Seismic Performance of Shear Wall with CFST Columns and Encased Steel Truss

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Abstract
A shear wall with concrete filled steel tube (CFST) columns and encased steel truss is a new type of shear wall. To determine the seismic performance of the new shear wall, an experiment was carried on a 1/5-scale model. Based on the experimental study, the load-carrying capacity, stiffness, ductility, hysteretic property, energy dissipation and failure phenomena of the model were analyzed. It shows that the seismic performance of a shear wall with CFST columns and encased steel truss has high bearing capacity, stiffness, energy dissipation capacity and good ductility. In addition, a numerical elastic-plastic finite element (FE) analysis of a shear wall with CFST columns and encased steel truss were carried out. The computation results were in good agreement with the test results. FE software, ABAQUS, was used to change the ratio of steel truss to steel tubes and normalized axial force. The influences of different parameters of shear walls were carried out.

Keywords: CFST; encased steel truss; shear wall; seismic performance; experimental research

1. Introduction
In high-rise buildings, the shear wall is usually the main structural component that resists the lateral force. Shear wall with CFST columns is a new type wall developed in recent years (Han and Yang, 2007). Researches have been carried out by some scholars. Kang, T.H.-K et al. (2013) made a careful study of a steel plate shear wall, and found that a properly designed steel plate shear wall would have considerable energy dissipation capacity, ductility, and ultimate strength. Probst, A.D. et al. (2010) studied the composite flexural behavior of full-scale concrete-filled tubes without axial loads. Abolhassan (2001) investigated a steel plate shear wall with CFST columns. During his test, the CFST columns were basically in an elastic state and the specimen showed good ductility and energy dissipation capacity. Qian et al. (2012) conducted a low cyclic loading test on a shear wall with CFST columns. The test results showed that the shear wall had larger load-carrying and deformation capacities relative to the conventional RC wall. Wang et al. (2015) studied the seismic behavior of a low-rise shear wall with CFST frame and embedded steel-plate by the time history analysis of the specimens. Xia and Liu (2005) carried out finite element analysis on a shear wall with CFST columns using SAP2000. The results showed that CFST columns had good seismic performance as the second line of resistance during an earthquake.

The authors’ research group has carried out relevant research of a shear wall with encased steel truss (Cao et al., 2007, 2008a, 2008b). The results showed that with introduction of an encased steel truss, the seismic performance of a shear wall was enhanced significantly.

Based on previous studies, new experimental and theoretical research of a shear wall with CFST columns and encased truss (Fig.1.) were carried out. The results show that the new shear wall formed multi-channel seismic resistance and has relatively good seismic performance.

2. Experimental Details
2.1 Test Model
A 1/5-scale shear wall model was tested with a shear-span ratio of 1.0. The thickness of the wall is kept as 140 mm and the outer diameter of the steel tube columns is 159 mm with a thickness of 3.7 mm. The cross-section of the plate bracings was 92 mm by 12 mm. Concrete shear walls and CFST columns are connected with U-shaped keys.
The concrete used in the model was specified as C50. Its average measured cubic concrete compressive strength and elastic modulus was 52.1 MPa and 3.5 x 10^4 MPa, respectively. The mechanical properties of steel are shown in Table 1.

2.2 Test Procedure

Cyclic loading on the test specimen was carried out with a normalized axial force ratio of 0.35. The normalized axial force ratio has considered the equivalent steel area of steel tube. Axial load of 870kN was applied. The development of cracking, buckling of steel tubes, and destruction of concrete were observed during the test. The load, displacement and strain were monitored through the IMP data gathering system.

3. Experimental Results and Analysis

3.1 Measured Data

Table 2. lists the measured data, $F_u$ is the ultimate load; $K_o$ is the initial tangent stiffness; $U_d$ is the elastic-plastic ultimate displacement, which is defined as the point at which the load-carrying capacity drops to 85% of the ultimate load; $\mu$ is defined as the ductility ratio of the shear wall.

| Steel Type         | Yield Strength($f_y$ (MPa)) | Ultimate Strength($f_b$ (MPa)) | Elongation Rate(%) | Elasticity Modulus (MPa) |
|--------------------|-----------------------------|--------------------------------|--------------------|-------------------------|
| Steel tube         | 312.33                      | 417.77                         | 27.50              | 1.91 x 10^5             |
| Inclined steel truss | 365.70                      | 536.37                         | 29.17              | 2.11 x 10^5             |
| $\Phi^4$ Steel Bar | -                           | 803.73                         | 10.00              | 1.80 x 10^5             |
| $\Phi^6$ Steel Bar | -                           | 563.21                         | 8.30               | 1.70 x 10^5             |

3.2 Hysteretic Behavior and Energy Dissipation Capacity

The experimental load-displacement hysteretic curves of the model are shown in Fig.2.

![Fig.2. Hysteretic Curves of "Load-Displacement" of the Model](image)

As shown on Fig.2., the shear wall displayed full hysteretic loop, and the middle loop pinched light. At the same time, the area of the hysteretic loop reflects the plastic energy dissipation of the structure. The measured energy dissipation is 62112.02 kN·mm.

