INFLUENCE OF SRC COLUMNS AND DETAILING OF RC BEAM-TO-SRC COLUMN JOINTS ON SEISMIC RESPONSE OF SOFT-STORY RC FRAMES

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by

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CERTIFICATE

This is to certify that the thesis entitled, ***"Influence of SRC columns and detailing of RC beam-to-SRC column joints on seismic response of soft-story RC frames"*** being submitted by ***Gautham A*** 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

Steel-reinforced concrete (SRC) columns are the composite members consisting of structural steel and plain or reinforced concrete (RC) components that work in tandem to resist the axial and lateral forces acting on them. The composite encased steel improves the load-carrying capacity, displacement ductility, and energy dissipation potential of SRC members, whereas the surrounding concrete protects the structural steel from fire and local buckling thereby making the components more durable. There is a growing interest for encased columns in the mid-rise to high-rise structures in the earthquake-prone regions owing to their inherent enhanced lateral load-resisting properties.

Current code provisions on the design of SRC columns under combined axial and flexural loadings underestimate the buckling strengths of these members. Past studies have also shown the premature failure of composite columns due to the spalling of cover concrete before attaining the code-predicted design strengths. In addition, the reinforcement detailing of SRC columns to reinforced concrete (RC) beam joints significantly influence the lateral load-resisting behavior of framed structures. In practice, the congestion of reinforcing steel bars in the beam-column joints also poses a challenge in maintaining the continuity of structural steel in SRC columns to achieve the desired lateral strengths. Therefore, there is a need for further study on the assessment of SRC columns as well as beam-to-column joints under cyclic loading conditions. The seismic behavior of SRC columns subjected to combined axial compression and lateral cyclic loading is evaluated using experiments and compared with that of an RC column. The reliability of the existing design standards in predicting the axial force–moment interaction curves of SRC columns is verified from the experimental tests and numerical finite element analysis simulations. The behavior of SRC column to RC beam joints under cyclic loading is investigated experimentally for different detailing schemes.

RC framed structures with weak/soft stories are vulnerable to severe damages or even complete collapse when subjected to earthquakes of medium or high intensities. In order to satisfy the amplified lateral strength, displacement ductility and energy dissipation demand in the weak/soft stories, both cross-sectional geometry and reinforcing steel of columns in these stories must be increased excessively as compared to those of columns in other stories. The present study considers the case study where SRC columns are used in place of the RC columns of the open ground story RC frame to prevent the soft-story collapse of the structure. The design of the ground story SRC columns is carried out using a Performance-based plastic design (PBPD) approach.

Numerical modelling of the SRC and RC columns and masonry infill panels is performed using fiber elements in *OpenSees* software and their cyclic performances are validated with the past experimental results. Analytical modelling of beam-to-column joints is carried out using Modified Compression Field Theory. The developed models include the effects of axial force-moment interactions, shear degradation response, pinched hysteresis behavior, bar-slip response, and the fatigue fracture of rebars. Global models of the multi-story RC frame and the proposed hybrid frame are modelled using the validated fiber elements and their seismic performances are evaluated from the results of static and dynamic analyses. Analysis results indicate that the proposed hybrid SRC frame improves the seismic behavior of the original frame and prevents a soft-story failure. Numerical investigations are also performed on several frame models to determine the optimal length of termination of the SRC columns in an SRC-RC hybrid frame for optimal seismic performance. Finally, design guidelines are proposed in this study.

