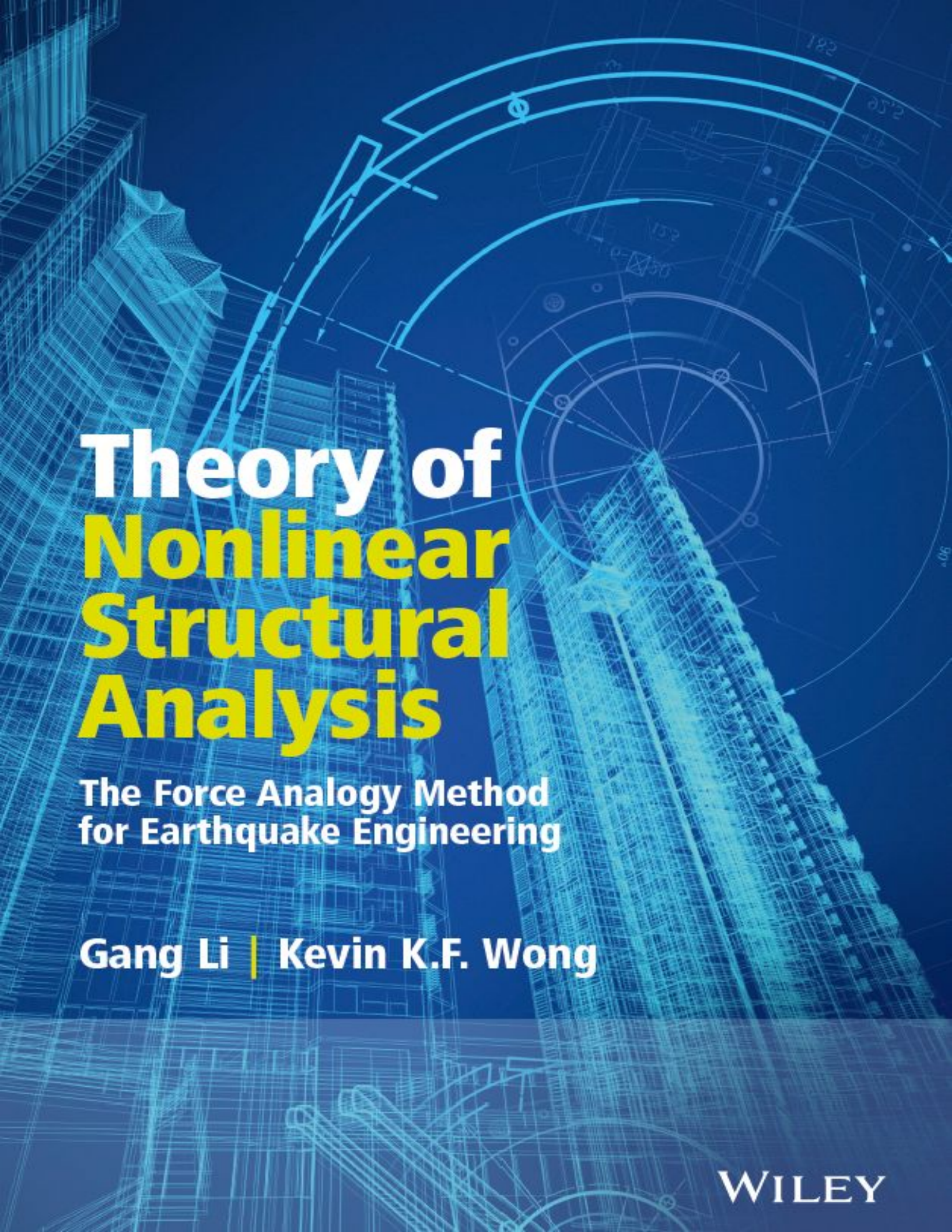




Theory of Nonlinear Structural Analysis

The Force Analogy Method
for Earthquake Engineering

Gang Li | Kevin K.F. Wong

WILEY

CONTENTS

[Cover](#)

[Title page](#)

[Copyright page](#)

[Preface](#)

[About the Authors](#)

[1 Introduction](#)

[1.1 History of the Force Analogy Method](#)

[1.2 Applications of the Force Analogy Method](#)

[1.3 Background of the Force Analogy Method](#)

[References](#)

[2 Nonlinear Static Analysis](#)

[2.1 Plastic Rotation](#)

[2.2 Force Analogy Method for Static Single-Degree-of-Freedom Systems](#)

[2.3 Nonlinear Structural Analysis of Moment-Resisting Frames](#)

[2.4 Force Analogy Method for Static Multi-Degree-of-Freedom Systems](#)

[2.5 Nonlinear Static Examples](#)

[2.6 Static Condensation](#)

[References](#)

[3 Nonlinear Dynamic Analysis](#)

[3.1 State Space Method for Linear Dynamic Analysis](#)

[3.2 Dynamic Analysis with Material Nonlinearity](#)

[3.3 Nonlinear Dynamic Analysis with Static Condensation](#)

[3.4 Nonlinear Dynamic Examples](#)

