Design Research and Application of D-shape Expansive Concrete-filled Steel Tube Supports in Roadway Support

Li-Min LIU\textsuperscript{1,a}, Jin-Peng ZHANG\textsuperscript{1,b,*}, Wei-Tao LIU\textsuperscript{1,c}, Xu YAN\textsuperscript{1,d}, Zhi-Kui WANG\textsuperscript{1,e} and Jun-Zhi CAO\textsuperscript{2,f}

\textsuperscript{1}College of Mining and Safety Engineering, Shandong University of Science and Technology, Qingdao, Shandong, China, 266590
\textsuperscript{2}Ark Mines Ltd. Tai'an, Shandong, China 271026
\textsuperscript{a}lmliuhhu@163.com, \textsuperscript{b}zhljinpeng@163.com, \textsuperscript{c}skdlwt@126.com, \textsuperscript{d}501253696@qq.com, \textsuperscript{e}2292578197@qq.com, \textsuperscript{f}fzkj001@126.com

*Corresponding author

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Abstract. In order to perfect the application of concrete-filled steel tube support (CFSTS) in roadway support, aiming at the shortcomings of the existing common CFSTS, this paper put forward the D-shape expansive concrete-filled steel tube support (D-ECFSTS). Firstly, this article uses the numerical simulation to carry on the optimization of circular steel tube, designs the D-shape steel tube, and carries on the comparative analysis of D-shape concrete-filled steel tube support (D-CFSTS) and circular concrete-filled steel tube support (CFSTS). Then, the scheme of expansive concrete is put forward, and the ratio of expansive concrete is tested by the test method. Finally, the D-ECFSTS was made by D-CFSTS and expansive concrete, then used in roadway support. The results show: The deformation of D-CFSTS is much smaller than that of circular CFSTS under the same load; The best ratio of expansive concrete includes that the ratio of cement, sand, gravel is 1:1.31:2.65, water cement ratio is 0.41, expansion agent ratio is 11% and water-reducing agent ratio is 0.5%; In the support of Pingdingshan coal mine roadway, the supporting effect of D-ECFSTS is much better than that of U36 support. So, D-ECFSTS is a good roadway support method.

Introductions

For the concrete block, its own carrying capacity is very limited. If apply a constraint around the concrete block and make the concrete in three direction stress state, the bearing capacity of the concrete will be significantly improved. It is more common in engineering that the steel tube is used as a constraint, this forms a concrete-filled steel tube structure (CFST). When the concrete is poured into the steel tube and reaches a certain strength, the concrete ensures the local stability of the thin-walled steel tube. In turn, the steel tube constrains the radial deformation of the concrete, which makes it in three direction stress state and delays the pressure longitudinal cracking, thereby enhances the bearing capacity of concrete-filled steel tube (CFST). As a composite material, CFST has the unique working characteristics: elastic working and plastic failure, high bearing capacity and large limit compression deformation. With high bearing capacity, corrosion resistance, ease of construction and a series of other advantages, CFST is widely used in civil engineering.

The axial bearing capacity of CFST in civil engineering is mainly considered [1-3]. When CFST is used in arch bridge, cable structure and so on, the flexural capacity of CFST is mainly considered[4,5]. In addition, some scholars study the composite structure of CFST and steel bar. Moon J etc[6] studied on the variation of the strength of CFST with or without reinforcement under the mixed load. Fong M etc [7]designed truss structure composed by steel tube filled with steel bar and concrete, and studied its the mechanical properties. According to the experience of CFST structures in civil engineering, to make full use of its bending performance, the ordinary steel tube
Concrete-filled steel tube support (CFSTS) has been proposed as a new passive support form for controlling the stability of surrounding rock in underground structures, especially for the case of high ground stress. Li Xuebin, Gao Yanfa etc [8,9] used circular CFSTS and the common mine support material to carry on the soft rock-high stress-roadway support, and had obtained the remarkable support effect. SU Lin-wang etc [10,11] used the finite element simulation software to analyze the mechanical behavior of CFSTS for purpose of fully evaluates the mechanical properties of CFSTS. Xu Chang etc[12] presented a numerical study on the technical performance of CFSTS. And a plastic damage model was used for the concrete and two interface models are adopted to describe the behaviors between the concrete and the steel tube.

