Reinforced concrete beam with pseudoelastic SMA hybrid with steel structure for seismic mitigation: A critical review of their prospective, influence factors, drawback and advantages

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Abstract. This paper presents a review paper of concrete beam reinforced with SMA hybrid with steel. Existing literature presented a number of analytical and experimental studies on the use of SMAs using pseudoplastic to be embedded in reinforced concrete beam for crack recovery. However, little research has been carried out on the use of pseudoelastic SMA as reinforcement as partial replacement in reinforced concrete beam. Hence the feasibility of pseudoelastic SMAs under austenitic temperature window and several components of RC building structures to exhibit stable superelastic under austenite crystallization were investigated. This paper is to review the feasibility study NiTi SMA as reinforcement rebar for seismic mitigation. This research investigates the application of concrete beams reinforced with pseudoelastic SMA longitudinal bars to evaluate the applicability of SMAs as alternative reinforcement, and to provide benchmark tests against the microstructure investigation to the performance of pseudoelastic NiTi used Malaysian ambient temperature for seismic mitigation design. The feasibility study of the superelastic NiTi SMA reinforcement bar for hybrid reinforcing of concrete beam also reviewed. The factors influence the design and performance parameter of SMA in reinforced concrete beam, Comparison of NiTi, Steel and other Alloys, advantages and disadvantages, drawbacks and restraint of using pseudoelastic SMAs were also studied.

1. Introduction
SMAs are a class of alloys that display several unique characteristics, including shape memory effects, pseudo-elasticity, and high damping characteristics. During deformation, SMA undergoes phase transformations instead of intergranular 2 dislocations as typically found in metals. These phase transformations refer to spontaneous shifts between martensitic and austenitic crystal forms. Nickel-Titanium (NiTi) alloy is the most used SMA. Figure 1 shows the properties of stress-strain properties of austenitic and martensitic shape memory alloys while Figure 2 shows the NiTi rod used for seismic reinforcement rebar. Both plots depict one cycle from zero load to a specific strain and back to zero load. SMAs are characterized by excellent centering capability, controlled level of force at moderate strain levels, strain hardening at large strain levels, hysteretic energy dissipation, excellent corrosion resistance and high fatigue strength make it the best candidate for seismic mitigation design. The distinctive properties of SMAs distinguish by phase transformation behaviour from austenite to martensite, make it ideal contender to be incorporated in reinforced concrete structure as
reinforcement to address some of the shortcomings of steel rebar and mitigate the problem of deformation explicitly by controlling permanent strains.

![Stress-strain properties of austenitic and martensitic shape memory alloys](image1)

![NiTi rod used for seismic reinforcement rebar](image2)

**Figure 1.** Stress-strain properties of austenitic and martensitic shape memory alloys  
**Figure 2.** NiTi rod used for seismic reinforcement rebar

2. Application of SMA As Reinforcing Material in Concrete Structures

Existing literature presented a number of analytical and experimental studies on the use of SMAs using pseudoplastic wire in reinforced concrete beam for crack recovery which response under martensitic temperature window, and several components of RC building structures using pseudoelastic SMAs which exhibit stable superelastic under austenite crystallization. However, little research has been carried out on the use of pseudoelastic SMA as reinforcement as partial replacement in reinforced concrete beam.

This paper is to review the feasibility study NiTi SMA as reinforcement rebar for seismic mitigation. This research investigates the application of concrete beams reinforced with pseudoelastic SMA longitudinal bars to evaluate the applicability of SMAs as alternative reinforcement, and to provide benchmark tests against the microstructure investigation to the performance of pseudoelastic NiTi used Malaysian ambient temperature for seismic mitigation design. The feasibility study of the superelastic NiTi SMA reinforcement bar for hybrid reinforcing of concrete beam also investigated. The factors influence the design and performance parameter of SMA in reinforced concrete beam, Comparison of NiTi, Steel and other Alloys, advantages and disadvantages, drawbacks and restraint of using pseudoelastic SMAs were also were reviewed.

In light of this exploratory study, the recentering capability of pseudoelastic Shape Memory Alloy to respond in stable hysteresis and achieved similar ductility with the steel reinforcement during catastrophic that make the pseudoelastic SMAs appealing to be an alternative in lieu of steel reinforcement bar structures [1] due to their the capacity to recover inelastic displacements is remained to be the vital characteristics and area of study. It is because, it can exhibit yielding and strain hardening to sustain in large displacement ductility.

