The Ultimate Load-Carrying Capacity of a Thin-Walled Shuttle Cylinder Structure with Cracks under Eccentric Compressive Force

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***Abstract* — The eccentric compression thin-walled shuttle cylinders structure is introduced, and elastic eigenvalue buckling of this kind of column with circumferential cracks is numerically simulated by the finite element method (FEM). Besides, based on the numerical results, ultimate load-carrying capacity analysis of eccentric compression thin-walled shuttle cylinders structure with cracks was studied in which geometric nonlinearity is included. The influences of some parameters, including the crack length, eccentricity, slenderness ratio and tapering ratio of thin-walled shuttle cylinders structure, have been taken into consideration. The results show that the ultimate load carrying capacity and the stability behavior can be improved by increasing the tapering ratio or decreasing slenderness ratio, eccentricity and crack length. And they also show that the eccentricity has a relationship with the influence of the crack length on stability behavior, that is, the ultimate load-carrying capacity is improved by decreasing the crack length only when the eccentricity is less than a certain value. Otherwise, when an eccentricity is larger than a certain value the crack length will have no effect on the ultimate load -carrying capacity of structure.**

Key words — thin-walled shuttle cylinders structure; ultimate load-carrying capacity; eccentric compressive; circumferential crack

I. INTRODUCTION

With the rapid development of economy, more and more thin-walled buildings are built. And the shuttle cylinders structures are widely adopted because of their high load-carrying capacity, good stability behavior, light weight and beautiful appearance. However, cracks, which may make the weak part of the structure fragile, are inevitable in the thin-walled structures because of the producing process of materials, welding or bad working environment. So the research on ultimate load-carrying capacity of thin-walled shuttle cylinders structure with cracks is essentially necessary, and the quantitative analysis of cracks on the structure and components are not taken into considered in current engineering design theory and method. So the thin-walled cylinders structure with cracks attracts more and more scholars' attention in recent years. EI Naschie[1] researched the influence of crack on the ultimate load of cylindrical shells. Dyshel[2] studied the impact of circumferential through-wall crack on the instability of the infinite thin wall cylindrical shell by the collocation method. Estekanch and Vafai[3] analysed the factors including crack length and crack direction that affect the stability of cylindrical shells under axial compression and axial tension load by finite element method. Zhou and Huang[4-6] studied the ultimate load-carrying capacity of thin-walled eccentric compression column and axial compression column with single and multiple cracks by using the energy method.

These papers took the impact of crack on the stability behavior of thin-walled structure into account, and draw some conclusions for reference. However, the research work was mainly on the stability of thin-walled cylindrical[7-9] structures. The literatures for the stability of thin-walled shuttle variable cross-section cylinders structure[10-12] only focus on the uncracked construction, and the literatures for the stability of thin-walled shuttle cylinders structure with cracks are rare.

In this paper, the stability of eccentric compression thin-walled shuttle variable cross-section cylinders structure is studied by using FEM. Elastic eigenvalue buckling of the thin-walled shuttle cylinders structure is numerically simulated. The buckling loads and the influences by the crack length, eccentricity, slenderness ratio and tapering ratio are obtained. And the ultimate load carrying capacity analysis of eccentric compression thin-walled shuttle cylinders structure with cracks is also studied.

II. THE FINITE ELEMENT MODEL OF THIN-WALLED SHUTTLE VARIABLE CROSS-SECTION CYLINDERS STRUCTURE

The model in this paper of thin-walled shuttle variable cross-section cylinders structure under eccentric compression load is shown as Figure (1). Two ends of the column are by hinge joints, and assume that, the length of the column is L, the end cross-section radius is d_0,the middle cross-section radius is d, tapering ratio $\gamma = d/d_0 - 1$, the range of tapering ratio γ=0.0~1.0, the thickness wall is t, the load is working on the longitudinal symmetric plane of the thin-walled column, z axis crosses through the section centroid, load P acts from the cross-sectional shape of the mandrel position e, where e

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is eccentric distance, the deformation of the column is linear, elastic and small.

