Performance Evaluation of FR welded connections to Inclined Column

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SUMMARY

As the complex-shaped buildings become a popular trend, more researches are needed to embody those twisted and tilted shapes into real structures. The studies on the inclined column and beam connection that appears frequently in the complex-shaped structures are not sufficient in comparison to those on the conventional structures so that the structural safety and the behavior are not clear yet. In this study, with a help of finite element analysis, the fracture potential and local buckling which can occur around the connection are examined and the results will be applied to evaluate the connection capacity. Also, the pre-analysis results will be used in the future experimental studies.

Keywords: Inclined column, welded connection, finite element analysis, fracture, local buckling

1. INTRODUCTION

Nowadays, it is a new trend of architecture and structural engineering that many tall buildings on all over the world have a complex shape such as twisted, tapered and tilted. Those buildings are regarded as landmarks of a nation and symbols of technological achievement. The complex-shaped tall building disassembles the orthogonality between beams and columns. Especially, such type of structural system can be found frequently in buildings having inclined columns. The inclined columns can transmit the gravity and lateral load simultaneously, and are necessary to display the architectural complexity. Nonetheless, the studies for the connection of inclined columns have not been conducted as much as those for the normal beam-column connections (Kim et al., 2011), so it is worth examining the behavior of inclined column-beam connection by using rigorous computational analysis and experiments.

In this study, a moment resisting frame which has been used for SAC project conducted in the United States (Gupta et al., 1999) was used as an model building frame. The model building was modified to have inclined columns at one side of its ground floor, and was analyzed with gravity loads to check the flow of forces at the inclined column-beam connections. After the global analysis of the example frame, which revealed that the inclined column gives an extra axial force to the beam, the finite element analysis (FEA) was conducted to examine the behavior of inclined column connection more precisely. For the FEA, three types of column-beam connection substructure were developed so that the two different inclined directions of column could be compared to the normal column-beam connection.

Finally, this study provides the prediction on the behavior of welded inclined column connection focused on the strain distribution and local buckling so that the fracture potential at the connection and strength degradation can be assessed.

2. MODEL BUILDING

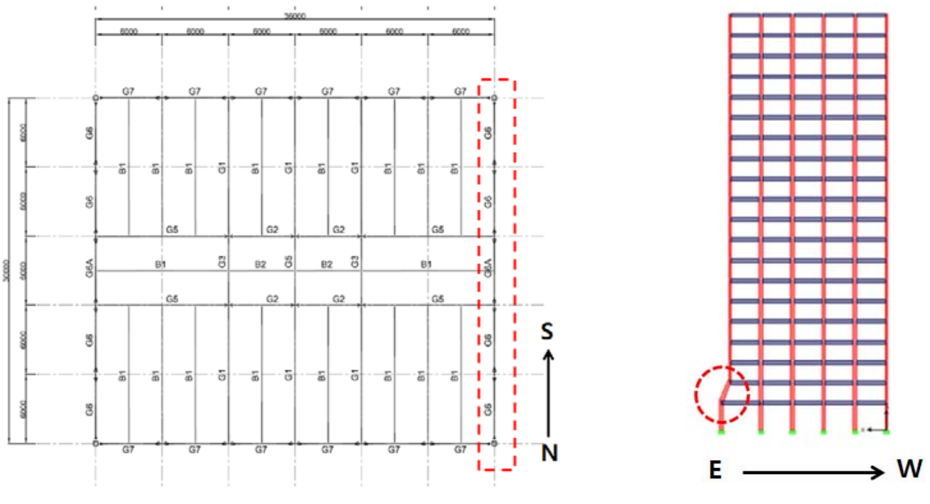
The structural plan of the model building is shown in Fig. 1(a). According to SAC project, it was assumed that the building is located in LA, having 20 stories and steel moment resisting frame system. The girders and columns in exterior frames are connected by fully restrained welded connections. For the modeling and elastic analysis of the model building, ETABS, a structural analysis software developed by Computers & Structures, Inc., was used. During the 3D modeling, the columns in the west side of the building on the 2nd floor, which are surrounded by a dashed box in Fig. 1(a), were modified to be inclined (see Fig. 1(b)). The building was analyzed for two different angles of the inclined columns, 1/10 and 1/5, which are equal to 5.7° and 11.3° from vertical.

