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Stress analysis of beam-to-column connection for earthquake-resistance welded steel structure based on FEM

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Abstract:

Brittle fracture of beam-to-column connection in steel construction under earthquake loading is affected greatly by the type of welded joints. In this study the artificial crack is formed by lack of fusion in the flange weld of beam in the beam-to-column connection, based on the model of typical beam-to-column connection in China, the stress distributions of connections have been computed by three-dimensional finite element method. It is concluded that stresses of connections could be reduced by connection reinforcement. Among reinforcements it is the most effective way to improve stress concentration at the root of flange weld by adding upstanding ribs on outside beam flange. In addition, stresses of hot spots in the connection without crack were computed first, then based on the driving force of crack calculated by formula of SIF, the stress intensity factors, K_I are obtained for cracks with 3 or 6 mm deep and with the length equal to width of beam web under two states, with or without residual stresses. Load equal to plastic moment of beam was assumed on this beam end to simulate moment loading under earthquake. Meantime the least fracture toughness of reinforced connection with cover plate to avoid brittle fracture is given among several reinforced forms. The analysis results can be used for earthquake-resistance design of beam-to-column connection of steel structure.

Key Words:

Beam-to-column connection, Earthquake-resistance, Stress intensity factor

1. Typical model of beam-to-column connection in China

In steel structure of high-rise buildings beam-to-column connections, which are joined by method of combining weld with bolt, are usually rigid. In these connections beam flanges are connected with column by grooved penetration weld, while beam web bolted by high-strength bolts with shear plate, which is connected to column with weld. Shear plate is used to carry shear force, while flange weld to carry moment loading. From the experiences of the well-known earthquakes of America and Japan, it can be seen that damages of steel structures due to failure of beam-to-column connection often took place at the root of flange weld, and that the initiation points of failure were more often at bottom flange weld than at top flange weld. To ensure the quality of weld, backing bar is used to support weld puddle of flange weld so that artificial crack is formed at the intersection of backing bar and column flange because of lack of fusion.

The examples of rigid beam-to-column connection used for FEM computation in this investigation are taken from Manual of anti-earthquake design of construction [1]. The intersection of beam and column are

Table 1: Mechanic property of weld and base metal of Q235B

Material	**σ_y(MPa)**	**σ_u (MPa)**	**δ (%)**
Q235B base metal	267	444	36.0
Q235B weld metal	372.8	492.2	36.4

hot-rolled type-H steel HK400×300×13.5×24 and HZ550×210×11.1×17.2 respectively. The span of beam is 7.2 meters. Table 1 shows mechanic property of material steel Q235B for column and beam,. Beam flanges are joined with column by penetration weld, while beam web is connected to column by shear plate, which is bolted with high-strength bolt, M20, Grade10.9. Fig.1 shows the detail of beam-to-column connection.

2. FEM analysis

Connection type with beam web unconnected to column is dealt as original type. When beam web connects with column flange thoroughly, it is equal to all-welded structure. In this case moment of structure mainly carried by flange weld will be reduced. Stress status of actual structure is between that of original type and all-welded type.

