# Working Mechanism of Axially-Compressed Short Column of Corroded Thin-walled Concrete-filled Circular Steel Tube

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Abstract
To investigate the deformation characteristic of thin-walled concrete filled circular steel tubular stub columns after corrosion and further understand of the working mechanism. The author designed 11 Concrete filled steel tubular short columns with three different wall thicknesses. By artificial electricity accelerated method, the author tried to accelerate corrosion of steel component to increase D/t ,The thin-walled steel pipe are given corrosion by axial compression mechanical properties test, by using digital image acquisition and analysis method ,the author analyses the components' whole destruction process of being destructed and deformed under the force. The results show that with equal corrosion steel and concrete can enter into the co working state earlier. With the increasing of D/t the deformation creep parts of the components gradually become weak and the shear failure mode of columns are the main destruction form. The mechanical properties are similar between thin-walled concrete filled circular steel tubular short columns under axial compression with equal corrosion and components of the same wall thickness without being corroded.
Keywords: THIN WALL, CONCRETE-FILLED CIRCULAR STEEL TUBULAR COLUMN, DIAMETER-TO-THICKNESS RATIO, WORKING MECHANISM OF AXIAL COMPRESSION, CORROSION RATE

## 1. Introduction

At present, concrete-filled steel tubular structures have been applied in China [1-5]. The use of thin-walled concrete-filled steel tubular column in the engineering can save steel and reduce construction cost. Thin-walled concrete-filled steel tube is defined by many scholars as the diameter-to-thickness ratio of cross section D/t (for concrete-filled circurlar steel tube) or width-to-thickness ratio B/t (for concrete-filled square steel tube) is more than 1.5 times of local stable threshold of double-skin steel-tube of corresponding compressed member [5].The current study on thick-walled concrete-filled steel tubular structures has ended with fruitful outcomes, but the study on thin-walled concrete-filled steel tube is widely carried out [6-8]. Under axial compression, working performance of thin-walled concrete-filled steel tubular column as superior compressed member remains to be further studied.

Steel tube is corroded due to exposure to the natural environment and long suffering from erosion effect of external environmental factors [9, 10]. Disastrous accidents caused by corroded steel tube often happen and have serious consequences [11].When the member of thin-walled concrete-filled circular steel tubular column, i.e. external steel tube, is corroded and peels off under the action of corrosive media, its thickness diameter is increased, and steel tube has a weak confinement effect on concrete. With the increase of corrosion rate of steel tube, the changing rule of axial compression bearing capacity of the members needs further research. In this paper, the test of axial compression was carried out for 11 thin-walled concrete-filled circular steel tubes in three types of wall thickness, and artificial accelerated corrosion of steel tube in the laboratory was used to test and study mechanical properties of axially-compressed short column of corroded thin-walled concrete-filled circular steel tube.

**2. Test Design**

In this paper, Q235 steel tube was used, experiment studies were conducted for 11 short thin-walled concrete-filled steel tubular columns designed for concrete with the compressive strength grade of C30. The wall thickness of steel tube was respectively 0.92mm, 1.42mm, 0.92mm. Column height was 500mm, tube diameter was 139mm, and the design for related parameters is shown in Table 1. In the laboratory, corrosion of 11 steel tubes was artificially accelerated, after reaching the designed corrosion rate, the static load test of axial compression was taken up, and the detailed loading method is shown in Figure 1.

Artificially-accelerated corrosion was carried out by using the constant current accelerated corrosion method. After constant direct current $I$=2mA/cm$^2$ was switched on, steel tube (Fe) was used as anode lose electrons, until the amount of corrosion was obtained. According to Faraday's Law, the required amount of corrosion Q was calculated, then the required time of corrosion T was calculated according to the given constant current I, as shown in the Formula (1), (2). The components suffer from uniform corrosion, so in this paper the ratio of corrosion thickness and wall thickness of steel tube was defined as corrosion ratio, expressed as percentage.

$$Q = 2 \times \frac{\Delta w}{M} \times N \times e \tag{1}$$

$$T = \frac{Q}{I} = 2 \times \frac{\Delta w}{MI} \times N \times e \tag{2}$$

| | |
|---|---|
| Δw: | =δ×W ; |
| Δw: | Mass of reinforced steel bar to be corroded (Kg); |
| *W:* | Total mass of reinforced steel bar (Kg); |
| δ: | Mass corrosion ratio of reinforced steel bar; |
| *Q:* | The required electric quantity (C) |
| *M:* | Molar mass of iron (56 g/mo1); |
| *N:* | Avogadro constant (6.02 ×1023 /m01); |
| *e:* | Electronic charge (1.602×10-19C); |
| *T:* | Time required by corrosion (s); |
| *I:* | Electric intensity of corrosion (A). |

