SEISMIC PERFORMANCE OF STRUCTURAL STEEL REINFORCED CONCRETE TRANSFER COLUMNS IN BUILDING FRAMES

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by

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CERTIFICATE

This is to certify that the thesis entitled, *"**Seismic Performance of Structural Steel Reinforced Concrete Transfer Columns in Building Frames**"* being submitted by ***Abhishek Jain*** 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 columns reinforced with structural steel, commonly known as steel-reinforced concrete (SRC) columns, are widely used in the construction of buildings and bridges because of their added advantages and benefits over conventional reinforced concrete (RC) and steel columns. Many buildings are now being built with SRC columns in some stories and RC columns in others. In such buildings, "transfer stories" consist of hybrid SRC-RC columns that are made up of partial SRC and partial RC sections along their heights. These transfer stories are prone to shear failure due to sudden changes in load bearing and stiffness properties. The present study aims to investigate the influence of the embedment length of structural steel in the hybrid SRC-RC columns on their load-bearing behavior when bent about strong and weak axes.

In the first phase, both experimental and numerical studies have been conducted at component levels to determine the optimum embedment length of structural steel and to propose the detailing of steel reinforcement in the hybrid columns. Five large-scale test specimens with varying lengths of embedment of structural steel were tested under gradually increasing lateral cyclic displacements and constant axial loads. The main parameters studied were the failure mechanism, hysteretic response, energy dissipation potential, and lateral stiffness of test specimens. Test results showed that all SRC-RC specimens, irrespective of the direction of lateral loading, had higher lateral strengths than the RC columns. However, test specimens with the smaller embedment of structural steel exhibited shear-dominated failure.

A numerical study based on finite element modeling was carried out to predict the lateral strength and ductility parameters of SRC-RC columns. Three-dimensional numerical models were created in a commercial software ABAQUS considering the concrete confinement by lateral ties and structural steel and the effect of embedment of the lateral and longitudinal reinforcement in concrete. A parametric study was carried out to investigate the lateral load-bearing capacity, ductility, and failure mechanism for varying axial load ratios, embedment lengths, and reinforcement detailing of the transfer columns. A structural steel embedment for 60% of column height with closer tie spacing at the truncation regions exhibited nearly similar lateral performance as the SRC columns.

In the second phase, the assessment of the seismic performance of building frames with SRC-RC columns was carried out numerically using OpenSees software. The numerical model was validated with the published experimental results of SRC-RC columns at the component level and the building frames at the structure level. A five-story building frame with SRC columns at the ground story and RC columns in other stories was considered as the 'study frame'. Nonlinear static (pushover) and time-history (dynamic) analyses were carried out to investigate the base shear vs. roof displacement response, failure mechanism, and drift response of the study frame. For dynamic analyses, a suite of twenty-two ground motions scaled to the maximum considered earthquake (MCE) and design basis earthquake (DBE) hazard levels were considered for the site. It was observed that the frames with the lower embedment of structural steel performed poorly owing to a sudden story shear failure. The increase in embedment alleviated this shear failure. In addition, an incremental dynamic analysis (IDA) was carried out to investigate the seismic collapse performance and to develop seismic fragility curves of the study frame. Building frames with smaller embedments (especially in the minor axis) exhibited a higher probability of collapse. It was concluded that a higher embedment of structural steel in the SRC-RC column should be adopted along with ductile detailing of the truncation zone for improved seismic performance of building frames.

सार

संरचनात्मक इस्पात से प्रबलित कंक्रीट स्तंभ, जिसे आमतौर पर इस्पात-प्रबलित कंक्रीट (SRC) स्तंभ के रूप में जाना जाता है, पारंपरिक प्रfबलित कंक्रीट (RC) और इस्पात स्तंभ पर उनके अतिरिक्त फायदे और लाभों के कारण इमारतों और पुलों के निर्माण में व्यापक रूप से उपयोग किया जाता है। कई इमारतें अब कुछ मंजिलों में SRC स्तंभ और कुछ में RC स्तंभ के साथ बनाई जा रही हैं। ऐसी इमारतों में, "स्थानांतरण मंजिल" (Tranfer stories) में हाइब्रिड एसआरसी-आरसी (SRC-RC) स्तंभ शामिल होते हैं जो आंशिक एसआरसी (SRC) और आंशिक आरसी (RC) अनुभागों से उनकी ऊंचाई के साथ बने होते हैं। भार वहन और कठोरता गुणों में अचानक परिवर्तन के कारण इन स्थानांतरण मंजिल में कतरनी विफलता का खतरा होता है। वर्तमान अध्ययन का उद्देश्य हाइब्रिड SRC-RC स्तंभों में संरचनात्मक इस्पात की एम्बेडमेंट लंबाई के प्रभाव की जांच करना है जब उन्हें मजबूत और कमजोर अक्षों के ओर मोड़ा जाता है।

