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A REVIEW OF UTILIZING SHAPE MEMORY ALLOY IN STRUCTURAL SAFETY

Abul Hasnat[a], Safkat Tajwar Ahmed[b], Hafiz Ahmed[c*]

***Abstract-* The advancement of material technology has paved the way for smart materials to emerge in the civil engineering sector. These smart materials possess the potential to encounter structural deterioration. Therefore, proper attention should be provided to smart materials regarding both research and application. Shape memory alloy (SMA) is a unique smart material that demonstrates growing applicability in numerous sectors. Recently, a lot of emphasis is being given to SMA research with a view to utilizing SMA in civil engineering structures. SMAs have some special properties such as high damping capacity, self-centering mechanism, two-way memory, self-adaptability etc. for which they can be used to make various types of structural control devices. An integrated assessment of the fundamental properties of SMAs, based on the existing data is presented by this paper in a concise and graphical manner. This paper also discusses the possibility of implementing SMAs in a wide range of civil engineering application, therefore motivating the large scale development of smart structures.**

***Keywords*: Shape memory alloy, Smart materials, Shape memory effect, Superelasticity, Structural Control**

I. INTRODUCTION

The advancement of material technology has paved the way for new and smart materials to come about in the civil engineering sector. These smart materials are potential candidates for encountering structural deterioration, thus requiring proper attention for both research and application. Smartness of material stands for several functionalities such as natural spontaneous adaptability, self-sensing, two-way memory, shape memory etc. With the change in temperature, the smart materials have the ability to alter their crystalline structure from Austenite to Martensite and vice versa. When this mutual transformation takes place, attributes such as pseudoelasticity or superelasticity, shape memory and two-way memory effect etc. are manifested. As a result, smart materials possess two mutually exclusive and unique properties, namely superelasticity and shapememory. By virtue of these two properties, smart materials can be used for applying prestress, creating self-centering mechanism and making actuators.

If a shape memory alloy is twisted by applying stress, the shape memory effect allows it to revert back to its previous shape when the stress is released. The mechanism of this phenomenon can be divided into two stages. In the first stage when stress is applied, the alloy is converted to Martensite phase from Austenite phase. Alternatively in the next stage, when the stress is released, the SMA changes back to Austenite phase, thus reattaining its initial shape. The properties of smart material can be utilized in various fields of science such as civil engineering infrastructures, aerospace engineering and biomechanics engineering. Smart materials can also be used as diagnostic tools. They have the ability to find out cracks and fractures in structural members by altering their properties. The utilities of smart materials do not end in just the diagnosis of faults. These materials are further used for self-repairing, which refers to the counterbalancing of the diagnosed faults. A specific type of smart material named Shape Memory Alloy (SMA) possesses both the self-adaptability and the ability to transform heat into mechanical work. SMAs were first brought to light during the 1930s. Since then, they have been used in different commercial industries like aerospace and mechanical manufacturing companies. Of all the smart materials, Nickel Titanium Alloy or Nitinol (Ni-Ti) is the most prevalent one. When a shape memory alloy is heated to a temperature that is lower than the 'Austenite Start Temperature' (As), its atomic layers become entwined as the adjoining layers move by one lattice constant. On the contrary, if SMA material is subjected to deformation at a temperature above As, it recovers its original shape by transforming into another phase. This specific characteristic of SMA in response to temperature change is called the one way memory effect. It is also possible to obtain two way memory effect by administering particular heat treatment. By heating or cooling, materials having two way memory is subjected to opposite and substantial size of deformation. It means that the SMA materials adopt two different memorized shapes when they are subjected to heating and cooling. This property can be utilized to make two way actuators. The most notable function of two way actuators is that they can apply or withdraw stress whenever needed by extending or contracting. SMA is considered as smart material because of these functions, therefore structures using SMA actuators are called smart structures. The temperatures in which this shape transformation process initiates are affected by both the constitution of the material and the condition of stress. This indicates that not only change in the temperature, but also stress change is responsible for shape change or phase transformation. This

[a] Assistant Professor, Civil Engineering, Faculty of Engineering, American International University-Bangladesh, Dhaka, Bangladesh
[b] Lecturer, Department of Civil Engineering, Sonargaon University, Dhaka, Bangladesh
[c] Graduate, Bachelor of Science in Civil Engineering, Islamic University of Technology (IUT), Bangladesh
* Corresponding Author Email: hafizahmedtoukir@gmail.com

property is highly significant as it enables SMA structures to repair themselves automatically. Concrete tends to crack when it is subjected to increased amount of stress. The phase transformation of SMA can be triggered by this increased tensile stress in structures. As a result, the SMA material will generate compressive stress to check the cracking procedure. Shape memory alloy can also be deployed to utilize shrinkage of structure and therefore, check the thermal expansion.

Shape memory effect was first documented in 1932 by Chang and Read when they discovered a specific type of phase transformation in Gold-Cadmium that was reversible. However, worldwide research and application of shape memory alloy started after 1962, when the shape memory transformation in Nickel-Titanium was detected by Buechler and his research companions. This discovery was made at Naval Ordnance Laboratory and the researchers named the material 'Nitinol' after their workspace (Song et al., 2006). After the revelation of Nitinol, several other smart materials were developed. However, most of them were created using highly expensive and rare elements, making them unsuited for commercial use (Mishra and Ravindra, 2014). The only smart material that came close to catch up Nitinol's place as the most suited smart material for commercial use was the copper based alloy. Nevertheless, the application of Nitinol flourished during the 1980s and 1990s as a significant number of companies started supplying Nickel-Titanium materials (Cai et al., 2003). Since their discovery, SMAs have been used to make numerous devices related to different mechanical industries. In recent years, it has also gained popularity in medical sciences and numerous engineering sectors (Miller, 2005; Norton, 1998; Jung, 2006). According to the research of Janke et al. (2005), smart memory alloys have the prospect to be utilized extensively in the civil engineering sector.

Most of the researchers placed smart materials in the passive devices category (Dolce and Marnetto, 2000; Aiken et al., 1993). On the contrary, smart materials were considered as semi-active devices rather than passive devices by Soong and Dargush (1997). In the research works of Mortazavi et al. (2013), they studied how shape memory elements can be utilized in the different phases of SMA. Hardwicke (2003) regarded shape memory alloys as intelligent materials because they autometically react and accommodate to changes in temperature or stress. Therefore, SMAs can be the key factor of building smart structures (Hardwicke, 2003). In the studies of DesRoches and Smith (2004), analysis of different experiments on the characteristics of SMAs is provided. However, the paper didn't provide any summarized result regarding those experiments. Wilson and Wesolowsky (2005) only analyzed the behavior of SMA under tension, despite the fact that the characteristics of SMAs under compression, torsion and shear are also essential for analyzing and designing structures. Although the above-stated studies investigated the mechanical properties of shape memory alloys, they didn't come up with any instruction on applying integrated SMA models into currently available finite element packages. As a result, it is not possible for engineers to design and analyze structures by using such SMA models (Alam et al., 2007). Austenite has a cubic crystal structure that is body-centred responsible for its being stable at higher temperatures. On the other hand, Martensite is stable at lower temperature as its structure is like a asymmetric parallelogram with twenty four different variations (Song et al., 2006). According to Dureig (1990), this dissimilarity in the structures of Austenite and Martensite is the reason behind Martensite phase being weaker and more susceptible to external stress.

