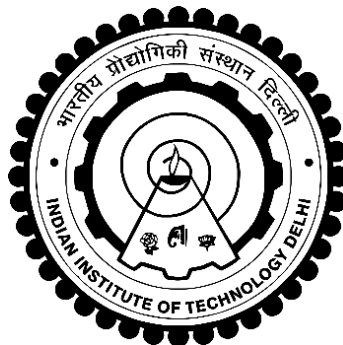


DEVELOPMENT AND SEISMIC PERFORMANCE ASSESSMENT OF ALL- STEEL SELF-CENTERING BUCKLING- RESTRAINED BRACES

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INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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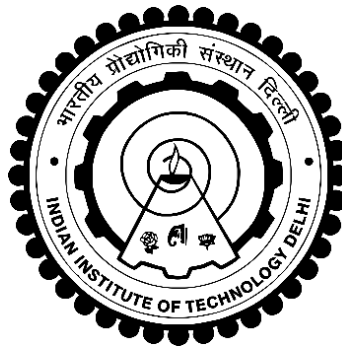
DEVELOPMENT AND SEISMIC PERFORMANCE ASSESSMENT OF ALL- STEEL SELF-CENTERING BUCKLING- RESTRAINED BRACES

by

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



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OCTOBER 2019

CERTIFICATE

This is to certify that the thesis entitled, ***“Development and Seismic Performance Assessment of All-steel Self-Centering Buckling-Restrained Braces”*** being submitted by ***Ahmad Fayeq Ghowsi*** 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 our supervision and guidance. The thesis, in our 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.

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- Ahmad Fayege Ghowsi

ABSTRACT

Conventional concentrically buckling-type steel braces are adopted as lateral force-resisting systems to increase the lateral strength, lateral stiffness, and displacement ductility. However, the global buckling of these braces under axial compressive loads results in the low-cyclic fatigue failure and the reduced energy dissipation potential under cyclic loading. This may lead to the formation of soft-story hinge mechanism in concentrically braced frames. Buckling-restrained braces (BRBs) are the special type of braces capable of yielding both in tension and compression loadings. Thus, BRBs exhibit the stable and nearly-symmetric hysteretic response with excellent displacement ductility under inelastic cyclic deformation. Conventional BRBs are consisted of the central yielding core elements restrained by mortar-filled casings. The main limitation of buckling-restrained frames (BRBFs) is their excessive residual drift response under major seismic events.

The present study is focused on the development of all-steel BRBs (ABRBs) with better self-centering potential in order to limit the excessive residual drift response of BRBFs. A numerical investigation has been conducted to study the influence of various geometric parameters, such as, friction and gap clearance between the central core element and restraining systems, the position and detailing of stoppers on the core elements, and the length of yielding core elements on the cyclic performance of all-steel BRBs. A parametric study has been carried out using finite element analysis method to determine the optimum values of these design parameters. An experimental investigation has also been conducted on ABRBs having the steel yielding core elements and the built-up steel angle sections as the restraining systems to study their hysteretic response and overall performance under cyclic loading. The influence of extruded and welded stoppers on the core elements on the cyclic performance of ABRBs has been evaluated.

In order to improve the self-centering potential, the ferrous-based shape-memory alloy (Fe-SMA), instead of steel, is used in the yielding core elements of ABRBs. Fe-SMA has the potential of providing self-centering during as well as the cyclic loading using heat treatment. Fe-SMA is used only in the central yielding segments those are welded to the elastic end segments of ABRBs. Five large-scale sub-

assemblages consisting of FSMA BRB and the conventional structural steel sections have been tested under cyclic loading conditions. The detailing of core plates and the position of stoppers of BRBs are varied in the experimental investigation. The main parameters investigated are the hysteretic response, failure mechanisms, strength-adjustment factors, and energy dissipation potential of FSMA BRBs

Self-centering BRBs consisting of SMA rods along with steel core BRBs have been proposed in the literature. In this study, a parametric study has been conducted numerically to determine the influence of geometric properties of SMA rods on the cyclic performance of self-centering BRBs. Both length and area of SMA rods are varied in relative to those of the core elements of BRBs. The results of parametric study are utilised in a study building to investigate its seismic performance. Nonlinear time-history analysis has been conducted on the study frames with self-centering braces.

A new self-centering BRB consisting of SMA rods using a single outer casing has been developed in this study. Two Nickel Titanium (NiTi) SMA rods are placed symmetrically with respect to BRB core element. Experimental investigation has been conducted on three self-centering BRB sub-assemblages with varying pre-stress levels in SMA rods. The tests results proved the concept of telescopic braces with reduced number of elements. Finally, a set of building frames representing the low- to high-rise structures are considered for the evaluation of seismic response. These building frames are designed as braced frames considering BRBs, self-centering BRBs and the combination of both. Nonlinear static and dynamic analyses are conducted to evaluate the lateral strength, failure mechanism, interstory drift and residual drift response of the study frames. Ground motion time-histories representing the near-field earthquakes have been considered in the nonlinear dynamic analyses. Both experimental and numerical investigations concluded that the self-centering BRBs not only exhibited the excellent energy dissipation potential but also controlled the residual drift response of prototype building frames.

