BEHAVIOR AND DESIGN OF COLD-FORMED STEEL BUILT-UP COLUMNS UNDER MONOTONIC AXIAL COMPRESSION LOADING

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This thesis is dedicated to my family, especially my parents who have been a driving force for me to pursue my higher studies.

CERTIFICATE

This is to certify that the thesis entitled, ***"Behavior and Design of Cold-formed Steel Built-Up Columns under Monotonic Axial Compression Loading"*** being submitted by ***Mohammad Adil Dar*** 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 our supervision and guidance. The thesis, in our 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

Cold-formed steel (CFS) is gaining a lot of popularity in the building construction industry, primarily due to its favourable features like higher strength-to-weight ratio, faster production, ease in fabrication and construction, etc. One of the key features of CFS construction is the flexibility to roll a steel strip into the desired shape/size to develop the required strength, without leading to any wasteful use of steel as a construction material, with limited reserves. Built-up members are commonly used in the steel construction, especially when the load demands on the structural members are large and the individual components of the built-up members do not suffice from strength or serviceability considerations. There are two types of steel built-up columns, viz., laced columns and battened columns, used in the practice. This efficiency of CFS members can be better achieved by adopting built-up members. The past research findings on CFS battened columns have been very limited, and no findings on CFS laced columns have been reported so far. Therefore, investigating the structural behavior of CFS laced and battened columns is necessary.

In this study, the nonlinear structural behavior of CFS built-up columns has been investigated both experimentally as well as numerically. Laced and battened columns with pin-ended support condition under monotonic concentric axial loading have been studied. Three groups of columns were fabricated. In the first group, plain angle sections were adopted as chord members with laced connections. In the second and third group, plain channel sections were adopted as chord members with battened and laced connections, respectively. Both steel bolts as well as self-drilling screws were used as fasteners. Local and global geometric imperfections were measured, in addition to the the actual material property determination through tensile testing of coupon specimens.

All the three categories of columns i.e., short columns, intermediate columns, and long columns were studied. The sectional compactness, overall slenderness, lacing slenderness, lacing configuration were the main parameters varied in the laced columns. Toe-to-toe spacing and intermediate batten spacing were varied in battened columns. All these variations were made to alter the ratio of unbraced chord slenderness to overall column slenderness, which significantly influences the behavior in built-up columns. Further, the test results were validated using finite element analysis (FEA). The numerical models were developed in ABAQUS. Apart from peak loads, the load *vs*. displacement response and the failure modes were also verified to get reliable finite element models (FEMs). Then, extensive parametric studies mainly on the variation of sectional compactness, lacing slenderness, toe-to-toe spacing, and overall slenderness (of the built-up columns) have been carried out. The design specifications on built-up columns in the current standards on CFS structures do not give clear guidelines, explicitly for laced and battened columns. Therefore, the adequacy of these standards for the same have been checked by both experimental as well as numerical studies. The results of this investigation indicated that the current design rules for CFS columns are not suitable for CFS battened columns. Hence, the improved design rules have been proposed for safe design strength predictions. Finally, design recommendations are proposed for improved structural performance of CFS built-up columns.

सार

कोल्ड फॉर्म्ड स्टील (सीएफएस) भवन निर्माण उद्योग में बहुत अधिक लोकप्रियता प्राप्त कर रहा है, मुख्य रूप से इसके अनुकूल विशेषताओं के कारण है जैसे उच्च शक्ति-से-वजन अनुपात, तेज उत्पादन, निर्माण में आसानी और गढ़ाई, आदि। प्रमुख विशेषताओं में से एक है, सीएफएस निर्माण सीमित ताकत के साथ, निर्माण सामग्री के रूप में स्टील के किसी भी बेकार उपयोग के लिए अग्रणी के बिना, आवश्यक ताकत विकसित करने के लिए वांछित आकार / परिमाण में एक स्टील की पट्टी को रोल करने के लिए लचीलापन है। बिल्ट अप अवयव का उपयोग आमतौर पर स्टील निर्माण में किया जाता है, खासकर जब संरचनात्मक सदस्यों पर लोड की मांग बड़ी होती है और बिल्ट अप अवयव के व्यक्तिगत घटक ताकत या सेवाक्षमता के विचार से ग्रस्त नहीं होते हैं। अभ्यास में उपयोग किए जाने वाले दो प्रकार के स्टील निर्मित स्तंभ हैं, अर्थात, लैसेड स्तंभ और बैटन कॉलम। सीएफएस सदस्यों की इस दक्षता को बेहतर तरीके से बनाया जा सकता है। सीएफएस पर आधारित स्तंभों पर पिछले शोध निष्कर्ष बहुत सीमित रहे हैं, और सीएफएस से संबंधित लैसेड स्तंभों पर कोई निष्कर्ष अब तक नहीं बताया गया है। इसलिए, सीएफएस लैसेड और बैटन किए गए स्तंभों के संरचनात्मक व्यवहार की जांच आवश्यक है।

