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A review on applications of iron based shape memory in civil engineering.

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Abstract: ***Shape memory alloy is one of the popular metals that have the sensual properties. The traditional building materials like brick, stone, concrete, timber, steel, etc. are incoherent as they are incompetence to feel their neighboring and modify themselves. A basic description of highly non-linear material behavior in terms of shape memory effect, pseudoelasticity, austenite, martensite and its damping behavior and changeable stiffness is explained. It is followed by a brief introduction to Ni-Ti and Fe-Mn-Si SMA's. Previous and new applications related to active vibration control, damping and prestressing or posttensioning of structures including tendons and fibers. SMA is frequently used as braces in frame structures, as self –rehabilitating structures. SMA is used in association with FRP as reinforcement in concrete structures to constrain the deflection. SMA-FRP bars have more power to improve the ductility and energy dissipation capability of concrete structures compared to conventional FRP bars. Moreover, the relatively high costs and difficulty in retaining posttensioning forces when using some types of SMA's are named. In this regard is Fe-Mn-Si-Cr discussed as future low cost SMA and alternative to the expensive Ni-Ti-based SMAs. Finally, new ideas for using iron based SMA's in civil engineering structures as an upgraded concept for the active confinement of concrete members. This paper presents the introduction of iron based shape memory alloys to the civil engineers of the world and appeal them to contribute to their wider use in civil engineering structures.***

Key words: Smart concrete, Iron based shape memory alloy, Recovery stress, Energy Dissipation, Damage-Fracture transition.

INTRODUCTION

Shape Memory Alloys (SMA, also known as memory metal) are materials capable of undergoing large recoverable strains of the 8% order while producing hysteresis. It is a metal that "remembers" its initial geometry during transformations. After a sample of SMA has been changed from its "original" conformation, it regains its original geometry during heating (one-way effect) or, regains two different geometry during both heating and cooling (two-way effect) or, at higher ambient temperatures, during unloading (pseudo-elasticity or super-elasticity). These extraordinary properties are due to the temperature and stress dependent phase transformation from a low-symmetry to a highly symmetric crystallographic structure. Those crystal structures are known as Martensite and Austenite (Clareda et al.,2014) [9]. Mf is the temperature at which the transition to martensite completes upon cooling. Accordingly, during heating As and Af are the temperatures at which the transformation from martensite to austenite starts and finishes. The maximum temperature at which SMAs can no longer be stress induced is called Md, where the SMAs are permanently deformed (Duerig and Pelton [1]).

The three main types of shape memory alloys are the copper-zinc, aluminium-nickel, copper-aluminium-nickel, and nickel-titanium (NiTi) alloys but SMA's can also be created by alloying zinc, copper, gold, and iron. Shape memory alloy was first discovered by Arne Olande in 1938. He observed the shape and recovery ability of a gold-cadmium alloy (Au-Cd). W.J. Buehler and Wang at the US Naval Ordinance Laboratory in 1963 observed the shape memory effect in a nickel and titanium alloy, today known as NITINOL (NIckel TItanium Naval Ordinance Lab). It was the most commonly used SMA until 1982, when the SME was observed in Fe–Mn– Si alloy and since then new iron-based SMAs have been looked into, which offer greater potential (Sato et al. [2]). Two groups of iron based SMAs exist. The first group contains alloys such as Fe–Pt, Fe–Pd and Fe–Ni–Co, displaying characteristics similar to Ni–Ti thermoelastic martensitic transformations with a narrow thermal hysteresis. The latter consists of alloys like Fe–Ni–C and Fe–Mn–Si, which, despite having larger thermal hysteresis in transformation, also display SME (Maruyama [3]).

This paper explores the damping capacity and other properties of Fe based SMAs and their advantages. Results of a number of laboratory tests will then be presented to show the great potential of Fe based SMAs for civil engineering applications. Lastly, recent laboratory tests for developing a new generation of Iron based SMA, more suitable for civil engineering applications will be presented as an alternative to existing high cost NiTi SMAs.

LITERATURE REVIEW

Duerig and Pelton [1] described some of the key properties of equiatomic and near-equiatomic tita· nium-nickel alloys with compositions yielding shape memory and super elastic properties. These alloys are commonly referred to as nickel-titanium, tita· nium-nickel, Tee-nee, Memorite, Nitinol, Tinel, and Flexon. These terms do not refer to single alloys or alloy compositions, but to a family of alloys with properties that greatly depend on exact compositional make-up, processing history, and small ternary additions. Each manufacturer has its own series of alloy designations and specifications within the "Ti·Ni~ range. A second complication that readers must acknowledge is that all properties change significantly at the transformation temperatures. Moreover, these temperatures depend on applied stress. Thus. any given property depends on temperature, stress, and history.