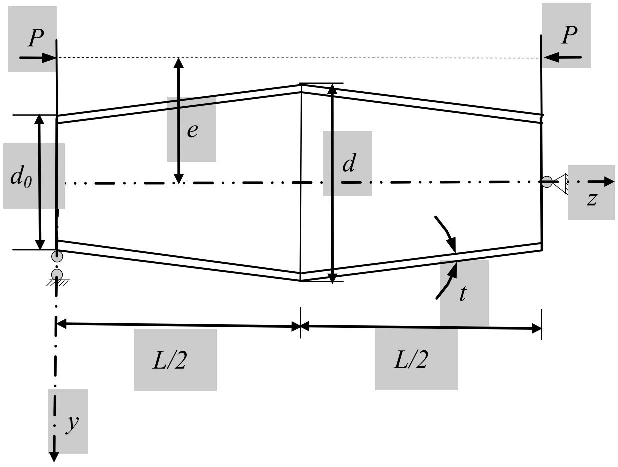

Fig.1 Thin-Walled Shuttle Cylinders Structure With Crack Under Eccentric Compression

The cracks are symmetrical on the cross-section and perpendicular to the z axis, x axis and y axis as shown in figure(2), and the crack located in the tension side of the column. The crack is open under eccentric compressive force. The cross section with crack is shown in figure (2), and we use angle θ to express the length of the crack.

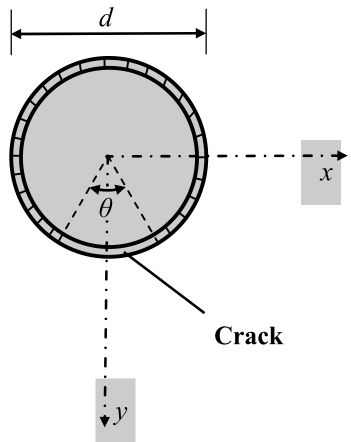

Fig.2 Cross Section With Crack

The finite element model of eccentric compression thin-walled variable cross-section cylinders structure with crack is established by ANSYS. A quarter-model is adopted due to the symmetry of the column, as shown in Figure (3).

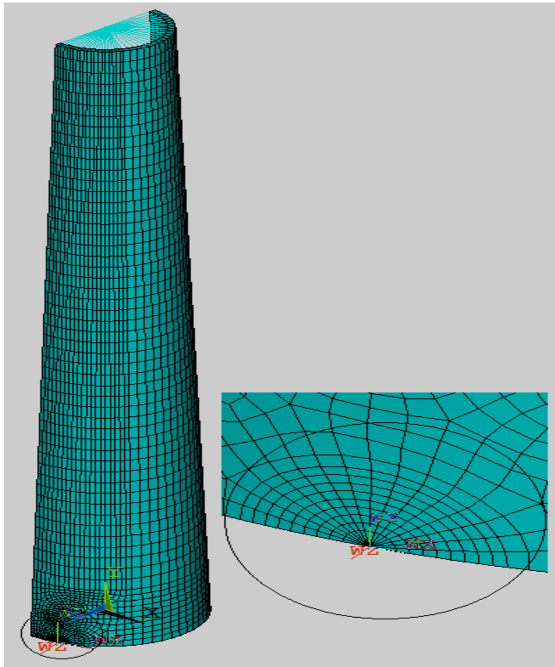

Fig.3 Finite Element Model of Thin Walled ShuttleCylinders Structure

APDL programming language used. The load in the paper are eccentric, which are equivalent to axial compressive loads and bending moments. The model cross section is hollow, so MPC184 units are employed to form a rigid beam.Because stress field of crack front is singular in $r^{-1/2}$ order and the cracking endpoint is discontinuous, the middle nodes in the unit are moved to the location a quarter of original length to the front edge when using the three-dimensional solid elements solid45 and solid95 to calculate. The degraded solid95 unit is adopted for the crack front. As shown in Figure(4), the simulation with the crack front stress singularities and high strain gradient works well.

