

**METALLIC ENERGY DISSIPATION  
DEVICES FOR SEISMIC STRENGTHENING  
OF REINFORCED CONCRETE FRAMES  
WITH SOFT-STOREY**

**OINAM ROMANBABU MEETEI**



**DEPARTMENT OF CIVIL ENGINEERING  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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OF REINFORCED CONCRETE FRAMES  
WITH SOFT-STOREY**

*by*

**OINAM ROMANBABU MEETEI**  
Department of Civil Engineering

*Submitted*

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



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**August, 2017**

# CERTIFICATE

This is to certify that the thesis entitled, “*Metallic Energy Dissipation Devices For Seismic Strengthening of Reinforced Concrete Frames with Soft-Storey*” being submitted by *Oinam Romanbabu Meetei* to the Indian Institute of Technology Delhi, for the award of 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 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.

**Dr. Dipti Ranjan Sahoo**  
*Associate Professor*  
Department of Civil Engineering  
Indian Institute of Technology Delhi  
Hauz Khas, New Delhi-110016 (INDIA)

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# ABSTRACT

Reinforced concrete (RC) buildings with open ground storey are seismically vulnerable to severe damages or even complete collapse. Most of these existing buildings have been designed only for gravity loads without considering the expected seismic force demand. Hence, there is a need to study the seismic performance of these structures and to develop the robust strengthening techniques in order to improve their seismic performance. In the present study, two strengthening schemes are investigated to enhance the seismic performance of the RC frames with soft-storey. In the strengthening scheme-I, only combined metallic yielding dampers (*CMDs*) are used as passive energy dissipating devices to reduce the lateral force demand on the existing RC frame. Strengthening scheme-II involves the strengthening of RC columns by steel caging technique in addition to the *CMDs* as supplemental devices. The strengthening requirement for a structure is evaluated using the energy-balance concept. Performance-based plastic design (PBPD) approach has been used for the design of strengthened frames to achieve a target drift and desired yield mechanism.

Slow-cyclic tests are carried out on two reduced-scale single-storey single-bay non-ductile RC frames to investigate their hysteretic response, energy dissipation, and failure mechanism. The damaged test specimens are rehabilitated as per the proposed strengthening schemes. These rehabilitated specimens are tested under the same loading conditions to assess the effectiveness of strengthening elements in improving their cyclic response. Pseudo-dynamic test is conducted on a half-scale two-storey single-bay RC frame with open ground storey to study its performance under scaled Elcentro ground motion. The test frame is then strengthened using the proposed scheme-I. Both

pseudo-dynamic and slow-cyclic tests are conducted on the strengthened frame to investigate the lateral strength, drift response, energy dissipation potential and failure mechanism. The strengthened frame reached a storey drift of 2.2% prior to the occurrence of shear failure of ground storey columns.

All test specimens are modelled numerically using a computer software *OpenSees* to predict their cyclic response. The numerical models are developed considering the axial-flexure interaction, shear force-displacement relationship, and bond-slip characteristics of the concrete members. The numerical models are validated by comparing the predicted response with the test results. The validated numerical model is extended to a typical non-ductile existing five-storey RC building with open ground storey to evaluate the effectiveness of the proposed strengthening scheme. Nonlinear cyclic pushover and dynamic analyses are conducted to compare the seismic response of the strengthened frame with the existing frame. Both test and analysis results showed that the proposed strengthening scheme not only resulted in the enhanced lateral strength and energy dissipation, but also significantly controlled the premature collapse of the RC frames with soft storey.

## सार

तल घर की मंजिल वाली प्रबलित कंक्रीट (आरसी) इमारतों में गंभीर क्षति या पूर्ण पतन के लिए भूकंपीय रूप से कमजोर होते हैं। इन मौजूदा भवनों में से अधिकांश केवल अपेक्षित भूकम्प बल की मांग पर विचार किए बिना गुरुत्वीय भार के लिए तैयार किए गए हैं। इसलिए, इन संरचनाओं के भूकंपीय प्रदर्शन का अध्ययन करने के लिए और उनके भूकंपीय प्रदर्शन को बेहतर बनाने के लिए बहुत सुदृढ़ तकनीक विकसित करने की आवश्यकता है। वर्तमान अध्ययन में, नरम मंजिला वाले आरसी फ्रेम के भूकंपीय प्रदर्शन को बढ़ाने के लिए दो महत्वपूर्ण योजनाओं की जांच की जाती है। महत्वपूर्ण योजना को सुदृढ़ करने के लिए, उपस्थित आरसी फ्रेम को पार्श्व बल की मांग को कम करने के लिए केवल एकमात्र संयुक्त धात्विक लब्धि डंपर्स (सीएमडी) का प्रयोग निष्क्रिय ऊर्जा विघटनकारी उपकरणों के रूप में किया जाता है। महत्वपूर्ण योजना-II में सीएमडी के अतिरिक्त पूरक उपकरणों के रूप में इस्पात ढाँचा (स्टील कैजिंग) तकनीक द्वारा आरसी स्तंभों को सुदृढ़ करना शामिल है। ऊर्जा-संतुलन की अवधारणा का उपयोग करके संरचना के लिए सुदृढ़ आवश्यकता का मूल्यांकन किया जाता है। निष्पादन-आधारित प्लास्टिक डिजाइन (पीबीपीडी) दृष्टिकोण का उपयोग लक्ष्य को कायम करने और वांछित उपज तंत्र को प्राप्त करने के लिए सुदृढ़ फ्रेम के डिजाइन के लिए किया गया है।