The cross section of CFSTS studied by the existing scholars is circular. However, because of the shape of the steel tube, the wrinkled area is liable to appear in the back side pressure area in the bending process of circular steel tube. So, after the steel tube is made into the support, the supporting force is clearly reduced. In addition, after the concrete is poured into the steel tube, only the concrete to enrich the steel tube, the CFSTS is achieved the overall force effect. To ensure that the steel tube is filled to the full with concrete and prevent the self-shrinkage of concrete and the cracks of hardened concrete, require the prepared concrete with moderate expansion property, that is able to compensate for shrinkage. The concrete compressive strength is the key to the bearing capacity of CFSTS; the concrete ratio must ensure that the compressive strength of concrete reaches a certain value.

In order to solve the problem that the bearing capacity of CFSTS is reduced due to the wrinkle in the back pressure area of the circular steel tube after bending, D-CFSTS is developed by numerical simulation. In order to solve the problem of moderate expansion performance of concrete, the influence of the content of expander and superplasticizer on the compressive strength of the test piece was studied by laboratory test.

**Optimization of Concrete-filled Steel Tube Section**

The section shape of the CFST is optimized by numerical simulation. The model selects Q235 steel and concrete with C60 strength, and the dimensions of steel tube is Φ150×5mm. The model is a section of circular steel tube which is simulated by plane42 element. Set to plane strain model and free grid division, the model is divided into quadrilateral element. The specific material parameters of steel tube and concrete are shown in Table 1 and Table 2.

![Fig. 1 The cross section of circular steel tube under vertical pressure](image_url)

When the constraint condition (DOF constraint) is applied, all the free degrees of the part of the surface underneath the section of the steel tube are constrained. Partial nodes on the upper surface is loaded with the load value of 2000N and the downward direction. Then solve it, the deformation of the steel tube section is shown in Fig.1, X, Y displacement is shown in Fig.2 and X, Y stress is shown in Fig.3.
From the analysis of Fig.2, we can know that in the X direction, the maximum deformation of the steel tube is in both sides, reaching to 18.6mm; In the Y direction, the maximum deformation of the steel tube is in the upper, reaching to 35mm, and the minimum deformation of steel tube is in the lower part, about 3.8mm. From the analysis of Fig.3, we can know that in the X direction, the overall stress distribution of steel pipe is relatively uniform, which is about 1700N. Stress concentration is appeared on the upper of the steel tube and both sides of the lower of steel tube, especially the upper part stress of the steel tube is more than 12200N; In the Y direction, the overall stress of the steel tube is larger than that of the X direction, the left shoulder of the steel tube appears stress concentration that the stress is about 6000N.

According to the stress displacement analysis, the deformation shape of steel tube close to capital letters D under the normal load deformation. So, this interface is used as the steel tube section of CFST, and CFST section is designed as a D shape. The optimized cross section of the tube is shown in Fig.4.

Figure 2. The displacement nephogram of X, Y.

Figure 3. The stress nephogram of X, Y.

Figure 4. Cross section of D-type tube (made by Φ 150×5 mm steel tube)(unit:mm).
Stress Analysis of Concrete-Filled Steel Tube Supports

Scheme Design and Model Optimization

Now, the shape of the CFSTS structure is designed to be horseshoe-shaped. D-CFSTS and circular CFSTS are equal in section perimeter of steel tube. The two kinds of CFSTS are filled with C60 high strength concrete. Then the overall performance of the D-CFSTS and the circular CFSTS is compared, analyzing whether the curved D-CFSTS has advantages in structure.

