

**SEISMIC DESIGN AND COLLAPSE-PERFORMANCE
ASSESSMENT OF STEEL PLATE SHEAR WALL
STRUCTURES**

ABHISHEK VERMA



**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

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By

ABHISHEK VERMA

DEPARTMENT OF CIVIL ENGINEERING

Submitted

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

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MAY 2019

CERTIFICATE

This is to certify that the thesis entitled “**Seismic Design and Collapse-Performance Assessment of Steel Plate Shear Wall Structures**” being submitted by **Abhishek Verma** to Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** is a bonafide record of research work carried out by him. He has worked under my supervision and guidance for the submission of this thesis, which in my opinion, has reached the requisite standard.

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

Hauz Khas, New Delhi-110016

(INDIA)

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ABSTRACT

Steel plate shear walls (SPSW) are used as one of the lateral-force-resisting systems in building structures. These systems possess excellent lateral strength, displacement ductility, and energy dissipation potential. Being relatively lighter in weight, SPSWs also do not significantly increase the force demand on the foundations of structures. Despite the numerous advantages that the SPSWs offer over other traditional systems, some critical issues associated with these systems include high axial demand in the columns and the formation of in-span plastic hinges in the horizontal and vertical boundary elements.

Furthermore, the effect of the presence of a floor slab on the seismic behaviour of the system is yet to be explored. Also, the collapse level seismic performance of the system has only been explored by a limited number of researchers. The present study aims to resolve these issues through analytical, numerical and experimental investigations to enhance the seismic performance of these systems for a broader application in the civil structures.

To simulate the elastic, post-yield and post-peak behavior of an SPSW system, numerical models are developed in the seismic simulation software, *OpenSEES*. The modelling parameters are calibrated and validated against past experimental studies. These models are utilized to conduct an extensive numerical study on the seismic behavior of SPSWs. To design an SPSW, the current code (ANSI/AISC 341-16) recommends neglecting the contribution of the boundary frame in resisting the lateral loads. This recommendation leads to high overstrength of the system and thus proves

to be uneconomical. A numerical study is thus conducted to investigate the contribution of the boundary frames in resisting the lateral loads. The study includes non-linear pushover analyses of single- and multi-story SPSW systems with varying aspect ratios. Semi-empirical equations are derived to estimate the contribution of the boundary frame to the lateral load resistance of SPSW systems. Non-linear dynamic analyses showed a satisfactory seismic performance of SPSWs redesigned by considering the boundary frame contribution.

A staggered-SPSW (S-SPSW) system is proposed to reduce the axial force demands in the columns. A design procedure is suggested, and the seismic performance of the system is evaluated through nonlinear static and dynamic numerical analyses. The system demonstrates a better design-level seismic performance than the conventional SPSW, in terms of the inter-story drift response and drift distribution. In addition to this, a seismic collapse performance evaluation is also performed as per FEMA-P695, for both conventional- and staggered- SPSW. This evaluation aims to verify the aptness of the seismic performance factors suggested by ANSI/AISC 341-16 for conventional SPSWs and to compare the performance of S-SPSW with that of the conventional SPSWs. The results showed that the relatively-narrow conventional SPSWs exhibited an early collapse due to the concentration of drift in the top stories and thus demonstrated an unsatisfactory performance. Staggering of the infill plates in an SPSW can be utilized as one of the solutions to this problem. The probability of sway-mechanisms which involve the formation of plastic hinges in the VBEs of the top stories, increases as the aspect ratio of the conventional SPSW decreases. The results indicate that staggered systems have a relatively consistent performance than their conventional counterparts in terms of ACMR values, with the variation in the aspect

ratio or the number of stories of an SPSW system. This may result in more efficient use of material when a common R-value is used for all configurations of the system.

