ANALYSIS METHOD FOR MULTI-HAZARD PROTECTION OF STRUCTURES FROM EARTHQUAKE, WIND, BLAST, AND FIRE

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by

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

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Dedicated to my family

For their endless love, support, and encouragement

CERTIFICATE

This is to certify that the PhD thesis titled, "**ANALYSIS METHOD FOR MULTI-HAZARD PROTECTION OF STRUCTURES FROM EARTHQUAKE, WIND, BLAST, AND FIRE**" being submitted by **TATHAGATA ROY** to the Indian Institute of Technology (IIT) Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** is a record of the bonafide research work carried out by him. He worked under my supervision for the submission of this PhD thesis, which to my knowledge has reached the requisite standard as demonstrated by excellent international publications in journals and conferences.

Further, the contents of his research work, in full or in parts, have not been submitted to any other institute or university for the award of any degree or diploma to the best of my knowledge and belief.

New Delhi
Monday, 5th April, 2021

Prof. Dr Vasant A. MATSAGAR

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"*It is good to have an end to journey toward; but it is the journey that matters, in the end*"

- Ursula K. Le Guin

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ABSTRACT

Multiple hazards, such as, earthquakes, strong winds, blasts, and fire outbreaks have caused extensive global devastations to civil structures since centuries in terms of physical and socio-economic losses. The rapid growth of infrastructure advancements in the last few decades has significantly increased the vulnerability of the structural systems under these multiple hazards. The increased vulnerability due to the multi-hazard (MH) scenario has been causing a major setback for the scientifically prospering society, thereby resulting in significant hindrance to the socio-economic developments. Although, scientific expertise has been developed to safeguard the existing and new constructed structures against a particular hazard, the new MH engineering is in evolving phase with limited knowledge in protection of structures against the MH scenario. A fundamental difference between the existing design approach and the new MH design approach is that the existing design guidelines, standards, and codes do not incorporate the integrated approach for all the exposed hazards, wherein the current design practice considers the hazards completely independent. In such scenario, the design is being governed by the controlling demand from the exposed hazards, which duly ignores the additional risk arising due to the other hazards. In this regard, the primary objective of the newly emerging MH engineering should consider addressing the effects of all hazard existent in the design life of structures. Hence, the increased risks under the exposed MH scenarios should be addressed categorically, which calls for devising some efficient frameworks that incorporates the effects of the hazards for achieving a safe and hazard-resilient built environment.

In order to develop efficient and fundamental approaches, it is imperative to recognize the distinguished features of the hazards occurring in a lifetime of a structure. Extreme natural hazards, such as, earthquake and strong winds, are mutually exclusive and collectively exhaustive events, as the probability of simultaneous occurrence for the hazards is zero. Hence, structures exposed to MH scenario of earthquakes and strong winds, experience no more than a particular hazard at one time. Existing approaches are unspoken of the standard risks of exceedance for identified limit states in regions where only earthquakes or winds occur. Moreover, the occurrence of fire outbreaks after an explosion by blast or an earthquake induce significant complexities in the system, as assessment strategies for such cascading scenarios is extremely limited. Post-blast fire (PBF) is a cause-and-effect phenomenon of such explosion scenarios that results in catastrophic failure of structures

through intricate cascading effects. In this regard, probabilistic methods have the potential to integrate the complexities in the system in order to quantify the vulnerability induced in the structure for obtaining reliable set of design values under MH scenario. Thus, the MH assessment strategy, therefore, will outstretch the prevailing methodology to ensure adequate safety and serviceability for structural resistance against such extreme forces.

In this thesis, the need and relevance of MH analysis and design of structures are elaborated, and existing MH assessment strategies are discussed with clear focus on the differences between the traditional and MH design approach. Three distinct MH frameworks are developed and employed to different structural systems under each proposed framework, which includes scenarios such as, earthquake and wind, and blast and fire. To achieve these objectives, probabilistic approaches are employed to develop the frameworks, which are further utilized to investigate the performance of structures for obtaining the additional risks induced the system due to the MH scenarios. The probabilistic approaches adopted for developing the MH frameworks show that the prescriptive guidelines utilizing the deterministic approach are relatively lesser rational and may overestimate the design values, which may not essentially evaluate the structural response accurately. Further, it is observed that there exists a range of frequencies, which govern the design of structures under earthquake and wind excitations, and typically, such assessment is governed by MH scenario. More importantly, the traditional design guideline that allows utilizing either of the maximum of earthquake or wind load may seriously underestimate the distress level likely to occur in passive control devices, thus questioning the global safety of the structure. Dealing with the cascading PBF scenario indicates that the fire resistance decreases by ~11 % to ~23 % for structural members. Hence, the relative decrease in time should be kept in mind by rescue teams for having adequate time to control the fire and safely evacuate the inhabitants from the PBF damaged structure. Finally, guidelines and recommendations for design of structure and infrastructure systems under the MH scenarios of natural and accidental/ manmade hazards, specifically in Indian context are presented. Key design strategies during design (service) life for normal civil engineering structures as well as critical infrastructures and facilities are recommended for major regions of India experiencing multiple hazards. Eventually, the proposed MH analysis and design framework tools can be used in other regions also, in order to have risk consistent approach for safety of structures under the extreme MH scenario.

सार

कई खतरों, जैसे, भूकंप, तेज हवाएं, विस्फोट, और आग के प्रकोपों ने सदियों से सामाजिक-आर्थिक नुकसान के लिए नागरिक संरचनाओं के लिए व्यापक वैश्विक तबाही मचाई है। पिछले कुछ दशकों में बुनियादी ढांचे की प्रगति में तेजी से वृद्धि ने इन कई खतरों के तहत संरचनात्मक प्रणालियों की भेद्यता में काफी वृद्धि की है। बहु-खतरा (MH) परिदृश्य के कारण बढ़ी हुई भेद्यता वैज्ञानिक रूप से समृद्ध समाज के लिए एक बड़ा झटका रही है, जिससे सामाजिक-आर्थिक विकास में महत्वपूर्ण बाधा उत्पन्न हुई है। यद्यपि, वैज्ञानिक विशेषज्ञता को एक विशेष खतरे के खिलाफ मौजूदा और नई निर्मित संरचनाओं की सुरक्षा के लिए विकसित किया गया है, नई MH इंजीनियरिंग MH परिदृश्य के खिलाफ संरचनाओं के संरक्षण में सीमित ज्ञान के साथ विकसित होने के चरण में है। मौजूदा डिजाइन दृष्टिकोण और नए MH डिजाइन दृष्टिकोण के बीच एक बुनियादी अंतर यह है कि मौजूदा डिजाइन दिशानिर्देश, मानक और कोड सभी उजागर खतरों के लिए एकीकृत दृष्टिकोण को शामिल नहीं करते हैं, जिसमें मौजूदा डिजाइन अभ्यास खतरों को पूरी तरह से स्वतंत्र मानता है। ऐसे परिदृश्य में, डिज़ाइन को नियंत्रित खतरों से नियंत्रित मांग द्वारा नियंत्रित किया जा रहा है, जो अन्य खतरों के कारण उत्पन्न अतिरिक्त जोखिम की विधिवत अनदेखी करता है। इस संबंध में, नए उभरते MH इंजीनियरिंग के प्राथमिक उद्देश्य को संरचनाओं के डिजाइन जीवन में मौजूद सभी खतरनाक प्रभावों को संबोधित करना चाहिए। इसलिए, उजागर किए गए MH परिदृश्यों के तहत बढ़े हुए जोखिमों को स्पष्ट रूप से संबोधित किया जाना चाहिए, जो कुछ कुशल रूपरेखाओं को तैयार करने के लिए कहता है जो एक सुरक्षित और खतरनाक-लचीला निर्मित वातावरण प्राप्त करने के लिए खतरों के प्रभावों को शामिल करता है।