एकमात्र सिंगल अतन्य आरसी फ्रेम का पार्श्व छद्म, बहाव प्रतिक्रिया, ऊर्जा अपव्यय क्षमता और विफलता तंत्र की जांच के लिए सुदृढ़ फ्रेम पर दोनों छद्म गतिशील और धीमी गति से चक्रीय परीक्षण किए जाते हैं। प्रस्तावित सुदृढ़ बनाने वाली योजनाओं के अनुसार क्षतिग्रस्त परीक्षण नमूनों का पुनर्वास किया जाता है। ये पुनर्वासित नमूनों का परीक्षण उनकी लोडिंग शर्तों के तहत किया जाता है ताकि उनकी चक्रीय प्रतिक्रिया में सुधार लाने में तत्वों को सुदृढ़ करने की प्रभावशीलता

का आकलन किया जा सके। छद्म गतिशील परीक्षण आंशिक रूप से दो मंजिला सिंगल-बे आर सी फ्रेम पर तल घर के साथ आयोजित किया जाता है ताकि पैमाना इल सेंट्रो भूमिगत कंपन के तहत इसके प्रदर्शन का अध्ययन किया जा सके। फिर प्रस्तावित योजना-I का उपयोग करके परीक्षण फ्रेम सुदृढ़ किया जाता है। पार्श्व छद्म, बहाव प्रतिक्रिया, ऊर्जा अपव्यय क्षमता और विफलता तंत्र की जांच के लिए सुदृढ़ फ्रेम पर दोनों छद्म गतिशील और धीमी गति से चक्रीय परीक्षण किए जाते हैं। जमीनी स्तर के स्तंभों की तंत्र विफलता की घटना से पहले सुदृढ़ फ्रेम 2.2% (झुकाव) की एक मंजिल पर पहुंच गई।

सभी परीक्षण नमूने एक कंप्यूटर सॉफ्टवेयर ओपनसीज का प्रयोग करके संख्यात्मक तरीके से मॉडलिंग कर रहे हैं ताकि उनकी चक्रीय प्रतिक्रिया का अनुमान लगाया जा सके। संख्यात्मक मॉडल अक्षीय-मोड़ परस्पर प्रभाव, तंत्र बल-विस्थापन संबंध, और कंक्रीट सदस्यों के बंध-खिसकाव विशेषताओं पर विचार कर विकसित किए जाते हैं। संख्यात्मक मॉडल परीक्षण परिणामों के साथ अनुमानित प्रतिक्रिया की तुलना करके मान्य हैं। प्रस्तावित सुदृढ़ीकरण योजना की प्रभावशीलता का मूल्यांकन करने के लिए तल घर के साथ एक विशिष्ट गैर-तन्य मौजूदा मौजूदा पांच मंजिला आर.सी. बिल्डिंग के लिए मान्य संख्यात्मक मॉडल बढ़ाया गया है। मौजूदा फ्रेम के साथ सुदृढ़ फ्रेम के भूकंपी प्रतिक्रिया की तुलना करने के लिए अरेखीय चक्रीय पुशोवर और गतिशील विश्लेषण किया जाता है। दोनों परीक्षण और विश्लेषण के परिणाम बताते हैं कि प्रस्तावित सुदृढ़ीकरण योजना न केवल बढ़ायी हुई पार्श्व शक्ति और ऊर्जा अपव्यय में हुई है, बल्कि नरम मंजिला के साथ आरसी फ्रेम के समय से पहले पतन को भी नियंत्रित करती है।