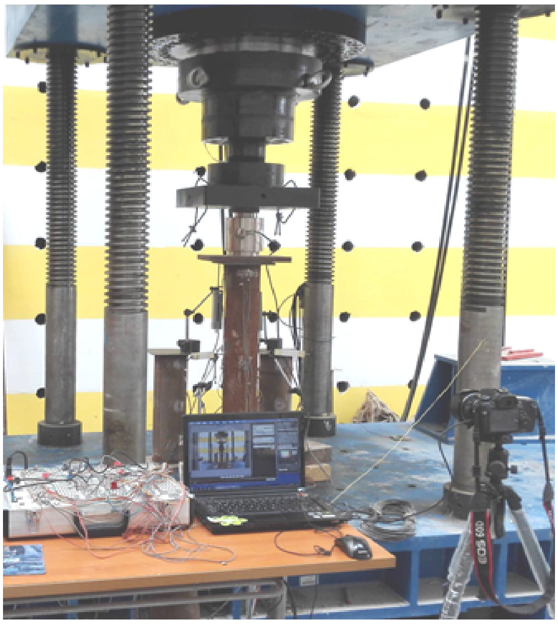


**Figure 1**. Loading map

**Table 1. Table for parameters of corrosion design of thin-walled concrete-filled steel tubular column**

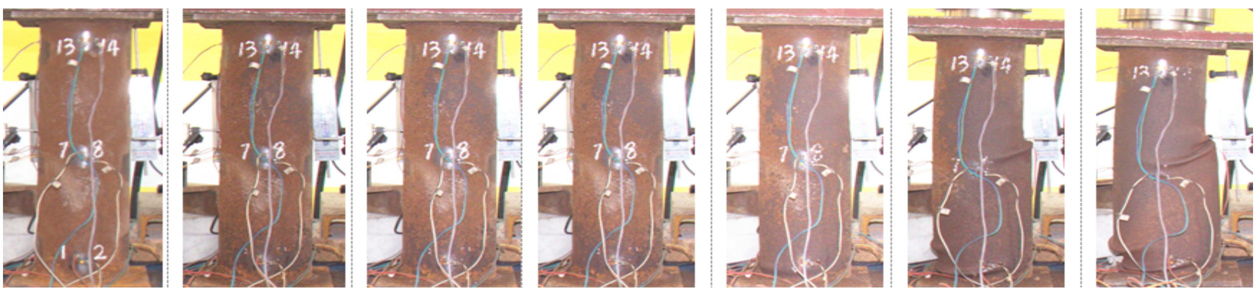
| Member No. | Wall thickness (mm) | Expected corrosion thickness | Actual thickness of corrosion | Corroded wall thickness | Corrosion Ratio | D/t | $\theta$ |
|---|---|---|---|---|---|---|---|
| CSCC1-1 | 0.92 | 0 | 0 | 0.92 | 0 | 151.09 | 0.407 |
| CSCC1-2 | 0.92 | 0.2 | 0.21 | 0.71 | 22.83% | 195.18 | 0.315 |
| CSCC1-3 | 0.92 | 0.46 | 0.45 | 0.47 | 48.91% | 293.83 | 0.208 |
| CSCC5-1 | 1.42 | 0 | 0 | 1.42 | 0 | 97.89 | 0.63 |
| CSCC5-2 | 1.42 | 0.3 | 0.31 | 1.11 | 21.83% | 124.67 | 0.499 |
| CSCC5-3 | 1.42 | 0.5 | 0.52 | 0.9 | 36.62% | 153.29 | 0.404 |
| CSCC5-4 | 1.42 | 0.7 | 0.7 | 0.72 | 49.30% | 191.11 | 0.323 |
| CSCC6-1 | 1.92 | 0 | 0 | 1.92 | 0 | 72.40 | 0.866 |
| CSCC6-2 | 1.92 | 0.5 | 0.49 | 1.43 | 25.52% | 96.51 | 0.652 |
| CSCC6-3 | 1.92 | 0.8 | 0.81 | 1.11 | 42.19% | 123.77 | 0.505 |
| CSCC6-4 | 1.92 | 1.0 | 1.01 | 0.91 | 52.60 | 150.53 | 0.413 |

### 3. Experimental Phenomenon

In the process of testing, digital cameras were used to shoot deformation of members at the fixed time under axial compression load, as shown in Figure 2. In the whole loading process, obvious local ring-shapted swelling deformation first appeared in the column bottom of components, shear deformation was formed in weak parts of components (middle, bottom), and then shear plane was formed until the components lost bearing capacity. From the failure process and pattern, once swelling deformation appeared in a part of a component, component's stress center will deviate and has difficulties in keeping the state of axial compression, accelerating the occurrence of shear deformation.