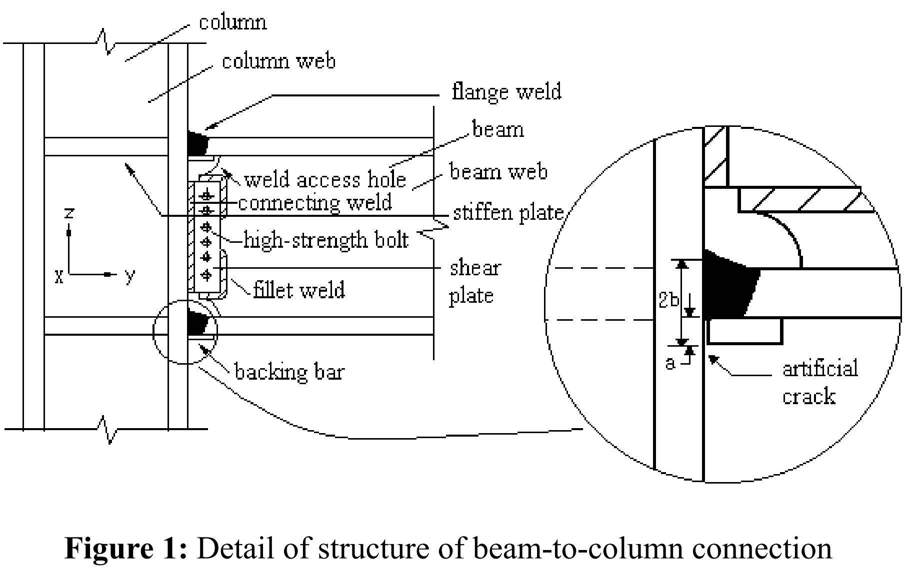

Figure 1: Detail of structure of beam-to-column connection

In addition to structure above, reinforced connections include connection with cover on flange, with stiffened rib inside beam and with upstanding rib on flange. Five alternative types of beam-to-column connection were modeled and analyzed as fellows:

Case one：Original structure (with artificial crack),

Case two：All-welded structure (with artificial crack),

Case three：Reinforced connections with cover plate(with artificial crack),

Case four：Reinforced connections with stiffened rib(with artificial crack),

Case five：Reinforced connections with upstanding rib(with artificial crack).

As examples, The sketch maps of three types of reinforced connection are shown in fig.2.

The example was modeled on eight-node brick elements using three-dimension elastic-plastic finite element program Algor-Feas. The material properties were modeled by Von Mises yield criterion with associated plastic flow rules. In order to mesh the structure, some simplification of bolted joint and weld shape was made. For its symmetry about plane perpendicular to X-axis, half of structure was used. Fig. 3 shows 3D mesh of beam-to-column connection. Artificial crack was treated as notch, which about 0.02 mm wide was at the root of flange weld.

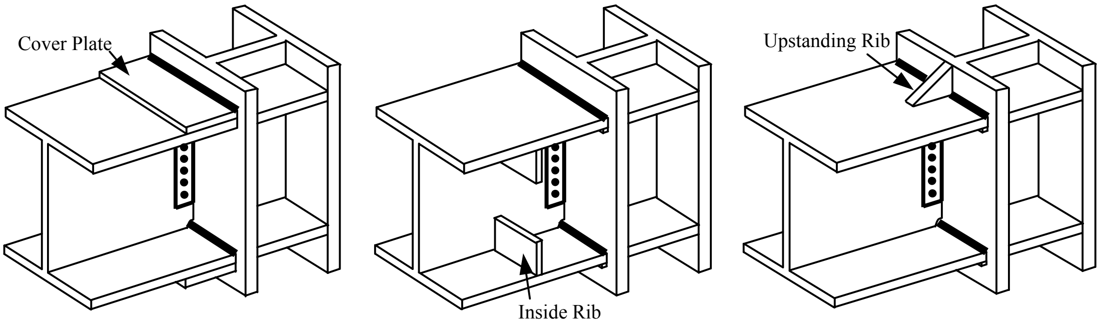

Figure 2: Three types of reinforced beam-to-column connections

3. Analysis result

From FEM computation, stress distribution of flange weld of different types could be obtained. As the stress in the symmetry plane of beam is higher than that of any other place, along beam width away from