पहले चरण में, संपूर्ण और संख्यात्मक अध्ययन दोनों को घटक (केवल स्तंभ) स्तरों पर संचालित किया गया है ताकि संरचनात्मक इस्पात की आदर्श अंतर्वेशन लंबाई निर्धारित की जा सके और संकर स्तंभों में इस्पात सुदृढीकरण का विवरण प्रस्तावित किया जा सके। संरचनात्मक इस्पात की विभिन्न अंतर्वेशन लंबाई के साथ पांच बड़े पैमाने के परीक्षण प्रतिरूप का क्रमिक रूप से बढ़ते पार्श्व चक्रीय विस्थापन और स्थिर अक्षीय भार के तहत परीक्षण किया गया। मुख्य मापदंड जो अध्ययन किए गए थे वे थे विफलता तंत्र, हिस्टरेटिक प्रतिक्रिया, ऊर्जा अपव्यय क्षमता, और परीक्षण प्रतिरूप की पार्श्व कठोरता। परीक्षण परिणामों से पता चला कि सभी SRC-RC प्रतिरूप, पार्श्व भार की दिशा की परवाह किए बिना, RC स्तंभों की तुलना में उच्च पार्श्व ताकत रखते थे। हालांकि, छोटे अंतर्वेशन (एंबेडमेंट) वाले इस्पात के साथ परीक्षण नमूनों ने कतरनी-प्रधान विफलता प्रदर्शित की।

संख्यात्मक अध्ययन, सीमित तत्व मॉडलिंग (Finite element modeling) के आधार पर, SRC-RC स्तंभों की पार्श्व शक्ति और नम्यता मापदंडों की पूर्वानुमान करने के लिए किया गया था। त्रि-आयामी संख्यात्मक मॉडलों को वाणिज्यिक सॉफ्टवेयर ABAQUS में बनाया गया, जिसमें पार्श्व बंधनों और संरचनात्मक इस्पात द्वारा कंक्रीट की परिरक्षण और कंक्रीट में पार्श्व और अनुदैर्ध्य सुदृढीकरण की अंतर्वेशन के प्रभाव को ध्यान में रखा गया। एक अध्ययन किया गया जिस्में विभिन्न अक्षीय भार अनुपात, अंतर्वेशन लंबाई और स्थानांतरण स्तंभों के सुदृढीकरण विवरण के लिए पार्श्व भार-वहन क्षमता, नम्यता और विफलता तंत्र की जांच की जा सके। स्तंभ की ऊंचाई के 60% के लिए संरचनात्मक इस्पात अंतर्वेशन के साथ और विच्छेदन क्षेत्रों में घनिष्ठ बंधन अंतराल के साथ, SRC स्तंभों के समान पार्श्व प्रदर्शन प्रदर्शित किया।

दूसरे चरण में, SRC-RC स्तंभों के साथ भवन ढाँचों के भूकंपीय प्रदर्शन का मूल्यांकन संख्यात्मक रूप से OpenSees सॉफ़्टवेयर का उपयोग करके किया गया। संख्यात्मक मॉडल को घटक (स्तंभ) स्तर पर SRC-RC स्तंभों के और संरचना स्तर पर भवन ढाँचों के प्रकाशित प्रयोगात्मक परिणामों के साथ सत्यापित किया गया। भूतल पर SRC स्तंभों और अन्य मंजिलों में RC स्तंभों के साथ एक पाँच मंजिला भवन ढाँचा को 'अध्ययन ढाँचा' के रूप में माना गया। आधार कतरनी बनाम छत विस्थापन प्रतिक्रिया, विफलता तंत्र, और अध्ययन ढाँचे की ड्रिफ्ट प्रतिक्रिया की जांच के लिए गैर-रैखिक स्थिर (पुशओवर) और समय-इतिहास (गतिशील) विश्लेषण किए गए। गतिशील विश्लेषण के लिए, अधिकतम माने गए भूकंप (MCE) और डिज़ाइन आधार भूकंप (DBE) खतरे के स्तरों पर स्केल किए गए बाईस भू-आंदोलनों का एक सेट साइट के लिए विचार किया गया। यह देखा गया कि कम अंतर्वेशन वाले संरचनात्मक इस्पात वाले ढाँचों ने अचानक मंजिलें कतरनी विफलता के कारण खराब प्रदर्शन किया। अंतर्वेशन में वृद्धि ने इस कतरनी विफलता को कम किया। इसके अलावा, भूकंपीय पतन प्रदर्शन की जांच करने और अध्ययन ढाँचे की भूकंपीय नाजुकता वक्र विकसित करने के लिए एक वृद्धिशील गतिशील विश्लेषण (IDA) किया गया। छोटे