Even though, there are also research discovered on self-centering of shape memory alloy fiber reinforced cement mortar members subjected to strong cyclic loading and an innovative approach to achieve recentering and ductility of cement mortar beams through randomly distributed pseudo-elastic shape memory alloy fibers by Shajil 2012 [2-3] this literature only be reviewed as a guideline for ‘re-centering’ and ‘cyclic loading’ is concerned.
Figure 3. SMA reinforcement detailing from previous study

Figure 4 shows the reinforcement detailing reviewed from the previous researchers. Saidii et al [4] experimentally exhibit the capability of NiTi rebar to recover from permanent deformations on a small scale concrete beam by study the load-deflection relationship for a series of hybrid beam under half cycle loads. The experimental results indicated that the average residual displacement of the treated beam was less than one-fifth of the control beam with steel reinforcement despite of the stiffness of the treated beam with NiTi was lower than the control beams with steel. As a result, hybrid system that incorporated NiTi combined with high strength steel or carbon fiber reinforced plastic bars was a better choice for design because of their relatively stiffness.

Abdulridha et al [5] and [6] experimentally evaluate the applicability of SMAs as alternative reinforcement to be validate with constitutive models using Vector 2 program. The study includes the effect of loading (monotonic, cyclic, and reverse cyclic), assesses the energy dissipation and inelastic displacement recovery capacities, and discusses crack patterns, failure modes and hysteretic response. The experiment demonstrates that the treated beams sustained comparable displacement ductility and energy dissipation to the control beam. However, the treated beam dissipated energy approximately 54% of the control beam under reverse cyclic loading. The bigger diameter of SMA used, performed similar in both scale size of the beam demonstrate the consistency and reliability of the SMAs. SMAs exhibit the superior capacity to recover the crack width to limit residual displacement and experienced higher ultimate loads compared to the control beam. The experiment demonstrates that the Nitinol bars did not rupture at the threaded ends near the mechanical couplers or at the transition zone.

Reinforced concrete structures also must be designed to satisfy the requirements of both the durability and serviceability limit state [4]. SMA also can sustain in high fatigue load. Therefore, is also essential to develop smart systems of RC structures that are not only excellent in recentering
capability, energy dissipation that can recover the crack width to limit residual displacement and also viable to sustain in high fatigue load whereby SMAs can be an ideal contender of smart material to manuvaure the objectives. The papers from Debbarma, 2012 [7] were reviewed to synthesizes information on this properties of Shape Memory Alloys (SMAs) and establish the current research work which also found rare to find in the literature.

In order to examine the capability of the SMA bar to recover and reduce permanent deformations of concrete flexural members subjected to cyclic load, Debbarma et al 2013 [8] was experimentally performed the study using pseudoelastic SMAs under monotonic and cyclic loading. It was designated that flexural RC members with SMA and steel provide a better choice for structures subjected to cyclic loads and earthquakes as the consequent of there were increase their self-restoration capacity in cyclic load. The increments in deflection also negligible and the ratio of residual deflection to maximum deflection was almost zero in beams with SMA bars.

Research findings on the instantaneous and time-dependent deflection behavior of SMA RC flexural members were analytically and experimentally studied by [7]–[10]. It was observed, that under similar load, SMA RC beams have comparable potential to restrict growth of instantaneous and long-term deflections to similar the steel RC beams.

The equation provided by the Canadian Standards Association (CSA 2004) for deflection calculation of steel RC beams was found have significantly overestimates the flexural stiffness of SMA RC beams, and thus significantly underestimates their deflection. This is expected because of the significant difference between the modulus of elasticity of SMA and that of steel. Therefore, an assessment of the available models for deflection analysis of SMA RC beams was reviewed in a companion paper and parametric study endeavored by Elbahy et al 2010, [11] to discuss the effects of the concrete compressive strength, modulus of elasticity for reinforcement, reinforcement ratio, varying dimensions (width and height) to the load–deflection behaviour of shape memory alloy (SMA) in reinforced concrete (RC) beams.

The parametric study indicated that the accuracy of the reinforced concrete beam depend on the reinforcement ratio and reinforcement modulus of elasticity parameters which have a significant effect on Ie but the concrete compressive strength and the cross-section width were found to have minor effects on the effective moment of inertia, Ie.