A quasi-static test is conducted on a large-scale single-story single-bay SPSW specimen to investigate the influence of floor slab on the behaviour of horizontal boundary elements (HBEs). In addition to this, the study also aims to investigate the efficacy of the provided connection detailing in improving the ductility of the system. The slab is cast over the top HBE, whereas the bottom HBE acts independently of the slab. The test specimen is subjected to gradually-increasing reversed-cyclic lateral displacements and vertical gravity loads. The main emphases of the study are the yielding behavior of the infill plate and the boundary elements, the crack propagation in the slab, and the failure modes of the SPSW components. Due to the presence of the slab, the top HBE exhibited a reduction in the axial forces but an increased vertical tension forces in the web region. The proposed connection detailing facilitated the axial-flexural plastic hinges in the HBEs to be formed away from the connections, which enhanced the ductility of the system in comparison to the past experimental studies. The specimen demonstrated a stable hysteretic response up to 6% story drift.

सार

स्टील प्लेट की कतरनी की दीवारों (एसपीएसडब्ल्यू) भवन संरचनाओं में पार्श्व-बल-विरोध प्रणालियों में से एक के रूप में उपयोग की जाती हैं। इन प्रणालियों में उत्कृष्ट पार्श्व शक्ति, विस्थापन नमनीयता और ऊर्जा अपव्यय क्षमता होती है। वजन में अपेक्षाकृत हल्का होने के नाते, एसपीएसडब्ल्यू संरचनाओं की नींव पर बल की मांग में काफी वृद्धि नहीं करते हैं। एसपीएसडब्ल्यू अन्य पारंपरिक प्रणालियों पर कई लाभों के बावजूद, इन प्रणालियों से जुड़े कुछ महत्वपूर्ण मुद्दों में स्तंभों में उच्च अक्षीय मांग और क्षैतिज और ऊर्ध्वाधर सीमा तत्वों में इन-स्पैन प्लास्टिक टिका के गठन शामिल हैं।

इसके अलावा, सिस्टम के भूकंपीय व्यवहार पर एक मंजिल स्लैब की उपस्थिति के प्रभाव का पता लगाया जाना बाकी है। इसके अलावा, सिस्टम के पतन स्तर के भूकंपीय प्रदर्शन को केवल सीमित संख्या में शोधकर्ताओं द्वारा ही खोजा गया है। वर्तमान अध्ययन का उद्देश्य नागरिक संरचनाओं में व्यापक अनुप्रयोग के लिए इन प्रणालियों के भूकंपीय प्रदर्शन को बढ़ाने के लिए विश्लेषणात्मक, संख्यात्मक और प्रयोगात्मक जांच के माध्यम से इन मुद्दों को हल करना है।

एक एसपीएसडब्ल्यू प्रणाली के लोचदार, पोस्ट-उपज और पोस्ट-पीक व्यवहार का अनुकरण करने के लिए, भूकंपीय सिमुलेशन सॉफ्टवेयर, ओपनसीईएस में संख्यात्मक मॉडल विकसित किए जाते हैं। पिछले प्रायोगिक अध्ययनों के खिलाफ मॉडलिंग मापदंडों को कैलिब्रेट और मान्य किया जाता है। इन मॉडलों का उपयोग एसपीएसडब्ल्यू

के भूकंपीय व्यवहार पर एक व्यापक संख्यात्मक अध्ययन करने के लिए किया जाता है। एक एसपीएसडब्ल्यू डिजाइन करने के लिए, वर्तमान कोड (एएनएसआई / एआईएससी 341-16) पार्श्व भार का विरोध करने में सीमा फ्रेम के योगदान की उपेक्षा करने की सिफारिश करता है। यह सिफारिश प्रणाली की उच्च अतिवृद्धि की ओर ले जाती है और इस प्रकार यह अनौपचारिक साबित होती है। एक संख्यात्मक अध्ययन इस प्रकार पार्श्व भार का विरोध करने में सीमा फ्रेम के योगदान की जांच करने के लिए किया जाता है। अध्ययन में अलग-अलग पहलू अनुपात के साथ एकल और बहु-कहानी एसपीएसडब्ल्यू सिस्टम के गैर-रैखिक पुशओवर विश्लेषण शामिल हैं। अर्ध-अनुभवजन्य समीकरण एसपीएसडब्ल्यू प्रणालियों के पार्श्व लोड प्रतिरोध के लिए सीमा फ्रेम के योगदान का अनुमान लगाने के लिए व्युत्पन्न हैं। गैर-रेखीय गतिशील विश्लेषणों ने सीमा फ्रेम योगदान पर विचार करके SPSWs के संतोषजनक भूकंपी प्रदर्शन को दिखाया।