सार

इस्पात-प्रबलित कंक्रीट (एसआरसी) स्तंभ संयुक्त अवयव होते हैं जिनमें संरचनात्मक इस्पात और अप्रतिबंधित या प्रबलित कंक्रीट (आरसी) अवयव होते हैं जो उन पर लागू करने वाले अक्षीय और पार्श्व बलों का अवरोध करना करने के लिए मिलकर काम करते हैं । समग्र संयुक्त इस्पात एसआरसी (SRC) अवयव की भार-वहन क्षमता, विस्थापन लचीलापन और ऊर्जा अपव्यय क्षमता में सुधार करता है, जबकि आसपास का कंक्रीट संरचनात्मक इस्पात को आग और स्थानीय बकलिंग से बचाता है जिससे अवयव को अधिक टिकाऊ बना दिया जाता है। भूकंप-प्रवण क्षेत्रों में मध्य-वृद्धि से उच्च-वृद्धि वाली संरचनाओं में उनके अंतर्निहित वर्धित पार्श्व भार-प्रतिरोध गुणों के कारण संयुक्त स्तंभों के लिए रुचि बढ़ रही है।. संयुक्त अक्षीय और बंकन लदान के तहत एसआरसी स्तंभ के डिजाइन पर वर्तमान भवन निर्माण संहिता के प्रावधान इन अवयव की बकलिंग ताकत को कम आंकते हैं। पिछले अध्ययनों ने भवन निर्माण संहिता निर्धारित डिजाइन ताकत प्राप्त करने से पहले आवरण कंक्रीट के तड़काना के कारण समग्र स्तंभों की समयपूर्व विफलता भी दिखाई है। इसके अलावा, प्रबलित कंक्रीट (आरसी) बीम और एसआरसी स्तंभ संधि-स्थल का सरिया-व्यवस्था पार्श्व भार-प्रतिरोध व्यवहार को महत्वपूर्ण रूप से प्रभावित करता है। व्यवहार में, बीम-स्तंभ संधि-स्थल में सरिया का अतिप्रजन के वजह से पार्श्व लदान को प्राप्त करने के लिए एसआरसी स्तंभ में संरचनात्मक स्टील की निरंतरता को बनाए रखने में एक चुनौती है।. इसलिए, चक्रीय बलों के तहत एसआरसी स्तंभ के साथ-साथ बीम-स्तंभ संधि-स्थल के आकलन पर आगे अध्ययन की आवश्यकता है। संयुक्त अक्षीय और पार्श्व चक्रीय बलों के अधीन एसआरसी स्तंभ के भूकंपीय व्यवहार का मूल्यांकन प्रयोगों का उपयोग करके और आरसी स्तंभ की तुलना किया गया है। पूर्वकथन भवन निर्माण संहिता और मौजूदा मानकों की एसआरसी स्तंभ के अक्षीय-बंकन बल संबंध का लेखाचित्र की विश्वसनीयता, प्रयोगात्मक परीक्षणों और संख्यात्मक परिमित तत्व विश्लेषण सिमुलेशन से

सत्यापित है। चक्रीय बलों के तहत एसआरसी स्तंभ से आरसी बीम संधि-स्थल के व्यवहार की विभिन्न विवरण योजनाओं के लिए प्रयोगात्मक रूप से जांच की गई है।.

मध्यम या उच्च तीव्रता के भूकंपों के अधीन कमजोर भवन स्तर वाली आरसी संरचनाएं गंभीर क्षति या यहां तक कि पूर्ण रूप से ढहने की परिस्थिति में होति हैं। कमजोर भवन स्तर में बढ़ी हुई पार्श्व शक्ति, विस्थापन लचीलापन और ऊर्जा अपव्यय मांग को पूरा करने के लिए, इन भवन स्तर में स्तंभों के क्रॉस-सेक्शनल ज्यामिति और स्तंभों के मजबूत स्टील दोनों को अन्य भवन स्तर में स्तंभों की तुलना में अत्यधिक बढ़ाया जाना चाहिए। वर्तमान अध्ययन उस केस स्टडी पर विचार करता है जहां संरचना के सॉफ्ट-स्टोरी पतन को रोकने के लिए ओपन ग्राउंड स्टोरी आरसी फ्रेम के आरसी स्तंभ के स्थान पर एसआरसी स्तंभ का उपयोग किया गया है। ग्राउंड भवन स्तर एसआरसी स्तंभ का डिज़ाइन प्रदर्शन-आधारित प्लास्टिक डिज़ाइन (पीबीपीडी) दृष्टिकोण का उपयोग करके किया गया है।. एसआरसी और आरसी स्तंभ और ईंट की दीवार वाली इनफिल पैनल का संख्यात्मक प्रतिरूपण, OpenSees सॉफ़्टवेयर में फाइबर तत्वों का उपयोग करके किया गया है और उनके चक्रीय प्रदर्शन को पिछले प्रयोगात्मक परिणामों के साथ मान्य किया गया है। बीम-स्तंभ संधि-स्थल का विश्लेषणात्मक प्रतिरूपण संशोधित संपीड़न क्षेत्र सिद्धांत का उपयोग करके किया गया है। विकसित मॉडलों में अक्षीय-बंकन बल संबंध, पार्श्व बल-क्षण के प्रभाव, अपरूपण अवक्रमण प्रतिक्रिया, पिंच हिस्टैरिसीस व्यवहार, सरिया- फिसल प्रतिक्रिया, और रिबारों के कमज़ोर और भंग होना शामिल हैं। बहु-मंजिला आरसी फ्रेम के वैश्विक मॉडल और प्रस्तावित हाइब्रिड फ्रेम को मान्य फाइबर तत्वों का उपयोग करके तैयार किया गया है और उनके भूकंपीय प्रदर्शन का मूल्यांकन स्थिर और गतिशील विश्लेषण के परिणामों से किया गया है। विश्लेषण के परिणाम बताते हैं कि प्रस्तावित हाइब्रिड एसआरसी फ्रेम मूल फ्रेम के भूकंपीय व्यवहार में सुधार करता है और सॉफ्ट-स्टोरी विफलता को रोकता है। इष्टतम भूकंपीय प्रदर्शन के लिए एसआरसी-आरसी हाइब्रिड फ्रेम में एसआरसी स्तंभ की समाप्ति की इष्टतम लंबाई निर्धारित करने के लिए कई फ्रेम मॉडल पर संख्यात्मक जांच भी की गई है। अंत में, इस अध्ययन में डिजाइन दिशानिर्देश प्रस्तावित किए गए हैं।.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A_a	Cross-sectional area of encased structural steel
A_c	Cross-sectional area of concrete
A_g	Gross sectional area of column
A_{gx}	Cross-sectional areas of the beams
A_{gy}	Cross-sectional areas of the columns
A_h	Design horizontal seismic acceleration coefficient
A_s	Cross-sectional area of reinforcement bars
b	Flange width of the structural steel
b_c	Centre-to-centre distance between the transverse stirrups in width of column
b_f	Width of flange
D	Damage level
D^+	Lateral displacement in the push direction
D^-	Lateral displacement in the pull direction
d_c	Centre-to-centre distance between the transverse stirrups in columns
d_{inf}	Equivalent diagonal length of the infill
d_{max}	Displacement at crushing in infills
d_u	Ultimate displacement in infills
d_w	Depth of the web
d_y	Corresponding displacement to yield force
E_c	Initial modulus of elasticity of concrete
E_d	Energy dissipation coefficient
E_e	Elastic energy
E_i	Total input energy
E_{inf}	Elastic modulus of the infill
E_m	Young's modulus of elasticity of the masonry infill panels
E_p	Plastic energy
E_{sec}	Secant modulus of concrete

