

CONTENTS

	PAGE
ENGLISH ABSTRACT	ii
THAI ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
CONTENS	v
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF SYMBOLS	xi
LIST OF TECHNICAL VOCABULARY AND ABBREVIATIONS	xiv
 CHAPTER	
1. INTRODUCTION	1
1.1 Research Overview	1
1.2 Objectives	2
1.3 Scope of Research	3
 2. REVIEW OF RELEVANT STUDIES	4
2.1 Introduction	4
2.2 Knee-Braced Moment Frames	4
2.2.1 Design Concept	4
2.2.2 Dynamic Response of KBMFs	6
2.3 Partially Restrained (PR) Connections or Semi-rigid Connections	10
2.3.1 Introduction	10
2.3.2 Behavior of PR connections	11
2.4 Knee-braced Moment Frame with Partially-restrained Connection	15
2.4.1 Cyclic Testing of KBMF with PR connections	15
2.5 Method for Predicting Rotational Behavior of PR Connections	19
2.5.1 Mathematical representation of Moment-Rotation Curve	19
2.5.2 Moment-Rotation Behavior Models	20
2.6 Cyclic testing of Braces and Buckling-restrained Braces	23
2.6.1 Cyclic Testing of Buckling Braces	23
2.6.2 Cyclic Testing of Buckling-Restrained Braces	24
 3. DEVELOPMENT OF KBMF-PR ANALYTICAL MODEL	29
3.1 Introduction	29
3.2 Modeling components of KBMF with PR connections	29
3.2.1 Top, Bottom and Web Angles	30
3.2.2 Contact and detachment of Angle with Column Flange	33
3.2.3 Column Panel zones	34
3.2.4 Beams and Columns	34
3.2.5 Regular Buckling Braces	34
3.2.6 Buckling-Restrained Braces (BRBs)	35
3.3 Experimental Verification	37
3.3.1 PR connection Model	37
3.3.2 KBMF with PR connections Model	38

4. DYNAMIC BEHAVIOR OF KBMFs	42
4.1 General	42
4.2 Study Building	42
4.3 KBMF with PR connections	44
4.4 Methods of Analysis	46
4.4.1 Nonlinear Static (Pushover) Analysis	46
4.4.2 Nonlinear Dynamic Analysis	46
4.5 Analytical Model of Study Building	47
4.6 Nonlinear Static Analysis of KBMF with PR connections	49
4.6.1 Pushover Curves	49
4.7 Nonlinear Dynamic Analysis of KBMF with PR connections	53
4.7.1 Dynamic Response under DBE Ground Motions	53
4.7.2 Dynamic Response under MCE ground Motions	59
5. SUMMARY AND CONCLUSIONS	66
REFERENCES	68
APPENDICES	70
A. Design and Simulation Example	70
B. Detail Results of Three-Story Study Frames	84
CURRICULUM VITAE	92

LIST OF TABLES

TABLE	PAGE
2.1 Section Properties of Frame Test	15
2.2 Standardized Connection Constants summarized by Dhillon et al.	21
2.3 Properties of Selected Braces Tested under Cyclic Load	23
2.4 BRB Tests Summary by Lopez and Sabelli	26
3.1 Section Properties of Frame	38
4.1 Load Definition of Study Building	43
4.2 Floor Masses of The Study Building	43
4.3 Lateral Forces of KBMF based on PBPD Procedure	43
4.4 Sectional Properties of PR Connection	44
4.5 Characteristics of Seven Selected Earthquake Records	47
4.6 Results From Nonlinear Static Analysis of Three-Story Structures	50
B.1 Ductility factor of beam rotation at beam-to-knee brace connections of KBMF with conventional brace under DBE ground motions	86
B.2 Ductility factor of beam rotation at beam-to-knee brace connections of KBMF with conventional brace under MCE ground motions	86
B.3 Ductility factor of beam rotation at beam-to-knee brace connections of KBMF with BRB under DBE ground motions	88
B.4 Ductility factor of beam rotation at beam-to-knee brace connections of KBMF with BRB under MCE ground motions	88
B.5 Axial deformation ratios of KBMF with conventional brace under DBE ground motions	90
B.6 Axial deformation ratios of KBMF with conventional brace under MCE ground motions	90