Since LA is a region of high seismicity, in the SAC project the structural design of the model building was governed by earthquake load, rather than wind load. Therefore, the model building was analyzed with seismic load as well as gravity load based on both UBC 94 and ASCE 7-10, and each frame member of the building was checked for demand/capacity ratio in terms of moments and forces. It is notable that the model building has been developed to represent pre-Northridge structures designed based on the UBC 94 which categorizes all moment resisting frames as the one identical system having a response modification factor of 12. The summary of seismic design information for model building is provided in Table 1.

Table 1. Seismic design information of the model building based on UBC 94

System	Steel Moment Resisting Frame
R factor (R_W)	12
Soil Type	S2 (Stiff Soil)
Zone Factor (Z)	0.4 (Zone 2)
Importance Factor (I)	1
Period (T_A)	2.3 sec
Design Base Shear Coefficient (C)	0.03
Seismic Weight	101722 kN

As a result of elastic analysis, it was found that there is a tensile axial force in the beam growing up proportional to the inclined angle of column.



(a) Plan (b) Elevation

Figure 1. Model building frames

3. FINITE ELEMENT MODELS

After the global analysis, a substructure model of the column-beam connection was developed for FEA. For the substructure model, a typical inclined column-beam connection on the second floor was chosen to be used. Table 2 shows material properties of frame members of the inclined column-beam substructure.

Table 2. Material properties of columns and beam used in analysis model

Member	Cross section	Young's Modulus (MPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Poisson's ratio
Column	H-417x458x30x50	205,000	345	448	21	0.3
Beam	H-900x300x16x28	205,000	248	414	23	0.3

The boundary and loading conditions for the analysis model of the beam-inclined column connection were set as shown in Fig. 2, considering the conditions for experimental study which will be conducted in the future. The analysis model includes the substructure of the model building having the inclined column-beam connection, disassembled by the cut at the inflection point in each components. The inflection points were restrained with a pin and a roller, and the beam was constrained against their out-of-plane behavior. The vertical displacement at the end of the beam was controlled monotonically by using a unit load and its proportionality factor.

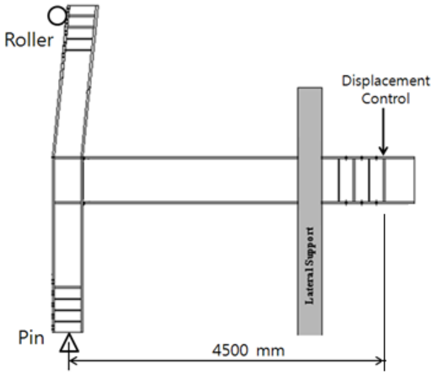
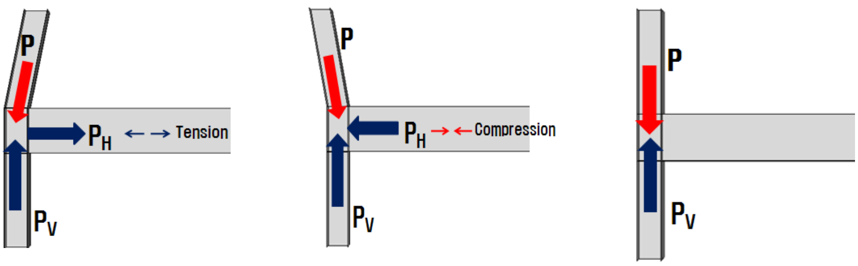


