SEISMIC PERFORMANCE AND DESIGN OF REDUCED STEEL BEAM SECTION WITH CONCRETE FILLED SQUARE TUBULAR COLUMN

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Received: 6 September 2011; Revised: 18 February 2012; Accepted: 29 February 2012

ABSTRACT: According to the anti-seismic design principle of strong column and weak beam, and of strong joint and weak member, reduced beam section (RSB) is often used to shift away plastic hinge from end of beam to the weaken region of the beam. The non-linear finite element models are established for concrete-filled steel square tubular column and reduced steel beam with holes in flange or in flange and web, considering geometric large deformation and material nonlinear. Comparison is made on load-displacement curves, the stress distribution of reduced beams, the ultimate load-carrying capacity, the ductility, and the energy-dissipating ability between analysis results of different RBS section and experimental results. It shows that the stiffness and ultimate load-carrying capacity of new RBS section are close to traditional RBS section, the plastic hinge in the new section with reduced beam section can be moved to the reduced region, and the new section display good ductility, energy-dissipating ability and seismic behavior. Based on Chinese codes and analysis results, the seismic design method of concrete-filled steel square tubular column and reduced steel beam section are proposed in this paper.

Keywords: Shape optimization, seismic design, Concrete-filled steel square tubular column, Beam-column joint, Reduced beam section, Nonlinear FEM

1. INTRODUCTION

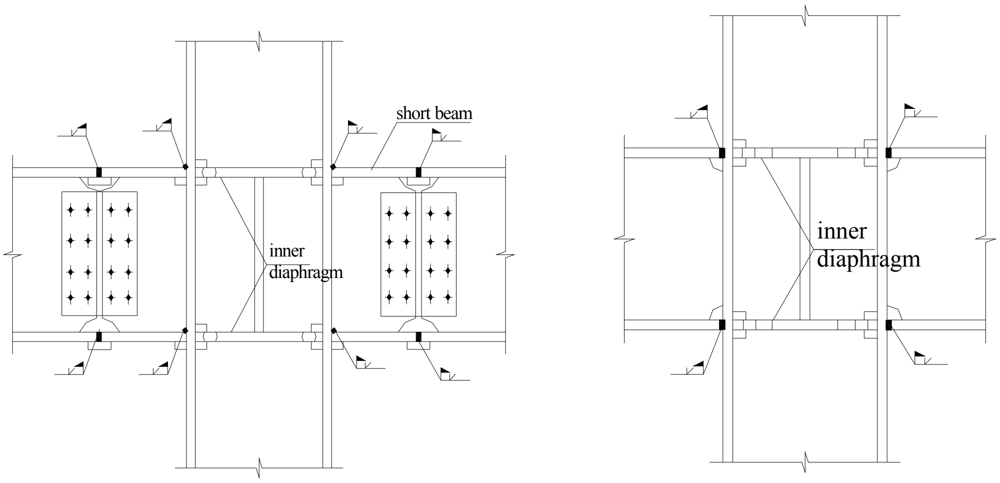
Since the earthquake of 1994 in Northridge and of 1995 in Kobe, intensive research and testing efforts have been underway to find better methods to design and construct seismic resistant steel frames. A number of improved beam-to-column connection design strategies have been proposed. According to the research results(CECS159-2004 [1], Cai [2], Ru et al.[3], FEMA-350 [4]) of researchers and considering the tradition connection of steel frame, 'Technical specification for structures with concrete-filled rectangular steel tube members'(CECS159:2004[1]) gives two kind of beam-to-column section, one with short-beam and inner diaphragm(Figure 1a) and the other with inner diaphragm(Figure 1b). Because the beam section in connection can't reach equal-strength for the tradition connection joint, the beam-to-column connection should adopt reduced beam section with shift-away of plastic hinge in seismic fortification intensity 8 of site-class 3 and 4 and seismic fortification intensity 9 according to the research results of steel frame section. The research results (FEMA-350 [4], Liu [5]) show arc-shape cutting is the best way to avoid stress concentration, but this cutting mode is difficult to operate. Cutting hole in web of beam is easy to operate and the hole in web of beam can convenient to arrange pipeline. Two new kinds of section with holes in flange or flange and web are suggested to use for concrete-filled steel square tubular column and reduced steel beam in this paper, Seismic performance of these two new kinds of section under monotonic and cyclic loading are analysis by finite element method (FEM), and the dimension of the new reduced beam section with high stiffener, load-carrying capacity, good ductility, and energy- dissipating ability are suggested for engineering. Based on Chinese codes (CECS159-2004 [1], GB50011-2008 [6], JGJ99-98 [7]) and analysis results, the seismic design method of concrete-filled steel square tubular column and reduced steel beam section are proposed in this paper.

2. STYLE OF REDUCED BEAM SECTION

The styles of reduced beam section include two kinds, reduced region in flange or in web (Guo [8]).

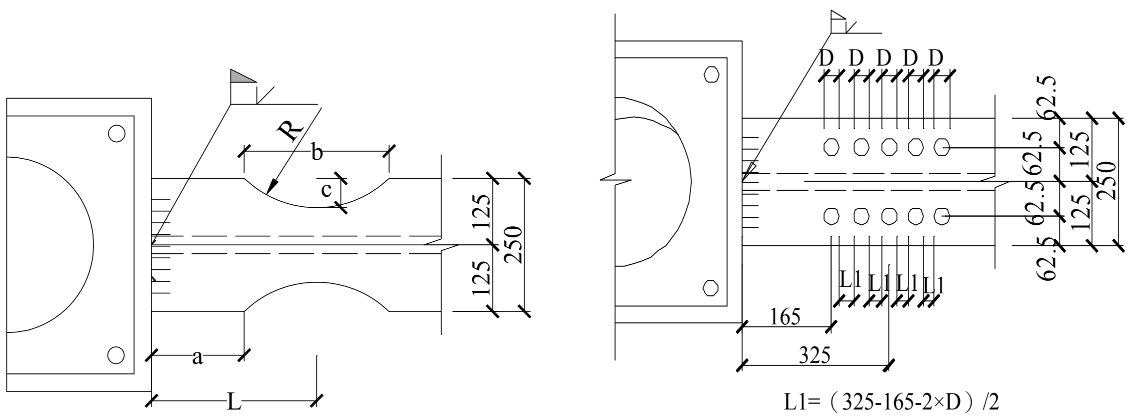
2.1 Reduced Beam Section with Drilled Flange

RBS with radius cut is the tradition shapes cutout (Figure 2a), which behaves with the highest rotational capacity. But it is difficult to trim away. Drilled hole is easy to operate. Three kinds of drilled flanges are suggested as shown in Figure 2b, Figure 2c, and Figure 2d. Figure 2b is single-row hole with same diameter. Figure 2c is single-row hole with different diameter. Figure 2d is two-row hole with same diameter. The dimension and location of drilled hole are reference to radius cut to ensure the same reduced area and location. The geometrical characteristics of the RBS section is $a = (0.5 \sim 0.75)b_f$, $b = (0.65 \sim 0.85)h_b$, $c \le= 0.25b_f$, $R \le= (4c^2 + b^2)/(8c)$, where h_b is beam depth, b_f is the flange width, and l is the distance of the intended plastic hinge ate the centre of the RBS from the column face.