LIST OF FIGURES

FIGURE	PAGE
1.1 (a) Yield Mechanism of KBMFs,	2
(b) Mechanism of Improved KBMFs	2
2.1 Yield Mechanism of KBMF System	5
2.2 Equilibrium of Forces in Knee Region of KBMF	5
2.3 Simulation of Test Result by Srechai	7
2.4 Four Cases of Three-Story Building Frame used by Srechai	8
2.5 Base Shear Versus Roof Drift from NSA of MRF (CASE 1), KBMF (CASE 2), KBMF (CASE 5), and KBMF (CASE 4) from Srechai	8
2.6 Average Maximum Inter-Story Drifts under DBE Ground Motions of Three-Story Study Frames	9
2.7 Average Maximum Inter-Story Drifts Under MCE Ground Motions of Three-Story Study Frames	9
2.8 Moment-Rotation Curves of PR Connections	10
2.9 Definition of Stiffness, Strength and Ductility Characteristics of Moment-Rotation Response of a PR Connections	11
2.10 Typical Types of PR Connections as summarized by Dhillon et al.	12
2.11 Typical Moment-Rotation Curves as presented by Dhillon et al.	13
2.12 Overview of Example Tested Connection carried out by Calado et al.	13
2.13 Moment-Rotation Hysteresis for Top and Seat Angle Connections with Double Web Angles obtained by Calado et al.	14
2.14 Development of a Gap at Column Flange as observed in the test carried out by Calado et al.	14
2.15 Schematic of Test Specimen	16
2.16 Loading History of KBMF Test Frame	17
2.17 Hysteretic Loops of Test Result	17
2.18 Opening of Gap between Column and Angle	18
2.19 Gap between Beam and Knee Brace	18
2.20 Plastic Hinging and Brace Yielding in Test Specimen at 5% Story Drift	18
2.21 Curves of E-P-P Moment-Rotation Equation presented by Chen	20
2.22 Finite Element Model used by Raffaele	22
2.23 Mechanical Model for Top and Seat Angle Connections with Web Angles Presented by Fealla et al.	22
2.24 Hysteretic Response of Slender Brace (Angle Section) carried out by Srechai	24
2.25 Hysteretic Response of Stocky Brace (Square Tube Section) carried out by Srechai	24
2.26 Mechanics of Buckling-Restrained Brace presented by Lopez and Sabelli	25
2.27 Behavior of Conventional Braces Versus Buckling-Restrained Braces	25
2.28 Specimen Dimensions as summarized by Merritt et al.	27
2.29 Overview of Example BRB Test carried out by Merritt et al.	28
2.30 Hysteretic Response of BRB obtained by Merritt et al.	28
3.1 Top and Seat Bolted Angle Connections with Double Web Angles and Mechanical Model as used by Kim et al.	30
3.2 Idealized Model of Angle by Kim et al.	30

