

MONOTONIC AND CYCLIC BEHAVIOUR OF CONCRETE BEAMS OF LOW SHEAR SPANS REINFORCED WITH HIGH-YIELD STRENGTH STEEL

SURAJ KUMAR SAHU



**DEPARTMENT OF CIVIL ENGINEERING
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by

SURAJ KUMAR SAHU

Department of Civil Engineering

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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, “*Monotonic and Cyclic Behaviour of Concrete Beams of Low Shear Spans Reinforced with High-Yield Strength Steel,*” being submitted by *Suraj Kumar Sahu* to the 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 under my supervision and guidance. The thesis, in my opinion has reached the requisite standard, fulfilling the requirements for the award of the 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.

Prof. Dipti Ranjan Sahoo
Professor
Department of Civil Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016 (INDIA)

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Suraj Kumar Sahu

ABSTRACT

High-strength materials can be efficiently utilized to provide durable, sustainable, and economical concrete structures with higher available floor area and reduced maintenance requirements. Hence, the demand for high-strength steel and concrete in the concrete industry has increased in recent years. The use of high-strength steel bars as reinforcement in concrete elements resisting earthquake effects has great potential in reducing bar congestion and problems associated with concrete placement in critical regions. Though many building codes allow the use of high-strength steel as longitudinal and confining reinforcement in concrete members, the design yield strength of shear reinforcement in beams has been limited to 420 MPa to control the width of the diagonal shear crack at serviceable load conditions and to ensure the yielding of stirrups before any possible sudden shear failure due to the crushing of the diagonal concrete strut. The lack of sufficient test data in Favor of the usability of high-strength steel as shear reinforcement in concrete beams may be the reason for the conservative approach being adopted in many design standards.

This study presents experimental and numerical investigation on concrete beams reinforced with high-strength steel having yield strengths in the range of 500-600 MPa. The influence of the yield strengths of reinforcing steel and the concrete grade on the shear behaviour of concrete beams of low to moderate shear span ratios has been studied. Six beam specimens with two different grades of steel (500 and 550 MPa) as the longitudinal reinforcement and three different stages of steel (500, 550, and 600 MPa) as the transverse reinforcement were tested until failure under monotonic loading conditions. Two different concrete grades were considered in the test specimens, whereas the shear span-to-depth (a/d) ratios varied in the range of 1.05-1.70. Significant

overstrength in the range of 3.5-3.6 was observed in the specimens as compared to the predicted design shear strengths. Further, the design concrete shear stresses predicted by the current design codes are found to be very conservative to avoid unwanted brittle shear failure of beams reinforced with high-strength steel. The test results indicated that high-strength steel of yield strength up to 600 MPa could be used as the transverse reinforcements in the beams without violating the serviceability requirements related to crack width limitation.

Numerical analysis has been conducted to predict the lateral load resistance and mode failure of concrete beams. The test specimens are modeled and analyzed in the commercial finite element analysis software ABAQUS. The predicted monotonic behaviour of beams matched well with the test results in terms of crack pattern, damage, load-displacement behaviour, and state of strain in reinforcement bars. The validated numerical models are used in a parametric study to investigate the effectiveness of high-strength shear reinforcements with different percentages of tensile steel and shear span ratios. A wide range of design capacity ratios showing different modes of failure, i.e., flexure and shear, is noted in the beams in which the yielding of high-strength stirrups is observed in resisting the shear demand before reaching their respective ultimate loads. Irrespective of the grade of high-strength stirrups used, their effectiveness in resisting shear is greatly influenced by their position in the shear zone.

Seven specimens with two different grades of concrete (M25 and M50) and three different grades of high-strength stirrups (i.e., 500, 550, and 600 MPa) were tested under quasi-static reversed-cyclic loading. The aim was to investigate the effectiveness of high-strength shear reinforcement in the expected plastic hinge regions of beams. Two different shear design approaches, i.e., ductile and non-ductile shear design approach, was considered to establish two extreme conditions for the high-strength shear reinforcement.