After comparing a component's bearing capacity with displacement deformation, it was found that before reaching the maximum bearing capacity, there was small vertical deformation, and the maximum deformation did not synchronize with the component's maximum bearing capacity; component deformation mainly happed after reaching the maximum bearing capacity, along with the increase of component deformation, its bearing capacity was declining. The peeling of column shaft's corrosion layer indicates that before reaching the maximum bearing capacity, and steel tube is deformed because of stress, so the corrosion layer peels off.

Figure 3 the component's failure pattern shows no matter what the corrosion ratio was, the component had the characteristics of shearing, failure and damage, failure pattern was not destroyed by drum-shaped deformation. From the point of test process, swelling and buckling first happened in weak positions, and then shear failure happened along the shear plane. In the shear plane, steel tube was deformed, there was obvious swelling, buckling, folding, but steel tube was not cracked. Deformation of steel tube enhanced the ductility of thin-walled components, and delayed the reduction of bearing capacity. With the decrease of confining factor $\theta$, component deformation became more and more obvious when failure, sustained load in the creep stage became small gradually, but its deformation was growing, showing that component ductility was weakened gradually.



0KN 613.09 KN 619.14KN 612.95KN 561.88 KN 495.72 KN 396.1 KN

**Figure 2.** Map of failure pattern of axially-compressed short column loading

$d$=25.52% $\theta$=0.652 | $d$=21.83% $\theta$=0.499 | $d$=36.62% $\theta$=0.404 | $d$=49.30% $\theta$=0.323 | $d$=52.60% $\theta$=0.413

**Figure 3.** Failure pattern of components with different $\theta$ and corrosion ratios

**4. Impact of Corrosion Ratio on Component Axial Compression Performance**

As lateral steel tube of the component was corroding and the corrosion ratio of the component was increasing, the bearing capacity of the component was on the decline, at the same time, the slope of the component in the nonlinear growth stage was increasing. It shows that after the stage of load deformation linear growth of the component, its deformation rate is accelerated, and the ability of sustained load deformation is weakened after reaching its ultimate bearing capacity, especially when approaching the stage of limit load, its deformation capacity is decreasing with the increase of corrosion ration. After reaching the maximum bearing capacity, in the descending stage, the slope is increasing, namely, sudden deformation occurs in the component, resulting in unloading, but the component do not completely lose its bearing capacity. With the increase of corrosion ratio, the sustained load value of creep deformation of the component is reduced. See Table 2 for geometrical parameters of corroded components. Figure 4- Figure 8 shows the map of load deformation of components with different wall thickness and corrosion ratios.

**Table 2. Parameter table of corroded component**

| Member No. | D/t | $\theta$ | Corrosion Ratio | $N_0$(KN) | ΔN | ΔN/ $N_0$ | 1-ΔN/ $N_0$ |
|---|---|---|---|---|---|---|---|
| CSCC1-1 | 151.09 | 0.407 | 0 | 648.8 | 0 | 0 | 1 |
| CSCC1-2 | 195.18 | 0.315 | 22.83% | 563.7 | 85.1 | 13.12% | 86.88% |
| CSCC1-3 | 293.83 | 0.208 | 48.91% | 505.6 | 143.2 | 22.07% | 77.93% |
| CSCC5-1 | 97.89 | 0.63 | 0 | 749.7 | 0 | 0 | 1 |
| CSCC5-2 | 124.67 | 0.499 | 21.83% | 630.2 | 119.5 | 15.94% | 84.06% |
| CSCC5-3 | 153.29 | 0.404 | 36.62% | 615.0 | 134.7 | 17.97% | 82.03% |
| CSCC5-4 | 191.11 | 0.323 | 49.30% | 552.2 | 197.5 | 26.34% | 73.66% |
| CSCC6-1 | 72.40 | 0.866 | 0 | 931.9 | 0 | 0 | 1 |
| CSCC6-2 | 96.51 | 0.652 | 25.52% | 780.4 | 151.5 | 16.26% | 83.74% |
| CSCC6-3 | 123.77 | 0.505 | 42.19% | 664.0 | 267.9 | 28.75% | 71.25% |
| CSCC6-4 | 150.53 | 0.413 | 52.60 | 619.1 | 312.8 | 33.57% | 66.43% |

Note: $N_0 = 0.9A_c f_c(1+\alpha\theta)$

$$\theta = \frac{A_a f_a}{A_c f_c}$$

$\alpha$ - Coefficients related to concrete strength grade;
$t$ - Outer diameter of steel tube;
$t$ - Wall thickness of steel tube;
$A_c$ - Cross sectional area of core concrete in steel tube;
$f_c$ - Design value of axial compressive strength of core concrete;
$A_a$ - Cross sectional area of steel tube;
$f_a$ - Design values of tensile and compressive strength of steel tube;
$\Delta N$ - Difference between the maximum bearing capacity of non-corroded components and that of corroded components in the same structure.