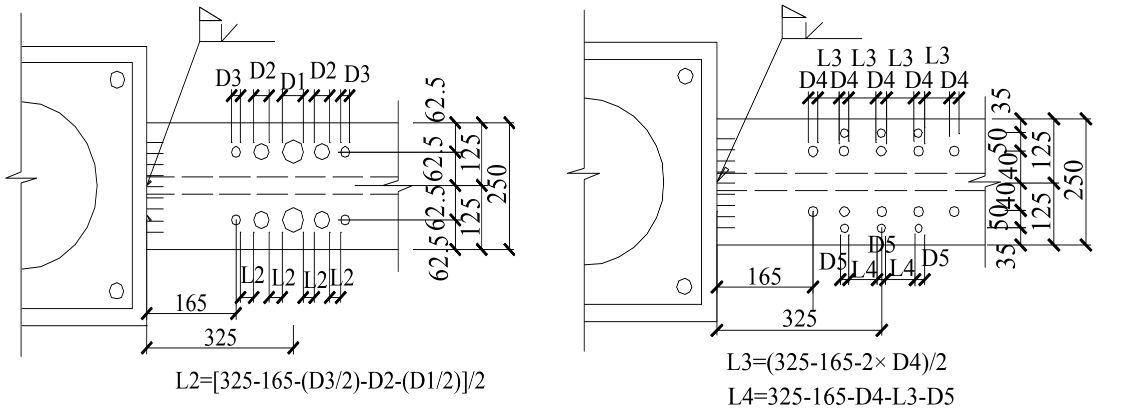


(a) Short Beam and Inner Diaphragm (b) Inner Diaphragm

Figure 1. RBS Joint

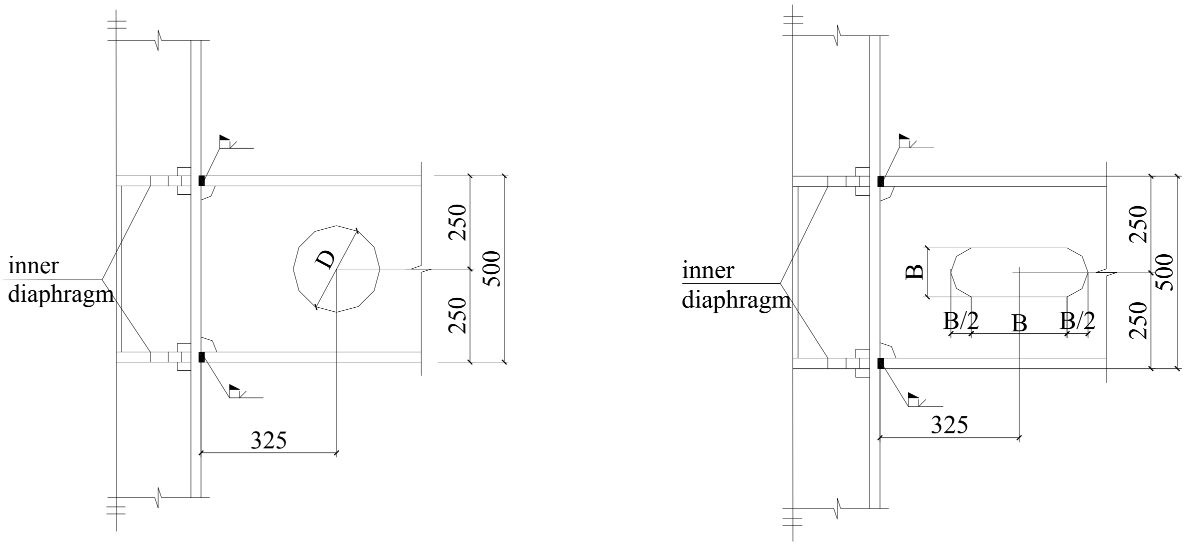


(a) Radius Cut (b) Drilled Single-row Same Hole



(c) Drilled Single-row Different Hole (d) Drilled Two-row Same Hole

Figure 2. Style of RBS Joint with Drilled Hole in Flange

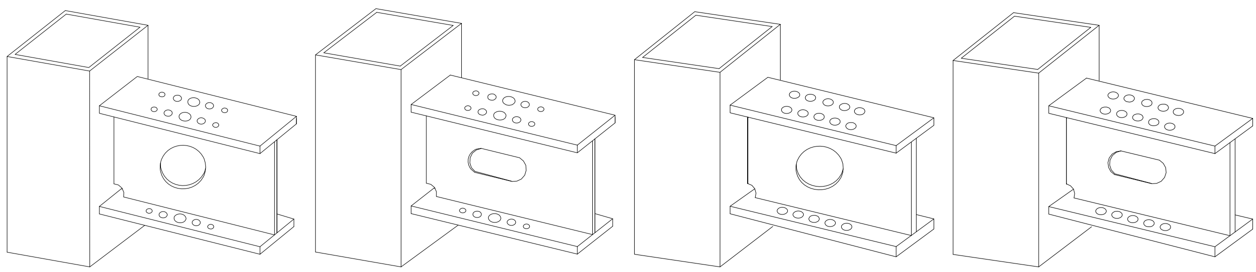


(a) Circular Hole in Web (b) Long-circular Hole in Web

Figure 3. Style of RBS Joint with Cut Hole in Web

2.2 Reduced Beam Section with Drilled Flange and Web

The flange and web bear shear of section bear moment and shear respectively. In order to ensure the maximum stress in flange and web to shift away the reduced zone simultaneously and easy to operate and use, the mode of section with drilled flange and web as shown in Figure 4 are suggested based on the drilled flange in Figure 2 and drilled web in Figure 3. Figure 4a is flange with single-row hole with different diameter and web with circular hole. Figure 4b is flange with single-row hole with different diameter and web with long-circular hole. Figure 4c is flange with single-row hole with same diameter and web with circular hole. Figure 4d is flange with single-row hole with same diameter and web with long-circular hole.



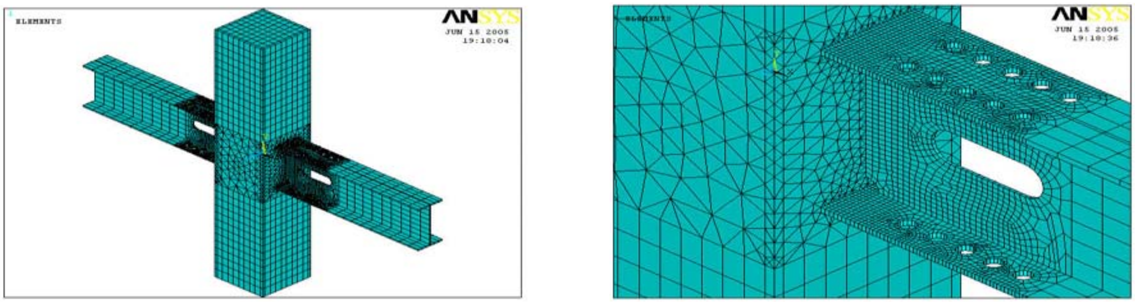
(a)Different hole in flange circular hole in web (b)Different hole in flange long- circular hole in web (c) Same hole in flange circular hole in web (d) Same hole in flange long-circular hole in web