Figure 2. Boundary and loading conditions

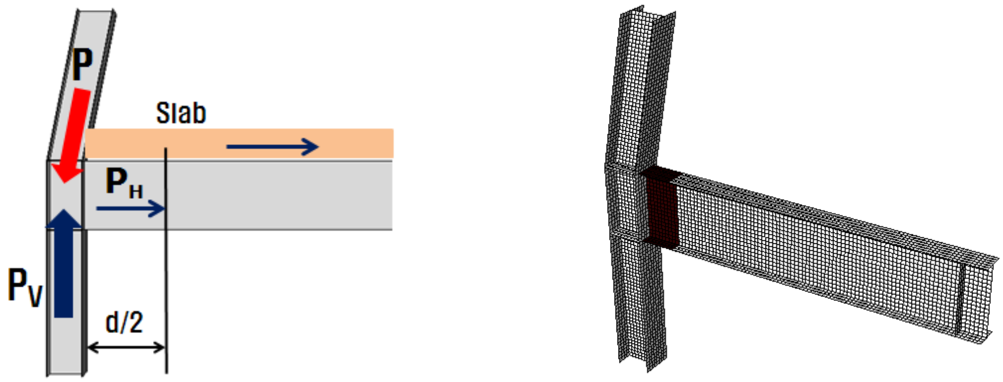
As expected in the global analysis, the horizontal force in the beam is developed from the axial force in the inclined column as shown in Fig. 3. However, since the beam is constrained by the slab which is expected to take most of the horizontal force, only a little region may be affected so it becomes a challenge in analysis of the substructure. Therefore, to determine the region which the horizontal force affects the beam only, an effective region was assumed. The effective region includes the beam web and flanges from the column face to a half of the beam depth (see Fig. 4).



(a) BC-T (b) BC-C (c) BC-N

Figure 3. Nodal forces in inclined column connections

In addition, for more precise investigation of the effect of horizontal distribution of column axial force to the beam, it was decided to apply axial stresses in the effective zone as an initial condition, corresponding to the columns having different inclined angles, rather than applying an axial force directly to the column.



(a) Effective region (b) Initial stress assignment

Figure 4. Effective region of beam and an example of initial stress assignment

The finite element analysis (FEA) was performed in ABAQUS. For the FE substructure modeling, it was assumed that Welded Unreinforced Flange-Welded Web (WUF-W) method was used for the connection without weld access holes, and shell elements having four nodes for reduced integration method (S4R) were assigned. Since the substructure model obtained from the model building has only tensile force in the beam as shown in Fig. 3(a), another case shown in Fig. 3(b) was suggested to consider the compressive force. Also, the performance of the beam-inclined column connections was compared to the vertical column-beam connection (see Fig. 3(c)) with same conditions.

4. ANALYSIS RESULTS

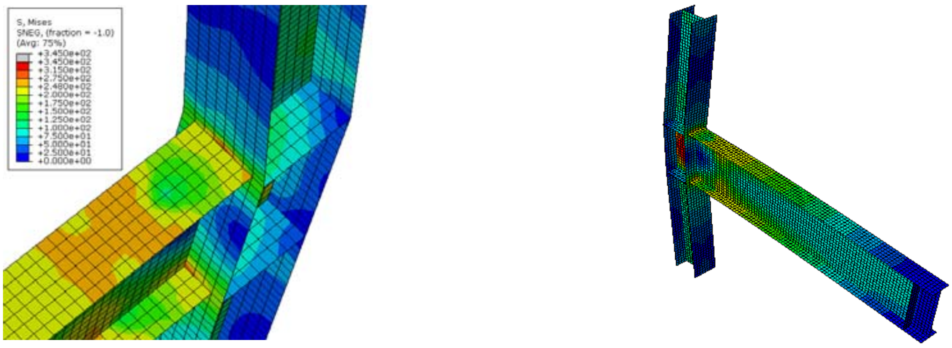
Since it was anticipated that the axial stress in the beam distributed from the inclined column would affect the beam-column behavior such as the potential of fracture at the column face and local buckling in beam flange, the finite element analysis focused on stress-strain and force-deformation relationship of substructure model. For the fracture potential, the plastic equivalent strain(PEEQ) at the beam flange was checked, while the relationship between the vertical displacement and applied load at the end of the beam was examined to check the flange local buckling(FLB). The PEEQ was measured in the effective region of top and bottom flanges, and the FLB was checked by using eigenvalue analysis and displacement controlled analysis with Riks method provided in ABAQUS (ABAQUS, 2010).