कुशल और मौलिक दृष्टिकोण विकसित करने के लिए, संरचना के जीवनकाल में होने वाले खतरों की विशिष्ट विशेषताओं को पहचानना अनिवार्य है। अत्यधिक प्राकृतिक खतरे, जैसे कि भूकंप और तेज हवाएं, पारस्परिक रूप से अनन्य और सामूहिक रूप से संपूर्ण घटनाएँ हैं, क्योंकि खतरों के लिए एक साथ होने की संभावना शून्य है। इसलिए, भूकंप और तेज हवाओं के MH परिदृश्य के संपर्क में आने वाली संरचनाएं एक समय में किसी विशेष खतरे से अधिक नहीं होती हैं। मौजूदा दृष्टिकोण उन क्षेत्रों में पहचाने गए सीमा राज्यों के लिए अत्यधिक जोखिम के मानक जोखिम से रहित हैं जहां केवल भूकंप या हवाएं होती हैं। इसके अलावा, विस्फोट या विस्फोट से विस्फोट के बाद आग लगने की घटना प्रणाली में महत्वपूर्ण जटिलताओं को प्रेरित करती है, क्योंकि इस तरह के कैस्केडिंग परिदृश्यों के लिए मूल्यांकन रणनीति बेहद सीमित है। विस्फोट के बाद की आग (PBF) ऐसे विस्फोट परिदृश्यों का एक कारण-और-प्रभाव घटना है जो जटिल कैस्केडिंग प्रभावों के माध्यम से संरचनाओं की भयावह विफलता का परिणाम है। इस संबंध में, संभाव्य तरीकों में MH परिदृश्य के तहत डिजाइन मूल्यों के

विश्वसनीय सेट प्राप्त करने के लिए संरचना में प्रेरित भेद्यता को निर्धारित करने के लिए प्रणाली में जटिलताओं को एकीकृत करने की क्षमता है। इस प्रकार, MH मूल्यांकन रणनीति, इसलिए, इस तरह के चरम बलों के खिलाफ संरचनात्मक प्रतिरोध के लिए पर्याप्त सुरक्षा और सेवाक्षमता सुनिश्चित करने के लिए प्रचलित पद्धति को आगे बढ़ाएगी।

इस थीसिस में, MH विश्लेषण और संरचनाओं के डिजाइन की आवश्यकता और प्रासंगिकता विस्तृत है, और मौजूदा MH मूल्यांकन रणनीतियों पर पारंपरिक और MH डिजाइन दृष्टिकोण के बीच अंतर पर स्पष्ट ध्यान देने के साथ चर्चा की जाती है। तीन अलग-अलग MH फ्रेमवर्क प्रत्येक प्रस्तावित ढांचे के तहत विभिन्न संरचनात्मक प्रणालियों में विकसित और नियोजित किए जाते हैं, जिसमें भूकंप और हवा और विस्फोट और आग जैसे परिदृश्य शामिल हैं। इन उद्देश्यों को प्राप्त करने के लिए, फ्रेमवर्क विकसित करने के लिए संभाव्य दृष्टिकोण का उपयोग किया जाता है, जो आगे MH परिदृश्यों के कारण सिस्टम को प्रेरित अतिरिक्त जोखिमों को प्राप्त करने के लिए संरचनाओं के प्रदर्शन की जांच करने के लिए उपयोग किया जाता है। MH चौखटे विकसित करने के लिए अपनाए जाने वाले संभावित दृष्टिकोण बताते हैं कि नियतात्मक दृष्टिकोण का उपयोग करने वाले पूर्व निर्धारित दिशा-निर्देश अपेक्षाकृत कम तर्कसंगत हैं और डिजाइन मूल्यों को कम कर सकते हैं, जो अनिवार्य रूप से संरचनात्मक प्रतिक्रिया का सही मूल्यांकन नहीं कर सकते हैं। इसके अलावा, यह देखा गया है कि आवृत्तियों की एक श्रृंखला मौजूद है, जो भूकंप और हवा के उत्तेजना के तहत संरचनाओं के डिजाइन को नियंत्रित करती है, और आमतौर पर, ऐसा मूल्यांकन MH परिदृश्य द्वारा नियंत्रित होता है। इससे भी महत्वपूर्ण बात यह है कि पारंपरिक डिजाइन दिशानिर्देश जो भूकंप या हवा के भार का अधिकतम उपयोग करने की अनुमति देता है, निष्क्रिय नियंत्रण उपकरणों में होने वाले संकट के स्तर को गंभीरता से कम कर सकता है, इस प्रकार संरचना की वैश्विक सुरक्षा पर सवाल उठाता है। कैस्केडिंग PBF परिदृश्य से निपटना इंगित करता है कि संरचनात्मक सदस्यों के लिए अग्नि प्रतिरोध ~ 11% से ~ 23% तक कम हो जाता है। इसलिए, पीबीएफ क्षतिग्रस्त संरचना से निवासियों को आग पर काबू पाने और निवासियों को सुरक्षित रूप से बाहर निकालने के लिए पर्याप्त समय होने के लिए बचाव दलों द्वारा समय में सापेक्ष कमी को ध्यान में रखा जाना चाहिए। अंत में, विशेष रूप से भारतीय संदर्भ में प्राकृतिक और आकस्मिक / मानव निर्मित खतरों के MH परिदृश्यों के तहत संरचना और बुनियादी ढांचे प्रणालियों के डिजाइन के लिए दिशानिर्देश और सिफारिशें प्रस्तुत की जाती हैं। सामान्य सिविल इंजीनियरिंग संरचनाओं के लिए डिजाइन (सेवा) जीवन के दौरान महत्वपूर्ण रणनीति और महत्वपूर्ण खतरों और सुविधाओं के लिए भारत के प्रमुख क्षेत्रों में कई खतरों का सामना करने की सलाह दी जाती है। आखिरकार, प्रस्तावित MH विश्लेषण और डिजाइन फ्रेमवर्क टूल का उपयोग अन्य क्षेत्रों में भी किया जा सकता है, ताकि चरम MH परिदृश्य के तहत संरचनाओं की सुरक्षा के लिए जोखिम लगातार दृष्टिकोण हो।

TABLE OF CONTENTS

CHAPTER		TITLE	PAGE NO.
		Abstract	**vii**
		Table of Contents	**xi**
		List of Tables	**xxiii**
		List of Figures	**xxvii**
		Mathematical Notations and Symbols	**xxxix**
		Abbreviations	**xlvii**
CHAPTER 1		**INTRODUCTION AND LITERATURE REVIEW**	**1-16**
	1.1	General	1
	1.2	Multi-Hazard Assessment under Independent Hazards of Earthquake and Wind	6
	1.3	Cascading-Hazard Assessment under Blast and Fire	7
	1.4	Cascading-Hazard Assessment under Earthquake and Fire	8
	1.5	Global Challenges in Multi-Hazard Assessment	10
	1.6	Need and Relevance of Present Study	11
	1.7	Objectives and Scope of Study in the Doctoral Thesis	13
	1.8	Organization of the Thesis	15
CHAPTER 2		**MULTI-HAZARD ASSESSMENT OF SINGLE-DEGREE OF FREEDOM (S-DOF) SYSTEM UNDER BASE AND MASS EXCITATIONS**	**17-36**
	2.1	General	17
	2.2	Response of S-DOF System Subjected to Harmonic Excitations	18
	2.3	Multi-Hazard Assessment Framework (MH Framework-I)	20
	2.4	Stochasticity in Base and Mass Excitations	22

CHAPTER		TITLE	PAGE NO.
	2.5	Energy Principle in a Multi-Hazard Scenario	23
	2.6	Results and Discussion	24
		2.6.1 Deterministic multi-hazard study	27
		2.6.2 Probabilistic multi-hazard study	29
	2.7	Closure	36
CHAPTER 3		**MULTI-HAZARD ASSESSMENT OF MULTI-DEGREE OF FREEDOM (M-DOF) SYSTEM USING PASSIVE CONTROL DEVICES UNDER BASE AND MASS EXCITATIONS**	**37-60**
	3.1	General	37
	3.2	Mathematical Modeling of M-DOF Systems	39
		3.2.1 Modeling of moment resisting frame (MRF)	41
		3.2.2 Modeling of steel braced frame (SBF)	40
		3.2.3 Modeling of fluid viscous damped frame (FVDF)	42
		3.2.4 Modeling of viscoelastic damped frame (VEDF)	43
	3.3	Multiple Hazard Scenarios	44
		3.3.1 Earthquake hazard	44
		3.3.2 Wind hazard	44
	3.4	Results and Discussion	45
		3.4.1 Discussion for 9-storey steel buildings	47
		3.4.2 Discussion for 20-storey steel buildings	51
		3.4.3 Discussion for 25-storey steel buildings	53
	3.5	Multi-Hazard Assessment of Steel Buildings	57
	3.6	Closure	60

