Shape Memory Alloys for Seismic Resilience

Cheng Fang · Wei Wang

Shape Memory Alloys for Seismic Resilience

Springer

Cheng Fang
Tongji University
Shanghai, China

Wei Wang
Tongji University
Shanghai, China

ISBN 978-981-13-7039-7 ISBN 978-981-13-7040-3 (eBook)
https://doi.org/10.1007/978-981-13-7040-3

© Springer Nature Singapore Pte Ltd. 2020
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

A resilient city is one, which is able to rebound quickly from a disaster (e.g. earthquake) that has caused structural collapse, casualties, infrastructure disruption and business interruption. Although nowadays, most code-compliant structures have satisfactory collapse resistance under design-level earthquakes, the permanent structural and non-structural damages can be difficult and time consuming to repair, thus posing a great challenge to the affected communities for restoring essential services. After the Christchurch earthquake in 2011, a large number of buildings in the affected zone have been pulled down and it was estimated that the total cost of the rebuild would take up 20% of New Zealand's annual GDP. An independent study claimed that in a developed region such as California, a magnitude 7.8 scenario earthquake would have resulted in an estimated USD113 billion in damages to buildings and lifelines, and nearly USD70 billion in business interruption.

Lessons drawn from past major earthquakes urged a pressing need of a fundamental shift in the design targets for buildings in seismic zones. This provides an impetus for the development of low-damage and high-performance alternatives to conventional structural systems. One of the most promising strategies is to introduce self-centring capability into a structure. The core intention of the self-centring structural design is to minimise the post-earthquake structural damage and to eliminate permanent inter-storey drift. One feasible way is to utilise a unique class of smart metals, namely shape-memory alloys (SMAs), to achieve seismic resiliency. This class of material is capable of recovering large strains either spontaneously or by heating, depending on the thermal–mechanical state. Since the early development in the 1960s, SMAs have been successfully applied in the medical, aerospace, robotic and automobile industries. The consideration of SMA as emerging materials for seismic protection started in the 1990s, and great research progress has been made since then. However, the practical application of SMA to the construction industry has not been common, partially due to the lack of effective knowledge exchange between the communities of material scientists and civil engineers.

This book is intended to make a comprehensive summary of the up-to-date research achievements promoting the use of SMA for civil engineering. It helps to remove the knowledge barriers across disciplines, and sheds considerable light on the opportunity of commercialising SMA products against the seismic hazard. The results from the analysis are demonstrated with religious experimental verifications supplemented by numerical and analytical investigations. The book is mainly written for senior undergraduates, graduate students, academic researchers and practising engineers in the disciplines of civil and seismic engineering. The cutting-edge research introduced in this work aims to provide technical incentives to encourage design professionals, contractors and building officials to use high-performance smart materials in structural design, allowing them to remain at the forefront of construction technology. While this book is also of scientific interest to the mechanical and material science community, much emphasis is placed on making the relevant subjects easier to learn by civil engineers. Therefore, in most cases, the presentation has been structured following the civil engineering custom and terminology.

With the knowledge provided in this work, the readers are expected to get acquainted with the fundamental material properties of SMA, and to gain an in-depth understanding of the detailed working mechanisms and applications of a series of SMA-based structural elements, devices and members. In particular, the state-of-the-art research on SMA-based self-centring connections, braces and dampers is presented in detail, and the dynamic responses of the self-centring structural systems under various types of earthquake excitations are revealed. In addition, the book attempts to provide member-level and system-level design recommendations, which are compatible with the existing seismic design provisions. The economic seismic loss is also evaluated, which allows the reader to have a more direct recognition of the competitiveness of the SMA technology from a financial point of view. It is hoped that this work can also enlighten the researchers and practitioners engaged in other relevant areas such as wind engineering, blast engineering, vibration control, etc. where the SMA technology could be utilised.