For each design approach considered, the significant parameters evaluated are the influence of the concrete grade and grade of shear stirrups on the hysteretic behaviour, crack patterns, failure modes, stiffness degradation, the contribution of stirrups in resisting shear load, shear distortion, and ductility, state of strain in reinforcements, energy dissipation capacity and equivalent viscous damping of RC beams. Irrespective of the volumetric ratio of high-strength shear reinforcement provided, all the specimens (both ductile and non-ductile) exhibited the crack widths within the permissible limits as prescribed by ACI 224R-01 and IS:456-2000 by their corresponding service loads even under cyclic loads. Further, all the specimens found their shear zone stirrups yielded for imparting comparable shear deformation behaviours with that observed by earlier researchers. As expected, the ductile specimens performed better than the non-ductile specimens having high-strength shear reinforcement. Test results indicated that the high-strength stirrups with yield strength up to 600 MPa can be used in the shear design of concrete members, including earthquake-resistant applications. Finally, the key findings of this study and future recommendations on the use of high-strength reinforcing steel are presented.

सार

उच्च उपलब्ध फर्श क्षेत्र और कम रखरखाव आवश्यकताओं के साथ टिकाऊ, संधारणीय और किफायती कंक्रीट संरचनाएं प्रदान करने के लिए उच्च शक्ति वाली सामग्रियों का कुशलतापूर्वक उपयोग किया जा सकता है। इसलिए, हाल के वर्षों में कंक्रीट उद्योग में उच्च शक्ति वाले स्टील और कंक्रीट की मांग बढ़ी है। भूकंप रोधी कंक्रीट संरचनाओं में उच्च शक्ति वाले स्टील बार का उपयोग सुदृढीकरण के रूप में महत्वपूर्ण जगहों में स्टील बारों की संख्या और कंक्रीट प्लेसमेंट से जुड़ी समस्याओं को कम करने में समर्थ है। हालांकि कई बिल्डिंग कोड कंक्रीट संरचनाओं में अनुदैर्घ्य और परिरोधी सुदृढीकरण के रूप में उच्च शक्ति वाले स्टील के उपयोग की अनुमति देते हैं, लेकिन बीम में कतरनी सुदृढीकरण की डिजाइन उपज शक्ति को 420MPa तक सीमित की गई है ताकि सेवा योग्य लोड स्थितियों पर विकर्ण कतरनी दरार की चौड़ाई को नियंत्रित किया जा सके और विकर्ण कंक्रीट स्ट्रूट के क्रशिंग के कारण किसी भी संभावित अचानक कतरनी विफलता से पहले स्टील रिंग की उपजना को सुनिश्चित किया जा सके। कंक्रीट बीम में शियर कतरनी सुदृढीकरण के रूप में उच्च शक्ति वाले स्टील की उपयोगिता के पक्ष में पर्याप्त परीक्षण डेटा की कमी कई डिजाइन मानकों में रूढ़िवादी दृष्टिकोण अपनाए जाने का कारण हो सकती है।

यह अध्ययन 500-600MPa की सीमा में उपज क्षमता वाले उच्च शक्ति वाले स्टील के साथ प्रबलित कंक्रीट बीम पर प्रयोगात्मक और संख्यात्मक जांच प्रस्तुत करता है। निम्न से मध्यम शियर कतरनी अवधि अनुपात के कंक्रीट बीम के शियर कतरनी व्यवहार पर मजबूत स्टील और कंक्रीट ग्रेड की उपज शक्तियों के प्रभाव का अध्ययन किया गया है। अनुदैर्घ्य सुदृढीकरण के रूप में स्टील के दो अलग-अलग ग्रेड (500 और 550 MPa) और अनुप्रस्थ सुदृढीकरण के रूप में स्टील के तीन अलग-अलग ग्रेड (500, 550 और 600 MPa) के साथ छह बीम नमूनों का मोनोटोनिक लोडिंग स्थितियों के तहत विफलता तक परीक्षण किया गया है। परीक्षण नमूनों में दो अलग-अलग

