TESTING AND EVALUATION OF SHORT-CORE BUCKLING-RESTRAINED BRACES FOR ENHANCED SEISMIC PERFORMANCE OF STEEL FRAMES

MUHAMED SAFEER PANDIKKADAVATH

DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER, 2017

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by

MUHAMED SAFEER PANDIKKADAVATH
Department of Civil Engineering

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

INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER, 2017

CERTIFICATE

This is to certify that the thesis entitled, ***“Testing and Evaluation of Short-Core Buckling-Restrained Braces for Enhanced Seismic Performance of Steel Frames”*** being submitted by ***Muhamed Safeer Pandikkadavath*** 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)

ACKNOWLEDGEMENTS

My profound gratitude goes first to Prof. Dipti Ranjan Sahoo, who intensely guided and encouraged me throughout my PhD program. His devotion for quality and accuracy inspired me to work hard and to refine myself as a good researcher. His humanitarian aspect at all the stages, gave strength to come back on right track. This dissertation would never have been completed without his enduring and comprehensive support. I would like to extend my gratitude to my entire research committee (Prof. Atul Kumar Mittal, Chairman; Prof. A. K. Darpe and Prof. Vasant Matsagar) for their valuable suggestions that led me in the right direction. My appreciation also extends to Structural Engineering Laboratory staffs Biri Singh, Nitin Chourasia and supporting staffs Sanjay Kashyap, Sanjay Kumar and Ramesh Chand who helped me in different stages of my experimental program.

The support and understanding of my colleagues, Dr. P. C. Ashwin Kumar, Dr. Oinam Romanbabu Meetei, Nitin Kumar and juniors have been helpful and valuable in solving technical problems of this dissertation. Their presence and support made many difficult situations much lighter. I am indebted to all my teachers especially Prof. T. K. Datta, Prof. A. K. Nagpal, Prof. A. K. Jain, Prof. Ayothiraman R., Prof. Suresh Bhalla, Prof. G. S. Benipal, Prof. Tanusree Chakraborty, Prof. R. P. R. Nair, Prof. Kouzer K. M. and Prof. Vijayan P and the assistance and support from my affectionate teachers namely Prof. K. V. Leela and Prof. Meera V. and Mrs. Sudha Vinod helped me to take right decisions and to pass through many difficult situations efficiently. The physical and mental support from all my friends particularly, Mr. Arun Unnikrishnan (Pachu), Mr. Ajish V. C., Mr. Noor Muhamed, Saqib Gulzar, Mr. Muhammad Arif A., Mrs. Deepika Malpani, Prof. Dhanaraj K. J., Prof. Prince Asok, Prof. Manoj M., Prof. V. I. Beena and Prof. Dhanya C. T. relieved my pressure and stimulated me to overcome the obstacles. The unconditional love, care and support from my wife Mumthas K., my daughter Khadeeja Safeer P. K., my brother Abdul Adhil P. K., my cousin Shameer K. (Shemicca) and my uncle Abdul Kareem A. P. (Vaappu) have decisive role for making this work a reality. Finally, I thank to my parents, students, siblings, relatives, well-wishers for their mental, physical, and emotional support. Without their love, support, and encouragement, I would not have finished this dissertation.

I dedicate this thesis to my late mother Khadeeja A. P., whose dream and passion for knowledge laid the foundation for this dissertation. In the end, I thank God for all his blessings and for giving all these wonderful people around me.

Muhamed Safeer Pandikkadavath

ABSTRACT

Concentrically braced frames (CBFs) with conventional buckling-type braces (BTBs) experiences severe degradation in strength and stiffness under strong ground motions. This results brace fracture and the formation of soft-story mechanism in CBFs. Buckling-restrained braces (BRBs) can provide stable and balanced hysteretic response along with excellent low-cycle fatigue capacity under inelastic reversed loading conditions. However, buckling-restrained braced frames (BRBFs) are susceptible to excessive residual drift response owing to the low axial stiffness of BRBs. The present study is focussed on the enhancement of axial stiffness of BRBs in order to improve the lateral stiffness of BRBFs as a whole. Two different methodologies are used to improve the axial stiffness of BRBs, namely, (i) by reducing the length of yielding core segments with a proportionate increase in the elastic segments of BRBs, referred to as a short-yielding core BRB (SBRB), and (ii) by using a combined bracing system consisting of a short BRB in series with elastic conventional steel brace segment, referred to as hybrid BRB (HBRB). Since the SBRBs and HBRBs have, relatively shorter yielding segments, the axial stiffness of these braces is expected to be higher than the conventional full-length BRBs.