Figure 4. Section of Reduced Web and Reduced Flange

3. FINITE ELEMENT MODELING

3.1 Specimens, Element and Model

The dimension of specimens analyzed by FEM can be found in reference(Zhou [9]). The yield stress of steel is 345N/mm^2. Compressive strength of concrete is 26.8 N/mm^2. The dimension of tube is 500x500x25mm and beam is H500x250x8x16. The thickness of inner diaphragm is 28mm and the diameter of big hole and litter hole in inner diaphragm are 250 and 25mm respectively. The number and dimension of reduced zone are shown in Table 1, where JD-3B is the experimental specimens in reference (Zhou [9]). The meanings of label of section are as follows, *Y, K, S, D, F, C,* and *R* indicate the flange, hole, same diameter, different diameter, web, circular hole and long-circular hole respectively. The finite element program ANSYS7.1 considering the material non-linear and geometry large deformation was used to simulate section. Element of *solid45* is used to simulate steel beam and column, which have 8 nodes and every node have three degrees of freedom. Element of *solid92* is used to simulate inner diaphragm, which have 10 nodes and every node have three degrees of freedom. Element of *solid65* is used to simulate concrete (Zhou et al.[10], Zhou et al.[11]). The FEM use Newton-Raphson method. Figure 5 shows a typical finite element meshing used in this study. As observed in Figure 5b a more refined mesh was applied at the regions near the RBS.



(a) FEM model (b) Refined mesh near reduced zone

Figure 5. FEM Model

Table 1. Dimensions of New Reduced Beam Section

number	place	specimen	practical style of RBS	label of RBS section	dimension of reduced zone
0	no	JD-3B	no	no	no
1	flange	RBS(tradition)	radius cut	radius cut	a=150,R=290,b=325
2		YK1S	same hole	YK1S40	D6=40
3		YK1D	different hole	YK1D30,40,50	D1=50,D2=40,D3=30
4				YK1D30,50,60	D1=60,D2=50,D3=30
5				YK1D30,40,60	D1=60,D2=40,D3=30
6		YK2	two row same hole	YK2,30,30	D1=30（inner row）,D2=20（out row）
7	flange and web	YK1SFKC	same hole in flange and circular hole in web	YK1SFKC40,150	D6=40, D_F=150
8				YK1SFKC30,120	D6=30, D_F=120
9				YK1SFKC30,140	D6=30, D_F=140
10				YK1SFKC30,150	D6=30, D_F=150
11				YK1SFKC35,120	D6=35, D_F=120
12				YK1SFKC35,130	D6=35, D_F=130
13				YK1SFKC35,140	D6=35, D_F=140
14		YK1DFKC	different hole in flange and circular hole in web	YK1DFKC30,40,50,150	D1=50,D2=40,D3=30, D_F=150
15				YK1DFKC30,40,50,120	D1=50,D2=40,D3=30, D_F=120
16				YK1DFKC30,40,50,100	D1=50,D2=40,D3=30, D_F=100
17				YK1DFKC20,40,50,120	D1=50,D2=40,D3=20, D_F=120
18		YK1SFKRC	same hole in flange and long-circular hole in web	YK1SFKRC30,180,90	D6=30, B=90
19				YK1SFKRC30,200,100	D6=30, B=100
20				YK1SFKRC30,220,110	D6=30, B=110
21		YK1DFKRC	different hole in flange and long-circular hole in web	YK1DFKRC30,40,50,200,100	D1=50,D2=40,D3=30,B=100
22				YK1DFKRC30,40,50,100,50	D1=50,D2=40,D3=30,B=150

3.2 Loading Procedure

The model analyzed in this paper is the joint in the inflection point of beam and columns as shown in Figure 6. Hinge is used in end of beam and bottom end of column. Vertical load and horizontal displacement are applied the top of column. The load arrangement is shown in Figure 6. The loading procedure for cyclic loading is as follows, Vertical load applied the top of column is 1000kN constant, horizontal load are applied at the top of column when load is less than yield load, and horizontal displacement are applied at the top of column when load is more than yield load. Horizontal load use 3~5 single cycle up to the yield strength. Then several complete horizontal displacement cycles are applied with displacement amplitudes in multiples of yield displacement. The loading protocol is shown in Figure 7.

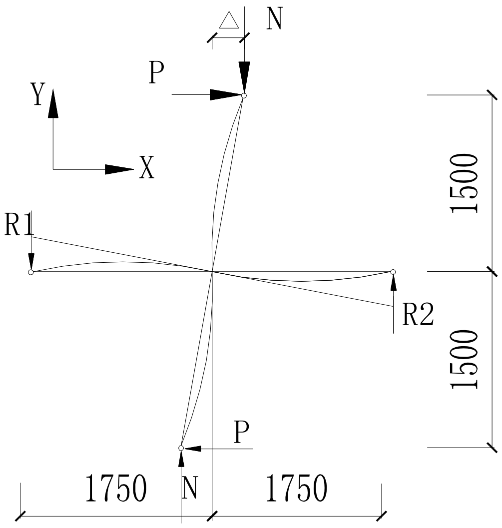


Figure 6. Loading Rrrangement

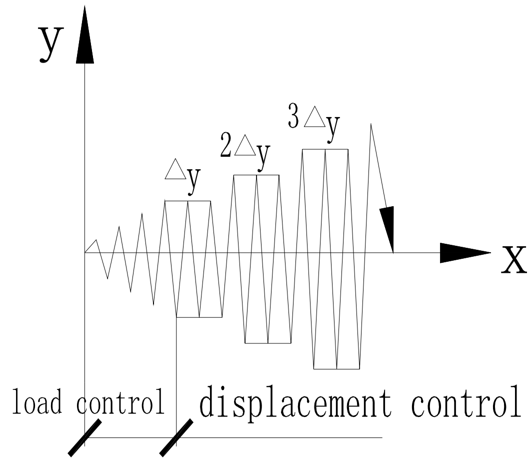


Figure 7. Loading Protocol

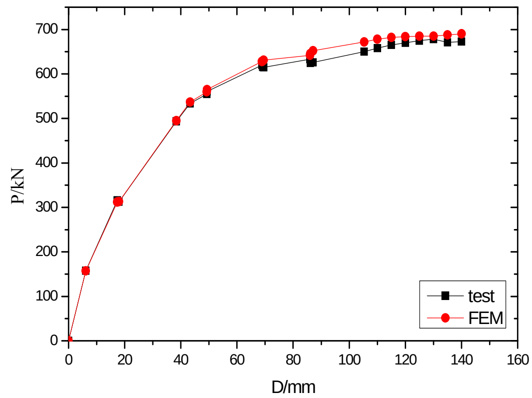


Figure 8. Comparison on JD-3B between Test and Analyzed Result

3.3 FEM Verification

The load versus displacement of RBS joint obtained from FEM is compared with which of test as shown in Figure 8. The curve of FEM is close to which of test. The error of yield load and ultimate load are less 5%. So FEM can be used analysis the seismic performance of different concrete-filled square tubular column and reduced steel beam section under different load style closely.