II. Basic Properties Of SMA

Due to the physical properties of SMAs, they possess the potential for being used in civil engineering structures as well as mechanical industries. They significantly contribute in the construction of smart devices such as two way actuators. These smart devices enable the structure to perform several smart functions such as actuation, dispersing energy, self-adapting, diagnosing faults in structure and taking counter-measures spontaneously. As a consequence, research activities regarding SMAs have accelerated significantly during the last decade. The main purpose of these studies is to implement SMAs in civil engineering related applications, especially in the seismic response controlling applications. For absorbing seismic energy and minimizing the impact of earthquakes on structures, a number of ingenious systems have been innovated. Reinforcing bars, stranded wires, single wires, strips, tubing, ribbons etc., mostly made of Nitinol and copper based SMAs are used in these smart systems (Menna et al., 2015).

A. Shape Memory Effect

In addition to the two main stable phases – Austenite and Martensite, smart materials also have two different configurations of Martensite materials. These two forms are called twinned and detwinned (figure 1).

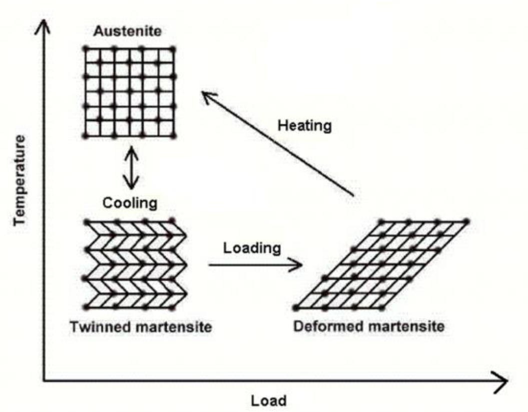

Fig. 1. Material crystalline arrangement during shape memory effect

Alteration of temperature triggers the phase transformation in smart materials, bestowing them with unique characteristics such as shape memory effect, super elasticity, two way memory etc.

Under external stress, the smart material transforms from twinned Martensite phase to detwinned Martensite phase which is shown in Procedure 1 (figure 2). While this transformation happens, there is no change in temperature. Under increased temperature, it transforms from detwinned Martensite to Austenite as indicated in Procedure 2. Upon the decrease in temperature, Austenite will go back to the twinned Martensite form as indicated in Procedure 3. Between Procedure 2 and Procedure 3, the number of characteristic temperature point is four. In ascending order; M_f = Martensitic Finish Temperature; M_s = Martensitic Start Temperature; A_s = Austenite Start Temperature; A_f = Austenite Finish Temperature.

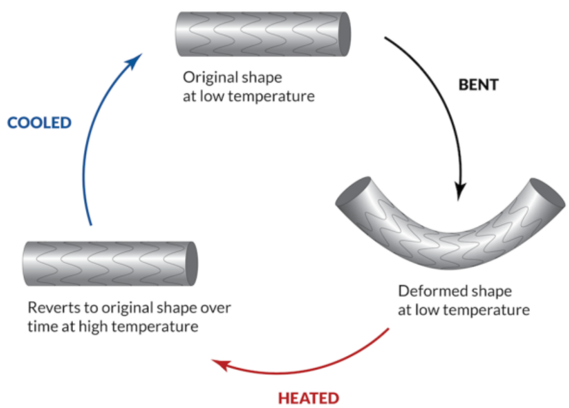

Fig. 2-a. Phase transformation process of SMAs

External stress change, increase in temperature and decrease in temperature are the three stages experienced by the smart material during Procedure 1, 2 and 3 (Cai et al, 2003). It eventually goes back to its initial twinned phase. A limitation of Procedure 3 is that a substantial force will generate during the recovery procedure of twinned Martensite from Austenite. There is scope of using this specific property in structural applications in various ways.

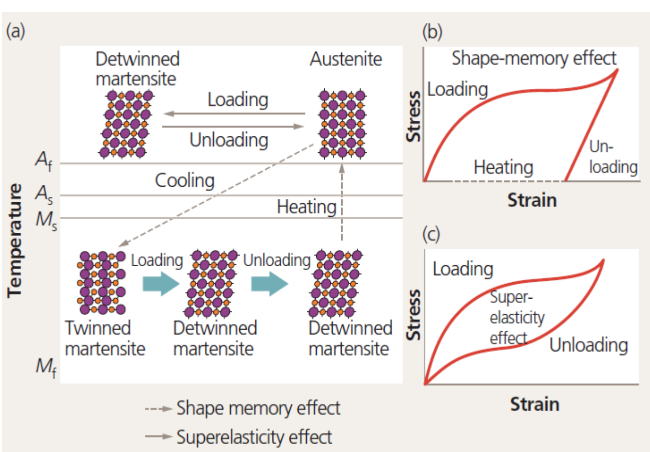

Fig. 2-b. Different phases of shape-memory alloy at different temperatures and their relationship with loading and unloading (Chang and Araki, 2016)

B. Superelasticity

Material will remain as Austenite in room temperature when the Austenite Finish Temperature (A_f) is comparatively very low. Detwinned Martensite can be obtained by transforming the superelasticity material under stress in this Austenite phase period. The detwinned Martensite, however, will reform to Austenite upon release of the external stress (figure 3).

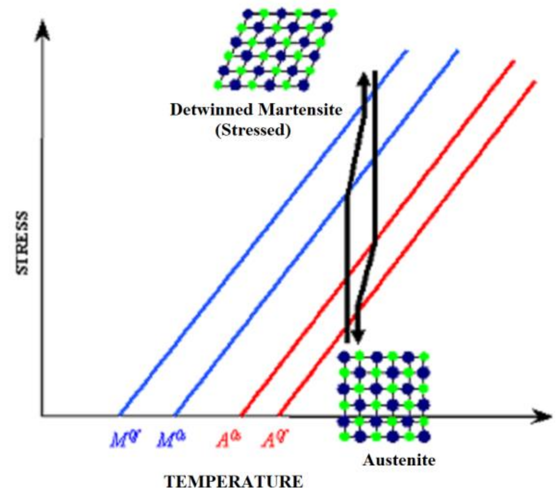

Fig. 3. Stress-induced transformations of Austenite materials (Lagoudas, 2002)

Smart materials show different characteristics in Martensite and Austenite phases from the stress-strain viewpoint. Conventional stress-strain curves are shown in figure 4a of smart materials at these stages. The stress-strain relationship is shown in figure 4b of the conventional phase changes of these materials.