[References](#)

[4 Flexural Member](#)

[4.1 Bending and Shear Behaviors](#)

[4.2 Inelastic Mechanisms of Flexural Members](#)

[4.3 Nonlinear Static Analysis of Structures with Flexural Members](#)

[4.4 Nonlinear Dynamic Analysis of Structures with Flexural Members](#)

[References](#)

[5 Axial Deformation Member](#)

[5.1 Physical Theory Models for Axial Members](#)

[5.2 Sliding Hinge Mechanisms](#)

[5.3 Force Analogy Method for Static Axial Members](#)

[5.4 Force Analogy Method for Cycling Response Analysis of Axial Members](#)

[5.5 Application of the Force Analogy Method in Concentrically Braced Frames](#)

[References](#)

[6 Shear Member](#)

[6.1 Physical Theory Models of Shear Members](#)

[6.2 Local Plastic Mechanisms in the FAM](#)

[6.3 Nonlinear Static Analysis of the Shear Wall Structures](#)

[6.4 Nonlinear Dynamic Analysis of RC Frame-Shear Wall Structures](#)

[References](#)

[7 Geometric Nonlinearity](#)

[7.1 Classical Stiffness Matrices with Geometric Nonlinearity](#)

[7.2 Stability Functions](#)

[7.3 Force Analogy Method with Stability Functions](#)

[7.4 Nonlinear Dynamic Analysis Using Stability Functions](#)

[7.5 Nonlinear Dynamic Analysis with Static Condensation Using Stability Functions](#)

[7.6 Nonlinear Dynamic Examples](#)

[References](#)

[8 Application of the Force Analogy Method in Modal Superposition](#)

[8.1 Nonlinear Static Pushover Analysis in the FAM](#)

[8.2 Modal Decomposition in the FAM](#)

[8.3 Modal Response Summation](#)

[8.4 Nonlinear Modal Superposition Method Example](#)

[References](#)

[9 Application: Structural Vibration Control](#)

[9.1 Passive Control Technique](#)

[9.2 Application of the FAM in Active or Semi-Active Structural Control](#)

[References](#)

[Index](#)

[End User License Agreement](#)

List of Tables

Chapter 04

[Table 4.1 The parameters of the bending primary curve.](#)

[Table 4.2 The parameters of the shear primary curve.](#)

[Table 4.3 The parameters of the bending primary curve.](#)

[Table 4.4 The parameters of the bending primary curve.](#)

[Table 4.5 The parameters of the shear primary curve.](#)

[Table 4.6 Numerical results of the RC column subjected to cyclic loadings](#)

[Table 4.7 The parameters of the bending primary curves for the columns and beams.](#)

[Table 4.8 The parameters of the shear primary curves for the columns.](#)

Chapter 05

[Table 5.1 Numerical results of the steel tube under cycling loads.](#)

Chapter 06

[Table 6.1 The Parameters of the shear wall structure.](#)

[Table 6.2 The numerical Parameters of the RC frame-shear wall structure.](#)

[Table 6.3 Numerical results of the shear wall subjected to cyclic loadings.](#)

Chapter 07

[Table 7.1 Comparison of geometric nonlinear stiffnesses, periods, and maximum responses.](#)

Chapter 09

[Table 9.1 Parameters of the structure.](#)

[Table 9.2 Parameters of the structural component.](#)

[Table 9.3 the main parameters of the structure.](#)

List of Illustrations

Chapter 01

[Figure 1.1 SDOF system and restoring force model.](#)

[Figure 1.2 Complex cyclic behaviors of structural members.](#)

[Figure 1.3 The framework for the combination of FAM and control algorithm.](#)

[Figure 1.4 Displacement patterns and the corresponding fixed-end forces.](#)

[Figure 1.5 One-story one-bay moment-resisting frame: \(a\) Three degrees of freedom system; \(b\) Applied forces at the degrees of freedom.](#)

[Figure 1.6 Displacement pattern using unit displacement at \$v_1\$.](#)

[Figure 1.7 Displacement pattern using unit displacement at \$\theta_2\$.](#)

[Figure 1.8 Displacement pattern using unit displacement at \$\theta_3\$.](#)

Chapter 02

[Figure 2.1 Definition of positive plastic rotations: \(a\) Beam with positive moments; \(b\) Beam with positive plastic rotations due to positive moments; \(c\) Positive plastic rotation at the left end. \(d\) Positive plastic rotation at the right end; \(e\) Beam member satisfying compatibility condition; \(f\) Beam member satisfying equilibrium condition.](#)

[Figure 2.2 Inelastic displacement in the force-displacement relationship.](#)

Figure 2.3 Force analogy method applied on a SDOF system: (a) A single-degree-of-freedom system; (b) Moment versus plastic rotation relationship; (c) Relationship between plastic rotation and inelastic displacement; (d) Force applied to satisfy compatibility condition; (e) Equivalent force applied to satisfy equilibrium condition.

Figure 2.4 Single-degree-of-freedom system: (a) A single-degree-of-freedom column; (b) Moment versus plastic rotation relationship; (c) System pushover curve.

