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To cite this article: Yeshuang Wu et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 397 012038

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A research on the shear capacity of column pier embedded steel tube

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Abstract. In order to research the action of embedded steel tube on improving shear performance of concrete bridge piers, the transverse static load tests of one reinforced concrete pier and six steel tube reinforced concrete piers were conducted. Test results indicate that the failure patterns of piers were shear diagonal compression failure. The local failure of the bridge piers embedded steel tube skeleton were more integrity. On the basis of the equation of mechanical equilibrium, formulas for calculating the shear capacity of the composite pier were established by considering the modification. The calculation results agreed well with the test conclusions, which provides references of the application of steel tubes embedding in bridge piers for both researching and designing.

1. Introduction
In recent years, with the development of the transportation industry, the accident of vehicle collisions has been increasing dramatically which has aroused widespread concern in engineering and academia.[1] In 2010, Buth et al. [2] summarized the accidents of vehicle collisions in the United States over the years and found that the failure shape of piers mainly manifested as shear failure. It is important to improve the shear performance and ultimate shear strength of piers for civil engineering structures. Thus, many different techniques to increase the shear strength of piers have been used in past decades. For example, fiber-reinforced polymer (FRP) composites,[3-4] high strength concrete,[5-6] steel fiber concrete [7]. Nevertheless, these enhancing measures need complex construction technology and special materials.

Bridge piers embedded steeltube are a new type of composite piers, combining steeltube and reinforced concrete pier. This type of composite structure has already been applied in construction in China. For example, in the Jade Terrace of Guangzhou City, Guangdong Province, where reinforced concrete columns embedded steeltube were employed. In addition, composite reinforced concrete columns embedded steeltube were adopted, respectively, for the 44-story Nanjing New Century Building which was finished in 2003 and the Hetai building located in Shenyang which was finished in 2010. However, far less application has been carried out on the shear performance of this type of bridge piers. Du et al.[8] performed finite element elastic analysis of composite specimens with embedded steel tube and prestressed steel strand by ADINA. This paper presents experimental studies of seven reinforced concrete piers with and without embedded steel tube under the lateral load. The research results indicate that this type of column piers embedded double steel tube with steel brace has a greater load-carrying capacity. According to the force equilibrium equations of failure section of specimens, a theoretical analysis model for flexural-shear failure of a reinforced concrete pier with embedded steel tube is proposed in this paper.
2. Experimental Details

2.1. Test Specimens
In this test, seven specimens were tested. SRCP-1 was a traditional reinforced concrete column pier. SRCP-2~ SRCP-4 were column piers embedded double steel tube. SRCP-5~ SRCP-7 were composite column piers embedded double steel tube with steel brace. The specimens were designed with the same shear span ratio of 1.87 and the same axial compression ratio of 0.1. The cross-section of the column pier specimens was rectangular. The steel tube of SRCP-2~ SRCP-7 were made of seamless round steel tubes. SRCP-5~ SRCP-7 were made by adding steel braces to SRCP-2~ SRCP-4. The dimensions and steel details of the specimens are shown in Figure 1. All dimensions are in millimeters. The mechanical properties of the materials used are listed in Table 1 and Table 2.

![Figure 1. Steel details of models.](image)

### Table 1. Results of concrete test.

| Specimen tag | Vertical steel ratio/% | Equivalent stirrup ratio/% | Axial pressure ratio | Compressive strength/MPa |
|--------------|------------------------|-----------------------------|---------------------|--------------------------|
| SRCP-1       | 3.87                   | 0.78                        | 0.1                 | 32.79                    |
| SRCP-2       | 3.87                   | 0.52                        | 0.1                 | 30.69                    |
| SRCP-3       | 3.87                   | 0.52                        | 0.1                 | 30.06                    |
| SRCP-4       | 3.87                   | 0.52                        | 0.1                 | 29.03                    |
| SRCP-5       | 3.87                   | 0.68                        | 0.1                 | 30.33                    |
| SRCP-6       | 3.87                   | 0.68                        | 0.1                 | 32.01                    |
| SRCP-7       | 3.87                   | 0.68                        | 0.1                 | 31.32                    |

### Table 2. Mechanical properties of steel.

| Steel type | Yield Strength/MPa | Ultimate strength/MPa | Elastic Modulus/GPa |
|------------|--------------------|-----------------------|---------------------|
| 10         | 379                | 472                   | 200                 |
| 12         | 406                | 522                   | 200                 |
| 12         | 365                | 465                   | 200                 |
| 14         | 397                | 519                   | 200                 |
| 16         | 412                | 557                   | 200                 |
| 22         | 393                | 519                   | 200                 |
| Steel Pipe | 266                | 363                   | 200                 |