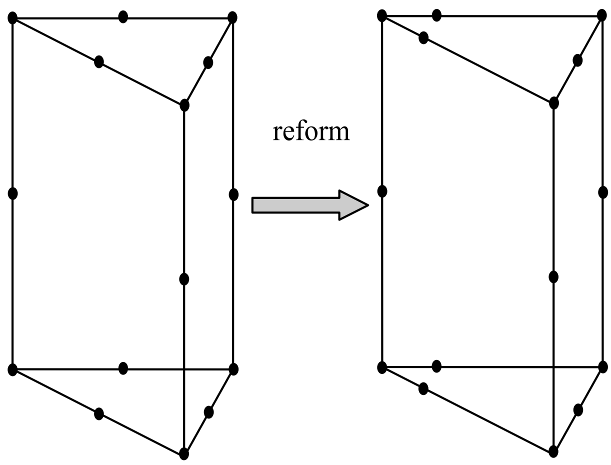

Fig.4 The Element of Crack Front About Before And After The Improvement

III. EIGENVALUE BUCKLING ANALYSIS OF THE THIN-WALLED SHUTTLE CROSS-SECTION CYLINDERS STRUCTURE

First the eigenvalue bucking of a complete thin-walled shuttle variable section cylinders structure of is analyzed by FEM to verify the correctness of the model and the unit used. The numerical results are compared with literature 12 in the Table I. In Table I, dimensionless buckling load $P_{cr}^{*} = P_{cr} / \pi^2 EA_0$ is used, where λ_{eff} is the equivalent slenderness ratio. The relationship between bucking load P_{cr}^{*} and equivalent slenderness ratio λ_{eff} is shown in Table I, where, E is the elastic modulus, A_0 is sectional area of the end portion. The results agree with each other basically.

TABLE I. COMPARISON OF RESULTS IN THIS PAPER AND REFERENCE 12

λ_{eff}	20	40	60	80	100
References12 $P_{cr}^{*}(10^{-5}\text{N})$	250.0	62.5	27.7	15.6	10.0
This paper $P_{cr}^{*}(10^{-5}\text{N})$	256.7	66.6	28.3	17.1	10.6

The eigenvalue buckling of a cracked thin-walled shuttle variable cross-section cylinders structure is analyzed, and the influences by the crack length, eccentricity, the slenderness ratio and wedge rate are studied. The calculation parameters are: end section radius d_0=0.10m, thickness of wall t =0.010m, length L =5m, elastic modulus E =206GPa, Poisson's ratio υ =0.3, the eccentricity $\varepsilon = e/d$,with the range ε =0.25~4.0, crack length at shuttle cross-section $2a$=0 ~ $2b$, the maximum crack length $b = \theta \cdot d/2$, where θ is the central angle corresponding to the half crack length with the range $\theta = 0 \sim \pi/4$, the ratio between crack length and the maximum crack length supposed to be $\xi = a/b$ with the range ξ=0.1~1.0.

(1) The buckling load P_{cr} influenced by the eccentricity ε and crack length ξ . Assume that, the equivalent slenderness ratio $\lambda_{eff} = 40$, wedge rate $\gamma = 1.0$, then the relationship between bucking load P_{cr} and crack length under the different eccentricity is shown in Figure (5), that is, P_{cr} is basically not changed by the crack length when the length of crack at a certain range. However, P_{cr} declines rapidly when the crack length exceeds a certain value. Therefore, there is a range of crack length in which the buckling load is not influenced by the crack length, and the range is decided by the degree of eccentricity.