A preliminary study has been conducted on a six-story braced frame to investigate the drift response and yield mechanism under seismic loading. Four types of braces, namely, conventional buckling-type braces (BTBs), BRBs, SBRBs and HBRBs are considered for the study frame. It is assumed that the inelastic force-deformation characteristics of SBRBs and HBRBs are exactly same as the BRBs. Non-linear static and dynamic analyses showed that the proposed SBRBs and HBRBs are successful in enhancing the lateral stiffness of the braced frames and controlled the drift response associated with them as compared to BRBF. Component tests are carried out on reduced-scale SBRBs to investigate their inelastic response and the design parameters associated with them. Three SBRB specimens with concrete-filled detachable casings as buckling-restraining mechanisms are tested under the reversed cyclic loading conditions. The results showed that SBRBs have acceptable inelastic response and energy dissipation. The design parameters of SBRBs are comparable to that of conventional BRBs up to an axial core strain of 4%.

Successively, the variation in equivalent elastic axial stiffness of BRBs is calculated assuming different segments of BRBs as linear spring models. Numerical studies showed that reduction in yielding length of BRBs and increase in the cross-sectional area of segments can improve the axial stiffness of BRBs. Both low cycle fatigue criteria and higher mode compression buckling criteria are considered to determine the limiting length of yielding core segments of BRBs for enhanced axial stiffness. In case of low cycle fatigue criteria, Coffin-Mansion relationship is used in conjunction with the code recommended qualifying cyclic loading protocols for BRBs. Out of the two approaches, the highest value is taken as the limiting length for core yielding segments of BRBs. Finite element analysis is carried out to predict the cyclic response of BRBs using a commercial software ABAQUS. The main parameter varied in the finite element models are the core yield lengths of BRBs. These models are validated with the results of component tests of SBRBs. The analysis results quantified the variation in elastic and post elastic stiffness as well as the ratio of post-yield stiffness to elastic stiffness of BRBs for different core yield lengths.

Sub-assemblage tests are conducted on six HBRB specimens under the reversed cyclic loading conditions. The main objective of this experimental investigation is to study the overall cyclic response, the behaviour of connections between BRB and BTB segments and the mode of failure of HBRB specimens. The same buckling inhibition arrangement as used in the component testing of SBRBs has been considered for SBRB segments of HBRB specimens. A rigid connection has been adopted at the interface of the BTB and BRB segments of HBRB specimens. Test results showed that HBRBs have excellent energy dissipation capacity with stable and balanced hysteresis. Strength adjustment factors for HBRB are found to be increased at the higher axial strain levels. Finally, a numerical study has been carried out on braced frames of different heights with four different types of braces, i.e., BTBs, BRBs, SBRBs and HBRBs. Two different values of response modification factor are considered in the design of study frame. Non-linear static and dynamic analyses concluded that HBRBF and SBRBF exhibited reduced drift response under design basis earthquake and maximum considered earthquake hazard levels with a marginal increase in ductility demands on SBRBs and HBRBs.

