Research on hysteretic behavior of external T-stiffener box-column I-beam space connections

L Jin¹, L P Chen¹ and Y Zhang*¹

¹ School of Civil Engineering, Shenyang Jianzhu University, Shenyang, China

* ZY_JZDX@163.com

Abstract. The bearing capacity and deformation performance of external T-stiffener box-column to I-beam space connections were analyzed in this paper. A great deal of full-path analysis of space connections has been carried out by using finite element program ABAQUS with different parameters, which are box-column section width, I-beam flange width, section height of I-beam, flange width and web length of T-stiffener. FEM is proposed for numerical simulation under cycling loading based on the mechanical properties of materials. The result show that the hysteresis curve is the spindle shape and relatively full of T-stiffener box-column I-beam space connections. The ductility coefficient $\mu$ is larger than 4.0 and equivalent viscous damping coefficient $\zeta$ is larger than 0.2 of the space connections, which have been met the limitation of the specification requirements. The bearing capacity and deformation performance of external T-stiffener box-column I-beam space connections can be improved with the increasing of T-stiffener flange width and web length effectively. Due to the fine performance of ductility, energy dissipation and seismic performance, the external T-stiffener box-column I-beam space connections can be proposed used in multi-layer steel structure engineering widely.

1. The first section in your paper

Box-column for steel structures are generally welded by four steel plates [1], as shown in figure 1. Generally, in order to improve the lateral stiffness and torsion resistance of box-column, an internal partition is provided in the connection between box-column and I-beam at a corresponding position [2].

However, the actual welding process between the inner partition and the four steel plates is the greatest difficulty [3]. In view of the problem, the actual welding process is time-consuming, laborious and the quality of the weld is not guaranteed.

The external T-stiffener box-column I-beam connections can be used to avoid the welding difficulties of box-columns during welding [4-6]. The relevant research shows that the external reinforcement is simpler, faster and more economical than the traditional method of adding diaphragm in the column, and the T-external reinforcement connections have enough strength, rigidity and rotation capacity [7-9]. The T-stiffener box-column I-beam connections is shown in figure 2 [10-12].

At present, most of the researches are focused on plane connections, for empty connections the research of space connections is relatively few [13-14]. Due to the uncertainty of the direction of seismic force, the stress of the middle column joint is characterized by spatial stress. Therefore, in this paper, T-stiffener box-column I-beam space connections is selected for research, as shown in figure 3. The hysteretic behavior of spatial connections is studied by changing the parameters of box columns, I-beams and T-stiffeners.
2. Finite element model

2.1. Connection design

The finite element program ABAQUS is used to build the modelling [15], the connection geometry model and loading method are shown in figure 4. Steel Q345B is selected and other properties of the material are shown in the table 1.

The constitutive relation is selected as a linear elastic elastoplastic mechanical model of double-fold line. The steel stress-strain relationship is shown in figure 5.

The external T-stiffener box-column I-beam space connections is referred to as ST in the following content. Eight kinds of working conditions for simulation analysis were designed. The working condition number is shown in figure 6.

| Table 1. Mechanical properties [16]. |
|--------------------------------------|
| material | Yield stress fy/MPa | Tensile strength (MPa) | Elasticity modulus (10^5MPa) | Poisson's ratio |
|-----------|----------------------|------------------------|-----------------------------|----------------|
| Q345B     | 375.7                | 544.5                  | 2.06                        | 0.3            |
| artifacts | Length of I-beam (mm) | Height of box column (mm) |
| ST        | 1250                | 750 mm above and below each box column |
2.2. Establishment of finite element model

According to Table 1 dimensions of beams and columns, the numerical model of spatial connection is established, the T-stiffener box-column I-beam space connections finite element model is shown in Figure 7.

The selection of mesh shape and global size of the finite element model will directly affect the calculation cost and accuracy of the calculation results. By comparison, when the overall dimensions of box column, I-beam and T-stiffener are 60 mm, 40 mm and 30 mm respectively, the calculation accuracy and calculation time are appropriate.

Tie restraint relationship were used between box column, I-beam and T-stiffener, reciprocating load is applied by displacement control at beam end [17-19].

Three stages of loading $\Delta/3$, $2\Delta/3$ and $\Delta$ before yield, one cycle per stage, after yielding, cycle three times for each stage according to $2\Delta$, $3\Delta$, $4\Delta$, $5\Delta$. The loading curve is shown in Figure 8.
3. Hysteresis performance

3.1. Hysteresis curve
The numerical model was established refer to the above steel constitutive. The working condition design numbers of the 8 space connections are shown in table 2. The hysteresis curves of the end of beam is shown in figure 9.

Table 2. Design condition.

| condition number | condition number |
|------------------|------------------|
| 1                | ST1-B250 h250 b150 d100 Ls300 |
| 3                | ST3-B300 h350 b200 d100 Ls300 |
| 5                | ST5-B350 h350 b200 d100 Ls300 |
| 7                | ST7-B300 h350 b200 d160 Ls300 |
| 2                | ST2-B250 h350 b150 d100 Ls300 |
| 4                | ST4-B350 h300 b200 d100 Ls300 |
| 6                | ST6-B300 h350 b150 d100 Ls300 |
| 8                | ST8-B300 h350 b200 d100 Ls400 |
The result show that the beam and column dimensions of connection ST1 and ST2 are much smaller than others. As a result, its bearing capacity decreases, but its ductility increases. Connection ST1- ST8 has a decrease in stiffness under cyclic loading.

