

**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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RC BEAM-TO-SRC COLUMN JOINTS ON SEISMIC  
RESPONSE OF SOFT-STORY RC FRAMES**

*by*

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**Submitted**

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

**to the**



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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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**Gautham A.**

# 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 होती 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 सॉफ्टवेयर 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 हिस्टैरिसिस व्यवहार, सरिया-फिसल प्रतिक्रिया, और रिबारों के कमजोर 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 डिज़ाइन दिशानिर्देश प्रस्तावित किए गए हैं।

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# 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                                 |
| $R_\mu$        | 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 struts                                      |
| $w_i$              | 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    |
| $\alpha$           | Stiffness degradation parameters                                             |
| $\alpha_c$         | Correction factor for SRC columns                                            |
| $\beta$            | Standard deviation of the ground motion index                                |
| $\gamma$           | Time period modification factor                                              |
| $\gamma_a$         | Partial safety factors for structural steel                                  |
| $\gamma_c$         | Partial safety factors for concrete                                          |
| $\gamma_j$         | Panel shear distortion                                                       |
| $\gamma_s$         | Partial safety factors for reinforcement bars                                |
| $\Delta_j^i$       | Peak lateral displacement for the $i^{th}$ drift cycles                      |
| $\Delta_y$         | Yield displacement                                                           |
| $\Delta_u$         | Ultimate displacement                                                        |
| $\varepsilon_x$    | Boundary strain in the x direction                                           |
| $\varepsilon_{cc}$ | Strain corresponding to the compressive strength of confined concrete        |
| $\varepsilon_{co}$ | Strain at peak compressive strength on unconfined concrete                   |
| $\varepsilon_y$    | Yield strain                                                                 |
| $\varepsilon_u$    | Ultimate strain                                                              |
| $\eta$             | Energy modification factor                                                   |

|             |                                                              |
|-------------|--------------------------------------------------------------|
| $\theta$    | Mean of the ground motion index                              |
| $\theta_b$  | Bend end rotation                                            |
| $\theta_j$  | Total shear rotation of the connection                       |
| $\theta_p$  | Plastic rotation in the ground story                         |
| $\theta_t$  | Target drift                                                 |
| $\theta_y$  | Yield drift                                                  |
| $\theta_u$  | Target drift                                                 |
| $\lambda_j$ | Stiffness degradation coefficient                            |
| $\mu$       | Displacement ductility factor                                |
| $\mu_s$     | Structural ductility factor                                  |
| $\rho_{cc}$ | Ratio of the area of longitudinal steel to the concrete core |
| $\rho_s$    | Volumetric ratio of transverse confining steel               |
| $\rho_{sx}$ | Area ratio of steel in the global $x$ direction              |
| $\rho_{sy}$ | Area ratio of steel in the global $y$ direction              |
| $\phi$      | Strength reduction factor                                    |
| $\phi_b$    | Flexure strength reduction factor                            |
| $\phi_c$    | 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                 |