Sato et al. [2] presented shape memory effect and mechanical behaviour of an Fe-30Mn-1Si alloy single crystal. This paper deals with deals with two main problems associated with the γ↔€ transformation in an Fe-30th-1Si alloy. The first is the shape memory effect and second concern the large hardening produced by the pre-injected € -martensite. A base material of an Fe-30Mn alloy was prepared by a usual melting and casting method with electrolytic iron under vacuum of 10^{-2} Torr. Single crystals of 20 mm in diameter and 150 mm in length were grown in Ar atmosphere by the usual Bridgman method. In the single crystal growing process, a small amount of Si was added by melting Fe3Si into the Fe-30Mn alloy. Results stated the characteristic features of the crossing of an € plate or slip with a pre-injected € plate have been examined, confirming that the observed large hardening comes from the strong blocking by the pre-injected €-plate in absence of an additional €→α transformation.

Maruyama and Kubo [3] reviewed the fundamental character of the Fe-Mn-Si-Cr SMA and reported on the latest industrial applications of the steel pipe joints and the rail joint bar (fishplate) of heavy-duty crane rails. The memory effect was associated with the strain field established by the formation of the hexagonal close packed (hcp) phase in the parent g phase. Various efforts had been made to develop these materials with an aim of producing high performance of the shape memory effect, high strength, high corrosion resistance, weldability and sufficient plasticity for industrial processing. Results showed that it was possible to attain ~. 4% shape recovery or 180 MPa stress in the Fe-Mn-Si-Cr SMA by heating the ferrous material up to 350 °C after 5. ~. 8% deformation for martensite formation.

M.S. Speicher et al. [4] investigated on NiTi shape memory alloy (SMA)-based recentering beam-column connection. In this paper, superelastic nickel-titanium SMA were used to assess its feasibility in the moment resisting frame. The problem statement is strong-column-weak-beam of steel scenario was used, tendon elements were made from 19.1cm dia. bars. 4 tendons fabricated were: Steel, NiTi Martensitic, NiTi Austenitic, Aluminium, Aluminium tendons were placed at the interior location whereas the remaining were placed at exterior locations, tested using loading protocol of SAC steel project and drift angle was selected as the governing parameter. Experimental results showed that NiTi tendons could fully recenter a connection at drift levels below 1% and it was able to recover 85% of its deformation after being cycled to 5% drift, viscous damping in NiTi connection was greater than that of NiTi+Al connection, prestraining the NiTi tendons at 0.5% was effective in increasing the recentering capability.

M.S. Alam et al. [5] predicted analytically the seismic behaviour of superelastic shape memory alloy in reinforced concrete elements. In this paper, comparison was carried out between superelastic SMA and conventional steel in beam-column joint and FE program was used to simulate its seismic behaviour. The problem statement is beam-column joint was studied. Then SMA and steel were embedded and the results were compared. SMA was placed in the plastic hinge region of beam-column joint in the top and bottom region. Length of SMA bar was 450mm and 2-SMA20 bars were used. They have concluded moment and its curvature could be calculated using incremental deformation technique, Paulay and Priestly equation was found to be most suitable for calculating plastic hinge length, Eurocode-2 was accurate for predicting the average crack spacing and maximum crack width, FE program could predict moment-rotation and load displacement curve, adequate bond-slip model was suggested for prediction of load-displacement relationship.

G. Song et al. [6] presented a review of applications of the SMA materials for passive, active and semi-active controls of civil structures. Characteristics of SMA are also presented. The shape memory effect (SME) and pseudo elasticity, two major properties of SMA associated with the thermal-induced or stress-induced reversible hysteretic phase transformation between austenite and martensite, are reviewed. These unique properties enable SMA to be used as actuators, passive energy dissipaters and dampers for civil structure control. And current research using SMA-based devices for passive, semi-active or active control of civil structures also discussed.

M. Nehdi et al. [7] investigated to develop corrosion free concrete beam-column joint with adequate seismic energy dissipation. In this paper, SMA FRP hybrid beam-column joint was proposed and FRP ties were used. SMA was used in plastic hinge region while FRP was used in remaining region. Results were compared with conventional steel RC beam-column joint. Size of specimen was scaled down by factor (3/4) while loading was scaled down to (3/4)2. Size of SMA was chosen such that yielding will be seen in SMA before rupture of FRP. There was constant axial load at the top of the column and reversed quasi-static cyclic load at the beam tip. Results showed that SMA-FRP joint could carry 89% of its load capacity beyond collapse limit, plastic hinge was relocated by one-quarter of beam depth in case of SMA-FRP BCJ, higher beam rotation was seen in SMA-FRP BCJ, lower residual strain was seen in SMA-FRP BCJ.