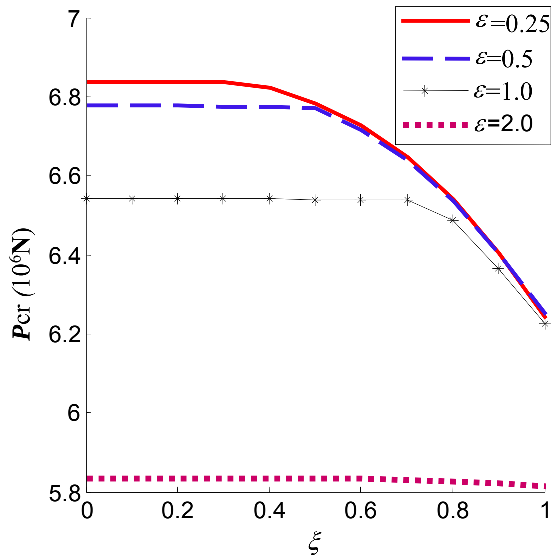

Fig.5 The Curve of Pcr—ξ With Eccentricity

Figure (6) shows how the buckling load is changed by crack length in order to investigate the relation in detail. Figure(6) shows that, P_{cr} decreases when the degree of eccentricity increases while the crack length is constant, and P_{cr} decreases slowly by the degree of eccentricity's increasing when $\varepsilon < 1.0$. However, P_{cr} rapidly decreases almost linearly as the eccentricity ε increases when $\varepsilon > 1.0$ .When $\varepsilon > 2.0$, for all the crack length, the curves of the relationship between bucking load and the eccentricity ε are nearly the same, that is, the crack length almost have no influence to P_{cr} , and the buckling load is no longer controlled by the track length.

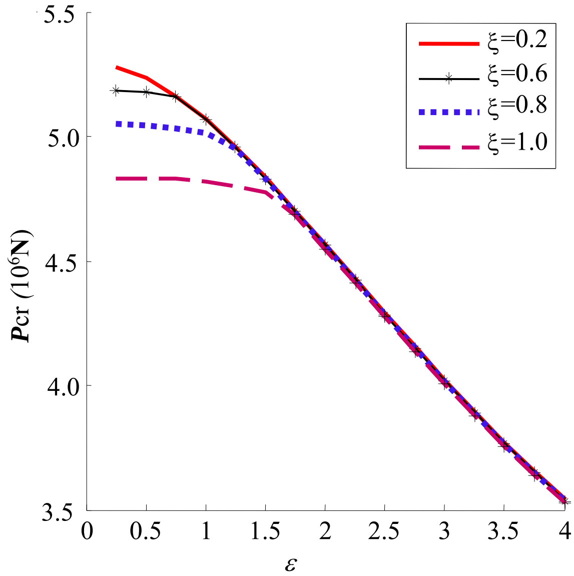

Fig.6 The Curve of Pcr—ε With Crack Length

In summary, the crack length should be kept in a certain range so as to assure that the bucking load P_{cr} will not be reduces in practical engineering. Moreover, the eccentricity should not be too large to avoid reducing the buckling load P_{cr}. At the same time, the buckling load will not be changed with crack length when the eccentricity exceeds a certain value. So attention should be paid in practical engineering that, the buckling load is determined by the interaction of the eccentricity and crack length.

(2) The influence of the buckling load P_{cr} by the wedge ratio γ. Figure (7) shows how the bucking load P_{cr} is changed by the wedge rate γ under the degree of eccentricity $\varepsilon = 2.0$ and the crack length $\xi = 0.6$. It is shown that, the bucking load P_{cr} grows rapidly almost linearly when the wedge rate increases. The wedge rate play a key role when calculating the buckling load, that is, the buckling load when γ=1 is 4 times larger than when γ=0. So the buckling load of a structure can be effectively improved by increasing the wedge rate. Therefore, structure stability performance should be improved by changing the wedge rate in practical engineering applications.