CHAPTER		TITLE	PAGE NO.
CHAPTER 4		**PROBABILISTIC MULTI-HAZARD ASSESSMENT OF MULTI-DEGREE OF FREEDOM (M-DOF) SYSTEM USING PASSIVE CONTROL DEVICES UNDER STOCHASTIC BASE AND MASS EXCITATIONS**	**61-84**
	4.1	General	61
	4.2	Mathematical Modeling of M-DOF Systems	63
	4.3	Multi-Hazard Framework (MH Framework-I) and Fragility Estimation	63
	4.4	Stochasticity of the Hazards	64
		4.4.1 Seismic hazard	64
		4.4.2 Wind hazard	64
	4.5	Results and Discussion	65
		4.5.1 Distribution of peak response data for steel buildings	67
		4.5.2 Failure density plots for steel buildings	74
		4.5.3 Fragility curves of steel buildings	80
	4.6	Closure	83
CHAPTER 5		**MULTI-HAZARD PERFORMANCE EVALUATION OF A REAL-LIFE BASE-ISOLATED BUILDING UNDER EARTHQUAKES AND LONG DURATION WINDS**	**85-110**
	5.1	General	85
	5.2	Structural Model and Analysis of the Base-Isolated Building	87
		5.2.1 Structural description	87
		5.2.2 Numerical model and analysis	89

CHAPTER		TITLE	PAGE NO.
	5.3	Multi-Hazard Framework (MH Framework-II) for Estimating Probable Earthquake or Wind Loads in Design Life of a Building	92
		5.3.1 Estimation of probability of earthquake or wind intensity	93
		5.3.2 Probability of occurrence for earthquake or wind	94
		5.3.3 Generation of earthquake or wind events in design life of a building	95
	5.4	Earthquake and Wind Hazards	95
		5.4.1 Generation of spectrum-compatible ground motions	95
		5.4.2 Generation of long duration wind time history	96
	5.5	Evaluation of Fatigue for the LRBs under Multi-Hazard Scenario	100
		5.5.1 Steps for constructing fatigue curve of LRB under high-cycle loading	100
	5.6	Results and Discussion	101
		5.6.1 Performance of Shinshiro City Hall under individual earthquakes and winds	103
		5.6.2 Performance of Shinshiro City Hall under proposed multi-hazard scenario	105
		5.6.3 Evaluation of fatigue response using the proposed methodology	107
	5.7	Closure	109
CHAPTER 6		**PERFORMANCE OF BASE-ISOLATED HIGH-RISE BUILDINGS UNDER MULTI-HAZARD SCENARIO OF EARTHQUAKES AND LONG DURATION WINDS**	**111-132**
	6.1	General	111

CHAPTER		TITLE	PAGE NO.
	6.2	Design of Base-Isolation System for High-Rise Building	113
	6.3	Modeling and Analysis of Base-Isolated High-Rise Buildings	114
		6.3.1 Structural description	114
		6.3.2 Numerical model and analysis	115
	6.4	Multi-Hazard Framework (MH Framework-II)	119
	6.5	High-Cycle Fatigue Estimation of LRB	119
	6.6	Results and Discussion	119
		6.6.1 Performance of high-rise buildings under individual hazard scenario	120
		6.6.2 Performance of high-rise buildings under proposed multi-hazard scenario	125
		6.6.3 Fatigue behavior of the LRBs using the proposed multi-hazard methodology	130
	6.7	Closure	132
CHAPTER 7		**PERFORMANCE ASSESSMENT OF REINFORCED CONCRETE PANELS UNDER BLAST AND FIRE LOADS**	**133-174**
	7.1	General	133
	7.2	Structural Details and Finite Element (FE) Modeling	137
		7.2.1 Structural description	137
		7.2.2 Finite element (FE) modeling approach	140
		7.2.3 Numerical solution scheme	141
	7.3	Material Model	144
		7.3.1 Material model for blast analysis	144
		7.3.1.1 *Strain-rate properties for blast analysis*	144
		7.3.1.2 *Mechanical properties for blast analysis*	145
		7.3.2 Material model for thermal analysis	147

CHAPTER		TITLE	PAGE NO.
		7.3.2.1 *Thermal properties for thermo-mechanical analysis*	148
		7.3.2.2 *Mechanical properties for thermal analysis*	149
	7.4	Loading Scenarios	151
		7.4.1 Blast load scenario	151
		7.4.2 Fire load scenario	153
	7.5	Fragility Functions	154
	7.6	Results and Discussion	156
		7.6.1 Deterministic assessment of the RC panels under independent blast and fire	157
		7.6.2 Probabilistic assessment of the RC panels under independent blast and fire	163
	7.7	Closure	173
CHAPTER 8		**PERFORMANCE OF REINFORCED CONCRETE PANEL UNDER CASCADED POST-BLAST FIRE SCENARIO**	**175-196**
	8.1	General	175
	8.2	Damage Mechanism under a Cascaded Post-Blast Fire Hazard Scenario	176
	8.3	Structural Details and Finite Element (FE) Modeling Approach	177
		8.3.1 Structural description and detailing	177
		8.3.2 FE model of RC wall panel	178
		8.3.3 Numerical solution scheme	179
	8.4	Plasticity-Based Modeling of Concrete and Steel	180
	8.5	Material Model	186
	8.6	Blast and Fire Loading Scenarios	186
	8.7	Results and Discussion	187
	8.8	Closure	196

CHAPTER		TITLE	PAGE NO.
CHAPTER 9		**PROBABILISTIC CASCADING HAZARD FRAMEWORK FOR INVESTIGATING REINFORCED CONCRETE WALL PANEL UNDER RANDOM POST-BLAST FIRE SCENARIO**	**197-214**
	9.1	General	197
	9.2	Structural Description and Numerical Modeling	198
	9.3	Material Model for Structural Analysis under Cascaded Post-Blast Fire	198
	9.4	Loading Scenarios	199
	9.5	Cascading Hazard Framework (MH Framework-III) for Post-Blast Fire Scenario	199
		9.5.1 Fragility estimation for a single hazard scenario	199
		9.5.2 Fragility estimation for a cascading hazard scenario	199
		9.5.3 Limit states of failure	200
	9.6	Stochasticity in Cascaded Post-Blast Fire Analysis	200
		9.6.1 Uncertainty in material strength	201
		9.6.2 Uncertainty in thermal properties	202
		9.6.3 Uncertainty in mechanical loading	203
		9.6.4 Uncertainty in blast loading	204
		9.6.5 Uncertainty in fire loading	205
	9.7	Results and Discussion	206
	9.8	Closure	214
CHAPTER 10		**MULTI-HAZARD ANALYSIS AND DESIGN GUIDELINES: RECOMMENDATIONS FOR STRUCTURAL SYSTEMS IN INDIAN CONTEXT**	**215-230**
	10.1	General	215
	10.2	Multi-Hazard Demography of India	216

CHAPTER		TITLE	PAGE NO.
		10.2.1 The Himalayan belt	216
		10.2.2 Great plains of alluvial deposit	218
		10.2.3 Hills of the peninsular India	219
		10.2.4 Coastal zones	219
	10.3	Multi-Hazard Assessment Strategies and Design Recommendation for India	220
		10.3.1 Design recommendations for earthquake and gusty wind/ cyclone	224
		10.3.2 Design recommendation for cascading post-explosion/-blast fire	225
	10.4	Analysis and Design Recommendations	226
	10.5	Summary	229
CHAPTER 11		**SUMMARY AND CONCLUSIONS**	**231-238**
	11.1	Summary	231
	11.2	Conclusions	232
	11.3	Future Scope of Research	236
APPENDIX 1		**VALIDATION STUDY**	**239-246**
	A1.1	Validation of 20-Storey Benchmark Steel Building under Earthquakes	239
	A1.2	Validation of Shinshiro City Hall from Observed Responses	241
	A1.3	Validation of Modeling Strategy for RC Panels under Blast and Fire Loadings	242
APPENDIX 2		**RECORDED GROUND MOTION DATABASE**	**247-250**

CHAPTER		TITLE	PAGE NO.
APPENDIX 3		**EFFECTIVENESS OF FRICTION DAMPERS IN CONNECTED ADJACENT STEEL BUILDINGS UNDER MULTI-HAZARD SCENARIO OF EARTHQUAKES AND WINDS**	**251-272**
	A3.1	General	251
	A3.2	Mathematical Modeling of Steel Buildings	252
		A3.2.1 Mathematical modeling of moment resisting frame (MRF)	254
		A3.2.2 Mathematical modeling of braced frame (BF)	255
		A3.2.1 Mathematical modeling of connected frame using friction damper (FD)	255
	A3.3	Multi-Hazard Scenario under Earthquake and Wind Excitations	258
	A3.4	Results and Discussion	258
		A3.4.1 Effectiveness of FD for dynamically similar connected buildings	261
		A3.4.2 Effectiveness of FD for dynamically dissimilar connected buildings	264
	A3.5	Summary and Conclusions	271
APPENDIX 4		**APPLICATION OF MH FRAMEWORK-I TO INDUSTRIAL STEEL STRUCTURE UNDER STOCHASTIC EARTHQUAKE AND WIND EXCITATIONS**	**273-292**
	A4.1	General	273
	A4.2	Mathematical Modeling of Industrial Structure	271
		A42.1 Structural description	274
		A4.2.2 Numerical modeling and analysis	275
	A4.3	Multi-Hazard Assessment Framework (MH Framework-I) for Industrial Structure	277
	A4.4	Stochasticity of Hazards	277

