

PREDICTION OF CONFINEMENT BEHAVIOUR OF CONCRETE-FILLED TUBULAR COLUMNS UNDER MONOTONIC AND CYCLIC AXIAL LOADING

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by

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*Submitted
in fulfilment of the requirements of the degree of Doctor of Philosophy
to the*



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Dedicated to my family

for their support, endless love, and encouragement

CERTIFICATE

This is to certify that the thesis entitled, “*Prediction of Confinement Behaviour of Concrete-Filled Tubular Columns under Monotonic and Cyclic Axial Loading*” being submitted by **Rahul Bhartiya** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him under my supervision and guidance. The thesis, in my opinion, has reached the requisite standard, fulfilling the requirements for the award of the degree of **Doctor of Philosophy**.

The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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ABSTRACT

Concrete-filled steel tubular (CFT) columns are the composite members in which steel tube is filled with concrete. CFT columns offer numerous benefits in terms of high axial resistance and stiffness by combining the advantages of both constituent materials and hence, are being used as the load-resisting elements in various civil infrastructures. The enhancements in axial resistance and deformation ductility of these members under axial compression loading are primarily dependent on the extent of concrete confinement. The important parameters that influence the concrete confinement in a CFT member are the type of cross-section, the length-to-lateral dimension ratio, the width-to-thickness ratio, and the nature of loading. The main goal of this study is to investigate the influence of these parameters on the monotonic and cyclic performance of CFT columns of both rectangular and circular cross-sections subjected to axial compression. In addition to experimental investigations, numerical and analytical studies have been conducted to predict the peak as well as the post-peak response of the CFT columns with and without steel reinforcing bars.

Three-dimensional finite element (FE) analyses are carried out using the computer software ABAQUS to evaluate the axial behaviour of CFT columns. Concrete damage plasticity (CDP) model is widely used to represent the constitutive behaviour of confined concrete in CFT columns. This model requires a constant dilation angle and a stress-strain base curve of concrete as the main input parameters. However, in the case of rectangular CFT columns, the variation in the level of confinement across the cross-section makes both the dilation angle and stress-strain base curve to be solution-dependent. In this study, a novel algorithm has been developed to estimate the dilation angles and to generate the

multiple stress-strain curves of concrete under various confining pressures. A numerical technique has been proposed for the modelling of confined concrete in the modified CDP model through the implementation of a solution-dependent field variable (SDFV). The efficacy of the proposed modelling technique has been verified through finite element validation of twenty previously tested reinforced concrete (RC), CFT, and reinforced-CFT (RCFT) columns under both concentric and eccentric axial loads. Tension stiffening effect of concrete has also been considered in the modelling of eccentrically loaded CFT columns. The proposed numerical models accurately predicted the load-deformation behaviour of CFT columns with and without confining reinforcement under concentric and eccentric axial monotonic loads.

A parametric study has been conducted on the validated FE models for width-to-depth (aspect) ratios varying between 1 to 2, tube width-to-thickness (B/t) ratio ranging between 10 and 266, percentage of longitudinal reinforcement varying between 0.87 to 6.21%, five different arrangements of internal ties and volumetric ratios of ties ranging from 0.12 to 3.14%. The peak axial strength, post-peak behaviour, and confined stress-strain characteristics of RCFT columns under axial compression loading are studied. The RCFT columns showed a significant increase in strength and ductility when effectively confined with internal transverse ties, even with a slender tube section. The results obtained from the numerical study are compared with the analytical confinement models and the design equations of building codes. Based on this study, suitable modifications are proposed for existing design equations to consider the effect of confining reinforcements.