सार

परम्परागत रूप से बकलिंग-टाइप स्टील ब्रेस को पार्श्व बल प्रतिरोध प्रणाली के रूप में अपनाया जाता है ताकि पार्श्व शक्ति, पार्श्व कठोरता और विस्थापन नमनीयता बढ़े। हालांकि, अक्षीय संपीड़ित भार के तहत इन ब्रेसिज की वैश्विक बकसुआ कम चक्रीय थकान की विफलता और चक्रीय लोडिंग के तहत कम ऊर्जा अपव्यय क्षमता का परिणाम है। यह केंद्रित रूप से बहादुरी फ्रेम में नरम-कहानी काज तंत्र के गठन का कारण बन सकता है। बकलिंग-संयमित ब्रेसिज (बी-आर-बी) एक विशेष प्रकार के ब्रेसिज हैं जो तनाव और संपीड़न भार दोनों में उपजाने में सक्षम हैं। इस प्रकार, बी-आर-बी, स्थिर और चक्रीय हिस्टैरिकेटिक प्रतिक्रिया का प्रदर्शन करता है, जो कि इनैलास्टिक चक्रीय विरूपण के तहत उत्कृष्ट विस्थापन नमनीयता के साथ होता है। पारंपरिक बीआरबी में मोटार से भरे केसिंग द्वारा नियंत्रित केंद्रीय उपज मूल तत्व शामिल हैं। बकलिंग-संयमित फ्रेम (बी-आर-बी-एफ) की मुख्य सीमा प्रमुख भूकंपीय घटनाओं के तहत उनकी अत्यधिक अवशिष्ट बहाव प्रतिक्रिया है।

वर्तमान अध्ययन बी-आर-बी-एफ के अत्यधिक अवशिष्ट बहाव की सीमा को सीमित करने के लिए बेहतर आत्म-केंद्रित क्षमता के साथ ऑल-स्टील बी-आर-बी (ए-बी-आर-बी) के विकास पर केंद्रित है। विभिन्न ज्यामितीय मापदंडों के प्रभाव का अध्ययन करने के लिए एक संख्यात्मक जांच का आयोजन किया गया है, जैसे, केंद्रीय कोर तत्व और निरोधक प्रणालियों के बीच घर्षण और अंतराल निकासी, मुख्य तत्वों पर स्टॉपर्स की स्थिति और विवरण, और मूल तत्वों की लंबाई ए-बीआरबी का चक्रीय प्रदर्शन। इन डिजाइन मापदंडों के इष्टतम मूल्यों को निर्धारित करने के लिए परिमित तत्व विश्लेषण पद्धति का उपयोग करके एक पैरामीट्रिक अध्ययन किया गया है। ए-बी-आर-बी पर एक प्रयोगात्मक जांच की गई है जिसमें स्टील उपज मूल तत्व और अंतर्निहित स्टील एंगल सेक्शन हैं जो चक्रीय लोडिंग के तहत उनकी हिस्टैरिकेटिक प्रतिक्रिया और समग्र प्रदर्शन का अध्ययन करने के लिए निरोधक प्रणाली के रूप में हैं। ए-बी-आर-बी के चक्रीय प्रदर्शन पर मूल तत्वों पर एक्सट्रूडेड और वेल्डेड- स्टॉपर्स के प्रभाव का मूल्यांकन किया गया है।

स्व-केंद्रित क्षमता में सुधार करने के लिए, लौह-आधारित आकृति-मेमोरी मिश्र धातु (एफ-एस-एम-ए), स्टील के बजाय, एबीआरबी के प्रमुख तत्वों का उपयोग किया जाता है। एफ-एस-एम-ए में गर्मी उपचार का उपयोग करते हुए चक्रीय लोडिंग के दौरान आत्म-केंद्र प्रदान करने की क्षमता है। एफ- एस-एम-ए का उपयोग केवल केंद्रीय उपज वाले खंडों में किया जाता है जिन्हें ए-बी-आर-बी के लोचदार अंत खंडों में वेल्डेड किया जाता है। एफ-एस-एम-ए-बी-आर-बी और पारंपरिक संरचनात्मक इस्पात वर्गों से युक्त पांच बड़े पैमाने पर उप-असेंबलियों का चक्रीय लोडिंग परिस्थितियों में परीक्षण किया गया है। प्रायोगिक जांच में कोर प्लेटों के विवरण और बीआरबी के स्टॉपर्स की स्थिति भिन्न होती है। जांच किए गए मुख्य पैरामीटर हिस्टैरिकेटिक प्रतिक्रिया, विफलता तंत्र, शक्ति-समायोजन कारक और एफ-एस-एम-ए-बी-आर-बी की ऊर्जा अपव्यय क्षमता हैं।