However, the hysteresis curve becomes fuller with the increasing of the cross-section width of the box column, the height of the I-beam and the length of the stiffener web. Hysteresis performance has been improved significantly.

3.2. Skeleton curve
The figure 10 represents the skeleton curves of the external T-stiffener box-column I-beam space connections. As shown in figure 10(a), with the section width of the box column increasing from 250 mm to 350 mm, the bearing capacity of connection ST6 is increased by 61.41% compared with connection ST2. The bearing capacity of connection ST5 is increased by 7.67% compared with connection ST3. As shown in figure 10(b), with the increasing of the height of the I-beam, the bearing capacity of connection ST2 is increased by 8.28% compared with connection ST1. The bearing capacity of connection ST5 is increased by 22.93% compared with connection ST4. As shown in figure 10(c) and figure 10(d), compared with connection ST3, the increasing of T-stiffeners’ flange width and web length leads to the load capacity of connection ST7 and ST8 increase by 0.83% and 1.14%, respectively.

3.3. Stiffness degradation
The figure 11 are the stiffness degradation curves of the external T-stiffener box-column I-beam space connections. As shown in the stiffness degradation curves and the table 3.

Since connection ST1 and connection ST2 are smaller size than others, it can be seen that the initial stiffness of the connection ST1 and ST2 is about 1.5 times lower than the initial stiffness of others as the same displacement. The stiffness of the connection ST5 is increased by 21.55% compared with connection ST4, the stiffness of the connection ST8 is 5.65% higher than that of connection ST3.
Increasing the section width of box column and the web length of T-stiffener can improve the stiffness of space connections effectively.

![Stiffness degradation curves](image)

**Figure 11.** Stiffness degradation curves.

Table 3. Cyclic stiffness of each connection.

| condition | Cyclic stiffness (N/mm) |
|-----------|-------------------------|
| K1 | K2 | K3 | K4 | K5 | K6 | K7 | K8 | K9 | K10 |
| ST1 | 18.774 | 17.686 | 11.903 | 10.212 | 8.428 | 7.149 | 6.238 | 5.576 | 5.041 | 2.611 |
| ST2 | 19.385 | 19.083 | 13.467 | 11.679 | 9.637 | 8.120 | 7.076 | 6.319 | 5.717 | 2.655 |
| ST3 | 34.503 | 31.639 | 20.984 | 17.615 | 14.466 | 12.117 | 10.476 | 9.143 | 6.793 | 5.756 |
| ST4 | 29.452 | 27.684 | 18.663 | 15.525 | 12.983 | 10.812 | 8.351 | 6.990 | 5.952 | 5.091 |
| ST5 | 35.798 | 34.075 | 22.592 | 18.743 | 15.542 | 11.761 | 8.832 | 7.340 | 6.362 | 5.575 |
| ST6 | 33.136 | 30.897 | 20.437 | 17.025 | 14.118 | 11.863 | 10.368 | 7.753 | 6.391 | 5.488 |
| ST7 | 34.947 | 31.908 | 21.176 | 17.790 | 14.528 | 12.190 | 10.568 | 9.272 | 7.186 | 6.090 |
| ST8 | 36.431 | 32.261 | 21.882 | 18.476 | 14.933 | 12.596 | 10.957 | 9.668 | 7.988 | 6.232 |

3.4. Ductility

The calculation of the carrying capacity and ductility coefficient $\mu$ of the space connections ST1-ST8 and other performance indicators are shown in table 4.

With the increasing of flange width of T-stiffener from 100 mm to 160 mm and length of T-tiffener web from 300 mm to 400 mm, the space connections ductility coefficient increased by 5.69% and 3.09%. The ductility coefficient $\mu$ is larger than 4.0 of each condition and can meet the requirement of seismic specifications.
### Table 4. Node carrying capacity and deformability.

| Condition | Yield capacity $F_y$/kN | Yield displacement $\delta_y$/mm | Ultimate capacity $F_u$/kN | Limit displacement $\delta_u$/mm | Ductility coefficient $\mu$ |
|-----------|-------------------------|---------------------------------|---------------------------|---------------------------------|-----------------------------|
| ST1       | 207.066                 | 11.786                          | 475.049                   | 106.751                         | 9.057                       |
| ST2       | 224.211                 | 11.786                          | 531.440                   | 94.293                          | 8.000                       |
| ST3       | 370.333                 | 11.789                          | 746.921                   | 80.1413                         | 6.797                       |
| ST4       | 324.351                 | 11.785                          | 625.164                   | 59.306                          | 5.032                       |
| ST5       | 398.732                 | 11.782                          | 721.154                   | 47.345                          | 4.018                       |
| ST6       | 361.889                 | 11.786                          | 710.112                   | 69.818                          | 5.924                       |
| ST7       | 373.416                 | 11.785                          | 764.652                   | 84.659                          | 7.184                       |
| ST8       | 375.536                 | 11.786                          | 769.999                   | 80.771                          | 6.853                       |

3.5. Energy consumption

The equivalent viscous damping coefficient $h_e$ and the energy dissipation coefficient $E$ of the peak hysteresis loop of each condition are shown in table 5.

