Behavior of Curved Concrete-Filled Circular Stainless Steel Tubular Struts under Compression

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Abstract—A finite element analysis (FEA) model for curved concrete-filled stainless steel tubular members under compression was developed by the universal FEA software ABAQUS. The failure modes of curved concrete-filled stainless steel tubular struts were compared with that of empty curved stainless steel tubes and curved concrete-filled steel tube. And the behavior of the curved composite members was analyzed. This paper analysis the relation of Load and Mid-Span Deflection of curved concrete-filled stainless steel tubular with the change in degree of bending. The results show that the numerical analysis is in good agreement with the experimental results and the analytical solution. The concrete filled stainless steel tubular columns have good ductility and stability due to the interaction between stainless steel tube and concrete. The curved concrete-filled steel tubular members have a higher flexible capacity. With the increase of bending degree, the slope of load and Mid-Span Deflection curve is becoming smaller.

Keywords—curved circular concrete-filled stainless steel tubes; compression behavior; initial deflection; finite element analysis

I. INTRODUCTION

Curved concrete filled stainless steel tubular (CCFSST), which is formed by pouring the concrete in curved hollow stainless steel tube, is believed to have great potential to apply in large-span structures not only for excellent structural properties and corrosion resistance but also for aesthetic appeals.

In the past, a large number of studies have been carried out on traditional straight concrete filled steel tubular (CFST) columns [1-4] and straight concrete filled stainless steel tube (CFSST) [5-9], however, very limited research has been conducted on curved CFSST subjected to compression or bending. As there are obvious differences between the properties of steel and stainless steel, and the curved axis of the member, there is a need to study the behavior of CCFSST members.

A finite element model (FEM) is developed to perform a mechanism analysis of CCFSST members subjected to axial compression in this paper, the failure models, load versus deflection curves and strain development are presented and discussed.

II. FINITE ELEMENT MODEL

A finite element analysis (FEA) model for curved concrete-filled stainless steel tubular members under compression was developed. As shown in Figure 1, u_0 is the

initial bending of the cross section of the curved bar and L is the specimen length. By defining different "sweep" path, the geometry of CCFSST was considered. The end part of the specimen was provided with a rigid end plate to make the stainless steel tube and concrete loaded together.

The 4-noded doubly curved shell elements with reduced integration S4R was used to model the buckling behavior of the stainless steel tube. Fine mesh of three-dimensional 8-Node solid elements (C3D8R) was used to model the core concrete and rigid end-plate. Material modeling of stainless steel tubes was taken as corrected by Rasmussen(2003) [10]. The damage plasticity model provided in the material library of ABAQUS was used for the core concrete in the analytical model. To simulate the core concrete under uniaxial compression, an equivalent stress-strain model had been proposed by Han et al [11]. The yield stress-cracking strain was for the tensile behavior of core concrete under the influence of tensile force. The contact between the stainless steel tube and the concrete was modeled by interface elements. The top and bottom surfaces of the concrete and rigid end plate also used "Tie" constraints. Normal contact between the stainless steel tube and the concrete used "hard" contact. Tangential bond slip between the two faces used Coulomb friction. The coefficient of friction between the two faces was taken as 0.25 in the analysis. The interface element only allowed the surfaces to separate but was not allowed to penetrate each other.

The load was applied as static uniform load using the displacement control at the center line of the loaded surface. The center lines of the top and bottom surfaces of the CCFSST were restrained against the displacement in X、Y、Z directions, except for the displacement in X direction at center line of one loaded end, as shown in Figure 1.

FIGURE I. BOUNDARY CONDITIONS FOR FEM MODEL OF CCFSST UNDER COMPRESSION

III. MODEL VERIFICATION

A comparison between the experimental results and finite element results was carried out to verify the finite element model. The load N versus additional lateral deflection at mid-height u_m curves was obtained from the tests (Uy[9],Zheng[12]) and finite element analysis (FEA). The experimental load-axial behavior (solid line), which are some specimen from Uy[9] and Zheng[12], is compared with the numerical prediction(dotted line). It can be seen that good agreement has been achieved between both results for most experimental results.