सार

परंपरागत ब्लेलिंग प्रकार के ब्रेसिज़ (बीटीबी) के साथ सांद्रित रूप से बांह के फ्रेम (सीबीएफ) मजबूत जमीन गति के तहत ताकत और कठोरता में गंभीर गिरावट का अनुभव करते हैं। यह परिणाम सीबीएस में मज़बूत फ्रैक्चर और नरम-कहानी तंत्र के गठन का परिणाम है। बक्ली-प्रतिरोधी ब्रेसिज़ (बीआरबी) स्थिर और संतुलित हिस्टैरिसीस प्रतिक्रिया प्रदान कर सकते हैं के साथ उत्कृष्ट कम चक्र थकान क्षमता रिक्ति उलटा लदान शर्तों के तहत। हालांकि, बीआरबी की कम अक्षीय कठोरता के कारण बाकिंग-प्रतिरोधी ढक्कन वाले फ्रेम (बीआरबीएफ) अत्यधिक अवशिष्ट बहाव प्रतिक्रिया के लिए अतिसंवेदनशील होते हैं। वर्तमान अध्ययन बीआरबी के अक्षीय कड़ाव को बढ़ाने पर केंद्रित है ताकि बीआरबीएफ की पार्श्व कठोरता में सुधार किया जा सके। बीआरबी की अक्षीय कठोरता में सुधार के लिए दो अलग-अलग तरीकों का इस्तेमाल किया जाता है, अर्थात् (i) बीआरबी के लोचदार खंडों में अनुपातिक वृद्धि के साथ कोर सेगमेंट देने की लंबाई को कम करके, एक लघु उपज वाली कोर बीआरबी (एसआरबीबी) के रूप में संदर्भित किया जाता है, और (ii) लोचदार पारंपरिक स्टील ब्रेस खंड के साथ श्रृंखला में एक छोटी बीआरबी से मिलकर संयुक्त संयम प्रणाली का उपयोग करके, जिसे संकर बीआरबी (एचबीआरबी) कहा जाता है। चूंकि एसआरबीबी और एचबीआरबी अपेक्षाकृत कम उपज देने वाले खंड हैं, इसलिए इन ब्रेसिज़ की अक्षीय कठोरता अपेक्षाकृत पूर्णकालिक बीआरबी से अधिक होने की उम्मीद है।

भूकंपीय लोडिंग के तहत बहाव प्रतिक्रिया और उपज तंत्र की जांच के लिए एक प्रारंभिक अध्ययन छह मंजिला बंधा हुआ फ्रेम पर किया गया है। चार प्रकार के ब्रेसिज़, अर्थात्, पारंपरिक फ्रेमिंग प्रकार के ब्रेसिज़ (बीटीबी), बीआरबी, एसआरबीबी और एचबीआरबी को अध्ययन के फ्रेम के लिए माना जाता है। यह माना जाता है कि एसआरबीबी और एचबीआरबी की स्थिर बल-विरूपण विशेषताएँ बीआरबी के समान हैं। गैर-रैखिक स्थैतिक और गतिशील विश्लेषण से पता चला है कि प्रस्तावित एसआरबीबी और एचबीआरबी ब्रैड फ्रेम की पार्श्व कठोरता को बढ़ाने में सफल रहे हैं और बीआरबीएफ की तुलना में उनके साथ जुड़े बहाव प्रतिक्रिया को नियंत्रित करते हैं। घटक परीक्षणों को उनके सशक्त प्रतिक्रिया की जांच करने और उनके साथ जुड़े डिज़ाइन मापदंडों की जांच के लिए कम-स्तरीय एसआरबीबी पर किया जाता है। कंक्रीट-भरे वियोज्य आवरण के साथ तीन एसआरबीबी नमूनों को बाकिंग-रिस्ट्रैनिंग तंत्र के रूप में बदलकर चक्रीय लोडिंग शर्तों के नीचे परीक्षण किया जाता है। परिणामों से पता चला है कि एसबीआरबी स्वीकार्य प्रतिरोधक प्रतिक्रिया और ऊर्जा अपव्यय है। एसआरबीबी के डिजाइन पैरामीटर परंपरागत बीआरबी के मुकाबले 4% के अक्षीय कोर तनाव के बराबर हैं।