Figure 2.5 Satisfying compatibility and equilibrium conditions with the FAM: (a) A multi-degree-of-freedom system with plastic hinges; (b) Force applied to satisfy compatibility condition; (c) Equivalent force applied to satisfy equilibrium condition.

Figure 2.6 One-story one-bay moment-resisting frame

Figure 2.7 Graphical illustration of the response of linear one-story frame.

Figure 2.8 Graphical illustration of the response of nonlinear one-story frame.

Figure 2.9 A SDOF system with two PHLs: (a) A single-degree-of-freedom system; (b) Moment versus plastic rotation relationships of the plastic hinges.

Figure 2.10 Graphical illustration of the responses of the SDOF system.

Figure 2.11 A SDOF system with two PHLs: (a) A single-degree-of-freedom system; (b) Moment versus plastic rotation relationships of the plastic hinges.

Figure 2.12 A two-story frame with 12 PHLs.

[Figure 2.13 Graphical illustration of the responses of the two-story frame.](#)

[Figure 2.14 Graphical illustration of the responses of the two-story frame after loads removed.](#)

Chapter 03

[Figure 3.1 A SDOF system.](#)

[Figure 3.2 Response of a SDOF system with period of 0.5 s due to 1995 Kobe earthquake.](#)

[Figure 3.3 Response of a SDOF system with period of 1.0 s due to 1994 Northridge earthquake.](#)

[Figure 3.4 Response of a SDOF system with period of 1.5 s due to 1940 El-Centro earthquake.](#)

[Figure 3.5 A SDOF system with one PHL.](#)

[Figure 3.6 Comparison of 0% damped SDOF responses due to 1995 Kobe earthquake.](#)

[Figure 3.7 Comparison of 2% damped SDOF responses due to 1994 Northridge earthquake.](#)

[Figure 3.8 Comparison of 5% damped SDOF responses due to 1940 El-Centro earthquake.](#)

[Figure 3.9 One-story one-bay moment-resisting frame as a SDOF system.](#)

[Figure 3.10 Global responses of the one-story one-bay moment-resisting frame.](#)

[Figure 3.11 Local responses of the one-story one-bay moment-resisting frame.](#)

[Figure 3.12 Two-story moment-resisting frame and a 2-DOF system.](#)

[Figure 3.13 Global displacement responses of the two-story moment-resisting frame.](#)

[Figure 3.14 Global velocity responses of the two-story moment-resisting frame.](#)

[Figure 3.15 Global acceleration responses of the two-story moment-resisting frame.](#)

[Figure 3.16 Global inelastic displacement responses of the two-story moment-resisting frame.](#)

[Figure 3.17 Moments at selected PHLs of the two-story moment-resisting frame.](#)

[Figure 3.18 Plastic rotations at selected PHLs of the two-story moment-resisting frame.](#)

[Figure 3.19 Hysteresis loops at selected PHLs of the two-story moment-resisting frame.](#)

[Figure 3.20 Six-story moment-resisting steel frame.](#)

[Figure 3.21 Global displacement responses of the 6-story moment-resisting frame.](#)

[Figure 3.22 Global velocity responses of the 6-story moment-resisting frame.](#)

[Figure 3.23 Global acceleration responses of the 6-story moment-resisting frame.](#)

[Figure 3.24 Local moment responses at selected PHLs of the 6-story frame.](#)

[Figure 3.25 Local plastic rotation responses at selected PHLs of the 6-story frame.](#)

[Figure 3.26 Hysteresis loops of selected PHLs of the 6-story frame.](#)

[Figure 3.27 Ten-story moment-resisting steel frame.](#)

[Figure 3.28 Global displacement responses of the 10-story moment-resisting frame.](#)

[Figure 3.29 Global velocity responses of the 10-story moment-resisting frame.](#)

[Figure 3.30 Global acceleration responses of the 10-story moment-resisting frame.](#)

[Figure 3.31 Local moment responses at selected PHLs of the 10-story frame.](#)

[Figure 3.33 Hysteresis loops of selected PHLs of the 10-story frame.](#)

Chapter 04

[Figure 4.1 Primary curve of the flexural member.](#)

[Figure 4.2 Hysteretic models: \(a\) Bending behavior; \(b\) Shear behavior.](#)

[Figure 4.3 Decomposition of bending displacement: \(a\) Branch AB; \(b\) Branch BC; \(c\) Branch CD; \(d\) Branch DE; \(e\) Branch EF.](#)

[Figure 4.4 The flexural member: \(a\) Cantilever column; \(b\) Equivalent SDOF system.](#)

[Figure 4.5 Determination of the displacements in the FAM: \(a\) Elastic displacement; \(b\) Plastic bending displacement; \(c\) Plastic shear displacement.](#)

[Figure 4.6 Schematic representation of the inelastic mechanisms for flexural members: \(a\) Total displacement; \(b\) Elastic component; \(c\) Plastic bending component; \(d\) Plastic shear component.](#)

[Figure 4.7 Backbone curves of the flexural member: \(a\) Bending backbone curve; \(b\) Shear backbone curve.](#)

[Figure 4.8 The SDOF system: \(a\) numerical model; \(b\) backbone curves.](#)

Figure 4.9 The SDOF column with two RHs and one SH: (a) Numerical model; (b) Sectional parameters.