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# LIST OF SYMBOLS

$A_b$	Cross section area of brace
$A_c$	Cross sectional area of column
$A_{ef}$	Effectively confined area in plan
$A_{hc}$	Total horizontal shear plane area
$A_g$	Gross cross sectional area
$A_{sb}$	Area of batten plate
$A_{st}$	Area of transverse reinforcement
$a$	Nodal acceleration vectors
$a'$	Shear span
$B$	Width of beam
$b'$	Distance between the C.G. of the angle sections
$b_{cl}$	Clear distance between steel angles
$b_f$	Width of flexure plates
$b_s$	Length of shear plate
$b_x$	Width of column along x-directions
$b_{xe}$	Clear distance between angle sections along x-directions
$b_y$	Width of column along y-directions
$b_{ye}$	Clear distance between angle sections along y-directions
$C_d$	Deflection amplification factor
$C_2$	Modification factor of target design drift
$c$	Viscous damping
$c'$	Width of angle sections
$D$	Depth of beam
$d$	Nodal displacement
$d_b$	Diameter of main reinforcement bar
$d_c$	Depth of the column core
$d'$	Effective depth
$d'_b$	Depth of batten plate
$d_m$	Diagonal length of infill panel
$E$	Modulus of elasticity or steel

$E_b$	Elastic modulus of brace material
$E_c$	Modulus of elasticity of concrete
$E_d$	Dissipated energy
$E_e$	Elastic energy absorbed
$E_{edd}$	Deficient energy
$E_i$	Input seismic energy
$E_{loop}$	Dissipated energy per hysteretic loop
$E_m$	Modulus of elasticity of masonry
$E_p$	Inelastic energy
$E_t$	Tangent modulus of elasticity
$E_{ts}$	Tension softening stiffness
$e_\eta$	Equivalent axial load ratio
$F_b$	Brace axial force
$F_i$	Equivalent inertia forces at level $i$
$F^+$	Peak positive force of hysteresis loop
$F^-$	Peak negative force of hysteresis loop
$f$	External excitation force
$f_c'$	Concrete compressive strength of the adjoining connection member
$f_{cc}$	Confined concrete compressive stress
$f_{co}$	Unconfined concrete compressive stress
$f_{eq}$	Bending strength of SFRC beam
$f_m$	Expected masonry prism strength
$f_{me90}$	Expected strength of masonry infill wall in horizontal direction
$f_{pc}$	Maximum compressive strength
$f_{pcu}$	Crushing strength
$f_t$	Tensile strength of concrete
$f_y$	Yield strength of main reinforcement
$f_{yb}$	Yield strength of batten
$f_{yf}$	Yield strength of flexural plate
$f_{ys}$	Yield strength of shear plate
$G$	Shear modulus
$g$	Acceleration due to gravity
$H_s$	Horizontal shear force of masonry infill

$H'_{ba}$	Design shear force of battens
$h$	Column height between centrelines of beams
$h_c$	Height of steel collar
$h_d$	Depth of shear plate
$h_l$	Height of ground storey
$h_m$	Height of infill panel
$h'$	Clear spacing between the battens
$I$	Importance factor
$I_{ang}$	Moment of inertia of single angle section
$I_b$	Moment of inertia of brace section
$I_c$	Moment of inertia of column section
$I_f$	Moment of inertia of flexural plate
$I_{sc}$	Moment of inertia of steel cage
$j_e$	Depth of the core concrete
$K_b$	Brace axial stiffness
$K_d$	Equivalent stiffness of <i>CMD</i>
$K_{deg}$	Shear stiffness degradation
$K_{eff}$	Effective lateral stiffness
$K_{eq}$	Equivalent lateral stiffness of the strengthened frame
$K_f$	Frame stiffness
$K_{sc}$	Stiffness of steel cage
$K_{unload}$	Bending stiffness degradation
$K'_{deg}$	Combined Shear and bending stiffness degradation
$K'_{sc}$	Stiffness of steel cage column
$k$	Stiffness
$k'$	Strength degradation
$k_{fd}$	Flexural plate stiffness
$k_s$	Buckling coefficient
$k_{sd}$	Shear plate stiffness
$L$	Span of beam
$L_b$	Length of brace
$L_m$	Length of masonry infill
$l$	Length of member
$l_p$	Plastic hinges length