अंतर्वेशन (विशेष रूप से कमज़ोर अक्ष में) वाले भवन ढाँचों में पतन की संभावना अधिक थी। निष्कर्ष निकाला गया कि भवन ढाँचों के बेहतर भूकंपीय प्रदर्शन के लिए SRC-RC स्तंभ में संरचनात्मक इस्पात के उच्च अंतर्वेशन को ग्रहण किया जाना चाहिए और विच्छेदन क्षेत्र का लचीला विवरण अपनाया जाना चाहिए।

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A_g	Gross sectional area of column
A_{ties}	Cross-sectional area of lateral ties
α	Ratio of V_f and V_v
b_w	Column width
b_f	Width of structural steel flange
β	EI_{SRC}/ EI_{RC}
Δ^P	Lateral displacement in the positive direction
Δ^N	Lateral displacement in the negative direction
Δ_u	Ultimate drift of the specimen
Δ_y	Yield drift of the specimen
d	Effective depth of section
d_s	Total depth of structural steel section
EI_{RC}	Flexural rigidity of reinforced concrete column
EI_{SRC}	Flexural rigidity of steel reinforced concrete column
E_{co}	Modulus of elasticity of unconfined concrete
E_{cc}	Modulus of elasticity of partially confined concrete
E_{sec}	Secant modulus of elasticity
ε_c	Strain of concrete at any point
ε_{cc}	Ultimate strain of partially confined concrete
ε_{co}	Ultimate strain of unconfined concrete
ε_{cr}	Cracking strain of concrete
F^P	Peak lateral forces recorded in the positive direction
F^N	Peak lateral forces recorded in the negative direction
F_u	Ultimate lateral strength of the specimen

f_{l1}, f_{l2}	Lateral confining pressure on concrete by reinforcement and lat'ral ties
f'_c	Cylinder compressive strength of concrete
f_{bo}/f_{co}	Ratio of equibiaxial compressive strength of concrete to the uniaxial compressive strength
f_{cc}	Ultimate compressive strength of partially confined concrete
f_{cm}	Mean compressive strength of concrete
f_{co}	Ultimate compressive strength of unconfined concrete
f_t	Tensile strength of concrete
f_{yr}	Yield strength of reinforcement steel
f_{yst}	Yield strength of structural steel
G_f	Fracture energy of concrete
G_{fo}	Base fracture energy of concrete
γ	Standard deviation of natural logarithmic of all the intensity measures
K_c	Multiplying factor for unconfined concrete peak strength to achieve partially confined concrete peak strength
K_e	Effective lateral stiffness
K_S	Multiplying factor for lateral confining pressure from reinforcement to achieve lateral confining pressure from structural steel flange
L	Clear length of the column
M_{RC}	Flexural capacity of the reinforced concrete section
M_{SRC}	Flexural capacity of the steel reinforced concrete section
μ	Displacement ductility factor
$\overline{\mu}$	Mean of natural logarithmic of all the intensity measures

N_u	Axial load on the specimen
φ	Standard normal distribution of specimen
σ	Stress
ρ_r	Percentage ratio of longitudinal reinforcement to the gross section of column
ρ_{st}	Percentage ratio of structural steel to the gross section of column
s	longitudinal spacing of stirrups
t_f	Flange thickness of the structural steel
t_w	Web thickness of the structural steel
V	Volume of the finite element of the specimen
V_{code}	Shear strength of RC section with all the strength reduction factors calculated as per ACI 318 (2019)
$V_{concrete}$	Shear strength of only concrete section
V_n	Limiting shear strength of the section
V_{ties}	Shear strength of lateral ties
V_V	Design lateral load bearing capacity (shear failure)
V_f	Design lateral load bearing capacity (flexural failure)

LIST OF ACRONYMS

ACI	American Concrete Institute
AIJ	Architectural institute of Japan
AISC	American Institute of Steel Construction
ASCE	American Society of Civil Engineers
CDP	Concrete Damage Plasticity
CFT	Concrete Filled Tubes
DBE	Design Basis Earthquake
DM	Damage Measure
FEMA	Federal Emergency Management Agency
ISHB	Indian Standard Heavy Beam
IDA	Incremental Dynamic Analysis
IIT	Indian Institute of Technology
IM	Intensity Measure of ground motion
IO	Immediate Occupancy
ISD	Inter-Story drift
LRFD	Load and Resistance Factor Design
LS	Life safety
LVDTs	Linearly Varying Differential Transducers
NLTH	Non-linear Time History
OPC	Ordinary Portland Cement
OpenSEES	Open System for Earthquake Engineering Simulation
RC	Reinforced Concrete
SRC	Steel Reinforced Concrete
SFRS	Seismic Force Resisiting System
UTM	Universal Testing Machine