Figure 4.10 The one-story one-bay RC frame.

Figure 4.11 The one-story one-bay RC frame.

Figure 4.12 Graphical illustration of the response of nonlinear one-story one-bay RC frame.

Figure 4.13 The two-story one-bay RC frame.

Figure 4.14 Graphical illustration of the responses of the two-story one-bay RC frame.

Figure 4.15 Loading branches: (a) Bending behavior; (b) Shear behavior.

Figure 4.16 Unloading branches: (a) Bending behavior; (b) Shear behavior.

Figure 4.17 Reloading branches: (a) Bending behavior; (b) Shear behavior.

Figure 4.18 The RC column: (a) Numerical model; (b) Sectional parameters.

Figure 4.19 Cyclic loading history.

Figure 4.20 Hysteretic loops of the RC column: (a) Restoring force F versus displacement x hysteretic behavior; (b) Moment M versus plastic rotation θ^p hysteretic behavior at RH; (c) Shear force V versus plastic deformation τ^p hysteretic behavior at SH.

Figure 4.21 Six-story RC frame with flexural members.

Figure 4.22 The cyclic increasing ground acceleration.

Figure 4.23 Global displacement responses: (a) displacement response of the first floor; (b) displacement response of the roof.

Figure 4.24 Global velocity responses: (a) velocity response of the first floor; (b) velocity response of the roof.

Figure 4.25 Hysteretic loops of restoring forces versus displacements: (a) hysteretic loop of the 1st floor; (b) hysteretic loop of the 2nd floor.

Figure 4.26 Local plastic responses: local plastic response at RH #1; (b) local plastic response at RH #13; (c) local plastic response at RH #49; (d) local plastic response at RH #50; (e) local plastic response at SH #85; (f) local plastic response at SH #91.

Figure 4.27 Hysteretic loops of selected RHs and SHs: (a) hysteretic loop of RH #1; (b) hysteretic loop of RH #13; (c) hysteretic loop of RH #49; (d) hysteretic loop of RH #50; (e) hysteretic loop of SH #85; (f) hysteretic loop of SH #91.

Figure 4.28 Global displacement responses: (a) displacement response of the first floor; (b) displacement response of the second floor.

Figure 4.29 Global velocity responses: (a) velocity response of the first floor; (b) velocity response of the second floor.

Figure 4.30 Hysteretic loops of restoring forces versus displacements: (a) hysteretic loop of the first floor; (b) hysteretic loop of the second floor.

Figure 4.31 Local plastic responses: (a) local plastic response at RH #1; (b) local plastic response at RH #13; (c) local plastic response at RH #49; (d) local plastic response at RH #50; (e) local plastic response at SH #85; (f) local plastic response at SH #91.

Figure 4.32 Hysteretic loops of selected RHs and SHs: (a) hysteretic loop of RH #1; (b) hysteretic loop

of RH #13; (c) hysteretic loop of RH #49; (d) hysteretic loop of RH #50; (e) hysteretic loop of SH #85; (f) hysteretic loop of SH #91.

Chapter 05

Figure 5.1 Hysteretic loop of the axial member.

Figure 5.2 Decomposition of brace axial displacement: (a) Region Aa-A; (b) Region A-B; (c) Region C-D.

Figure 5.3 Axial member in compression: (a) Displacement decomposition; (b) Two sliding hinges plastic mechanisms.

Figure 5.4 Axial member in tension: (a) Displacement decomposition; (b) Two sliding hinges plastic mechanisms.

Figure 5.5 Backbone curve of axial member.

Figure 5.6 Model of the steel tube in tension.

Figure 5.7 Model of steel tube in compression.

Figure 5.8 Relation of the load and displacement in Region B-C.

Figure 5.9 Relation of the load and displacement in Region C-D.

Figure 5.10 Relation of the load and displacement in Region D'-A2.

Figure 5.11 Relation of the load and displacement in Region D-E.

Figure 5.12 Relation of the load and displacement in Region E-F.

Figure 5.13 Relation of the load and displacement in Region A2-A a2.