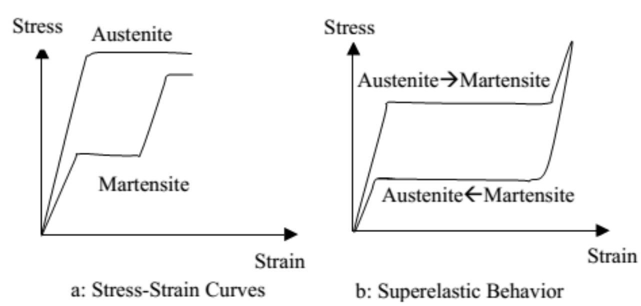

Fig. 4. Stress-strain relationship of Austenite and Martensite

The transformation of Austenite to Martensite under stress is represented by the upper plateau while inverse procedure with stress release is represented by the lower plateau. In case of using superelasticity material as reinforcement bar, it is possible to use this characteristic to retrofit cracking of concrete. Highly dependable energy dissipation extent through replicable phase transformation, hysteretic damping, adequate resistance to corrosion and magnificent fatigue properties are some other notable properties of superelasticity materials (Alam et al, 2007).

C. *Behavior under Repeated Cyclic Loading/Damping Properties*

Martensite diversifications reorientation is from where the damping capability of SMAs comes, which demonstrates shape memory effect and stress-induced Martensic conversion to the Austenite stage, which demonstrates superelasticity. Active, semi-active and passive controls are the three methods that exist to control vibration in civil engineering structures caused by external dynamic loading. Passive control is reliant on SMA's capability to dispel oscillation energy of structures due to dynamic loading. In a study, Cardone and Dolce (2001) focused on superelastic Nitinol wires subject to tension loading. It was noted that the damping capability depends on temperature, number of loading cycles and loading frequency. The indication from the results was that within a useful range, stability in the mechanical behavior of the wires was seen, taking into account the seismic applications. It was suggested to pre-tension the Austenite wires in order to escalate productivity of energy dissipation (Ip, 2000). The Martensite and Austenite damping of Nitinol bars, subjected to torsion was observed by Dolce and Cardone. Liu et al discovered that an increase in the strain amplitude increases the damping capacity of a Martensic Nitinol bar subject to tension-compression cycles and with loading cycles it decreases prior to reaching a steady minimum value (Liu et al., 1999). It was found that the damping capacity of the Austenite Nitinol bar was lower than that of the Martensite bar. However, the Martensite Nitinol bar failed to persist at its highest value with the residual strain accumulation. Another observation was that the mechanical behavior of the Martensite bar did not depend on loading frequency whereas the Austensite bar's mechanical behavior depended on it (Dolce and Cardone, 2001). The working capability of both Austenite and Martensite Nitinol bars in a wide frequency range and their suitability for seismic protection can be concluded (Mishra and Ravindra, 2014). SMAs have become fascinating for diverse engineering practices for its distinctive properties. The cyclic properties of SMAs have been tested by several researchers under shear, torsion, tension and compression. Under cyclic axial, shear and torsion forces, the standard stress-strain diagrams of Austenite SMA are shown in Fig. 5, and under cyclic axial and torsion forces, the stress-strain diagrams are shown in Fig. 6. An SMA specimen dissipates a definite amount of energy under a cycle of deformation within the strain range of its superelasticity without permanent deformation. This is a result of the phase transformation during loading from Austenite to Martensite and the opposite process at the time of unloading, which ensures a net release of energy. The yields stress of SMA is almost consistent after the primary elastic deformation when it is loaded in the Martensite phase and shows strain hardening at wider strains. Some residual strain remains there at zero stress when unloaded. A complete hysteresis loop is generated near the origin by this Martensitic formation of SMAs (Fig. 6). Thus, because of the larger hysteresis loop, Martensite SMA dissipates a fairly bigger quantity of energy than what an Austenite SMA does. The highest amount of stress achieved in compression has been observed to be roughly twice in tension than in the Martensite stage subject to tension-compression cycles (Fig. 6). The distinction in the cyclic hardening and softening process may be the cause behind it that materializes in tension-compression at maximum and 0 strain, respectively (Liu et al., 1999). However, it requires to be stated that Martensite cannot balance itself.

Compared to Martensitic SMA, the dissipation capability of superelastic SMA is less. However, regarding the residual strain, superelastic SMA is more advantageous than Martensitic SMA. After removal of load, superelastic SMA exhibits a very negligible amount of residual strain (Orgeas et al., 1997). Under torsion, the hysteresis of SMA materials are observed to be exceedingly stable and repetitive. Frequency of loading affects the mechanical properties of SMA within the superelastic range. However, these properties are not affected by loading frequency when the SMA is in Martensite phase (Dolce and Cardone, 2001).

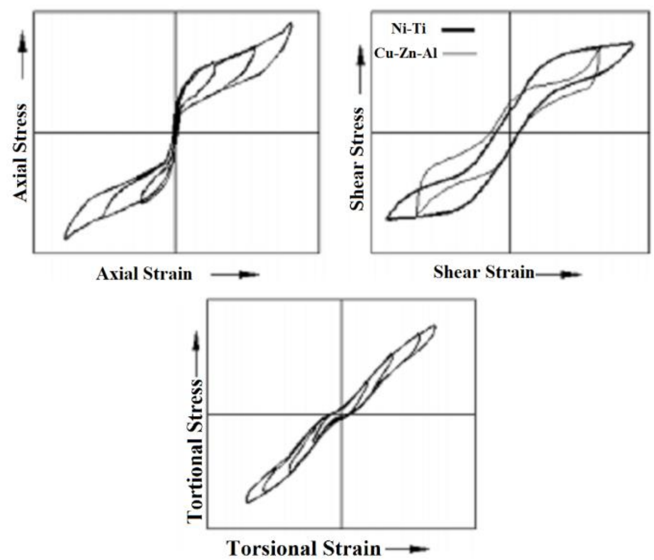

Fig. 5. Typical stress-strain curve of superelastic shape memory alloy under cyclic axial, shear, and torsion stresses (Alam et al., 2007)

Usually, localized slips are responsible for the gradual reduction of the loading plateau and the hysteresis loop accompanied by gradual rise in residual strain. This process is done in several consecutive loading cycles and results in the development of Martensite. However, if the number of loading cycles becomes significantly large, the aforementioned tendency steadily decreases (Miyazaki et al., 1986). The physical properties of SMA are also affected by strain rate. SMAs are capable of dissipating lesser amount of energy when the strain rate is considerably high. As the strain rate increases, the stresses also escalate during both the loading and unloading periods, resulting in a narrow hysteresis loop. As a result of this, the material is subjected to self -heating during cycling, which can be held accountable for the reduction of energy-dissipation capacity in SMAs.