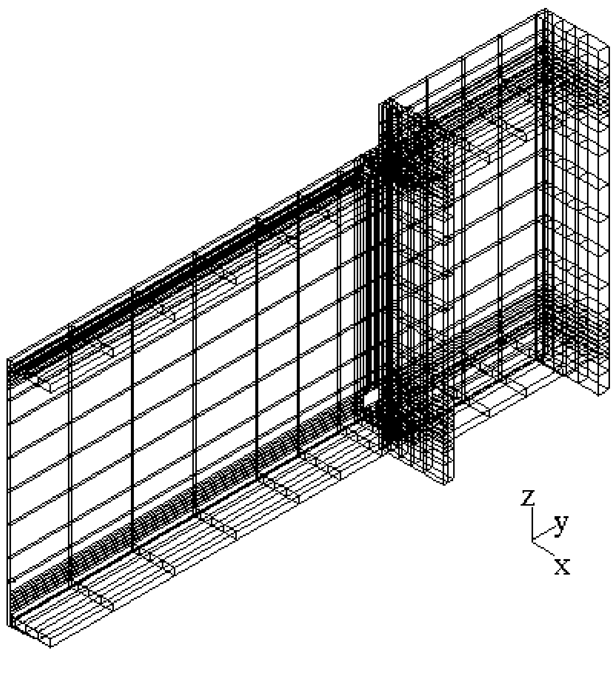

Figure 3: Three-dimensional mesh of beam-to-column connection

symmetry plane the stress reduces. There are high stress in the middle of flange weld of intersection of beam and column and intersection point between flange and web at the weld access hole. These hotspots where exist stress concentration are weak point of structure, such as point A, B and C that corresponds to maximum stress of artificial crack. The subscript 1 and 2 to point A, B and C are used to specify top and bottom flange weld, respectively. Table 2 lists stress concentration and stresses of weak point.

It concludes from the comparison as fellow:

[1] It is useful to reduce the stress of weak point, such as intersection of weld access hole and middle point at flange weld, through strengthening connection by adding cover plate on flange weld, stiffened rib inside beam or upstanding rib outside beam flange.

[2] It is also proved by actual earthquake that floor which usually connects the top beam flange acts as cover plate, so fracture rarely initiated from top flange.

[3] It also concludes that adding upstanding rib outside beam flange is the most effective measure to improve stress concentration of flange weld.

[4] That no matter which type of connection is taken stress of bottom flange is always higher than that of top flange also accords with that fracture inclined to take place at the root of bottom flange on actual earthquake.

However, extend of amelioration of stress concentration is limited, because the supposition of exiting of artificial crack is more stringent than actuality.

Table 2 Stress concentration factor or Mises stress of weak point of different structure forms

SCF	**A1**	**B1**	**A2**	**B2**	**Stress (C1) (MPa)**	**Stress (C2) (MPa)**
Type one	1.43	2.33	1.25	2.38	114.0	370.0
Type two	1.52	3.83	1.44	3.98	367.5	372.0
Type three	1.42	2.52	1.25	2.12	86.45	371.6
Type four	1.40	2.04	1.31	2.06	114.0	371.9
Type five	—	—	—	—	101.0	200.6

4. Fracture mechanics analyses

The methods of fracture mechanics are used to estimate the acceptability of a crack in a structure. The use of the fracture mechanics approach has given useful results for required toughness [2]. Firstly, these calculations are based on the finite element analysis results. Secondly, fracture toughness determination involves more parameters in real materials and assumptions have had to be made about residual stresses and defect size. The finite element calculations were only elastic. This fracture mechanics assessment gives strong support for more detailed research on the reinforced connections.

Stresses of hot spots in the connection are used to compute the driving force of crack by the fracture mechanics formula. In this study only elastic FEM analysis was carried out. Five alternative types of beam-to-column connection were modeled and analyzed again. Analysis models by FEM are the same as above, but this time the calculation is without crack.

Finite element analysis was performed to determine the distribution of stresses in beam-to-column connections when subjected to moment loading as would arise under earthquake loading. The magnitude of the loading used was intended to make the beam reach its full plastic moment capacity. The moment load was formed by applying opposite surface stress to upper beam flange and lower beam flange. The values of surface stress equals to yield stress of beam, about 267N/mm^2.

The patterns of the stress distribution along the intersection face of beam flange and column flange showed peak values close to the centerline of the beam web which reduced towards the edge of the flange. The results are given in Table 3 and Table 4 in the form of peak stress concentration factors, i.e. the ratio of the maximum stress at the center of the beam width to the remote uniform tension stress.

Of the several Northridge researchers, Kaufmann and Fisher [3] investigated weld defects from the fracture surfaces of damaged connections and tested specimens. Defects [4] observed in the damaged connections were believed to have had an initiate depth of 3-6mm and their initiate length would have been approximately equal to the web thickness, about 11mm in this paper. In calculations defects are supposed to be semi-ellipse surface crack to compute stress intensity factors through fracture mechanics equation [5].

