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# Mechanical Behavior of Cross-shaped Partially Encased Composite Columns under Axial Compression

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***Abstract:*** The mechanical properties of two cross-shaped PEC columns were investigated by an axial compression experiment. The experimental results showed that when the cross-shaped PEC columns were destroyed, the concrete was crushed and the flanges were locally buckled. Based on the experimental parameters, the ABAQUS software was used for finite element simulation, and the results of the finite element analysis agree well with the test results. To prevent concrete cracking and flange local buckling in the cross-shaped PEC column, a transverse link connection method was presented. The finite element simulation demonstrates that this method improves the ultimate carrying capacity and ductility of the columns. The effects of link spacing, link diameter, flange width-to-thickness ratio, and limb width ratio are also investigated.

***Key words:*** Cross-shaped PEC column; experimentation; finite element analysis; axial compression

## 1. Introduction

The partially encased composite (PEC) structure takes advantage of steel and concrete materials, resulting in excellent force performance, fire resistance, prefabrication, assemblability, cost, and construction speed. It has attracted the attention of researchers in recent years. PEC columns can be rectangular, cross-shaped, T-shaped, L-shaped, octagonal, or any other shapes. PEC columns with rectangular shapes have received extensive research, whereas other types of PEC columns have received relatively little attention.

Begum et al. conducted many researches on rectangular-shaped PEC columns. In paper, they used a dynamic explicit solution strategy and a concrete damage plasticity model to forecast the behavior of PEC columns in finite element analysis. In another study, they investigated the behavior of PEC columns with high strength concrete. In addition, they conducted a parameter study on the eccentrically-loaded PEC columns under major axis bending. Chen et al.conducted a series of experiments and numerical researches on PEC columns under axial and cyclic loads. They concluded that the links could effectively prevent local buckling of column flanges with larger width-to-thickness ratios. Zhao et al. investigated the axial compression performance of the rectangular PEC short columns, as well as the failure mode and ultimate bearing capacity of the columns, it was discovered that the smaller of the distance between the transverse links the higher of the column's ductility, and the transverse links did not yield before reaching the ultimate load; after reaching thethe ultimate load, the concrete was crushed and the flange partially buckled. Lin et al. used finite element simulation to investigate the effect of longitudinal reinforcement, flange links, and section aspect ratio on the ultimate bearing capacity of a rectangular section PEC column, and finally proposed a formula for the overall stability design of PEC columns under axial compression and bending.

Jamkhaneh et al. carried out extensive research on octagonal-shaped PEC columns. In paper, they investigated the mechanical properties of octagonal PEC columns under axial and torsion loading by experimental and numerical analysis. The influence of width-to-thickness ratio of the flange, transverse link spacing and diameter, welding line arrangements, and various types of retrofit of cross-shaped steel were all investigated. The results revealed that stirrup confinement had little effect on increasing the torsion capacity of the specimens; however, using transverse links could greatly improve the column's torsion resistance. Furthermore, installing steel shear plates at the column's end zones may improve its torsion resistance. A formula for axial compression bearing capacity was also provided.

There are currently few studies on cross-shaped PEC columns. To compensate for the lack of related research, relevant experimental research and finite element analysis for cross-shaped PEC columns are carried out in this paper. The purpose of this paper is to investigate the extreme carrying capacity and the damage process of cross-shaped PEC columns with different inner structural methods under axial loading. Furthermore, a most reasonable construction method is proposed.

## 2. Experimental Study

2.1 Specimen Design

Two cross-shaped PEC column specimens were designed, as shown in Figure 1. Both members have a section (length x width x height) of 400 x 400 x 1200mm, the width of the steel plate flanges was both 200mm, and the flange and web thicknesses were both 6mm. PEC-C1 was filled with plain concrete in orthogonal double H-type steel column, while PEC-C2 was filled with concrete after U-shaped hooks were welded on the steel web. U-shaped hooks were made by HPB300 steel bars with a diameter of 6mm. They were spaced 200mm apart along the length of the column in the middle of the steel web. The two rows in the same area, on the other hand, were staggered by 100mm. Figure 2 shows the photos of the specimens.

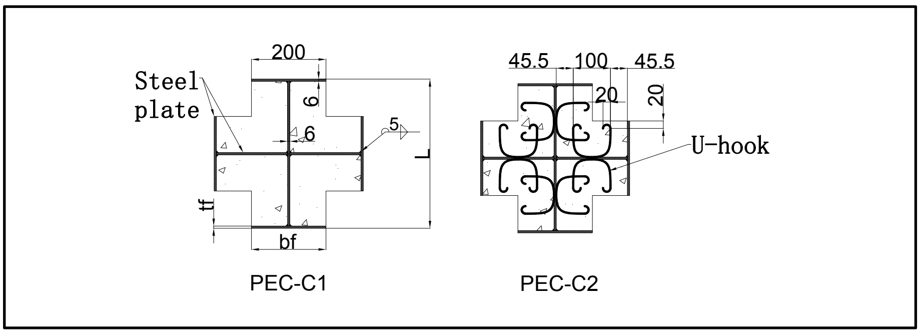



**Figure 1**. Details of cross-shaped PEC column PEC-C1 and PEC-C2


**Figure 2.** Photos of cross-shaped PEC column PEC-C1 and PEC-C2

2.2 Material properties

The design strength of the concrete was C25, and the actual concrete strength value was 24.5Mpa. All steel plates used in the column specimens were Q235, and the material parameters of steel plates were shown in Table 1.