Compared with non-corroded thin-walled components, components with a large wall thickness clearly showed strong plastic deformability (e.g. CSCC6-1). With the decrease of wall thickness, the components' maximum bearing capacity and ductility after the components reached the maximum bearing capacity was significantly changed. After thin-walled components reached the ultimate bearing capacity, there were obvious rapid unloading and sudden increase of deformation (CSCC1-1,CSCC5-1), and then the components entered into the stage of load deformation growth, showing obvious characteristics of creep deformation. With the continuous increase of deformation, there was the failure of components.

As for corroded thin-walled components, with the increase of corrosion ratio, the wall thickness of components became thinner. The thinner the wall thickness of components is, the steeper the N-mm curve descending stage is, namely, loads drop suddenly and fastly, showing that steel tube has a weak confinement effect on concrete deformation.

After compared with corroded thin-walled components CSCC6-3, CSCC1-3, CSCC5-2 and CSCC5-4, it was found that all tests of thin-walled components showed the characteristic, namely, after reaching the maximum bearing capacity, the components' bearing capacity was on the decline, as shown in Figure 5, Figure 6 and Figure 7. The diameter-thickness ratio and confining factor of component CSCC6-1 are in the allowable range of the *Technical Specifications for Concrete-Filled Steel Tubular Structures* (CECS28-2012), not in the thin-walled category, and its N-mm curve presented severe load creep and increase of bearing capacity of components made of similar steel materials.