Elbahy 2009 et al [12] conducted a parametric study to identify the monotonic moment-curvature relationship for steel and SMA RC sections with maximum concrete strain εc max, and by utilize the stress block parameters, a1 and β1, to simplify the nonlinear stress–strain curve for concrete for flexural members reinforced with pseudoelastic shape memory alloys. The artificial neural networks (ANNs) was developed by [13] to compute a reduction factor of β to be used in the calculation of the effective moment of inertia for SMA RC beams.

In particular, NiTi alloy has been forward to be the most promising for seismic application. Nickel–Titanium (NiTi), consisting of approximately 56% nickel and 44% titanium alloy, is the most common type of SMA investigated for pseudoelastic for structural and seismic applications [4]. NiTi is one of the most commonly used type because of their superior mechanical properties [81] and NiTi has a thermal coefficient close to that of concrete with a value of 11.0 x 10–6°C (6.11x10–6°F).Thus under temperature fluctuations, no significant internal thermally stresses are induced in a NiTi reinforced concrete member [3].

However, there are researchers raised several concern about the machining difficulties and high cost in utilizing pseudoelasticNiTi for construction that limit their extensive practical use [8]. They start to concern about to explore a relatively low cost using Cu-Al-Mn which are reported to have superelasticity comparable to that of NiTipseudoelastic reinforcement and they have essentially no risks to human health as reported by Toshihiro 2007, [14] Sutou 2004, 2008, [15-16] and Araki 2010 [17]. A feasibility study and finite element computation by Shrestha et al 2012 [18] and [19] in one-third scale of reinforced concrete, illustrated the superiority of the newly developed Cu-Al-Mn, as high machinability and low cost material for partial replacements of steel rebar in term of recentering, crack recovery capabilities compared to steel reinforcement beam and attribute large recovery strain.
Zafar and Andrewes [20] proposed a new type of SMA-based composite reinforcement conceived to withstand high elongation while exhibiting pseudoelastic behavior. The composite reinforcement was made of small-diameter SMA wires embedded in a thermostet resin matrix with or without additional glass fibers. The proposed SMA-FRP composite square rebars were embedded in small scale concrete T-beam and tested under three-point bending using a cyclic displacement controlled regime until failure. It was found that the SMA-FRP composite reinforcement was able to enhance the performance of concrete member by providing recentering and crack closing capability as shown in the figure 4.

![Figure 4. Reinforcement details of SMA-reinforced beams proposed adopted from Zafar and Andrews](image)

Abdulridha et al. [5] investigated the structural performance of simply supported flexure-critical concrete beams reinforced with either Nitinol SMA bars or conventional deformed reinforcement under monotonic, cyclic, and reverse cyclic loading. RC beams exhibited a superior performance in limiting residual displacements and crack widths in the concrete beams (recovering up to 85% of the midspan displacement). Moreover, under cyclic loading, the SMA beam dissipated energy comparable to the conventional reinforced beam; under reverse cyclic loading, it dissipated approximately 54% of the energy dissipated by the conventional reinforced beam.
3. Factors Influence the Design and Performance Parameter of SMA in reinforced concrete beam

SMA in reinforced concrete beam being identified by previous researcher for SMA wire for beam by Deng At Al 2006 [6] include the area of the beam, numbers of SMA wires, curing condition, curing time, volume fraction and diameter of SMA wire. Kuang et al 2009 [7] study the influence factor of deformation behaviour of SMA which include the number of SMA bars, prestrain of SMA and steel bar in tensile zone. NiTi composition and heat treatment also as the influenced factor was reviewed from Abdul Ridha 2013 [8].

Influence of self-repair capacity of polymer beam by [9] including the influence of installation, prestrain of SMA, properties of SMA, influence of unbounded length in embedded SMA and material characterization of beam. Debbarma et al 2012 [10] studied the influence factor of SMA as reinforcement in concrete flexural members for cross-sectional area, reinforcement ratio, yield strength rebar and span of the beam. While influence factor for deflection behaviour such as cross-section height, cross section width, reinforcement ratio, modulus of elasticity and compression strength were studied by Elbahy et 2010 [11].

However, for this research the influence factor including reinforcement ratio, modulus of elasticity, composition of SMA and effect of heat treatment will be further investigate because this factors are significant in order to increase the load-displacement capacity and strength.