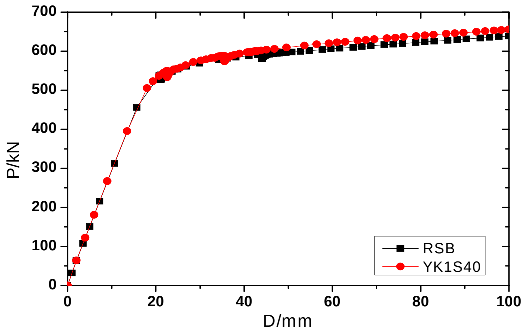
4. RESULT UNDER MONOTONIC LOADING

Two kinds of new RBS section are analyzed by FEM. The ultimate load-carrying capacity and Von-Mises stress of reduced region are compared with traditional RBS, and the dimension of new RBS section with excellent reduced performance are suggested.

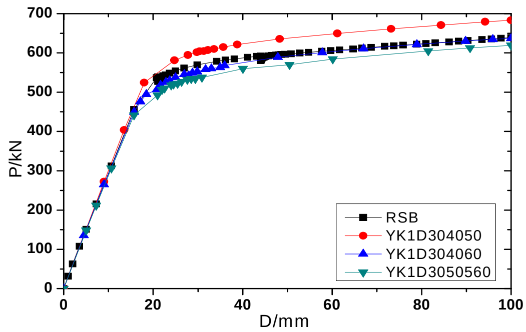
4.1 Curve of Load Versus Displacement and Stress Distribution of RBS with Drilled Flange

The curve of load versus displacement and stress distribution of reduced beam section with drilled flange are shown in Figure 9 and Figure 10 respectively.

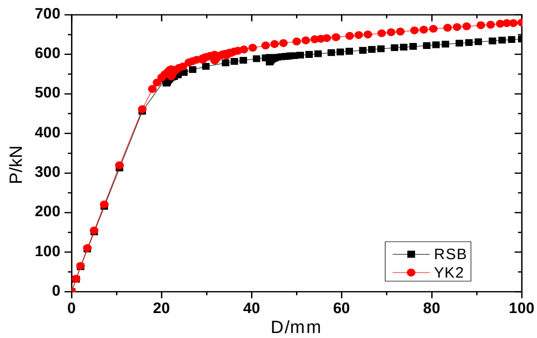
As shown in Figure 9, the curve of load versus displacement of reduced beam section with different drilled flange is close to which of traditional RBS joint, which observe that the ultimate load-carrying capacity of reduced beam section with different drilled flange don't decrease. The new RBS sections have good load-carrying capacity. As shown in Figure 10, stress distribution of YK1S and YK2 indicate that plastic hinge can't be shifted away column face to center of reduced region. So these two new sections can't be suggested to use. Stress distribution of YK1D30.40.50 indicates that plastic hinge can't be shifted away column face to center of reduced region. But Stress distribution of YK1D30.40.60 and YK1D30.50.60 as reduced region increased indicate that plastic hinge can be shifted away column face to center of reduced region, and the stress of column face are 331~386N/mm^2 and 334~389 N/mm^2 which are less than yield strength. So these two new RBS section can be suggested to use. The dimension of new suggested RBS joint is, D_3=2D_1,D_2/H=0.08~1,D_1/H=0.06, where D_1, D_2, and D_3 is the diameter of drilled hole.



(a) YK1S



(b) YK1D

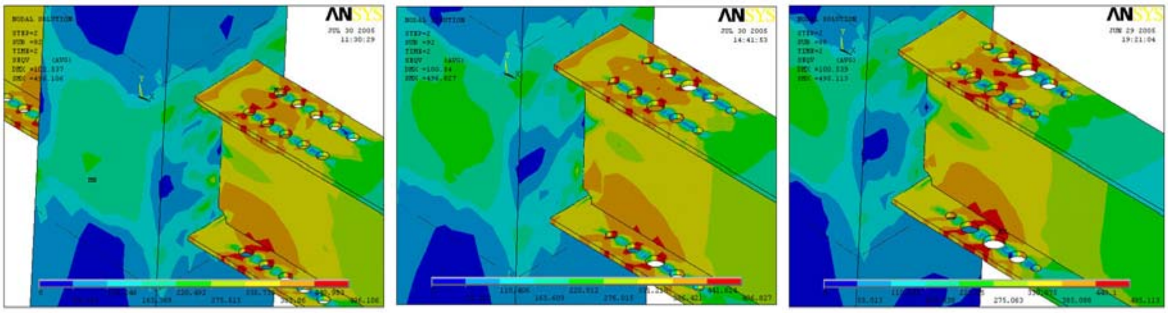


(c) YK2

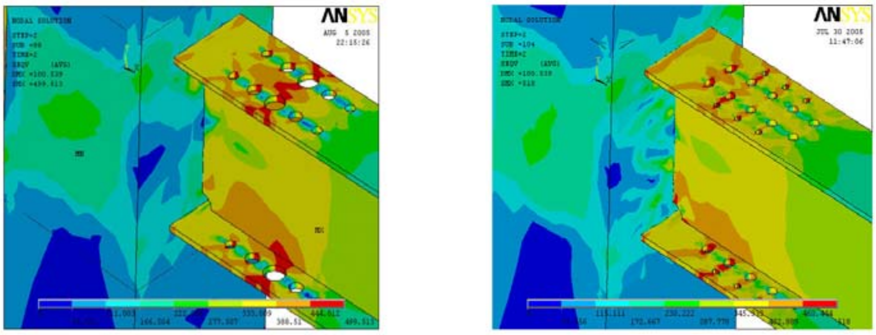
Figure 9. Load-displacement Curve of Section of Reduced Flange

4.2 Curve of Load Versus Displacement and Stress Distribution of RSB with Drilled Flange and Web

The curve of load versus displacement of reduced beam section with drilled flange and web are shown in Figure 11 respectively. The curve of stress distribution of reduced beam section with drilled flange and web are shown in Figure 12, Figure 13, Figure 14, and Figure 15.



