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Investigation of an articulated quadrilateral bracing system utilizing shape memory alloys

Matthew S. Speicher [a,*,1], Reginald DesRoches [b], Roberto T. Leon [c]

[a] National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD, United States
[b] School of Civil & Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Drive, Atlanta, GA 30332-0355, United States
[c] Department of Civil & Environmental Engineering, Virginia Polytechnic Institute and State University, 102-D Patton Hall, Virginia Tech, Blacksburg, VA 24061, United States

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ABSTRACT

A shape memory alloy based articulated quadrilateral bracing system is developed and experimentally tested for seismic resisting applications. The articulated quadrilateral arrangement provides a scalable, reconfigurable, convenient means of combining nickel-titanium (NiTi) wires and energy dissipating elements. This configuration creates a system with an adjustable amount of recentering and damping, which could potentially be used in a wide variety of new and existing buildings. For these prototype tests, NiTi wire bundles were combined with long C-shaped dampers to create a system with a good balance of recentering and energy dissipation. The system was subjected to cyclic loading to assess the behavior. The system maintained strength, ductility, and recentering after being cycled to 2% drift, which is a typical maximum in structural systems if non-structural elements are to be preserved. An analytical case study demonstrated that shape memory alloy systems tend to distribute the deformation more evenly over the height of the structure compared to traditional systems, which is a desirable seismic performance characteristic. It is envisioned that, by using the same basic bracing setup, a wide range of force-deformation responses can be at an engineer's disposal.

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1. Introduction

This study presents the design and proof-of-concept testing of a shape memory alloy (SMA)-based recentering articulated quadrilateral (AQ) bracing system. The 1994 Northridge and 1995 Kobe earthquakes revealed deficiencies in a large number of welded moment frames [1], which were previously held as the "gold-standard" in terms of ductile seismic behavior. This unexpected performance under moderate earthquake shaking resulted in a reevaluation of the seismic integrity of steel moment resisting frames. Moreover, researchers began to revisit other lateral load resisting systems, giving the engineering community new options in earthquake-resistant design.

Braced frames are one of the main viable alternatives to moment resisting frames. To obtain the desired level of ductility, traditional braced frame systems are designed with special attention to the connections, slenderness ratios, and width-to-thickness ratios of the braces, as well as to the effect of brace overstrength on adjacent members [2]. However, even with these special measures, traditional braces are characterized by a loss of load carrying capacity due to buckling and by degrading behavior and fracture due to low-cycle fatigue and strain localization.

To achieve improved performance, newer systems, such as buckling-restrained braced frames (BRBFs), have become attractive and popular options. The BRBF performance is generally characterized by a buckling-restrained brace (BRB) with an elastoplastic-type response in both tension and compression. The BRB generally has reliable energy dissipation, controlled strength, and excellent ductility. Though the BRBF has been shown to have a high level of performance, it provides no specific mechanism with which to reduce residual drifts of a structure; which may be the determining factor in whether a damaged building can be repaired [3]. Several researchers have noted this concern with traditional braced frames as well as BRBFs [4–7]. Moreover, recent events, such as the 2011 Christchurch Earthquake [8], have provided a reminder of how important designing beyond the traditional "life safety" level can be (e.g., using low-damage systems [9]); the social and economic impact can be significant even when "life safety" is largely achieved.

As an alternative to a BRBF (or any other elastoplastic-type system), several researchers have investigated the benefits of systems that have deliberate recentering mechanisms [10,11]. Analytical and experimental studies have shown promise in recentering system response, demonstrating that they are a viable alternative to both traditional and

* Corresponding author.
E-mail addresses: matthew.speicher@nist.gov (M.S. Speicher), reginald.desroches@ce.gatech.edu (R. DesRoches), rleon@vt.edu (R.T. Leon).
[1] Formerly Ph.D. Candidate, Georgia Institute of Technology.

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advanced systems, especially when residual deformations are of concern.

In this study an SMA-based recentering system is developed and tested (as part of a larger investigation of SMA applications [12]). This system provides both recentering and damping in a scalable arrangement. Driven by SMA's unique ability to recover strains of up to approximately 8% through a diffusionless phase transformation, the cornerstone of the bracing proposed herein is the ability to adjust the energy dissipation in a recentering hysteretic loop through the use of an AQ arrangement. SMA wire bundles are installed within the AQ and are tested alone and in parallel with C-shaped steel dampers. A schematic of the loading frame and the AQ is shown in Fig. 1. Though C-shaped dampers are used, a variety of options are available to provide paralleled damping, some of which are discussed in the next section.

To gain an understanding of the behavior of such a system, the details of the AQ are first outlined and then the experimental results from three braced frame experiments are presented. The behavior is then assessed in terms of strength, stiffness, recentering, and energy dissipation. This behavior is then used in an analytical study to demonstrate the potential benefits of the system.