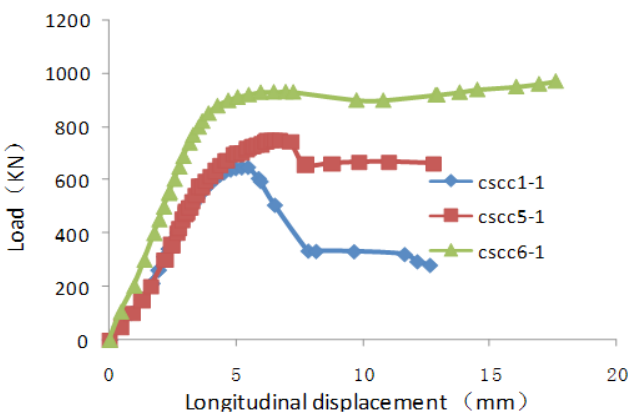



**Figure 4.** Influence of wall thickness on bearing capacity

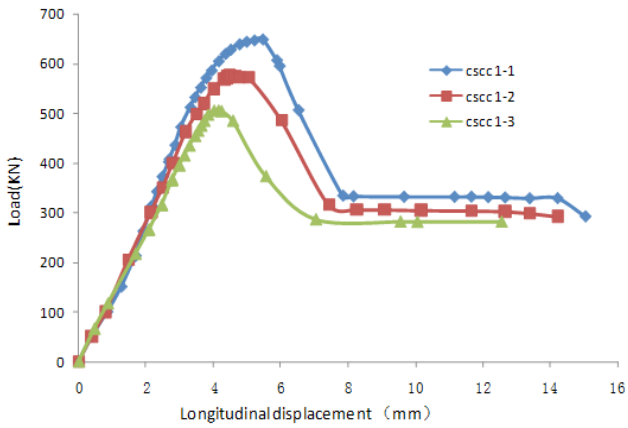



**Figure 5.** Longitudinal displacement diagram for bearing capacity of CSCC1 series of corroded components

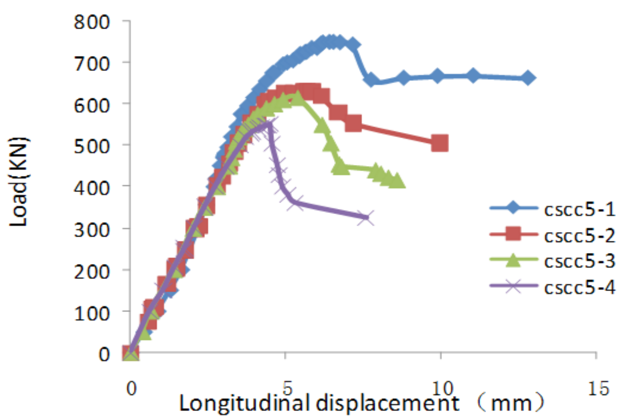



**Figure 6.** Longitudinal displacement diagram for bearing capacity of CSCC5 series of corroded components

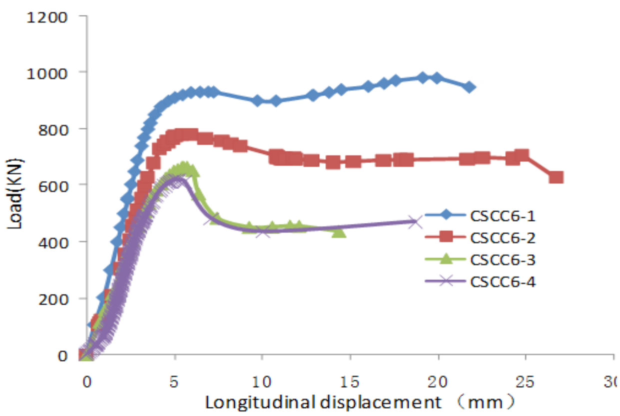
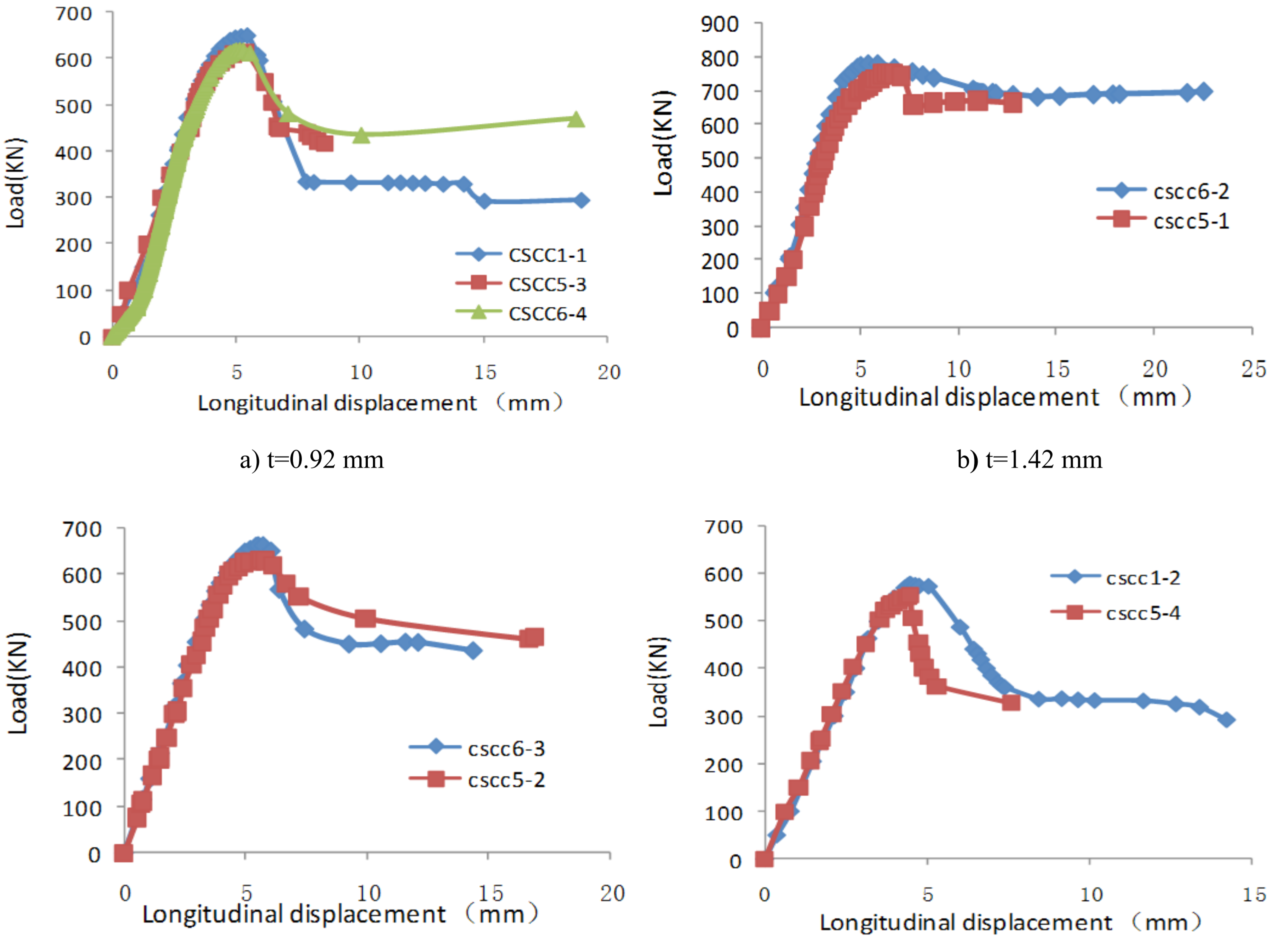