कंक्रीट ग्रेड प्रयुक्त किया गया, जबकि शियर कतरनी अवधि-से-गहराई (a/d) अनुपात 1.05-1.70 की सीमा के अंदर रखा गया है। अनुमानित डिज़ाइन शियर कतरनी ताकत की तुलना में नमूनों की ताकत 3.5-3.6 गुना अधिक प्रभावपूर्ण देखी गई। इसके अलावा, डिजाइन ठोसउच्च शक्ति वाले स्टील के साथ प्रबलित बीम की अवांछित भंगुर शियर कतरनी विफलता से बचने के लिए वर्तमान डिज़ाइन कोड द्वारा अनुमानित शियर कतरनी तनाव बहुत रूढ़िवादी पाए जाते हैं। परीक्षण के परिणामों ने संकेत मिलता है कि 600MPa तक की उपज क्षमता वाले उच्च शक्ति वाले स्टील का उपयोग दरार की चौड़ाई सीमा से संबंधित सेवाक्षमता आवश्यकताओं का उल्लंघन किए बिना बीम में अनुप्रस्थ सुट्टीकरण के रूप में किया जा सकता है।

कंक्रीट बीम के लेटरल भार-प्रतिरोध और विफलता के प्रकार का आंकलन करने के लिए संख्यात्मक विश्लेषण किया गया है। परीक्षण नमूनों की मॉडलिंग और विश्लेषण वाणिज्यिक परिमित तत्व विश्लेषण सॉफ्टवेयर ABAQUS में की गई है। दरार पैटर्न, क्षति, लोड-विस्थापन व्यवहार और सुट्टीकरण स्टील बार में तनाव की स्थिति के संदर्भ में बीम का अनुमानित मोनोटोनिक व्यवहार परीक्षण परिणामों के साथ अच्छी तरह से मेल खाता है। मान्य संख्यात्मक मॉडल का उपयोग पैरामीट्रिक अध्ययन में तन्यता स्टील और शियर कतरनी अवधि अनुपात के विभिन्न प्रतिशत के साथ-साथ उच्च शक्ति शियर कतरनी सुट्टीकरण की प्रभावशीलता की जांच करने के लिए किया गया है। डिज़ाइन क्षमता अनुपात की एक विस्तृत श्रृंखला विफलता के विभिन्न प्रकारों को दिखती है, जिसमें - फ्लेक्सर और शियर कतरनी प्रकार की विफलता इस अध्ययन की बीम में मानी गई है। जिसमें उच्च शक्ति वाले स्टील रिंग, संबंधित अंतिम भार तक पहुंचने से पहले शियर कतरनी की मांग का विरोध करते हुए उपज होते देखी गई है। उपयोग किए जाने वाले उच्च शक्ति वाले स्टील रिंग के ग्रेड के बावजूद, शियर कतरनी का विरोध करने में उनकी प्रभावशीलता शियर कतरनी क्षेत्र में उनकी स्थिति से काफी प्रभावित हुई है।

बीम के अपेक्षित प्लास्टिक काज क्षेत्रों में उच्च शक्ति वाले शियर कतरनी सुदृढीकरण की प्रभावशीलता की जांच करने के लिए, कंक्रीट के दो अलग-अलग ग्रेड (M25 और M50) के साथ सात नमूने और उच्च शक्ति वाले स्टील रिंग के तीन अलग-अलग ग्रेड (यानी, 500, 550, और 600 MPa) का परीक्षण क्रासी स्टैटिक रिवर्स साइकलिक लोडिंग के तहत किया गया है। उच्च शक्ति शियर कतरनी सुदृढीकरण के लिए दो चरम स्थितियों को स्थापित करने के लिए दो अलग-अलग शियर कतरनी डिजाइन दृष्टिकोण, यानी, तन्य और गैर-नमनीय शियर कतरनी डिजाइन दृष्टिकोण पर विचार किया गया। विचार किए गए प्रत्येक डिजाइन दृष्टिकोण के लिए, मूल्यांकन किए गए प्रमुख पैरामीटर में कंक्रीट ग्रेड और शियर कतरनी स्टील रिंग के ग्रेड का हिस्टेरैटिक व्यवहार पर प्रभाव, दरार पैटर्न, विफलता प्रकार, कठोरता गिरावट, शियर कतरनी भार का विरोध करने में स्टील रिंग का योगदान, शियर कतरनी विरूपण और लचीलापन, सुदृढीकरण में तनाव की स्थिति, ऊर्जा अपव्यय क्षमता और आरसी बीम की समतुल्य विसकस डैपिंग शामिल हैं। प्रदान किए गए उच्च-शक्ति शियर कतरनी सुदृढीकरण के वॉल्यूमेट्रिक अनुपात के बावजूद, सभी नमूनों (डक्टाइल और नॉन-डक्टाइल दोनों) ने अपने संबंधित सेवा भार द्वारा ACI 224R-01 और IS : 456-2000 द्वारा निर्धारित अनुमेय सीमा के भीतर दरार की चौड़ाई प्रदर्शित की और चक्रीय भार के तहत भी। इसके अलावा, सभी नमूनों में पाया गया कि उनके शियर कतरनी क्षेत्र स्टील रिंग पहले के शोधकर्ताओं द्वारा देखे गए तुलनीय शियर कतरनी विरूपण व्यवहार प्रदान करने में सक्षम थे। जैसा कि अपेक्षित था, लचीले नमूनों ने उच्च शक्ति वाले शियर कतरनी सुदृढीकरण वाले नॉन-डक्टाइल नमूनों की तुलना में बेहतर प्रदर्शन किया। परीक्षण परिणामों से संकेत मिलता है कि 600 MPa तक की उपज क्षमता वाले उच्च शक्ति वाले स्टील रिंग का उपयोग भूकंप रोधी अनुप्रयोगों सहित कंक्रीट संरचना के शियर कतरनी डिजाइन में किया जा सकता है। अंत में, इस अध्ययन के

