

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

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

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*Submitted  
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to the*



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# 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 *Muhammed 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.

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# 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-Manson 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-assembly 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 ब्रेसिज (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 मजबूत फ्रैक्चर और नरम-कहानी तंत्र के गठन का परिणाम है। बक्ली-प्रतिरोधी ब्रेसिज (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 ब्रेसिज 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 ब्रेसिज, अर्थात्, पारंपरिक फ्रेमिंग प्रकार के ब्रेसिज (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 डिजाइन 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 बढ़ाएँ 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, कॉफीन-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 हिस्टैरिसिस के साथ उत्कृष्ट ऊर्जा अपव्यय क्षमता है। उच्च अक्षीय तनाव स्तरों पर एसआरबीबी के लिए शक्ति समायोजन कारकों को बढ़ाया जाना पाया जाता है अंत में, चार अलग-अलग प्रकार के ब्रेसिज़, अर्थात्, 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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# LIST OF SYMBOLS

|                             |                                                               |
|-----------------------------|---------------------------------------------------------------|
| $\bar{\varepsilon}^{pl}$    | Equivalent plastic strain                                     |
| $\dot{\bar{\varepsilon}}^p$ | Equivalent plastic strain rate                                |
| $Q_\infty$                  | 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                                |
| $C_l$                       | 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                     |
| $C_\beta$                   | Slope co-efficient for compression strength adjustment factor |
| $C_\omega$                  | 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-Manson relationship              |
| $K_{py}$          | Post yield stiffness                                          |
| $K_d^{NM}$        | Load stiffness matrix                                         |
| $K_\zeta$         | 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                            |
| $M_\beta$         | Slope co-efficient for compression strength adjustment factor |
| $M_{\beta\omega}$ | Slope co-efficient for combined strength adjustment factor    |
| $M-\theta$        | Moment – rotation interaction                                 |
| $M_\omega$        | 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                                                    |
| $P-M$     | 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                                               |
| $S_I$     | Mapped MCE spectral response acceleration parameter at long period (1s)     |
| $S_{DI}$  | Design spectral response acceleration parameter at long period (1s)         |
| $S_{DS}$  | Design spectral response acceleration parameter at short periods (0.2s)     |
| $S_{MI}$  | 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 $x$ |
| $\alpha_k$                       | Back stress co-efficient                                           |
| $\beta$                          | Compression strength adjustment factor                             |
| $\gamma_l$                       | Hardening law parameter                                            |
| $\gamma_k$                       | Rate of decrease of kinematic hardening moduli                     |
| $\Delta_b$                       | Brace deformation for axial strain calculation of BRBFs            |
| $\Delta_{by}$                    | Yield displacement of brace                                        |
| $\delta_x$                       | Elastic lateral stiffness of braced frame                          |
| $\delta_{xe}$                    | Inelastic lateral stiffness of braced frame                        |
| $\varepsilon/\varepsilon_c$      | Axial core strain of brace                                         |
| $\varepsilon_e$                  | Elastic strain                                                     |
| $\varepsilon_p$                  | Plastic strain                                                     |
| $\varepsilon_t$                  | Total axial core strain of braces                                  |
| $\lambda$                        | Damage index co-efficient                                          |
| $\lambda_i$                      | Eigen value                                                        |
| $\mu$                            | Mean                                                               |
| $\mu + \sigma$                   | Mean + standard deviation (SD)                                     |
| $\mu_{cum}$                      | Cumulative ductility demand                                        |
| $\mu_{mxm}$                      | Maximum ductility demand                                           |
| $\sigma$                         | Effective stress tensor                                            |
| $\zeta_{eq}$                     | Equivalent viscous damping                                         |
| $\sigma_o$                       | Yield stress corresponding to zero plastic strain                  |
| $\sigma^o$                       | Initial yield stress                                               |
| $\sigma_x / \sigma_y / \sigma_z$ | Stresses along $x$ , $y$ and $z$ axis                              |
| $\phi$                           | Resistance factor (LRFD)                                           |
| $\Omega$                         | System over-strength factor                                        |
| $\omega$                         | 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                              |