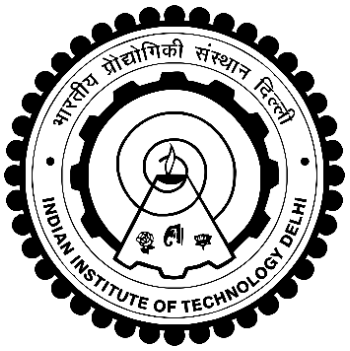
SEISMIC FRAGILITY OF LONG-SPAN SPECIAL TRUSS MOMENT FRAMES WITH MULTI-PANEL DUCTILE SEGMENTS

RAJESH KUMAR



DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER, 2021

SEISMIC FRAGILITY OF LONG-SPAN SPECIAL TRUSS MOMENT FRAMES WITH MULTI-PANEL DUCTILE SEGMENTS

by

RAJESH KUMAR

Department of Civil Engineering

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

INDIAN INSTITUTE OF TECHNOLOGY DELHI

SEPTEMBER, 2021

CERTIFICATE

This is to certify that the thesis entitled, ***"Seismic Fragility of Long-Span Special Truss Moment Frames with Multi-Panel Ductile Segments"*** being submitted by ***Rajesh Kumar*** 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.

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

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

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisors, Prof. Dipti Ranjan Sahoo and Prof. Ashok Gupta who have been very consistent in guiding me over the past 7 years. This research work would not have been possible without their guidance, continuous support, and positive criticism, throughout the entire period of research during PhD. Their mentoring has been exceptional. Because of the valuable guidance and support of my mentors, it helped me to grow as an independent researcher. Especially, Prof. Dipti Ranjan Sahoo has helped me a lot during my research through constant motivation and imparting high quality research work in a disciplined manner. It needs to be mentioned here that, Prof. Dipti Ranjan Sahoo taught me the efficient and effective way of doing research, be it conducting experiments or writing journal papers properly.

I am also thankful to my research committee members Prof. Vasant Matsagar, Prof. K. S. Rao and Prof. S. Pradyumna, for acting as my committee members even at hardship.

My sincere thanks to my seniors Dr. Ashwin Kumar, Dr. Romanbabu M. Oinam, Dr. Abhishek Verma and Dr. Ahmad Fayeq Ghowsi for being a source of inspiration. I would like to thank my research group friends (Dr. Mohammad Adil Dar, Ruban Sugumar, Pratik Patra, Sourabh Sharma, Suraj Sahu and Gautham Anbumani) who have been very supportive and encouraging, particularly during my experimentation. They always extended their helping hand, especially during my difficult times. I am also grateful to the staff of Heavy Structures Laboratory who have worked very hard in the fabrication of my test specimens. They have been very patient in learning the fabrication of built-up members which requires immense patience.

I really enjoyed the time with the research groups especially Dr. Romanbabu M. Oinam, Dr. Abhishek Verma, Dr. Mohammad Adil Dar and Dr. Ahmad Fayeq Ghowsi spent during tea breaks as there were a lot of discussion excited towards my research. I am lucky to have such a wonderful research group.

It would not be possible to complete my thesis without the support of my family. My brother, Rakesh Kumar deserves a special thanks for providing endless support during COVID-19 lockdown period. My sister, Swati Suman deserves also a special thank for providing support during writing the journal papers. I would like to express special thanks to Mrs. Manju Kumari and her daughter, Trisha Rani for providing mental and emotional support during my thesis work along with Mr. Ramanuj Kumar.

I express thanks to my dear friends (Er. Sujeet Kumar, Er. Satish Kumar, Er. Rishikesh Kumar and Er. Sanjeev Kumar etc.), who have encouraged for the pursuance towards my research.

At last, I am extremely grateful to god almighty, for blessing me with such great people, who have imparted positivity in my life.