**Figure 7.** Longitudinal displacement diagram for bearing capacity of CSCC6 series of corroded components

For bearing capacity and vertical deformation of corroded components with similar wall thickness. It can be seen from the figure that after the component was corroded, loading of steel tubes with the same wall thickness basically fits the curve of vertical displacement, and the difference is that after reaching the maximum bearing capacity, the component had a different unloading process. Steel tube components with an initial wall thickness had a gently-unloading process, and high sustained loading in the stage of sustained loading deformation. As shown in Figure 8 a), sustained loading value of CSCC6-4 is higher than that of CSCC1-1 and CSCC5-3, and is gentle in the unloading stage.

Relative to non-thin-walled components, axial compression bearing capacity of thin-walled components was on the decline with the increase of corrosion ratio. After accelerating the corrosion of components with a wall thickness of 0.92, its D/t was increased from 151.09 to 151.18 and 293.83, and its increasing proportions was respectively 29.18% and 94.47%; the corrosion rates of the component were 22.83% and 8.91%, and its ultimate bearing capacity was decreased respectively by 13.12% and 22.07%. After electrically corroding components with a wall thickness of 1.42, its D/t was increased from 97.89 to 124.67, 153.29 and 191.11, its increase rates were 27.36%, 56.59% and 95.23% respectively, and the components' corrosion rates were respectively 21.83%, 36.62% and 49.30%, and its ultimate bearing capacity was decreased by 15.94%, 17.97% and 26.34% respectively. After electrically corroding components with a wall thickness of 1.92, its D/t was increased from 72.40 to 96.51, 123.77 and 150.53, its increase rates were 33.30%, 70.95% and 107.91% respectively, and the components' corrosion rates were respectively 25.52%, 42.19% and 52.60%respectively, and its ultimate bearing capacity was decreased respectively by 16.26%, 28.75%, 33.57%.

Tests show that even if the D/t exceeds the limiting value stipulated in *Technical Specifications for Concrete-Filled Steel Tubular Structures* (CECS28-2012), thin-walled concrete-filled steel tubular column still has the ductility, and the difference is that the component's ductility is decreasing gradually with the increase of D/t, the shorter the stage of nonlinear deformation is, the more the slope is. After reaching the ultimate bearing capacity, the unloading velocity is increasing gradually, and the unloading ratio is increasing.




a) t=0.92 mm

b) t=1.42 mm

(a) t=1.11 mm

(b) t=0.71 mm

**Figure 8.** Longitudinal displacement diagram for bearing capacity of corroded components with a similar wall thickness

Figure 9- Figure 11 show the load-strain diagram of steel tube, and strain changes recorded two stages which steel tube underwent, namely, elastic deformation and plastic deformation. From Figure 8 and Figure 9, it can be seen that with the decrease of wall thickness, the component's longitudinal strain was increasing with the increase of loading, and the bearing capacity corresponding to the stage of plastic deformation was decreasing; with the increase of corrosion ratio, the component's transverse strain under the same load was increasing gradually, showing that squeezing action of concrete for steel tube become early.

From the point of test data, the component's early linear deformation grew slowly, and its linear deformation grew sharply in the medium-term. The component transferred stress from end plate to steel tube and concrete. End plate and steel tube were welded together for the reason of construction, so linear deformation happened in steel tube starting from being loading, earlier than that in concrete. In the meantime, concrete deformation was less than that of steel tube, without squeezing steel tube, so the component's load deformation was mainly from steel tube; with the increase of load, there were cracks inside concrete wall, concrete deformation was more than that steel tube, squeezing steel tube, and both of them started to jointly carry load; at this point, the component was characterized by an interaction of two materials, and component rigidity was increased.

