Ultimate Capacity of Uniaxially Compressed Steel Plates Strengthened by CFRP

Xin Tao¹, S Y Cao¹
¹Key Laboratory of Concrete and Prestressed Concrete Structures of Ministry of Education, Southeast University, Nanjing, China

Email: seutaoxin@gmail.com;101000873@seu.edu.cn;

Abstract. This paper presents experimental studies on the ultimate capacity of steel plates strengthened by Carbon Fiber-reinforced polymer (CFRP). Some 40 plates are tested under uniaxial compression along its longitudinal direction. The effect of CFRP pasting, plate slenderness ratio and the boundary conditions are illustrated on the studies. The study shows that the steel plates strengthened by CFRP exhibited higher capacity in comparison to similar plates without CFRP. It also can be seen that multi-layers CFRP pasting were better than the single layer, pasting multi-direction is better than pasting uni-direction, pasting the transverse layer outside is better than pasting the longitudinal layer outside, and the effect of longitudinal layer was better than the transverse layer.

1. Introduction

In the past several decades, Fiber-reinforced polymer (FRP) has been widely used in the strengthening of steel structures because of its high strength to weight ratios, excellent resistance to corrosion, environmental degradation, very flexible to form all kinds of shapes, and easy to handle during construction. At the same time, thin-walled plates and tubes made from metals have been used extensively in many different applications [1], including the construction, infrastructure, aeronautical, aerospace, automotive, marine and sporting industries. A relatively recent advent to compression members is the combination of metal and FRP tubes produced by external bonding fibers to the metal section.

In axial compression applications, the motivation for strengthening thin-walled steel structures with FRP is to control buckling deformations and/or provide increased compression capacity [2]. Shaat and Fam (2006) [3] experimented short and long HSS columns with high modulus CFRP sheets and increase the column axial strength by up to 23%. A nonlinear model of this experimental study was developed [4] to predict the axial load capacity, the results show that CFRP effectiveness increases for columns with larger out-of-straightness deficiencies and columns of higher slenderness. Then a simplified analytical model was proposed [5] to predict the ultimate axial load of FRP-strengthened slender steel columns. Bambach (2006,2010a,2010b) [6-8] experimented short hollow structural section(HSS) with different fiber layouts, and observed that the capacity and mean crush load of the composite metal-CFRP HSS exceed the sum of those for the individual metal HSS and CFRP HSS, by up to 1.8 times. A three dimensional finite element model has been developed by Devi [2], and the parametric studies show that the capacity increases with the increase in the number of CFRP layers. It is clear from the above literature review that FRP is good at strengthening the compression member, especially to the HSS columns. However, more research is still required in this field. This paper focused on the ultimate capacity of uniaxially compressed steel plates strengthened by CFRP with different pasting method of FRP, different plate slenderness ratio and different boundary conditions.
Figure 1. Geometry conditions of the strengthened plate

Figure 2. Test rig of the plates

Table 1. Details and the results of the plate specimens

| Group | Thickness (mm) | b/t | CFRP pasting | boundary conditions | Specimen no. | $P_{ult}$ (kN) | Specimen no. | $P_{ult}$ (kN) | Specimen no. | $P_{ult}$ (kN) |
|-------|----------------|-----|--------------|---------------------|--------------|---------------|--------------|---------------|--------------|---------------|
| 1     | 2.61           | 92  | LT           | 2c2s                | CP92-2       | 64.0          | SFSCP92-2    | 67.9          |
|       |                |     |              | 2c1s1f              | CP92-3       | 41.8          | SFSCP92-3    | 53.5          |
|       |                |     |              | 3s1f                | CP92-4       | 23.1          | SFSCP92-4    | 36.6          |
| 2     | 3.64           | 66  | LT           | 2c2s                | CP66-2       | 88.8          | SFSCP66-2    | 90.1          |
|       |                |     |              | 2c1s1f              | CP66-3       | 41.8          | SFSCP66-3    | 53.5          |
|       |                |     |              | 3s1f                | CP66-4       | 23.1          | SFSCP66-4    | 36.6          |
| 3     | 5.58           | 43  | LT           | 2c2s                | CP43-2       | 287.3         | SFSCP43-2    | 367.0         |
|       |                |     |              | 2c1s1f              | CP43-3       | 244.2         | SFSCP43-3    | 272.9         |
|       |                |     |              | 3s1f                | CP43-4       | 197.2         | SFSCP43-4    | 206.3         |
| 4     | 3.64           | 66  | L            | 2c2s                | CP66-2       | 88.8          | SFSCP66-2    | 176.3         |
|       |                |     |              | 2c1s1f              | CP66-3       | 41.8          | SFSCP66-3    | 53.5          |
|       |                |     |              | 3s1f                | CP66-4       | 23.1          | SFSCP66-4    | 36.6          |