Rajesh Kumar

ABSTRACT

Steel truss moment frames (STMFs) are used as the lateral force-resisting systems in buildings located in high seismic regions. These systems are lightweight and offer excellent lateral resistance and hysteretic energy dissipation when subjected to seismic actions. Despite of various advantages of such systems, some of the associated issues/limitations warrant for further investigation for their wider application in practice. The primary issues are the limitation on aspect ratios of Vierendeel panels, the behavior of long-span and multi-panel STMFs, the seismic collapse performance assessment of STMFs, and the behavior of STMFs with composite floor slabs. The present study aims at exploring these issues through detailed numerical and experimental investigations for achieve the enhanced seismic performance of STMFs.

Numerical models of STMFs are developed in non-linear analysis software PERFORM-3D to simulate their elastic and post-elastic behavior. The modelling parameters are validated by comparing the predicted hysteretic response with the past test results. The validated numerical models are adopted to carry out the collapse performance assessment and to determine the seismic performance factors of STMFs in accordance with FEMA P695 methodology. The numerical models of wide range of archetypes of different heights and varying aspect ratios of Vierendeel panels are developed. In addition to the nonlinear static analyses, incremental dynamic analyses are carried out for forty-four earthquake ground motions to develop the seismic fragility curves. The seismic performance was assessed through yield mechanism, drift response and rotational demand at the end of the special segments of STMF archetypes at the Design basis earthquake (DBE) and Maximum considered earthquake (MCE) ground motions. The analyses results showed that

the aspect ratio of Vierendeel panel of ductile segment could be increased to 2.5 and the height of STMFs could be increased to 65 m. while ensuring the acceptable seismic performance.

The experimental investigations were conducted on two geometrically identical STMFs with and without composite floor slabs. Panel aspect ratios of special segments of test specimens exceeded the current limitations of building codes in order to assess the cyclic performance of long-span STMFs. The main emphasis of the study on first test specimen was the yielding of the chords within the ductile segments, behavior of the elements outside the ductile segment, behavior of the columns, buckling in the flanges at the location of plastic hinges and behavior of the ductile segment. The test frame exhibited stable hysteresis response during the experiment i.e. 6% story drift. The detailing at the end of the special segment ensured the plastic hinge at the desired locations. In the second experiment, the frame with slab was also laterally loaded cyclically till 6% drift. The main emphasis of the study on frame with slab was the yielding of the chords within the ductile segments, behavior of the elements outside the ductile segment, behavior of the columns, buckling in the flanges at the location of plastic hinges, behavior of the ductile segment and crack propagation of slab. The test frame with slab also showed stable hysteresis response till 6% story drift under cyclic load. The detailing in the panel zone of the column was improved with stiffener detailing delayed the shear yielding effectively. The lateral buckling of the special segment was also delayed due to the presence of the slab. Conclusions drawn from the findings of numerical and experimental investigations are reported in this thesis.

सार

स्टील ट्रस मोमेंट फ्रेम (एसटीएमएफ) का उपयोग उच्च भूकंपीय क्षेत्रों में स्थित इमारतों में पार्श्व बल-प्रतिरोध प्रणालियों के रूप में किया जाता है। भूकंपीय क्रियाओं के अधीन होने पर ये सिस्टम हल्के होते हैं और उत्कृष्ट पार्श्व प्रतिरोध और हिस्टेरेटिक ऊर्जा अपव्यय प्रदान करते हैं। ऐसी प्रणालियों के विभिन्न लाभों के बावजूद, कुछ संबंधित मुद्दे/सीमाएं व्यवहार में उनके व्यापक अनुप्रयोग के लिए आगे की जांच के लिए वारंट करती हैं। प्राथमिक मुद्दे वीरेंडील पैनलों के पहलू अनुपात, लंबी अवधि और बहु-पैनल एसटीएमएफ के व्यवहार, एसटीएमएफ के भूकंपीय पतन प्रदर्शन मूल्यांकन, और समग्र मंजिल स्लैब के साथ एसटीएमएफ के व्यवहार पर सीमाएं हैं। वर्तमान अध्ययन का उद्देश्य एसटीएमएफ के बढ़े हुए भूकंपीय प्रदर्शन को प्राप्त करने के लिए विस्तृत संख्यात्मक और प्रयोगात्मक जांच के माध्यम से इन मुद्दों की खोज करना है।