2.2. Test Procedure
Vertical loading was applied to the top of the specimens and lateral loading was applied horizontally to the 500mm height of the specimens through push-pull jacks. The column pier specimens were loaded in the reaction frame and reaction wall shown in Figure 2. During the loading, all strains, displacements and loads were recorded and analyzed with the data gathering system connected to the specimens. The cracking of the specimens was also visually monitored during the experiments.
3. Test Result and Discussions

3.1. Load-Bearing Capacity

According to the test results, one can obtain the improvement efficiency of strength of concrete piers embedded steel tube. All the piers have the same reinforcement ratio (3.87%) and almost the same equivalent stirrup ratio, but express different strength. Table 3 lists the effective yielding load, \( F_y \), the ultimate load-bearing capacity, \( F_u \), and the ultimate shear capacity, \( V \), of the seven specimens, where \( P_z \) is the support reaction of the top of the specimens, and \( F_u \) is the ultimate load, which is the maximum horizontal load applied to the specimens.

| Specimen | Steel ratio/% | Equivalent stirrup ratio/% | \( F_y \)/kN | \( F_u \)/kN | \( V = F_u - P_z \)/kN |
|----------|---------------|----------------------------|--------------|--------------|------------------------|
| SRCP-1   | 3.87          | 0.78                       | 206.38       | 247.94       | 211.27                 |
| SRCP-2   | 3.87          | 0.52                       | 283.59       | 357.83       | 305.54                 |
| SRCP-3   | 3.87          | 0.52                       | 297.38       | 339.93       | 288.23                 |
| SRCP-4   | 3.87          | 0.52                       | 298.95       | 336.14       | 284.71                 |
| SRCP-5   | 3.87          | 0.68                       | 319.90       | 410.64       | 340.18                 |
| SRCP-6   | 3.87          | 0.68                       | 322.39       | 357.83       | 328.53                 |
| SRCP-7   | 3.87          | 0.68                       | 312.15       | 390.08       | 334.63                 |

The results show that: 1) the effective yielding load, \( F_y \), of column piers embedded double steel tube and column piers embedded double steel tube with steel brace increases by 42.1% and 54.16% in average, respectively, in comparison with traditional RC column pier. 2) The ultimate load, \( F_u \), and shear capacity, \( V \), of column piers embedded double steel tube with and without steel braces are always greater than traditional RC column pier. For example, the average ultimate load of column piers embedded double steel tube with steel brace increases by 55.76% in comparison with traditional RC column pier. 3) These comparison results indicate that the improvement efficiency of shear strength of SRCP-2~SRCP-4 are better than that of SRCP-1, and the improvement efficiency of shear strength of SRCP-5~SRCP-7 are better than that of SRCP2~SRCP-4Thus, the improvement efficiency of shear strength of column piers embedded double steel tube with steel brace is the best.

3.2. Load Displacement Analysis

The curve of load-displacement (figure3) demonstrates stiffness of these specimens at the elastic deformation stage. The embedded steel tube and the steel brace provide additional lateral stiffness for the reinforced concrete column pier.
3.3. Failure Patterns
Figure 4 shows the failure process of SRCP-1, SRCP-3, SRCP-6. Conditions 1(C1) are the concrete cracking patterns and Conditions 2(C2) are the failure patterns.

From these photographs and analysis of data gathering, one can observe that:
1) Concrete crack distribution and development in reinforced concrete piers with embedded steel tube and steel brace are relatively adequate, as can be seen in Figure 4.
2) The applied load can still be increased gradually, even though partial steel had yielded and concrete cracks had developed. It indicates that failure patterns of the reinforced concrete piers with embedded steel tube (from SRCP-2 to SRCP-7) have ductile failure mode. With the improvement of deformation ability of reinforced concrete piers with embedded steel tube, which obviously changes the sudden and dangerous shear failure states of common reinforced concrete piers.
3) When the concrete crushed, the pier specimens with embedded steel tube nearly reached their ultimate strengths. Though the steel tube and brace did not yield at the failure state, the pier specimens have lost the ability to work under the disappearance of stirrups confinement.

4. Calculating the Shear Strength Capacity
To simplify the formula, the actual stress distribution is equal to average compressive and average shear stress. The failure criterion for concrete is assumed as

\[ \tau = A\sigma + B\sigma^\prime \]  

\[ (1) \]

Where, \( \tau \) is concrete shear strength; \( \sigma \) is the concrete compressive strength; \( f_c \) is concrete axial compressive strength; A and B are parameters.