स्तंभों में अक्षीय बल मांगों को कम करने के लिए एक कंपित-एसपीएसडब्ल्यू (एस-एसपीएसडब्ल्यू) प्रणाली प्रस्तावित है। एक डिजाइन प्रक्रिया का सुझाव दिया जाता है, और सिस्टम के भूकंपीय प्रदर्शन का मूल्यांकन नॉनलेयर स्टैटिक और डायनेमिक संख्यात्मक विश्लेषण के माध्यम से किया जाता है। सिस्टम इंटर-स्टोरी ड्रिफ्ट रिस्पॉन्स और ड्रिफ्ट डिस्ट्रीब्यूशन के संदर्भ में पारंपरिक एसपीएसडब्ल्यू की तुलना में बेहतर डिजाइन-स्तरीय भूकंपीय प्रदर्शन को प्रदर्शित करता है। इसके अलावा, पारंपरिक और चौंका देने वाला- SPSW दोनों के लिए FEMA-P695 के अनुसार भूकंपीय पतन प्रदर्शन मूल्यांकन भी किया जाता है। इस मूल्यांकन का उद्देश्य पारंपरिक SPSWs के लिए एएनएसआई / एआईएससी 341-16 द्वारा सुझाए गए भूकंपीय प्रदर्शन कारकों की उपयुक्तता को

सत्यापित करना और पारंपरिक एसपीएसडब्ल्यू के साथ एस - एसपीएसडब्ल्यू के प्रदर्शन की तुलना करना है। परिणामों से पता चला कि अपेक्षाकृत संकीर्ण पारंपरिक एसपीएसडब्ल्यू ने शीर्ष कहानियों में बहाव की एकाग्रता के कारण एक प्रारंभिक पतन का प्रदर्शन किया और इस तरह एक असंतोषजनक प्रदर्शन किया। एक एसपीएसडब्ल्यू में इन्फिल प्लेटों की डगमगाते हुए इस समस्या के समाधान में से एक के रूप में उपयोग किया जा सकता है। शीर्ष-कहानियों की VBEs में प्लास्टिक टिका के गठन में स्व-तंत्र की संभावना बढ़ जाती है, क्योंकि पारंपरिक एसपीएसडब्ल्यू का पहलू अनुपात घट जाता है। परिणाम इंगित करते हैं कि कंपित सिस्टम में ACMR मूल्यों के संदर्भ में उनके पारंपरिक समकक्षों की तुलना में अपेक्षाकृत समान प्रदर्शन होता है, जिसमें पहलू अनुपात में भिन्नता या एसपीएसडब्ल्यू प्रणाली की कहानियों की संख्या होती है। यह सामग्री के अधिक कुशल उपयोग के परिणामस्वरूप हो सकता है जब सिस्टम के सभी कॉन्फिगरेशन के लिए एक सामान्य आर-मूल्य का उपयोग किया जाता है।

क्षैतिज सीमा तत्वों (HBEs) के व्यवहार पर फर्श स्लैब के प्रभाव की जांच के लिए एक बड़े पैमाने पर एकल-कहानी एकल-बे एसपीएसडब्ल्यू नमूना पर एक अर्ध-स्थैतिक परीक्षण किया जाता है। इसके अलावा, इस अध्ययन का उद्देश्य सिस्टम की लचीलापन में सुधार के लिए प्रदान किए गए कनेक्शन के विवरण की प्रभावकारिता की जांच करना भी है। स्लैब को शीर्ष एचबीई पर डाला जाता है, जबकि नीचे का एचबीई स्लैब के स्वतंत्र रूप से कार्य करता है। परीक्षण नमूना धीरे-धीरे बढ़ते उलट-चक्रीय पार्श्व विस्थापन और ऊर्ध्वाधर गुरुत्वाकर्षण भार के अधीन है। अध्ययन के मुख्य लक्षण इन्फिल प्लेट और सीमा तत्वों के उपज व्यवहार, स्लैब में दरार प्रसार और एसपीएसडब्ल्यू घटकों की विफलता मोड हैं। स्लैब की उपस्थिति के कारण, शीर्ष एचबीई ने अक्षीय बलों में कमी का प्रदर्शन किया लेकिन