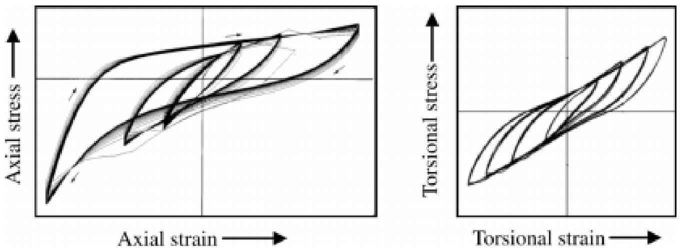

Fig. 6. Typical stress-strain curve of martensite shape memory (Alam et al., 2007)

III. Analysis Model Of Shape Memory Alloys

By heating above the transformation temperature, smart materials have the ability to remember their actual shape after they become physically deformed. Smart materials can recover maximum eight percent of strain through this process. Constitutive models are primary requisites in order to clearly perceive these physical and mechanical characteristics of smart materials. Therefore, utmost priority should be given to the development of appropriate constitutive models (Cai et al., 2003). However, developing constitutive models tends to be difficult as shape memory effect and pseudo-elasticity along with the unusual behavior of shape memory alloys have complicated the development of constitutive models. It can be regarded as a sophisticated three dimensional problem due to the fact that selection of proper variables to describe the properties of SMA can be very cumbersome. That's why constitutive modelling of smart materials is the main hindrance to widespread application of SMA. Some of the existing models are briefly reviewed below.

A. Ferroelectrics Model

Muller and Wilamski (1979) suggested a model that was established on the basis of different properties of ferromagnetism and ferroelectrics, such as statistical physics, thermodynamics and free energy. The relation between these variables can be extended to constitutive modelling, through which the phase transformation and other properties of smart materials can be understood clearly by presuming two coexisting phases in smart materials. Falk and Hoffman modified the model proposed by Muller in order to utilize and implicate it in engineering applications (Falk, 1980; Hoffman and Zheng, 1986). Hoffman considered free energy as a function of two variables namely the absolute temperature and the higher order strain. Although this model appears to be appropriate for the simulation of Martensitic transformation, it still cannot be utilized in some engineering applications due to the interdiction of computational aspects.

B. Plasticity Model

The constitutive relationship among smart materials was documented in the plasticity model proposed by Kafka (1987). The shape memory effect and superelasticity of smart materials can be exhibited by adjusting Kafka's model. By following the experimental works of Muller and Xu, a single crystal model was proposed by Brandon and Rogers (1992). Although being dependent on the temporal history of strain and phase functions, this model successfully accommodates an extensive range of physical properties of smart materials. Moreover, the behavior of single crystal smart materials during the transformation from elastic to plastic can also be described using this model.

C. Hysteresis Model

Another model is proposed by Graesser and Cozzarelli (1990) that is comparable to inelastic creep formation which exhibits both elastic and viscous characteristics when deformed, and also contains a backstress. The hysteresis model of damping materials was used as the base of this one dimensional constitutive model. The model is capable of differentiating between the loading and the unloading stages of smart materials. It can also project the elastic and inelastic states of smart materials and speculate both the Austenite and the Martensite twining hysteresis (Graesser and Cozzarelli, 1990).

D. Non-Isothermal Model

The inter-relationship between the complete transition event and the halted loading or unloading stages is provided by Ivshin and Pence. This model also accommodates the conversion of isothermal loading to adiabatic loading inside an environment that allows heat convection. The limitation of this model is that it is unable to explain certain twining incidents related to shape memory effect of materials (Ivshin and Pence, 1995).

IV. Applications Of SMA

A. Problems Associated with Highways and Bridges

Uneven joints, also known as bumps at the end of bridges are generally originated by differential or uneven settlement between bridges and pavements. Heavy vehicles like trucks or passenger buses have to drive over the bumps while entering and exiting bridges, therefore generating large impact loads on both the bridge and the pavement. It is established beyond doubt that these bumps can lead to vehicle damage, degradation of pavement and bridge surface, and in the worst-case scenarios, can result in road accidents. The degradation of pavement and bridge can be manifested in numerous forms. Problems like pavement cracking and bridge damage due to fatigue, cracking or chipping of joint edges, dissociation of pavement topping and base can be attributed to uneven joints or bumps. Differential settlement between successive piers of bridge or approach spans can also induce similar problems. In addition to aforementioned drivability problems, various unanticipated internal forces are also generated in the structure during differential settlement. These forces call for subsequent maintenance of the joints which can be both expensive and troublesome for the concerned authorities. Typically, engineers concentrate on improving the foundation designs for coping with these problems, which is unfortunately proven to be mostly ineffective. In case of indeterminate structures, internal restraint forces can also be triggered by time-dependent factors such as temperature variation, creep and shrinkage. These forces as well as other external forces caused by moving vehicles are responsible for cracking of existing pavement or bridge structure. Alternatively, to deal with these detrimental effects caused by the internal forces, structural designs are modified which increases the initial cost for new construction. Moreover, the performance of bridge bearing is also subjected to different problems. Factors like deterioration of bearings material and clogging of dirt can stop the bearing from functioning properly resulting in substantial stresses at the bearing region. Spontaneous adjustment of forces among the bearings can solve these complexities. These problems need to be addressed and proper steps need to be taken in order to avoid bridge failure and excessive maintenance cost.