मुख्य निष्कर्ष और उच्च शक्ति सुदृढ़ीकरण स्टील के उपयोग पर भविष्य की सिफारिशें प्रस्तुत की गई हैं।

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LIST OF SYMBOLS

Δ_y	Yield displacement
ε_c	Strain in compression steel
ε_s	Strain in tension steel
ε_{su}	Elongation
γ_{avg}	Average shear distortion
ε_{0c}^{el}	Elastic compressive strain of concrete
ε_{0t}^{el}	Elastic tensile strain of concrete
ε_c^{in}	Inelastic compressive strain of concrete
ε_t^{in}	Inelastic tensile strain of concrete
ε_t^{ck}	Inelastic cracking strain of concrete
ε_c^{pl}	Plastic compressive strain of concrete
ε_t^{pl}	Plastic tensile strain of concrete
ε_t	Tensile strain of concrete
γ_{avg}	Average shear distortion
μ_f	Ductility at failure loads
μ_{ult}	Ductility at ultimate loads
ρ_s	Percentage of transverse reinforcement
ρ_{sc}	Percentage of longitudinal compression steel
ρ_{st}	Percentage of longitudinal tension steel
ρ_{sv}	Percentage of transverse reinforcement
ρ_w	Percentage of transverse reinforcement
σ_c	Compressive stress of concrete
σ_t	Tensile stress of concrete
$\tau_{c,exp}$	Measured concrete shear stress
τ_{cn}	Nominal concrete shear stress
τ_c	Design shear stress of concrete

a	Shear span
a_{ge}	Effective size of coarse aggregate
A_g	Gross Area of Section
A_{sc}	Area of longitudinal compression steel
A_{sh}	Area of special confining reinforcement
A_{st}	Area of longitudinal tension steel
A_{sv}	Area of shear stirrups
b	Width of beam
b_b	width of the beam
b_c	width of the column
b_j	effective width of the joint
c	Clear cover
c_1	displacement data from diagonally installed 1 st string pot
c_2	displacement data from diagonally installed 2 nd string pot
d	Effective depth of beam
d'	Effective cover till centroid of longitudinal rebars
D	Depth of the beam section
d_v	Effective shear depth
d_t	Tension damage parameter of concrete
d_{tc}	transverse distance between the top and bottom steel
d_c	Compression damage parameter of concrete
E_0	Initial elastic stiffness of concrete
e_c	Compression strain in longitudinal steel at the section
e_t	Tensile strain in longitudinal steel at the section
f	Compressive stress of concrete
f_c'	Cylinder compressive strength
f_{b0}	Biaxial compressive stress of concrete
f_{c0}	Uniaxial compressive stress of concrete
f_{ck}	Characteristic cube compressive strength
f_{ckm}	Measured mean cube compressive strength of concrete
f_{cm}'	Estimated mean cylinder compressive strength of concrete