E_t	Tensile modulus of concrete
F^+	Peak lateral forces recorded in the push direction
F^-	Peak lateral forces recorded in the pull direction
F_c	Cracking force
F_i	Lateral force in i^{th} story
F_{max}	Maximum crushing strength of the masonry
F_u	Residual strength in the panel
F_{ys}	Yield strength of structural steel
f'_c	Cylinder compressive strength of concrete
f_{cc}	Peak compressive strength of confined concrete
f_{ck}	Characteristics compressive strength of concrete
f_{co}	Peak compressive strength of unconfined concrete
f_{cd}	Design strength of concrete
f_{cm}	Mean compressive strength of concrete
f'_l	Effective lateral confining stress due to the lateral transverse reinforcements
f'_{ls}	Effective lateral confined stress
f_m	Compressive strength of the masonry infills
f_s	Yield strength of steel reinforcement bars
f_{sd}	Design strength of reinforcement bars
f_t	Tensile strength of concrete
f_{tp}	Masonry crack stress
f_u	Ultimate stress
f_x	Boundary stress in the x direction
f_y	Boundary stress in the y direction
f_{yd}	Design strength of structural steel
f_y	Yield stress of structural steel
f_{yt}	Yield strength of transverse stirrups
G_f	Fracture energy
g	Acceleration due to gravity
H	Story height
H_c	Story height

H_{inf}	Height of the infill
H_w	Depth of web
h	Height of the structural steel
h'	Height of the infill panel
h_1	Height of the ground story columns
h_c	Height of the concrete column
h_e	Damping coefficient
h_i	Height of story i measured from the base of the structure
h_n	Neutral axis depth
I	Importance factor
I_c	Moment of inertia of the RC column member
IM_i	Ground motion index for i^{th} earthquake record
j_d	Distance between the compression and tension longitudinal rebars
K_{eff}	Effective lateral stiffness
K_{deg}	Slope of the unloading stiffness degradation
K_j	Rigidity coefficient
k	Total number of cycles applied for the i^{th} drift
L_b	Span of the beam
L_{in}	Length of the infill panel
l	Outstand length of flange
l_c	Characteristic length
M	Total mass of the system
M_B	Moment developed in the beam due to end reaction
$M_{max,Rd}$	Maximum bending resistance of the composite cross-section
M_{pb}	Plastic moment capacity of a reinforced concrete beam
M_{pc}	Moment capacity of the ground story columns
$M_{pl,Rd}$	Design plastic moment resistance of composite cross-section
m	Number of bays
$N_{pl,Rd}$	Maximum design plastic resistance in axial compression