वेब क्षेत्र में वर्टिकल टेंशन बलों में वृद्धि हुई। प्रस्तावित कनेक्शन डिटेल्स ने कनेक्शनों से दूर बनने के लिए एचबीई में अक्षीय-फ्लेक्सुरल प्लास्टिक टिका की सुविधा प्रदान की, जिसने पिछले प्रयोगात्मक अध्ययनों की तुलना में प्रणाली की लचीलापन बढ़ाया। नमूना ने 6% कहानी के बहाव पर एक स्थिर हिस्टैरिक प्रतिक्रिया का प्रदर्शन किया।

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LIST OF SYMBOLS

A	Aspect ratio of SPSW
A_b	Cross-sectional area of a HBE
A_c	Cross-sectional area of a VBE
A_{eq}	Area of equivalent truss for preliminary design of SPSW
A_s	Cross-sectional area of the strips in the strip model of SPSW
A_w	Cross-sectional area of the web of I-section
C_d	Deflection amplification factor
C_{vi}	Assumed ratio of design lateral force at any i^{th} floor level to design base shear
C_s	Seismic response coefficient
D	Diameter of the perforations in perforated SPSW
D_B	Depth of HBE
D_C	Depth of VBE
E	Young's modulus of steel
F	Total downward force on HBE
F_i	Story force on the boundary frame at i^{th} floor level
F_{Mi}	Proportion of force corresponding to fundamental mode, applied at i^{th} floor level
H	Height of the building
H_i	Height of i^{th} floor measured from the base

I_b	Moment of inertia of HBE, taken perpendicular to the direction of the infill plate line
I_c	Moment of inertia of VBE, taken perpendicular to the direction of the infill plate line
I_{ci}	Column moment of inertia at the i^{th} story
I_e	Importance factor for a building
I_i	Moment of inertia of cantilever beam at the i^{th} story
K	Fraction of load carried by the plate
K_{ci}	Stiffness of Boundary frame, at the i^{th} story
K_i	Stiffness of SPSW, at the i^{th} story
K_{pi}	Stiffness of infill plates, at the i^{th} story
K_{perf}	Stiffness of perforated web panels of SPSW
K_{solid}	Stiffness of solid web panels of SPSW
L	Distance between VBE centerlines
L_{cf}	Distance between the inner flanges of the two VBEs
M_{al}	Reduced moment capacity at the left end of left HBEs of S-SPSW
M_{ar}	Reduced moment capacity at the right end of left HBEs of S-SPSW
M_{bl}	Reduced moment capacity at the left end of right HBEs of S-SPSW
M_{br}	Reduced moment capacity at the right end of right HBEs of S-SPSW
M_c	Flexural capacities of the section, calculated as per Chapter E and Chapter C in ANSI/AISC 360-16 (2016)
M_{COUP}	Moments of the couple of pier vertical reaction forces
$M_{HBEi}(x)$	Bending moment at any location at a distance of x from one end, in an intermediate HBE
M_i	Moment capacity of HBE section at the i^{th} story