[Figure 5.14 Cycle loading history.](#)

[Figure 5.15 General parameters summary of the steel tube.](#)

[Figure 5.16 Hysteretic loop of the steel tube.](#)

[Figure 5.17 Concentrically braced frame model.](#)

[Figure 5.18 one-bay one-story CBF model.](#)

[Figure 5.19 Graphical illustration of the responses of the one-story CBF.](#)

[Figure 5.20 Two-story CBF model.](#)

[Figure 5.21 An actual two-story CBF.](#)

[Figure 5.22 Graphical illustration of the responses of the actual CBF.](#)

[Figure 5.23 One-bay one-story model under earthquakes.](#)

[Figure 5.24 A one-bay two-story model under earthquakes.](#)

Chapter 06

[Figure 6.1 The macro model proposed by Linde and Bachmann \(1994\).](#)

[Figure 6.2 The spring force versus displacement relationship of the outer vertical springs: \(a\) Small cycle; \(b\) Big cycle.](#)

[Figure 6.3 Spring force versus displacement relationship of the horizontal spring.](#)

[Figure 6.4 Shear wall member model in the FAM.](#)

[Figure 6.5 The VSH hysteretic behavior.](#)

[Figure 6.6 The HSH hysteretic behavior.](#)

[Figure 6.7 The numerical model of RC shear wall.](#)

[Figure 6.8 Numerical model: \(a\) Basic information; \(b\) Sectional parameters.](#)

[Figure 6.9 Numerical model.](#)

[Figure 6.10 Graphical illustration of the response of the RC frame-shear wall structure. \(a\) Deformations; \(b\) Internal forces.](#)

[Figure 6.11 The two-story RC frame-shear wall structure.](#)

[Figure 6.12 Graphical illustration of the response of the RC frame-shear wall structure: \(a\) Deformations; \(b\) Internal forces.](#)

[Figure 6.13 Cyclic loading history.](#)

[Figure 6.14 Hysteretic behaviors of local plastic mechanisms: \(a\) hysteretic behavior of VSH #1; \(b\) hysteretic behavior of VSH #2; \(c\) hysteretic behavior of HSH #3.](#)

[Figure 6.15 Hysteretic behaviors of the RC shear wall structure: \(a\) hysteretic behavior of moment versus rotation; \(b\) hysteretic behavior of shear force versus shear displacement.](#)

[Figure 6.16 The cyclic increasing ground acceleration.](#)

[Figure 6.17 Global displacement responses of the two-story RC frame-shear wall structure: \(a\) response of the first floor; \(b\) response of the second floor.](#)

[Figure 6.18 Hysteretic behaviors of the first floor: \(a\) hysteretic behavior of moment versus rotation; \(b\) hysteretic behavior of shear force versus shear displacement.](#)

[Figure 6.19 Plastic responses at selected local plastic mechanisms: \(a\) plastic response at VSH #1; \(b\).](#)

plastic response at VSH #3; (c) plastic response at HSH #5; (d) plastic response at PHL #2.

Figure 6.20 Hysteretic behaviors at selected local plastic mechanisms: (a) hysteretic behavior at VSH #1; (b) hysteretic behavior at VSH #3; (c) hysteretic behavior at HSH #5; (d) hysteretic behavior at PHL #2.

Figure 6.21 Global displacement responses: (a) response of the first floor; (b) response of the second floor.

Figure 6.22 Global velocity responses: (a) response of the first floor; (b) response of the second floor.

Figure 6.23 Hysteretic behaviors of the first floor: (a) hysteretic behavior of moment versus rotation; (b) hysteretic behavior of shear force versus shear displacement.

Figure 6.24 Plastic responses at selected local plastic mechanisms: (a) plastic response at VSH #1; (b) plastic response at VSH #3; (c) plastic response at HSH #5; (d) plastic response at PHL #2.

Figure 6.25 Hysteretic behaviors at selected local plastic mechanisms: (a) hysteretic behavior at VSH #1; (b) hysteretic behavior at VSH #3; (c) hysteretic behavior at HSH #5; (d) hysteretic behavior at PHL #2.

Chapter 07

Figure 7.1 Four cases of deflected shapes.

Figure 7.2 Displacement patterns and the corresponding fixed-end forces.

Figure 7.3 Displacement patterns for computation of moments at the plastic hinge locations.

[Figure 7.4 Displacement patterns for computation of moments due to unit plastic rotations.](#)

[Figure 7.5 Beam member subdivided into three elements.](#)

[Figure 7.6 One-story one-bay moment-resisting frame.](#)

[Figure 7.7 Pushover curve of the one-story frame with update on geometric nonlinearity.](#)

[Figure 7.8 Comparison of pushover curves on geometric nonlinearity with and without updates.](#)

[Figure 7.9 A single-degree-of-freedom column with geometric nonlinearity.](#)

[Figure 7.10 Displacement responses of the SDOF column using different stiffnesses.](#)

[Figure 7.11 Velocity responses of the SDOF column using different stiffnesses.](#)

[Figure 7.12 Acceleration responses of the SDOF column using different stiffnesses.](#)

[Figure 7.13 A single degree of freedom column with two plastic hinges.](#)

[Figure 7.14 Global responses of the SDOF column with geometric nonlinearity.](#)

[Figure 7.15 Local plastic hinge responses of the SDOF column with geometric nonlinearity.](#)

[Figure 7.16 One-story one-bay moment-resisting frame with gravity loads.](#)

[Figure 7.17 Global response comparisons of the one-story frame with geometric nonlinearity.](#)

[Figure 7.18 Local response comparisons of the one-story frame with geometric nonlinearity.](#)

[Figure 7.19 Two-story moment-resisting frame with gravity loads.](#)