$N_{pm,Rd}$	Axial compression corresponding to point C
n	Number of stories
$P_c(h)$	Axial capacity of the columns in the soft story frame
P_{hor}	Horizontal boundary force
P_{no}	Design compressive strength of a composite encased column
P_{vert}	Vertical boundary force
P_u	Axial compressive force
Q_i	Lateral load distribution for the seismic loads
R	Response reduction factor
R_μ	Ductility reduction factor
r	Post-yield stiffness
S_a	Normalized pseudo-acceleration of the ground motion
S_d	Spectral displacement at the roof level
S_v	Pseudo velocity of the ground motion
s'	longitudinal spacing of stirrups
s_t	spacing of the stirrups
T	Fundamental time period of the system
T_B	Tension acting in the beam rebars at the bottom
t_f	Flange thickness of the structural steel
t_{inf}	Thickness of the infill
t_w	Web thickness of the structural steel
V_B	Design base shear acting along the base of the structure
V_C	Measured shear force in the column
V_j	Shear force in beam column joint panel
V_j^i	Peak lateral force for the i^{th} drift cycles
$(V_n)_{comp}$	Shear capacity of composite column
$V_{u,r}$	Shear capacity of RC section
$V_{u,s}$	Shear capacity of steel
V_y	Design yield base shear of the structure
W	Total seismic weight of the structure
W_i	Seismic weight of each i^{th} story

w	Width of the equivalent diagonal structs
w_i	Clear distance between two longitudinal bars
Z	Zone factor
Z_{pa}	Plastic section moduli of the structural steel about their centroidal axis
Z_{pan}	Plastic section moduli of the structural steel about their neutral axis
Z_{pc}	Plastic section moduli of the concrete about their centroidal axis
Z_{pcn}	Plastic section moduli of the concrete about their neutral axis
Z_{ps}	Plastic section moduli of the reinforcement bars about their centroidal axis
Z_{psn}	Plastic section moduli of the reinforcement bars about their neutral axis
α	Stiffness degradation parameters
α_c	Correction factor for SRC columns
β	Standard deviation of the ground motion index
γ	Time period modification factor
γ_a	Partial safety factors for structural steel
γ_c	Partial safety factors for concrete
γ_j	Panel shear distortion
γ_s	Partial safety factors for reinforcement bars
Δ_j^i	Peak lateral displacement for the i^{th} drift cycles
Δ_y	Yield displacement
Δ_u	Ultimate displacement
ε_x	Boundary strain in the x direction
ε_{cc}	Strain corresponding to the compressive strength of confined concrete
ε_{co}	Strain at peak compressive strength on unconfined concrete
ε_y	Yield strain
ε_u	Ultimate strain
η	Energy modification factor

θ	Mean of the ground motion index
θ_b	Bend end rotation
θ_j	Total shear rotation of the connection
θ_p	Plastic rotation in the ground story
θ_t	Target drift
θ_y	Yield drift
θ_u	Target drift
λ_j	Stiffness degradation coefficient
μ	Displacement ductility factor
μ_s	Structural ductility factor
ρ_{cc}	Ratio of the area of longitudinal steel to the concrete core
ρ_s	Volumetric ratio of transverse confining steel
ρ_{sx}	Area ratio of steel in the global x direction
ρ_{sy}	Area ratio of steel in the global y direction
ϕ	Strength reduction factor
ϕ_b	Flexure strength reduction factor
ϕ_c	Reduction factor for axial compression

LIST OF ABBREVIATIONS

ACI	American Concrete Institute
AIJ	Architectural institute of Japan
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
BF	Bare Frame
CDP	Concrete Damage Plasticity
CEFT	Concrete encased and filled steel tube
CFST	Concrete filled steel tubes
CFT	Concrete-Filled Tubes
COV	Coefficient of variance
CP	Collapse prevention
DBE	Design Basis Earthquake
DM	Damage measure
EB	Energy balance
EEP	Elastic Perfectly Plastic
FEM	Finite element method
FEMA	Federal Emergency Management Agency
FF	Fully infilled
FRC	Fiber reinforced concrete
FRP	Fiber reinforced polymer concrete
HCC	Highly confined concrete
HSC	High Strength Concrete
HYSD	High Yield Strength Deformable
IDA	Incremental dynamic analysis
IM	Intensity measures
IO	Immediate occupancy
ISD	Inter-story drift
LRB	Lead Rubber Bearing
LRFD	Load and Resistance factor design

LS	Life safety
LVDTs	Linearly varying differential transducers
MCE	Maximum Considered Earthquake
MCFT	Modified compression field theory
NTH	Non-linear Time History
OGS	Open ground story
OPC	Ordinary Portland Cement
PBPD	Performance-Based Plastic Design
PCC	Partially confined concrete
PEC	Partially Encased Composite Columns
PES	Partially Encased Steel
PGA	Peak ground acceleration
PSDM	Probabilistic Seismic Demand Models
RC	Reinforced Concrete
RPHM	Refined Plastic Hinge Method
RSI	Resilient Sliding Isolation
SCM	Strain Compatibility Method
SR	Strength Ratio
SRC	Steel-Reinforced Concrete
STSRC	Steel tubed Steel reinforced concrete
TH	Time History
TRC	Tubed reinforced concrete
TSRC	Tubed steel reinforced concrete
UCC	Unconfined concrete
UHSC	Ultra-High Strength Concrete
UTM	Universal Testing Machine