Design support boundary conditions: The bottom of support is fixed and the top of that is subjected to stress analysis; taking into account the impact of horizontal stress on the supports, the pressure applied to the side arch is the same as that applied to the top pressure. According to the site geological conditions, the estimated pressure is 15 MP, and the top and side of the support at the same time is added 15 MP surface force. In order to facilitate the calculation of horseshoe-shaped support, the horseshoe-shaped support’s structure is simplified as the following figure of the semi-circular arch supports. The simplified model is shown in Fig. 5. This model is mainly composed of the top arch section and two side arch sections of the horseshoe-shaped support that three arch sections are the same and the corresponding center angle of each arch section is 70°. Then, the same load is applied to the top arch section and two side arch sections of the model, and the displacement constraints are applied to two ends of arch support.

![Simplified model of the concrete filled steel tube scaffold.](image)

Figure 5. Simplified model of the concrete filled steel tube scaffold.

Compression Analysis of Concrete-Filled Steel Tube Supports

The D-CFSTS is analyzed; displacement of the curved D-CFSTS is shown in Fig. 6:

![Displacement diagram of X and Y of D-CFSTS.](image)

Figure 6. Displacement diagram of X and Y of D-CFSTS.
The circular CFSTS is analyzed, displacement of the circular CFSTS is shown in Fig.7:

From the displacement diagram, we can know: When a uniform load is applied to a member, the displacement occurs mainly at the top of the member. The bottom end of the member is fixed, so the displacement deformation is close to 0 and the displacement from the bottom to the top is gradually increased. It shows that the simulation results are in accordance with the theory and the experimental data is of reference value.

As can be seen from the comparative analysis of Fig.6 and Fig.7, the displacement of D-CFSTS is 0.004596mm and the displacement of circular CFSTS is 0.94863mm. Description: when the same load is applied to the CFSTS, the deformation of the circular CFSTS is much larger than that of the D-CFSTS. So, the bearing capacity of the D-CFSTS is higher than that of the circular CFSTS.

Proportioning Test of Expansive Concrete

In order to ensure that the CFSTS is filled with concrete to prevent the cracks between the steel tube and the hardening concrete due to the autogenous shrinkage of the concrete. The concrete is required to have a moderate expansion property, that is, the compensation shrinkage. To compensate shrinkage concrete mix design, in accordance with the requirements of the "Design Code of Concrete Mix Proportion" (JGJ55-2000), study on the raw materials, mix design, and other aspects. According to the choice of the expansion agent and water reducing agent in the "Code for utility technical of concrete admixture" (GB50119 2003), the ratio of concrete is designed. Through the experimental analysis of the slump and strength of concrete, finally selects a set of optimum proportion.

Raw Material Selection

1) Cement: In this experiment, the 42.5# ordinary portland cement is used and the amount of cement per cubic concrete is not less than 300kg.
2) Sweller: In this experiment, the most common calcium aluminate expansive agent is used and the content of calcium aluminate is between 10%~12%.
3) Water reducer: the water demand of compensatory shrinkage concrete preparation is relatively large. The water cement ratio increases with the increase of water usage, thereby reducing the expansion rate and increase shrinkage. So, it should be mixed with appropriate amount of water-reducing agent. But adding water-reducing agent will accelerate the formation of ettringite, also reduce the expansion rate. Therefore, weighing the pros and cons, choose MF type superplasticizer and appropriate amount of incorporation.
4) Aggregate: Refer to the "Building Sand" (GB/T14684 - 2001), "Building Gravel" (GB/T14685 - 2001) in the relevant provisions, select the quality river sand as fine aggregate, select the solid and clean gravel with the reasonable size 5~10mm as coarse aggregate.
Preliminary Calculation of Ratio

The strength of the compensating shrinkage concrete required to reach up to C40 after 28 days, the admixture is added in the form of replacing cement dosage among it. According to the performance of raw materials and the technical requirements of the initial calculation of the concrete, draw a preliminary mix proportion conclusion, in order to meet the requirements of the laboratory, strength and other technical requirements after the lab test with adjustment.