(a)YK1S40 (b)YK1D30,40,50 (c)Y1D30,50,60



(d)YK1D30,40,60 (e)YK2,30,30

Figure 10. Stress Distribution of Section of Reduced Flange

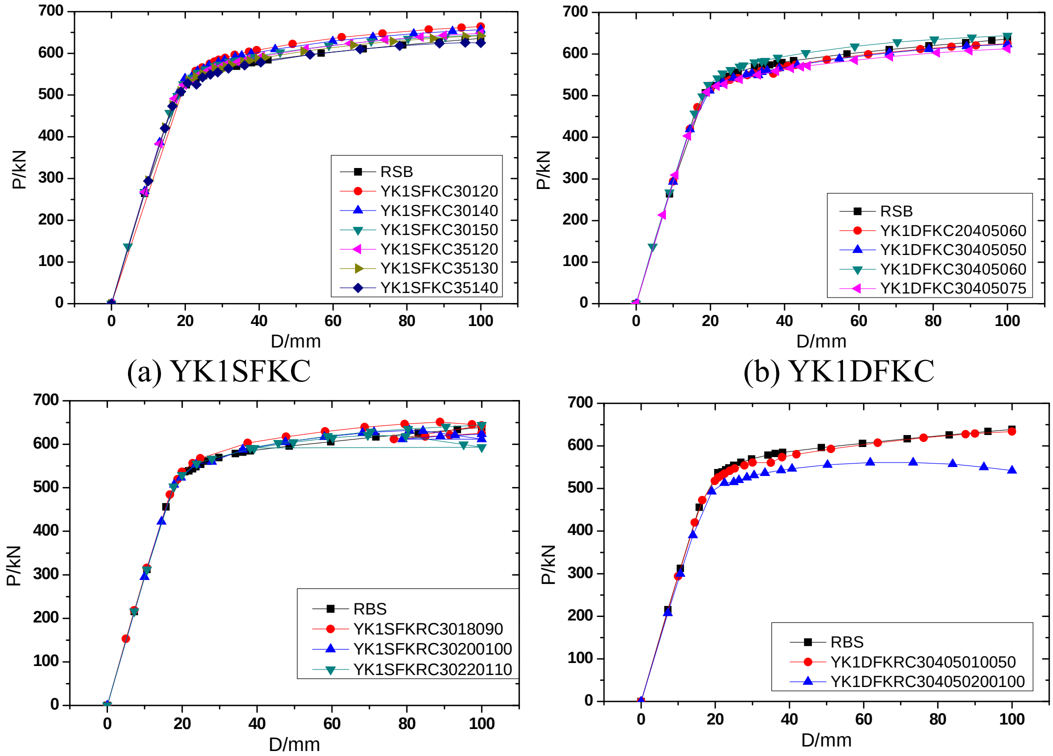
As shown in Figure 11a, the curve of load versus displacement of YK1SFKC is close to which of traditional RBS joint, which indicate the new RBS section have good load-carrying capacity. As shown in Figure 12, stress distribution of YK1SFKC indicate that plastic hinge can be shifted away column face to reduced region, but only plastic hinge of YK1SFKC30.140 can be shifted to center of reduced region and the stress of column face are 340~400N/mm^2 which are less than yield strength. So this new joint can be suggested to use. The dimension of new suggested RBS joint is, D_F/H=0.28,D/H=0.06, where D and D_F is the diameter of drilled hole of flange and web respectively.

As shown in Figure 11b, the curve of load versus displacement of YK1DFKC is close to which of traditional RBS joint, which indicate the new RBS section have good load-carrying capacity. As shown in Figure 13, stress distribution of YK1SFKC indicates that plastic hinge can’t be shifted away column face to the center of reduced region, So these new section can’t be suggested to use.

As shown in Figure 11c, the curve of load versus displacement of YK1SFKRC30.180.90 is only close to which of traditional RBS joint, which indicate the new RBS section have good load-carrying capacity. As shown in Figure 13, stress distribution of YK1SFKRC indicate that plastic hinge can be shifted away column face to the center of reduced region and the stress of column face are 340~400N/mm^2 which are less than yield strength. So this new joint can be suggested to use. The dimension of new suggested RBS joint is, B/H=0.18,D/H=0.06, where D and B is the diameter of drilled hole of flange and web respectively.

As shown in Figure 11d, the curve of load versus displacement of YK1DFKRC is close to which of traditional RBS joint, which indicate the new RBS section have good load-carrying capacity. As shown in Figure 15, stress distribution of YK1DFKRC indicate that plastic hinge can be shifted away column face to the center of reduced region, but these new joint have too many holes and are difficult to operate. So these new section can’t be suggested to use.

According to comparison on analysis results by FEM of two kinds of new RBS section under monotonic loading, four new RBS section are suggested to use, YK1D30.40.60 and YK1D30.50.60 of reduced beam section with drilled flange and YK1SFKC30.140 and YK1SFKRC30.180.90 of reduced beam section with drilled flange and web.



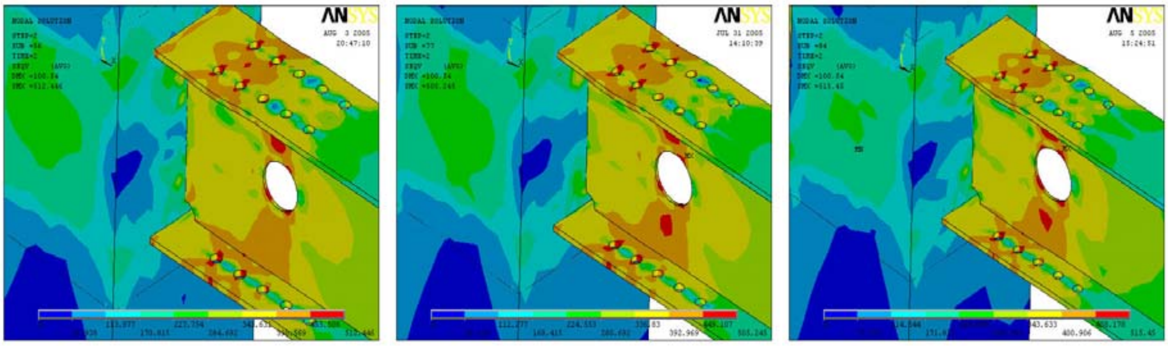
(a) YK1SFKC (b) YK1DFKC

(c) YK1SFKRC (d) YK1DFKRC

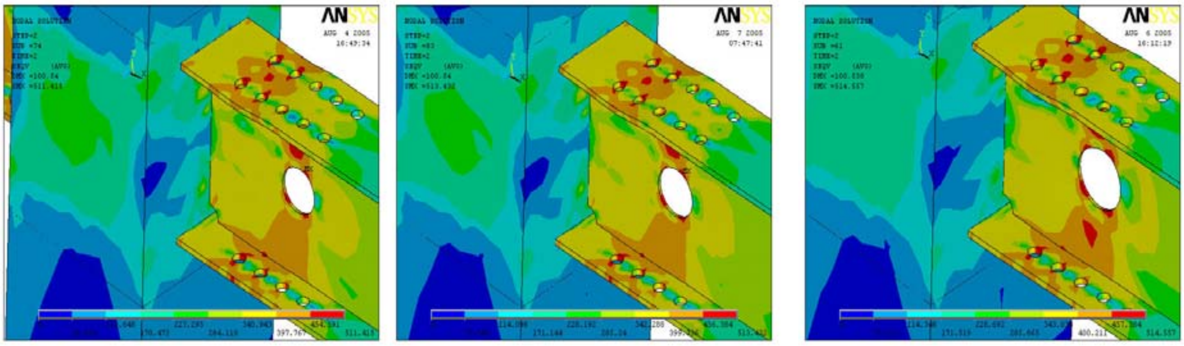
Figure 11. Load-displacement Curve of Section of Reduced Flange and Web

4.3 Stress Distribution of Suggested Reduced Beam Section

The stress along length of beam of four new suggested RBS section is shown in Figure 16 as 100mm lateral displacement, and the stress along width of beam at column face and beam reduced region is shown in Figure 17. The stress along width of beam of four new suggested RBS section at column face and beam reduced region is shown in Figure 18 as yield load. As shown in Figure 16 and 17, the stress of column face is less than which of beam region as 100mm lateral displacement, and as shown in Figure 18 the stress of column face is less than which of beam region and yield strength as joint reach yield. These show that the plastic hinge of new suggested RBS joint can shift away column face to reduced region effectively.