Table 2. Material properties

| Material Properties | t(mm) | Young’s modulus(MPa) | Yield stress(MPa) | Tensile strength(MPa) |
|---------------------|-------|----------------------|-------------------|-----------------------|
| Steel plate         | 2.61  | 206                  | 287.9             | 434.1                 |
|                     | 3.64  | 206                  | 253.2             | 369.3                 |
|                     | 5.58  | 206                  | 228.7             | 327.8                 |
| CFRP                | t(mm) | Young’s modulus(MPa) | Fiber mass per unit area(g/m²) | Tensile strength(MPa) |
|                     | 0.167 | 260                  | 300               | 3492.5                |
2. Scope of the investigation

In the investigations reported in this paper, the ultimate capital of steel plates strengthened by CFRP is considered. As shown in Figure 1, the length and width of the plate is b, the thickness of steel and CFRP sheets are given as t and tₜ, respectively. All the plates tested were: (i) square, since they can be assumed to represent a single wave of a buckled plate; (ii) subjected to uniform displacement loading along its longitudinal direction. Some parametric variations have been considered as follows:

1. The situation of the CFRP pasting. Some of them were plates without CFRP, some were plates with single side CFRP pasting and some were plates with double sides CFRP pasting, the direction and the number of layers were also studied in this paper.

2. Plate slenderness ratio b/t, which is an important parameter that governs the plate strength. In this study, the Plate slenderness ratio b/t was 92, 66 and 43, respectively, corresponding to the steel plate’s width t of 2.61mm, 3.64mm and 5.58mm.

3. The boundary conditions of the plates. Four kinds of boundary conditions were studied in this paper, those are: (i) all four are simply supported (4s); (ii) two opposite loaded edges are clamped while the remaining two edges are simply supported (2c2s); (iii) two opposite loaded edges are clamped, one edge is simply supported, and the fourth edge is free (2c1s1f); and (iv) three edges simply supported while the fourth edge which is unloaded is free (3s1f).

3. Test setup

The ultimate capacity of uniaxially compressed steel plates strengthened by CFRP was studied with experimental method, and a test rig has been fabricated in the laboratory (see Figure 2), the test rig was used in combination with existed universal hydraulic jack of 2000 kN maximum capacity. The applied loads were measured by the static strain testing systems, which were composed by Force sensor, DH3816 and computer. The displacement and deformation of the plates were achieved by displacement meters.

A total of 40 specimens were manufactured, of which 12 were steel plates without reinforcement (CP), 12 were steel plates with single side FRP pasting (SFSCP), and the rest 16 specimens were plates with double sides FRP pasting (FSCP). The specimens were divided into four groups (see Table 1); the tests in Group 1, 2 and 3 were to study the influence of the boundary condition and the CFRP pasting. By comparing the tests in those three groups, the influence of the plate slenderness ratio b/t also can be studied. The details of the specimens were in Table 1. In the table, L and T means one longitudinal layer of CFRP sheet and one transverse layer of CFRP sheet, respectively. LT means one longitudinal layer pasting inside and then one transverse layer pasting outside, TL is exactly the opposite. LT2 means two longitudinal layers pasting inside and then two transverse layers pasting outside. The Material properties were in Table 2.

4. Results and discussion

4.1 Failure patterns

Figure 3 shows the typical failure pattern of these plates. The reason why it isn’t so obvious to see the final Out-of-plane deflection is that the experiments were ended soon after the bearing capacity declines. From Figure 3, we can see that the failure mechanism consists four yield lines which start from the four corners and end near the hole edges, also the steel plates and CFRP have a good coordinated working performance throughout the experiment.