3.3 Failure Patterns

The ultimate failure patterns of the model are shown in Fig.3. The shear wall shows the following failure behaviour.

Cracks in the shear wall were thin and widely distributed. They developed slowly because of the encased steel truss. In the later period of loading, swell appeared at the bottom of the steel tube, and appeared on both sides which were parallel to the horizontal force. Subsequently, the drum occurred on the opposite sides which were vertical to the horizontal force after cyclic load. As the load frequency increased, the drum increased to form an intensive energy consumption area. Due to the effect of steel truss support and self pressure-bearing, the dispersion and development of the inclined cracks in the panel was quite homogeneous without the main wide inclined cracks. The panel failed as a result of concrete crushing at the bottom.

![Fig.3. Failure Modes and Cracks](image)
4.1 Finite Element Model

In this paper, the Q235 steel was used, and the mathematical expression of the model is as follows:

\[
\sigma_e = \begin{cases} 
    E\varepsilon_e & \varepsilon_e \leq \varepsilon_y \\
    f_y & \varepsilon_y < \varepsilon_e \leq \varepsilon_\text{ut} \\
    f_y + 0.045 \frac{f_y - f_{\text{u}c}}{\varepsilon_\text{ut} - \varepsilon_c} & \varepsilon_c < \varepsilon_e \leq \varepsilon_\text{ut} \\
    1.6 f_y & \varepsilon_e > \varepsilon_\text{ut}
\end{cases}
\]

\[
\varepsilon_e = 0.8 f_y / E_y, \varepsilon_{c1} = 1.5 \varepsilon_e, \varepsilon_{\text{ut}} = 10 \varepsilon_e, \quad B = 2 A e_{c1}, C = 0.8 f_y + A e_y - B \varepsilon_e
\]

Cold drawn bar was used for the wall distribution bar whose stress-strain curve is similar to hardened steel. The formula proposed by Cheng (1982) was adopted. The formulae are given as follows.

\[
0 \leq \varepsilon_e \leq \varepsilon_y, \quad \sigma_e = E\varepsilon_e, \quad \varepsilon_y < \varepsilon_e \leq \varepsilon_\text{ut}, \quad \sigma_e = A f_y - \frac{B}{\varepsilon_e}
\]

Where \(f_y\) is the reinforced tensile strength, \(\varepsilon_y\) is reinforcement proportional limit corresponding strain, taken as \(2.5 \times 10^{-3}\), according to a constant defined by steel bar tensile testing and the difference of ultimate strength, taking \(A\) as \(1.025\)–\(1.125\) and \(B\) as 0.6.

The uniaxial stress-strain relationship applicable to ABAQUS finite element analysis proposed by Liu (2005) was adopted for core concrete. The formulae are given below which are based on the summary of relevant ABAQUS finite element analysis of steel tube concrete. It considers the characteristics of the core concrete and modifies the concrete axial stress-strain relationship curve at ultimate strain and the descending based on comprehensive calculations and analyses.

\[
y = \begin{cases} 
    2 \cdot x - x^2 & (x \leq 1) \\
    \frac{x}{\beta_b \cdot (x-1)^9 + x} & (x > 1)
\end{cases}
\]

\[
x = \frac{\varepsilon}{\varepsilon_0}, \quad y = \frac{\sigma}{\sigma_0}, \quad \sigma_0 = f_y
\]

\[
\varepsilon_0 = \varepsilon_y + 800 \cdot \varepsilon_0^{0.2} \cdot 10^{-6}
\]

\[
\varepsilon_\text{ut} = (1300 + 12.5 \cdot f_y) \cdot 10^{-6}, \quad \eta = 2
\]

\[
\beta_b = \left(2.36 \times 10^{-7}\right)^{\frac{1}{25+e_{\text{u}c}^0.55}}, f_y^{0.5} \cdot 0.5 \geq 0.12
\]

4.2 Load-Displacement Curve

The calculated load-displacement curve of the shear wall is shown in Fig.5. It can be seen that the calculated curve fits well with the test results.
4.3 Working Performance of Each Stage

To compare and study the development of micro-stress state at different stages, such as stress and strain, three reference points of time were adopted for analysis. The 1st, 2nd and 3rd time is defined as when the initial cracks appeared on the concrete wall, when the steel tube reached the yield stress, and when the concrete shear wall model reached the ultimate load.

The principal plastic strain vector graph provided by the post-processing system of ABAQUS can indicate the approximate distribution, the width of the cracks in concrete wall and other features. The principal plastic strain vector graph of the concrete shear wall model is shown in Fig.6. As shown in the figure, when the load increases, the region of the maximum primary plastic strain expands, and cracks in concrete wall develop continuously. Cracks at the bottom of the concrete wall develop and reach the yield stress, and when the concrete shear wall model reached the ultimate load.