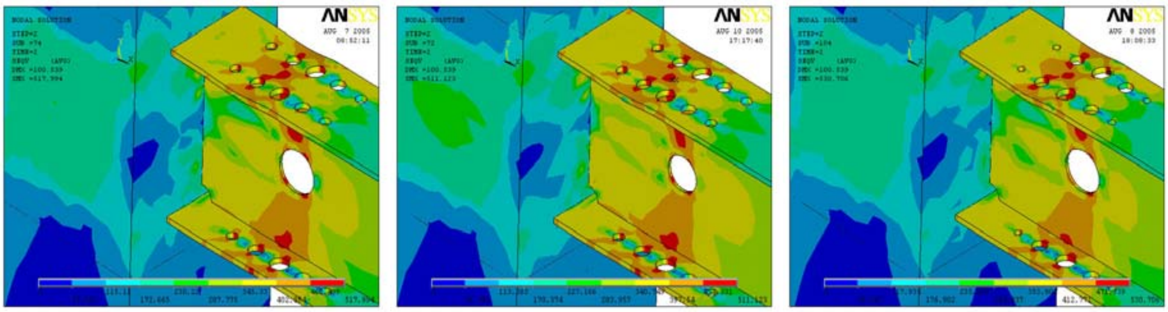


(a) YK1SFKC30,120 (b) YK1SFKC 30,140 (c) YK1SFKC 30,150



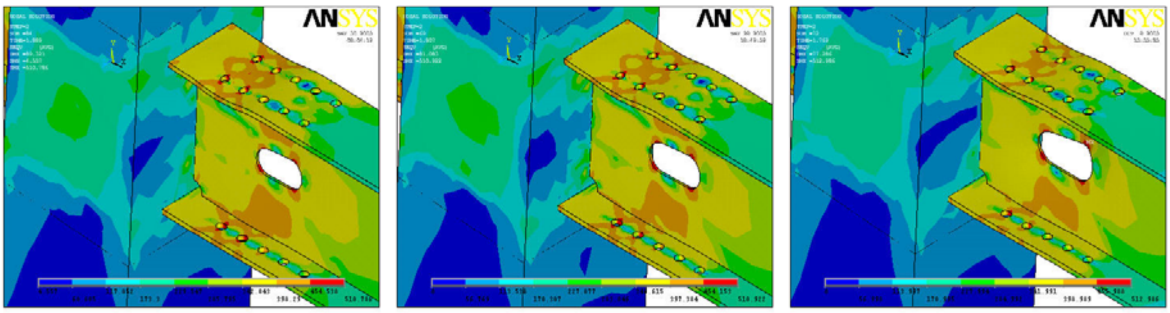
(d) YK1SFKC 35,120 (e) YK1SFKC 35,130 (f) YK1SFKC 35,140

Figure 12. Stress Distribution of Section of *YK1SFKC*



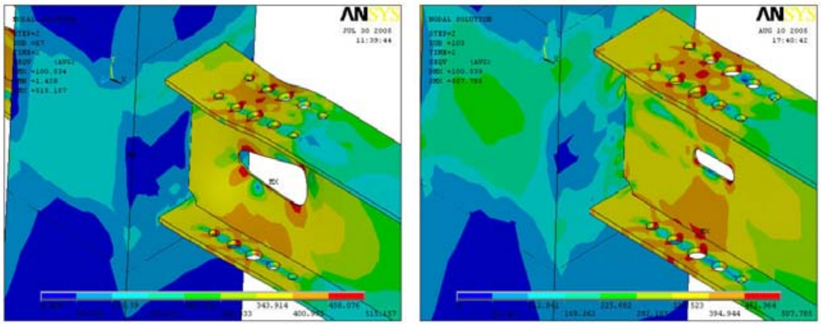
(a) 304050120 (b) 304050100 (c) 204050120

Figure 13. Stress Distribution of Section of *YK1DFKC*



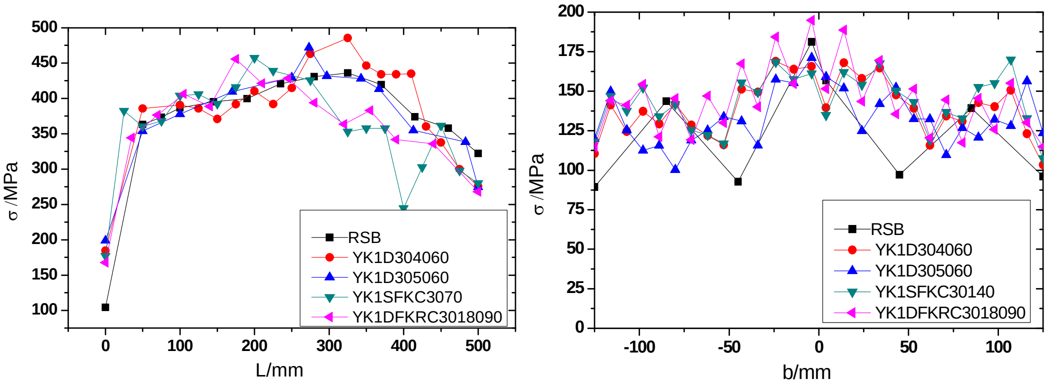
(a) YK1SFKRC30,180,90 (b) YK1SFKRC30,200,100 (c)YK1SFKRC30,220,110

Figure 14. Stress Distribution of Section of *YK1SFKRC*



(a)YK1DFKRC30,40,50,200,100 (b) YK1DFKRC 30,40,50,100,50

Figure 15. Stress Distribution of Section of *YK1DFKRC*



(a) Column face (b) Reduced zone

Figure 16. Stress Distribution of Beam along Beam Length

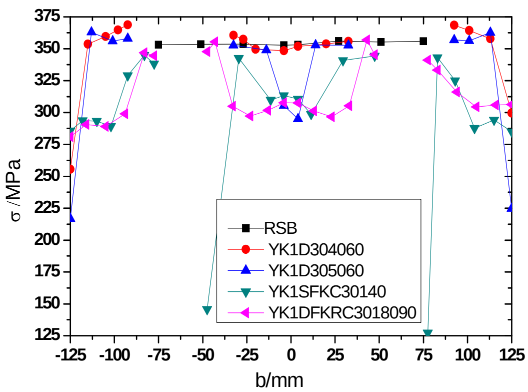
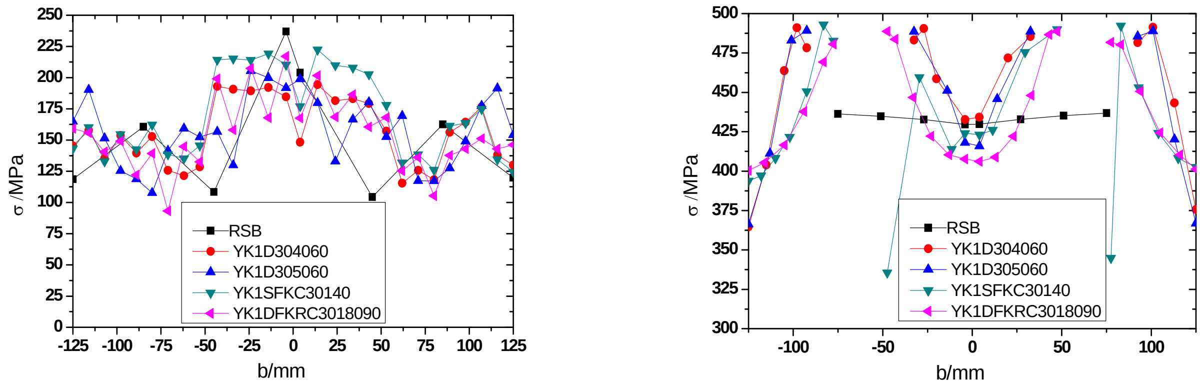


Figure 17. Stress Distribution of Beam along Beam Width when Displacement is *100mm*

5. RESULT UNDER CYCLIC LOADING

The suggested RBS sections are analyzed under cyclic loading by finite element method. The hysteretic curves are shown in Figure 19. The curves of *JD-3B* and *RBS* are obtained in reference (Zhou et al. [9]).

