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Steel Braced Frame Reinforced with NiTi Shape Memory Alloy Wires

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ABSTRACT

Shape memory alloys offer unique characteristics that can be utilized in enhancing the seismic performance of various types of structures. An innovative steel frame braced with tension-only pseudoelastic nickel-titanium (NiTi) shape memory alloy (SMA) wires was developed in this research for seismic retrofit applications. The structural performance of the developed system was experimentally compared with standard steel frame braced with tension-only plates. The proposed system was designed to achieve a self-centering response while dissipating earthquake-like induced energy. Test results showed that the SMA braced frame had significant re-centering capabilities (i.e. recovered large portions of the post-elastic drifts), and a potential for moderate energy dissipation. Design recommendations were made to improve the energy dissipation capability of the developed system.

Keywords: Civil Engineering, Seismic retrofit, Advanced material, shape memory alloy, NiTi

INTRODUCTION

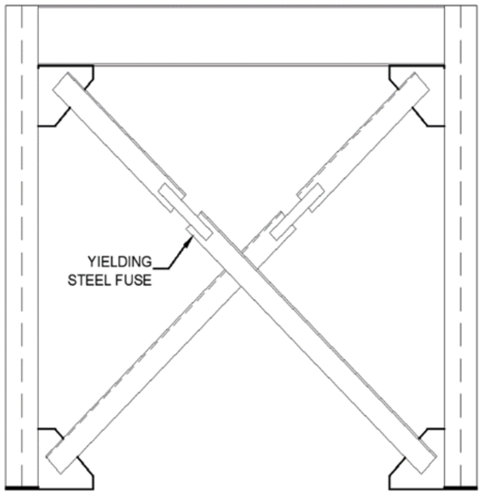
The National Building Code of Canada (NBCC 2015) [1] requires all buildings to be designed for a minimum earthquake load. It also requires structures to have a clearly defined Seismic Forced Resisting System (SFRS) and load path that will transfer the inertial forces generated by the earthquake to the foundations. The direct application of the NBCC 2015 requirements to existing structures built prior to the advancements in the seismic code provisions may lead to prohibitive retrofit costs. This initiates the need to explore alternative seismic retrofit techniques that can balance the cost of retrofitting structures to the benefit perceived in terms of improved safety and functionality.

Conventional seismic design systems rely on the inelastic behaviour of critically detailed structural components to dissipate the seismic energy. Structures designed to dissipate the induced energy are likely to survive the seismic excitation although the functionality of the structure may be jeopardized due to excessive deformation. Recently, seismic design has shifted focus from solely ensuring a structure can remain standing until the earthquake motion stops, irrespective of the structural functionality, to focusing on both collapse prevention and minimizing the amount of damage due to an earthquake excitation. This can be accomplished using advanced materials, damage avoidance design (DAD) [3, 4], or resilience-based design [5].

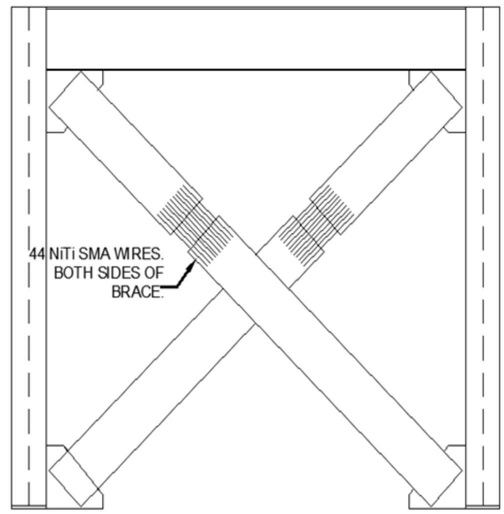
In this research, a practical self-centering brace system utilizing Shape Memory Alloy (SMA) material is developed and validated for seismic retrofit applications. The use of this new class of smart materials has been attracting researchers from different fields [6,7]. The SMA is a unique class of alloy with the ability to undergo large deformations (up to 8%) and return to its original shape through stress removal. Recently, analytical models and studies have been investigated on the idea of utilizing SMA in steel braces [8,9]. In this research, pseudoelastic (PE) NiTi wires were used to brace a steel frame. The performance of the proposed system was evaluated experimentally under a cyclic load. The structural performance was analyzed and compared with the behaviour of a typical steel braced frame designed for an equivalent lateral strength.

