Study on Strengths of Steel Cone-to-Cylinder Socket Connections under Axial Compression

その他のタイトル	軸圧縮を受ける鋼製円錐-円筒ソケット接合部の耐力に関する研究
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論文の内容の要旨

論文題目

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under Axial Compression
(軸圧縮を受ける鋼製円錐－円筒ソケット接合部の耐力に関する研究)

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本文

A new type of steel connection, which is named steel cone-to-cylinder socket connection, is developed in the Steel Structure Laboratory of the University of Tokyo to reduce the seismic damage occurred at the pile head of building structures. Strength of the connections under axial compression has been studied since 2005. Four potential failure modes: cylinder edge failure, ring tension failure, cone bending failure, and cone buckling failure were summarized. Several models were created and formulae for predicting the yield strength, full plastic strength, and collapse strength of connections were proposed. However, several issues have not been clarified up to now. Though the simple law of friction proposed by Amonton and Coulomb can be employed to simulate the friction contact between cone and cylinder, how to set the value of the friction coefficient for practical design has not been made clear. The distributions of stress and deformation in the connections have not been investigated. The plastic regions in cylindrical wall, tapered ring, conical wall and lid plate at yield, full plastic and ultimate loads respectively, have not been analyzed. The failure modes need to be reinvestigated in detail, especially for the welded connections with cone buckling failure, because the predicted strength is much greater than the experimental results. Furthermore, the influence of interaction of stress resultants on the failure mechanisms has not been studied.

This thesis is aimed to clarify the failure mechanisms and proposed more precise and easy-to-use formulae for predicting the strength of all the connections. This thesis first estimates effective Finite Element (FE) models by considering the influence of friction coefficient on collapse strength and then clarifies the stress transformation mechanisms. Secondly, the failure mechanisms are judged based on the FE Analysis results and the previous experimental results. Thirdly, the interaction of stress resultants is investigated, and then the complicated equation of Mises' yield condition for revolutional shells under axisymmetric loading is simplified into an explicit and easy-to-use form and validated by the effective FEA results. Finally, plastic collapse mechanisms are proposed and limit analysis is undertaken by considering the interaction of axial (meridional) stress resultants with hoop stress resultant and axial (meridional) bending moment. More precise and easy-to-use formulae for strength of connections are proposed and validated by comparing them with the previous ones and the relevant experimental and FEA results.

This thesis has three major parts. The first part built in Chapter 2 is to reinvestigate the failure modes of connections based on the previous experimental results. The second part is assigned to Chapters 3~5 and focuses on the prediction of strength of metal touch connections. The frictional contact characteristics between cone and cylinder are discussed and the satisfactory value of friction coefficient for practical design work is proposed. The failure mechanisms are judged and their full plastic strength is derived by limit analysis. The final part is Chapter 6 and focuses on the prediction of strength of welded connections. The failure mode is determined based on the proposed criteria. The full plastic strength is also calculated by limit analysis.

The content of the thesis is detailed as follows:

Chapter 1 Introduction

The concept and advantage of steel cone-to-cylinder socket connections are introduced. A comprehensive review of the study related with the steel cone-to-cylinder connections are carried out. The unclarified issues are addressed, and the purpose and scope of the dissertation are presented.

Chapter 2 Discussion on Failure Modes Based on Previous Experimental Results

The whole schedule of the previous experiments is addressed. The strength and ultimate behavior of specimens are analyzed. The failure modes are discussed based on the experimental results.

Chapter 3 Strength of Metal Touch Connections with Cylinder Edge Failure

A comprehensive review of the preceding study on cylinder edge failure is addressed. Effective FEA (Finite Element Analysis) is then employed to analyze the friction coefficient between cone and cylinder and investigate the distributions of stresses and deformations of cylinder edge. Based on the FEA results and the preceding experimental results, the failure mode is determined by the proposed criteria. The limitations of the previous mechanical models are presented, and then a new mechanical model is created. Limit analysis is undertaken and the formula for predicting the full plastic strength of models is proposed. Based on the formula for full plastic strength, the prediction of ultimate strength and general yield strength is undertaken.

Chapter 4 Strength of Metal Touch Connections with Tapered Ring Failure

A comprehensive review of the preceding study on the reinforcement effect of rings on strength of cylindrical shells is addressed. FEA is employed to analyze the friction coefficients both between cone and cylinder and between cylinder and ring. And then, the distributions of stress and deformation of tapered ring are investigated. The failure mode is judged by the proposed criterion. The limitations of the previous mechanical model are presented, and then a new mechanical model is created. Limit analysis is undertaken and formula for predicting the full plastic strength of models is proposed. Based on the formula for full plastic strength, the prediction of ultimate strength and general yield strength is undertaken.