An experimental investigation has been conducted on twenty-two CFT column specimens subjected to monotonic axial compressive loading and twenty-seven (including ten aged) column specimens subjected to cyclic axial compressive loading

until their failure. The main parameters varied in the test specimens are the grade of concrete, slenderness i.e., length-to-depth (L/D) ratios, and tube compactness i.e., depth-to-thickness (D/t) ratios. The L/D ratios are varied in the range of 3-10 for two different values of D/t ratios (i.e., 13 and 26). The performance of CFT columns is evaluated in terms of peak axial strength, ductility, and post-peak resistance. Test results showed the improved peak axial resistance as the grade of concrete is increased. Further, the increase in the L/D ratios resulted in a steeper degradation in the post-peak stiffness of the CFT columns. The results of the cyclic compression tests are compared with the monotonic tests. For the CFT columns, the backbone curve obtained from the cyclic test is similar to the monotonic load-deformation curve.

An analytical investigation has also been conducted to predict the axial strengths using the available confinement models and eight different international design codes. The D/t ratios are varied in the range of 10-120, whereas the L/D ratio is varied between 3 to 48 in the analytical study. Based on both experimental and analytical investigations, a modified confinement model has been proposed to predict the peak axial strength as well as the post-peak axial resistance of CFT columns. The proposed model includes the effects of material grades, tube compactness ratio, and column slenderness (L/D) ratio. The accuracy of previous cyclic confinement models is evaluated in predicting the behaviour of concrete confinement in the CFT columns. Thereafter, modifications are proposed to the existing cyclic confinement model to predict the cyclic load-deformation behaviour.

सार

कंक्रीट से भरे इस्पात नलीदार (सीएफटी) स्तंभ संयुक्त अवयव होते हैं जिनमें इस्पात नली कंक्रीट से भरी होती है। सीएफटी स्तंभ दोनों घटक पदार्थों के लाभों को मिलाकर उच्च अक्षीय प्रतिरोध और कठोरता के संदर्भ में कई लाभ प्रदान करते हैं और इसलिए, विभिन्न बुनियादी ढांचों में भार-प्रतिरोधी तत्वों के रूप में उपयोग किया जा रहा है। अक्षीय संपीड़न भार के तहत इन सदस्यों के अक्षीय प्रतिरोध और विरूपण लचीलापन में वृद्धि मुख्य रूप से कंक्रीट परिरोध की सीमा पर निर्भर है। सीएफटी सदस्य में कंक्रीट परिरोध को प्रभावित करने वाले महत्वपूर्ण मापदण्ड अनुप्रस्थ काट के प्रकार, लंबाई-से-पार्श्व आयाम अनुपात, चौड़ाई-से-मोटाई अनुपात और भार की प्रकृति हैं। इस अध्ययन का मुख्य लक्ष्य अक्षीय संपीड़न के अधीन आयताकार और वृत्ताकार अनुप्रस्थ काट के सीएफटी स्तंभ के एकविध और चक्रीय व्यवहार पर इन मापदंडों के प्रभाव की जांच करना है। प्रायोगिक जांच के अलावा, बिना इस्पात प्रबलन सरिया और इस्पात प्रबलन सरिया के साथ सीएफटी स्तंभ की शिखर के साथ-साथ शिखर के बाद प्रतिक्रिया का अनुमान करने के लिए संख्यात्मक और विश्लेषणात्मक अध्ययन आयोजित किए गए हैं।

सीएफटी स्तंभ के अक्षीय व्यवहार का मूल्यांकन करने के लिए संगणक युक्ति ABAQUS का उपयोग करके त्रि-आयामी परिमित तत्व (FE) विश्लेषण किया गया है। कंक्रीट क्षति सुघट्य (सीडीपी) प्रतिरूप का व्यापक रूप से सीएफटी स्तंभ में परिरुद्ध कंक्रीट के रचनात्मक व्यवहार का अभिवेदन करने के लिए उपयोग किया जाता है। इस प्रतिरूप को मुख्य निविष्ट मापदण्ड के रूप में सतत फैलाव कोण और कंक्रीट के प्रतिबल-विकृति वक्र की आवश्यकता होती है। हालांकि, आयताकार सीएफटी स्तंभ के मामले में, अनुप्रस्थ काट में परिरोध के स्तर में भिन्नता, फैलाव कोण और प्रतिबल-विकृति वक्र दोनों को समाधान-निर्भर बनाती है। इस अध्ययन में, फैलाव कोणों का आकलन करने और विभिन्न परिरोध दबावों के तहत कंक्रीट के कई प्रतिबल-विकृति वक्र उत्पन्न