$M$	Total mass of structure
$M_{ang}$	Moment capacity of the individual angles
$M_{nv}$	Moment capacity of angle sections
$M_{pb}$	Plastic moment capacity of beam
$M_{pc}$	Plastic moment capacity of column
$M_{pcr}$	Plastic moment capacity of strengthened column
$M_{yb}$	Yield Moment of beam
$M_{yc}$	Yield Moment of column
$M_{yf}$	Yield Moment of flexural plate
$M'_{ba}$	Design bending moment of battens
$M^r_{pc}$	Require column moment
$m$	Nodal mass
$m'$	Ratio of the concrete strain at the edge of the core concrete to $\varepsilon_{cp}$
$N$	Number of battens on each side of caging
$N_w$	Vertical load on masonry panel
$n_b$	Number of bays
$n_c$	Number of column
$n_s$	Number of storey
$P$	Ultimate load
$Q_d$	Target strength of <i>CMD</i>
$Q_r$	Residual strength of <i>CMD</i>
$Q_{rs}$	Residual shear strength
$Q_{se}$	Elastic buckling strength of <i>CMD</i>
$Q_u$	Ultimate strength of <i>CMD</i>
$Q_y$	Characteristic yield strength of <i>CMD</i>
$Q_{yf}$	Yield strength of flexural plate
$Q_{ys}$	Yield strength of shear plate
$R_\mu$	Ductility reduction factor
$r$	Restoring force vector
$S$	Bond slip
$S_a$	Normalized pseudo-acceleration
$S_u$	Ultimate loaded-end bar slips
$S_v$	Design spectral pseudo-velocity
$S_y$	Yield loaded-end bar slips

$s$	Centre-to-centre spacing of battens
$s_e$	Effective spacing of battens
$s_t$	Spacing of transverse reinforcement
$T$	Fundamental period
$t_b$	Thickness of batten plate
$t_{inf}$	Thickness of infill panel
$t_f$	Thickness of flexure plates
$t_s$	Thickness of shear plate
$V_{cr}$	Shear cracking forces of masonry infill
$V_i$	Total required shear force
$V_{mi}$	Initial shear strength of masonry infill panel
$V_{mf}$	Final shear strength of masonry infill panel
$V_n$	Shear strength
$V_{pb}$	Beam shear capacity
$V_{pc}$	Column shear capacity
$V_{res}$	Residual shear force
$V_{sc}$	Shear capacity of steel cage
$V_{slide}$	Initial sliding-shear capacity of masonry infills
$V_y$	Yield base shear
$V_{ys}$	Yield shear force
$V_{pc}^r$	Required shear force per column
$V_{sc}^r$	Ultimate shear capacity of steel cage column
$v$	Nodal velocity vectors
$v'$	Maximum nominal shear stress
$W$	Total weight of structure
$W_d$	Dry weight
$W_s$	Saturated weight
$w$	Effective width of diagonal compression strut
$Z$	Zone factor
$\alpha$	Dimensionless parameter
$\alpha'$	Shear plate aspect ratio
$\alpha_E$	Effective confinement coefficient
$\alpha_n$	Reduction factor for effective confinement in plan
$\alpha_o$	Dimensionless parameter used in the local bond-slip relation

$\alpha_s$	Reduction factor for effective confinement in elevation
$\beta$	Shear plate depth-to-thickness ratio
$\beta_{eq}$	Equivalent viscous damping
$\beta_n$	Constant term for Newmark method
$\delta$	Downward movement of upper beam
$\delta_b$	Buckling displacement of shear plate
$\delta_f$	Fracture displacement of <i>CMD</i>
$\delta_{su}$	Ultimate shear plate deformation
$\delta_u$	Ultimate displacement of <i>CMD</i>
$\delta_y$	Yield displacement of <i>CMD</i>
$\delta_{ys}$	Yield displacement of shear plate
$\delta_{yf}$	Yield displacement of flexural plate
$\Delta_d$	Inter storey drift
$\Delta_{td}$	Damper target displacement
$\Delta_{yd}$	Damper yield displacement
$\Delta t$	Time interval
$\Delta_u$	Flexural ultimate displacement of column
$\Delta^+$	Peak positive displacement of hysteresis loop
$\Delta^-$	Peak negative displacement of hysteresis loop
$\Delta'_y$	Shear yield displacement of column
$\Delta'_p$	Allowable plastic shear displacement of column
$\Delta'_u$	Shear ultimate displacement of column
$\varepsilon$	Strain
$\varepsilon_{cc}$	Confined strain
$\varepsilon_{co}$	Unconfined concrete peak strain
$\varepsilon_{cp}$	Strain at maximum stress for the core concrete
$\varepsilon_{cu}$	Ultimate strain of confined concrete
$\varepsilon_{sc0}$	Strain at maximum compressive strength
$\varepsilon_{scu}$	Strain at crushing strength
$\phi$	Angle of sliding friction along the bed joints
$\phi_y$	Yield curvature
$\phi_u$	Ultimate curvature