CHAPTER		TITLE	PAGE NO.
		A4.4.1 Seismic hazard model	277
		A4.4.2 Wind hazard model	279
	A4.5	Results and Discussion	281
		A4.5.1 Deterministic study	284
		A4.5.2 Probabilistic study: distribution of peak response data	285
		A4.5.3 Probabilistic study: joint probability of failure	287
		A4.5.4 Probabilistic study: fragility curves	288
	A4.6	Summary and Conclusions	290
APPENDIX 5		**APPLICATION OF MH FRAMEWORK-III FOR ASSESSMENT OF REINFORCED CONCRETE PORTAL FRAME UNDER POST-EARTHQUAKE FIRE SCENARIO**	**293-312**
	A5.1	General	293
	A5.2	Structural Details and Finite Element Modeling Approach	294
		A5.2.1 Structural description and numerical modeling	294
		A5.2.2 FE model of RC portal frame	295
		A5.2.3 Numerical solution scheme	296
	A5.3	Material Model for Structural Analysis under Cascaded Post-Earthquake Fire	297
	A5.4	Cascading Hazard Framework (MH Framework-III) for Post-Earthquake Fire Scenario	297
		A5.4.1 Limit states of failure	297
	A5.5	Loading Scenarios	298
		A5.5.1 Seismic load scenario	299
		A5.5.2 Fire load scenario	299

CHAPTER		TITLE	PAGE NO.
	A5.6	Stochasticity in Cascaded Post-Earthquake Fire Analysis	299
	A5.7	Results and Discussion	300
		A5.7.1 Deterministic study	302
		A5.7.1 Probabilistic study	308
	A5.8	Summary and Conclusions	311
		REFERENCES	**313-340**
		LIST OF PUBLICATIONS	**341-344**

LIST OF TABLES

TABLE	CAPTION	PAGE NO.
1.1	Examples of MH catastrophes occurred across the globe in the last few decades	3
2.1	Deterministic input parameters considered for the base and mass excitations	24
2.2	Statistics of the input parameters considered for the base and mass excitations	25
2.3	Statistics of the considered responses for damped S-DOF system	30
2.4	Statistics of the input parameters failing under Type-I, Type-II, and Type-III scenarios	32
2.5	Statistics of observed response parameters under Type-I, Type-II, and Type-III scenarios	32
3.1	General properties for the *n*-degree of freedom (*n*-DOF) system of the moment resisting frame (MRF) building	45
3.2	Modal analysis results for the *n*-DOF system in terms of period (s)	46
3.3	General characteristics of the historical earthquake loadings used in the study	46
3.4	General characteristics of the site-specific wind excitations used in the study	46
3.5	Comparison of the peak response for the different steel building systems under real-time earthquake loadings	49
3.6	Comparison of the peak response for the different steel building systems under site-specific wind loadings	50
4.1	Statistics of the stochastic parameters of the earthquake and wind excitations	65
4.2	Statistics of 50 earthquake ground motion and 200 simulated wind excitations	66

TABLE	CAPTION	PAGE NO.
4.3(a)	Comparative study* of the peak acceleration responses from probabilistic and deterministic investigations under earthquake and wind scenarios	72
4.3(b)	Comparative study* of the peak drift responses from probabilistic and deterministic investigations under earthquake and wind scenarios	72
4.3(c)	Comparative study* of the peak normalized base shear responses from probabilistic and deterministic investigations under earthquake and wind scenarios	73
4.3(d)	Comparative study* of the peak displacement responses from probabilistic and deterministic investigations under earthquake and wind scenarios	73
4.4	Effectiveness of the passive control devices under the MH scenario of earthquake and wind	79
5.1	Characteristics of the passive control devices used in Shinshiro City Hall	92
5.2	Parameters of probabilistic distribution of earthquake and wind intensity for Nagoya city	94
5.3	List of the earthquakes used for phase spectrum	99
5.4	Sequence of the phase spectrum earthquakes in the timeline of events	99
6.1	Target performance for base-isolated buildings (JSSI, 2018)	114
6.2	Characteristics of the LRBs used in 20- and 25-storey high-rise RC buildings	114
6.3	Details of beams and columns for 20-storey base-isolated high-rise building	116
6.4	Details of beams and columns for 25-storey base-isolated high-rise building	117
6.5	Details of the earthquakes used in Section 6.6.1	121
6.6	Details of the winds used in Section 6.6.1	121

TABLE	CAPTION	PAGE NO.
7.1	Accidental eccentricity and mechanical load assumed for the analysis	139
7.2	Boundary condition of the RC slab and wall panels	141
7.3	Dynamic increase factors (DIFs) used for concrete and steel	146
7.4	Mechanical and thermal properties of concrete at ambient temperature	151
7.5	Mechanical and thermal properties of reinforcing steel at ambient temperature	151
7.6	Blast and fire loading parameters	152
7.7	Deterministic and stochastic parameters of structural capacity used for the independent blast and thermo-mechanical analysis	157
7.8	Deterministic and stochastic parameters of demand used for the independent blast and thermo-mechanical analysis	158
7.9	Difference in charge weight required to cause 50 % failure probability	172
8.1	Parameters used for the concrete damaged plasticity (CDP) model	183
8.2(a)	Compression damage parameters (d_c) used for the CDP model for high strain-rate and thermal loadings	184
8.2(b)	Tension damage parameters (d_t) used for the CDP model for high strain-rate and thermal loadings	185
10.1	Summary of districts having substantial MH risk areas (NBC, 2016)	217
A1.1	Comparison of peak response quantities under three earthquakes	241
A1.2	(a) Details of the wind data used for validation, comparison of maximum wind response for (b) acceleration and (c) displacement	243
A3.1	Modeling properties of the elastic-plastic friction damper (FD)	259
A3.2	Modal periods of the unconnected steel MRF and BF structures	259
A3.3(a)	Details of the earthquake ground motion	260

TABLE	CAPTION	PAGE NO.
A3.3(b)	Details of the wind time history	260
A3.4	Combinations of dynamically similar and dissimilar connected buildings	260
A3.5(a)	Peak top floor displacement and acceleration responses of similar connected buildings for equal storey height under historical earthquake ground motions	265
A3.5(b)	Peak top floor displacement and acceleration responses of similar connected buildings for equal storey height under simulated wind forces for different gust speeds	266
A3.6(a)	Peak top floor displacement and acceleration responses of dissimilar connected buildings for unequal storey height under historical earthquake ground motions	269
A3.6(b)	Peak top floor displacement and acceleration responses of dissimilar connected buildings for unequal storey height under winds for different gust speeds	269
A3.7	Effectiveness of the FDs for different configurations of the connected dynamic similar and dissimilar steel buildings under earthquake ground motions and gust wind speeds	270
A4.1	Statistical characteristics of parameters used in the earthquake model	279
A4.2	Statistics of the stochastically generated parameters of the wind excitations	281
A4.3	Statistics of the stochastically generated parameters of the earthquake and wind excitations	284
A5.1	Earthquakes considered for the deterministic study	300
A5.2	Deterministic and stochastic parameters of demand used for the earthquake and cascaded thermo-mechanical analysis	301

LIST OF FIGURES

FIGURE	CAPTION	PAGE NO.
1.1	Classification and distribution of natural hazards across the globe until January, 2018 showing the outstretch of MH exposure (modified from Munich Re, Geo Risks Research, NatCatSERVICE)	2
1.2	Classification of MH assessment based on probability of occurrence	5
2.1	Mathematical modeling of the equivalent single-degree of freedom (S-DOF) system under base and mass excitations	19
2.2	Average fast Fourier transform (FFT) spectrum of 100 real earthquake and wind loadings	20
2.3	Framework showing the methodology of MH assessment for under equal energy input	25
2.4	Deterministic plots of response under base and mass excitations	27
2.5	Frequency domain plots of response under base and mass excitations	28
2.6	Probability distribution curves (lognormal) for the considered responses of the undamped and damped S-DOF systems under base and mass excitations	30
2.7	Transmissibility index of the responses for undamped and damped S-DOF systems	31
2.8	Probability distribution curves for the considered input parameters corresponding to the structure failing under Type-I, Type-II, and Type-III scenarios	33
2.9	Overlap of probability density function (PDF) curves denoting the joint probability of failure for the damped S-DOF system under base and mass excitations	34

