

DEVELOPMENT AND SEISMIC PERFORMANCE EVALUATION OF BUCKLING-INHIBITED ALUMINUM AND STEEL SHEAR YIELDING DAMPERS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
MARCH 2022**

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by

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



INDIAN INSTITUTE OF TECHNOLOGY DELHI

MARCH 2022

CERTIFICATE

This is to certify that the thesis entitled, “*Development and Seismic Performance Evaluation of Buckling-inhibited Aluminum and Steel Shear Yielding Dampers*” being submitted by **Deepak Yadav** 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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This thesis is dedicated to my parents

*My journey from a village in Rajasthan to where I am today is only
because of their faith in the positive impact of education on society*

ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my supervisor **Prof. Dipti Ranjan Sahoo** for his invaluable guidance, encouragement, and support. I have learned a lot from his immense knowledge. His vision and hardworking attitude have deeply inspired me. It was a great privilege and honor to work under his supervision.

I would like to thank my SRC members, **Prof. Mukesh Khare**, **Prof. Vasant Matsagar** and **Prof. A.K. Darpe** for their reviews, suggestions, and insightful comments to make this research more impactful.

I would like to extend thanks to laboratory staff for their continuous support in my experiments. Support from my research colleagues in the experiments is also acknowledged, especially help by **Mr. Saurabh Sharma** in conducting the experiments is worth mentioning. I would like to thank my seniors **Dr. Romanbabu Oinam**, **Dr. Abhishek Verma**, and **Dr. P.C. Ashwin Kumar** for their guidance.

I would like to thank my parents **Smt. S.B. Yadav** and **Sh. R.C. Yadav**, my wife **Anju**, and my sisters **Priyanka** and **Supriya** for their unwavering support, love, and sacrifices. Support from my family kept me motivated to do this research work. I thank all my friends, especially **Hemant Kumar Jangid** and **Manish Saini**, for their continuous encouragement and support in my difficult times. I would like to extend thanks to **Piyush Santhalia**, **Rimpi Rajput** and **Rahul Bhartiya** for being on my side in this journey.

I am deeply grateful to **Bhagwan Shri Krishna** for showering me with blessings throughout my life and keeping me on the path of *Dharma*.

Deepak Yadav

ABSTRACT

Seismic-induced vibration of civil structures is often controlled through supplemental energy dissipation devices, thereby minimizing damages to the primary load-resisting elements. The vibration-control devices are broadly categorized as active, passive, semi-control, and hybrid devices. Metallic energy dissipation devices are used to dissipate the seismic energy through hysteresis due to the inelastic deformation of materials. These devices are strategically installed in a structure such that the energy dissipating elements would be subjected to relative axial/flexure/shear displacements under seismic loading. Dampers based on shear yielding of metallic plates exhibit excellent strength, ductility, and energy dissipation characteristics. However, the shear buckling and the presence of residual stresses of web plates not only influence the hysteretic energy dissipation but also may cause premature failure of these devices. This study is focused on the prediction of the cyclic performance of aluminum shear yielding devices (AlSYDs) as well as the development, testing, and numerical modeling of buckling-inhibited shear yielding devices (BISYDs).

A parametric study is conducted on eighteen AlSYDs numerical models developed in a computer software ABAQUS to investigate the influence of web aspect ratios, web slenderness ratios, and position of vertical stiffeners on their hysteretic behavior, energy dissipation potential, and displacement ductility. The energy dissipation potential of these devices is found to be strongly dependent on the aspect ratio and slenderness ratio of the web plates. A simplified expression has been proposed to estimate the hysteretic energy dissipation potential of AlSYDs. Limiting values of web aspect ratio and web slenderness ratio have been recommended for the design of AlSYDs.

A novel BISYD is developed in which the energy dissipating web plates of the hourglass and rectangular shapes are sandwiched between the built-up steel angle restrainers. Thin web plates having a high web slenderness ratio are used to fabricate the BISYDs. An experimental investigation has been conducted to investigate the seismic performance of BISYDs fabricated using three different materials (i.e., annealed aluminum Al-19000 alloy, unannealed aluminum Al-40800 alloy, and mild steel) as the web plates. Two specimens in each type of web plate are tested without the built-up steel angle restrainers to compare their cyclic performance with those of BISYDs. Test results demonstrated that the BISYDs made of annealed Al-19000 alloy showed very stable cyclic behavior and excellent energy dissipation potential in high shear strain levels as compared to BISYDs made of unannealed Al-40800 alloy and mild steel plates.