[Figure 7.20 Global displacement responses of the two-story frame with geometric nonlinearity.](#)

[Figure 7.21 Global velocity responses of the two-story frame with geometric nonlinearity.](#)

[Figure 7.22 Global acceleration responses of the two-story frame with geometric nonlinearity.](#)

[Figure 7.23 Global inelastic displacement responses of the frame with geometric nonlinearity.](#)

[Figure 7.24 Moments at selected PHLs of the two-story frame with geometric nonlinearity.](#)

[Figure 7.25 Plastic rotations at selected PHLs of the frame with geometric nonlinearity.](#)

[Figure 7.26 Hysteresis loops at selected PHLs of the frame with geometric nonlinearity.](#)

[Figure 7.27 Six-story moment-resisting steel frame with a leaning column.](#)

[Figure 7.28 Global displacement responses of the 6-story frame with geometric nonlinearity.](#)

[Figure 7.29 Global velocity responses of the 6-story frame with geometric nonlinearity.](#)

[Figure 7.30 Global acceleration responses of the 6-story frame with geometric nonlinearity.](#)

[Figure 7.31 Selected PHL moment responses of the frame with geometric nonlinearity.](#)

[Figure 7.32 Selected PHL plastic rotation responses of the frame with geometric nonlinearity.](#)

[Figure 7.33 Hysteresis loops of selected PHLs of the frame with geometric nonlinearity.](#)

[Figure 7.34 Ten-story moment-resisting steel frame with a leaning column.](#)

[Figure 7.35 Global displacement responses of the 10-story frame with geometric nonlinearity.](#)

[Figure 7.36 Global velocity responses of the 10-story frame with geometric nonlinearity.](#)

[Figure 7.37 Global acceleration responses of the 10-story frame with geometric nonlinearity.](#)

[Figure 7.38 Selected PHL moment responses of the 10-story frame with geometric nonlinearity.](#)

[Figure 7.39 Selected PHL plastic rotation responses of the frame with geometric nonlinearity.](#)

[Figure 7.40 Hysteresis loops of selected PHLs of the frame with geometric nonlinearity.](#)

Chapter 08

[Figure 8.1 A SDOF system and corresponding normalized-mass system model.](#)

[Figure 8.2 A normalized SDOF system and loads history.](#)

[Figure 8.3 Mass-normalized force, moment and plastic rotation responses: \(a\) Normalized-mass force; \(b\) normalized-mass moment; \(c\) Plastic rotation; \(d\) normalized-mass moment and plastic rotation relation.](#)

[Figure 8.4 n-DOFs system model.](#)

[Figure 8.5 Plastic hinges distribution at last displacement step.](#)

[Figure 8.6 Responses of structure under 1st model shape-dependent lateral loads: \(a\) Base shear; \(b\) moment at PHL #1; \(c\) moment at PHL #9; \(d\).](#)

moment at PHL #11; (e) plastic rotation at PHL #1; (f) plastic rotation at PHL #9; (g) plastic rotation at PHL #11; (h) moment and plastic rotation relation of PH #1; (i) moment and plastic rotation relation of PH #9; (j) moment and plastic rotation relation of PH #11.

Figure 8.7 Plastic hinges distribution.

Figure 8.8 Responses of structure under 1st model shape-dependent lateral loads: (a) Base shear; (b) moment at PHL #3; (c) moment at PHL #11; (d) plastic rotation at PHL #3; (e) plastic rotation at PHL #11; (f) moment and plastic rotation relation of PH #3; (g) moment and plastic rotation relation of PH #11.

Figure 8.9 System model and response: (a) MDOF system model and corresponding jth modal SDOF system; (b) relation of base shear and roof displacement.

Figure 8.10 Responses of 1st modal SDOF system: (a) 1st modal displacement; (b) 1st modal velocity; (c) 1st modal acceleration; (d) 1st modal plastic rotation; (e) 1st modal moment; (f) 1st modal inelastic displacement.

Figure 8.11 Responses of 2nd modal SDOF system: (a) 2nd modal displacement; (b) 2nd modal velocity; (c) 2nd modal acceleration; (e) 2nd modal moment.

Figure 8.12 Response comparison of the MDOF system using the MSM and SSM: (a) First floor displacement; (b) Roof displacement; (c) first floor velocity; (d) roof velocity; (e) first floor acceleration; (f) roof acceleration.

Figure 8.13 A 6-story 2-bay steel moment-resisting frame.

Figure 8.14 First, six model shapes: (a) 1st model; (b) 2nd model; (c) 3rd model; (d) 4th model; (e) 5th model; (f) 6th model.

Figure 8.15 Responses of 1st modal SDOF system: (a) Base shear; (b) moment at PHL #1; (c) moment at PHL #37; (d) moment at PHL #41; (e) plastic rotation at PHL #1; (f) plastic rotation at PHL #37; (g) plastic rotation at PHL #41; (h) moment and plastic rotation relation of PH #1; (i) moment and plastic rotation relation of PH #37; (j) moment and plastic rotation relation of PH #41.