सफलतापूर्वक, बीआरबी की बराबर लोचदार अक्षीय कठोरता में भिन्नता बीआरबी के विभिन्न खंडों को रैखिक वसंत मॉडल के रूप में मानते हैं। संख्यात्मक अध्ययनों से पता चलता है कि बीआरबी की लंबाई में कमी और क्षेत्रों के क्रॉस-आंशिक क्षेत्र में वृद्धि से बीआरबी की अक्षीय कठोरता में सुधार हो सकता है। दोनों कम चक्र थकान मानदंड और उच्च मोड संपीड़न बिलिंग मानदंडों को बढ़ाए अक्षीय कठोरता के लिए बीआरबी के मुख्य क्षेत्रों की उपज की सीमा निर्धारित करने के लिए माना जाता है। कम चक्र थकान मानदंडों के मामले में, कॉफ़ीन-मैन्शन रिलेशन का उपयोग कोड के साथ किया जाता है, जो कि बीआरबी के लिए चक्रीय लोडिंग प्रोटोकॉल क्वालिफाइंग है। दो दृष्टिकोणों में से, उच्चतम मूल्य को बीआरबी के कोर उपज सेगमेंट के लिए सीमित अवधि के रूप में लिया जाता है। वाणिज्यिक सॉफ्टवेयर एबीएक्यूयूएस का उपयोग करके बीआरबी की चक्रीय प्रतिक्रिया का अनुमान लगाने के लिए परिमित तत्व विश्लेषण किया जाता है। परिमित तत्व मॉडल में भिन्न मुख्य पैरामीटर बीआरबी की मुख्य उपज लंबाई हैं। इन मॉडलों को एसआरबीबीएस के घटक परीक्षण के परिणाम से सत्यापित किया गया है। विश्लेषण परिणाम लोचदार और बाद की लोचदार कठोरता के साथ-साथ विभिन्न मुख्य उपज लंबाई के लिए बीआरबी की लोचदार कठोरता के बाद उपज कठोरता के अनुपात में भिन्नता की मात्रा निर्धारित करते हैं।

उप-संयोजन परीक्षण छह एचबीआरबी नमूनों पर उलट किए गए चक्रीय लोडिंग शर्तों के तहत आयोजित किए जाते हैं। इस प्रयोगात्मक जांच का मुख्य उद्देश्य समग्र चक्रीय प्रतिक्रिया का अध्ययन करना है, बीआरबी और बीटीबी खंडों के बीच संबंधों का व्यवहार और एचबीआरबी नमूनों की विफलता के तरीके। एसबीआरबी के घटक परीक्षण में प्रयुक्त एक ही बाकिंग निरोधक व्यवस्था को एचबीआरबी नमूनों के एसआरबीबी खंड के लिए माना गया है। एचबीआरबी नमूनों के बीटीबी और बीआरबी खंडों के इंटरफेस में एक कठोर कनेक्शन को अपनाया गया है। परीक्षण के परिणाम बताते हैं कि एचबीआरबी के पास स्थिर और संतुलित हिस्टैरिसीस के साथ उत्कृष्ट ऊर्जा अपव्यय क्षमता है। उच्च अक्षीय तनाव स्तरों पर एचआरबीबी के लिए शक्ति समायोजन कारकों को बढ़ाया जाना पाया जाता है अंत में, चार अलग-अलग प्रकार के ब्रेसिज़, अर्थात, बीटीबी, बीआरबी, एसआरबीबी और एचबीआरबी के साथ विभिन्न ऊंचाइयों के ढक्कन के फ्रेम पर एक संख्यात्मक अध्ययन किया गया है। प्रतिक्रिया संशोधित कारक के दो अलग-अलग मूल्यों को अध्ययन फ्रेम के डिजाइन में माना जाता है। गैर-रैखिक स्थैतिक और गतिशील विश्लेषण ने निष्कर्ष निकाला कि एचबीआरबीएफ और एसआरबीबीएफ ने डिजाइन आधार भूकंप के तहत कम बहाव की प्रतिक्रिया और एसआरबीबी और एचबीआरबी पर लचीलापन की मांग में मामूली वृद्धि के साथ अधिकतम भूकंप के खतरे के स्तर का प्रदर्शन किया।

