Utilizing superelastic shape memory alloy strand

I tried to maintain the story in following order:

1. General background on steel MFRs before Northridge earthquake
2. What happened after Northridge Earthquake and still what are the problems remaining?
3. What are the approaches taken to solve the problem?
4. Concept of Post tensioned connection
5. Studies on PT connection with steel
6. Alternative to steel strand (previous studies on SMA strand).
7. Objective of this study.

Feasibility study of utilizing superelastic shape memory alloy strand in post tensioned steel beam column connections for improved seismic performance

Introduction:

During the 1960s, welded steel beam-column connections were considered to be the most ductile system against earthquake. Therefore, a number of industrial and commercial buildings were constructed in the western part of united states at that time. However, the Northridge earthquake of January 14, 1994, indicated that welded connections are susceptible to brittle fracture at the beam-to-column joints. This failure mode was observed even for structures subjected to a moderate level of ground shaking. Although, these buildings didn’t collapse (which is desired by the building code), the connection behavior was not as expected. Further investigation revealed that similar damage was observed in a limited number of buildings during 1992 Landers, 1992 Big Bear and 1989 Loma Prieta earthquake (FEMA-350). Studies have been carried out to investigate the reasons behind it. Based on the investigation, significant design changes was implemented to the pre-Northridge moment resisting frame designs (Engelhardt and Sabol, 1997).

Post-Northridge structures are designed in such a way that it is still expected to sustain damage during severe earthquake but without affecting the life safety limit (Chancellor et al. 2014). Residual deformation that may exist after the earthquake can require expensive repair works and in some cases the demolition of total structures. Depending on the scenario, the total cost of demolition or repair work can be a burden to the overall economy of a country. An example can be the earthquake of magnitude 6. 5 that occurred in Christchurch, New Zealand in May 2014. The repair works required 40$ billion (New Zealand’s dollar) which was approximately 20% of the total GDP of the country. In another study, McCormick et al. (2008) showed that the repair of structures with residual drift greater than 0. 005 rad is not economically feasible.

Conventional moment resisting frames are designed to resist collapse by using the inelastic properties of nonreplaceable elements. Therefore, these systems can dissipate energy during large inelastic deformation but unable to recover the residual deformation. In this regard, research has been done to improve the performance by introducing reduced beam section (RBS) (Tremblay and Filiatrault, 1997), connection reinforced with cover plates (Engelhardt and Sabol, 1997), haunches (Uang et al. 2000), and side plates (Shiravand and Deylami, 2010). However, the existence of residual deformation after severe earthquake is still possible.

To address this above mentioned issues, a new class of lateral force resisting system has been developed which can sustain severe earthquake with little or no residual deformation. This smart structure can return to its plumb position after load removal (herein referred to as a full self-centering), without any residual deformation. This new system is termed as post tensioned (PT) steel moment resisting frames. In this system, beams are post tensioned to the columns, which run parallel to the beams and pass through the column flanges, are used to provide self-centering to the moment resisting frames (Moradi and Alam, 2015). The reduction of residual displacement in PT connection is controlled by a gap opening mechanism. Due to the gap opening between steel column and beams, a significant reduction in stiffness occurs, which is desirable. As the decrease in stiffness attracts less force to the connection (i. e. softening occurs without structural damage) by lengthening the structural period (Chancellor et al. 2014).

Past few years, several researchers have investigated and still investigating the seismic performance of self-centering steel moment resisting frames. Ricles et al. (2002), experimentally investigated the self-centering behavior of steel PT connection on five cruciform shaped specimens. The results showed that steel PT connection sustain small residual deformation compared to the conventional welded connection. Further study based on several affecting parameters such as flange reinforcing plate, shim plate, number of PT strand, angle size, and gage length are considered by Garlock et al. 2003, 2005. The effect of floor diaphragm on the self-centering behavior of steel moment resisting frames were investigated by Garlock et al. (2007). A performance based design guideline for self-centering PT connection was also outlined. In design procedure, the interaction between the floor system and the self-centering PT connection was considered. Dobossy et al. (2006) proposed a method for assessing structural limit state probabilities for a self-centering frame (with top-and-seat angles). Monte Carlo simulation was used for generating demand curves. The possibility of exceeding a limit state at each floor of the structure was determined based on the demand and capacity curves. Herning et al. (2011) used a reliability based method to evaluate the likelihood of reaching the limit state of PT strand yielding. A predictive relationship between the beam-column relative rotation and the story drift was proposed. Based on the results, the response of three nonlinear models of prototype self-centering frames was found to be adequate to thousands of synthetic ground motions. The probability of reaching the limit state of strand yielding ranged from 0 to 15%.

The self-centering capability of PT connection can also be improved by using smart materials such as shape memory alloys (SMAs). Shape Memory Alloy (SMA) is a class of equiatomic metal showing mechanical properties not present in materials usually employed in engineering application (Fugazza, 2003). In most cases NiTi is referred to as a shape memory alloy. But some other alloys show the same characteristics of NiTi alloy. If not stated otherwise, NiTi will be used as SMA throughout this paper. The importance of Shape Memory Alloy (SMA) in civil engineering application is increasing rapidly due to its capability of large strain recovery, absence of residual strain upon unloading and high energy dissipation ability. This exceptional property can be used in post tensioned steel beam column connection. The idea of implementing shape memory alloy on post tensioned connection has already been investigated by a number of previous studies. Ocel et al. 2004 considered two partially restrained (PR) connection to investigate their performance during static and cyclic loading. Martensitic phase (Shape memory effect) was used in both connection. The tested connection was capable of dissipating large energy without any strength degradation up to a drift level of 4%. Using SMA tendons, about 54% and 76% of the beam tip displacement was recovered with or without simulated dead loads, respectively. Ma et al. (2007) presented a highly ductile steel beam column connection by using shape memory alloy bolt. The bolts shanks are 1. 2 times longer than the conventional steel bolt. These bolts provide the ductility to the connection by absorbing inelastic deformation. After the deformation phase, it can regain its original shape by recovering 94% of the total deformation. Desroches et al. (2010) studied the behavior of shape memory alloy (SMA) on both austenite and martensite phase. The superelastic SMA bars were found to be responsible for reducing the residual deformation and martensitic bars were efficient in controlling peak deformations. Ellingwood et al. (2010) evaluated the performance of steel frames with or without SMA connections based on probabilistic framework. Four interior steel beam column connection incorporating different types of SMA (i. e. martensitic NiTi and austenite NiTi) and steel tendon, were investigated by Speicher et al. (2011). The connection incorporating superelastic NiTi alloy was able to recover up to 85% of its deformation after being loaded upto 5% drift.

The objective of this study can be categorized in two phase. In phase one, an attempt has been made to reduce the strand length of existing PT connection without affecting the performance of the connection. In parallel to this study, the objective of phase two was to use shape memory alloy with reduced length. A recent study done by Chowdhury et al. (2017) show that the reduction of PT strand length directly affect the stiffness, strength and moment capacity. Besides, PT connection loses self-centering capability due to the yielding of steel strand. This is due to the high stress concentration in steel and its low strain capacity. In this regard, shape memory alloy can be an efficient alternative due to its large strain capability (recoverable strain up to 8% for NiTi). The cost of NiTi alloy is a major concern during its application. Therefore, reduced strand length will reduce the cost without affecting performance.