(1) Determination of concrete strength
According to the rules of JGJ55-2000, the preparation of strength is as follow:

\[ f_{cu,0} = f_{cu,k} + t\sigma \]  

where, \( f_{cu,0} \) represents concrete strength, MPa; \( f_{cu,k} \) represents concrete design strength grade, MPa; \( t \) represents strength guarantee rate, generally take 1.645; \( \sigma \) represents standard deviation of concrete strength, MPa; when the strength of concrete is greater than C35, \( \sigma = 6.0 \).

Therefore,

\[ f_{cu,0} = 40 + 1.645 \times 6.0 = 49.87 \text{ (MPa)} \]

(2) Determination of water cement ratio of concrete
According to the formula:

\[ \frac{W}{C} = \frac{A f_{ce}}{f_{cu,0} + AB f_{ce}} \]

where, \( W \) represents the amount of water per cubic meter of concrete, kG; \( C \) represents the amount of water per cubic meter of concrete, kG; \( f_{ce} \) is determined by experiment or calculated by \( f_{ce}=1.13f_c \), in which \( f_c \) is the strength grade of cement; \( A \) and \( B \) represent the empirical coefficients, when used in gravel, \( A=0.46, B=0.07 \).

Therefore, water cement ratio is as follow:

\[ \frac{W}{C} = \frac{0.46 \times 1.13 \times 40}{49.87 + 0.46 \times 0.07 \times 1.13 \times 40} = 0.405 \]

(3) Determination of the amount of concrete cement and water consumption.
The amount of cement prepared to compensate the shrinkage of concrete is no less than 300kg/m³. According to the empirical formula, the amount of cement takes 350kg/m³, so the water consumption \( W=0.405\times 350=141.75\text{kg/m}^3 \). According to the principle of the unity of the slump, the water consumption reduced after using the water reducer.

(4) Calculation of the amount of coarse and fine aggregate(S0,G0)
The absolute volume method, which assumes that the volume of concrete mixture is equal to the air contained in the absolute volume and the mix material in volume. Each material dosage in 1m³ concrete is shown in the formula (3), the calculation formula for sand ratio is shown(4). The amount of sand and stone in 1m³ concrete can be obtained by two simultaneous equations.

\[ \frac{C_0}{\rho_0} + \frac{S_0}{\rho_{0S}} + \frac{G_0}{\rho_{0G}} + \frac{W_0}{\rho_w} + 10\alpha = 1000L \]  

\[ S_p = \frac{S_0}{S_0 + G_0} \times 100\% \]

where, \( C_0 \) and \( W_0 \) represent the amount of cement and water in 1m³ concrete, kg; \( S_0 \) and \( G_0 \) represent the amount of sand and gravel, kg; \( \rho_c \) and \( \rho_w \) represent density of cement and water, g/cm³, usually \( \rho_c =3.1, \rho_w =1.0 \); \( \rho_{0S} \) and \( \rho_{0G} \) represent the density of sand and stone in concrete,
g/cm³, the sand test density is 1.47 g/cm³, the stone test density is 1.45 g/cm³; α represents the percentage of gas in concrete, when the air entrained admixture is not used, α=1; Sp represents the concrete in the sand ratio, %.

Take Sp=33%, simultaneous (3) (4), substituting the data S₀ =353.5 kg, G₀ =707.7 kg.

**The Experimental Determination of the Mix Ratio**

Selecting the raw materials according to the design standard, adding expansive agent instead of cement, adding water reducing admixture. According to the characteristics of the slump and workability, adjust the amount of sand and gravel.