- (a)- c1-1a - $D \times t \times L$ (mm)= 113.6 $\times$ 2.8 $\times$ 485(mm), f_y =288.6MPa;
c1-2a - $D \times t \times L$ (mm)= 113.6 $\times$ 2.8 $\times$ 1540(mm), f_y =288.6MPa;
c1-3a - $D \times t \times L$ (mm)= 113.6 $\times$ 2.8 $\times$ 2940(mm), f_y =288.6MPa;
(b)- c2-1a - $D \times t \times L$ (mm)= 101 $\times$ 1.48 $\times$ 440 (mm), f_y =320.6MPa;
c2-2a - $D \times t \times L$ (mm)= 101 $\times$ 1.48 $\times$ 1340 (mm), f_y =320.6MPa;
c2-3a - $D \times t \times L$ (mm)= 101 $\times$ 1.48 $\times$ 2540 (mm), f_y =320.6MPa;
(c)-C-1-1-c - $D \times t \times L$ (mm)= 114 $\times$ 2.74 $\times$ 580 (mm), f_y =310MPa; u_0 =7.5mm;
C-1-2-c - $D \times t \times L$ (mm)= 114 $\times$ 2.4 $\times$ 580 (mm), f_y =270MPa; u_0 =15mm;
(d)-C-2-2-c - $D \times t \times L$ (mm)= 114 $\times$ 2.74 $\times$ 1720 (mm), f_y =310MPa; u_0 =15mm;
C-2-3-c - $D \times t \times L$ (mm)= 114 $\times$ 2.4 $\times$ 1720 (mm), f_y =310MPa; u_0 =30mm;

FIGURE II. COMPARISON OF EXPERIMENTAL AND FINITE ELEMENT ANALYSIS OF N-UM CURVES FOR SPECIMEN. (f_{cu} =45MPa)

Figure 2 compares the finite element analysis of $N-u_m$ curves with typical measured curves presented previously in [9,10]. u_0 is the initial bending of the cross section of the curved bar, D is the outer diameter of CFSST, t is the thickness of the stainless steel tube, f_y is the stainless steel tube yield stress, f_c is cubic compressive strength of concrete. Due to the limit of this paper, the test result of six specimens from Uy is compared. As shown in Figure 2, the model is good for the CFSST under compression. It can be seen the load of the columns decrease as the L/D and u_0/L increasing, but the decreasing rate becomes slower. The corresponding mid-span deflection by maximal load is increasing as the L/D and u_0/L increasing.

The predicted ultimate strengths N_{uc} are compared with those obtained from tests (N_{ue}) in Figure 3. In [9, 12,13,14], N_{ue} was taken a same value as the maximum or first peak load. A mean ratio (N_{uc} / N_{ue}) of 1.0016 is obtained with a standard deviation of 0.051.

FIGURE III. COMPARISON BETWEEN PREDICTED AND EXPERIMENTAL ULTIMATE STRENGTH

IV. MECHANICAL PROPERTY ANALYSIS

The CFSST under compression is adopted by the finite element analysis model. The curve form of the specimens is arc. The parameters of typical model are defined. D =400mm, t =9.31mm, L =4000mm, f_y =345MPa, f_{cu} =60MPa. The models of the coefficient of bending- u_0/L have 0、0.025、0.05 and 0.1.

FIGURE IV. FAILURE MODELS

A. Failure Models

Figure 4 gives failure models of curved concrete-filled stainless steel, curved concrete-filled steel and curved stainless steel. To be viewed clearly, all the deflection from them is magnified 5 times. As can be seen from the figure, the curved stainless steel is not supported by core concrete so that there is obvious invagination phenomenon on the most unfavorable concentrically loaded cross section at the first. And the plastic buckling is developed rapidly on the section, and the local buckling is obvious. The buckling of the curved concrete-filled stainless steel is developed slowly due to the concrete. Because of the expanding plastic area of mid-span, the deformation resistance and bearing capacity of the curved CFSST both are higher. At the same time, the failure model of curved concrete-filled stainless steel is similar to curved concrete-filled steel's. They are neither obvious invagination. The additional lateral deflection of the curved CFSST at mid-height is larger than the curved CFST. Therefore, the

ductility of the curved CFSST is better.

B. Mechanism of Axial Compression

Typical load (N) versus mid-height additional lateral deflection (u_m) curves are presented in Figure 5. The dotted line represents the curved CFST. The steel has yield when curved CFSST's ultimate strength has not been reached. Thereafter, the axial loads of stainless steel will no longer increase. But the circumferential stress grows rapidly after the stainless steel has yield. Then the stainless steel will bring binding force on the core concrete. Longitudinal bearing capacity of concrete in compression area becomes higher due to binding the force. $N-u_m$ curves of curved CFSST still maintain an upward trend. At the same time, ultimate strength of the concrete has not been reached. The core concrete enters the softening section with the increase of axial load. The concrete reach ultimate strength after the curved CFSST reach peak load. The curved CFSST in working mechanism is similar to the curved CFST. Because of the better ductility of the stainless steel, the curved CFSST in constraint effect is better than the curved CFST. So the load of the curved CFSST has been greater since the interaction between the stainless steel tube and concrete begins. Since then the load is always greater than the curved CFST. In addition, plastic hinges are formed at the mid-section after the stainless steel tube appears internal concave phenomenon due to lack of concrete support. The bearing capacity drop suddenly. It indicates the stainless steel tube is not as good as the curved CFSST in resisting deformation ability.