The book is mostly from the research findings published over the past decade by the research team at Tongji University. Investigations by many other independent research groups, complemented by the authors' interpretations, are also included in this book with appreciation. The financial supports from the National Natural Science Foundation of China (NSFC), the State Key Laboratory of Disaster Reduction in Civil Engineering (SLDRCE) of China, International Joint Research Laboratory of Earthquake Engineering (ILEE) and Central University Fund for Interdisciplinary Research, Tongji University are gratefully acknowledged, and in addition, the authors would like to express their sincere gratitude to the following individuals: Prof. Yiyi Chen, Prof. Michael Yam, Prof. James Ricles, Prof. Richard Sause, Prof. Roberto Leon, Prof. Yunfeng Zhang and Prof. Bing Qu, for their long-term collaboration and assistance; Prof. Canxing Qiu for kindly sharing the original data for Chaps. 2 and 5; Dr. Yue Zheng for providing technical support for the manufacturing of the SMA cables; graduate students Hongliang Shao, Ce He, Jia Liu, Xiao Yang, Ao Zhang, Qiuming Zhong, Weikang Feng, Junbai Chen, Linting Huang, Dong Liang and Shuling Hu, for their excellent work in this area over the years; and Zong Cao for assistance with the artwork during the preparation of the manuscript.

Shanghai, China
Cheng Fang & Wei Wang

Endorsement

Improving community resilience requires development of more robust structural and non-structural systems and materials for infrastructure, both for new and existing buildings and facilities. In particular, it requires more sustainable and durable construction materials so that our society can respond to natural and man-made disasters in a more equitable way. This book, by providing the first detailed and comprehensive treatment of the use of shape memory alloys in seismic applications, is a very timely and welcome addition to the literature for this class of materials. The book focuses in developments in the last decade and emphasizes the synergies between the material properties and its applications. Its treatment of the topic follows a logical path, starting from basic properties and heat treatments, to their implementation in energy dissipative and recentering devices, and finally to the response of entire structures. It concludes with a very thorough application example that clearly demonstrates the potential for this technology. This clearly written and well-organized book will be an invaluable resource to anyone interested in innovative solutions to seismic design problems.

—Roberto T. Leon, DM ASCE,
D.H. Burrows Professor of Construction Engineering
Virginia Tech (Blacksburg, VA)

Contents

Notation

All symbols used in this book are defined where they first appear. For the reader's convenience, the principal meanings of the commonly used notations are contained in the list below. The reader is cautioned that some symbols may denote more than one quantity; in such cases, the meaning is clarified when read in context.

Abbreviations

2D, 3D	2-dimension, 3-dimension
BRB	Buckling-restrained braces
BRBF	Buckling-restrained braced frame
CoF	Coefficient of friction
CoV	Coefficient of variation
DBE	Design-based earthquake
DCH	Ductility class high
DCM	Ductility class medium
DIC	Digital image correlation
DM	Damage measure
DS	Damage state
DSC	Differential scanning calorimeter
DV	Decision variable
EDM	Electrical discharge machining
EDP	Engineering demand parameter
EVD	Equivalent viscous damping
FE	Finite element
FEMA	Federal Emergency Management Agency
HSS	High-strength steel
IDA	Incremental dynamic analysis
IDR	Inelastic displacement ratio
IM	Intensity measure

IMF	Intermediate moment frame
MCE	Maximum considered earthquake
MID	Maximum inter-storey drift
MRF	Moment-resisting frame
NiTi	Nickel–titanium
OWSME	One-way shapememory effect
PFA	Peak absolute floor acceleration
PFV	Peak floor velocity
PAR	Plasma arc remelting
PBSD	Performance-based seismic design
PEER	Pacific Earthquake Engineering Research
PGA	Peak ground acceleration
PGV	Peak ground velocity
PT	Post-tensioned/posttensioning
RDR	Residual displacement ratio
RID	Residual inter-storey drift
SC	Self-centring
SCBF	Self-centring braced frame
SDOF	Single degree of freedom
SEM	Scanning election microscope
SE-P	Superelastic–plastic
SMA	Shape-memory alloy
SME	Shape-memory effect
SMRF/SMF	Special moment-resisting frame
SE	Superelastic effect/superelasticity
TEM	Transmission electron microscopy
THA	Time-history analysis
TWSME	Two-way shape-memory effect
TIF	Transformation-induced fatigue
UTM	Universal test machine
VIM	Vacuum induction melting
VAR	Vacuum arc remelting

Roman Symbols

a_{max}	Peak absolute acceleration
a_t	Total acceleration
A	Cross section area
A_b	Shank area of bolt
A_{BRB}	Cross section area of the BRB steel core
A_f	Austenite finish temperature
A_s	Austenite start temperature
c	Damping coefficient