$\gamma$	Energy modification factor
$\gamma_n$	Constant term for Newmark method
$\gamma'$	Ratio of minimum axial load and maximum axial load
$\eta$	Ratio of reduced area of typical hysteretic loop to the corresponding full loop
$\eta_p$	Maximum axial load ratio
$\lambda$	Unloading slope and initial slope ratio
$\lambda_d$	Characteristics slenderness ratio
$\lambda_h$	Non-dimensional parameter expressing the relative stiffness of the infill to the frame
$\mu$	Coefficient of sliding friction along bed joint
$\mu_s$	Structural ductility factor
$\theta$	Angle between the infill height and infill length
$\theta_b$	Acute angle of inclination of braces with horizontal
$\theta_d$	Inter storey drift angle
$\theta_p$	Inelastic drift
$\theta_{td}$	Target damper drift
$\theta_u$	Ultimate drift
$\theta_{ud}$	Average damper drift
$\theta_y$	Yield drift
$\theta_{yd}$	Damper yield drift
$\rho_{st}$	Percentage of steel reinforcement
$\rho''$	Transverse reinforcement ratio
$\sigma$	Bar stress
$\sigma_m$	Vertical stress of masonry infill
$\sigma_{cr}$	Cracking stress capacity of masonry
$\sigma_{ub}$	Longitudinal reinforcement ultimate stress
$\sigma_x$	Lateral confining stress along x-directions
$\sigma_{xe}$	Effective lateral confining stress along x-directions
$\sigma_y$	Lateral confining stress along y-directions
$\sigma_{yb}$	Longitudinal reinforcement yield stress
$\sigma_{ye}$	Effective lateral confining stress along y-directions

$\tau_o$	The cohesive capacity of mortar beds
$\tau_y$	Shear yield stress
$\tau_b$	In-elastic buckling stress
$\tau_E$	Elastic critical stress
$\nu$	Poisson's ratio
$\omega$	Natural angular frequency
$\zeta$	Modal damping ratio

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# LIST OF ACRONYMS

<i>ADAS</i>	Added damping and stiffness
<i>BRBFs</i>	Buckling resistant brace frames
<i>BMD</i>	Bending moment diagram
<i>CBFs</i>	Concentrically braced frames
<i>CFT</i>	Concrete filled tube
<i>CMD</i>	Combined metallic yielding damper
<i>DOFs</i>	Degrees of freedoms
<i>DBE</i>	Design basis earthquake
<i>EBFs</i>	Eccentric brace frames
<i>EP</i>	Elastic plastic
<i>FE</i>	Finite element
<i>FRP</i>	Fibre reinforced polymer
<i>FRPC</i>	Fibre reinforced polymer composite
<i>HAZ</i>	Heat affected zone
<i>IDA</i>	Incremental dynamic analysis
<i>IDR</i>	Inter-storey drift ratio
<i>IRA</i>	Initial rate of absorption
<i>LVDT</i>	Linear varying differential transformer
<i>MCE</i>	Maximum considered earthquake
<i>MFs</i>	Moment frames
<i>OPC</i>	Ordinary Portland cement
<i>OCBF</i>	Ordinary concentric braced frames
<i>PBD</i>	Performance based design
<i>PBPD</i>	Performance based plastic design
<i>PBSD</i>	Performance-based seismic design
<i>PGA</i>	Peak ground acceleration
<i>PsD</i>	Pseudo-dynamic
<i>RC</i>	Reinforced concrete
<i>RDR</i>	Residual drift ratio
<i>RIDR</i>	Residual inter-storey drift ratio

<i>RS-1</i>	Retrofitted specimen-1
<i>RS-2</i>	Retrofitted specimen-2
<i>S-1</i>	Specimen-1
<i>S-2</i>	Specimen-2
<i>SDOF</i>	Single degree of freedom
<i>SFD</i>	Shear force diagram
<i>SFRC</i>	Steel fibre reinforced concrete
<i>SLBF</i>	Shear-link braced frame
<i>SLS</i>	Serviceability limit state
<i>SLTMF</i>	Shear-link truss moment frame
<i>SP</i>	Shear panels
<i>SPI</i>	Seismic protection index
<i>SPSW</i>	Steel plate shear walls
<i>STMFs</i>	Special truss moment frames
<i>TADAS</i>	Triangular-plate added damping and stiffness
<i>TMFs</i>	Truss moment frames
<i>TMT</i>	Thermos mechanical treated
<i>TRM</i>	Textile-reinforced mortar
<i>WA</i>	Water absorption
<i>ULS</i>	Ultimate limit state

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