The principal stress vector graph of the concrete shear wall (see Fig.7.) shows that the stress of the wall is mainly compressive stress when cracks appear. As the extent of the distribution of the compressive stress increases, the absolute value increases. This is due to the horizontal load being applied on the left end. The tensile stress value is larger in the lower left corner part of the wall. The compressive stress value is larger in the lower right corner part of the wall. The vertical load is first applied followed by the horizontal load. When the vertical load is applied, the compressive stress in the wall is vertical. After applying horizontal load, most of the compressive stresses in the wall are at an angle to the horizontal.

The bars stress distribution (see Fig.8.) shows that when cracks appear, the stress of the distribution reinforcement in the wall is comparatively small. The maximum compressive stress is greater than the maximum tensile stress. The transverse distribution reinforcement in the wall is all in the tensile stress state. The vertical distribution reinforcement's stress changes from tensile to compressive. The maximum tensile stress distributes in the lower left corner part of the wall. The maximum compressive stress distributes in the lower right corner part of the wall. When the
The model reaches the ultimate load, the bottom of the most vertical distribution reinforcement yields in tension. The reinforcement at the bottom of the right side yields in compression. The other distribution reinforcement does not yield.

The truss stress distribution (see Fig.9.) shows that the high-level stress region distributes in the tension side and the base of the frame column in the compression side, while the high-level stress of the diagonal brace appears in the end portion. Meanwhile stress concentration appears in the joint of a steel tube and diagonal brace. Therefore, it is of great importance to ensure their reliable connection in practical application.

4.4 Mechanism Analysis
When lateral loading was carried out, the first cracks appeared at the tension side of the concrete wall, and then the bottom of the steel tube yielded, meanwhile, the stress of steel truss and steel bar increased. Compared with the steel bar, the steel truss yielded first. With the increase of lateral loading, cracks at the bottom of concrete wall expanded to the compression side, the height of the compression zone was small. The steel bar on the left side of the wall yielded in tension, the steel bar on the right side yielded in compression, and the capacity of the shear wall gradually reached peak value. Eventually, shear cracks appeared in the diagonal direction of the wall, while a plastic angle was formed at the bottom of the CFST columns. The damage mode of the shear wall presented bending shear failure.

4.5 Parameter Analysis
Parameter analysis was conducted using ABAQUS software. The influence of the area ratio of steel truss on steel tube (s) and axial compression ratio (n) are investigated. Finite element models were established according to the above elastic-plastic finite element analysis. Three shear walls with CFST columns and encased truss were analyzed. Table 6. shows the design parameters of steel truss and calculated ultimate load.

| Model | Section of inclined steel truss (mm) | Parameters of Steel tubes (mm) | Area ratio of steel truss to steel tubes | Calculated ultimate load (kN) |
|-------|--------------------------------------|-------------------------------|----------------------------------------|------------------------------|
| 1     | 92 x 4                               | Diameter 159, thickness 3.7   | 0.20                                   | 896.51                       |
| 2     | 92 x 8                               | Diameter 159, thickness 3.7   | 0.41                                   | 1024.87                      |
| 3     | 92 x 12                              | Diameter 159, thickness 3.7   | 0.61                                   | 1108.24                      |

Fig.10. "Load-Displacement" Curves of Shear Wall with Different Values

Fig.11. "Load-Displacement" Curves of Shear Walls with Different Axial Compression Ratios
When the area ratio of steel truss to steel tube increased from 0.2 to 0.41, the ultimate load increased to 14.3%. When the area ratio of steel truss to steel tube increased from 0.41 to 0.6, the ultimate load increased to 8.1%. Hence, the rate of increase reduced. All three composite shear wall models showed good ductility.

4.5.2 Normalized Axial Force Ratio

Normalized axial force ratio is an important factor of shear wall. Fig.11. shows the Load-displacement curves of shear walls with different normalized axial force ratios. For common engineering practice, normalized axial force ratios (n) are set as 0.2, 0.35 and 0.5, respectively.

As seen in Fig.11., the influence of normalized axial force ratio on the model’s initial elastic stiffness is very small. The elastic-plastic stiffness of the shear wall increased with the normalized axial force ratio from yield load to ultimate load stage.

Due to compressive stresses, hindering the emergence of the diagonal cracks and increasing the load at various stages, the crack load, yield load and ultimate load of the shear wall increased with the normalized axial force ratio.

When the normalized axial force ratio is relatively small, such as 0.2, the shear wall model showed good ductility with the increasing load. The reason is that the cross-section of a shear wall in the compression zone is relatively reduced with the decrease of normalized axial force ratio.

5. Conclusion

(1) A shear wall with CFST columns and concealed truss has excellent seismic performance.

(2) The concealed truss embedded in the wall can help to lead crack development, limit the width of the main crack, extend crack distribution area and increase the seismic capacity of a shear wall significantly.

(3) The calculated elastic-plastic load-displacement curve of the shear wall with CFST columns and concealed truss fits well with the test skeleton curve. The influence of different parameters of shear wall were carried out.

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