करने के लिए एक नयी कलन विधि विकसित की गयी है। समाधान-निर्भर क्षेत्र चर (एसडीएफवी) के कार्यान्वयन के माध्यम से संशोधित सीडीपी प्रतिरूप में परिरुद्ध कंक्रीट के प्रतिरूपण के लिए एक संख्यात्मक तकनीक का प्रस्ताव किया गया है। प्रस्तावित प्रतिरूपण तकनीक की प्रभावकारिता को पहले से परीक्षण किए गए बीस प्रबलित कंक्रीट (आरसी), सीएफटी, और प्रबलित-सीएफटी (आरसीएफटी) स्तंभों के परिमित तत्व सत्यापन के माध्यम से संकेंद्रित और उत्केंद्रित अक्षीय भार दोनों के तहत सत्यापित किया गया है। कंक्रीट के तनाव सख्त प्रभाव को उत्केंद्रित रूप से भारित सीएफटी स्तंभ के प्रतिरूपण में भी लिया गया है। प्रस्तावित संख्यात्मक मॉडल ने संकेंद्रित और उत्केंद्रित अक्षीय एकविध भार के तहत बिना इस्पात प्रबलन सरिया और इस्पात प्रबलन सरिया के साथ सीएफटी स्तंभ के भार-विरूपण व्यवहार की सटीक अनुमान किया।

1 से 2 के बीच चौड़ाई-से-गहराई (अभिमुखता) अनुपात के लिए मान्य एफई प्रतिरूप पर एक प्रचलित अध्ययन किया गया है जिसमें ट्यूब चौड़ाई-से-मोटाई (B/t) अनुपात 10 और 266 के बीच है, अनुदैर्घ्य प्रबलन का प्रतिशत 0.87 से 6.21% के बीच है, आंतरिक छल्लों की पांच अलग-अलग व्यवस्थाएं और छल्लों के आयतन अनुपात 0.12 से 3.14% तक हैं। अक्षीय संपीड़न भार के तहत आरसीएफटी स्तंभ की चरम अक्षीय ताकत, शिखर के बाद व्यवहार, और परिरुद्ध प्रतिबल-विकृति विशेषताओं का अध्ययन किया गया है। आरसीएफटी स्तंभों ने आंतरिक अनुप्रस्थ छल्लों के साथ प्रभावी ढंग से परिरुद्ध होने पर ताकत और लचीलापन में उल्लेखनीय वृद्धि दिखाई, यहां तक कि एक पतला नली अनुभाग के साथ भी। संख्यात्मक अध्ययन से प्राप्त परिणामों की तुलना विश्लेषणात्मक परिरोध प्रतिरूपों और भवन निर्माण संहिता के रचना समीकरणों से की गयी है। इस अध्ययन के आधार पर, परिरुद्ध प्रबलन के प्रभाव के लिए मौजूदा रचना समीकरणों के लिए उपयुक्त संशोधन प्रस्तावित हैं।