**Table 1.** Material parameters of steel plates

| Material | Static Yield Stress （MPa） | Static Ultimate Stress（MPa） | Elastic Modulus (MPa) |
|---|---|---|---|
| 6mm steel plate | 249 | 382 | 200000 |

2.3 Experimental equipment and procedures

The experiment was carried out in the school's civil engineering laboratory building, and the main experimental equipment was a 1000t micro-control electro-hydraulic servo pressure testing machine, as shown in Figure 3. The two specimens were subjected to axial load in the experiment, the loading method was displacement control, and the loading rate was 0.005mm/s. After reaching the limit load, stop loading until the specimens destroyed.

**Figure 3.** The experimental equipment and specimen

2.4 Experimental results and discussion

The axial load-displacement curves of the two specimens are shown in Figure 4. The maximum load and displacement values for each sample are shown in Table 2. It can be seen that the load-displacement curves of the two specimens are fairly similar overall, but the ultimate bearing capacity of PEC-C2 is slightly lower than that of PEC-C1. It demonstrates that even plain concrete-filled cross-shaped PEC columns can achieve a significant bearing capacity, and that adding U-shaped hooks not only does not increase the carrying capacity of the column, but actually reduces it, most likely because the U-shaped hook may cause shear damage to the internal concrete.

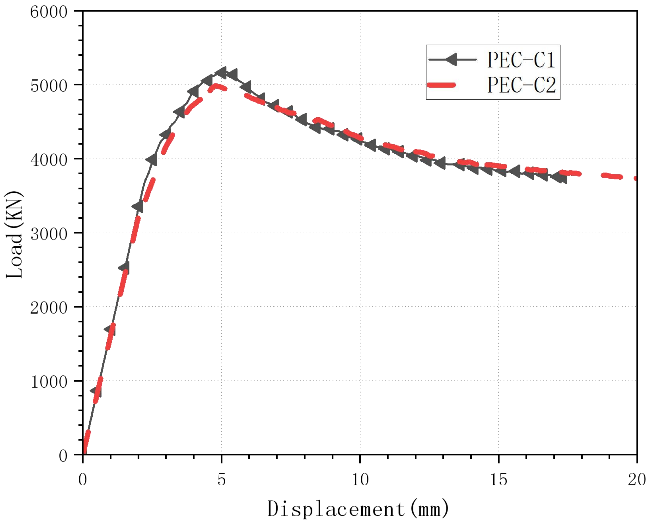



**Figure 4.** Load-displacement curves of PEC-C1 and PEC-C2

**Table 2.** Maximum load and maximum displacement of PEC-C1 and PEC-C2

| Specimen | P(KN) | Δ(mm) |
|---|---|---|
| PEC-C1 | 5190 | 5.09 |
| PEC-C2 | 4996 | 4.79 |

Small concrete oblique cracks appeared near the center of the two specimens before reaching the ultimate bearing capacity during loading, but the concrete was not crushed and the steel plate did not yield. When the two specimens continued to be loaded after reaching their ultimate bearing capacity, both specimens experienced local buckling of the flange and the flange separated from the concrete, but the concrete had not yet been crushed, as shown in Figure 5. It demonstrates that the two specimens will not be damaged quickly after attaining the ultimate load and have a high deformation capability. Adding U-shaped hooks to the web, on the other hand, does not help prevent concrete cracking and flange buckling. As a result, we'll look into installing flange links to prevent concrete cracking and flange buckling.