An analytical study is carried out to predict the lateral strength, initial stiffness, and post-yield stiffness of both aluminum and steel BISYDs. A simplified strut-and-tie-based macro model is proposed to predict the behavior of BISYDs which can be used to analyze the structures employing these devices in the commercial software. In this study, numerical investigations are carried out to evaluate the low-cyclic fatigue performance of aluminum BISYDs. The cumulative fatigue damage law is used to calibrate the fatigue design parameters for the BISYDs made of Al-6063 alloy material. Experimental investigations are also carried out to calibrate the cumulative fatigue damage law for BISYDs made of annealed Al-19000 alloy. Hourglass-shaped web plates showed better fatigue performance than the rectangular-shaped web plates of BISYDs. Aluminum BISYDs showed better ductility, energy dissipation potential, hysteresis response, and low-cycle fatigue performance. Thus, the developed devices can be used for retrofitting existing deficient structures as well as can be employed in the new structures.

सार

नागरिक संरचनाओं के भूकंपीय-प्रेरित कंपन को अक्सर पूरक ऊर्जा अपव्यय उपकरणों के माध्यम से नियंत्रित किया जाता है, जिससे प्राथमिक भार-प्रतिरोधी तत्वों को नुकसान कम होता है। कंपन-नियंत्रण उपकरणों को व्यापक रूप से सक्रिय, निष्क्रिय, अर्ध-नियंत्रण और संकर उपकरणों के रूप में वर्गीकृत किया जाता है। धात्विक ऊर्जा अपव्यय उपकरणों का उपयोग सामग्री के बेलोचदार विरूपण के कारण हिस्टैरिसिस के माध्यम से भूकंपीय ऊर्जा को अवशोषित करने के लिए किया जाता है। इन उपकरणों को एक संरचना में रणनीतिक रूप से स्थापित किया जाता है जिससे कि भूकंपीय भार के दौरान ऊर्जा अपव्यय तत्वों को सापेक्ष अक्षीय/ वंक संबंधी/ अपरूपण विस्थापन के अधीन किया जाए। धातु की चादरों के अपरूपण यील्ड पर आधारित अवमंदक उत्कृष्ट शक्ति, तन्यता और ऊर्जा अपव्यय विशेषताओं का प्रदर्शन करते हैं। हालांकि, अपरूपण व्याकुंचन और वेब चादरों के अवशिष्ट प्रतिबल की उपस्थिति न केवल शैथिल्य ऊर्जा अपव्यय को प्रभावित करती है बल्कि इन उपकरणों की समयपूर्व विफलता का कारण बन सकती है। यह अध्ययन एल्यूमीनियम अपरूपण यील्डिंग उपकरणों (AISYDs) के चक्रीय व्यवहार के आकलन के साथ-साथ व्याकुंचन-अवरोधित अपरूपण यील्डिंग उपकरणों (BISYDs) के विकास, परीक्षण और संख्यात्मक प्रतिरूपण पर केंद्रित है।

वेब अभिमुखता अनुपात, वेब पतलापन अनुपात, और लंबवत स्टीफनर्स की स्थिति का शैथिल्य व्यवहार, ऊर्जा अपव्यय क्षमता, और विस्थापन तन्यता पर प्रभाव की जांच के लिए संगणक युक्ति ABAQUS में विकसित अठारह AISYDs संख्यात्मक प्रतिरूपों पर एक प्रचलित अध्ययन किया गया है। इन उपकरणों की ऊर्जा अपव्यय क्षमता को वेब चादरों के अभिमुखता अनुपात और पतलापन अनुपात पर दृढ़ता से निर्भर पाया गया है। AISYDs की शैथिल्य ऊर्जा अपव्यय क्षमता का आकलन करने के लिए एक सरलीकृत समीकरण का प्रस्ताव किया गया है। AISYDs की रचना के लिए वेब अभिमुखता अनुपात और वेब पतलापन अनुपात के अनुकूल मूल्यों की अनुशंसा की गई है।