C	Spring index of helical springs
C_A	Change of critical stresses that induce reverse transformation with changing temperatures
C_M	Change of critical stresses that induce forward transformation with changing temperatures
C^{AS}, C^{SA}	Clausius–Clapeyron constants for the phase transformations
C_F	Coefficient of friction
d	Wire diameter of helical springs
d_h	Bolt hole diameter
D	Diameter
D_e	External diameter of Belleville washers or ring springs
D_i	Internal diameter of Belleville washers or ring springs
E	Young's modulus
E_A	Young's modulus of austenite SMA
E_M	Young's modulus of martensite SMA
E_s	Young's modulus of single-variant martensite
f_d	Damping force
f_{el}	Maximum force of linear elastic system
f_{max}	Maximum force of inelastic system
f_y	Yield strength/resistance
f_{yp}	Yield strength of the end-plate
$F_{b,pre}$	Preload applied to the SMA bolts
$F_{b,y}$	Yield resistance of SMA bolts/tendons
$F_{BRB,y}$	Yield resistance of the BRB
F_e	Yield force of helical springs
$F_{r,pre}$	Preload applied to the SMA ring springs
F_{rst}	Restoring force
$F_{r,y}$	Yield resistance of SMA ring spring set
$F_{Rd,y}$	Design yield resistance
$F_{w,pre}$	Preload applied to the SMA washers
$F_{w,y}$	Yield resistance of SMA Belleville washers
F_y	Yield strength/resistance (general)
g	Gravitational acceleration
g_1, g_2	Dimensions of steel angles
G	Shear modulus of material
h_i	Distance of the ith bolt row to the rotation centre
h_j	Distance of the jth SMA washer to the rotation centre
H^{AS}, H^{SA}	Scalar quantities in Auricchio model
H	Height of Belleville washers or ring springs
I	Second moment of area
I_a	Second moment of area of angle section
k	Stiffness (general)
k_i	Effective stiffness of SMA bolt with the consideration of preload
k_r	Stiffness of each single SMA ring spring
$k_{r\text{-}SMA}$	Reverse transformation stiffness of SMA material

k_w	Stiffness of SMA washer group
$K_{b,ini}$	Design/estimated initial stiffness of brace
$K_{c,ini}$	Design/estimated initial stiffness of connections
$K_{d,ini}$	Design/estimated initial stiffness of device
K_e	Elastic stiffness of subassembly system
K_o, K_t, K_g	Three-stage stiffness of steel angles under tension
$K_{r\text{-}ang}$	Reverse stiffness of single steel angle
$K_{r\text{-}rot}$	Reverse rotational stiffness of self-centring connection
$K_{r\text{-}SMA}$	Reverse stiffness of single SMA bolt
L_{arm}	Beam arm length
L_b	Beam length/span
$L_{e,BRB}$	Effective working length (yielding region) of BRB
L_p	Parallel/working length of the SMA bolts/tendons
m	Mass
M_{ang}	Moment contributed by steel angles
$M_{b,el}$	Design elastic moment resistance of connected beam
$M_{b,pl}$	Design plastic moment resistance of connected beam
M_f	Martensitic finish temperature
$M_{j,Rd}$	Design yield moment resistance of connections
M_{max}	Moment capacity of connections
M_{np}	Bolt moment strength
M_{pa}	Plastic moment capacity of angle section
M_{rev}	Reverse moment
M_{rst}	Restoring moment
M_s	Martensitic start temperature
M_{SMA}	Moment contributed by SMA bolts
M_{ya}	Yield moment capacity of angle section
n	Total number of SMA outer rings
N	Number of active coils in a helical spring
N_{ya}	Yield capacity of angle section
P	Applied load
P_{ang}	Maximum force of steel angle at the peak deformation
P_{rst}	Restoring bolt force of SMA
P_{rev}	Reverse force of steel angle
P_t	Bolt tensile strength
P_y, P_s, P_u	Three-stage load resistance of steel angle
R	Radius or strength ratio, as specified in the text
R_f	Rhombohedral phase finish temperature
R_s	Rhombohedral phase start temperature
s	Compressive deformation of Belleville washers
S	Overall cross-sectional tensile force of SMA outer ring
S_a	Spectral response acceleration
t	Thickness
$t_{pReq'd}$	Required end-plate thickness for SMA-bolted connections
T	Temperature or natural period of vibration, as specified in the text