Chapter 5 Strength of Metal Touch Connections with Conical Wall Failure

A comprehensive review of conical wall failure under external pressure or along with axial compression is addressed. FEA is employed to analyze the friction coefficient between cone and cylinder. And then, the distributions of stress and deformation of conical wall are investigated. The failure mode is judged by the proposed criteria. The limitations of the previous mechanical model are presented, and then a new mechanical model is created. Limit analysis is undertaken and the formula for predicting the full plastic strength of models is proposed. Based on the formula for full plastic strength, the prediction of ultimate strength and general yield strength is undertaken.

Chapter 6 Strength of Welded Connections with Joint Region Failure

A comprehensive review of prediction of strength of welded cone-to-cylinder connections is addressed. FEA is employed to investigate the distributions of stress and deformation of conical and cylindrical walls. The failure mode is judged by the proposed criteria for plastic collapse. A new mechanical model is created and then limit analysis is undertaken. The formula for predicting the full plastic strength of models is proposed. Based on the formula for full plastic strength, the prediction of ultimate strength and general yield strength is undertaken.

Chapter 7 Conclusions and Future Research

Appendix A Coupon Test Results of Connections

Appendix B Load versus Axial Deformation Curves of All the Experimental Specimens

Appendix C Comparison of Load versus Axial Deformation Curves and Deformation between Experiments and FEA

Appendix D Influence of Gap between Conical Wall and Cylinder Edge on Collapse Strength of Metal Touch Connections.

Appendix E Influence of Eccentricity of Compressive Loading on Collapse Strength of Connections

<u>The main conclusions are obtained as follows:</u>

(1) For Metal Touch Connections

① Failure mechanisms of connections with different kinds of boundary condition between conical wall and cylinder edge are determined by the proposed criteria. For the connections with cylinder edge failure, failure mode is controlled by plastic collapse of cylindrical shell; For the connections with tapered ring failure, failure mode is not only controlled by hoop tension of ring but also by plastic collapse of cylindrical shell; and For the connections with conical wall failure, failure mode is controlled by plastic collapse of conical shell.

② The simplification of Mises' yield condition for axisymmetrically loaded revolutional shells with perfectly-plastic material, as shown in the following, can be employed as the basis of plastic analysis of shell structures.

$$\left|\frac{2n_{\theta\max}-n_{s\max}}{\sqrt{4-3n_{s\max}^2}}\right|^{2.5}+\left(\frac{2\sqrt{3}m_{s\max}}{4-3n_{s\max}^2}\right)^2=1$$

where, $n_{\theta\max}$, $n_{s\max}$, $m_{s\max}$ are the normalization of hoop stress resultant, meridional stress resultant and meridional bending moment in shell walls.

③ The full plastic strength of connections is predicted well by plastic collapse mechanism, in which the correlation of stress resultants is considered. The prediction of collapse strength and general yield strength of connections, based on the formula for full plastic strength, are also in good agreement with experimental and FE analysis results.

④ In practical design, conical shell, employed as pile head, is desirable to fail before the edge of cylindrical pile in order to protect the pile from damage. When conical shell bends inward, friction coefficient μ between conical wall and cylinder edge will be greater than 0.20 due to the breakdown of oxide film. Therefore, setting μ=2.0 can be acceptable because it gives an obvious under-prediction for the strength of pile.

⑤ In order to make sure that conical shell fails before the edge of cylindrical pile, it is necessary to know the collapse strength of connections with all the failure modes. The failure mode with minimum collapse strength is assumed to occur. Predicted mode by the proposed formulae coincides well with actual one.

(2) For Welded Connections

① The strength of intersection of conical wall and cylinder edge is weak because the meridional bending moment, hoop stress resultant and radial deformation are all much greater than those in other regions.

② The failure mechanism of welded connections in this study is assumed to be governed by "plastic collapse of joint region" based on the proposed criteria, because the number of plastic hinges is sufficient and the kinematically admissible state is reached at ultimate load.

③ The proposed plastic collapse mechanism can predict the full plastic strength of models more precisely than the previously proposed plastic buckling equation for conical shell.

④ Plastic buckling strength of conical and cylindrical shells needs to be studied in order to make clear the bound of plastic collapse mechanism of joint region.