एक नया BISYD विकसित किया गया है जिसमें ऊर्जा को अवशोषित करने वाली बालू घड़ी और आयताकार आकृतियों की वेब चादरों को निर्मित इस्पात कोणीय काट प्रावरोधको के बीच में रखा गया है। उच्च वेब पतलापन अनुपात वाली पतली वेब चादरों का उपयोग BISYDs को बनाने के लिए किया गया है। वेब चादर के रूप में तीन अलग-अलग सामग्रियों (यानी, तापानुशीतित एल्युमिनियम A1-19000 मिश्र धातु, बिना तापानुशीतित एल्युमिनियम A1-40800 मिश्र धातु, और इस्पात) का उपयोग करके गढ़े गए BISYDs के भूकंपीय व्यवहार की जांच के लिए एक प्रायोगिक जांच की गई है। प्रत्येक प्रकार की वेब चादर में दो नमूनों का परीक्षण BISYDs के साथ उनके चक्रीय व्यवहार की तुलना करने के लिए निर्मित इस्पात कोणीय काट प्रावरोधको के बिना किया गया है। परीक्षण के परिणामों ने प्रदर्शित किया कि A1-40800 मिश्र धातु और इस्पात चादरों से बने BISYDs की तुलना में तापानुशीतित A1-19000 मिश्र धातु से बने BISYDs ने उच्च अपरूपण विकृति स्तरों में बहुत स्थिर चक्रीय व्यवहार और उत्कृष्ट ऊर्जा अपव्यय क्षमता दिखाई।

एल्युमीनियम और इस्पात BISYDs दोनों की पार्श्व शक्ति, प्रारंभिक कठोरता और यील्ड के बाद की कठोरता का आकलन करने के लिए एक विश्लेषणात्मक अध्ययन किया गया है। BISYDs के व्यवहार के आकलन के लिए एक सरल स्ट्रट-एंड-टाई-आधारित समष्टि प्रतिरूप का प्रस्ताव किया गया है जिसका उपयोग वाणिज्यिक युक्ति में इन उपकरणों को नियोजित करने वाली संरचनाओं का विश्लेषण करने के लिए किया जा सकता है। इस अध्ययन में, एल्युमीनियम BISYDs के निम्न-चक्रीय क्लान्ति व्यवहार का मूल्यांकन करने के लिए संख्यात्मक जांच की गई है। संचयी क्लान्ति क्षति नियम का उपयोग A1-6063 मिश्र धातु सामग्री से बने BISYDs के लिए क्लान्ति रचना मापदंडों के अंश शोधन के लिए किया जाता है। तापानुशीतित A1-19000 मिश्र धातु से बने BISYDs के लिए संचयी क्लान्ति क्षति नियम के अंश शोधन के लिए प्रायोगिक जांच भी की गई है। बालू घड़ी के आकार की वेब चादरों ने BISYDs के आयताकार आकार की चादर की तुलना में बेहतर क्लान्ति व्यवहार दिखाया। एल्युमीनियम BISYDs ने बेहतर तन्यता, ऊर्जा अपव्यय क्षमता, शैथिल्य प्रतिक्रिया और निम्न-चक्रीय क्लान्ति व्यवहार दिखाया। इस प्रकार, विकसित उपकरणों का उपयोग मौजूदा कमियों वाली संरचनाओं की मरम्मत के लिए किया जा सकता है और साथ ही नई संरचनाओं में नियोजित किया जा सकता है।