According to the energy dissipation coefficient $E$ in table 5, through the comparison of the two groups of connections ST2, ST6 and connections ST3, ST5. It can be seen that the energy consumption capacity of the enlarged box-column section width is increased by about 1.18% and 3.91% respectively. With the cross-section height of the I-beam increasing, for example, from connection ST1 to ST2, from connection ST4 to ST5, it can be seen that the energy consumption capacity is increased by 1.33% and 6.36% respectively.

Comparing the energy dissipation coefficient $E$ of the connection ST3 and ST6, it is known that the energy consumption capacity of the flange of the I-beam is increased by 7.89%.

As shown in table 5, figure 12 and figure 13, connection ST3, ST7 and ST8, with increasing width of the flange of the T-stiffener and the length of the web of the T-stiffener, resulting in an increase in energy consumption of 2.59% and 6.79% respectively.

The equivalent viscous damping coefficient $h_e$ of the eight space connections is larger than 0.2, indicating that this type of space connection can meet the requirements of seismic design energy performance.

![Figure 12. $E$-displacement curves.](image1)

![Figure 13. $h_e$-displacement curves.](image2)

### Table 5. Energy dissipation coefficients.

| Dissipation coefficient $h_e$ | ST1 | ST2 | ST3 | ST4 | ST5 | ST6 | ST7 | ST8 |
|-------------------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| $h_e$                         | 0.240 | 0.263 | 0.230 | 0.223 | 0.237 | 0.246 | 0.231 | 0.237 |
Conclusions
The performance of the external T-stiffener box-column I-beam space connections have been studied. The research focuses on the influence of changing the section width of the box column, the width of the I-beam flange, the height of the section, the width of the T-stiffener flange and the length of the web on the bearing capacity and deformation performance. The following conclusions are got:
- the hysteresis curves of the T-stiffener box-column I-beam space connections are the full spindle shape. The performance of deformation is strong in the elastoplastic stage;
- the ductility coefficient $\mu$ of the space joints with T-stiffener is larger than 4.0 and meets the requirement of seismic specifications;
- the stiffness decreases significantly with the increasing of the displacement. The rate of descent has a rapid decrease followed by a slow decrease.
- The equivalent viscous damping coefficient $h_e$ is larger than 0.2 and energy dissipation coefficient $E$ is larger than 1.4.

Acknowledgement
The work presented in this paper was supported by the natural foundation guidance program of Liaoning province, China (2019-ZD-0678) and the program for “Xing Liao Talent” of Liaoning province, China (XLYC1807188).

References
[1] Mao H Jia B L and Bu Y 2011 *J. Electric Welding Machine* **41** pp 53-57
[2] Deylami A and Gholipou R M 2011 *J. Procedia Engineering* **2011** pp 3252-3259
[3] Zhao X B, Zheng Z K and Pan J F 2016 *J. Steel Construction* **31** pp 92-95
[4] Wang Y, Liu Y, Wang P and Gao P 2011 *J. Progress in Steel Building Structures* **13** pp 1-7
[5] Shanmugam N E 1997 *J. Journal of Structures* **17** pp 36-60
[6] Shanmugam N E and Ting L C 1995 *J. Journal of Structural Engineering* **121** pp 824-830
[7] Yang X D 2011 *D. Xian University of Architecture and Technology*
[8] Nia Z S, Mazroii A, Ghassieh M and Pezeshki H 2014 *J. Earthq Eng & Eng Vib* **13** pp 717-29
[9] Kato B 2014 *J. Journal of the Structure Division* **108** pp 343-360
[10] Wang M, Shi Y and Wang Y 2013 *J. Constructional Steel Research* **90** pp 140-152
[11] Mirghaderi S R, Torabian S and Keshavarzi F 2011 *J. Engineering structures* **2011** pp 2034-2048
[12] Jin L 2006 *D. Harbin Institute of Technology*
[13] Shao Y S, Jin L, Xie L L and Zhang Y C 2009 *J. Journal of Harbin Institute of Technology* **41** pp 20-25
[14] Li F X and Wang X W 2018 *J. Steel Construction* **33** pp 98-102
[15] Xu P Z, Yang L, Zhu Y G and Jing H K 2018 *J. Steel Construction* **33** pp 93-97
[16] Zhang Z X 2015 *D. China University of Mining and Technology*
[17] Liu E H 2017 *D. Chang an University*
[18] Wei K F, Li J F, Liu S X, Li X and Chen H 2018 *J. Steel Construction* **33** pp 17-20
[19] Xu Z G, Zhang Z B and Deng C G 2017 *J. Sichuan Building Science* **43** pp 75-79