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$\bar{\varepsilon}^{pl}$	Equivalent plastic strain
$\dot{\bar{\varepsilon}}^{p}$	Equivalent plastic strain rate
Q_∞	Limiting change of the size of the yield surface
A_b	Cross sectional area of elastic segment of HBRB
A_c	Cross sectional area of S/H/BRB core
A_{eff}	Effective cross sectional area in compression
A_j	End/connection zone cross sectional area of S/H/BRB
A_t	Transition zone cross sectional area of S/H/BRB
b	Rate of change of yield with respect to plastic strain
b_c	Width of core plate of S/H/BRB
C_1	Hardening law parameter
C_d	Deflection amplification factor
C_k	Initial kinematic hardening moduli
C_p	Material constant for Coffin-Mansion relationship
C_s	Seismic response co-efficient
C_t	Building period co-efficient
C_{vx}	Vertical lateral load distribution factor
C_β	Slope co-efficient for compression strength adjustment factor
C_ω	Slope co-efficient for tension strength adjustment factor
d/t	Width to thickness ratio
$D^{+/-}$	Maximum tensile and compression displacement in braces
D_{bi}	Displacement amplitude of the loading in i^{th} cycle
D_{bm}	S/H/BRB deformation corresponding to 1% of story drift
D_{by}	Yield displacement of S/H/BRB for ductility calculation
d_i	Perpendicular distance to the frame from the centre
D_{mxm}	Maximum displacement of S/H/BRB for ductility calculation
$D_{plastic}$	Plastic deformation of S/H/BRB for ductility calculation
E	Young's modulus of the material
e_{acc}	Accidental torsional eccentricity

E_{loop}	Area of force-displacement hysteresis loop
$F^{+/-}$	Maximum tensile and compression force in braces
F_a	Site co-efficient corresponding to short period (0.2s)
F_{cr}	Critical buckling stress
F_e	Elastic buckling stress
F_v	Site co-efficient corresponding to long period (1.0s)
F_x	Vertical lateral distribution of seismic force
F_y	Nominal yield stress of HSS/Beams/Columns
f_y	Nominal yield stress of S/H/BRB core
f_{yp}	Nominal yield stress of mild steel plate
h_i /h_x	Height from the base to the level i or x
h_n	Total height of the structure
I_c	Moment of inertia of S/H/BRB cross section
I_e	Importance factor of the building
K	Effective length factor
k	Time period exponent
K_e	Effective elastic axial stiffness
K_{eq}	Equivalent axial stiffness
K_i	Spring stiffness of member
K_o^{NM}	Base state stiffness matrix
K_p	Material constant for Coffin-Mansion relationship
K_{py}	Post yield stiffness
K_Δ^{NM}	Load stiffness matrix
K_ς	Regression co-efficient for equivalent viscous damping
L	Work point to work point or end to end length of member
L_b	Length of elastic segment of HBRB
L_j	Length of end/connection zone of S/H/BRB
L_t	Length of transition zone of S/H/BRB
L_{yc} /L_c	Length of yielding core of S/H/BRB
M_β	Slope co-efficient for compression strength adjustment factor
$M_{\beta\omega}$	Slope co-efficient for combined strength adjustment factor
M-θ	Moment – rotation interaction
M_ω	Slope co-efficient for tension strength adjustment factor

n	Higher mode compression buckling order
N	Number of back stresses
N_f	Number of fatigue cycles before failure
N_{fi}	number of cycles required to cause failure in i^{th} cycle
N_i	Number of displacement strain amplitudes in i^{th} cycle
P_C	S/H/BRB design compressive force
P_{cr}	Buckling strength of BTB
$P\text{-}M$	Axial load – moment interaction
P^N	Prior loading in the FE model
P_T	S/H/BRB design tensile force
P_{uc}	S/H/BRB maximum compressive force reached
P_{ut}	S/H/BRB maximum tensile force reached
P_y	Tensile yield strength of BTB
P_{yt}	S/H/BRB tensile yield force
Q_E	Earthquake load
Q^N	Incremental loading
R	Response modification factor
R_i	Frame participation factor for sharing the lateral load
r_{min}	Radius of gyration (critical)
R_y	Material over-strength factor
S_1	Mapped MCE spectral response acceleration parameter at long period (1s)
S_{D1}	Design spectral response acceleration parameter at long period (1s)
S_{DS}	Design spectral response acceleration parameter at short periods (0.2s)
S_{M1}	MCE spectral response acceleration parameter at long period (1s)
S_{MS}	MCE spectral response acceleration parameter at short periods (0.2s)
S_S	Mapped MCE spectral response acceleration parameter at short periods (0.2s)
t	Thickness of the member
T_a	Approximate time period of the structure
t_c	Thickness of the S/H/BRB steel core plate
V	Design base shear