3.3	Deformation Process as presented by Kim et al.	31
3.4	Force-Displacement Relationship of Trilinear Inelastic Element	32
3.5	Force-Displacement Relationship of Nonlinear Contact Element	33
3.6	Diagram of Contact and Detachment	34
3.7	Backbone Curve of Regular-Buckling Braces	35
3.8	Backbone Curve of BRBs	36
3.9	Hysteretic Model of BRBs	36
3.10	Test Specimen by Calado et al.	37
3.11	Experimental and Analytical Hysteretic Responses	37
3.12	Analytical Model of Test Specimen	38
3.13	Top and Seat Angle Connections with Double Web Angles	39
3.14	Simulation of Test Result	40
3.15	Comparison of KBMF Model with Different Type of Braces	40
3.16	Strain in Knee Braces	41
3.17	Mechanism of KBMF System	41
4.1	Plan View of Study Building	42
4.2	Three-Story of KBMF Study Frame	44
4.3	KBMF with PR Connections Study Frame Used in Seismic Evaluation	45
4.4	Three-Story KBMF with BRBs	45
4.5	Scaled Pseudo-Acceleration Spectra of DBE Ground Motions (5% Damping)	46
4.6	Scaled Pseudo-Acceleration Spectra of MCE Ground Motions (5% Damping)	47
4.7	Analytical Models of Three-Story KBMF	48
4.8	Pushover Curve of KBMFs	49
4.9	Base Shear Versus Roof Drift From Nonlinear Static Analysis of KBMF with PR Connections	50
4.10	Compressive Internal Forces of Two Different Types of Braces	51
4.11	Strain in Knee Braces	51
4.12	Inter-Story Drift Profiles of KBMF with Buckling Braces	52
4.13	Inter-Story Drift Profiles of KBMF with BRBs	52
4.14	Maximum Inter-Story Drift Profiles of KBMF Regular Buckling Braces under DBE Ground Motions	54
4.15	Maximum Inter-Story Drift Profiles of KBMF with BRBs under DBE Ground Motions	54
4.16	Maximum Average Inter-Story Drifts of Three-Story Study Frames under DBE Ground Motions	55
4.17	Maximum Mean-Plus-One-Standard-Deviation Values Inter-Story Drift of Three-Story Study Frames under DBE Ground Motions	55
4.18	Inelastic Activities of KBMF with Conventional Braces under Selected DBE Ground Motion (LA10)	56
4.19	Inelastic Activities of KBMF with BRBs under Selected DBE Ground Motion (LA10)	56
4.20	Inelastic Activities of KBMF with Conventional Braces under Selected DBE Ground Motion (LA16)	57
4.21	Inelastic Activities of KBMF with BRBs under Selected DBE Ground Motion (LA16)	57
4.22	Normalized Moment at Connections under DBE Ground Motions (a) LA10, (b) LA16	58

4.23	Maximum Inter-Story Drift Profiles of KBMF with Regular Buckling Braces under MCE Ground Motions	60
4.24	Maximum Inter-Story Drift Profiles of KBMF with BRBs under MCE Ground Motions	60
4.25	Maximum Average Inter-Story Drifts under MCE Ground Motions	61
4.26	Maximum Mean-Plus-One-Standard-Deviation Inter-Story Drifts under MCE Ground Motions	61
4.27	Inelastic Activities of KBMF with Conventional Braces under Selected MCE Ground Motion (LA10)	62
4.28	Inelastic Activities of KBMF with BRBs under Selected MCE Ground Motion (LA10)	62
4.29	Inelastic Activities of KBMF with Conventional Braces under Selected MCE Ground Motion (LA16)	63
4.30	Inelastic Activities of KBMF with BRBs under Selected MCE Ground Motion (LA16)	63
4.31	Normalized Moment at Connections under MCE Ground Motions (a) LA10, (b) LA16	64
A.1	Moment-Rotation Curve	79
A.2	Double Web Angle	81
B.1	Node numbers at beam-to-knee brace connections of three stories KBMF with conventional brace	85
B.2	Node numbers at beam-to-knee brace connections of three stories KBMF with conventional brace	87
B.3	Knee braces number of three stories KBMF with conventional brace	89
B.4	Knee braces number of three stories KBMF with BRB	89

LIST OF SYMBOLS

SYMBOL

A	=	Cross section area
a_0	=	Mass-proportional damping coefficient
a_1	=	Stiffness- proportional damping coefficient
a_c	=	Throat thickness of the welds
C_e	=	Normalized design pseudo-acceleration (with g)
$[C]$	=	Viscous damping matrix d
d_2	=	Distance from the center of rotation of the top angle to the line of the force V_{pt}
d_4	=	Distance from the center of rotation of the angle connection to the line of the force V_{pa}
d_b	=	Beam depth
d_c	=	Column depth
d_h	=	Diameter of the bolt hole
E	=	Elastic modulus
F_{cr}	=	Buckling strength
F_i	=	Lateral force at level i
F_y	=	Yield strength
G	=	Shear modulus
g_1	=	Distance from the back of the angle to the center line of the bolts on the column
g_2	=	Distance from the back of the angle to the center line of the bolts on the beam
$h_i; h_j$	=	Height of floor level i (or level j) of the structure above the ground
h_n	=	Total height of the structure
I	=	Moment of inertia
K_0	=	Initial stiffness
K_{it}	=	Initial stiffness contributed by the top angle
K_{is}	=	Initial stiffness contributed by the seat angle
K_{ia}	=	Initial stiffness contributed by the web angle
K_s	=	Secant stiffness