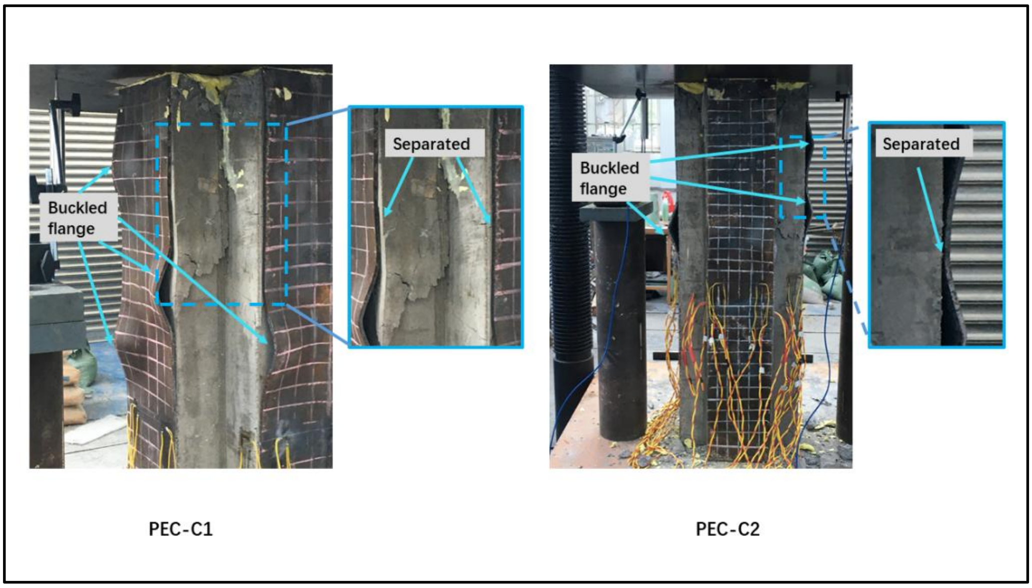



**Figure 5.** The final damage pattern of PEC-C1 and PEC-C2

## 3. Finite Element Analysis

3.1 Finite Element Modeling

A dynamic explicit solution strategy was used in finite element analysis. The concrete used plastic damage model, while the steel used the double broken line model, which was the ideal elastoplastic model; the concrete column and U-shaped hook used the C3D8R solid element, while the section steel used the S4R shell element to better simulate the local buckling effect. The experimental failure process revealed that there was no separation between concrete and steel plate until local buckling occurred in the flanges, so the "penalty contact" algorithm was chosen in the tangential direction, while "hard contact" and "allow separation after failure" were chosen in the axial direction. The boundary condition was that the two ends of the column were hinged, which was controlled by displacement loading, similar to the loading process in the experiment. Figure 6 depicts the model of PEC-C1 and PEC-C2 created by the ABAQUS software.

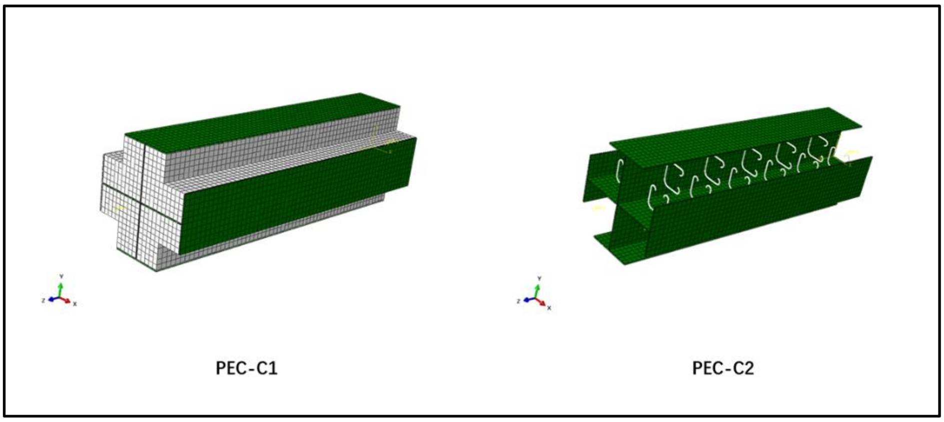



**Figure 6.** Finite element models of PEC-C1 and PEC-C2

3.2 Comparison of experimental and finite element simulation

Figure 7 depicts the experimental and finite element simulation curves. Although there are occasional errors between the curves, the majority of them are constant. The cause of these errors is that there are unavoidably numerous accidental errors and initial faults in the testing process, such as the column processing error and the inability to be completely aligned during loading, and so on. Because of these starting inaccuracies, the test results are smaller than the results of the finite element analysis. The experimental and finite element simulations of the two columns when they reach their maximum bearing capacity are shown in Figure 8, and the position of the steel plate flange buckling and the position of the concrete crack are similar for both. In conclusion, finite element simulation with experiment delivers a high level of accuracy and dependability. As a result, we will conduct additional analysis and discussion using finite element method.