Figure 8.16 PHs distributions of the 1st modal SDOF system in the NSPA.

Figure 8.17 PH distributions of modal SDOF systems: (a) 2nd model; (b) 3rd model.

Figure 8.18 Base shear of modal SDOF systems: (a) 2nd model; (b) 3rd model.

Figure 8.19 Displacement and acceleration responses of the first three modal SDOF systems: (a) 1st modal displacement; (b) 1st modal acceleration; (c) 2nd modal displacement; (d) 2nd modal acceleration; (e) 3rd modal displacement; (f) 3rd modal acceleration.

Figure 8.20 Response comparison of the structure using MSM and SSM: (a) first floor displacement; (b) roof displacement; (c) first floor acceleration; (d) roof acceleration.

Figure 8.21 Global responses of the frame: (a) moment response at PHL #37; (b) moment response at PHL #41; (c) moment and plastic rotation relation of PH #37; (d) moment and plastic rotation relation of PH #41.

Figure 9.1 Force-displacement relations of: (a) viscous damper; (b) viscoelastic damper. Reproduced with permission from John Wiley and Sons, (License No. 3132491366031).

Figure 9.2 Force-displacement relations of: (a) friction damper; (b) metallic yielding damper. Reproduced with permission from John Wiley and Sons, (License No. 3132491366031).

Figure 9.3 Model of a diagonal brace equipped with a PEDD (F_d is the horizontal force generated by PEDD; P is the axial force of diagonal brace): (a) diagonal brace model; (b) simplified axial force; (c) simplified horizontal force. Reproduced with permission from John Wiley and Sons, (License No. 3132491366031).

Figure 9.4 Model of a chevron brace equipped with a PEDD: (a) chevron brace model; (b) simplified braced joint forces; (c) simplified framed joint forces. Reproduced with permission from John Wiley and Sons, (License No. 3132491366031).

Figure 9.5 Damping force distributed on framed joints.

Figure 9.6 A MDOF structure with PEDDs model.

Figure 9.7 Model of the structure.

Figure 9.8 Displacement, velocity and acceleration responses of the structures: (a) first floor displacement; (b) roof displacement; (c) first floor velocity; (d) roof velocity; (e) first floor acceleration; (f) roof acceleration.

Figure 9.9 Moments at selected PHLs responses: (a) PHL #1; (b) PHL #2; (c) PHL #9; (d) PHL #23; (e) PHL #37.

[Figure 9.10 Moment versus plastic rotation of selected PHLs: \(a\) PHL #1; \(b\) PHL #2; \(c\) PHL #9; \(d\) PHL #23; \(e\) PHL #37.](#)

[Figure 9.11 Hysteretic loops of seven yielded dampers: \(a\) Damper #1; \(b\) Damper #2; \(c\) Damper #3; \(d\) Damper #4; \(e\) Damper #5; \(f\) Damper #6; \(g\) Damper #7.](#)

[Figure 9.12 Schematic diagram of MBC nonlinear control strategy based on FAM.](#)

[Figure 9.13 The model of structure with magnetorheological damper. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.](#)

[Figure 9.14 Responses of the structure with and without controlling: \(a\) displacement; \(b\) velocity; \(c\) acceleration; \(d\) plastic rotation at PHL #1. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.](#)

[Figure 9.15 A six-story structure with dampers model. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.](#)

[Figure 9.16 Response of the structure: \(a\) first floor displacement; \(b\) roof displacement; \(c\) first floor velocity; \(d\) roof velocity; \(e\) first floor acceleration; \(f\) roof acceleration. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and](#)

FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.

Figure 9.17 Plastic rotation of selected PHs: (a) #1; (b) #3; (c) #7; (d) #9. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.

Figure 9.18 Damping force versus inter-story displacement and velocity relation of the MRD in second floor: (a) D#1; (b) D#2. Gang Li, Qifeng Liu, Hongnan Li. Inelastic structural control based on MBC and FAM, Mathematical Problems in Engineering, vol. 2011, Article ID 460731, 18 pages, 2011. doi:10.1155/2011/460731.

Theory of Nonlinear Structural Analysis

The Force Analogy Method for Earthquake Engineering

Gang Li

Dalian University of Technology, P. R. China

Kevin Wong

Ph.D., University of California Los Angeles, USA

WILEY

This edition first published 2014
© 2014 John Wiley & Sons, Singapore Pte. Ltd.

Registered Office

John Wiley & Sons, Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628.

For details of our global editorial offices, for customer services and for information about how to apply for permission to reuse the copyright material in this book please see our website at www.wiley.com.

All Rights Reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as expressly permitted by law, without either the prior written permission of the Publisher, or authorization through payment of the appropriate photocopy fee to the Copyright Clearance Center. Requests for permission should be addressed to the Publisher, John Wiley & Sons, Singapore Pte. Ltd., 1 Fusionopolis Walk, #07-01 Solaris South Tower, Singapore 138628, tel: 65-66438000, fax: 65-66438008, email: enquiry@wiley.com.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Designations used by companies to distinguish their products are often claimed as trademarks. All brand names and product names used in this book are trade names, service marks, trademarks or registered trademarks of their respective owners. The Publisher is not associated with any product or vendor mentioned in this book. This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. It is sold on the understanding that the publisher is not engaged in rendering professional services and neither the publisher nor the author shall be liable for damages arising herefrom. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Library of Congress Cataloging-in-Publication Data applied for.

