Construction and Building Materials 158 (2018) 389–400

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Resilience and life-cycle performance of smart bridges with shape memory alloy (SMA)-cable-based bearings

Yue Zheng [a], You Dong [b,*], Yaohan Li [b]

[a] Department of Bridge Engineering, Tongji University, Shanghai, China
[b] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

HIGHLIGHTS

- An approach to evaluate life-cycle loss and resilience of novel bridges is proposed.
- Fragility curves of bridges with SMA-cable-based bearings are assessed.
- Development of smart bridges using SMA is proposed.
- Life-cycle loss and resilience are assessed considering representative hazards.
- A decision-making tool for application of smart materials is provided.

ARTICLE INFO

Article history:
Received 1 June 2017
Received in revised form 17 September 2017
Accepted 5 October 2017

Keywords:
Shape memory alloy
Earthquake
Fragility curve
Life-cycle loss
Smart materials
Resilience

ABSTRACT

Due to its unique properties within hazard mitigation, shape memory alloy (SMA) has been developed and adopted within the design and retrofit of civil infrastructures to improve the seismic performance. The performance benefit associated with the SMA bridges in a long term has not been well recognized by the decision maker, thus, the wide application of SMA within the civil infrastructures is still limited. This paper aims to apply the resilience and life-cycle loss assessment to the comparative performance assessment of novel and conventional bridges and to promote the application of smart materials within the civil engineering. Both the direct and indirect costs are considered within the life-cycle assessment process. Specifically, the corresponding structural performance, resilience, and life-cycle loss associated with different bridge systems are addressed. The methodology accounts for the life-cycle loss assessment considering the representative hazard scenarios that could happen within the investigated region. The proposed approach is applied to highway bridges with and without using the SMA-cable-based bearings. The benefit associated with the application of the proposed novel bearing is quantified in terms of resilience and life-cycle loss.

1. Introduction

Earthquakes can bring disastrous consequences to our society and economy. For instance, the 2015 Nepal earthquake killed nearly 9000 people and more than 600,000 structures in Kathmandu and the nearby towns were either damaged or destroyed. Thus, it is of paramount importance to mitigate structural damage under seismic hazard. To address this concern, several seismic improvements have been adopted within the design codes to enhance seismic performance of bridges. Many studies showed that isolation devices can dissipate a large amount of energy as these devices introduce a discontinuity between the superstructure and substructure and reduce the energy transferred to the superstructure. Accordingly, isolation devices have been developed to reduce the bridge damage under seismic hazard and have been implemented with the structural design process, especial for the essential structures. The conventional isolation devices include lead-rubber bearings, high damping bearings, and magneto-rheological dampers, etc. [23,45,6]. The disadvantages associated with these traditional isolation devices are obvious in terms of ageing and durability, strict maintenance requirements, long-term performance and residual displacement [17,16]. Shape memory alloys (SMAs), which are characterized by their super-elasticity and energy dissipation, have the potential to be adopted within the bridge design and retrofit to improve the structural

* Corresponding author.
E-mail addresses: yzheng@tongji.edu.cn (Y. Zheng), you.dong@polyu.edu.hk (Y. Dong), yaohan.li@connect.polyu.hk (Y. Li).

https://doi.org/10.1016/j.conbuildmat.2017.10.031
0950-0618/

performance under earthquakes. The relevant studies are conducted within this study.

SMAs are generally associated with high strength, good fatigue and corrosion resistance besides the super-elasticity and energy dissipation; thus, can get rid of several drawbacks with respect to the traditional isolation devices [15,40,11]. Within the traditional bridge seismic design, steel is expected to yield for energy dissipation, which could result in a large residual deformation and hamper bridge functionality. To solve this problem, SMA could be implemented to resist the high seismic load without significant permanent residual deformations. In this paper, SMA is adopted within the highway bridges and is investigated to improve the seismic performance. Previously, the steel bar restrainer installed at in-span hinge or interface between the girder and abutment has been adopted to prevent the girder from unseating during the earthquakes. However, many bridges installed with conventional restrainer have experienced severe damage or collapse under earthquakes and the steel bar restrainers were found to remain elastic during earthquakes without energy dissipation [9,8]. To overcome this shortcoming, SMA-cable/bar restrainer was developed to mitigate the seismic damage of bridges and proved to be an efficient solution [15]. Later, Choi et al. [11] developed a device that integrated SMA wires with rubber/elastomeric bearing to reduce the permanent residual deformation of the bridges under earthquakes. Xue and Li [47] proposed a rubber bearing installed with pre-tensioning SMA-wires and applied it to a lattice shell structure for seismic mitigation. In this paper, the authors propose a novel frictional sliding bearing with SMA-cable, which fully takes advantages of the properties of SMAs, such as self-centering, super-elasticity, and energy dissipation. Another difference from the previous devices with application of SMA is that the SMA-cable is adopted instead of the wire to improve the re-centering capacity of SMA-wire. Additionally, this type of bearing is more easily to be manufactured and installed. The effects of the proposed SMA-cable-based device on the bridge seismic performance are investigated.