एसटीएमएफ के संख्यात्मक मॉडल गैर-रैखिक विश्लेषण सॉफ्टवेयर PERFORM-3D में विकसित किए गए हैं ताकि उनके लोचदार और पोस्ट-लोचदार व्यवहार का अनुकरण किया जा सके। पिछले परीक्षण परिणामों के साथ अनुमानित हिस्टेरेटिक प्रतिक्रिया की तुलना करके मॉडलिंग मापदंडों को मान्य किया गया है। फेमा पी695 कार्यप्रणाली के अनुसार पतन प्रदर्शन मूल्यांकन करने और एसटीएमएफ के भूकंपीय प्रदर्शन कारकों को निर्धारित करने के लिए मान्य संख्यात्मक मॉडल अपनाए जाते हैं। विभिन्न ऊंचाइयों के आर्कटाइप्स की विस्तृत श्रृंखला के संख्यात्मक मॉडल और वीरेंडील पैनल के अलग-अलग पहलू अनुपात विकसित किए गए हैं। गैर-रेखीय स्थैतिक विश्लेषणों के अलावा, भूकंपीय नाजुकता घटता विकसित करने के लिए चौवालीस भूकंप जमीनी गतियों के लिए वृद्धिशील गतिशील विश्लेषण किए जाते हैं। डिजाइन के आधार पर भूकंप (डीबीई) और अधिकतम माना भूकंप (एमसीई) जमीनी गतियों पर एसटीएमएफ आर्कटाइप्स के विशेष खंडों के अंत में उपज

तंत्र, बहाव प्रतिक्रिया और घूर्णी मांग के माध्यम से भूकंपीय प्रदर्शन का आकलन किया गया था। विश्लेषण के परिणामों से पता चला है कि डक्टाइल सेगमेंट के वीरेंडील पैनल का पहलू अनुपात 2.5 तक बढ़ाया जा सकता है और एसटीएमएफ की ऊंचाई 65 मीटर तक बढ़ाई जा सकती है। स्वीकार्य भूकंपीय प्रदर्शन सुनिश्चित करते हुए।

प्रायोगिक जांच दो ज्यामितीय रूप से समान एसटीएमएफ पर मिश्रित फर्श स्लैब के साथ और बिना आयोजित की गई थी। लंबी अवधि के एसटीएमएफ के चक्रीय प्रदर्शन का आकलन करने के लिए परीक्षण नमूनों के विशेष खंडों के पैनल पहलू अनुपात बिल्डिंग कोड की वर्तमान सीमाओं को पार कर गए हैं। पहले परीक्षण नमूने पर अध्ययन का मुख्य जोर डक्टाइल सेगमेंट के भीतर कॉर्ड्स की उपज, डक्टाइल सेगमेंट के बाहर के तत्वों का व्यवहार, कॉलम का व्यवहार, प्लास्टिक के टिका के स्थान पर फ्लैंग्स में बकलिंग और डक्टाइल का व्यवहार था। खंड। परीक्षण फ्रेम ने प्रयोग के दौरान स्थिर हिस्टैरिसीस प्रतिक्रिया प्रदर्शित की यानी 6% स्टोरी ड्रिफ्ट। विशेष खंड के अंत में विवरण ने वांछित स्थानों पर प्लास्टिक का काज सुनिश्चित किया। दूसरे प्रयोग में, स्लैब वाले फ्रेम को भी ६% बहाव तक चक्रीय रूप से लोड किया गया था। स्लैब के साथ फ्रेम पर अध्ययन का मुख्य जोर डक्टाइल सेगमेंट के भीतर कॉर्ड्स की यील्डिंग, डक्टाइल सेगमेंट के बाहर के तत्वों का व्यवहार, कॉलम का व्यवहार, प्लास्टिक के टिका के स्थान पर फ्लैंग्स में बकलिंग, डक्टाइल का व्यवहार था। स्लैब का खंड और दरार प्रसार। स्लैब के साथ परीक्षण फ्रेम ने चक्रीय भार के तहत 6% स्टोरी ड्रिफ्ट तक स्थिर हिस्टैरिसीस प्रतिक्रिया भी दिखाई। कॉलम के पैनल ज़ोन में डिटेलिंग में सुधार किया गया था जिसमें स्टिफ़नर डिटेलिंग ने शीयर यील्ड को प्रभावी ढंग से विलंबित किया। स्लैब की उपस्थिति के कारण विशेष खंड के पार्श्व बकलिंग में भी देरी हुई। इस थीसिस में संख्यात्मक और प्रयोगात्मक जांच के निष्कर्षों से निकाले गए निष्कर्ष बताए गए हैं।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