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LIST OF SYMBOLS

α	Backstress in kinematic hardening
N	Number of backstresses
C	Kinematic hardening modulus
γ	Rate of recovery in kinematic hardening
$d\boldsymbol{\varepsilon}_p$	Incremental plastic strain
$d\boldsymbol{\varepsilon}_{ep}$	Incremental equivalent plastic strain
R	Increase in yield surface
Q_∞	Limiting value of isotropic hardening component
b	Rate of change in size of the yield surface
n	Number of panels in ALSYDs
SR_w	Web slenderness ratio
AR_w	Web aspect ratio
l_w	Length of the web plate
l_{eq}	Equivalent length of the web plate
t_f	Thickness of the flange in ALSYDs
t_s	Thickness of the stiffeners in ALSYDs
d_w	Depth of the web plate
t_n	Nominal thickness of the web plate
t_w	Measured thickness of the web plate
E	Modulus of elasticity of the material
ED	Energy dissipation
HF	Hardening factor
η	Stress triaxiality

σ_y	Yield tensile stress
σ_u	Ultimate tensile stress
ϵ_p^f	Equivalent failure strain
ω^f	Damage variable
τ_y	Yield shear stress
τ_u	Ultimate shear stress
G	Shear modulus of the material
Q_y	Yield shear strength
Q_u	Ultimate shear strength
δ_y	Yield displacement
c	Calibration coefficient
k_s	Elastic shear stiffness
k_s'	Post-yield shear stiffness
λ	Post-yield shear stiffness ratio
Ω	Over-strength factor
ξ	Equivalent viscous damping of the specimens
ED_{cycle}	Energy dissipated in a cycle
k_{eff}	Equivalent stiffness of the specimen
Q_+	Peak force in positive direction of displacement time history
Q_-	Peak force in negative direction of displacement time history
δ_+	Peak displacement in positive direction of loading cycles
δ_-	Peak displacement in negative direction of loading cycles
γ_s	Stiffener rigidity ratio
I_s	Moment of inertia of stiffener at stiffener-web interaction surface
ν	Poisson's ratio

D	Flexural rigidity of the web plate per unit width
μ	Maximum ductility
μ_c	Cumulative plastic ductility
σ_y'	Yield tensile stress of struts and ties
σ_u'	Ultimate tensile stress of struts and ties
ε_y'	Yield tensile strain of struts and ties
ε_u'	Ultimate tensile strain of struts and ties
Q	Restoring shear force of the BISYD
a_1 and b_1	Fitting parameters for ultimate shear strength
a_2 and b_2	Fitting parameters for post-yield branch of backbone curve of BISYDs
τ_e	Critical buckling stress
k_b	Buckling coefficient
ε_b	Buckling shear strain
C_{m1} and $c1$	Fatigue performance parameters calibrated based on plastic strain range
$\Delta\varepsilon_{ip}$	Plastic strain range in i^{th} cycle
N_f	Number of cycles required for fatigue failure
D_m	Amount of damage in the BISYD
C_{m2} and $c2$	Fatigue performance parameters calibrated based on total strain range
$\Delta\varepsilon_i$	Total strain range in i^{th} cycle

LIST OF ACRONYMS

ADAS	Added damping added stiffness
Al	Aluminum
Al6-SYD	Aluminum shear yielding device (Al-6063 alloy)
Al-BISYD	Aluminum buckling inhibited shear yielding device
AlSYD	Aluminum shear yielding device (Al-6063 and Al-1100 alloy)
Anal.	Analytical
BISYD	Buckling inhibited shear yielding device
BRB	Buckling restrained brace
CMDs	Combined metallic devices
CNC	Computer numerical control
Cum.	Cumulative
DBE	Design basis earthquake
EBF	Eccentrically braced frame
ED	Energy dissipation
EDD	Energy dissipation device
Eq.	Equivalent
Exp.	Experimental
FEA	Finite element analysis
HAZ	Heat affected zone
ISA	Indian standard angle
LVDT	Linear variable displacement transducer
LYP	Low yield point
Max.	Maximum

MCE	Maximum considered earthquake
Min.	Minimum
MPC	Multi point constraint
MRF	Moment resisting frame
MPSW	Metallic plate shear wall
Num.	Numerical
PED	Passive energy dissipation device
PGA	Peak Ground Acceleration
PTD	Pure torsional damper
RC	Reinforced concrete
SAFYD	Shear and flexural yielding device
SPSW	Steel plate shear wall
St-BISYD	Steel buckling inhibited shear yielding device
SYD	Shear yielding device
TIG	Tungsten inert gas
UTM	Universal testing machine
VD	Viscous damping