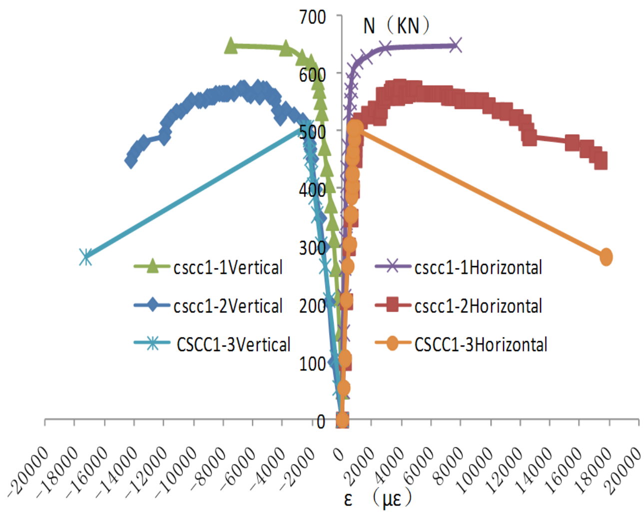



**Figure 9**. Load-strain diagram for CSCC1 steel tube

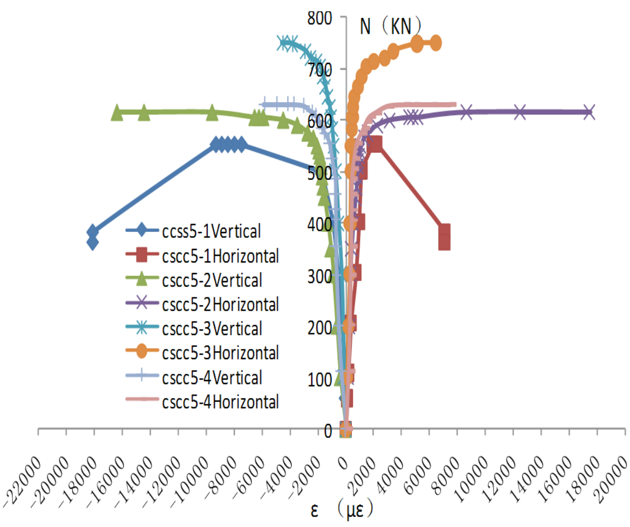



**Figure 10.** Load-strain diagram for CSCC5 steel tube

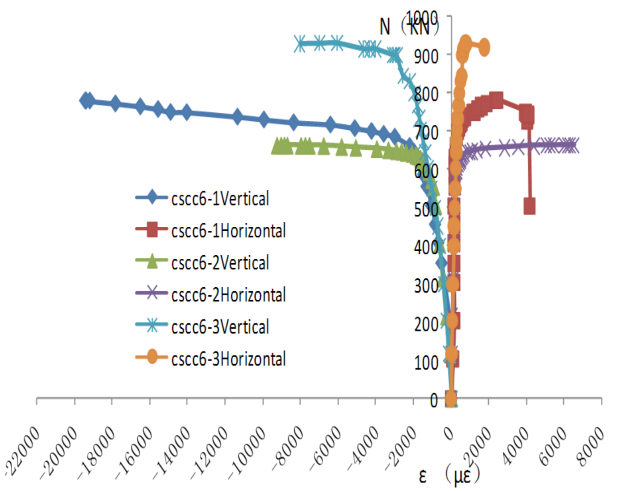



**Figure 11.** Load-strain diagram for CSCC6 steel tube

**5. Working Process of Axially-Compressed Short Column of Thin-walled Concrete-filled Circular Steel Tube**

Han Linhai [5] calculated the typical axial compression σsc-ε relation curve of concrete-filled circular steel tubular column on the basis of finite elements. In this paper, combined with the deformation process diagram and analysis of N-mm chart, the working process of axially-compressed short column of thin-walled concrete-filled circular steel tube is analyzed as below:

The first stage is the stage of linear growth of steel tube under stress, where end plate is unable to completely fit and work together with concrete, and end plate and steel tube are welded together, so steel tube has to first carry external load. The second stage is the stage of linear growth of the interaction of steel tube and concrete, with the increase of load, the component's end plate and concrete are closely contacted

At this time, concrete and steel tube are jointly stressed, and the component shows its characteristics of composite material, namely, its stiffness is significantly more than that of pure steel tube. The third stage is the stage of nonlinear growth, where concrete and steel tube interact after there are cracks in concrete; with the continuous growth of cracks in concrete, circumferential and radial stress received by steel tube are increasing, steel tube is still in the elastic stage, but there is no yield plastic deformation, and its confinement effect on concrete is still kept. Due to the growth of cracks in concrete, its squeezing action on steel tube is enhanced continuously, when reaching the maximum bearing capacity, nonlinear deformation starts to happen in the component. The fourth stage is the stage of deformation load shedding after exceeding the limit load; after that, cracks in concrete grow continuously, and continue to squeeze steel tube, especially, the maximum stress point of steel tube (relative to the weakest point) is deformed seriously, providing favorable conditions for the component's failure surface. When the confinement effect of steel tube is less than the squeezing action of concrete on it, cracks in concrete grow continuously, so deformation of external steel tube suddenly increases, and the component's bearing capacity suddenly drops. The fifth stage is the creep stage of sustained load deformation; after that, internal concrete is piled again, and the component is still able to carry a certain amount of external load, thus the creep stage of sustained load deformation is formed. The sixth stage is the failure stage, with the continuous growth of component deformation, constraint force of external steel tube on internal concrete is reducing gradually, and the component begins to lose bearing capacity with the increase of deformation.