साहित्य में स्टील कोर बी-आर-बी के साथ-साथ एस-एम-ए रॉड से मिलकर स्व-केंद्रित बी-आर-बी प्रस्तावित किया गया है। इस अध्ययन में, स्व-केंद्रित बी-आर-बी के चक्रीय प्रदर्शन पर एस-एम-ए छड़ के ज्यामितीय गुणों के प्रभाव को निर्धारित करने के लिए संख्यात्मक रूप से एक पैरामीट्रिक अध्ययन किया गया है। एस-एम-ए रॉड की लंबाई और क्षेत्रफल बी-आर-बी के मूल तत्वों के

सापेक्ष भिन्न हैं। पैरामीट्रिक अध्ययन के परिणामों को अपने भूकंपीय प्रदर्शन की जांच के लिए एक अध्ययन भवन में उपयोग किया जाता है। नॉनलाइनियर टाइम-हिस्ट्री एनालिसिस स्टडी फ्रेम पर सेल्फ सेंट्रिंग ब्रेसेस के साथ किया गया है।

इस अध्ययन में एक एकल बाहरी आवरण का उपयोग करते हुए एस-एम-ए छड़ से युक्त एक नया आत्म-केंद्रित बीआरबी विकसित किया गया है। दो निकेल टाइटेनियम (नी-ताई) एस-एम-ए रॉड को बी-आर-बी कोर तत्व के संबंध में सममित रूप से रखा गया है। तीन आत्म-केंद्रित बी-आर-बी उप-संयोजनों पर प्रायोगिक जांच एस-एम-ए-रॉड में पूर्व-तनाव के स्तर के साथ आयोजित की गई है। परीक्षण के परिणाम तत्वों की कम संख्या के साथ दूरबीन ब्रेसिज की अवधारणा साबित हुए। अंत में, भूकंपीय प्रतिक्रिया के मूल्यांकन के लिए कम-से-ऊँची संरचनाओं का प्रतिनिधित्व करने वाले फ्रेम का एक सेट माना जाता है। इन बिल्डिंग फ्रेम को बी-आर-बी, सेल्फ-सेंट्रिंग बी-आर-बी और दोनों के संयोजन को देखते हुए लटके हुए फ्रेम के रूप में डिजाइन किया गया है। नॉनलेयर स्टैटिक और डायनेमिक एनालिसिस स्टडी फ्रेम की लेटरल स्ट्रेंथ, फेल्योर मैकेनिज्म, इंटरस्टोरी ड्रिफ्ट और रेजीड्यूअल ड्रिफ्ट रिस्पॉन्स का मूल्यांकन करने के लिए किया जाता है। निकट-क्षेत्र के भूकंपों का प्रतिनिधित्व करने वाले ग्राउंड मोशन टाइम-हिस्ट्री को नॉनलाइनियर डायनामिक एनालिसिस में माना गया है। दोनों प्रयोगात्मक और संख्यात्मक जांच ने निष्कर्ष निकाला कि स्व-बी-आर-बी ने न केवल उत्कृष्ट ऊर्जा अपव्यय क्षमता का प्रदर्शन किया, बल्कि प्रोटोटाइप निर्माण फ्रेम के अवशिष्ट बहाव प्रतिक्रिया को भी नियंत्रित किया।

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LIST OF SYMBOLS

$\bar{\epsilon}^{pl}$	Equivalent plastic strain
$\dot{\bar{\epsilon}}^p$	Equivalent plastic strain rate
ϵ_r	Residual strain
A_c	Cross-sectional area of BRB core
b	Rate of change of yield with respect to plastic strain
C_0	Gap clearance from the contact pressure
C_1	Initial kinematic hardening modulus
C_d	Deflection amplification factor
C_k	Material constant for hardening model
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
d	Surface to surface contact penetration distance
D	Overall damage value
$D^{+/-}$	Maximum tensile and compression displacement in braces
D_{bi}	Displacement amplitude of the loading in i^{th} cycle
D_{bm}	ABRB deformation corresponding to 1% of story drift
D_{by}	Yield displacement of ABRB of ductility calculation
D_{mxm}	Maximum displacement of ABRB of ductility calculation
$D_{plastic}$	Plastic deformation of ABRB of ductility calculation
E	Young's modulus of the material
E_i	Initial elastic modulus
e	Initial contact penetration distance
E_{loop}	Area of the force-displacement hysteresis loop
f_f	Friction forces
$F^{+/-}$	Maximum tensile and compression force in braces
F_a	Site co-efficient corresponding to a short period (0.2s)

