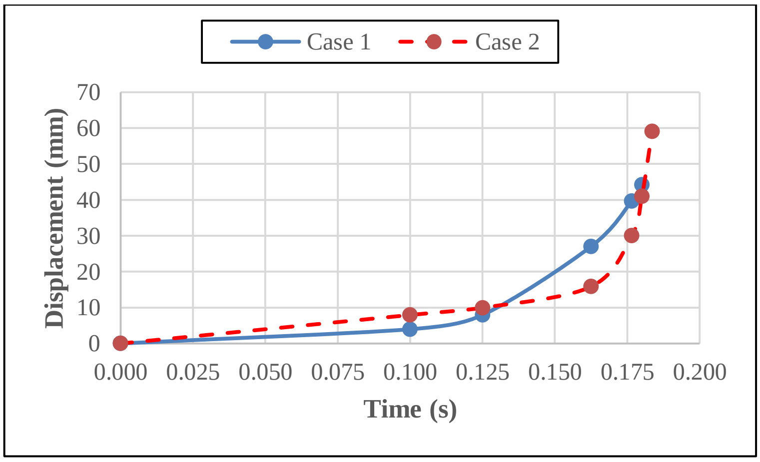


Figure 15: Deflection comparison between case 1 and 2

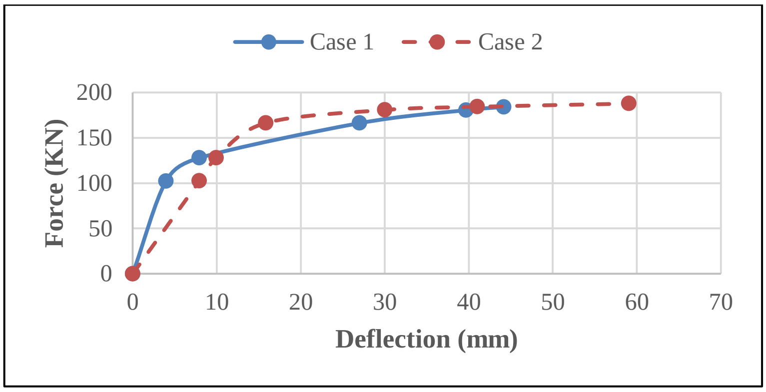


Figure 16: Pushover comparison between case 1 and 2

5. Conclusion

A model has been simulated to study the behavior of steel column – beam connection. Ultimate load capacity and deflection were examined by pushover analysis method using finite element software. Concentrated load and distributed load has been applied to indicate the capacity of the connection. The analytical results were compared and discussed. The evaluations showed that the proposed technique is well appropriated for application to stability problems. This study has led to the following conclusion:

The results show that the distributed load is more effective over the beam, whilst less contribution for concentrated load has been obtained. The study shows that the increase of distributed load from 50 MPa (case 1) to 100 MPa (case 2), has caused only 25 % increase in displacement. The incremental in length was 15 mm. On the other hand, with increasing the uniform distributed load the base shear has increased by 2% in of total base shear where induced at the column fixed end base.

The reduction in ductility value in case 2 is about 30% in comparison to case 1. In addition, the ultimate load has been slightly reduced of about 2% whereas the capacity load reduced by about 8% when it is subjected to load of 100 MPa.

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