4.1. Fracture Potential

El-Tawil et al.(1998) and Yoo(2006) has studied on the PEEQ of a steel component as an index of the local failure, and proved that large PEEQ indicates the high potential of fracture. Referring to those previous research achievements, this study also measured PEEQ to assess the fracture potential as well as the yielding occurrence. The applied initial stress in the beam which acts as a distributed column axial force will obviously give extra deformation of beam flanges and web. Consequently, the beam will have larger plastic strain than vertical column-beam connection, which means that yielding will occur earlier and fracture potential will be higher, when there is a same amount of beam deflection.

Therefore, as a criterion for the assessment of the effect of inclined column on the yielding and fracture potential at the connection, PEEQ was checked in ABAQUS, with tip vertical displacement of 70mm which was thought to be a reasonable condition to see yielding at column face in every case. Since it was predicted that the top and bottom flanges would go over the largest stress and strain when the beam deflects under the gravity load, variation of the PEEQ was examined along the effective region of the beam at the middle of the flange width as shown in Fig. 5.

As mentioned earlier, the forces in the beam were supposed to be applied according to the horizontal distribution of axial forces in the inclined column. However, 25% and 50% of yield strength of the beam were applied in order to observe the amplified results, instead of considering realistic or practical inclined angle of the column which gives a force of less than 20% of beam yielding strength. One can see the distribution of Von Mises stress around the beam flange and column face in Fig. 5(a) and the deformed shape of substructure in Fig. 5(b), which were captured when yielding begins to occur. The overall schedule for the FEA is listed in Table 3.



(a) Von Mises stress distribution (b) Deformed shape at onset of yielding

Figure 5. Stress distribution and deformed shape of substructure model when yielding occurs

Table 3. Analysis models

Model name	Direction of axial force	Amount of axial force (stress)
BC-T-25	Tension	25% f_y
BC-T-50		50% f_y
BC-C-25	Compression	25% f_y
BC-C-50		50% f_y
BC-N	No initial stress	Not applicable

From Fig. 6, it can be noticed that, if the top flange of the beam carries tensile stress due to the flexure, in case of that the horizontally distributed column axial force is a tensile force (BC-T), the plastic deformation occurs more severely than that in the normal column-beam connection (BC-N) at the same amount of beam deflection. It is also possible to point out from Fig. 6 that, as expected earlier, the tensile initial stress causes larger potential of fracture since the PEEQ at the column face increases in proportion to the inclined angle.

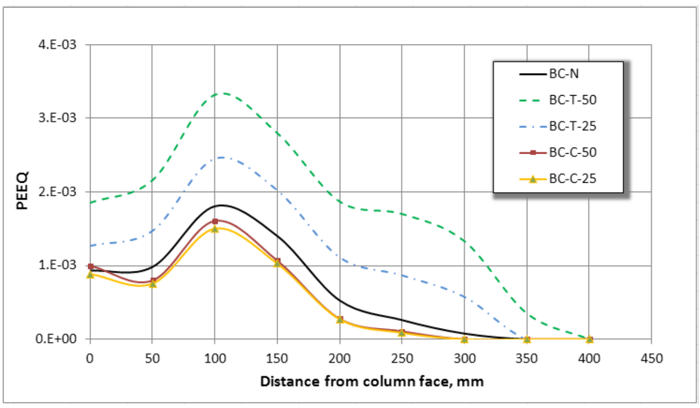


Figure 6. PEEQ distribution in the top flange of beam

On the other hand, as Fig. 7 shows, in case of that a compressive axial force acts in the beam (BC-C), the top flange undergoes smaller plastic deformation than the normal one.