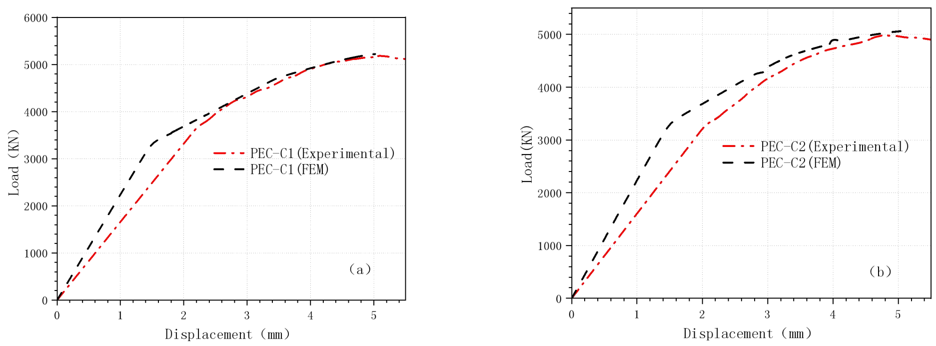
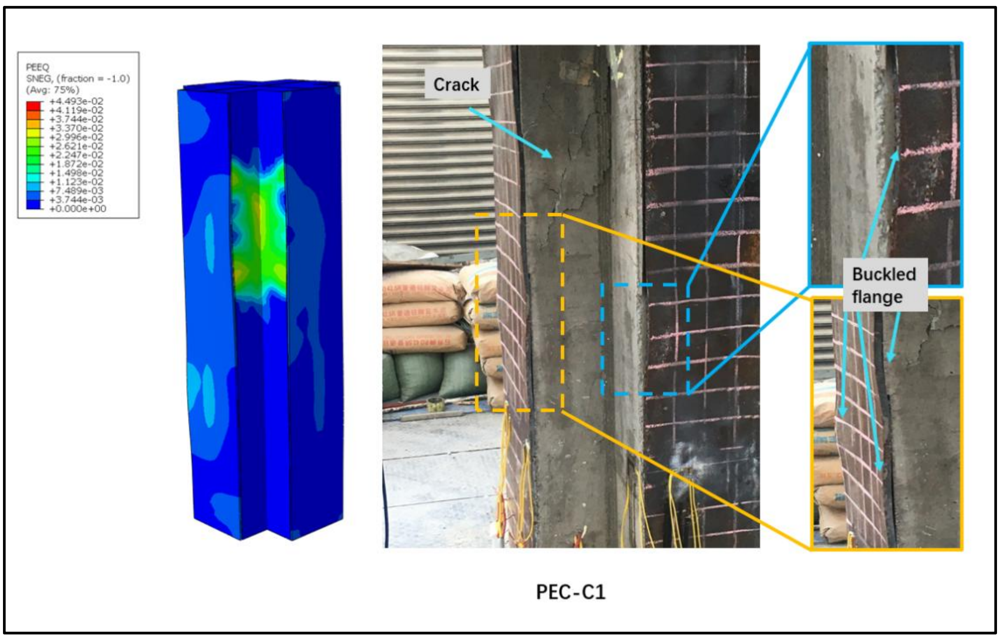