The calculation model is shown in Figure 5.[10] Considering the friction between steel tube and concrete, the shear contribution of steel tube is multiplied by a factor of 1.5.[11]

The following basic assumptions were made:
1) Any tensile strength in the concrete under tensile zone was considered insignificant.
2) Steel in the experimental structures was elastic before yielding, and maintained a yielding
stress after yielding.

3) To simplify the calculation, the bite force and dowel action are ignored in this analytical model.

4) Shear stress and compressive stress distribute homogeneous

According to the equilibrium conditions of forces, three equilibrium equations can be established as follows:

\[ \Sigma X = 0 \quad V_c = bh_0f_{cn} + A_wf_{ct} + A_wf_{ct}(1 + \sin\phi)C/S_1 + 1.5A_wf_{sw1} \]  \hspace{0.5cm} (2)

\[ \Sigma Y = 0 \quad A_sf_{sw1} + A_wf_{ct} + A_wf_{ct}\cos\phi \]  \hspace{0.5cm} (3)

\[ \Sigma M = 0 \quad V_c = abh_0(h_0+\xi h_0/2) + A_wf_{ct}C \times C/2S_1 + A_wf_{sw2}(1 + \sin\phi)C \times C/2S_2 \]  \hspace{0.5cm} (4)

Where, \( \tau \) is concrete shear strength; \( b \) is width of pier model section; \( h_0 \) is the effective height of the pier model section; \( \xi \) is the height of the section relative to the compression zone \( \xi = 0.5 - 0.1 \xi^2 \); \( A_w \) is the cross section area of steel braces; \( f_{sw2} \) is the tensile strength of steel braces; \( A_{sw1} \) is the cross-sectional area of steel tube; \( f_{sw1} \) is the shear strength of steel tube; \( f_y \) is the tensile strength of steel tube; \( \phi \) is the angle between the steel braces and the vertical direction; \( C \) is the projection length of the critical oblique crack in the vertical direction, \( C = 0.9h_0 + 0.3a \); \( a \) is the Loading height; \( S_1 \) is stirrup spacing; \( S_2 \) is the equivalent spacing of steel braces; \( \sigma \) is the concrete compressive strength; \( A_{sw1} \) is the Pulled longitudinal reinforcement area; \( f_{sw1} \) is the longitudinal tendons tensile strength.

When axial compression force (N) exists, piers experience an increase in shear capacity \([12]\), bring formula (1) into equilibrium equation, and consider nonuniform strain in stirrups, steel braces and the axial compression force (N). The shear capacity of the composite piers is therefore:

\[ V_c = \frac{B(1 - \xi/2)}{1 - \xi/2 - \lambda_1} \frac{f_yw_1}{f_{cn}} + \frac{h_0(\xi/2 - 1)}{1 - 1/A_2 + \xi/2A_1} \frac{1.5A_w/f_{sw1} + \left(n_1f_{ct}A_1 + n_2f_{ct}A_2(1 + \sin\phi)C \right) \left(1 - \xi/2 - A_2(0.9 + 0.3a)A_2 \right)}{A_1A_2/S_1} + 0.07N \]  \hspace{0.5cm} (5)

where \( n_1, n_2 \) is thenonuniform coefficient of stirrups and steel braces, respectively. \( n_3 \) is the reduction of steel tube strength. The rest of the symbols are the same as above.

The values of \( n_1, n_2, n_3 \) based on literature\([13]\). The calculation results for SRCP-2~SRCP-7 are show in table 4. Table 4 demonstrates a good agreement between the above equations and the experimental results.

**Table 4. Ultimate load comparisons of calculation and test results.**

| Calculation results \( V_c/kN \) | Test results \( V_t/kN \) | Relative deviation \( V_c/V_t \) |
|-----------------|-----------------|------------------|
| SRCP-2          | 280.64          | 305.54           | 0.92             |
| SRCP-3          | 283.15          | 288.23           | 0.98             |
| SRCP-4          | 269.38          | 284.71           | 0.95             |
| SRCP-5          | 313.04          | 340.18           | 0.92             |
| SRCP-6          | 319.75          | 328.53           | 0.97             |
| SRCP-7          | 324.43          | 334.63           | 0.97             |

5. Conclusion

1. Steel tubes and steel braces embedded in reinforced concrete piers can greatly enhance structural performances of piers in shear. The ultimate shear strength is increased by 54.7%. This type of steel reinforced concrete piers with embedded steel tube and steel brace is a promising structure member.

2. The embedded steel tube and steel brace inhibit the development of concrete cracking and prolong the progress from yielding to ultimate failure.

3. The calculate model proposed in this study can reasonably predict the ultimate shear strength of reinforced concrete piers embedded steel tube with and without steel brace, which agreed well with the test results.

Acknowledgments

The research described in this paper was sponsored by the National Natural Science Foundation of
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