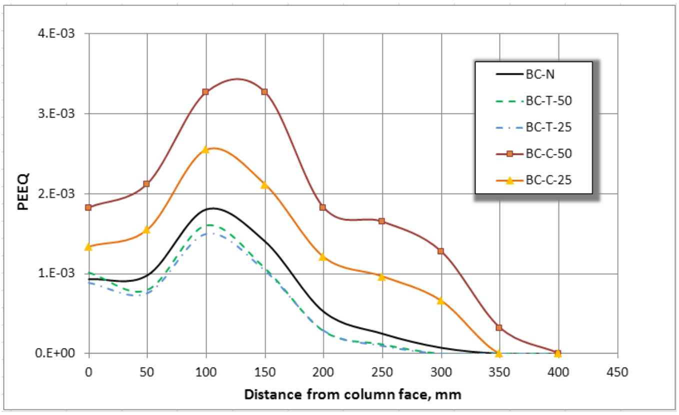


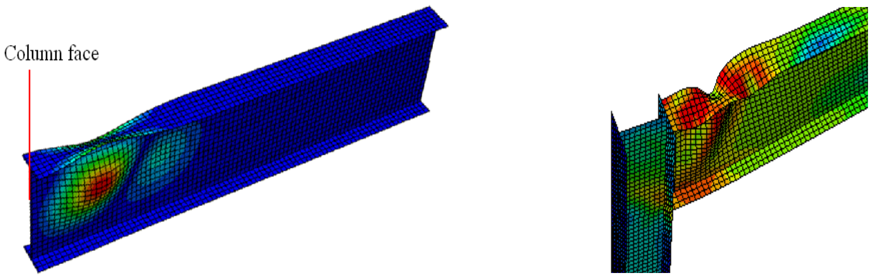
Figure 7. PEEQ distribution in the bottom flange of beam

Therefore, it can be concluded that, if the horizontal distribution of an inclined column acts in a beam with flexure, the smaller or larger deflection under the same deflection is expected comparing to the vertical column connection, depending on the inclined angle and direction of column. Although this study used extreme cases for the analysis, the results still provide the prediction of a change in plastic strain distribution which affects the local failure. Furthermore, the possible change in plastic hinge rotation can be expected.

4.2. Local Buckling

Due to the fact that the axial stress acting in the beam will cancel or amplify the compressive stress which grows during the flexural deformation depending on its direction, the onset of the FLB in the beam can be delayed or advanced. Also, once the local buckling occurs, the column-beam connection will undergo the strength degradation because of its capacity loss. Therefore, to verify and visualize this effect, by using ABAQUS, the eigenvalue analysis was conducted considering the buckling mode as shown in Fig. 8(a), then the displacement controlled analysis using Riks method, which is a nonlinear analysis considering the buckling, was performed.

For the eigenvalue and Riks analysis, the upward displacement at the end of the beam was applied and increased until the tip displacement reaches 500mm, which induces about 0.12 radians of end rotation at the column face and thought to be enough to see the FLB in every case. The initial imperfection was defined as 1/10 of the beam flange. Fig. 8(b) describes buckled shape of the beam, and Fig. 9 and Fig. 10 show the buckling analysis results of each model.



(a) Flange local buckling mode (b) Buckled shape of beam

Figure 8. Flange local buckling mode and buckled shape of beam

To compare the occurrence of flange local buckling in beams connected to columns having different angle, 25%, 50% and additionally 75% of yield strength of beam in tension and compression, which also represent extraordinary amount of inclined angle of column, were applied. Fig. 9 demonstrates the relationship between the upward displacement and the vertical force at the end of the beam when the tensile stress is acting in the beam. In contrast, Fig. 10 shows the same plot from the beam having compressive axial stress.