**Figure 7.** Comparison of load-displacement curve between FEM and experimental results of PEC-C1 and PEC-C2



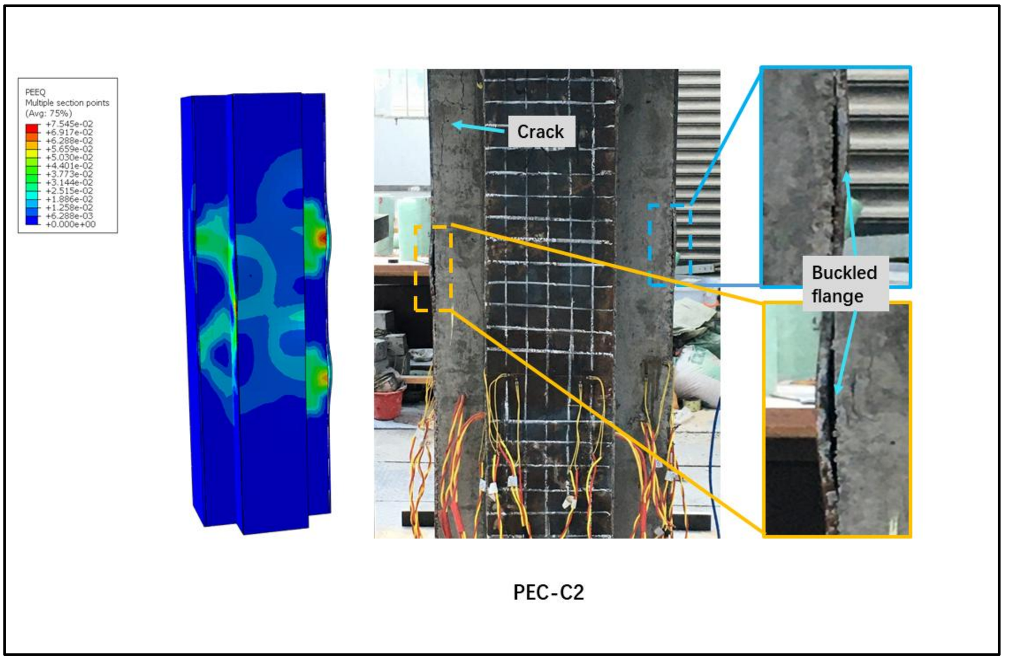



**Figure 8.** Local bucking and concrete crushing under ultimate load of PEC-C1 and PEC-C2

3.3 A new strategy of link connection method

Combining the experimental process and FEM analysis of PEC-C1 and PEC-C2, it is possible to predict that after the two columns reach their maximum bearing capacity, the steel flange and the concrete will separate under continuous loading, affecting the column's performance. As a result, a transverse link connection method between the flange and the web is proposed as shown in Figure 9. HRB335 steel bars with an 8mm diameter were used to make the links, which were spaced 200mm apart along the length of the column in the middle of the steel web. In the finite element model, the links are represented by the B31 beam elements. After simulation with ABAQUS software, it was discovered that this transverse link method could not only delay column damage, but also increase column ductility, as shown in Figure 10. Simultaneously, Figure 11 demonstrates that the PEC-C3 column has a lower deformation value than PEC-C1 and PEC-C2. In short, it is the best inner structural method of the three ways mentioned above, and it significantly improves the mechanical properties of the cross-shaped PEC column. We then performed parametric analyses to better understand the mechanical properties of this column, such as changing the spacing of the links, the diameter of the links, the width to thickness ratio of the flange, and the ratio of limb length-to-thickness. Considering that the load-displacement curve may abruptly drop due to concrete cracking when the concrete column reached its ultimate bearing, we changed the concrete strength grade from C25 to C30 in the subsequent parameter analysis.