Test results show that as a combination of two materials, concrete-filled steel tube materials gave full play to the characteristics of each material, showing strong ductility under the conditions of static-load axial compression test, and there were linear growth and nonlinear growth deformation in the stage of load growth (see Figure 4- Figure 10). In this paper, according to test results, the limiting bearing value of axially-compressed short column of corroded thin-walled concrete-filled circular steel tube should be taken at the end of linear growth, and the stage of nonlinear growth deformation is considered as the stage of emergency capacity and overload warning. Thus, it can make full use of material properties of thin-walled circular steel tubular column, and guarantee normal use of security components and structure.

**6. Conclusions**

1. Serious corroded parts of thin-walled steel tubular component are in its weak position; after steel tube is corroded, with the increase of corrosion thickness, the component's bearing capacity will be decreased and its ductility is weakened. After reaching the maximum bearing capacity, sudden drop of bearing capacity similar to brittle failure will happen in thin-walled components, deformation suddenly increases along with sudden drop of bearing capacity, but its entire stage of bearing capacity decline is different from that thick-walled concrete-filled steel tube and that of plain concrete material.

2. Failure pattern and mechanism of short thin-walled concrete-filled circular steel tubular column are different from those of thick-walled components, especially, in the early stage of loading, steel tube is stressed but not enter the plastic state, namely, starting to work together with concrete. Two materials show a good collaborating effect, and strong bearing capacity during the working period of jointly being stressed, and the component's sustained load deformation ability is gradually weakened with the reduction of steel tube wall thickness.

3. Failure pattern of thin-walled concrete-filled circular steel tubular column is different from that of thick-walled components, and is typical shear failure. Shear deformation increases after or when reaching the maximum bearing capacity. Concrete continues to crack, and the confinement action of steel tube on concrete constraint is relatively weakened, resulting in the increase of shear deformation.

4. For short thin-walled concrete-filled circular steel tubular columns, it is suggested that its $N_0$ value is set the end of elastic deformation and the start point of nonlinear deformation under the combined action of steel tube and concrete, which is conducive to making full use of its bearing capacity and rigidity, ensuring its bearing capacity.

**Acknowledgements**

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**References**

1. Zhong Shantong (2003) *Steel tube concrete structure, Third Edition*, Beijing, Tsinghua University press.

2. Cai Shaohuai (2002) Recent Development of Steel Tube Confined High Strength Concrete Structures in China. *Building science*, 18(4), p.p.1-7.
3. Yang Jie (2008) Research and development of steel tube concrete. *Engineering Structure*, 25, p.p.174-175.
4. Xu Chengxiang, Zhu Chang'an, Xu Shuzhen (2009) Experimental research on concrete-filled square thin-walled steel tubular stub columns with steel bar stiffeners. *Journal of Building Structures*, 2009(S2), p.p.231-236.
5. Han Linhai (2007) *Theory and practice of concrete filled steel tubular structure*, Beijing, Science Press.
6. Zhan Meisen (2007) *Research on Behaviour of Concrete-Filled Thin-Walled Steel Tube under Axial Compression*, Nanchang University
7. Zhang Yaochun, Wang Qiuping, Mao Xiaoyong, Cao Baozhu (2005) Research on Mechanics Behavior of Stub-column of Concrete-filled Thin-walled Steel Tube Under Axial Load. *Building Structure*, 35(1), p.p.22-27.
8. Gao Jianping, Wu Yonggen, Huo Jingsi (2012) Experimental study on the hysteretic behaviors of thin-walled corrugated concrete-filled steel tube column. *World Earthquake Engineering*, 28(3), p.p.34-34
9. Cao Baozhu, Zhang Yaochun (2004) Limit of width-thickness ratio of steel plates in concrete-filled square thin-walled steel tube columns. *Journal of Harbin Institute of Technology*, 36(12), p.p.1713-1716.
10. Chen Bo, Hao Zhe, Bai Huiwen, Zhao Yingna (2014) Corrosion Types under Different Conditions of Stainless Steels and the Present Research Status. *Total Corrosion Control*, 28(7), p.p.15-19.
11. A.V.Shanbhag, T.V.Venkatesha, B.M.Praveen, S.B. (2014) Abd Hamid,Inhibition Effects of Chloroquinolines on Corrosion Of Mild Steel in Hydrochloric Acid Solution. *Journal of Iron and Steel Research*, 21(8), p.p.804-808.

# Decision Rule Extraction for Maritime Accidents in Inland Rivers Based on Rough Set

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