विफलता तक एकविध अक्षीय संपीड़न भार के अधीन बाईस सीएफटी स्तंभ नमूनों पर और चक्रीय अक्षीय संपीड़न भार के अधीन सत्ताईस (दस जीर्ण नमूनों सहित) स्तंभ नमूनों पर एक प्रयोगात्मक जांच की गई है। परीक्षण नमूनों में भिन्न मुख्य मापदण्ड कंक्रीट का ग्रेड, पतलापन यानी लंबाई-से-गहराई अनुपात (L/D), और नली सघनता यानी गहराई से मोटाई अनुपात (D/t) हैं। अनुपातों के दो अलग-अलग मूल्यों (यानी, 13 और 26) के लिए L/D अनुपात 3-10 की सीमाओं के बीच रखे गए हैं। सीएफटी स्तंभ के व्यवहार का मूल्यांकन शिखर अक्षीय ताकत, लचीलापन और शिखर के बाद प्रतिरोध के संदर्भ में किया गया है। कंक्रीट के ग्रेड में वृद्धि के रूप में परीक्षण के परिणामों ने बेहतर शिखर अक्षीय प्रतिरोध दिखाया। इसके अलावा, L/D अनुपात में वृद्धि के परिणामस्वरूप सीएफटी स्तंभों की शिखर के बाद की कठोरता में भारी गिरावट आई है। चक्रीय संपीड़न परीक्षणों के परिणामों की तुलना एकविध परीक्षणों से की गयी है। सीएफटी स्तंभ के लिए, चक्रीय परीक्षण से प्राप्त आधार वक्र एकविध भार-विरूपण वक्र के समरूप होता है।

उपलब्ध परिरोध प्रतिरूपों और आठ अलग-अलग अंतरराष्ट्रीय रचना संहिताओं का उपयोग करके अक्षीय ताकत का अनुमान करने के लिए एक विश्लेषणात्मक जांच भी की गई है। D/t अनुपात 10-120 सीमाओं के बीच, जबकि विश्लेषणात्मक अध्ययन में L/D अनुपात 3 से 48 के बीच रखे गए हैं। प्रयोगात्मक और विश्लेषणात्मक दोनों तरह की जांच के आधार पर, एक संशोधित परिरोध प्रतिरूप का प्रस्ताव दिया गया है जो शिखर अक्षीय ताकत के साथ-साथ सीएफटी स्तंभों के बाद के चरम अक्षीय प्रतिरोध का आकलन करता है। प्रस्तावित प्रतिरूप में सामग्री ग्रेड, नली सघनता अनुपात, और स्तंभ पतलापन अनुपात (L/D) के प्रभावों को लिया गया है। पिछले चक्रीय परिरोध प्रतिरूपों की सटीकता का मूल्यांकन सीएफटी स्तंभों में कंक्रीट परिरोध के व्यवहार का अनुमान करने के लिए किया गया है। इसके बाद, चक्रीय भार-विरूपण व्यवहार का अनुमान करने के लिए मौजूदा चक्रीय परिरोध प्रतिरूप में संशोधन प्रस्तावित किया गया है।

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LIST OF SYMBOLS

Symbol	Description
a	Coefficient used in the estimation of plastic strain
A_c	Cross-sectional area of concrete infill
A_s	Cross-sectional area of steel tube
A_{sr}	Cross-sectional area of steel rebars
b	Width of concrete infill
b_c	Core dimensions along the center line of perimeter hoop along the width
B	Width of the cross-section (where $B \geq D$)
c	Cover from the inner face of steel tube to the centre of the perimeter tie
d	Depth of concrete infill
D	Depth of the cross-section
d_c	Core dimensions along the center line of perimeter hoop along the depth
D_c	Diameter of concrete infill
d_{max}	Maximum coarse aggregate size
e	Eccentricity in axial loading
t	Thickness of the steel tube
E_c	Young's modulus of concrete
E_{sr}	Young's modulus of steel rebars
E_{st}	Young's modulus of steel tube
F_{cr}	Buckling stress
f_{bo}	Initial equi-biaxial compressive yield stress
f_c	Axial stress in concrete
f_{co}	Cylindrical compressive strength of concrete
f_{cc}	Strength of confined concrete
f_{new}	Point of revised stress
f_{ro}	Start point of reloading stress
f'_t	Tensile strength of plain concrete
f_{un}	Unloading stress
f_{ysr}	Yield strength of steel reinforcement bar
f_{yst}	Yield strength of steel tube
$\overline{f_{yst}}$	Effective yield stress of steel tube in compression