4. Comparison of NiTi, Steel and other Alloys
The comparison of NiTi, Steel and other Alloys, their advantages and disadvantages were described in the table 1.
Table 1. Comparison of NiTi, Steel and other Alloys

| Advantage                                                                 | Disadvantage                                                                 |
|---------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Exhibit ductility, and having excellent SE and SME properties, corrosion resistance, and fatigue resistance for many application in engineering field | Manufacturing of Ni-Ti SMA is the most expensive compared to other alloys, Hence, optimization of the materials are restricted for large-scale application. |
| Capability of recentering and recovering more than 80% of the induced strains, high modules of elasticity. | Nitinol has a small area under stress-strain curve and little cyclic energy dissipation capacity. |
| Similar behavior in tension and compression                               | Exhibits semi brittle and alarmless fracture with little ultimate fracture strain (less than 15%). |
| High quality for making machined components such as bolts and high resistance to corrosion as well as fatigue. | Problems include difficulty in welding and machining, as well as its high price (Jalaeefer, 2013). |
| Great promise for either reinforcing or repairing existing structures. No friction losses, no requirement for anchor heads and ducts and no space necessity for hydraulic | Highly sensitive to compositional changes, any such variations in the composition of an SMA can cause major undesirable changes in its mechanical properties |
| The main advantages of structural steel as reinforcement are the capability to bear up to 35% strain before rupture A large area under stress-strain curve or high cyclic energy dissipation capacity | Steel undergoes large permanent plastic strain and has a weak recentering capability. |
| Gradual and alarming fracture (showing obvious deformations) and softening phase in the stress-strain curve | Its quality for making machined components, such as bolts, due to porosity coupled with its low resistance to fatigue |
| It is also known to exhibit similar behavior in tension and compression | Major factors in its favor are the simplicity of machining and welding, and especially the cost, making it viable for large scale construction. |
| Major factors in its favor are the simplicity of machining and welding, and especially the cost, making it viable for large scale construction. | Exhibit similar behavior in tension and compression |

5. Drawbacks and restraint of using pseudoelastic SMAs
The drawbacks and restraint of using pseudoelastic SMAs were described in table 2.
Table 2. Drawbacks and restraint of using pseudoelastic SMAs

| Author                                      | Limitation                                                                                                                                 |
|---------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| DesRoches and Smith (2004) (Desroches & Smith, 1972) | The properties and the mechanical behaviour of SMAs strongly depends on its composition. Small variations of the NiTi composition can significantly leading to undesirable characteristics. The properties of SMAs can also be greatly modified by mechanical working and through heat treatment. Quality control measures would be required to ensure proper consistent composition and appropriate properties. |
| McCormics Et al (2006) (DesRoches, McCormick, & Delemont, 2004) | The degradation of its properties will continued cycling at large strain levels. Cyclic fatigue effects on the forward transformation stress, residual strain, and equivalent viscous damping are best limited by prior mechanical training at high strain levels for allow number of cycles. Superelasticity is highly sensitive to temperature. |
| Alaa Abdul Ridha, Dan Palermo and Simon Foo (2011) (Abdulridha et al., 2013b) | Due to the nature of the material, the forward and reverse phase transformations are effected differently by changes to the temperature. The area of the hysteresis, and subsequently energy dissipation of the structural element are functions of temperature. Extreme temperature conditions can completely eliminate the superelastic effects. Extreme temperatures can be tailored to suit the needs of a particular application through manipulation of constituents and training. To be useful in civil engineering applications, the superelastic temperature of SMAs must have a wide range about the average ambient temperature. |

6. Conclusion
The design philosophy of conventional structural system through dissipating energy prior to damage are vulnerable and prone to excessive permanent deformations in major earthquake. High intensity of earthquake leads to significant strains in the steel reinforcement and consequently, damage in the plastic hinge zones. Thus leading to large residual deformations that make the member unserviceable after the earthquake. Two distinctive properties of SMAs distinguish by phase transformation behaviour from austenite to martensite, make it ideal contender to be incorporated in reinforced concrete structure as reinforcement to address some of the shortcomings of steel rebar and mitigate the problem of deformation explicitly by controlling permanent strains. Hence, the feasibility study of the superelasticNiTi SMA reinforcement bar for hybrid reinforcing of concrete beam, factors influence the design and performance parameter of SMA in reinforced concrete beam, comparison of NiTi, steel and other alloys, advantages and disadvantages, drawbacks and restraint of using pseudoelastic SMAs were reviewed in order to propose new design of selfhealing reinforced concrete beam base on the papers reviewed to mitigate the problems of the integrity of the reinforced concrete using the Shape Memory Alloy (SMA) as smart material reinforcing element to develop a durable, robust and high performance construction by emphasize on the use of the most optimnickel-titanium (NiTi) ratio as a hybrid reinforcement with steel to be embedded in concrete.
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