LOCAL AND GLOBAL PERFORMANCE ASSESSMENT AND SEISMIC DESIGN OF SPECIAL CONCENTRICALLY BRACED FRAMES

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LOCAL AND GLOBAL PERFORMANCE ASSESSMENT AND SEISMIC DESIGN OF SPECIAL CONCENTRICALLY BRACED FRAMES

by

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

This is to certify that the thesis entitled, "**Local and Global Performance Assessment and Seismic Design of Special Concentrically Braced Frames**" being submitted by **P. C. Ashwin Kumar** 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.

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P. C. Ashwin Kumar

ABSTRACT

Special concentrically braced frames (SCBFs) are used as the primary lateral force resisting systems (LFRSs) in buildings located in high seismic regions. However, past studies have shown that these systems may collapse prematurely due to the occurrence of soft-story mechanism, low-cyclic fatigue fracture of braces or failure of gusset plate connections or failure of foundation of braced frame columns. Hence, there is a need for further research to improve the seismic performance of the SCBFs.

This study is focussed on the performance evaluation and improvement of braced frames at the local (component/ sub-assemblage) and global (system) levels. Nonlinear finite element (FE) analysis has been conducted to predict the overall cyclic response and low-cyclic fatigue fracture of hollow square (HSS) and circular (HCS) braces. Both slenderness ratio and width (or diameter)-to-thickness ratio of braces have been varied in this study to compare their cyclic response and ductility. Slow-cyclic tests have also been carried out on three HSS and six HCS brace specimens to evaluate their cyclic response and to validate the numerical study results. A relationship between the limiting values of brace slenderness ratio and width (or diameter)-to-thickness ratio has been proposed to achieve the desired displacement ductility of the HSS and HCS braces. Both numerical and experimental studies have been conducted on the brace-gusset plate assemblies for varying values of brace slenderness ratios and linear clearance in gusset plate detailing. Based on these studies, an optimum value of linear clearance in the detailing of middle gusset plates has been proposed.

In order to avoid the soft-story collapse of SCBFs, the current seismic design procedure has been modified in this study using different design approaches. These modified design procedures are based on quantifying the force demands in the components in the post-elastic stages of SCBFs. Nonlinear static and dynamic analyses have been conducted on the modified-designed SCBFs for varying frame heights and brace configurations. The modified design procedures resulted in improved seismic performance without any soft-story failure of SCBFs. Finally, the efficacy of the staggered braced frames has been investigated in order to eliminate the foundation failure of braced frame columns. Based on the findings of this study, recommendations are also provided for the design of braced frames in the Indian context.

सार

विशेष सांद्रता वाली तंतुओं वाले फ्रेम (एससीबीएफ) को उच्च पार्श्वक क्षेत्रों में स्थित इमारतों में प्राथमिक पार्श्व बल प्रतिरोध प्रणाली (एलएफआरएस) के रूप में उपयोग किया जाता है। हालांकि, पिछले अध्ययनों से पता चला है कि ये तंत्र नरम-मंजिला तंत्र, ब्रेकन्स की कम चक्रीय थकान फ्रैक्चर या गसैट प्लेट कनेक्शन की विफलता या ब्रेस्टेड फ्रेम कॉलम की नींव की विफलता के कारण समय से पहले ही गिर सकता है। इसलिए एससीबीएफ के भूकंपीय प्रदर्शन को बेहतर बनाने के लिए आगे की शोध की आवश्यकता है।

यह अध्ययन स्थानीय (घटक / उप-संयोजन) और वैश्विक (सिस्टम) स्तरों पर प्रदर्शन मूल्यांकन और फ्रेम के सुधार पर केंद्रित है। कुल चक्रीय प्रतिक्रिया और खोखले वर्ग (एचएसएस) और सर्कुलर (एचसीएस) ब्रेसिज़ की कम चक्रीय थकान फ्रैक्चर का अनुमान लगाने के लिए गैर-रेखीय परिमित तत्व (एफई) विश्लेषण किया गया है। चक्रीय प्रमेय और लचीलापन की तुलना करने के लिए इस अध्ययन में धीमे अनुपात और चौड़ाई (या व्यास)-मोटाई अनुपात दोनों अलग-अलग हैं। तीन एचएसएस और छह एचसीएस ब्रेस नमूनों पर धीरे-चक्रीय परीक्षण भी किए गए हैं ताकि उनकी चक्रीय प्रतिक्रिया का मूल्यांकन किया जा सके और संख्यात्मक अध्ययन परिणामों को मान्य किया जा सके। एचएसएस और एचसीएस ब्रेसिज़ की वांछित विस्थापन लचीलापन हासिल करने के लिए ब्रेस स्लेडेनेस अनुपात और चौड़ाई (या व्यास) से मोटाई अनुपात के सीमित मूल्यों के बीच एक संबंध प्रस्तावित किया गया है। ब्रेस-गसेट प्लेट विधानसभाओं पर ब्रेस स्लेन्डेनेस अनुपात के गुणों को अलग-अलग और गसैट प्लेट में रैखिक निकासी में दोनों संख्यात्मक और प्रायोगिक अध्ययन आयोजित किए गए हैं। इन अध्ययनों के आधार पर, मध्य गस्रेट प्लेटों के विवरण में रैखिक निकासी का एक अधिकतम मूल्य प्रस्तावित किया गया है।