G_F	Fracture energy of concrete
I_c	Moment of Inertia of concrete infill
I_{sr}	Moment of Inertia of steel rebars
I_{st}	Moment of Inertia of steel tube
K_c	The ratio of the second stress invariant on the tensile meridian to that on the compressive meridian
L	Overall length of the column
P_{cr}	Elastic critical buckling load
P_o	Nominal bearing capacity
P_t	Percentage of longitudinal reinforcement
P_{uc}	Nominal axial load capacity
P_{ue}	Observed peak axial resistance
P_{us}	Squash load
s'	Clear spacing of ties along length of the column
S	Spacing of ties along length of the column
w'_i	Clear distance between the longitudinal rebars
γ_u	Factor to consider the scale effect
ε^*	Normalized strain
ε_{1c}	Principal strain in concrete
ε_{33}	Strain in concrete in axial direction
ε_c	Axial strain in concrete
ε_c^E	Elastic component of axial strain in concrete
ε_c^a	Adjusted axial strain in concrete
ε_{cc}	Strain at peak stress in confined concrete
ε_{cu}	Strain corresponding to σ_{cu}
ε_{cc}^i	Strain at peak stress at i^{th} increment
ε_{cmax}	Maximum axial strain in concrete
ε_c^p	Plastic component of axial strain in concrete
ε_c^u	Axial strain in unconfined concrete
ε_{co}	Strain at peak stress in unconfined concrete
ε_l^E	Elastic component of lateral strain in concrete
ε_l^p	Plastic component of lateral strain in concrete
ε_{pl}	Plastic strain
ε_r^i	Strain at the last load reversal
ε_{ro}	Start point of reloading strain

ε_{un}	Unloading strain
ε_{ust}	Ultimate strain of steel tube
ε_{yst}	Yield strain of steel tube
ν_c	Poisson's ratio of concrete
ν_s	Poisson's ratio of steel
σ^*	Normalized stress
σ_{1c}	Principal stress in concrete
σ_c	Axial stress in concrete
σ_c^a	Adjusted axial stress in concrete
σ_{cc}	Peak axial stress in confined concrete
σ_{cc}^i	Peak stress corresponding to i^{th} $\Delta\sigma_l$ increment
σ_c^u	Axial stress in unconfined concrete
σ_{cu}	Peak axial stress in unconfined concrete
σ_l	Lateral stress in concrete
σ_{leff}	Effective average confining pressure for rectangular section
σ_{lmax}	Maximum lateral stress in concrete
σ_{lsr}	Confining pressure due to rebar ties
σ_{lst}	Confinement pressure due to steel tube
σ_r	Confinement pressure for circular section
σ_r^i	Stress at the last load reversal
σ_{sh}	Hoop stress in steel tube
σ_{sl}	Longitudinal stress in steel tube
ψ_0	Initial value of dilation angle of concrete
$\Delta\sigma_l$	Incremental lateral stress in concrete
$\Delta\varepsilon$	Incremental axial strain in concrete
Δf_c	Post peak correction factor
$\ni$	Flow potential eccentricity
ϕ	Rebar diameter in mm
ξ	Confinement factor
χ	Reduction factor
λ	Slenderness ratio
ψ	Dilation angle

LIST OF ACRONYMS

Acronym	Description
CDP	Concrete damaged plasticity
CFDST	Concrete-filled double-skin steel tubes
CCFT	Confined concrete-filled tube
CFT	Concrete-filled tube
CTM	Compression testing machine
FE	Finite element
FEM	Finite element method
FRP	Fibre reinforced polymer
LVDT	Linear variable differential transformer
RCFT	Reinforced concrete-filled tube
SDFV1	Solution dependent field variable 1
SDFV2	Solution dependent field variable 2
SG	Strain gauge
SRC	Steel reinforced concrete
TRC	Steel tube reinforced concrete
VUSDFLD	User defined subroutine in ABAQUS