DESIGN OF SPECIMENS

Two tension-only braces (i.e. braces were designed to resist tension force only and the members were not connected at the intersection point) systems were considered in this research as shown in Figure 1; SMA Braced Frame (SMA-BF); and Control Braced Frame (CBF). Both systems were designed for an equivalent lateral load capacity. The SMA-BF system was composed of a unique brace configuration. SMA wires (300 mm long; 2mm diameter; 88 wires) were anchored against conventional steel plates using a newly developed mechanical anchor as shown in Figure 2. The anchor was developed and tested as part of this research. The CBF system was compared of conventional steel plate brace. A steel fuse was sized to ensure that the CBF lateral capacity is equivalent to that of the SMA-BF system. One of the main objectives of this study was to ensure a ductile failure of the structure, at the location of the plastic hinge (the location of the fuse) in the brace, using a pushover analysis. The column and strut members were sized in accordance to CSA-S16-14 to remain elastic during the cyclic loading. Table 1 lists the members sizes that were chosen.



a) Control Braced Frame (CBF)



b) SMA Braced Frame (SMA-BF)

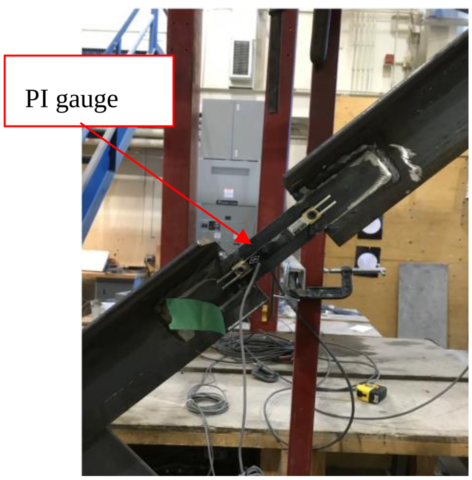
Figure 1:Specimen details

Table 1. Frame member sizes

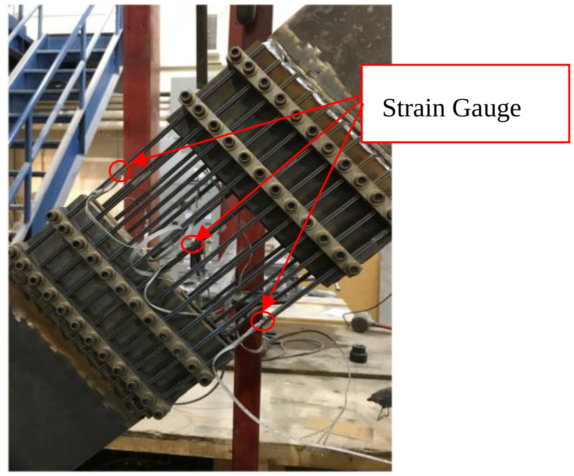
Columns	**Cross Beam**	**CBF Brace**	**Steel Yielding Fuse**	**SMA-BF Brace**	**SMA Fuse**
W150x30	W250x22	L102x102x6.4	PL300x45x6	PL200x6	88-2mmϕ wires

The steel yielding fuse adopted in this research is not covered in CSA S16-14 or the NBCC 2015, as it is expected that braces with short lengths fail at limited drifts, especially if the fuse is subject to flexural yielding in compression due to buckling. So rather, bracing members having the same cross section throughout their length is what is typically done. However, the CBF was not designed to represent current industry practice, but rather, for a comparative means for the behaviour of the SMA-BF. Furthermore, being limited by the maximum lateral load that could be applied by the actuator and a realistic amount of PE SMA wire that could be used, a small yielding fuse was developed and designed.