F_v	Site co-efficient corresponding to a long period (1.0s)
F_x	Vertically lateral distribution of seismic force
F_y	Nominal yield stress of HSS
f_y	Nominal yield stress of 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_e	Importance factor of the building
i	Refers to the buckling mode at i^{th} mode shape
K	Effective length factor
k	Time-period exponent
K_e	Effective elastic axial stiffness
K_0^{NM}	stiffness matrix corresponding to the base state
K_{Δ}^{NM}	Differential of initial stress and load of stiffness matrix
K_i	Initial penalty stiffness
K_f	Final penalty stiffness
K_{Total}	Total stiffness
K_{ABRB}	Axial stiffness of ABRB
K_{frame}	Lateral stiffness of frame
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_c	Length of yielding core of BRB
M	Eigen vectors
N	Number of backstresses
n	Higher mode compression buckling order
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_{uc}	ABRB maximum compressive force reached
P_{ut}	ABRB maximum tensile force reached
P_{yt}	ABRB tensile yield force
Q^N	Incremental loading
Q_∞	The maximum change in the size of the yield surface
R	Response modification factor
R_y	Material over-strength factor
SP	String-pot potentiometer
SG	Strain gauges
S_s	Gap of restraining from strong surface of BRB
S_w	Gap of restraining from the weak surface of BRB
S_1	Mapped MCE spectral response acceleration parameter at 1s
S_{D1}	Design spectral response acceleration parameter at 1s
S_{DS}	Design spectral response acceleration parameter at short periods (0.2s)
S_{M1}	MCE spectral response acceleration parameter at 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 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_c	Wide of the BRB core plate
$w_i / center$	Portion of the total effective seismic weight at height i or x
α_k	Backstress
β	Compression strength adjustment factor
γ_k	Rate of decrease of kinematic hardening moduli
Δ_{by}	Yield displacement of brace

$\varepsilon/\varepsilon_c$	Axial core strain of brace
ε_p	Elastic strain
ε_p	Plastic strain
ε_t	Total axial core strain of braces
λ_i	Eigen value
μ	Ductility
Ave	The calculated mean value from Inter story and residual drift
$Ave+\sigma$	Mean + standard deviation
μ_{cum}	Cumulative ductility demand
μ_{mxm}	Maximum ductility demand
σ	Effective stress tensor
ξ	The damping of the system
η	Stress triaxiality
Δ_d	the maximum displacement
σ_L	Transformation stress
σ_{UL}	Revers transformation stress
ξ_{eq}	Equivalent viscous damping
λ_i	The eigen value
ν_i^M	The buckling mode
ζ_e	Equivalent viscous damping
$\sigma _0$	Initial yield stress
γ	The rate at which the kinematic hardening modulus decreases
$\sigma_x/\sigma_y/\sigma_z$	Stresses along x, y and z-axis
ω	Tension strength adjustment factor
ω_n	The natural frequency of the system
Ω	System over-strength factor

LIST OF ACRONYMS

ADAS	Added damping and added stiffness
AISC	American institute of steel construction
ANSI	American national standard institute
ASCE	American institute of civil engineers
ABRBs	All-steel buckling restrained brace
BC	Beam-column connection
BRB	Buckling-restrained brace
BRBF	Buckling-restrained braced frame
BFRP	Basalt fiber reinforced polymer
CBF	Concentrically braced frame
DBE	Design basis earthquake
DC-SCB	Dual-core self-centering braces
EBF	Eccentrically braced frame
FE	Finite element
FEMA	Federal emergency management agency
Fe	Ferus
FSMA	Ferus based shape memory alloy
HCS	Hollow circular steel section
HSS	Hollow square/rectangular steel section
ISDR	Inter-story drift ratio
MCE	Maximum considered earthquake
MRF	Moment resisting frame
NAO	Non-asbestos-organic material
NiTi	Nickle and Titanium
NRCD	Non-re-centering devices
PT	Post-tensioning
RDR	Residual drift ratio
RCD	Re-centering devices
SAC	SEAOC + ATC +
SAFYD	Shear and flexural-yielding damper
SC	Self-centering

SCB	self-centeirng braces
SCBF	Special concentrically braced frame
SC-BRB	Self-centering buckling restrained braces
SCED	Self-centering energy dissipative device
SD	Standard deviation
SDOF	Single degree of freedom
SEAOC	Structural engineers association of California
SFDB	self-centering friction damping brace
SFDB-NF	SFDB without friction element
SMA	Shape memory alloy
SMRF	Special moment-resisting frame
SRCD	Supplemental re-centering devices
TADAS	Triangular ADAS
UTM	Universal testing machine
UMAT	User define material