FIGURE	CAPTION	PAGE NO.
2.10	Probability of exceedance of the observed failure acceleration and displacement responses under Type-I, -II, and -III scenarios	35
2.11	Fragility curves for the damped S-DOF system for limit state of displacement under Type-I scenario	36
3.1	Mathematical model of *n*-storey (a) steel moment resisting frame (MRF), (b) steel braced frame (SBF), (c) fluid viscous damped frame (FVDF), and viscoelastic-damped frame (VEDF)	40
3.2	Response spectrum of the selected earthquakes for (a) ground motion acceleration and (b) ground motion displacement	47
3.3	Wind speed at a specific height for the (a) 9-storey, (b) 20-storey, (c) 25-storey along with the frequency content (FFT spectra) and power spectral density (PSD)	48
3.4	Distribution of the peak load of responses for the 9-storey steel building under the multiple hazard scenarios of earthquake and wind	48
3.5	Distribution of the peak load of responses for the 20-storey steel building under the multiple hazard scenarios of earthquake and wind	52
3.6	Acceleration of the top floor for 25-storey steel building under the considered earthquakes	53
3.7	Inter-storey drift for the 25-storey steel building under the selected earthquakes	54
3.8	Base shear and displacement of the top floor for 25-storey steel building under the considered earthquakes	55
3.9	Acceleration and displacement of the top floor for 25-storey steel building under the gust wind speed of 46 m/s	56
3.10	Inter-storey drift for the 25-storey steel building under the selected winds	56

FIGURE	CAPTION	PAGE NO.
3.11	Distribution of the peak load of responses for the 25-storey steel building under the multiple hazard scenarios of earthquake and wind	57
3.12	Distribution of the peak (a) base shear and (b) top floor displacement for the 20-storey steel building under the earthquakes and winds showing limit for response worsening	58
3.13	Distribution of the peak (a) base shear and (b) top floor displacement for the 20-storey steel building under the earthquakes and winds showing limit for response worsening	59
4.1	Comparison of FFT amplitude spectra for considered earthquake and wind excitations	64
4.2	(a) Acceleration and (b) displacement response spectrum plots for the 50 real time earthquake ground motions considered	67
4.3	Framework for the MH assessment of the steel buildings proposed through this study	68
4.4	Box plots for the 20-storey steel buildings under the earthquake and wind loads	69
4.5	Box plots for the 25-storey steel buildings under the earthquake and wind loads	70
4.6	PDFs of failure in limit states of the top floor acceleration and inter-storey drift for the 20-storey steel buildings under the earthquakes and winds	75
4.7	PDFs of failure in limit states of the normalized base shear and top floor displacement for the 20-storey steel buildings under the earthquakes and winds	76
4.8	PDFs of failure in limit states of the top floor acceleration and the inter-storey drift limit states for the 25-storey steel buildings under the earthquakes and winds	77
4.9	PDFs of failure in limit states of the normalized base shear and top floor displacement limit states for the 25-storey steel buildings under the earthquakes and winds	78

FIGURE	CAPTION	PAGE NO.
4.10	Fragility curves of the 20-storey steel buildings under the earthquakes and winds	80
4.11	Fragility curves of the 25-storey steel buildings under the earthquakes and winds	82
5.1(a)	3-D view of Shinshiro City Hall located in Aichi prefecture (Google coordinates: 34.8990° N, 137.4978° E)	88
5.1(b)	3-D view of Shinshiro City Hall modeled in STERA_3D	89
5.2(a)	Sectional view X-X of the Shinshiro City Hall in EW direction	89
5.2(b)	Sectional view Y-Y of the Shinshiro City Hall in NS direction	90
5.3	Hysteresis model of nonlinear bending spring	90
5.4	Response spectrum of Nagoya city for different return periods	94
5.5(a)	Random sampling of intensity and recurrence period	95
5.5(b)	Set of L events with different intensities I_i having interval ${}_iT_j$	96
5.5(c)	Generating timelines for earthquake and wind during design life of a structure	96
5.6	Framework for generating timeline for earthquake and wind during design life of a structure	97
5.7	Timelines of earthquakes and winds generated through the proposed methodology	98
5.8	Spectrum matching for the three considered earthquakes with the target spectrum, and time-history data for the three considered earthquakes	102
5.9	Peak-to-peak deformation amplitude	103
5.10	Fatigue curve for the LRBs indicating fatigue response	103
5.11	Displacement and acceleration of the top floor under considered earthquake and wind loads	104
5.12	Force-deformation and energy dissipation of the LRB (I3) under phase spectrum of different design level earthquakes	105
5.13	Earthquake and wind responses under MH and IH event	106

FIGURE	CAPTION	PAGE NO.
5.14	Comparison of dissipated energy by LRBs (I3 and I4) under the final MH event with other individual earthquakes from the same timeline	106
5.15	Fatigue response of the LRBs I3 and I4 under the IH events (Section 5.6.1) and MH scenario timelines	107
5.16(a)	Cumulative energy accumulated in design life of 100 years showing the fatigue life of isolator I3	108
5.16(b)	Cumulative energy accumulated in design life of 100 years showing the fatigue life of isolator I4	109
6.1	Elevation of the base-isolated high-rise building	115
6.2(a)	Element model for beam	117
6.2(b)	Moment-rotation relationship for bending spring	118
6.3	Multi-spring model for column and force-deformation curves for concrete and steel springs	118
6.4	Spectrum compatibility of the considered ten earthquakes	120
6.5	Peak response quantities for the 20- and 25-storey base-isolated high-rise RC buildings under individual ten earthquakes and six winds	122
6.6	Force-deformation of the LRBs in 20- and 25-storey base-isolated high-rise RC buildings under selected two earthquakes and winds	124
6.7	Fourier amplitude under the considered ten earthquakes and six winds	125
6.8(a)	Period and mode shapes of the 20-storey high-rise before and after the MH events	126
6.8(b)	Period and mode shapes of the 25-storey high-rise before and after the MH events	126
6.9	Isolator response of 20-storey building for seismic loadings under the IH and MH scenario	127
6.10	Isolator response of 20-storey building for wind loadings under the IH and MH scenario	128

FIGURE	CAPTION	PAGE NO.
6.11	Fourier amplitude of the response under IH and MH scenario	129
6.12	Fatigue curve for the LRBs indicating fatigue response	130
6.13(a)	Fatigue life of the LRB installed in 20-storey high-rise building	131
6.13(b)	Fatigue life of the LRB installed in 25-storey high-rise building	131
7.1	3-D view showing blast exposure and sectional cross-section view showing reinforcement details	138
7.2	3-D view showing fire exposure and sectional cross-section view showing reinforcement details of the RC panels	139
7.3	Stress-strain curves of concrete and steel for different strain rates	147
7.4	Thermal properties of concrete at different temperatures	148
7.5	Thermal properties of steel at different temperatures	149
7.6	Stress-strain curves of concrete under (a) compression and (b) tension for different temperatures	150
7.7	Damage criterion considered for the RC wall panels	155
7.8	Out-of-plane displacement and principal stress of the RC wall panels under surface and air blast loadings	159
7.9	Out-of-plane deflection of the RC of the RC panels under (a) transverse out-of-plane loading, (b) compressive in-plane loading, and (c) temperature responses at the exposed and unexposed sides of the RC panels under transverse out-of-plane loading	160
7.10	Principal stress ($\sigma_{11,f}$) of the RC panels under different mechanical loadings exposed to fire	162
7.11	Box plots representing the degree of uncertainty in the obtained blast responses of the RC wall panels	163
7.12	Box plots representing the degree of uncertainty in the obtained thermo-mechanical responses of the RC panels	164
7.13	(a) Vertical and (b) horizontal out-of-plane deflection for the 75 mm size RC panels under transverse out-of-plane and compressive in-plane loadings	165