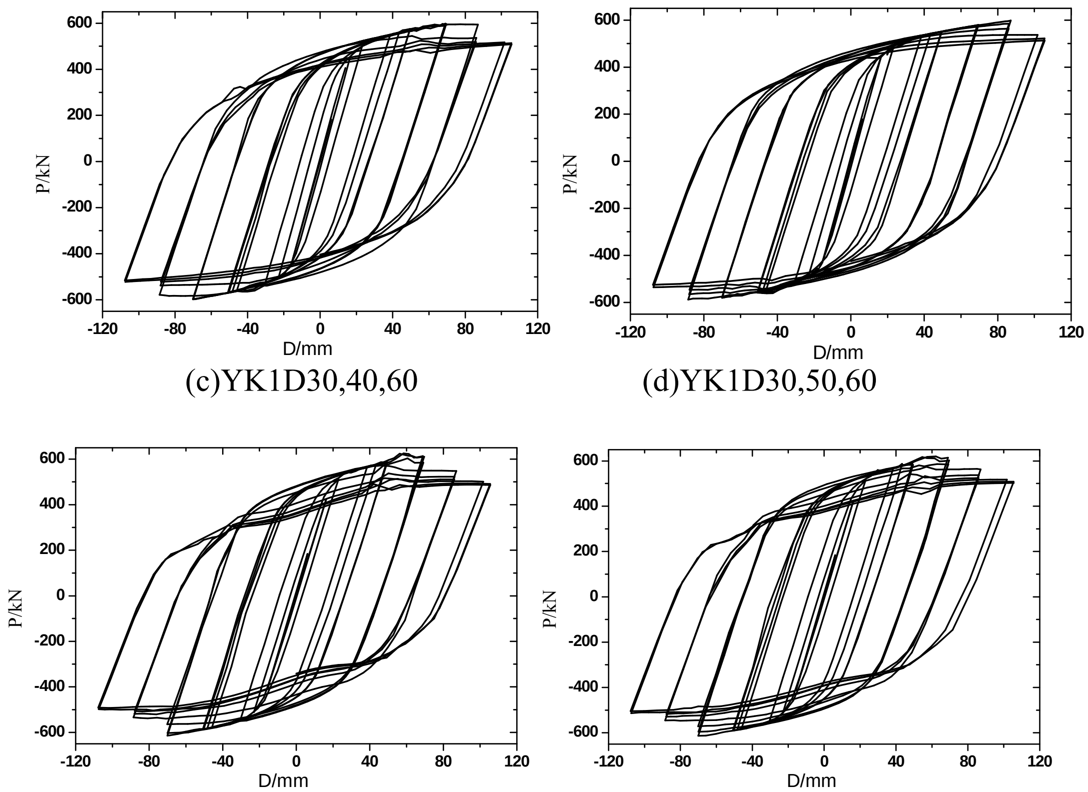
As shown in Figure 19, the suggested RBS section show plump hysteretic curve as *JD-3B* and *RBS,* which indicate that the suggested RBS section have good energy-dissipating ability.



(a) Column face (b) Reduced zone

Figure 18. Stress Distribution of Beam along Beam Width when Section Yield

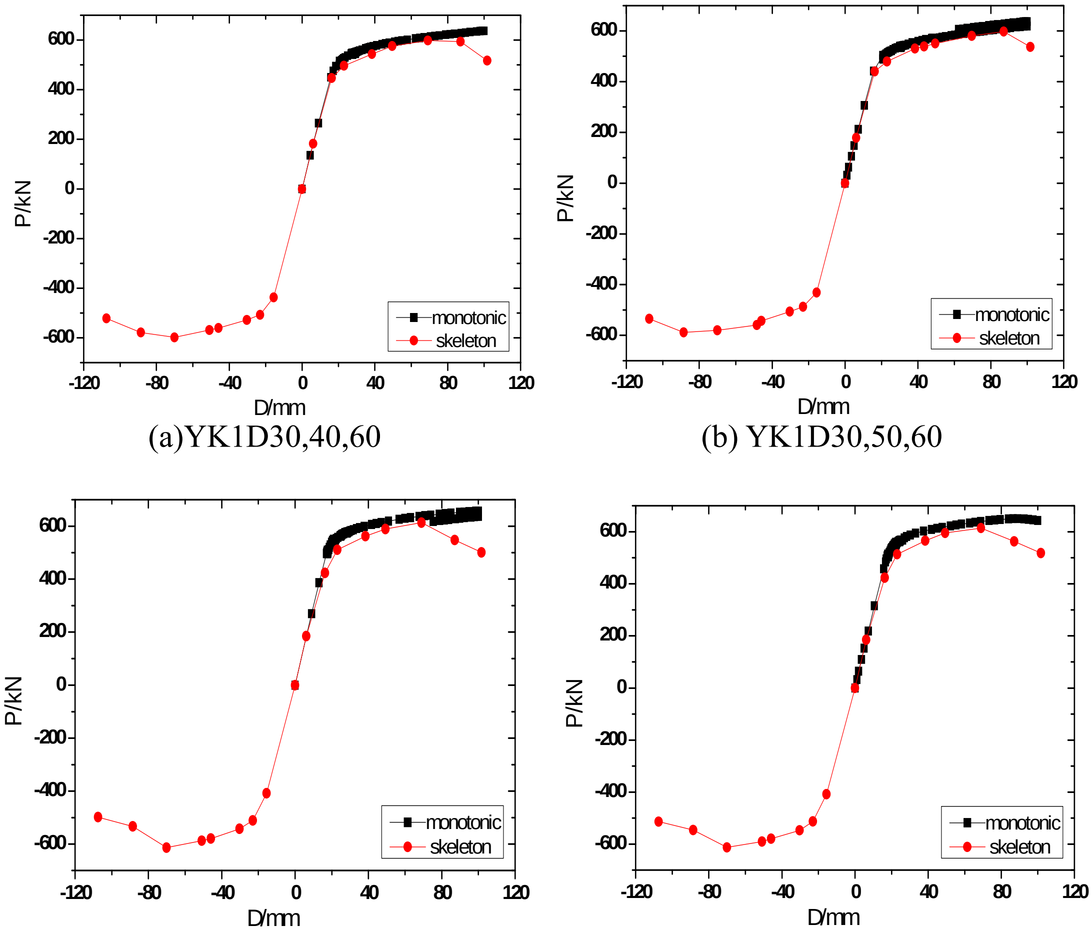
Comparison on skeleton curve of suggested RBS section under cyclic loading and curve of load versus displacement of traditional RBS joint under monotonic loading are shown in Figure 20. As shown in Figure 20, the skeleton curve are close to curve of load versus displacement when the displacement is less 60mm, which indicate that the load-carrying capacity don't decrease in previous eight cycle. The load-carrying capacity have less decrease in last other cycle, and the suggested RBS section can continue to bear capacity when initial yielding occurred.