From Fig. 9, it can be found that, as the axial tensile stress in the beam increases, a plateau in the curve appears at larger tip displacement, which means that the onset of buckling is delayed as the inclined angle of column increases, while Fig. 10, a case of compressive stress in the beam, shows the reversed result. Also, it shall be noted that, as the inclined angle of column increases, the initial stiffness of the inclined column-beam substructures is reduced earlier because of the advanced yielding in the beam flange due to the extra axial stress. Therefore, when a steel beam connected to the inclined column is designed, the limit state for the FLB and the elastic stiffness should be considered carefully.

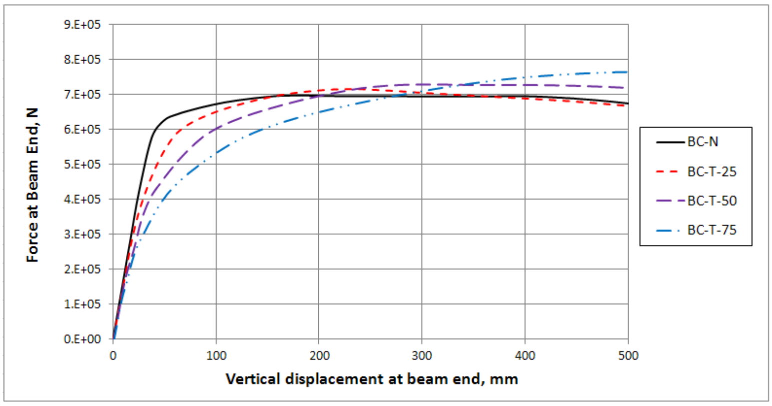


Figure 9. Load-displacement relationship of beam with tensile stress considering FLB

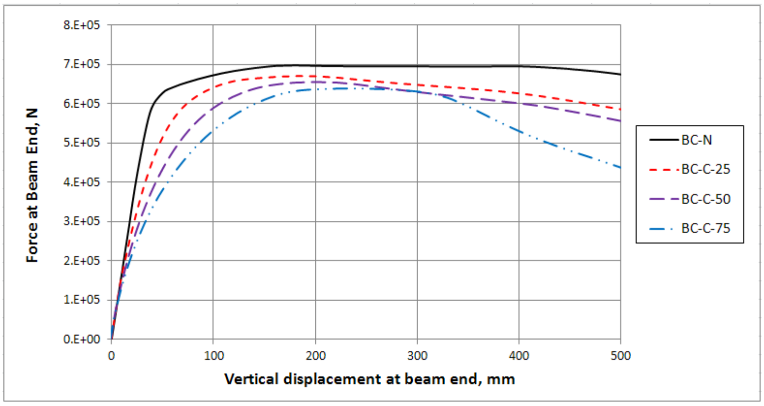


Figure 10. Load-displacement relationship of beam with compressive stress considering FLB

5. CONCLUSION

As described above, there exists a tensile or compressive stress in the beam connected to the inclined column, increasing with respect to the inclined angle. This horizontally distributed axial force from the inclined column affects the stress and strain distribution in the beam directly, so the resisting capacity of beam against the flexural deformation changes.

In this study, the plastic strain distribution and local buckling in beam flange were examined to assess the seismic performance of inclined column-beam connection. Although the amplified amount of force was applied to the model, which means that the inclined angle of column is unrealistic, the results of this study proved that the horizontal distribution of the axial force in the inclined column affects the potential of fracture at the connection by causing early yielding, and that it also delays or facilitates flange local buckling. Therefore, it is possible to conclude that the extra check for the inelastic behavior, local failure and buckling shall be considered when the inclined column-beam connection is designed.

Since this study deals only with the strain distribution and local buckling of beam flanges, it is still necessary to check fatigue at the connection, because they are also crucial for the seismic performance of structural members, and sensitive to the amount of axial stress around the welded connection joint. Furthermore, a full scale experiment shall be performed to prove the prediction of behavior from finite element analysis.

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