FIGURE	CAPTION	PAGE NO.
7.14	Different levels of damage for the RC wall panels under surface and air blast loadings	166
7.15	PDF of the support rotation for the RC wall panels under the surface-burst and free airburst scenarios	167
7.16	PDF of the responses for the RC panels under the thermo-mechanical loadings	168
7.17	Fragility curves of the RC wall panels members under surface blast loading considering charge weight as intensity measure parameter	170
7.18	Fragility curves of the RC wall panels members under air blast loading considering charge weight as intensity measure parameter	170
7.19	Fragility curves of the RC panels under the thermo-mechanical loadings considering fuel load as intensity measure parameter	172
8.1	3-D and sectional view showing blast and fire exposure	177
8.2	3-D view of wall panel showing blast and fire exposure along with sectional cross-section view showing reinforcement details	178
8.3	Framework for linking Python-programming interface and the ABAQUS® solver	187
8.4	Displacement time history (δ_b) at center of the RC wall panels under dynamic blast loading	188
8.5	Tensile damage (d_t) at the exposed and unexposed faces under the blast loading	189
8.6	Compressive damage (d_c) at the exposed and unexposed faces under the blast loading	191
8.7	Out-of-plane deflection (δ_f) at the center of the RC wall panels under NF and PBF scenarios	192
8.8	Principal stresses ($\sigma_{11,f}$) at the exposed and unexposed sides of the RC panels under NF and PBF scenarios	193

FIGURE	CAPTION	PAGE NO.
8.9	Compressive damage (d_c) at the exposed face of the RC wall panels under NF and PBF scenarios	194
8.10	Plastic strains ($\varepsilon_{pl,f}$) at the center of the RC wall panels under NF and PBF scenarios	195
9.1	Framework showing the methodology for assessment of the RC panels under cascaded PBF scenario	201
9.2	Stochastic distribution of input parameters used in blast analysis	206
9.3	Stochastic distribution of input parameters used in fire analysis	207
9.4	Set of blast and time temperature history curves used in the study	207
9.5	Box plots of different responses for the RC panels under NF and PBF scenarios	208
9.6	Out-of-plane deflections for the 75 mm size RC panels (a) NF and (b) cascaded PBF scenarios	209
9.7	PDFs of the maximum deflection response for the RC panels with different thicknesses under NF and PBF scenarios	211
9.8	Fragility curves of the RC panels under NF and PBF scenarios considering fire load density as IM parameter	212
9.9	Fragility curves of the RC panels under NF and PBF scenarios considering duration as IM parameter	214
10.1	MH zoning map of India (Bach et al., 2014)	221
10.2	Technical framework for optimal assessment of the structures under multiple hazard scenarios in entirety	223
10.3	Schematic to highlight augmentation of MH analysis and design in the conventional design approach for structure and infrastructure systems	227
10.4	Proposed generalized MH analysis and design technique for structures and infrastructure systems	228
A1.1	Comparison of maximum acceleration of the floors with Spencer et al. (1999)	239

FIGURE	CAPTION	PAGE NO.
A1.2	Comparison of maximum inter-storey drift of the floors with Spencer et al. (1999)	240
A1.3	Comparison of time histories of top floor displacement with Spencer et al. (1999)	240
A1.4	Fourier spectrum ratio (FSR) under different seismic ground motions	242
A1.5	Comparison of observed response to that with the obtained numerical response	243
A1.6	Validation of independent RC wall panels under fire and blast scenarios	244
A3.1	Mathematical models of *N*-storey (a) unconnected (U) moment resisting frame (MRF), (b) unconnected (U) braced frame (BF), (c) connected frames (configuration A), (d) connected frames (configuration B), and (e) connected frames (configuration C) for equal storey height	253
A3.2	Mathematical models of *N*-storey (a) unconnected (U) moment resisting frame (MRF), (b) unconnected (U) braced frame (BF), (c) connected frames (configuration A), (d) connected frames (configuration B), and (e) connected frames (configuration C) for unequal storey heights	253
A3.3	(a) Elastic behavior of brace, (b) hysteretic loop of friction damper, and (c) resultant elasto-plastic behavior of the friction damper in brace	257
A3.4	Acceleration and displacement response spectrum of the considered historical earthquake ground motions	259
A3.5	Wind speed at specific height for 10 and 15 storey buildings along with the frequency content (FFT spectra)	261
A3.6(a)	Time history response of top floor displacement and acceleration of connected steel 5-5 MRF-MRF buildings with under different earthquake ground motions	262

FIGURE	CAPTION	PAGE NO.
A3.6(b)	Time history response of top floor displacement and acceleration of connected steel 5-5 BF-BF buildings with under different earthquake ground motions	263
A3.7	Time history response of top floor displacement and acceleration of connected steel 15-15 MRF-MRF buildings with under different wind gust speeds	264
A3.8(a)	Peak top floor displacement and acceleration responses of dissimilar connected MRF-BF buildings for equal storey height under historical earthquake ground motions and simulated wind forces	267
A3.8(b)	Peak top floor displacement and acceleration responses of dissimilar connected BF-MRF buildings for equal storey height under historical earthquake ground motions and simulated wind forces	268
A4.1	(a) Elevation of the industrial structure and (b) layout of tie bracings at bottom chord level	275
A4.2	Isometric view of braced industrial steel structure	276
A4.3	Probability density function of the intensity measures (IMs) of the simulated earthquake and wind excitations	282
A4.4	Framework for the MH assessment of the industrial steel structure	283
A4.5	Acceleration and displacement time history at the eaves level under Loma Prieta earthquake, 1989	284
A4.6	Acceleration and displacement time history at the eaves level under 3-seconds gust wind speed, 38 m/s	285
A4.7	Box plots of the eave level acceleration response data for industrial steel structure under earthquake and wind loads	286
A4.8	Box plots of the drift response data for industrial steel structure under the earthquake and wind loads	287
A4.9	Failure PDFs for the given limit states for unbraced and braced industrial steel structure under the earthquake and wind loads	288

FIGURE	CAPTION	PAGE NO.
A4.10	Fragility curves of the unbraced and braced industrial steel structures under earthquake and wind loads	289
A5.1	(a) Plan and (b) elevation of the residential building considered for the study	294
A5.2	Details of the reinforcement in the RC portal frame with loading pattern	295
A5.3	Displacement-time history of RC portal frame for different earthquakes	302
A5.4(a)	Stresses (MPa) in the RC portal frame after seismic loading due to (i) Imperial Valley, 1979, and (ii) Coalinga, 1983	303
A5.4(b)	Stresses (MPa) in the RC portal frame after seismic loading due to (iii) ChiChi, 1999 and (iv) Tottori, 2000	304
A5.5	Temperature distribution in (a) the beam and (b) the column of the RC portal frame after fire loading	305
A5.6	Peak displacement-time history in (a) the beam and (b) the column of the damaged and undamaged RC portal frame after subsequent fire loading	306
A5.7	Plastic strains in the RC portal frame (a) after seismic loading and (b) post-earthquake fire loading	307
A5.8	Probability density function plots considering parametric variation in capacity of the structure following lognormal distribution	308
A5.9	Fragility curve for the RC portal frame under PEF scenario for fire load density as intensity measure (IM)	310
A5.10	Fragility curve for the RC portal frame under PEF scenario for duration as intensity measure (IM)	310

MATHEMATICAL NOTATIONS AND SYMBOLS

σ	Cauchy stress tensor
γ	Co-coherence or correlation of turbulence along the structure
Λ	Constant depending on the structural type and topography
κ	Decaying phase of the modulating function
φ	Diameter of reinforcing steel
$\in$	Eccentricity parameter of plastic potential surface
δ	Inter-storey drift of the M-DOF system
A	Nonlinear exponent of damping for fluid viscous damper and viscoelastic damper
B	Nonlinear exponent of stiffness for viscoelastic damper
Γ	Parameter deepening on opening factor and thermal inertia
ψ	Random vector associated with the dynamic excitations
ε	Strain tensor
θ	Support rotation angle of the structural member
$\langle\bullet\rangle$	Macaulay bracket indicating the quantities within the bracket take either 0 or positive values
σ'_c	Compressive strength of cylinder at ambient temperature
σ'_{cT}	Compressive strength of cylinder at elevated temperature, *T*
ε'_{ctT}	Tensile strain at peak stress
σ'_t	Tensile strengths of cylinder at ambient temperature
σ'_{tT}	Tensile strength of cylinder at elevated temperature, *T*
ρ^*	Density of given state of matter
ω_0	Natural frequency at the time instance, T_0
$\dot{\varepsilon}_0$	Strain-rate at quasi-static condition
$\varepsilon_{11,b}$	Principal strain in the structural member due to blast load
$\sigma_{11,b}$	Principal stress of the structural member due to blast load
$\varepsilon_{11,f}$	Principal strain in the structural member due to fire load
$\sigma_{11,f}$	Principal stress of the structural member due to fire load
θ_a	Horizontal angle subtended by steel brace and beam
θ_b	Horizontal angle subtended by fluid viscous and viscoelastic damper brace and beam
δ_b	Out-of-plane deflection of the structural member due to blast load
$\delta_{b,e}$	Elastic displacement of the structural member under blast load
$\delta_{b,f}$	Transverse out-of-plane displacement in beam of RC portal frame
$\delta_{b,max}$	Maximum displacement of the structural member under blast load
α_c	Coefficient of thermal expansion of concrete
σ_c	Dynamic compressive stress of concrete
ε_c	Strain of concrete for compressive stress, σ_c
σ_c	Stress under uniaxial compression, *c*
$\delta_{c,e}$	Transverse in-plane displacement in column of RC portal frame
$\varepsilon_{c,lim}$	Limiting strain value after which the descending branch of the stress-strain curve originates
ε_{c1}	strain at maximum compressive stress of concrete