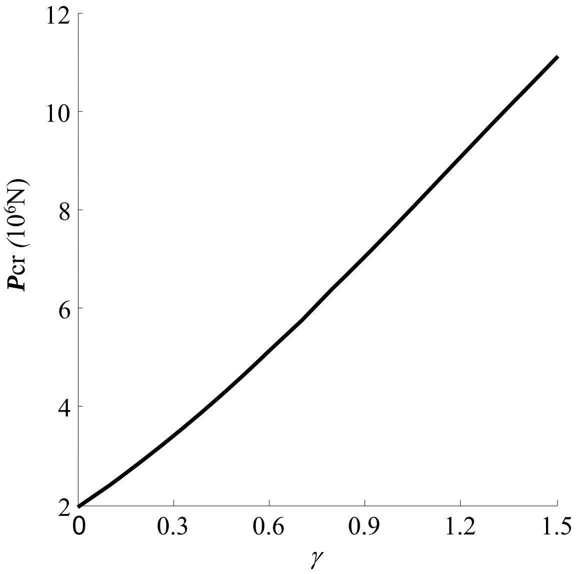

Fig.7 The Curve of *P*cr—γ With Crack Length

(3) The influence of the equivalent the slenderness ratio λ_{eff} on the bucking load P_{cr}. Fig.(8) shows the effect of the equivalent slenderness ratio on the bucking load P_{cr} under the wedge rate γ = 1.0, the eccentricity $\varepsilon = 2.0$,and the crack length $\xi = 0.6$ .It shows that, P_{cr} decreases gradually and the decreasing amplitude also decreases as the equivalent slenderness ratio λ_{eff} increases. So the bucking load can be enlarged by reducing the equivalent slenderness ratio λ_{eff}. Therefore, structural stability can be improved by reducing the equivalent slenderness ratio in practical engineering application.

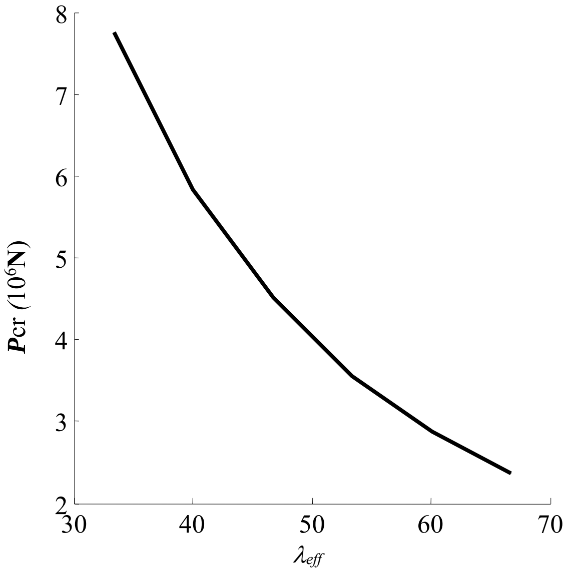

Fig.8 The Curve of *P*cr—λ_{eff} With Crack Length

IV. GEOMETRIC NONLINEAR ELASTICITY STABLE ULTIMATE LOAD-CARRYING CAPACITY

Based on the eigenvalue buckling analysis, the elastic stable carrying capacity of cracked shuttle thin-walled shuttle variable cross-section cylinders structure is studied by introducing the initial geometrical defects. The load-displacement of shuttle thin-walled cylinders structure is simulated by large deflections elastic shell elements, and the linear elastic material is adopted. The effect of different crack length and the slenderness ratio on limit performance and stability of shuttle thin-walled cylinders structure is analyzed by the finite element model of the first-order characteristic model whose initial defect is 1/1000 length of the bar.

Fig.(9) shows the load-displacement curve under different crack length, where the wedge rate γ = 0.5, equivalent the slenderness ratio λ_{eff} =46, and the eccentricity $\varepsilon = 2.0$ .The vertical ordinate is the ratio of the external load to its corresponding characteristic bucking load P/P_{cr}, and the horizontal ordinate is the ratio of column span maximum displacement to the column length δ/L.