v_i^M	Different buckling mode
V_i^M,	Normalized vector
W	Seismic weight of the structure
w_i / w_x	Portion of the total effective seismic weight at height *i* or *x*
α_k	Back stress co-efficient
β	Compression strength adjustment factor
γ_I	Hardening law parameter
γ_k	Rate of decrease of kinematic hardening moduli
Δ_b	Brace deformation for axial strain calculation of BRBFs
Δ_{by}	Yield displacement of brace
δ_x	Elatic lateral stiffness of braced frame
δ_{xe}	Inelatic lateral stiffness of braced frame
$\varepsilon/\varepsilon_c$	Axial core strain of brace
ε_e	Elastic strain
ε_p	Plastic strain
ε_t	Total axial core strain of braces
λ	Damage index co-efficient
λ_i	Eigen value
μ	Mean
$\mu+\sigma$	Mean + standard deviation (SD)
μ_{cum}	Cumulative ductility demand
μ_{mxm}	Maximum ductility demand
σ	Effective stress tensor
ς_{eq}	Equivalent viscous damping
σ_o	Yield stress corresponding to zero plastic strain
σ^o	Initial yield stress
$\sigma_x/ \sigma_y/ \sigma_x$	Stresses along *x*, *y* and *z* axis
ϕ	Resistance factor (LRFD)
Ω	System over-strength factor
ω	Tension strength adjustment factor

LIST OF ACRONYMS

ADAS	Added damping and added stiffness
AISC	American institute of steel construction
ANSI	American national standard institute
ASCE	American society of civil engineers
ATC	Applied technology council
BIB	Buckling inhibited braces
BRB	Buckling-restrained brace
BRBF	Buckling-restrained braced frame
BTB	Buckling type brace
CBF	Concentrically braced frame
C-BRB	Conventional full length BRB
CUREE	Consortium of universities for research on earthquake engineering
DBE	Design basis earthquake
DI	Damage index
DL	Dead load
EBF	Eccentrically braced frame
FE	Finite element
FEA	Finite element analysis
FEMA	Federal emergency management agency
FPB	Friction pendulum bearing
HBF	Hybrid braced frame
HBRB	Hybrid buckling-restrained brace
HBRBF	Hybrid buckling-restrained braced frame
HCS	Hollow circular steel section
HDEB	High damping elastomeric bearing
HDRB	High damping rubber bearing
HSS	Hollow square/rectangular steel section
IBC	International building code
ICC	International code council
ISDR	Inter-story drift ratio

LL	Live load
LRB	Lead rubber bearing
LRFD	Load and resistance factor design
LVDT	Linearly variable differential transformer
MBRB	Miniature BRB
MCE	Maximum considered earthquake
MRF	Moment resisting frame
NCREE	National center for research on earthquake engineering
PBPD	Performance based plastic design
RDR	Residual drift ratio
RLBRB	Reduced length BRB
SAC	SEAOC + ATC + CUREE
SAFYD	Shear and flexural yielding damper
SBRB	Short-yielding core-length BRB
SBRBF	Short-yielding core-length BRB frame
SCBF	Special concentrically braced frame
SCED	Self centering energy dissipative device
SD	Standard deviation
SEAOC	Structural engineers association of California
SEI	Structural engineering institute
SMRF	Special moment resisting frame
TADAS	Triangular ADAS
TMF	Truss moment resisting frame
USGS	United states geological survey
UTM	Universal testing machine