f_s	Stress in tension steel
f_{sc}	Stress in compression steel
f_{sv}	Yield strength of transverse steel
f_t	Tensile strength of concrete
f_u	Tensile strength of steel reinforcement
f_y	Tensile yield strength
f_{yh}	Yield strength of shear stirrups
f_{yl}	Nominal yield strength of longitudinal steel
f_{yt}	Yield strength of shear stirrups
f_{ysm}	Measured mean tensile strength of steel stirrup
f_{ym}	Measured mean tensile strength of steel stirrup
f_{ys}	Yield strength of shear stirrups
f_{yv}	Nominal yield strength of shear stirrups
h_j	effective depth of the joint
K	Shape factor
M_p	Plastic moment capacity
M_u	Flexural resistance (Design moment capacity)
M_{ud}	Design bending moment demand
P_y	Yield load
s_v	Spacing of shear stirrups
U_x	Translation in “X” direction
U_y	Translation in “Y” direction
U_z	Translation in “Z” direction
V_c	Design shear resistance of concrete
V_c'	Shear force at strain initiation in stirrups
V_{exp}	Observed shear strength
V_{jc}	Nominal capacity of the beam-column joint
V_n	Design Shear resistance
V_{nd}	Design shear force demand
V_{ns}	Shear resistance at service load

V_s	Design shear resistance of stirrups
V_u	Total Shear resistance
$(x_u)_{max}$	Maximum depth of neutral axis
(x_u)	Depth of neutral axis
θ	Angle of inclination of diagonal shear cracks
ψ	Dilation angle
Υ	Max shear strain
μ	Viscosity parameter
ϕ	Curvature of the section
ϕ_{tc}	Curvature at any section considered
ϕ	Strength reduction factor
ϕ_s	Strength reduction factor steel
ϕ_c	Strength reduction factor concrete
ϵ_x	Longitudinal strain of beam at mid depth
F_y	Characteristic yield strength of reinforcement
F_{ys}	Characteristic yield strength of stirrup.
A_s	Cross-sectional area of stirrup legs
f_s	Stress in stirrups
Υ_m	Maximum shear distortion,
P_n	Peak load
Υ_{ys}	shear distortion at yielding of stirrup
Υ_c	shear distortion at first appearance of shear crack
Υ_{my}	Net shear distortion beyond yielding of stirrup
Υ_{mc}	Net shear distortion beyond first initiation of shear crack
μ_{ult}	Displacement ductility at the ultimate (peak) load
Δ_{ult}	Displacement at ultimate (peak) load
Δ_y	Yield displacement
μ_f	Displacement ductility at failure, is the
Δ_f	Displacement at failure load.
ξ_{eff}	Equivalent viscous damping ratio
E_{cycle}	Energy dissipated in the cycle

ξ_{el}	Elastic damping ratio
μ	Displacement ductility
$k(avg)$	Average lateral stiffness

LIST OF ACRONYMS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C	Cement
C3D8R	3-dimensional, 8-noded solid brick elements with reduced integration
CA	Coarse aggregate
CDP	Concrete damage plasticity
CSA	Canadian Standards Association
CTD	Cold twisted deformed
DLF	Design load factor
DCR	Design capacity ratio
EDI	Energy dissipation index
FA	Fine aggregate
FEM	Finite element method
FEMA	Federal Emergency Management Agency
FRP	Fiber-reinforced polymer
HPC	High performance concrete
HSC	High-strength concrete
HSS	High-strength steel
IS	Indian standard
LVDT	Linear variable displacement transducer
M	Grade of concrete
MCFT	Modified Compression Field Theory
NIST	National Institute of Standards and Technology

NZS	New Zealand Standard
OYS	Observed yield stress
PCA	Portland Cement Association
RC	Reinforced concrete
RSZ	Right shear zone
SCR	Stirrups contribution ratio
SD	Super ductile
SF	Silica fumes
SG	Strain gauge
SS	Shear span
ST	Transverse stirrups
STM	Strut and tie model
SYS	Specified yield stress
TL	Total load
T3D2	Two-node truss elements
T/Y	Tensile-to-yield strength ratio
TMS	Target mean strength
TMT	Thermo-mechanically treated
UHSS	Ultra-high strength steel