2. Background

2.1. Articulated quadrilateral

As an alternative to a traditional bracing system, this study investigates a tension-only system that has the ability to dissipate energy and to recenter. Tension-only braced frames are typically not used in seismic regions due to their poor cyclic behavior [13]. However, in this work this deficiency has been addressed by inserting an articulated quadrilateral (AQ) element at the center of the bracing system, keeping the brace in tension over the entire cycle. Assuming rigid connecting elements, when one diagonal goes in tension, the opposite diagonal is also engaged in tension due to the kinematics of the AQ (i.e., for every unit expansion of the diagonal that intersects the AQ acute angle corners, the opposite diagonal has a contraction greater than that unit expansion). Therefore, the braces are continuously engaged even during load reversals. For non-rigid connecting elements, some slack is introduced in the opposite diagonal but the elements in the center of the AQ are essentially always actively engaged.

This AQ setup, pioneered by Pall and Marsh [14], has been investigated by several researchers in the past several decades in a variety of ways [15–18]. Recently, Renzi et al. [19,20] inserted C-shaped elements along the diagonal of the AQ to obtain energy dissipation. Though other options are available, in this study the authors selected the C-shaped element for the energy dissipater due to the good response reported in the literature. Collectively, the previous research has shown that tension-only AQ braces can produce stable cyclic behavior via either friction or material yielding driven by the AQ kinematics.

2.2. Recentering systems

The key characteristic of the bracing system studied in this research is its recentering ability. Recentering, as an approach to lateral load resistance, has been studied by several researchers since at least the early 1990s. Some of the first tests were a series of experiments on post-tensioned precast concrete connections [21–24]. Other researchers have expanded the idea to steel moment-resisting frames [25–27] and bracing systems [28,29].

A comprehensive study on recentering systems was conducted by Wang and Filiatrault [27]. This study consisted of shake-table testing of a three-story post-tensioned steel frame and an accompanying in-depth investigation into a single-degree-of-freedom system. Overall, the study demonstrated that good seismic performance can be reached with a recentering system. Peak story drifts were comparable to those of a traditional system (i.e., elastoplastic response) while residual drifts were essentially eliminated. However, the analysis did indicate higher maximum accelerations for the recentering system. Similar observations are noted in other single-degree-of-freedom studies [30].

Additionally, recentering systems based on allowing the frame to “rock” have gained attention in both the research and practitioner community. Several recent studies have shown the fidelity of such systems, such as work done by Eatherton et al. [31] and Roke et al. [32]. As a consequence, several rocking systems have been implemented in recent new buildings designs and existing building retrofits [33].

2.3. SMAs

SMAs have drawn considerable attention in the civil engineering community over the past two decades because of their unique stress-strain behavior. The combination of recentering and energy dissipation makes SMAs ideal for applications in earthquake-resistant design. In the 1990s the European Commission launched a research initiative, known as the MANSIDE (Memory Alloy for New Structural Isolation Devises) project, to investigate and implement SMAs into civil engineering structures [34]. From this project, several retrofit schemes were investigated and/or developed using SMA wires and bars [35–40]. Other researchers have since investigated the mechanical properties of SMAs [41,42] and their use in braced frames [43–45], beam-column connections [46–49], bridge deck restrainers [50,51], and reinforced concrete [52]. Though each of these investigations has shown varying degrees of success, limited applications have been implemented into real structures. Thus, this research seeks to explore another method of implementing

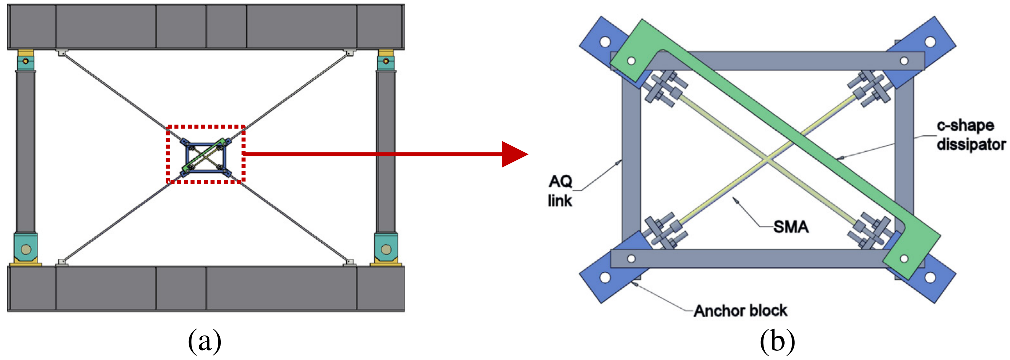

Fig. 1. (a) Loading frame schematic and (b) general articulated quadrilateral (AQ) setup with shape memory alloy (SMA) elements.