$ACMR_{10\%}$	Acceptable value of the adjusted collapse margin ratio (ACMR), on average, for the performance group of interest
$ACMR_{20\%}$	Acceptable value of the adjusted collapse margin ratio (ACMR) for an individual archetype of the performance group of interest
A_g	Gross cross-sectional area
B_1	Numerical coefficient for effective damping and the fundamental time period of the structure
C_d	Deflection amplification factor
C_s	Seismic response coefficient
C_u	Coefficient for the upper limit on the calculated time period
C_{vx}	Vertical distribution factor
D_l	Plastic rotation at ultimate strength
D_r	Plastic rotation at strength loss
D_u	Plastic rotation at strain hardening
E	Modulus of elasticity of structural steel
F_a	Short-period site coefficient
$F_d(S_{aT})$	Fragility function for damage state, d evaluated at spectral acceleration, S_{aT}
F_i	Lateral force at i^{th} floor
F_v	Long-period site coefficient
F_{ye}	Expected yield strength of material
F_y	Material yield stress of structural steel
I	Importance factor of the structure
I_c	Moment of inertia of chord member of the special segment
I_v	Moment of inertia of intermediate vertical member
L	Length of truss girder
L_{pd}	Maximum allowed unbraced length
L_s	length of the special segment
M	Bending moment
M_n	Nominal flexural capacity
M_{nc}	Nominal flexural strength of a chord member of SS

M_{nv}	Nominal flexural strength of intermediate vertical member
M_p	Plastic moment capacity of chord members of the special segment
M^*_p	Ultimate flexural strength of the composite section under monotonic loading
M_u	Ultimate flexural capacity
P	Axial force
P_{cr}	Strength of X-diagonal in compression buckling
P_n	Nominal axial capacity
P_{nc}	Nominal compressive strength of a diagonal member of SS
P_{nt}	Nominal tensile strength of a diagonal member of SS
P_u	Ultimate axial capacity
P_y	Yield-strengths of X-diagonal in tension
P_{ye}	expected axial yield force
R	Response modification factor
Ry	Ratio of the expected yield stress to the specified minimum yield stress
S_{aT}	Particular value of intensity of response spectra
$S_{aT(50\%)}$	Median of the response spectra for a particular damage state
S_{CT}	Median collapse intensity
S_{DS}	Design spectral response acceleration in the short period range
S_{D1}	Design spectral response acceleration at a period of 1.0 s
S_{MS}	Maximum considered earthquake spectral acceleration at short period
S_{MT}	MCE intensity at the fundamental period
S_{M1}	Maximum considered earthquake spectral acceleration at one second
S_S	Mapped maximum considered earthquake spectral response acceleration at short period
S_T	Period based spectral acceleration
S_1	Mapped maximum considered earthquake spectral response acceleration at one second
T	Calculated time period of structure
T_L	Long–period transition period
T_1	Fundamental time period of structure determined from eigenvalue analysis
V_{db}	Design base shear of the structure
V_E	Elastic base shear
V_{max}	Maximum base shear
V_{ne}	Expected shear strength of special segment