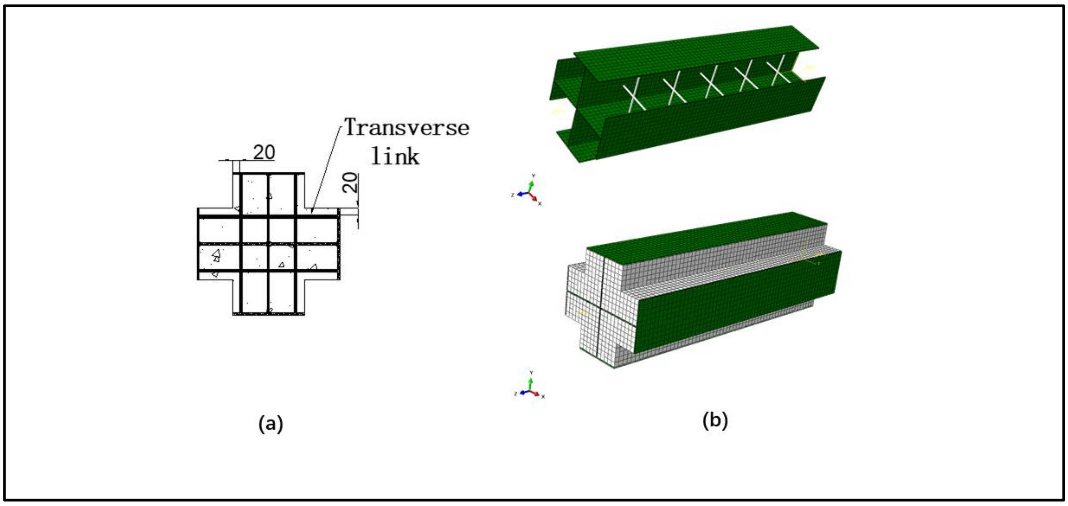



**Figure 9.** Sectional form and finite element models of PEC-C3

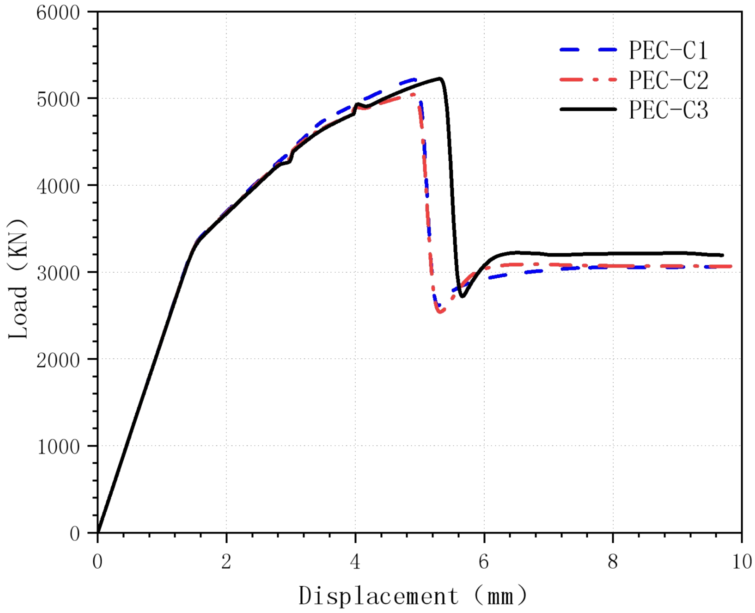



**Figure 10.** Comparison between the load-displacement curve of PEC-C1, PEC-C2 and PEC-C3

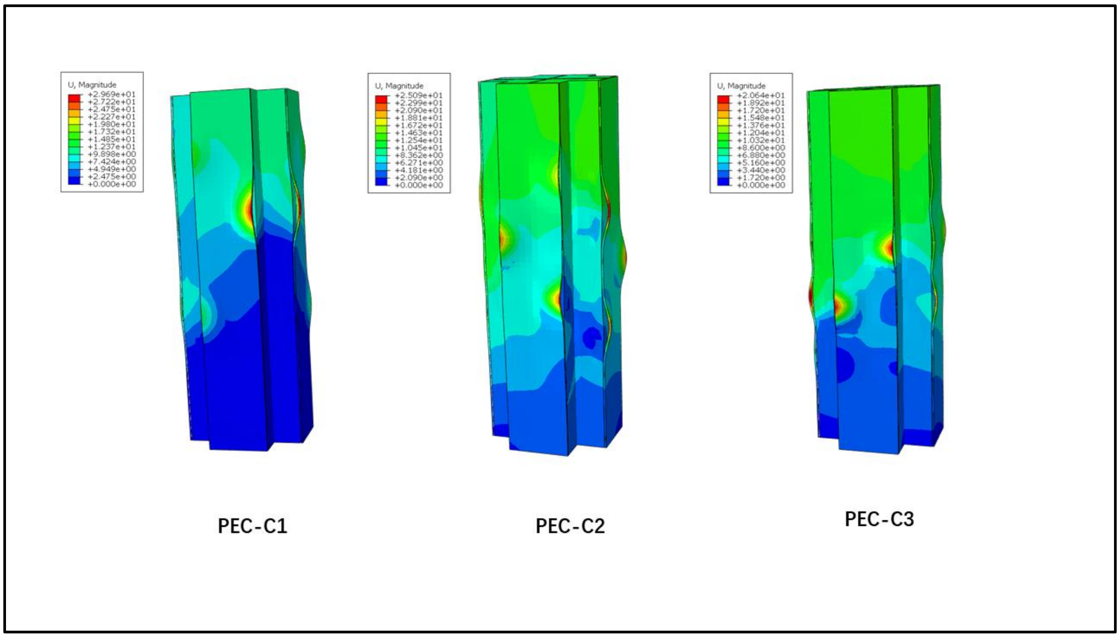



**Figure 11.** Final damage pattern of PEC-C1, PEC-C2 and PEC-C3

3.4 Parameter analysis

3.4.1 Link Spacing

Figure 12 shows the load-displacement curve of PEC-C3 with link spacing of 100mm, 200mm, and 300mm. When the link spacing is increased from 300 to 200, the ultimate bearing capacity and ductility of the column increase slightly. However, when the link spacing is increased from 200 to 100, the ultimate bearing capacity and ductility increase significantly. It shows that the smaller of the link spacing the higher of the ultimate bearing capacity and ductility; the column with 100mm link spacing has the greatest bearing capacity and ductility. It is advised to set the link spacing to 100mm, which is half of the column width.

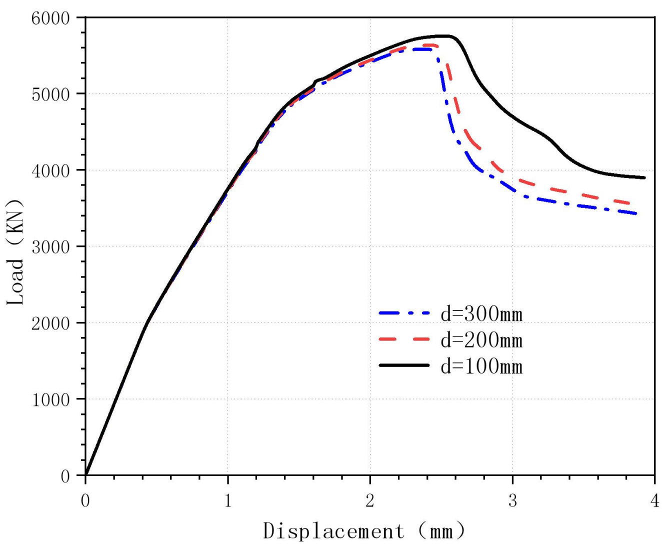



**Figure 12.** Load-displacement curve of PEC-C3 with link spacing of 100mm, 200mm and 300mm

3.4.2 Diameter of links

Figure 13 shows the load-displacement curve of PEC-C3 with link diameter of 6mm, 8mm and 10mm. It can be seen that the ultimate bearing capacity and ductility of the column increase when the link diameter changes from 6mm to 8mm, but not significantly from 8mm to 10mm. It is recommended that the link diameter should be set to 8mm.