B. SMAs as Reinforcing Material in Concrete Structures

Recently, the practice of using superelastic Shape Memory Alloys (SMAs) as reinforcing material in concrete structures has become immensely popular among the researchers. The reason behind this is that SMA as reinforcement has changed researchers' perception of reinforced concrete structures and the way these structures should be dealt with under seismic loads. Permanent deformation of structures can be reduced to a significant degree by using SMAs as they possess some distinctive mechanical properties compared to ordinary steel. Additionally, SMA reinforced concrete demonstrates the strength and ductility properties similar to deformed steel bars as SMAs has the capability to respond with stable hysteresis. In seismic design of RC structures, where performance based approach is usually adopted, these aspects of SMAs possess significant practical importance. In the research of Czerderski et al. (2006), a reinforced concrete beam was made using SMA wires of more than 4 millimetre diameter as reinforcement. The beam had a span of 1.14 metres and was subjected to a number of different deformation cycles in a specific arrangement of bending having four points. The paper concluded that RC beams having different strength and stiffness could be achieved just by varying the amount of prestress that is employed in the SMA wires. Deng et al. (2006) evaluated SMA reinforcement as a means to control beam deflection. In his research, prestrained NiTi SMA wires were used as RC beam reinforcement. They found that electrical heating triggers martensite-to-austenite phase transformation in SMA, which generates a vital amount of prestress in the SMA wires by means of strain recovery. This phenomenon can be used to adjust the beam deflection whenever required. Alam et al. (2010) compared between traditional steel rebar and SMA rebar in RC buildings using three different configurations. In the first case, only steel reinforcements were used in the structures. Secondly, only the plastic hinged regions of the beams contained SMA rebar and lastly, beams were completely reinforced using SMA rebar. Nonlinear static pushover analysis was conducted and the results showed that beams containing SMA reinforcements had 16% less ductility than that of steel RC beams. Furthermore, it was also evident that inter story and roof drift was higher in case of SMA-based frames. These findings implied that while using SMA reinforcements, structures must be designed considering the lesser amount of effective moment of inertia and stiffness of the structure. Abdulridha et al. (2013) assessed flexure-critical simply supported concrete beams performing under three types of loading: monotonic loading, cyclic loading and reverse cyclic loading. Both Nitinol SMA wires and conventional steel bars were used in separate beams and compared based on structural performance. It was found that Nitinol-reinforced beams recovered up to 85% of mid-span displacement, thus keeping the crack widths and the residual displacements under certain limit. On top of that, the SMA beams dispersed less energy which was about 54% of the energy dispersed by the traditional beams. A new type of SMA-based reinforcement named SMA-FRP composite reinforcement was adopted by Zafar and Andrawes (2013). This new type of reinforcement consisted of SMA wires of small diameter which were immersed in a thermoset resin matrix. In some cases, supplemental glass fibers were added. Three-point bending tests using a cyclic displacement controlled regime was conducted on concrete T-beams reinforced with the SMA-FRP composite reinforcement. The results suggested that the composite reinforcement had the capability of recentering and crack closing, therefore enhancing the performance of the tested concrete members.

C. SMA-Based Structural Joints

During seismic activities, the connections between beams and columns become vulnerable to damage. For a long time, the most appropriate structural system against seismic loading considered by the designers and the engineers was steel frames that could resist moment. The connections between beams and columns in these frames were fully restrained by welding and this system was widely used up to the 1990s. This perception changed in 1994 when a significant number of these beam-to-column connections experienced brittle failure during the Northbridge earthquake. In response to other seismic events after that, successive research initiatives were carried out to find a new connection system, such as partially restrained connections that would be more suitable to handle extreme seismic loads. In case of typical earthquake resistant beam-to-column connections, either the beams or the connections are subjected to permanent deformation after the earthquake. Generally, the beams are affected by irrecoverable deformation when full-strength connections are used, whereas in case of partial strength connections, the connections are mostly affected. In order to solve these problems, it is necessary to develop a self-centering mechanism. In that respect, many researchers has proposed using posttensioned high-strength steel bars inside the connections, which might eliminate the necessity of strenuous and expensive repair procedures. Along with that, SMA-reinforced structures are also considered as a potential way of controlling the reaction of structural connections under substantial seismic loading, particularly in steel structures. The main function of SMA connectors is to efficiently withstand comparatively large deformations by contributing damping properties to the structure. Besides, superelastic SMAs are capable of automatically recover up to 8% of strain, which provides the structures with a simplified recentering mechanism that limits the damage to major structural member.

(1) Joints in Steel Structures

Leon et al. (2001) carried out a study where full-scale beam-to-column connections with and without the Nitinol tendons were compared where the Nitinol tendons acted in the shape memory mode (purely martensitic). Following the repeated 4% cyclic strains, the tendons were heated to reinstate the connection to its actual formation and the recorded hysteric loops were found to be nearly identical. These findings concluded that the SMA connection's strength did not degrade despite undergoing significant repeated deformation. Ocel et al. (2004) adopted the same shape memory effect by using four NiTi SMA tendons to connect the column and beam flanges together. The experiment was done on partially restrained steel beam-column joints under cyclic and quasi-static loading. The beam recovered as far as 76% of its tip displacement by applying heat to the SMA bars. Reinspection of the connection revealed repeatable and stable behaviour along with significant energy dissipation.

(2) Joints in Reinforced Concrete Frames

Much like steel structures, the connection between columns and beams are considered as weak spots in reinforced concrete (RC) structures as well. During seismic events, SMA materials dissipates large amount of energy with minimal residual deformation and rotation. As a result, SMA wires have been considered as reinforcement in the plastic hinge regions of reinforced concrete beams and columns. After comparing the performance of both Niti SMA reinforced and conventional steel reinforced beam-column joints of RC members on large scale specimens, Youssef et al. (2008) observed that though the SMA based RC members dissipated less energy and had lower bond strength, they could recover from post-yielding deformation to a significant extent. A similar experiment was conducted by Alam et al. (2008), where he introduced SMA bars in the plastic hinge region of the beam and conventional steel bars in the remaining section of the joint. In this experiment, the steel and SMA rebars were connected using single barrel screw lock couplers. Ultimately, after comparison, this study also confirmed the superiority of SMA-reinforced joints in recovering post-elastic strain, whereas the steel joints manifested higher energy dissipation capability because of larger hysteric loops.

D. Seismic Dampers And Isolators

Throughout the service life of a bridge, it is subjected to deterioration due to both environmental and functional exposures. Marine environment related corrosion is one of the two major deterioration mechanisms, while the other one is fatigue from repeated traffic loads and meteorological actions. Wind, storms, temperature etc. are considered as meteorological actions that damage bridge structures. The main solution to limit these two above mentioned phenomena is to use materials that are corrosion resistant. Other than that, another potential solution is reducing the amplitude of cable oscillation resulting in increment of innate damping capacity of the cable (usually less than 0.01%). The cable oscillation can be controlled in three ways- Active, Semi active and passive control techniques. Active control is done by controlling the transverse force and the axial stiffness or tension. Semi active controlling systems, tuned mass dampers being an example, use magneto-rheologic fluids. In case of passive control, the damping devices consist of external, internal and crosstied dampers (Rahman and Hasnat, 2020; Rahman and Hasnat, 2018; Ashrafuzzaman et al., 2016).