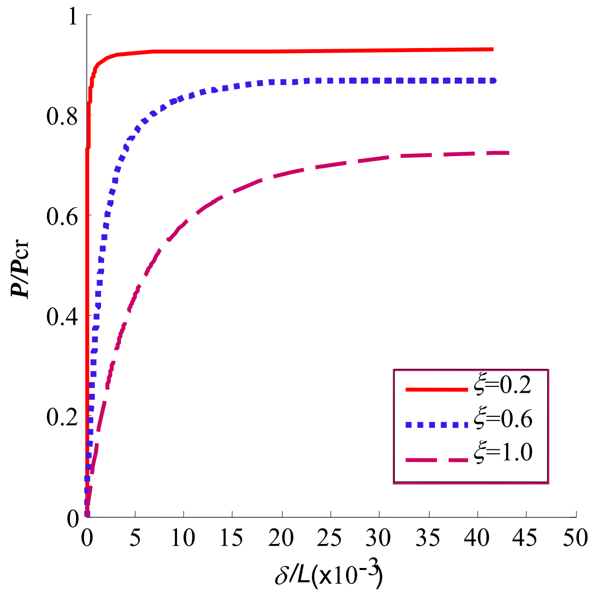

Fig.9 The Curve of Load-Displacement With Crack Length

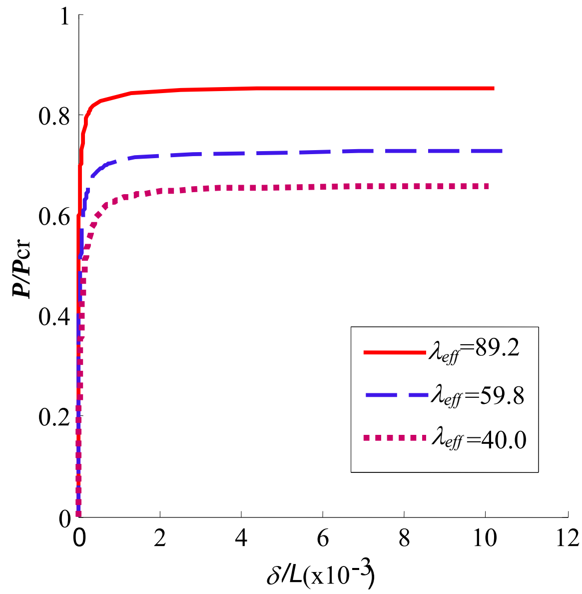

Fig.10 The Curve of Load-Displacement With Slenderness Ratio

Fig.(9) shows that, there is no bifurcation during buckling compared with the complete structure when the cracked thin-walled shuttle cylinders structure are under the eccentric loads;the load-displacement curve gradually changes as the crack length changes; there is ultimate point of load when the crack length is short, whereas the load-displacement curve monotonic rises when the crack length is long until sudden fracture. That is, the broken way of the cracked thin-walled shuttle cylinders structure under eccentric load is changed from the extreme point bucking yielding to the fracture broken as the crack length increases. At the same time, the ultimate bearing capacity also decreases as the crack length increases. Therefore the crack lowers the ultimate bearing capacity of the structure.

Fig.(10) is the load-displacement at different equivalent slenderness ratio, where the crack length ξ=0.2, and the eccentricity $\varepsilon = 2.0$ .It shows that, under the different equivalent slenderness ratio, the geometric nonlinear elastic buckling load-displacement curve is basically the process of primary buckling. There is an extreme points on each equilibrium path. The bucking load increases as the equivalent slenderness ratio increases. Therefore, the structure ultimate bearing capacity can be improved by increasing the equivalent slenderness ratio.

V. CONCLUSION

Through the research on the ultimate load-carrying capacity shuttle thin-walled cylinders structure with circumferential cracks in eccentric compression elastic buckling eigenvalues when geometric nonlinearity included, and the analysis of the influence of the crack length, eccentricity, and the wedge rate to the bucking load and ultimate bearing capacity, the conclusions are made as following:

(1) Eccentricity has relationship with the influence of crack length to stability performance of the structure. The structural ultimate load-carrying capacity can be improved by reducing the crack length when eccentricity less than a certain value. However, the crack length has no influence to the structural ultimate load-carrying capacity when the eccentricity is larger than a certain value.

(2) The wedge rate plays a key role to the ultimate bearing capacity. The ultimate bearing capacity when the wedge rate γ =1.0 is 4 times than when the wedge rate γ =0.0---the circular section structure. In order to improve the load-carrying capacity, it is necessary to adopt the shuttle cross-section structures.

(3) The ultimate load-carrying capacity and the structural stability of shuttle thin-walled cylinders structures can be improved by increasing the wedge rate, reducing the slenderness ratio, reducing the eccentricity and reducing the crack length in the practical engineering structure

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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