V_p	Ultimate shear capacity of special segment
V_{ult}	Ultimate shear capacity of SS considering composite action
W	Effective seismic weight of the structure
Z_p	Plastic section modulus
b	Width of flange
d	A particular value of d_s
d_s	Damage state at performance levels
h	Depth of web
h_i	Height from the base of structure to i^{th} level
h_x	Height from the base of structure to level x
l	Length of element
l_c	Length of column
m	Number of intermediate vertical member
r_y	Radius of gyration of individual component about the weak (y) axis
t_w	Thickness of web
t_f	Thickness of flange
w_x	Seismic wt of the structure at level x
w_i	Seismic wt. of the structure at i^{th} level
α	Angle made by X-diagonals with the horizontal
β	Ratio of cyclic flexural strength to monotonic flexural strength
β_{DR}	Design related collapse uncertainty
β_{MDL}	Modeling related collapse uncertainty
β_{RTR}	Record-to-record collapse uncertainty
β_{TD}	Test data related collapse uncertainty
β_{TOT}	Total system collapse uncertainty
δ	Design elastic displacement
δ_E	Expected inelastic displacement
δ_u	Roof displacement corresponding to 80% of maximum base shear strength
$\delta_{y,eff}$	Effective yield displacement
λ_{DR}	Random variable representing design requirements-related collapse uncertainty
λ_{MDL}	Random variable representing modeling-related collapse uncertainty
λ_{RTR}	Random variable representing record-to-record collapse uncertainty
λ_{TD}	Random variable representing test data-related collapse uncertainty

ϕ	Ratio of post-buckling to initial buckling strength of X-diagonals
$\phi_{1,r}$	Ordinates of the fundamental mode at roof level
$\phi_{1,x}$	Ordinates of the fundamental mode at floor level x
θ_p	Roof drift ratio
θ_y	Yield rotation
Ω	Overstrength factor

LIST OF ACRONYMS

AR	Aspect Ratio
ACMR	Adjusted collapse margin ratio
BRBs	Buckling restrained braces
BRBTMF	Buckling restrained braced truss moment frame
BRKBTMF	Buckling restrained knee braced truss moment frame
CBFs	Concentrically braced frames
CMR	Collapse margin ratio
CP	Collapse Prevention
CT-CP	Column truss connecting plate
DBE	Design basis Earthquake
DL	Dead Load
DR	Design requirements uncertainty
DTMFs	Dissipative truss moment frames
DVSTMF	Ductile Vierendeel steel special truss moment frame
EBF	Eccentrically braced frame
EDDs	Energy dissipation devices
ED-CGL	Elastic Design-Chao Goel distribution
ED-IT	Elastic design with Inverted Triangular distribution
ELF	Equivalent lateral force
FE	Finite element
FF	Far-Field
FLB	Flange local buckling
FTMF	Fused truss moment frame
GP	Gusset plate
IDA	Incremental dynamic analysis
IDR	Inter-story drift ratio
IO	Immediate Occupancy
ISMB	Indian standard medium weight beam
ISMC	Indian standard medium weight channel
IVMs	Intermediate vertical members

LL	Live load
LS	Life safety
LTB	Lateral torsional buckling
MCE	Maximum Considered Earthquake
MDL	Modelling uncertainty
MRF	Moment-resisting frame
OMRF	Ordinary moment-resisting frame
PBPD	Performance based plastic design
PD	Plastic design
PG	Performance group
RTR	Record-to-record uncertainty
SDC	Seismic Design Category
SMFs	Steel moment frames
SS	Special segment
SSF	Spectral shape factor
STMF	Special Truss Moment frame
TD	Test data uncertainty
TMF	Truss Moment Frame
UTM	Universal testing machine