इस अध्ययन में, सीएफएस निर्मित स्तंभों के नॉन-लिनियर संरचनात्मक व्यवहार की जांच दोनों प्रयोगात्मक रूप से और साथ ही संख्यात्मक रूप से की गई है। मोनोटोनिक संकेंद्रित अक्षीय लोडिंग के तहत पिन-एंडेड सपोर्ट कंडीशन वाले लैसेड और बैटन कॉलम का अध्ययन किया गया है। स्तंभों के तीन समूह गढ़े गए थे। पहले समूह में, सादे कोण वर्गों को कॉर्ड के सदस्यों के रूप में अपनाया गया था। दूसरे और तीसरे समूह में, सादे चैनल अनुभागों को क्रमश: बैटन और लैसेड कनेक्शन वाले कॉर्ड सदस्यों के रूप में अपनाया गया था। दोनों स्टील बोल्ट के साथ-साथ स्व-ड्रिलिंग पेच का उपयोग फास्टनरों के रूप में किया गया था। कूपन नमूनों के तन्य परीक्षण के माध्यम से वास्तविक भौतिक गुण निर्धारण के अलावा, स्थानीय और वैश्विक ज्यामितीय अपूर्णता को मापा गया। सभी तीन श्रेणियों के कॉलम यानी लघु कॉलम, इंटरमीडिएट कॉलम और लंबे कॉलम का अध्ययन किया गया। अनुभागीय कॉम्पैक्टनेस, समग्र पतलापन, लेसिंग स्लेंडर्नस, लेसिंग कॉन्फ़िगरेशन मुख्य पैरामीटर थे, जो लेस्ड कॉलम में भिन्न थे। टो-टू-

टो स्पेसिंग और इंटरमीडिएट बैटन स्पेसिंग बैटल कॉलम में भिन्न थे। इन सभी विविधताओं को समग्र कॉलम दुबलापन के लिए असंबंधित कॉर्ड स्लेंडर्नस के अनुपात को बदलने के लिए बनाया गया था, जो बिल्ट-अप कॉलम में व्यवहार को काफी प्रभावित करता है। इसके अलावा, परिमित तत्व विश्लेषण (FEA) का उपयोग करके परीक्षण के परिणाम सत्यापित किए गए थे। संख्यात्मक मॉडल ABAQUS में विकसित किए गए थे। पीक लोड के अलावा, लोड बनाम विस्थापन प्रतिक्रिया और विफलता मोड को भी विश्वसनीय परिमित तत्व मॉडल (एफईएम) प्राप्त करने के लिए सत्यापित किया गया था। फिर, मुख्य रूप से अनुभागीय कॉम्पैक्टनेस की भिन्नता पर व्यापक पैरामीट्रिक अध्ययन, लेसिंग स्लेंडर्नस, टो-टू-टो स्पेसिंग, और समग्र स्लेंडर्नस (बिल्ट-अप कॉलम का) किया गया है। सीएफएस संरचनाओं पर वर्तमान मानकों में बिल्ट-अप कॉलम पर डिज़ाइन विनिर्देश स्पष्ट दिशा-निर्देश नहीं देते हैं, स्पष्ट रूप से लैसेड और बैटन किए गए स्तंभों के लिए। इसलिए, इन मानकों की पर्याप्तता को प्रायोगिक और संख्यात्मक अध्ययन दोनों द्वारा जांचा गया है। इस जांच के परिणामों ने संकेत दिया कि सीएफएस कॉलम के लिए मौजूदा डिजाइन नियम सीएफएस से जुड़े कॉलम के लिए उपयुक्त नहीं हैं। इसलिए, सुरक्षित डिज़ाइन शक्ति पूर्व-सूचना के लिए बेहतर डिज़ाइन नियम प्रस्तावित किए गए हैं। अंत में, सीएफएस बिल्ट-अप कॉलम के बेहतर संरचनात्मक प्रदर्शन के लिए डिजाइन सिफारिशें प्रस्तावित हैं।

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LIST OF SYMBOLS

χ	Reduction factor
α	Imperfection factor
$\bar{\lambda}$	Non-dimensional slenderness ratio
a	Spacing of intermediate fasteners
A_e	Effective cross-sectional area
B	Toe-to-toe spacing
b, b_w	Web depth of chord member
b_{b1}	Width of end batten
b_f	Width of individual channel's flange
b_b	Width of intermediate batten
D	Depth of the section
E_o	Modulus of Elasticity
F_e	Least of elastic flexural, torsional and flexural-torsional buckling stress
F_n	Critical buckling stress
H	Height of the column
I	Radius of gyration about the relevant axis
K	Effective length factor
L	Length of the column
l_b	Length of end batten
L_{cr}	Buckling length
N_{cr}	Elastic critical force

P_{EC3}	Design strength predicted by EC-1993-3
P_{FEA}	Ultimate FEA predicted strength
P_{NAS}	Design strength predicted by AISI-S100
$P_{M.NAS}$	Design strength predicted by modified AISI-S100
P_{Test}	Ultimate Test strength
r	Minimum radius of gyration of column
r_1	Minimum radius of gyration of chord member
r_i	Root radius at the flange-web junction
t	Thickness of channels
t_b	Thickness of batten
ε_u	Strain at fracture
λ_c	Critical slenderness ratio parameter
f_y	Yield strength
σ_u	Ultimate strength
Δ	Lateral displacement at peak axial load
β	Reduction coefficient for proposed equation for AISI-S100
ζ	Reduction coefficient for proposed equation for EC-1993-3
λ_c	Critical slenderness ratio
λ	Overall column slenderness ratio
CFS	cold-formed steel
FEA	Finite element analysis
FEM	Finite element model
NAS	North American Specification AISI S-100
EC3	European Code EN
P_{EC3}	Design strength predicted by EC3-1-3
P_{FEA}	Ultimate FEA predicted strength

P_{NAS}	Design strength predicted by NAS
P_{Test}	Ultimate Test strength