K_t	=	Transition stiffness
K_u	=	Post-yielding stiffness
$[K]$	=	Stiffness matrices of the system
L	=	Length of span
L_k	=	Length of the knee portion
L_c	=	Length of the clear span
M_{max}	=	Maximum moment can be develop in beam
M_{os}	=	Plastic moment in the seat angle
M_p	=	Plastic moment
M_{pt}	=	Plastic moment in the top angle
M_u	=	Ultimate moment capacity
M_y	=	Yield moment capacity of the angle section
$[M]$	=	Mass matrix
n	=	Shape parameter
P_{cr}	=	Buckling strength of knee braces
P_s	=	Second yielding load
P_y	=	Yield load
R	=	Response reduction factor
R_{ki}	=	Initial connection stiffness
R_μ	=	Ductility reduction factor
r	=	Radius of gyration
r_c	=	Web-to-flange radius of the column
r_{sa}	=	Fillet radius of the seat angle
T	=	Fundamental period of the structure
t_{cf}	=	Thickness of the column flange
t_{sa}	=	Thickness of the seat angle
t_{bf}	=	Thickness of the beam flange
t_{cf}	=	Thickness of the column flange
t_w	=	Thickness of the column web
V	=	Base shear
V_d	=	Design base shear
V_i	=	Static story shear at level
V_{max}	=	Maximum shear can be develop in beam
V_n	=	Static story shear at the top level n

V_{pt}	=	Plastic shear force in vertical leg of the top angle
V_y	=	Base shear at system yielding
W	=	Total seismic weight of the structure
w	=	Angle width per bolt
w_i, w_j	=	Weight of the structure at level i (or level j)
w_n	=	Weight of the structure at the top level n
	=	Post-Buckling strength reduction factor
	=	Design base shear parameter
	=	Post-yield stiffness factor
α_i	=	Shear proportioning factor
	=	Lateral drift
Δ_y	=	Roof drift at system yielding
	=	Numerical factor (For knee brace design)
	=	Modification factor for the energy balance equation
α_i	=	Proportioning factor of the equivalent lateral force at level i
μ	=	Ductility factor
μ_s	=	Structural ductility factor
	=	Angle that the knee brace makes with the beam
θ_0	=	Reference plastic rotation
Δ_p	=	Plastic story drift
ω_n	=	Natural circular frequency
	=	Overstrength factor
Ω_i	=	Overstrength factor of the beam at level i
	=	Damping as a fraction of critical damping

LIST OF TECHNICAL VOCABULARY AND ABBREVIATIONS

BRB	=	Buckling-Restrained Brace
DBE	=	Design Basis Earthquake
ft	=	Foot
ft ²	=	Square foot
in	=	Inch
in ²	=	Square inch
KBMF	=	Knee-Braced Moment Frame
kip	=	Kilo Pound
kips.ft	=	Kilo Pound foot
kips/ft	=	Kilo Pound per foot
kips.in	=	Kilo Pound inch
kips/in ²	=	Kilo Pound per square inch
kN	=	Kilo Newton
kN.m	=	Kilo Newton meter
kN/m	=	Kilo Newton per meter
kN/m ²	=	Kilo Newton per square meter
kN.m/rad	=	Kilo Newton meter per radian
ksi	=	Kilo Pound per square inch
lb	=	Pound
lbs/ft	=	Pound per foot
m	=	Meter
m ²	=	Square meter
MCE	=	Maximum Considered Earthquake
MRF	=	Moment Resisting Frames
NDA	=	Nonlinear Dynamic Analysis
NSA	=	Nonlinear Static Analysis
PBPD	=	Performance-Based Plastic Design
PR	=	Partially Restrained
rad	=	Radian