FIGURE 5. LOAD (N) VERSUS MID-HEIGHT ADDITIONAL LATERAL DEFLECTION (u_m) CURVES ($u_0/L=0.025$)

In order to discuss conveniently, three feature points are selected. The maximum fiber stress pressure of the stainless steel tube runs up to the limit of ratio at A point. The load reaches peak load at B point. The load falls to 85% of the ultimate load at C point. $N-u_m$ curves have the following characteristics:

Elastic stage (OA): The stainless steel tube and core concrete is in elastic stage in this phase. The interface contact stress is very small between them. Most of the cross section is under compression. The maximum fiber stress pressure of the stainless steel tube runs up to the limit of ratio at A point. Maximum longitudinal compressive stress is $0.48f_c'$ in the section of middle span. (f_c' is compressive strength of concrete cylinder).

Elastic- plastic stage (AB): The plastic in compression area of mid-span section develop continuously after A point. The non-uniform interface contact stress between the stainless steel tube and core concrete increases. The curved CFSST is in elastic- plastic. The neutral axis of mid-span section moves to the centroidal axis gradually. The load reaches peak load at B point. The plastic in mid-span section of stainless steel begins to develop. The mid-span section is entering reinforcement. The longitudinal compressive stress of concrete is increasing rapidly. The value is $1.03f_c'$. Then the strength of concrete has improved due to interface between the stainless steel tube and core concrete. As it is shown in Figure 6, the stress distribution rule of section is essentially in agreement with the curved CFST. But the value of the stress is different, the curved CFSST is 61.88MPa and it is larger than the curved CFST whose stress is 58.69MPa. So the peak load of the curved CFSST is higher.

Descending stage (BC): Descending stage of $N-u_m$ curves is coming due to the influence of the two order effect. The neutral axis of mid-span section moves to the centroidal axis continuously. The plastic in mid-span section of stainless steel develop inward constantly. The area of compression zone increased significantly. The maximal value of the longitudinal compressive stress is $1.15f_c'$. It can also be seen from the figure, the load of the curved CFSST is larger in compressive stress at the whole stage. It shows that the bearing capacity of curved CFSST is better.

FIGURE 6. THE LONGITUDINAL STRESS DISTRIBUTION OF THE CORE CONCRETE(S11)

C. Influence of Different Bending Degree

Figure 7 gives $N-u_m$ curves of concentrically loaded curved CFSST with different initial deflection. As it can be seen, because of the influence of bending moment on the cross section, the mid-span deflection which is corresponding to peak load is increasing with the increase of curvature

coefficient. But the bearing capacity of concentrically loaded curved CFSST drops. Later the better ductility of stainless steel is, the slower descending segment of $N-u_m$ curves is.

FIGURE VII. N-UM CURVES OF CONCENTRICALLY LOADED CURVED CFSST WITH DIFFERENT INITIAL DEFLECTION

Figure 8 gives the longitudinal stress distribution in the core concrete section of curved concrete-filled stainless steel tubular member with different u_0/L . The figure shows that all mid-section of the core concrete is under compression, there is no tension area when the curvature coefficient is small. This behavior is the result of combined effect of axial force and bending moment. It appears tension area with the increase of curvature coefficient when the load is up to the maximum. And the tension area becomes larger. The influence of bending moment is more obvious, the peak load is lower.

FIGURE VIII. THE LONGITUDINAL STRESS DISTRIBUTION IN THE CORE CONCRETE SECTION OF CFSST TUBULAR MEMBER WITH DIFFERENT U_0/L

V. CONCLUSION

(1) A finite element analysis (FEA) model for curved concrete-filled stainless steel tubular members under compression has been developed by the software ABAQUS. The comparison between the finite element results and the experimental results of the columns with different initial deflection shows good agreement in predicting the behavior and strength of the columns.

(2) There is obvious invagination phenomenon on the stainless steel tube under concentrically loaded. But the curved CFSST has good ductility because of the interaction with stainless steel and concrete during the whole loading process. When compared with the curved CFST, the curved CFSST is higher in bearing capacity and is slower in the descending segment of $N-u_m$ curves, and it can't be seen obvious buckling.

(3) The maximal load of the curved CFSST is decreasing with the increase of the curvature coefficient and slenderness ratio.

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