ISBN: 978-1-118-71806-3

A catalogue record for this book is available from the British Library.

1 2014

Preface

Although the seismic design for buildings is currently based on elastic analysis, nonlinear structural analysis has become increasingly important in the investigation of structural response to environmental loads, especially during earthquakes. Nonlinear structural analysis in civil engineering is not a new topic, but the existing method used for calculating the nonlinear behavior of civil engineering structures is often by changing the structural member stiffness. With respect to the dynamic analysis algorithms, the typical method is the time integral of variable stiffness matrices, such as the Wilson- θ and Newmark- β methods. For these conventional methods, the primary problem is that significant iterative computations have to be carried out to ensure numerical convergence once the structure experiences yielding and nonlinear deformation. As a result, the iterative operation is time consuming and the entire dynamic analysis process becomes practically uneconomical. The Force Analogy Method as a relatively new algorithm was first developed in 1999 for solving nonlinear dynamic analysis problems, in which the state transition matrix needs to be computed only once due to the consistent use of initial stiffness, and this greatly simplifies the overall computation and makes the nonlinear analysis readily available for solving various practical problems.

This book focused on the Force Analogy Method, a novel method for nonlinear dynamic analysis and simulation. A review of the current nonlinear analysis method for earthquake engineering is summarized and its importance explained. Additionally, how the force analogy method can be used in nonlinear static analysis will be discussed

through several nonlinear static examples. The emphasis of this book is to extend and develop the force analogy method to performing dynamic analysis on structures under earthquake excitations, where the force analogy method is incorporated in the flexural element, axial element, shearing element and so on will be exhibited. Moreover, the geometric nonlinearity into nonlinear dynamic analysis algorithm based on the force analogy method is included in this book. The application of the force analogy method in seismic design for buildings and structural control area will be discussed combined with practical engineering. This book will be a milestone of nonlinear dynamic analysis and may bring about significant advancement in earthquake engineering.

The authors would like to express their appreciation to Professor Hong-Nan Li at the Dalian University of Technology (DUT), for his advice and support, Professor Larry A. Fahnestock at University of Illinois at Urbana & Champaign, Mr. Yu Zhang, a Ph. D candidate at DUT, and Mr. Feng Zhang, a graduate student at DUT, for their collaborative works, and Mr. Ying Li, for his early contributions. In addition, many thanks go to Zhi-Qian Dong, Yong-Qiang Jin, Jia-Long Li and Li-Hua Zhu, present students at DUT, for their work on the figures.

Gang Li

About the Authors

Gang Li is an associate professor of the Faculty of Infrastructure Engineering, Dalian University of Technology, China. He received a B.S. degree in civil engineering from the Hebei University of Engineering, China and Ph.D. degree in civil engineering from the Dalian University of Technology, China. His research interest is in the earthquake engineering, structural control, structural dynamic analysis, steel structures, large-scale structural experiments, etc. Some of his techniques have been applied to many engineering structures.

Kevin K.F. Wong is a research structural engineer at the National Institute of Standards and Technology (NIST) in the United States. He received a B.S. degree in civil engineering from the University of Hawaii and M.S. and Ph.D. degrees in civil engineering from the University of California, Los Angeles (UCLA). His research areas include structural dynamics, nonlinear structural analysis, earthquake engineering, and structural control.

Dr. Wong was first exposed to the Force Analogy Method as a graduate research assistant under the supervision of Dr. T. H. Lin at UCLA in 1992 while conducting research on the development of plastic strains in high-cycle fatigue of materials. He successfully captured the essence of the method and applied it to the nonlinear analysis of civil engineering structures, where he summarized the work in his Ph.D. thesis titled *Optimal Linear Control of Inelastic Building Response During Earthquakes* in 1996. Since then, he has published over 30 journal articles and 30 conference papers related to the method.

Prior to joining NIST, Dr. Wong was an assistant professor at the University of Utah, USA, for four years, and the

Nanyang Technological University, Singapore, for six years. He coauthored the textbook *Structural Dynamics for Structural Engineers* for John Wiley & Sons in 2000 with his Ph.D. advisor, Dr. Gary Hart. Currently at NIST, he is a member of the National Earthquake Hazards Reduction Program research group, conducting research on the development of Codes and Standards on the use of nonlinear analysis for performance-based seismic engineering.

Disclaimers:

The opinions expressed in this book are those of the authors and do not necessarily reflect the opinions of the National Institute of Standards and Technology or the United States Government. While the information in this book is believed to be correct, the National Institute of Standards and Technology and the authors assume no liability for, nor express or imply any warranty with regard to, the information contained herein. Users of the information contained in this book assume all liability arising from such use.