Strain gauges were mounted on each specimen’s yielding fuse. For the CBF a 100mm PI gauge was utilized for ease of construction purposes. For the SMA-BF, general-purpose strain gauges were mounted to individual wires at the ends and in the middle of the fuse, as shown in Figure 2.



a) (CBF) Yielding Fuse



b) (SMA-BF) Yielding Fuse

Figure 2: Yielding fuse details

MATERIAL PROPERTIES

The coupon tests for the NiTi SMA wires were conducted according to ASTM E8-E8M to determine the tensile properties of the SMA wires. The average Austenite yielding stress was found to be 500MPa and the fracture stress was found to be 1248MPa. The SMA is present in its Austinite phase at room temperature. The coupon tests for the steel specimens were provided by the manufacture; 427 MPa for the yield stress and 500 MPa for the ultimate stress.

LOADING REGIME

The loading regime consisted of two phases; gravity load application, and lateral load application. Roh and Reinhorn [10] suggested that gravity loads in real-life applications range between 5% and 20% of the column axial strength. The columns in this research were subjected to approximately 7% of the column axial strength (65kN). The specimens were subjected to a quasi-static lateral loading in a displacement control mode following the axial load application. The quasi-static testing program started at a displacement of 2mm in both positive and negative directions, then increased in increments of 2mm at a rate of 0.5mm/sec. Once drift levels reached 1%, the displacement increased to increments of 4mm at a rate of 1mm/sec up to a drift of 3% in both positive and negative directions and then increased to 2mm/sec. From 0-1% drift, one cycle was conducted at each increment; after 1% drift was achieved, a total of 3 cycles were conducted at each displacement increment.

FRAME BEHAVIOUR

The hysteretic load-displacement relationships of the CBF specimen is shown in Figure 3. The failure mode of the specimen was fracture in the steel brace at approximately 2% lateral drift. The fuse remained elastic and stable for small drift levels (below 0.7%). At 0.7% drift, the fuse began to yield, which resulted in a decrease in stiffness in the subsequent cycles. This trend continued as the steel fuse accumulated residual strain, and eventually fractured. The failure mode of the fuse was in tension at a load of approximately 127kN. The expected fracture load was 95kN, this difference can be attributed to the design assumption that the compressed brace does not take any load.