SMA actuators have the capability of controlling the height of SMA material by rising and falling as required. These SMA actuators are made using the unique two-way memory effect of SMAs. SMA can also be used in the mass production of smart strands. Smart strands can be defined as one kind of actuator that has the ability to be activated either by external heating or internal stress change or both. At first, these strands are deformed and then embedded inside concrete. After that, it can be used to provide sufficient prestress and self-repair effects to the concrete structure at any point of its entire life span. Figure 7 shows the use of smart strands and smart bearings in the development of a smart bridge. During the shape memory effect of SMA materials, their heights will be calibrated by the smart bearings. Modification of height in this way will rectify the problem regarding unevenness or bumps. Moreover, it will deal with the internal forces previously discussed- internal forces caused by differential settlements, time dependent factors such as creep and shrinkage and temperature variation. On top of that, the prestress force can also be modified on an as-needed basis in both positive moment and negative moment regions with a view to dealing with cracking problems. In a brief, by applying the smart strands and the smart bearings combinedly, not only the internal force distribution of a bridge can be modified, but also the bridge becomes adapted to different environmental loads through mobilizing each element.

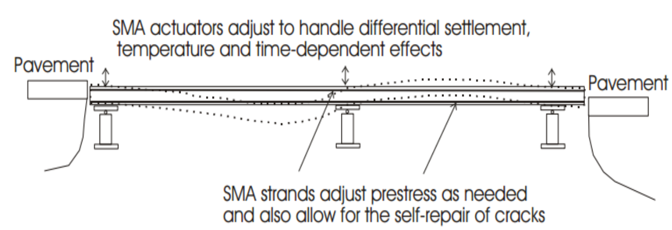

Fig. 7. Sketch of a smart bridge

External damping devices made of SMA materials are used to achieve superior corrosion-resistance properties and more efficient damping system. These materials possess some unique properties that make them perfectly suited to deal with stay-cable issues. Among these properties, the superelastic functioning and the capability of recovering significant amount of strain are two of the most noteworthy ones. These two properties combinedly grant the structural member a remarkable resistance to fatigue. Shape memory alloy materials have an intrinsic characteristic temperature which is denoted by Af. Beyond this intrinsic temperature, SMA materials tend to follow considerable mechanical strain which is mostly reversible. This hysteretic behavior can be credited to the martensitic transformation through a crystal rearrangement. SMA materials convert mechanical work into heat, firstly by an exothermic martensitic transformation and then through an endothermic reverse transformation. This mechanical hysteretic cycle of SMA gives it the characteristic damping capability. This attribute enables the SMA materials to function as a passive system that can dissipate mechanical work or energy in every cycle of oscillation without the need of external control.

There is another particular type of damper known as isolation devices which provides discontinuity between the superstructure and its substructure. As a result of this discontinuity, relative horizontal displacement of the superstructure and the substructure is allowed. During earthquake, the isolation devices filter and consequently reduce the seismic energy that transfers from substructures to superstructures. So, it can be said that the principal feature of an ideal isolator should be its capacity to dissipate large amount of energy. Taking the capability of complete recentering and the capacity of dissipating large energy into consideration, SMAs appear to be a potential candidate to be used in these vibration-isolation devices.

A base isolation system for elevated highway bridges was examined in the research of Wilde et al. (2000). Both SMA isolation system and conventional isolation system was constructed. These two types of isolation systems were compared using simulations consisting of three excitation levels- small, medium and severe loading. In the case of small excitation, the SMA based isolation system held the deck and the pier sturdily. On the contrary, the traditional system could not prevent the relative motion between the pier and the deck. For medium excitation level, the SMA bars were subjected to martensitic transformation triggered by stress. Because of that, a relative displacement comparable to that of the ordinary isolation system was allowed. Lastly, when severe load is applied, the maximum displacement of the SMA isolation system was only 20% of the displacement of the conventional isolation system. The explanation behind this significant difference is that unlike the conventional bars, the SMA bars go into an elastic range of martensite at severe loading. This result suggests that the damage energy of the bridge is significantly small for SMA isolation system compared to the conventional one. A complete SMA based (Nitinol wire) isolation system was developed and examined by Dolce et al. (2001). In this study, the practicableness of Nitinol wire for oscillation isolation was reviewed. The working principle of the isolation system is represented with diagrams in Fig. 8. Three stubs, which are attached to the tubes are coiled with SMA wire. Whenever relative displacements occur between the foundation and the superstructure, the SMA wire is stretched, therefore damping the magnitude of oscillation. The isolation system can achieve displacement as far as 180 millimetres and has the ability to bear a maximum load of 600 kilonewton. The isolation system was examined under cyclic loading to handle the vibration of an original base-isolated building having an initial displacement of 140 mm. The test revealed that the isolation system is highly effective in filtering energy transfer and has the ability to vary its stiffness according to the loading intensity. These findings validate the appropriateness of SMA based isolation systems for the purpose of passive structural control.

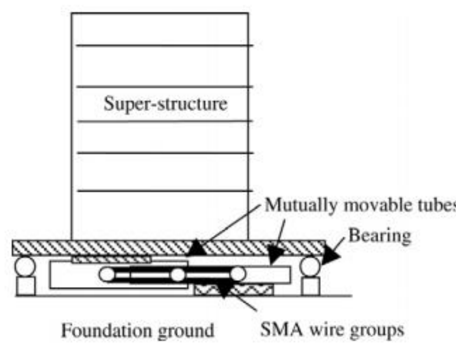

Fig. 8. Schematic of the SMA isolation system for buildings (Dolce et al., 2001)

E. *Retrofitting of Structures*

Two of the most common practices to retrofit defective structures are fibre-reinforced polymer (FRP) and steel. Another prospective contender that has a handful of edges over FRP and steel are the SMAs. Whenever structures are subjected to slippage, elastic deformation or lost torque, we can again apply structural forces to recover if we use SMAs in place of FRP and steel. Re-entering capability is another prime attribute of super-elastic SMA materials. In earthquake-prone areas, to retrofit structures, it can be brought into service as dampers and bracings. On top of that, compared to steel, SMAs are exceedingly unsusceptible to corrosion. FRP is fragile and ill-protected against fire, whereas SMA materials are not only pliable with comparatively greater resistance to fire, but also with the increase in temperature up to a definite point, increases its strength. Shape memory effect was used for the first ever field execution for a concrete structure posttensioning (Soroushian et al., 2001). Inadequate shear resistance which led to inappropriate cut-off of longitudinal flexural reinforcement was the reason behind the cracks on the bridge in Michigan, located on US-31 highway. It resulted in shear cracks on the reinforced concrete T-beam in its web and the average width of them was 0.55 mm. At the two faces of the web, shape memory alloy rods were assembled like a harp to strengthen the bridge girder. The SMA rods that were used had a diameter of 10.4 mm and were made of iron-manganese-silicon-chromium (Motavalli et al., 2009). A 1000 Ampere current was run through to heat each rod for them to reach 300°C. 120 Mpa was the eventual recovery stress that persisted in the rods after they were cooled down to atmospheric temperature and there was an astonishing 40% reduction in the crack width.