एससीबीएफ के नरम मंजिला पतन से बचने के लिए, विभिन्न डिजाइन दृष्टिकोणों का उपयोग करते हुए इस अध्ययन में वर्तमान भूकम्पीय डिजाइन प्रक्रिया को संशोधित किया गया है। इन संशोधित डिजाइन प्रक्रिया एससीबीएफ के बाद के लोचदार चरणों में घटकों में बल मांगों को बढ़ाते हुए आधार पर आधारित होती है। फ्रेम हाइट्स और ब्रेस कॉन्फ़िगरेशन के लिए संशोधित-डिज़ाइन एससीबीएफ पर गैर-अक्षीय स्थिर और गतिशील

विश्लेषण किया गया है। संशोधित डिजाइन प्रक्रियाओं के परिणामस्वरूप एससीबीएफ की कोई नरम मंजिल की विफलता के बिना बेहतर भूकंपीय प्रदर्शन में हुई। अंत में, लटकी हुई फ़्रेम कॉलम की नींव विफलता को खत्म करने के लिए कंपकंपीदार तख्ते के फ्रेम की जांच की गई है। इस अध्ययन के निष्कर्षों के आधार पर, भारतीय संदर्भ में ढक्कन के फ्रेम के डिजाइन के लिए सुझाव भी प्रदान किए जाते हैं।

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LIST OF SYMBOLS

A_g	gross cross sectional area
A_{gv}	gross area of brace in shear
B/t	external width-to-thickness ratio
B_W	Whitmore's width
b	rate of change of yield surface
C_D	deflection amplification factor
C_k	initial kinematic hardening moduli
C_s	seismic response coefficient
C_T	building period coefficient
D	external diameter
D_M	damage variable
D/t	external diameter-to-thickness ratio
d_i	individual damage variable
E	Young's modulus
e_{EW}	eccentricity in east-west direction
e_{NS}	eccentricity in north-south direction
F	axial force
F_a	short period site coefficient
F_{cr}	critical compressive stress
F_{EXX}	filler metal strength
F_e	Euler buckling stress
F_u	ultimate strength of steel
F_v	long period site coefficient

F_y	material yield stress
f_{cr}	buckling stress
f_u	ultimate stress
GL	gauge length
h	story height
h_n	structure height
I_e	importance factor
i	i^{th} buckling mode
K	effective length coefficient
K_0^{NM}	stiffness matrix corresponding to base state
K_Δ^{NM}	differential initial stress and load stiffness matrix
L	length of brace
L_B	effective length of brace
L_C	brace to gusset connection length
L_1	gusset plate lengths
L_2	gusset plate lengths
L_3	gusset plate lengths
M	degree of freedom
M_p	plastic moment capacity
N	degree of freedom
N_S	number of shear planes
N_W	number of weld length
N_α	number of back stress
P	axial force
P_{cr}	buckling strength

P^N	preloads
P_u	ultimate tensile strength
P_{ut}	maximum expected capacity of brace in tension
P_y	axial yield load
p	pressure stress
Q	mises equivalent stress
Q^N	incremental load pattern
Q_∞	maximum change in yield surface
q	mises equivalent stress
R	response modification constant
R_y	ratio of expected yield stress to the specified minimum yield stress
r	radius of gyration
S_1	mapped MCE spectral response acceleration parameter at 1s
S_S	mapped MCE spectral response acceleration parameter at short periods
S_{DS}	design spectral response acceleration parameter at short periods
S_{D1}	design spectral response acceleration parameter at 1s
S_{MS}	MCE spectral response acceleration parameter at short periods
S_{M1}	MCE spectral response acceleration parameter at 1s
T_a	fundamental time period
t	thickness of the brace
t_f	brace wall thickness
t_p	thickness of gusset plate
V	story shear
v_i^M	eigen vectors
W	effective seismic weight

w_2	brace to gusset weld leg size
x	floor level under consideration
Z_p	plastic section modulus
α	overall back-stress
β	balance factor
λ	slenderness ratio
ε	strain
$\bar{\epsilon}^p$	equivalent plastic strain
$\dot{\bar{\epsilon}}^p$	equivalent plastic strain rate
γ_k	rate of decrease of kinematic hardening moduli
λ_i	eigen value
σ	effective stress tensor
$\bar{\sigma}$	stress in the material in the absence of damage
σ_y	yield stress
σ^0	initial yield stress
$\sigma\vert_0$	yield stress at zero plastic strain
η	stress triaxiality
ω_D	state variable
θ	story drift angle
Δ_a	axial deformation in brace
Δ	axial deformation
Δ_y	axial yield displacement
Ω	system over-strength factor
μ	mean
$\mu+\sigma$	mean plus standard deviation

LIST OF ACRONYMS

BF	base fixed
BP	base pinned
CBF	concentrically braced frame
CD	conventionally designed
CF	compression first
DBE	design basis earthquake
DOF	degree of freedom
FE	finite element
FEA	finite element analysis
HCS	hollow circular steel
HSS	hollow square steel
IDR	inter-story drift ratio
LFRS	lateral force resisting system
MCE	maximum considered earthquake
MRF	moment-resisting frame
OCBF	ordinary concentrically braced frame
SCBF	special concentrically braced frame
TF	tension first