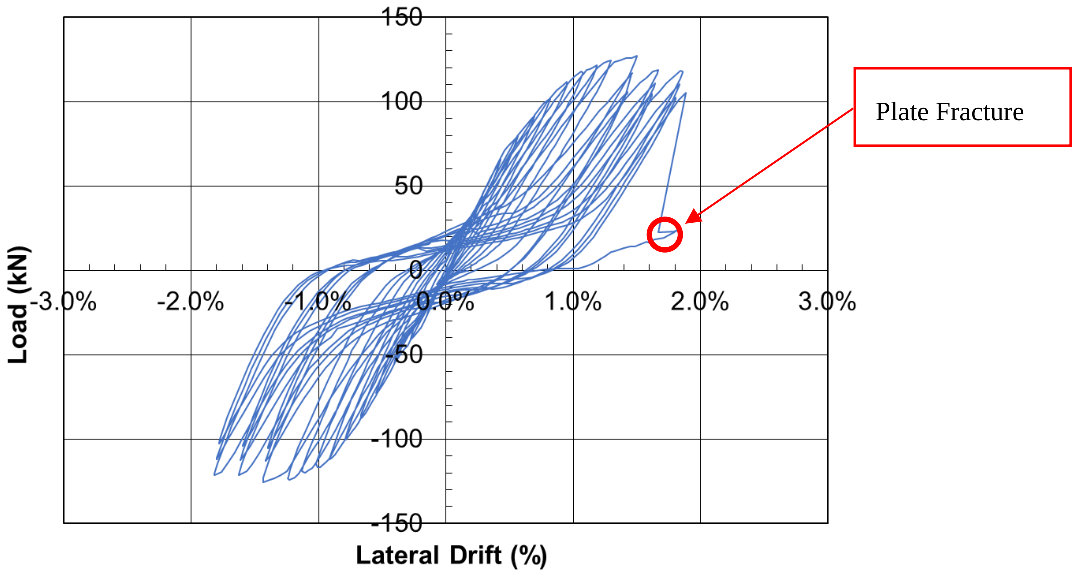


Figure 3: Hysteresis Loop - CBF

The hysteretic load-displacement response of the SMA-BF is shown in Figure 4. The response of the system was evaluated against three performance objectives: (a) achieving a self-centering response; (b) achieving the target ultimate capacity; and (c) achieving adequate energy dissipation. The system achieved both (a) and (b) as evident from the hysteretic response. The system, however, experienced insignificant energy dissipation capability. This was due to the slippage of the SMA wires inside the anchor upon load-reversal. As the tensioned brace was undergoing the reverse loading, the wires started bending out-of-plane. However, as it was being loaded in tension, the wires started tensioning. This behavior led to significant reduction in the structural stiffness and the energy dissipation capability of the system. The slippage did not allow for the full utilization of the material. Research efforts are underway to further improve the anchorage performance of the proposed system.

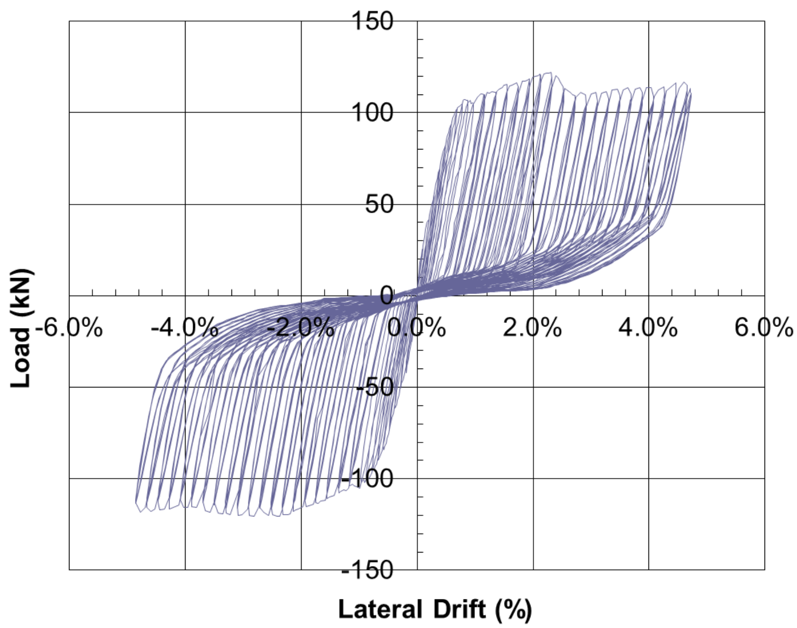


Figure 4: Hysteresis Loop - SMA-BF

COMPARISON OF RESULTS

Re-centering

An advantageous property of PE SMA is the ability to be strained up to 8% and return to its original shape without residual deformations. The re-centering ability of the proposed system was evaluated by examining the residual strains recorded after the last cycle at each drift cycle. The residual strains were measured using strain gauges mounted on the SMA wires in the SMA-BF system and mounted on the steel fuse plate in the CBF system. The residual brace strain at the end of the last cycle at each drift cycle is shown in Figure 4. The amount of residual strain developed in the CBF fuse was 0.41% at a 1% drift compared to the SMA wires which was 0.04% at a 1% drift. It is, thus, concluded that the SMA-BF specimen experienced a self-centering behavior. It is interesting to note that though visible slipping of the wires was observed, it did not have an effect on the re-centering properties of the system. With the slipping, a gradual loss of the re-centering capacity would be expected, however that is not the case as seen in Figure 5. An explanation for this is that the wires never slipped out of their connection completely; a repetitive sequence of minor slipping then the clamps re-grabbing hold of the wire continued for the duration on the test thus still providing re-centering abilities of PE NiTi wires.