Through the above calculation, determine that the proportion of cement, gravel sand is 1:1.31:2.65. According to the orthogonal test method and the different mixing amount of water reducing agent, three groups of experiments were designed. The water reducing agent of the first group was 0.3%, the second group was 0.5%, the third group was 0.7%. In each group, the content of the expansion agent was 10% and 11% respectively. Make standard concrete test block in the premise of ensuring good workability and slump. Measure the compressive strength every 4 days until the end of 28 days. Select the strength to meet the C40 standard, the optimal proportioning scheme is that the strength of concrete is greater than 49.77 MPa. Detailed test results are shown in Fig.8.

![Figure 8. Compressive strength of concrete specimens in each group.](image-url)

From the Fig.8 we can see: In the first group tests, the compressive strength of concrete specimens with an expansive agent content of 10% is 49.3 MPa, and when the expansive agent content 11%, the compressive strength is 52.6 MPa. In the second group tests, the compressive strength of concrete specimens with an expansive agent content of 10% is 52.5 MPa, and when the expansive agent content 11%, the compressive strength is 55.4 MPa. In the third group tests, the compressive strength of concrete specimens with an expansive agent content of 10% is 50.8 MPa, and when the expansive agent content 11%, the compressive strength is 52.6 MPa. In the three
groups of experiments, when the amount of water reducing agent is the same and the amount of expansive agent was increased from 10% to 11%, the compressive strength of concrete block was increased; when the water reducing agent is increased from 0.5% to 0.8%, the compressive strength of the test block is increased little or decreased. Through the comparison of the three groups, it can be seen that, when the expansion agent is the same and the water reducing agent is increased from 0.3% to 0.5%, the compressive strength of the test block is significantly increased; when the water reducing agent is increased from 0.5% to 0.8%, the compressive strength of the test block is increased little or decreased. From the results on a composite of Fig.8 and the relevant parameters of the slump, liquidity and workability, get the best proportion: the ratio of cement, sand and gravel is 1:1.31:2.65, water cement ratio is 0.41, the expansive agent dosage is 11%, water reducing agent dosage is 0.5%.

Support Processing

Using cement wrapped sand and concrete mixing technology, according to the construction procedure, fristly add the sand, mix with water, add the cement mixing, plus gravel mixing, then add water and mix admixture. The production of D-ECFSTS is completed by three steps: tube bending, support assembly, concrete casting.

(1) Tube bending. The cold pressing method is adopted to process the steel tube, which makes the steel tube to be processed into a curved surface, which ensures that the curvature radius of the steel tube is in accordance with the design standard, and the steel tube surface is smooth without damaged or folded.

(2) Support assembly. The supporting frame is composed of casing tube joint and D-shape steel tube arc, and the supporting frame is assembled on the ground. Labeling and assembling the support ordinarily, polishing the end of the steel tube before assembling to ensure the D-CFSTS segments uniform stress.

(3) Concrete casting. With special concrete pump machine, pour expansive concrete from the top of D-CFSTS. After pouring 1/3 height, vibrat compaction from outside every 1/3 height. In order to compensate for the loss caused by the solidification of the expansive concrete at the top of the grouting hole, after 24h, the supporting frame is finished to fill up, until the grouting hole is opened.

Engineering Applications

Pingdingshan ten mines is located in the hilly area of the Ruhe south and the Shahe north, the terrain in the northwest is higher than in the southeast. The long of the minefield from the east to west is 5.6Km and the tilt of that from the north to the south is 7.0Km. The total thickness of coal-bearing rocks is about 900m, the total thickness of main coal mining group is 13.74m and the angle of coal seam inclination is 0~35°. Affected by the occurrence condition of coal seam and the mountain in ground surface, the depth of coal seam is about 450~1100m. The immediate roof and the immediate floor of coal seam are mainly sandy mudstone and mudstone, the basic roof and the basic bottom of coal seam are mainly sandstone.