M_{Pi}	Moment capacity of HBE section at the i^{th} story
M_{PIER}	Moments of the couples VBE vertical reaction forces
M_{PL}	Plastic moment capacities of HBE section at the left ends
M_{PR}	Plastic moment capacities of HBE section at the right ends
$M_{P(req)i}$	Minimum required moment capacity of HBE at i^{th} floor level
M_r	Bending demand
M_{TOTAL}	Summation of M_{COUP} , M_{PIER} and M_{VBE}
M_{VBE}	Reaction moment at the base of VBE
N	Number of rows of the perforations in perforated SPSW
P, P_i	Force resisted by infill plate in addition to lateral forces
P_{bli}	Axial forces at the left end of HBES
P_{bri}	Axial forces at right end of HBES
P_c	Axial capacities of the section, calculated as per Chapter E and Chapter C in ANSI/AISC 360-16 (2016)
P_{di}	Design story force at i^{th} floor level
P_{cr}	Critical shear load of the steel plate panel
$P_{HBEi}(x)$	Axial force at any location at a distance of x from one end, in an intermediate HBE
P_r	Axial demand
Q	Lateral force applied to SPSW
R	Response modification factor
R_{yp}	Ratio of the expected to the nominal yield stress of the infill plates
\hat{S}_{CT}	Median spectral acceleration
S_{diag}	Spacing of the perforations in perforated SPSW
S_{MT}	Spectral acceleration at maximum considered earthquake level

S_S	5% damped spectral response acceleration parameter at short periods for MCE level
S_1	5% damped spectral response acceleration parameter at a period of 1 s for MCE level
S_{MS}	5% damped spectral response acceleration parameter at short periods, adjusted for site class effects
S_{M1}	5% damped spectral response acceleration parameter at a period of 1 s, adjusted for site class effects
S_{DS}	5% damped, design spectral response acceleration parameter at short periods
S_{D1}	5% damped, design spectral response acceleration parameter at a period of 1 s
T	Calculated fundamental time period of building
T_a	Code recommended approximate time period of building
T_1	Fundamental time period of system calculated using Eigen analysis
V	Seismic story shear
V_{al}	Shear forces at the left end of left HBES in S-SPSW
V_{ar}	Shear forces at the right end of left HBES in S-SPSW
V_{bl}	Shear forces at the left end of right HBES in S-SPSW
V_{br}	Shear forces at the right end of right HBES in S-SPSW
V_d	Design base shear of SPSW
V_i	Total design shear force acting at the i^{th} floor level
V_{li}	Shear forces at the left ends of HBES in conventional SPSW, at i^{th} floor
V_{max}	Ultimate base shear capacities
V_n	Shear capacity of section

V_{perf}	Shear capacities of a perforated SPSW web panel
V_{ri}	Shear forces at the right ends of HBES in conventional SPSW, at i^{th} floor
V_{solid}	Shear capacities of a solid SPSW web panel
V_{CS}	Expected lateral strength of Conventional SPSW
V_F	Base shear capacity of staggered SPSW considering frame action, after the plate and HBE section sizes have been determined during design process
V_M	Lateral force resisted by moment frame action in conventional SPSW
V_{MS}	Lateral force resisted by moment frame action in staggered SPSW
V_T	Base shear capacity of staggered SPSW after the plate and HBE section sizes have been determined during the design process
V_W	Base shear capacity of staggered SPSW considering infill plate action, after the plate and HBE section sizes have been determined during design process
W	Seismic weight of the building
W_i	Story weight at i^{th} floor level
a	Length of the loaded side of the plate
b	Strain hardening ratio
d_{HBEi}	Depth of HBE
d_s	Distance between the strips in strip model of SPSW
f_b	Natural frequency cantilever deforming in bending
f_s	Natural frequency cantilever deforming in shear
g	Constant acceleration due to gravity
h	Distance between the center-lines of HBES
h_i	Distance between the center-lines of HBE at the i^{th} story