Previously, the performance benefit associated with the SMA bridges has not been well recognized by the decision maker and life-cycle loss has not been emphasized within the decision-making process. Thus, the life-cycle engineering should be incorporated within the performance assessment process of bridges using SMA-cable based bearing. In order to investigate the life-cycle performance, the bridge performance and damage consequence should be identified firstly. Pacific Earthquake Engineering Research (PEER) Center has developed a performance-based assessment approach considering repair loss, downtime, and fatalities. This approach is adopted within this study to compare the performance of different structural systems in a life-cycle context. Wen and Kang [46] used the life-cycle cost as a design objective to obtain the optimal design strategies for structures under single and multiple hazards; Padgett et al. [35] presented an approach to assess the cost-benefit ratio associated with different retrofit strategies in a life-cycle context; Dong and Frangopol [20] investigated the life-cycle loss of highway bridges under multiple hazards considering the effects of climate change. To the best knowledge of the authors, the life-cycle concept and performance-based engineering have not been well incorporated within the assessment and comparison of conventional and novel systems using SMA. In this paper, the comparative assessment of the life-cycle performance of conventional and SMA bridges is conducted based on the performance-based engineering in a life-cycle context.

Nowadays, with respective to the hazard management of infrastructures, a widely-recognized indicator is resilience. Researchers have turned attention to the challenge of making infrastructure systems more resilient against devastating earthquakes. Resilience is related with the ability of a structural system to mitigate the hazard damage to infrastructures, society, and economy. A methodology to evaluate the seismic resilience of conventional and novel bridges is obliged to meet current performance requirements. The seismic resilience associated with smart bridge systems with SMA is investigated in this paper and comparative assessment between the conventional and novel bridges is emphasized. Overall, a performance-based assessment framework that incorporates both resilience and life-cycle engineering is provided in this paper.

An approach to assess the seismic resilience and life-cycle performance of conventional and novel bridge systems is presented. The structural vulnerability of the conventional and novel structural systems is computed based on three-dimensional (3D) nonlinear finite element (FE) models. The seismic vulnerability of the structural components (e.g., columns and bearings) is studied by using nonlinear time-history analysis. The life-cycle loss associated with seismic hazard is computed considering the representative hazard scenarios that can happen during the investigated time interval and is incorporated within the performance-based assessment process. The life-cycle loss and resilience of these structural systems are computed in a life-cycle context. The proposed approach is illustrated on the conventional and novel bridge systems, which can be effectively used for the comparative assessment of different infrastructure systems to aid the application of emerging materials within the civil engineering.

2. Structural seismic vulnerability

In order to evaluate the life-cycle loss and resilience of the bridge under seismic hazard, the structural seismic vulnerability analysis should be conducted as indicated in Fig. 1. Fragility curves are the commonly used method to quantify the probability of exceeding a certain damage state associated with structural components and systems under given hazard intensity. Fragility analysis of different types of bridges has been conducted by many studies [39,10,49,36,18,31]. The seismic demand should be computed to derive the analytical fragility curves based on the nonlinear time history analyses. The seismic demand assesses the engineering demand parameters as a function of a chosen ground motion intensity and can be quantified using appropriate seismic

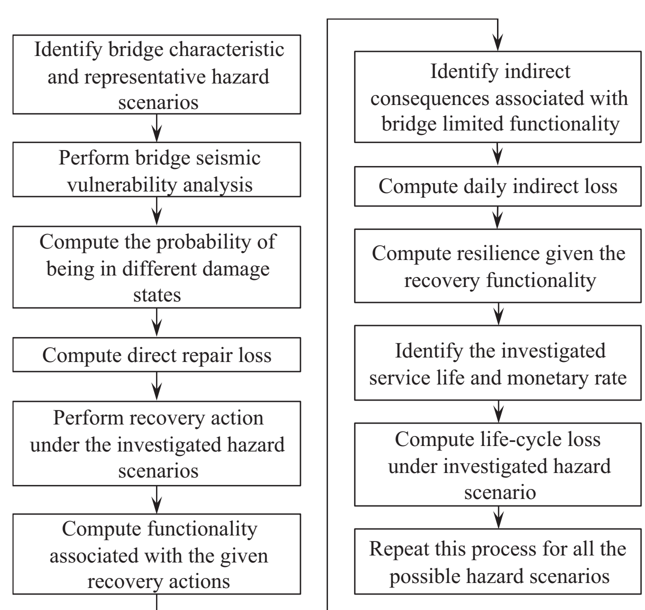

Fig. 1. Flowchart for the performance-based assessment incorporating vulnerability, loss, resilience, and life-cycle loss.