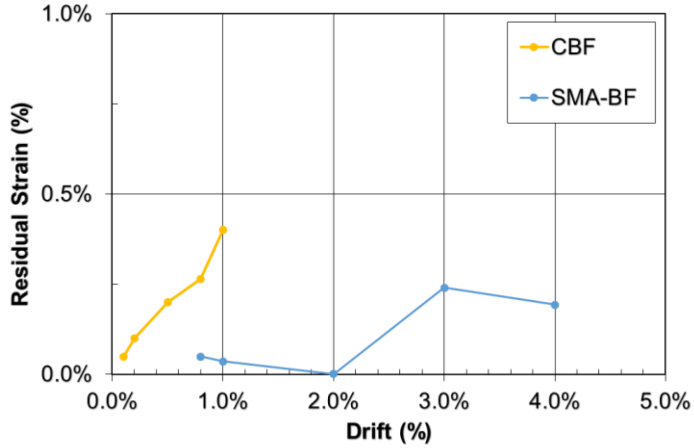


Figure 5:Residual strain in the brace after the last cycle at each drift level

Energy dissipation

As seen in Figure 4, the amount of energy dissipated in the SMA-BF specimen is very small compared to that of the CBF specimen. This is further detailed in Figure 6 as the value of energy dissipated (ED) was calculated for the first cycle at each drift level. At approximately 1% drift, both systems had reached their yield; the CBF exhibited a larger ED than the SMA-BF. Then, as the drift level increased, the CBF ED increased at a faster rate than the SMA-BF. As the drift increased past 2%, the ED for the SMA-BF started to plateau. An explanation for this, is that the wires slipped before they were able to reach their full potential.

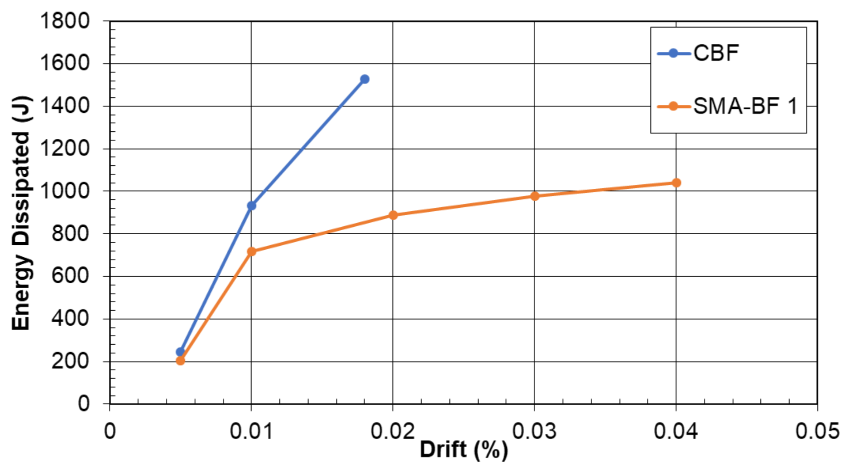


Figure 6:Energy dissipated over a range of drift levels

CONCLUSIONS & RECOMMENDATIONS

A new SMA braced frame system was proposed, designed, and examined in this research. The system is composed of a brace element uniquely configured to achieve a self-centering behavior. Shape Memory Alloy wires were utilized in detailing the braced system. The frame response was experimentally compared with that of a conventional steel braced system. Experimental testing indicated the ability to achieve a self-centering response upon reversal of load. The energy dissipation ability of the system, however, was found to be insignificant. This was due to the occurrence of slippage at the mechanical anchors holding the SMA wires combined with undesired out-of-plane bending. The research team is actively designing an alternative anchorage system to avoid possible SMA slippage. With an improved anchorage system, this research aims to not only provide a fully self-centering system, but will improve the inelastic behavior of the structure, have moderate energy dissipation, and minimize the damage done to structural members.

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