h_w	Depth of HBE web
k	Seismic force distribution exponent
l	Distance between the plastic hinges of HBE
$m_{eff,i}$	Effective modal mass for i^{th} mode
m_j	Mass of j^{th} story
m_T	Total mass of system
s	Length of longer side of the subpanels
t_w	Thickness of steel infill plate in SPSW
w_h	Horizontal components of the uniformly distributed forces per unit length exerted by infill plate on VBEs
w_v	Vertical components of the uniformly distributed forces per unit length exerted by infill plate on HBEs
x_{span}	Location of plastic hinge formation in the HBE.
Δ	Lateral displacement at the top HBE
Ω_0	SPSW system overstrength obtained from pushover analysis
α	Tension field angle
β	Overstrength factor for the plate strength incorporated in design procedure.
β_{TOT}	Total uncertainty factor
β_{DR}	Uncertainty factors related to design requirements
β_{MDL}	Uncertainty factors related to modelling
β_{TD}	Uncertainty factors related to test data
β_{RTR}	Uncertainty factors related to record-to-record variability
γ	Base shear reduction factor
δ_u	Ultimate roof drift

$\delta_{y,eff}$	Effective yield drift
ϵ_c	Strain of steel at peak strength
ϵ_u	Ultimate strain of steel at peak strength
ϵ_w	Strain in infill plate
ϵ_y	Yield strain of steel
ζ	Empirical constant to account for variation in predicted strength of web plate
η	Moment reduction factor for reduced beam section
θ	Angle that inclined line passing through the center of the circular perforations makes with the horizontal in perforated SPSW
ϑ	Empirical constant
κ_{bal}	Ratio of shear force to be resisted by the plate alone to the design shear force
μ	Poissons ratio for steel
μ_l	Mean of the a logarithmic data set
μ_T	Fundamental-period based displacement-ductility
ξ	Aspect ratio of the steel subpanels in stiffened SPSW
ρ	Percentage load carried by infill plates
σ	Standard deviation of a logarithmic data set
σ_c	Peak strength of steel
σ_w	Stress in infill plate
σ_y	Yield strength of steel
τ_{cr}	Critical shear stress of steel plate panel
ϕ_b	Resistance factor used for the design of HBEs
ϕ_p	Resistance factor used for the design of plates

\emptyset	Acute angle of the equivalent brace with respect to the column for preliminary design of SPSW
ω_{xbi}	Horizontal components of the uniformly distributed forces per unit length exerted by infill plate on HBEs at i^{th} floor level
ω_{xci}	Horizontal components of the uniformly distributed forces per unit length exerted by infill plate on VBEs at i^{th} floor level
ω_{xi}	Horizontal components of the net forces applied by infill plates on HBE at i^{th} floor level
ω_{ybi}	Vertical components of the uniformly distributed forces per unit length exerted by infill plate on HBEs at i^{th} floor level
ω_{yci}	Vertical components of the uniformly distributed forces per unit length exerted by infill plate on VBEs at i^{th} floor level
ω_{yi}	Vertical components of the net forces applied by infill plates on HBE at i^{th} floor level
Φ_{ij}	Mode shape factor for i^{th} mode of j^{th} story

LIST OF ACRONYMS

ACMR _{10%}	Acceptable value of ACMR for 10% probability of collapse at S_{MT}
ACMR _{20%}	Acceptable value of ACMR for 20% probability of collapse at S_{MT}
ACMR	Adjusted collapse margin ratio
PGA	Peak ground acceleration
PGV	Peak ground velocity
PSA	Peak spectral acceleration
Conv-SPSW	Conventional steel plate shear wall
CMR	Collapse margin ratio
DBE	Design basis earthquake
DC	Degree of coupling
ELF	Equivalent lateral force
FEM	Finite element modelling
HBE	Horizontal boundary element
ICD	Indirect capacity design approach
IDA	Incremental dynamic analysis
ISDR	Inter story drift ratio
ISMB	Indian standard medium weight beam
ISMC	Indian standard medium weight channel
LE+CD	Combined linear elastic computer programs and capacity design concept
LVDT	Linear variable differential transformer

LYP	Low yield point
MCE	Maximum considered earthquake
RBS	Reduced beam section
SPSW	Steel plate shear wall
SRSS	Square root of sum-of-squares
SSF	Spectral shape factor
S-SPSW	Staggered steel plate shear wall
VBE	Vertical boundary element