Zhang and Dong [6] used (2-D) thermo-mechanical simulations of the multi-pass welding procedure for the lower flange connection to provide the first quantitative descriptions of the residual stress fields. It pointed out that at the top of or root of the butt flange weld there are residual tensile stress, but in the middle of flange weld stressed are compressive. The tensile stress at the top or at the root of flange weld could be at the level of the yield strength of the weld metal. In this paper residual tensile stress are assumed to equal to 300N/mm^2.

The results for SCFs at center of beam flange width and the required fracture toughness are listed in tables 3 to 4 where the following categories are distinguished:

- Defect with depth 3mm without residual stress (σ res=0)
- Defect with depth 6mm without residual stress (σ res=0)
- Defect with depth 3mm with residual stress (σ res=300N/mm^2)
- Defect with depth 6mm with residual stress (σ res=300N/mm^2)

Tab.3: Required fracture toughness with defect size 3mm or 6mm and without residual stress

	SCF	**Required fracture toughness (N mm$^{-3/2}$) a=3mm, σ_{res}=0**	**Required frcture toughness (N mm$^{-3/2}$) a=6mm, σ_{res}=0**
Case 1	2．22	1875.2	2362.5
Case 2	1．88	1584.2	1996.0
Case 3	1．37	1154.2	1454.2
Case 4	1．76	1489.4	1876.5
Case 5	1．78	1502.0	1892.4

Tab.4 Required fracture toughness with defect size 3mm or 6mm and with residual stress

	SCF	**Required fracture toughness (N mm$^{-3/2}$) a=3mm, σ_{res}=300MPa**	**Required fracture toughness (N mm$^{-3/2}$) a=6mm, σ_{res}=300MPa**
Case 1	2．22	2823.8	3557.7
Case 2	1．88	2532.9	3191.2
Case 3	1．37	2102.8	2649.4
Case 4	1．76	2438.0	3071.7
Case 5	1．78	2450.7	3087.6

5. Conclusion

From the analysis above, conclusions can be reached.

[1] Area of high stress concentration exits at the root of flange weld from the study of stress distribution. The stress concentration at the root of bottom beam flange weld is obviously higher than that of top beam flange weld. At the same time, stress concentration also exits at the intersection point between beam flange

and web near the weld access hole.

[2] The experience showed that brittle fracture under earthquake load was the combined effect of weld defects and stress concentration. To improve property of beam-to-column connection, stress concentration must be reduced from design point of view. As the backing bar exits, the artificial crack is origin of stress concentration at the root of flange weld. Therefore to ensure carrying capability of important structure, penetrated flange weld, removing backing bar or weld all around backing bar should be taken to reduce the effect of defect.

[3] The action of reducing stress concentration through reinforcement of connections by adding cover plate, inside rib or upstanding rib is effective. Among the reinforcement of connection, effect of reducing stress concentration is remarkable by using upstanding rib. Improvement of stress concentration will be significant, if other actions, such as raise the fracture toughness of material and decrease the defect, can be taken in company with reinforcement in the meantime.

[4] The finite element analysis revealed the presence of a stress concentration factor of 2.22 at the center of the beam flange to column joint. The reinforced connection with cover and stiffened rib gave low level of stress concentration at critical area, and particularly reinforced connection with cover plate required toughness is least.

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References

1. Editorial committee of practical manual of anti-earthquake design of construction, Practical manual of anti-earthquake design of construction. Beijing：Publishing company of construction of China, 1997, in Chinese.
2. F.M. Burdekin, A.Pardali, Considerations of design, material properties and inspection requirements for earthquake resistant steel frame connections. Task Group B Draft, IIW JWG on Brittle Fracture of Moment Connection in Seismically Affected Structures, 1999,5.
3. Kauffmann EJ, Fisher JW. A study of the effects of material and welding factors on moment frame weld joint performance using a small scale tension specimen. Technical Report SAC 95-08, 1995.
4. Changbin Joh, Wai-Fah Chen, Fracture strength of welded flange-bolted web connections, Journal of Structure Engineering, Vol.125, No.5: 565~571.
5. Zhang J, Dong P, Residual stress in welded moment frames and implications on structural performance. J. of Struct Engng, ASCE, 1999 [in press].
6. Shen Chengkang，Fracture mechanics，Publishing house of Shanghai Tongji University，1996, in Chinese.