V. Limitations Of Shape Memory Alloy

SMA materials are extremely responsive to variations of formation. Remarkable modification may occur in the mechanical characteristics of the material with just simple alterations to the components of an alloy. So in order to acquire appropriate properties, emphasis must be given to quality control process. Additionally, SMA properties rely on viable and ambient temperatures because of the thermo-mechanical susceptivity of the material. SMA material and SMA-based appliance production is comparatively expensive, which is another main reason behind the restriction of diverse application of SMAs in structural engineering. Civil engineering structures and corresponding loads are usually of large scales that require a lot of material, further adding to the restrictions of diverse use of SMA in this field. The cost elevates due to the struggle of making desired shaped high-strength NiTi materials (Menna et al., 2015). However, in recent times, Iron based SMA development, such as Fe-Mn-Si-X SMA has resulted in a notable alleviation in the SMA price scenario, reducing material cost by tenfold than traditional NiTi. NiTi bars with large diameters are hard, which makes machining those using typical tools and crafts exceptionally inconvenient. Welding NiTi to steel appears to be way more troublesome due to the fragile connection on all sides of the weld zone, although there are many methods of soldering and welding NiTi such as friction, resistance, using e-beam and laser brazing and welding using Ag based filler metals (Hall, 2003).

VI. Conclusion

An assessment of the fundamental properties of SMAs is presented by this paper. It also focuses on their implementations in active, semi-active and passive command over civil structures. It consists of a few innovative and inquisitive research works on Shape Memory Alloy devices such as the base isolators and dampers. The outcome verified them to be productive and the reaction of structures to massive seismic loading was improved. The cost of retrofitting of a variety of structures can be very efficiently reduced by the recentring capacity of SMAs. Prestressing is another potential use of SMAs. It can assist the structure to vigorously facilitate added loading or retrieve prestress losses over time. Super elastic SMAs also have self-repairing abilities. By utilizing that, the preload loss in fasteners like bolted joints may be regained which can supply required clamping forces to hold the joint members in conjunction. Utilizing SMAs in civil structures – there has been a considerable amount of research work on this. Still there are areas to be explored through further experiments. The short-term and long-term deflection responses, is one as an example, of flexural members of concrete. The cost of NiTi has remarkably decreased, despite the fact that the cost of SMA is yet significantly more than the price of other materials used for construction works. The production quality and quantity of SMAs has indeed increased because of the improvement in manufacturing technologies and the process. The result was very economical. In the 90s, the price was more than $1000/kg that went down to less than $100/kg in the next decade, and subsequent reduction is anticipated with the increased use of SMAs (Menna et al., 2015). Recently, to attain highest performance in structural control, a tendency of integrating the advantages of austenite and martensite has been observed. The potential of unique materials in civil engineering works has been stipulated in the literature review which indicated to the conduction of some research in this field. It is required to point out the local applications needing little amount of these materials through research. Dynamic damping is also a prospective application. Enough research work has been done on the utilization of SMAs on individual components of a structure, but there is scope of investigation on the combination of many components in a structure. A pressing issue about SMAs is that diverse use of SMAs is limited in the construction sector due to their high cost. So it is absolutely imperative to reduce the price significantly of these alloys. It is possible that Fe-based SMAs will be cheaper and appropriate for applications in steel and cement based concrete or mortar. For SMAs to have an immense prospect of turning into an indispensable construction material in the days ahead, two things must be done– increasing the mouldability and decreasing the price.

References

[1] G. Song, N. Ma, and H.N. Li, "Applications of shape memory alloys in civil structures," *Engineering Structures*, 2006, 28. 1266–1274

[2] M. Mishra, and A. Ravindra, "A comparison of conventional and ironbased shape memory alloys and their potential in structural applications*," Int. J. Struct. & Civil Engg.* Res. 2014, Vol. 3, No. 4, ISSN 2319 – 6009

[3] C. S. Cai, W. Wu, S. Chen, and G. Voyiadjis, "Applications of Smart Materials in Structural Engineering," *Louisiana Department of Transportation and Development or the Louisiana Transportation Research Center, LTRC*, 2003, Project No. 02-4TIRE, State Project No. 736-99-1055

[4] A. Miller, "Multi-fastener surgical apparatus and method," 2005, United States Patent No. 6837893

[5] K.H. Norton, Disk drives, 1998, United States Patent No. 5808837

[6] M.S. Jung, 2006. Microactuator and fluid transfer apparatus using the same. United States Patent No. 7128403

[7] L. Janke, C. Czaderski, M. Motavalli, and J. Ruth. "Applications of shape memory alloys in civil engineering structures overview, limits and new idea", Materials and Structures, 2005, 38:578-592

[8] M. Dolce, and R. Marnetto. "Passive seismic devices based on shape memory alloys." *12WCEE 2000*, I.D. 2386, 2000

[9] I.D. Aiken, D.K. Nims, A.S. Whittaker, and J.M. Kelly. "Testing of Passive Energy Dissipation Systems." *Earthquake Spectra*, 1993, 9, No. 3, 1993, 335-369

[10] T.T. Soong, and G.F. Dargush. "Passive Energy Dissipation Systems in Structural Engineering.", *John Wiley & Sons, Chichester*, 1997, 1-2

[11] S.M.R. Mortazavi, M. Ghassemieh, and S.A. Motahari. "Seismic Control of Steel Structures with Shape Memory Alloys." *International*

Journal of Automation and Control Engineering, 2013, Volume 2 Issue 1

[12] C.U. Hardwicke, "Recent developments in applying smart structural materials." *JOM, ABI/INFORM Trade & Industry*, 2003, 55: 15-16

[13] MS. Alam, MA. Youssef, and M. Nehdi. "Utilizing shape memory alloys to enhance the performance and safety of civil infrastructure: a review." *Canadian Journal of Civil Engineering*, 2007, 34(9): 1075-1086

[14] T.W. Duerig, "Engineering aspects of shape memory alloys." London: Butterworth-Heinemann, 1990.