$\delta_{cip,w}$	Compressive in-plane deflection of the structural member due to fire load
ε_{cr}	Strain at cracking of the concrete
δ_f	Deformation amplitude until failure
ψ_g	Randomness in the base accelerations
φ_k	Random phase uniformly distributed between 0 and 2π
ω_{max}	Maximum Eigen value of the element
σ_{max}	Maximum principal effective stress
Ω_{max}	Root mean square of strong-motion phase
ω_N	Natural frequency at the time instance, T_N
σ^o	Static yield stress at non-zero plastic strain
ε_{pl}	Plastic strain in the structural member
σ_t	Stress under uniaxial tension, t
Δt	Time increment
σ_{t0}	Uniaxial tensile stress at failure
$\delta_{top,s}$	Transverse out-of-plane deflection of the structural member due to fire load
σ_u	Standard deviation of the fluctuating component of wind speed
$\Delta v(t,z,\psi_{\Delta v})$	Random fluctuating wind speed of the mass-excited force
$\Delta v(z, t)$	Fluctuating wind speed
$[\tilde{c}']$	Equivalent structural damping obtained from fluid viscous damper
$\dot{e}^{-pl}$	Equivalent plastic strain-rate
$[\tilde{k}']$	Total stiffness imparted by the columns and the steel braces of the building
$[\hat{k}']$	Total stiffness imparted by the columns of the building
$\hat{\alpha}^{dev}$	Deviatoric part of the backstress
$\hat{\sigma}^0$	Size of the yield surface for reinforcing steel
$\bar{\sigma}_c$	Effective compressive cohesion stress
$\bar{\sigma}_t$	Effective tensile cohesion stress
$\dot{e}^{-pl}$	Plastic flow rate
$\ddot{u}_g(t, \psi_g)$	Random acceleration of the base-excited force
$[\widetilde{c}]$	Generalized damping matrix of the n-th degree of freedom
$[\hat{k}]$	Stiffness matrices obtained after static condensation
$[\widetilde{m}]$	Generalized mass matrix of the n-th degree of freedom
$\bar{\alpha}$	Dimensionless constants used in yield surface of CDP model
$\hat{\alpha}, \hat{\beta}, \hat{\gamma}$	Parameters of Hilber-Hughes-Taylor (HHT) integration
$\bar{\beta}$	Dimensionless constants used in yield surface of CDP model
$\bar{\gamma}$	Dimensionless constants used in yield surface of CDP model
$\dot{\varepsilon}$	Strain-rate for concrete and steel for given loading rate
ε_c^{pl}	Plastic strain under uniaxial compression, c
ε_t^{pl}	Plastic strain under uniaxial tension, t
$\bar{\theta}$	Lode similarity angle
$\hat{\lambda}$	First Lamé constant
$\hat{\mu}$	Shear modulus
$\bar{\xi}$	Distance from stress space to stress plane
$\bar{\rho}$	Octahedral radius

$\bar{\sigma}$	Yield stress at non-zero plastic strain
$\bar{\varphi}$	Friction angle used in CDP model
$\bar{\psi}$	Dilation angle defining amount of plastic volumetric strain induced in plastic shear
ω_d	Damped angular frequency
ω_n	Natural angular frequency
$P_n(t)$	Probability for occurrence of *n* number of earthquake or wind events during *t* period
$\bar{U}(z)$	Mean wind speed at 10 m from the ground level
$\bar{c}$	Cohesion used in CDP model
$f_E(\cdot)$	Probability density functions of responses under the earthquake occurrences
$f_W(\cdot)$	Probability density functions of responses under the wind occurrences
$\bar{p}$	Hydrostatic pressure stress
$\tilde{p}(t)$	Generalized force vector of the *n*-th degree of freedom
$\bar{q}$	von Mises equivalent stress
$\tilde{x}$	Generalized displacement coordinates of the *n*-th degree of freedom
$\bar{x}$	Median value of the demand
$[\tilde{k}]$	Generalized stiffness matrix of the *n*-th degree of freedom
$[\hat{m}]$	Mass matrices obtained after static condensation
$[c]$	Damping matrix of M-DOF model
$[c_{df}]$	Damping matrix of nonlinear fluid viscous damper
$[c_{dv}]$	Equivalent structural damping obtained from viscoelastic damper
$[k'_b]$	Total stiffness imparted by the columns and the steel braces
$[k'_v]$	Total stiffness imparted by the columns and the viscoelastic damper
$[k]$	Stiffness matrix of M-DOF model
$[k_b]$	Stiffness imparted by the steel brace
$[m]$	Mass matrix of M-DOF model lumped at joint nodes
$\{I\}$	Internal force vector obtained from stresses generated in elements; $\{P\}$ is the external force vector
$\{r\}$	Influence coefficient vector
$\{\varphi\}$	Modal matrix
μ	Ductility ratio of the structural member
A	Exposed area due to wind
a, b	Gutenberg-Richter coefficients
A_{gust}	Amplitude of the wind speed gust
$A_m(\psi_a)$	Random amplitude of the base accelerations
b-factor	Thermal inertia of concrete
c	Damping of S-DOF system
c_c	Specific heat capacity of concrete
c_d	Dilatational wave speed
$\overline{C_d}$	Drag coefficient
C_d	Equivalent damping of friction damper
C_{ij}	Coefficients governing co-coherence exponential decay
C_k	Constant depending on the type of material
C_r	Coefficient of reflection of blast overpressure
D	Demand in the structure due to any event

D_0^{el}	Initial or elastic stiffness tensor
d_c	Compression damage variable
d_j	Euclidian distance or distance between two nodes of reference
d_t	Tension damage variable
E	Random variables associated with the failure response under the independent earthquake event
E_0	Initial elastic modulus
E_1	Coefficient of energy content calculated for the base and mass excitation forces
E_2	Energy coefficient used to denote the cases dominated by base excitation
E_3	Energy coefficient used to denote the cases dominated by mass excitation
E_{be}	Total energy content obtained under base excitation
E_{c1}	Secant modulus at maximum dynamic compressive stress of concrete
E_{ci}	Tangent modulus of concrete in MPa
E_{cid}	Modulus of elasticity of concrete at high strain-rate
E_{ciT}	Elastic modulus at elevated temperature, T
E_d	Structural damping
E_{df}	Limiting value of absolute difference of the energies (tolerance limit)
E_{me}	Total energy content obtained under mass excitation
E_n	Input energy for base and mass excitations
f	Frequency spectrum of the wind load
$f(t)$	Time-varying forcing function
f_{b0}	Biaxial compressive yield strength
f_{c0}	Uniaxial compressive yield strength
f_{cm}	Maximum dynamic compressive stress of concrete
f_{cms}	Characteristic strength of concrete
f_{ctmd}	Dynamic tensile strength of reinforcing steel at given strain-rate
f_{ctms}	Tensile strength of concrete under quasi-static condition
f_{df}	Output viscous damping force for nonlinear fluid viscous damper
$f_E(E = e_L)$	Marginal mass functions of the event, E
F_i	Sampling intensity
F_r	Fragility expressed in terms of MH demands
f_u	Ultimate stress of steel
$f_W(W = w_L)$	Marginal mass functions of the event, W
f_y	Yield stress of steel
g	Acceleration due to gravity
h	Height of compressive in-plane loaded member
$h[(t\text{-}t_i),\theta(t_i)]$	Pseudo-acceleration response of an S-DOF linear oscillator under a unit impulse
H_c	Convective heat transfer coefficient
h_c	Cracks re-closing after tension-compression reversal
h_t	Recovery of concrete in crushing after compression-tension reversal
I_0	Minimum intensity level considered for earthquake or wind
I_1	1st invariant of stress tensor
J	Material Jacobian