T_0	Reference temperature
T_1	Fundamental period of vibration
T_p	Pulse period
$T_{p\text{-}v}$	Equivalent pulse period
u	Displacement
u_{el}	Maximum displacement of linear elastic system
u_{max}	Maximum displacement of inelastic system
u_{res}	Residual displacement
u_y	Yield displacement
V	Base shear
w	Uniformly distributed load along the perimeter of SMA outer ring
W	Seismic weight
W_D	Energy loss per cycle
W_E	Strain energy stored in a linear system that has the same maximum load and deformation as the nonlinear system
y_e	Yield displacement of helical springs
Y_p	Yield line mechanism parameter

Greek Symbols

α	Taper angle of SMA ring springs or post-yield stiffness ratio, as specified in the text
α_{is}	Empirical factor for initial stiffness of device with SMA ring springs
α_r	Parameter for reduction of yield resistance of SMA components
α_{sc}	Parameter for design of SMA preload in SMA-BRB hybrid braces
α^{AS}, α^{SA}, α_m	Material constants in Auricchio model
β	Energy dissipation factor or dispersion
β_c	Ratio of the maximum compression force to the maximum tension force of BRBs
β_m	Internal variable that describes martensite reorientation in Auricchio model
χ	Reduction factor for SMA performance
δ	Deformation
δ_u	Ultimate deformation
Δ	Displacement of each half-piece of SMA outer ring
Δ_b	Beam tip displacement
$\Delta\sigma$	Incremental Kirchhoff stress
$\Delta\varepsilon$	Incremental Kirchhoff strain
ε_{Af}	Reverse transformation finish strain
ε_{As}	Reverse transformation start strain
ε^e	Elastic strain in Auricchio model
ε_L	Transformation strain
ε_{Ms}	Forward transformation start strain

ε_{Mf}	Forward transformation finish strain
ε_{peak}	Peak strain
ε_{pre}	Prestrain
ε_{r}	Transformation-induced residual strain
ε_{res}	Residual strain
ε_{u}	Ultimate tensile strain
θ	Pitch or core angle of helical springs or Belleville washers
θ_{c}	Maximum inter-storey drift associated with the performance objective of collapse prevention
θ_{el}	Elastic inter-storey drift
θ_{p}	Plastic rotation
θ_{res}	Residual rotation
$\theta_{r,max}$	Maximum residual inter-storey drift among all stories
θ_{t}	Strain tensor related to thermal coefficient of expansion
$\theta_{t,max}$	Maximum transient inter-storey drift among all stories
κ	Training parameter in Auricchio model
ν_{A}	Poisson's ratio of austenite phase
ν_{M}	Poisson's ratio of martensite phase
π^{AS}, π^{SA}	Material constants in Auricchio model
ρ^{AS}, ρ^{SA}	Activation factors in Auricchio model
σ	Stress (general)
σ_{As}	Reverse transformation start stress
σ_{Af}	Reverse transformation finish stress
σ_{Ms}	Forward transformation start stress
σ_{Mf}	Forward transformation finish stress
σ_{max}	Maximum stress of SMA
σ_{OM}	Stress at the reference location OM of Belleville washers
σ_{pre}	Bolt prestress
σ_{s}^{cr}	Twinned martensite to detwinned martensite transformation start stress
σ_{f}^{cr}	Twinned martensite to detwinned martensite transformation finish stress
σ_{p}	Stress at the onset of plastic deformation of SMA
σ_{Rs}	Stress when reverse transformation is initiated for the case of $\sigma_{max} < \sigma_{Mf}$
σ_{rst}	Restoring SMA bolt stress
ΣF	Overall frictional force along the perimeter of SMA outer ring
ΣF_{V}	Vertical component of frictional force along the perimeter of SMA outer ring
ΣP	The force applied at one taper face of SMA outer ring
ΣP_{H}	Horizontal component of the force applied at one taper face of SMA outer ring
ΣP_{V}	Vertical component of the force applied at one taper face of SMA outer ring
υ	Velocity exponent

Ω	Phase transformation strain tensor
ω	Strain hardening adjustment factor for BRBs
ξ_{eq}	Equivalent viscous damping (EVD)
ξ_{mv}	Martensite volume fraction
ξ_R	Residual part of martensite volume fraction
ξ_s	Stress-induced martensite volume fraction
ξ_T	Temperature-induced martensite volume fraction
ξ_V	Reversible part of martensite volume fraction
ψ	Coefficient of thermal expansion
ζ	Viscous damping ratio