[15] C. Menna, F. Auricchio, D. Asprone. "Applications of Shape Memory Alloys in Structural Engineering." *Shape Memory Alloy Engineering*, 2015, ISBN 978-0-08-099920-3

[16] W. Chang and Y. Araki. "Use of shape-memory alloys in construction: a critical review." I*CE Proceedings Civil Engineering*, 2016, 169. 87-95. 10.1680/jcien.15.00010

[17] D.C. Lagoudas, "Introduction to Shape Memory Alloys." *Smart Lab at TAMU*, 2002. http://martensite.tamu.edu/overview/overview.html. Dec. 2002

[18] M. Dolce and Cardone D, "Mechanical behavior of shape memory alloys for seismic application 1. Martensite and Austenite NiTi bars subjected to torsion", *International Journal of Mechanical Sciences;* 2001, Vol. 43, pp. 2631–56

[19] K H Ip "Energy dissipation in shape memory alloy wire under cyclic bending", *Smart Materials and Structures*; (2000), Vol. 9, pp. 653–9

[20] Y. Liu, Xie Z and Humbeeck J V "Cyclic deformation of NiTi shape memory alloys", *Materials Science and Engineering*, (1999), pp. A273–275:673–8

[21] L. Orgeas, Liu, Y., and Favier, D. "Experimental study of mechanical hysteresis of NiTi during ferroelastic and superelastic deformation" *Journal de physique,* (1997). IV, 7: C5-477-C5-482

[22] S. Miyazaki, Imai, T., Igo, Y., and Otsuka, K. "Effect of cyclic deformation on the pseudoelasticity characteristics of Ti-Ni alloys" *Metallurgical Transactions*, (1986), *A*, 17: 115-120

[23] I. Muller, and Wilamski, K. "A Model for Phase Transformation in Pseudoelastic Bodies." *I1 Nuova Cimento*, (1980), 57B, 1980, pp.238-318

[24] F. Falk, "Model Free Energy, Mechanics, and Thermodynamics of Shape Memory Alloys." *Acta Metallurgica et Materialia*, (1980), Vol. 28, 1980, pp.1773-1780

[25] K.H. Hoffman, and Zheng, S.M. "Uniqueness for Nonlinear Coupled Equations Arising from Alloy Mechanism," *Technic Report No.14, Center for Applied Mathematics, Purdue University*, 1986

[26] V. Kafka, "Inelastic mesomechanics" World Scientific Publication, Co., Singapore, New Jersey, Hong Kong, 1987. 10

[27] D. Brandon, and R.C. Rogers, "Constitutive Laws for Pseudo-elastic Materials." *Journal of Intelligent Material Systems and Structures*, Vol.3, 1992, pp.333-346. 11

[28] E.J. Graesser, and F.A. Cozzarelli, "Extension of a One-dimensional Model for Hysteresis to Three Dimensions: Procedure and Verification, High Temperature Constitutive Modeling: Theory and Experiment," *Ph.D dissertation, State University of New York at Buffalo, New York,* (1990)

[29] Y. Ivshin, and T.J. Pence, "A Thermomechanical Model for a One Variant Shape Memory Materials." *Journal of Intelligent Material Systems and Structures,* Vol. 5, 1995, pp.455-473

[30] RT. Leon, R. DesRoches, J. Ocel, G. Hess, S. Liu, "Innovative beam column connections using shape memory alloys." *Smart Struct Mater Smart Syst Bridg Struct Highw* 2001;4330:227e37 (SPIE, Newport Beach, CA, USA).

[31] J. Ocel, R. DesRoches, RT. Leon, WG. Hess, R. Krumme, JR. Hayes, et al. (2004) "Steel beam-column connections using shape memory alloys" *J Struct Eng* ASCE 2004;130(5):732-40

[32] MA. Youssef, MS. Alam, M. Nehdi, "Experimental investigation on the seismic behavior of beam-column joints reinforced with superelastic shape memory alloys" *J Earthq Eng* 2008;12(7):1205-22

[33] MS. Alam, MA. Youssef, M. Nehdi "Analytical prediction of the seismic behaviour of superelastic shape memory alloy reinforced concrete elements" *Eng Struct 2008*;30(12):3399-411

[34] M. Rahman and A. Hasnat. "Response Surface Methodology based Multi- Objective Optimization of Stock Bridge Damper for Pump Induced Floor Vibration." *International Conference on Computation, Automation and Knowledge Management (Iccakm – 2020)*

[35] M. Rahman, and A. Hasnat. "Modified Roof-Top Garden as a Tuned Mass Damper for Vibration Control of Building Structure Under Earthquake Excitation." *Sonargaon University Journal*, 2018, Vol 2, Issue 2

[36] M. Ashrafuzzaman, M. Rahman, T. Tafsirojjaman, and A. Hasnat. "Seismic Performance Assessment of Laminated Rubber Bearing on Kadamtaly Flyover." *Sonargaon University Journal*, 2016, 1. 90 – 97

[37] K. Wilde, P. Gardoni, Y. Fujino, "Base isolation system with shape memory alloy device for elevated highway bridges" *Engineering Structures 2000*; 22:222–9

[38] M. Dolce, D. Cardone, R. Marnetto, "SMA re-centering devices for seismic isolation of civil structures" *Proceedings of SPIE 2001*;4330: 238–49

[39] P. Soroushian, K. Ostowari, A. Nossoni, H. Chowdhury, "Repair and Strengthening of Concrete Structures through Application of Corrective Posttensioning Forces with Shape Memory Alloys" *Transportation Research Record*, 2001(1770); p.20-26

[40] M. Motavalli, C. Czaderski, A. Bergamini, L. Janke, "Shape memory alloys for civil engineering structures – on the way from vision to reality" *Architecture civil engineering environment (ACE)*, 2009, No. 4/2009

[41] P.C. Hall, "Laser welding nitinol to stainless-steel" 4th International Conference on Shape Memory and Superelastic Technologies, *Pacific Grove*, (2003), *Calif.*, 4-8 . Edited by A.R. Pelton and T. Duering. SMST Society Inc., Menlo Park, Calif. pp. 219-228.

Mr. Abul Hasnat received his Bachelor of Science degree from Dept. of Civil and Environmental Engineering from Islamic University of Technology (IUT). He completed his Masters in Science in Structural Engineering from Bangladesh University of Engineering and Technology (BUET). Currently, he is working as Assistant Professor in Faculty of Engineering, American International University-Bangladesh (AIUB). He has several Local and International publications in the related field.

Safkat Tajwar Ahmed is currently working as a lecturer at the Department of Civil Engineering of Sonargaon University (SU), Dhaka. His work focuses on the transportation engineering field, specifically traffic safety, comfort and other service quality attributes. Mr. Ahmed has published a number of conference papers and received awards in academic competitions. He completed his BSc in Civil Engineering from Islamic University of Technology (IUT) in 2017 and currently, he is planning to pursue higher studies abroad.

Hafiz Ahmed completed his Bachelor of Science in Civil Engineering from Islamic University of Technology (IUT). He is currently doing his MBA in HRM from Khulna University. He has worked in Crown Cement and is now involved in the trading business of construction materials in South Bengal region. He has worked on a few research projects and published multiple conference papers. He is set to leave for Australia for higher studies in his field.