4.2 Load-deflection curves

Some typical relationships between compressive load and in-plane displacement of the plates have been plotted in Figure 4. Traditional three-phase curves occurred to those specimens. In these cases, deflection increased linearly with enhancing load at the beginning of the test. As the load continued to
increase, non-linearity between load and displacement became evident due to the yielding of local materials. Great increases in in-plane deflection caused by small increments of load were unavoidable in the final phase. From Figure 4 we can see that the pasting of CFRP can increase the stiffness before buckling, also it can improve the mechanical property afterwards.

![Figure 3. Typical failure patterns of specimen](image)

![Figure 4. Load-deflection curves of specimens](image)

### 4.3 Ultimate load

#### 4.3.1 The situation of the CFRP pasting

Figure 5 shows the influence of the CFRP pasting. Some conclusions can be obtained as following:

1. As shown in Figure 5-a, the ultimate load of FSCP specimens is bigger than CP specimens, but the ultimate load of SFSCP specimens was not stable. Considering of the final buckling mode of the plate, it comes out that if CFRP was pasted on the convex surface of the final buckling mode of the plate, it...
will improve the capacity of steel plates very well; otherwise, it will be almost of no effect. So in the practical, if we can be sure that the FRP sheet is pasting in the drum surface, the influence of FRP can be considered, otherwise, it should be carefully considered. Take the compression of hollow steel tube for example, it has be foreseen that one of the opposite sides will be outward buckling and the other couple will be inward buckling, so only the FRP sheets pasted in the outward buckling sides will be considered in design.

2. It also can be seen from Figure 5-b that multi-layers were better than the single layer (LT2 has the highest ultimate capacity). Pasting multi-direction is better than pasting uni-direction (LT and TL have better ultimate capacity than T and L). Pasting the transverse layer outside is better than pasting the longitudinal layer outside (LT has better ultimate capacity than TL). The effect of longitudinal layer was better than the transverse layer (L has better ultimate capacity than T).

![Figure 5. The situation of the CFRP pasting](image)

4.3.2 The boundary conditions of the plates. The influence of the boundary conditions of the plate was in Figure 6. It can be seen that the boundary conditions affect the ultimate load of the plates great. Results the ultimate load of plates with the different boundary conditions were as follows: 2c2s, 4s, 2c131f, 3s1f. We also find that the smaller the plate slenderness ratio, the plates is more sensitive to the boundary conditions.

4.3.3 Plate slenderness ratio b/t. Figure 7 shows the influences of plate slenderness ratio b/t on ultimate capacity of plates. It can be seen that the ultimate capacity variations of plates strengthened by CFRP are very similar to the pure plates, that is, the ultimate capacity first degrades quickly as b/t is gradually enlarged, then degrades slowly. So in the design, a modified thickness method can be used to consider the role of CFRP sheets.

![Figure 6. The boundary conditions of the plates](image)
5. Conclusions and future trends
The study presented in this paper explores the use of CFRP sheet for strengthening of steel plates subjected to uniaxial compression. In general, test results show that the CFRP sheets provided an excellent strengthening system for steel structures.

Based on the test results, some conclusions and the further studies can be drawn:
1. The pasting of CFRP can increase the stiffness before buckling, also it can improve the mechanical property afterwards.
2. The ultimate load of FSCP specimens is bigger than the CP specimens, and the ultimate load of SFSCP specimens was not stable.
3. Multi-layers of CFRP were better than the single layer, pasting multi-direction is better than pasting uni-direction, pasting the transverse layer outside is better than pasting the longitudinal layer outside, the effect of longitudinal layer was better than the transverse.
4. The smaller the plate slenderness ratio, the plates is more sensitive to the boundary conditions.
5. The results and insights developed from the present study will be very useful for the propose of a modified thickness method, which the role of CFRP sheets can be considered.

In the further research, a FE model will be established, and parameter analysis are also needed to propose a modified thickness method to calculate the buckling load, and then the ultimate load can be calculated according to the specification for structural steel buildings. The elastic buckling of perforated plates strengthened with FRP under uniaxial compression also will be studied through the experimental and numerical simulation methods.

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