Mine had been using U-shaped steel support to support roadway. Due to the influence of the lateral mining and the surrounding broken rock, the floor heave, rib spalling and paste cracking in -320 level return roadway of Pingdingshan ten mines were serious and the roadway needed to be expanded once or twice a year. In order to seek a more effective and reliable support method than the original one, the two section test roadway was set up in Pingdingshan ten coal mine. In one of the test section, the above mentioned D-ECFSTS was adopted as the main support method and the supporting method is shown in Fig.9. In the second test section of the roadway, the U36 steel support was used to support the roadway, and the support shape is shown in Fig.10.

The components parameters of D-ECFSTS: The steel type is Q235, the steel tube is Φ150×5mm; The concrete specifications is C60 expansion concrete; The perimeter of the support is 11530mm, the width of the support is 4680mm, the height of the support is 4050mm, the support spacing is (650+50) mm; The casing type is Φ165×6.5mm and the length of that is 400mm; The supports for the horseshoe shaped are divided into four sections.
The parameters of U36 steel support: The perimeter of U36 steel support is 12350mm, the support spacing is (650+50)mm, the width of the support is 4530mm, the height of the support is 3980mm; The arch support is divided into six sections; The connection method for the sections is cable connection, each lap must be connected with three clips, and the lap length is 400mm.

Figure 9. The structure figure of D-ECFSTS.

Figure 10. The structure figure of U36 steel support.

After a period of time, the roadway deformation of U-shape steel support in test section roadway was so serious that the roadway was not used normally. After repairing the surrounding rock, the roadway tended to be stable. The surrounding rock of roadway in test section roadway that D-ECFSTS supported was stable after small deformation and the roadway could be used for a long time. As the test section roadway that U36 steel support supported was repaired, so the data of it was not analyzed. The supporting results of the D-ECFSTS are shown in Fig11. In this paper, selected the representative points of D-ECFSTS to analyze. The displacement evolution law of the top-floor of the roadway and the roadway's sides in the measuring point are shown in the following Fig.12.

Figure 11. Supporting results of the D-ECFSTS.
Because there was a certain gap between the D-ECFSTS and the roadway wall, the support was not fully played in the early stage. So, the roadway roof subsidence in the early stage is obvious, and the change rate was fast. After a period of time, the surrounding rock of the roadway and the D-ECFSTS started the real contact, and the high strength supporting effect of the supports began to appear. With the gradual expansion of the contact area, the high strength supporting effect of the supports gradually increased, the rate of the roadway surface displacement was significantly reduced, and finally the relative displacement of the roadway was stable. Due to the holistic effect of the supports, the roof subsidence of the surrounding rock had led to the outward expansion of the roadway's sides. So, the two sides showed a gradual increase in the evolution trend. In the whole observation process, the D-ECFSTS was in good condition, and had no obvious damage.

Conclusion

In order to solve the shortcomings of existing CFSTS, the D-shaped concrete-filled steel tube support and expansive concrete are developed by numerical simulation and experiment. The D-ECFSTS is put forward:

(1) The surface part of the circular steel tube is applied the load. Regular deformation occurs to the steel tube, the shape of the deformation is closed to capital letters D. When the same load is applied to the CFSTS, the deformation of the circular CFSTS is much larger than that of the D-CFSTS. The bearing capacity of the D-CFSTS is higher than that of the circular CFSTS.

(2) Using the formula to calculate the initial ratio of expansive concrete, the ratio of cement, sand and gravel is 1:1.31:2.65. The effect of expansive agent and water reducing agent on the compressive strength of concrete specimen was studied by orthogonal test. The water-cement ratio of expansive concrete was 0.41, the expansive agent dosage is 11%, water reducing agent dosage is 0.5%.

(3) Through the application of the D-ECFSTS in the test roadway, the D-ECFSTS produced by D-shaped steel tube and the best proportion of expansive concrete can effectively control the deformation of roadway, and the support effect is remarkable.

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