(c)YK1D30,40,60 (d)YK1D30,50,60

(e)YK1SFKC30,140 (f) YK1SFKRC30,180,90

Figure 19. Hysteretic Curve



(a)YK1D30,40,60 (b) YK1D30,50,60

(c)YK1SFKC30,140 (d) YK1SFKRC30,180,90

Figure 20. Load-displacement Curve of RBS and Recommended Models

Ductility coefficient of story drift and equivalent viscous damping coefficient of suggested and traditional RBS section are shown in Table 2.

As shown in Table 2, the ductility coefficient of story drift of suggested RBS section are less 8% than which of traditional RBS, and equivalent viscous damping coefficient of suggested RBS section are less 5% than which of traditional RBS. Thus the new suggested RBS sections have excellent dissipating energy ability and deformability.

Table 2. Story Drift Ductility Coefficient and Equivalent Viscous Damping Coefficient

specimen	Δ_y (mm)	Δ_u(mm)	μ	h_e
JD-3B	39.1	105	2.68	2.205
RBS	28	112	4.0	2.362
YK1D304060	26.8	106	3.96	2.398
YK1D305060	27.5	108	3.9	2.462
YK1SFKC30140	26	96	3.69	2.378
YK1SFKRC3018090	26.5	105	3.9	2.413

6. SEISMIC DESIGN OF SUGGESTED *RBS* SECTION

'Technical specification for structures with concrete-filled rectangular steel tube members' give the regulation that the beam-to-column connection should adopt reduced beam section with shift-away of plastic hinge in seismic fortification intensity 8 of site-class 3 and 4 and seismic fortification intensity 9. The suggested RSB sections have the same behaviors with the traditional RBS. So the seismic design of suggested RBS section can be proposed according to related Chinese codes.

6.1 Bending Load-carrying Capacity

1) Bending load-carrying capacity of beam-to-column joint and connection under frequent earthquake. The design bending stress of the beam-to-column joint and connection shall satisfy the following:

$$\sigma = \frac{M_{b}}{W_{nx}} \leq f / \gamma_{RE} \tag{1}$$

Where

σ— bending stress of welds of column face and beam of reduced zone of RBS section considering combination of seismic action for connection and joint respectively,
M_b—design bending moments of welds of column face and beam of reduced zone of RBS section considering combination of seismic action for connection and joint respectively,
W_{nx}—net section modulus of weld of column face and beam of reduced zone of RBS section respectively,
f — design value of material strength of steel,
γ_{RE} —seismic adjusting factor for load-load-carrying capacity, 0.9 and 0.75 for connecting weld of column face and beam of reduced zone of RBS section respectively according to reference (CECS159-2004[1], GB50011-2008[6], JGJ99-98[7]).

2) Bending load-carrying capacity of beam-to-column joint and connection under rarely earthquake. In order to make the plastic hinge shifting to RBS zone under rarely earthquake, the follow equation should be check.

$$M_1 / \gamma_{RE}^{w} \geq \left(\frac{M_{b1}}{M_{b2}} \right) M_2 / \gamma_{RE} \tag{2}$$

Where

M_1 —elastic ultimate bending load-carrying capacity of weld, $M_1=W_{nx1}f_{wy}$,
M_2 —elastic ultimate bending load-carrying capacity of reduced zone of beam, $M_2=W_{nx2}f_y$,
γ_{RE},γ_{wRE} —seismic adjusting factor for load-load-carrying capacity, 0.9 and 0.75 for connecting weld of column face and beam of reduced zone of RBS section respectively according to reference (CECS159-2004[1], GB50011-2008[6], JGJ99-98[7]).
f_{wy}, f_y —yield strength of weld and steel.

Eq. 2 can be expressed as Eq.2a,

$$M_1 \geq 1.2\left(\frac{M_{b1}}{M_{b2}}\right)M_2 \tag{2a}$$

The reduced zone of beam shall satisfy the following equation in order to have enough strength reserves,

$$M_{u2} \geq 1.2\ M_{p2} \tag{3}$$

Where

M_{u2} — ultimate bending load-carrying capacity of top and bottom flange of reduced zone of beam，

$M_{u2}=A_f\,(H_b - t_{bf})\,f_u$,
M_{p2} — plastic bending load-carrying capacity of reduced zone of beam， $M_{p2}=W_{p2}\,f_y$,
W_{p2} — plastic section modulus of reduced zone of beam,
f_u、f_y —tensile and yield strength of steel.

According to Eq. 1, 2, and 3, the basic seismic design rule can be seen. Firstly, Eq. 1 makes the connection and reduced zone in elastic stage under frequent earthquake. Secondly, the Eq.2 can make the plastic hinge shifting away to reduced zone and protect the end of beam. Lastly, the Eq.3 make the reduced zone of beam have some strength reserves, so the building don't collapse under rarely earthquake.

6.2 Shear Strength

1) The shear strength of weld connection of section shall be check by the following formula under frequent earthquake:

$$\tau_1 = \frac{V_b S_{w2}}{I_{wx2} t_w} \leq f_v^w / \gamma_{RE}^w \tag{4}$$

Where

V_b—shear force of column face；
I_{wx2},S_{w2}—moment of inertia and static moment of gross section；
f_{vw} — design value of shear strength of weld.

2) The ultimate shear strength of weld connection of section shall be check by the following formula

$$V_b \leq V_u / \gamma_{RE} \tag{5}$$

Where

V_b —design value of shear strength of beam at column face, $V_b=1.1(2M_p / l_n)+V_{Gb}$, $V_u=0.58A_w f_u$,
V_u —ultimate shear strength of weld,

γ_{RE} —seismic adjusting factor for load-load-carrying capacity,0.9 for connecting weld according to reference(CECS159-2004[1], GB50011-2008[6], JGJ99-98[7]),
Mp — plastic bending load-carrying capacity of beam at column face，$M_p=W_p f_y$,
l_n — net length of beam;
V_{Gb}—design shear of beam at column face under the representative value of gravity load,
f_u— tensile strength of steel.

7. CONCLUSION

Based on the non-linear finite element models established for concrete-filled steel square tubular column and reduced steel beam with holes in flange or flange and web, considering geometric large deformation and material nonlinear and related Chinese codes, the main conclusions are summarized as follows.

Comparison was made on load-displacement curves, the stress distribution of reduced beams, the ultimate load-carrying capacity, the ductility, and the energy-dissipating ability between suggested RBS section and traditional RBS section. The stiffness and ultimate load-carrying capacity of four kinds of new RBS sections cutting hole in flange or flange and web which are easy to operate and convenient to arrange pipeline are close to traditional RBS, the plastic hinge in the section with reduced beam section can be moved away to the reduced region. So these four kinds of new RBS sections are suggested to use in engineering.

The new suggested RBS section under cyclic loading show plump hysteretic curve, ductility coefficient of story drift is up to 2.68~4, and equivalent viscous damping coefficient is 2.205~2.462. Thus the new RBS sections have excellent Seismic performance.

Seismic design method of bending loading-carrying capacity and shear strength of suggested RBS section is proposed according to related Chinese codes.

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