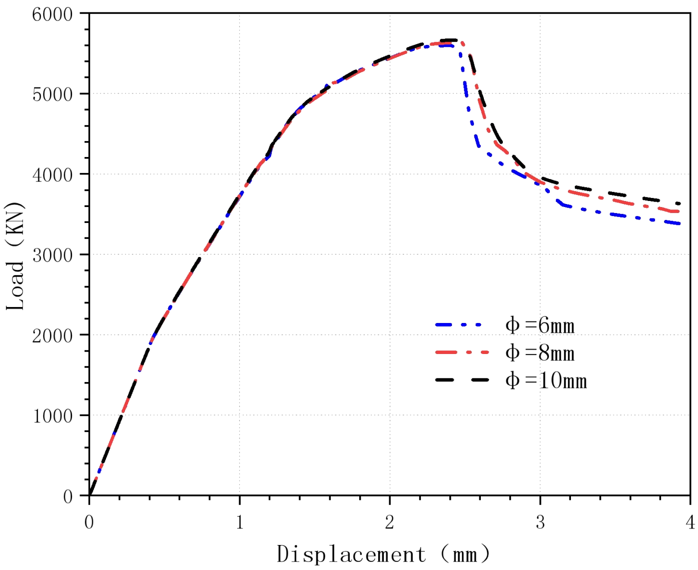



**Figure 13.** Load-displacement curve of PEC-C3 with link diameter of 6mm, 8mm and 10mm

3.4.3 Ratio of flange width to thickness

To investigate the effect of flange width-to-thickness ratio on column force performance, the flange width-to-thickness ratios are set to 20, 25, and 32, respectively. The Canadian Code CSA S16-14 specifies a maximum flange width-to-thickness ratio of 32, which is greater than the maximum specified by other relevant specifications. Figure 14 depicts a load-displacement curve comparison. It is shown that although the ultimate bearing capacity and ductility of the column decrease as the flange width-to-thickness ratio increases, the shape of the load-displacement curve in the three cases is very similar, and the large width ratio does not result in local instability of the flange or separation of the flange from the concrete, which is because the increased transverse link can ensure the local stability of the flange.

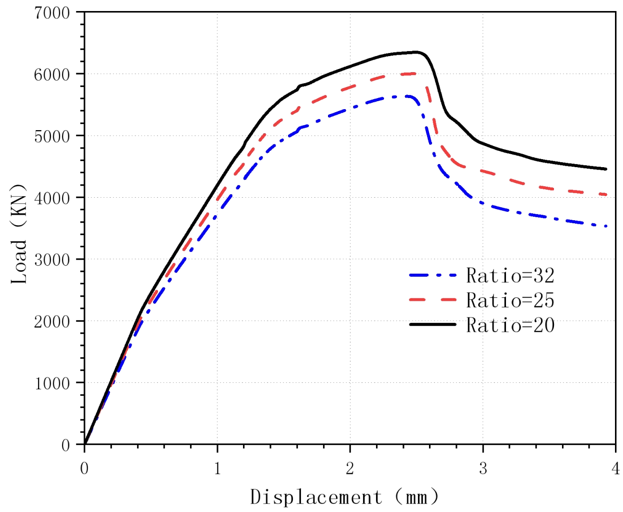



**Figure 14.** Load-displacement curve of PEC-C3 with flange width to thickness ratio of 20, 25 and 32

3.4.4 Ratio of limb length-to-thickness

To investigate the effect of limb length-to-thickness ratio on column force performance, the limb length-to-thickness ratios are set to 1.5, 2, 2.5, 3, 3.5, and 4, respectively, in accordance with the design specification of special-shaped column (JGJ 149-2017). The JGJ 149-2017 specifies a maximum ratio of limb length-to-thickness ratio of four. Figure 15 depicts a load-displacement curve comparison. It is shown that when the ratio of length-to-thickness is less than 2.5, the ultimate bearing capacity and ductility of the column increase as the ratio increases, because a high steel ratio can increase the ultimate bearing capacity and ductility of the column; however, when the ratio of limb length-to-thickness is greater than 3, the column's bearing capacity drops abruptly after reaching the ultimate bearing capacity because the concrete is crushed. Therefore, the ratio of limb length-to-thickness should be limited to 2.5 in this column. Overall, this value is related to the concrete strength grade used in the column. In the subsequent work, the relationship between the limb length-to-thickness ratio and the concrete strength grade in cross-shaped PEC columns should be thoroughly investigated.

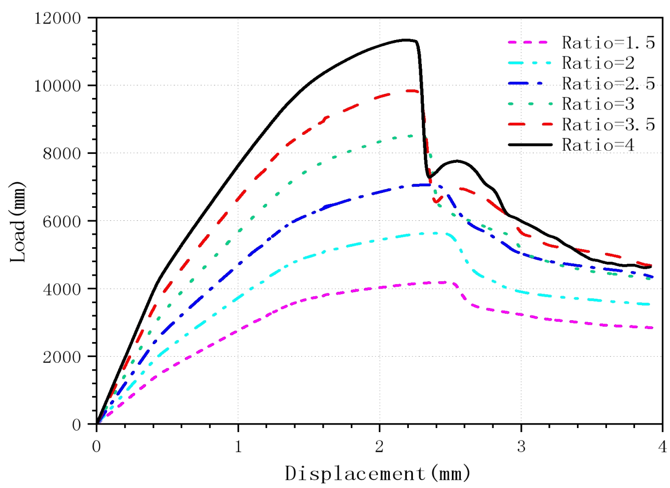



**Figure 15.** Load-displacement curve of PEC-C3 with limb length-to-thickness of 1.5, 2, 2.5, 3, 3.5, and 4

## 4. Conclusion

Experimentation and finite element analysis for cross-shaped PEC columns subjected to axial loading are carried out in this paper. According to the experimental results, the concrete has minor oblique cracks before loading to the maximum carrying capacity of the column, and as the load continues, the column's flange buckles locally and separates from the concrete. The following conclusions can be drawn from experimentation and finite element parameter analysis:

(1) Even plain concrete-filled cross-shaped PEC columns have a significant bearing capacity, and adding U-shaped hooks does not increase, but actually decreases the column's carrying capacity. Increasing the transverse link, on the other hand, can not only delay column damage but also increase column ductility.

(2) The transverse link spacing and diameter of the links can affect the ultimate bearing capacity and ductility of the cross-shaped column; the smaller the link spacing, the higher the limit bearing capacity and ductility of the column. Maximum ultimate bearing capacity and ductility is observed at a link spacing of 100 mm and the link diameter of 8 mm.

(3) The ultimate bearing capacity and ductility of the column decrease as the flange width-to-thickness ratio increases, but the transverse link can ensure the local stability of the flange.

(4) Maximum ultimate bearing capacity and ductility are observed when the length-to-thickness ratio is 2.5, and when the length-to-thickness ratio is greater than 3, the column's bearing capacity drops abruptly after reaching the ultimate bearing capacity because the concrete is crushed. As a result, in this column, the limb length-to-thickness ratio should be limited to 2.5. Overall, this value is related to the concrete strength grade used in the column; therefore, it is suggested that the relationship between the limb length-to-thickness ratio and the concrete strength grade in cross-shaped PEC columns should be thoroughly investigated.

## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

## References

[1] Begum M., Driver R.G., Elwi A. E. (2007). Finite-element Modeling of Partially Encased Composite Columns using the Dynamic Explicit Method. *Journal of Structural Engineering-ASCE*, 133(3):326-34.

[2] Begum M., Driver R.G., Elwi A.E. (2013). Behaviour of Partially Encased Composite Columns with High Strength Concrete. *Engineering Structures*, 56:1718-1727.

[3] Begum M., Driver R.G., Elwi A.E. (2015). Parametric Study on Eccentrically-loaded Partially Encased Composite Columns under Major Axis Bending. *Steel & Composite Structures*, 19(5):1299-1319.

[4] Chen Y.Y., Wang T., Yang J., Zhao X.Z. (2010). Test and Numerical Simulation of Partially Encased Composite Columns Subject to Axial and Cyclic Horizontal Load. *International Journal of Steel Structures*, 10(4):385-393.

[5] Li W., Chen Y.Y. (2015). Experimental Study on the Behavior of Partially Encased Composite Bending Members with Different Links. *Progress in Steel Building Structures*, 17(03):1-6.

[6] Chen Y.Y. (2017) Static Loading Test and Shear Strength Calculation of Assembled Frame Connections of Partially Encased Composite Structures. *Journal of Building Structures*, 8:83-92.

[7] Zhao G.T., Feng C. (2012). Axial Ultimate Capacity of Partially Encased Composite Columns. *Applied Mechanics and Materials*, 166: 292-295.

[8] Zhao G.T., Zhu X.J., Feng C. (2012). Behavior of Partially Encased Composite Columns Subjected to Axial Compression. *Journal of Inner Mongolia University of Science Technology*, 31(02): 200-204.

[9] Lin D.H., Chen Y.Y. (2019). Overall Stability Analysis of Partially Encased Composite Columns. *Journal of Engineering Mechanics*, 36:71-77+85.

[10] Jamkhaneh M.E., Kafi M.A. (2017). Experimental and Numerical Investigation of Octagonal Partially Encased Composite Columns Subject to Axial and Torsion Moment Loading. *Civil Engineering Journal*, 3(10):939-955.

[11] Jamkhaneh M.E., Kafi M.A. (2018). Equalizing Octagonal PEC Columns with Steel Columns: Experimental and Theoretical Study. *Practice Periodical on Structural Design Construction*, 23(3).

[12] Jamkhaneh M.E., Kafi M.A., Kheyroddin A. (2019). Behavior of Partially Encased Composite Members under Various Load Conditions: Experimental and Analytical Models. *Advances in Structural Engineering*, 22(1): 94-111.

[13] Abaqus GJDSSC, Providence, RI, USA. Abaqus 6.11. 2011.

[14] CSA. CSA S16–14, Limit States Design of Steel Structures. Mississauga,Ontario: Canadian Standards Association, 2014.

[15] China MoHaU-RDotPRo. JGJ 149-2017, Technical Specification for Concrete Special-shaped Column Structure. Beijing: China Architecture & Building Press, 2017.