J_2	2^{nd} invariant of deviatoric stress tensors
J_3	3^{rd} invariant of deviatoric stress tensors
k	Stiffness of S-DOF system
k_1	Correction factor for coarse aggregates used in concrete
k_2	Correction factor for mineral admixtures used in concrete
K_c	Ratio of second deviatoric stress invariant on tensile to that of the compressive meridians
k_c	Thermal conductivity of reinforcing steel
K_d	Equivalent stiffness of friction damper
L_e	Characteristic length of the smallest element in the domain
L^N	Sum of all Lagrange multiplier forces associated with DOF, N
L_z	Turbulence length
m	Mass of S-DOF system
$N(I)$	Average annual occurrence rate of earthquake or wind with intensity more than I
N_0	Average annual occurrence rate of earthquake or wind for minimum intensity I_0
N_f	Number of cycles until failure
O	Opening factor due to openings in a structure
$P(E)$	Probability of failure under the earthquake event
$P(F \mid S^b = s^b, S^{bf} = s^{bf})$	Probability of failure F due to S^{bf} conditional on S^b
$P(S^b)$	Probability of occurrence of blast in terms of the reflected overpressures
$P(S^{bf} \mid S^b = s^b)$	Conditional probability of occurrence of fire after occurrence of blast with characteristics, S^b
$P(S^f)$	Probability of occurrence of fire in terms of time-temperature curves
$P(W)$	Probability of failure under the wind event
P_0	Atmospheric pressure
$P_D(\omega_k)$	Power spectral density function of wind turbulence
$p_E = P(E)$	Probability mass functions associated with the responses under the earthquake
p_E	Probability that the limit state (LS) is reached at assumed load e_L
p_f	Probability of failure for any structural system
P_{pos}	Incident pressure of blat wave
P_r	Reflected peak pressure pf blast wave from ground
$p_W = P(W)$	Probability mass functions associated with the responses under the wind
p_W	Probability that the limit state (LS) is reached at assumed load w_L
q	Fire load density
Q	Heat transferred from outside
$\bar{q}$	Limiting criteria for the total energy that describe the condition to be dominant under base excitation
$q(t)$	Deterministic and non-negative modulating function
$\bar{r}$	Limiting criteria for the total energy that describe the condition to be dominant under mass excitation
R_d	Radial distance from the point of consideration to the source of detonation
R	Residual error
r^*	Stress state parameter

S	Deviatoric stress tensor
s	standoff distance from the point of consideration to the source of detonation
S^b	Reflected overpressures characterized by charge weight or standoff distance
S^{bf}	Fire hazard characterized by fire load density, q
s_c	Dimensionless coefficient considering stress state and stiffness recovery effects under uniaxial compression, c
S^f	Thermal load characterized by fire load density or duration
$s_i(t)$	Filter function used to simulate non-stationary earthquake
s_t	Dimensionless coefficient considering stress state and stiffness recovery effects under uniaxial tension, t
S_u	Single point power spectral density of the von Karman spectrum for the turbulence in x-direction
$T(I)$	Average return period of earthquake or wind with intensity more than I
T_1	Start time of strong-motion phase
T_2	End time of strong-motion phase
t_a	Arrival time of blast load
T_c	Temperature at reference surface
T_{eg}	End time of the wind gust speed
T_{er}	End time of the wind ramp speed
T_f	Ambient temperature
t_{pos}	Positive phase duration of blat wave
T_{sg}	Starting time of the wind gust speed
T_{sr}	Starting time of the wind ramp speed
$U_{3s\text{-}10}$	3-second gust speed at 10 m height from the ground
$\ddot{u}_g$	Base acceleration/ Earthquake ground motion acceleration
u_i	Standard normal random variable
$V'(z)$	Mean wind speed
$V'(z,\psi,V')$	Random mean wind speed of the mass-excited force
v_a	Average wind speed with statistical parameters
V_b	Base shear of the M-DOF system
v_g	Wind gust
v_r	Wind ramp speed
v_t	Wind turbulence
$v_{w,top}$	Reference wind speed at height, h_{ref}
$v_{\omega,i}(t)$	Wind speed at height h_i
w	Charge weight of blast load in terms of the mass of equivalent trinitrotoluene (TNT)
W	Random variables associated with the failure response under the independent wind event
$\ddot{x}(t)$	Acceleration response for S-DOF or M-DOF system
$x(t)$	Displacement response for S-DOF or M-DOF system
$\dot{x}(t)$	Velocity response for S-DOF or M-DOF system
Z	Scaled distance
Β	Variability associated with the demand
ε_c	Strains for given σ_c
ε_t	Strains for given σ_t
ζ_{df}	Damping ratio for the fluid viscous damper

ζ_{dv}	Damping ratio for the viscoelastic damper
ζ_i	Fraction of critical damping for *i*-th mode
μ^*	Mean of any component
σ^*	Standard deviation of any component
Φ	Normal cumulative distribution function
$\omega(\psi_\omega)$	Random loading frequency for both the base and mass excitations
ω_g	A constant (=2π)
$P(F\|S^* = s^*)$	Probability of failure, *F* conditional on the intensity of blast or fire loadings characterized by reflected overpressures or time-temperature relation
$f(\hat{\sigma} - \hat{\alpha})$	Equivalent Mises stress with respect to the backstress $\hat{\alpha}$

ABBREVIATIONS

3-D	Three-Dimensional
AIJ	Architectural Institute of Japan
ASCE	American Society of Civil Engineers
BIS	Bureau of Indian Standards
CB	Concentric Brace
CDE	Collateral Damage Estimation
CDF	Cumulative Distribution Function
CDP	Concrete Damaged Plasticity
CFFT	Concrete-Filled Fiber Tube
CFRP	Carbon Fiber-Reinforced Polymer
CLB	Cross Linear Bearing
CoV	Coefficient of Variation
CP	Collapse Prevention
DIF	Dynamic Increase Factor
DL	Dead Load
DM	Damage Measure
DOF	Degree of Freedom
DV	Decision Variable
EC	Eurocode
EDP	Engineering Demand Parameter
ELM	Equivalent Linearized Method
ESWL	Equivalent Static Wind Load
FD	Friction Damper
FDM	Finite Difference Method
FE	Finite Element
FEM	Finite Element Method
FFE	Fire Following Earthquake
FFT	Fast Fourier Transform
FOS	Factor of Safety
FSR	Fourier Spectral Ratio
FVD	Fluid Viscous Damper
FVD	Fluid Viscous Damper
GEV	Generalized Extreme Value
GI	Galvanized Iron
IH	Individual Hazard
IL	Isolation Level
IM	Intensity Measure
IO	Immediate Occupancy
IRF	Impulse Response Function
IS	Indian Standard
ISA	Indian Standard Angle
JMA	Japanese Meteorological Agency
JSSI	Japan Society of Seismic Isolation
LGPC	Los Gatos Presentation Center
LL	Live Load
LPHC	Low Probability-High Consequence
LRB	Lead Rubber Bearing
LS	Limit State

MCS	Monte Carlo Simulation
M-DOF	Multi-Degree of Freedom
MH	Multi-Hazard
MRF	Moment Resisting Frame
MS	Multi Spring
MSS	Multi-Shear Spring
NBC	National Building Code
NF	Normal Fire
NOWS	NatHaz Online Wind Simulator
NRB	Natural Rubber Bearing
OD	Oil Damper
PB	Performance-Based
PBF	Post-Blast Fire
PDF	Probability Density Function
PEER	Pacific Earthquake Engineering Research
PEF	Post-Earthquake Fire
PGA	Peak Ground Acceleration
PSD	Power Spectral Density
PSHA	Probabilistic Seismic Hazard Analysis
Q-Q	Quantile-Quantile
RC	Reinforced Concrete
RMS	Root Mean Square
RP	Return Period
SB	Steel Bracing
SBF	Steel Braced Frame
S-DOF	Single-Degree of Freedom
SFPE	Society of Fire Protection Engineers
STERA_3D	STructural Earthquake Response Analysis_3D
THA	Time History Analysis
TNT	Trinitrotoluene
UFC	Unified Facilities Criteria
UT	Union Territory
VBIED	Vehicle-Borne Improvised Explosive Device
VED	Viscoelastic Damper
VEDF	Viscoelastic Damped Frame