M.S. Alam et al. [8] examined to calculate seismic over strength and ductility of concrete building with superelastic shape memory alloy. Non-linear static pushover analysis and dynamic time history analysis were performed using records of 10 earthquakes. 3 building storeys (3, 6, 8) were considered in this study where each building had 3 different types of rebar in their beams i.e. steel, steel-SMA, SMA. For steel-SMA building, SMA was used in the plastic hinge region of the beam. Experimental results showed that over strength factor of SMA-RC frame was similar to that of steel RC frame with maximum difference of 8% and ductility of SMA frame was found at least 16% less compared to steel RC frames whereas for steel-SMA frame it ranges from 8 to 18% less from that of steel RC frame.

A. Cladera et al. [9] presented a review of properties and applications of iron-based shape memory alloys to study properties like recovery stress, corrosion resistance, weldability and workability of iron-based shape memory alloy. Iron-based SMA tendons do not require any anchor heads and ducts. No friction losses are seen and they do not require space for applying force with hydraulic device. Cheaper and new Fe-Mn-Si alloys show higher elastic stiffness than nitinol. These have good workability with properties like anti-corrosion, weldability and high recovery stresses.

C. Czaderski et al. [10] studied about the feasibility of iron-based SMA strips for prestressed strengthening of concrete structures. The methodology was to use Iron-based SMA strips instead of FRP strips for near-surface mounted reinforcement in prestressing. The problem statement is recovery stresses were investigated in a tensile testing machine combined with the climate chamber. The temperature of the strips was increased up to 1600C to provoke the phase transformation in the SMA. The bond behaviour of Fe-SMA strip was studied in lap-shear experiment. After the concrete was cured, the Fe-SMA strips were activated by heating and the prestressing effect on the concrete bar was measured by a mechanical strain gauge. Hence concluded that the recovery stresses were found to be in the range of 250-300MPa, bond behaviour of Fe-SMA was found suitable for strengthening application, the ratio of bond shear stress and ultimate stress was found similar to CFRP.

Jose et al. [11] investigated experimentally on a prototype partially restrained connection using copper-based shape memory alloy bars. Four CuAlBe of 3mm diameter bars in austenite phase were used to prestressed the end plate to the column flange. Problem statement is given as a rectangular hollow structural steel beam connected to a wide flange column by four 240mm long 3mm dia. SMA bars fixed into anchorages specially designed to allow for prestressing of the bars. The loading protocol followed for the test was similar to the SAC steel project protocol. Resulted showed that a stable cycle of deformations was obtained with appropriate thermal treatment, the rotations up to 0.03 rad were obtained and hysteretic loops were quite stable and repeatable, CuAlBe rods at the beam-column connections increase the displacement response of structure of ground motions since SMA connections are more flexible than rigid ones.

S. Malagisi et al. [12] investigated to model smart concrete beams with shape memory alloy actuators. An original transition damage fracture technique was used to simulate the microcrack arising and its development. FE simulations are developed to reproduce the behaviour of concrete beams subjected to three-point bending tests. Technique followed was as follows: - a concrete beam containing #2, 4mm dia. steel bars at the top and #5, 2mm dia. SMA bars at bottom were used. Then three-point bending test was performed using a testing machine characterized by a distance between the supports of 350mm. The cyclic loading was applied. Investigational results concluded that a reduced damage evolution occurs before the macrocrack development. The differences could be noted in the classical force-displacement curves during the first phases of the formation of macrocracks due to the complexity of the structural system.

Alaa Abdulridha et al. [13] studied the effect of different kind of loading on the SMA reinforced beam and comparison with conventional steel reinforcement. Use of nitinol as partial reinforcement in beams along with steel is the method followed. 7 beams were casted out of which 3 beams were reinforced with conventional steel subjected to monotonous, cyclic, reverse cyclic loading. Then 3 more beams were casted with partial replacement by nitinol bars along with steel bars subjected to same three loadings. Nitinol was placed in critical region. Test results showed that performance of SMA bars was consistent irrespective of the scale taken i.e. whether they were used in large scale concrete beams or smaller scale. Displacement and crack width in the concrete beams reinforced with nitinol bars was less in comparison with conventional steel bars. Energy dissipated for SMA beam under cyclic loading was comparable to steel reinforced beams where as it was half of steel reinforced beam in case of reverse cyclic loading.

Paul and Saha [14] investigated to find load carrying capacity of RCC T-beam bridge longitudinal girder by replacing steel bars with SMA bars. Experimental and analytical study of longitudinal T-beam bridge girder was carried out using ANSYS. In this paper, a three-dimensional finite element model was developed and tested under two-point loading system to examine the structural behaviour of the longitudinal girder of a reinforced Concrete T-beam bridge, reinforcing with steel and shape memory alloy bars respectively. FEA study done on the same bridge girder with replacing 25% of steel bars by SMA bars using ANSYS. Both experimental and analytical results showed that deflection value at mid span is almost reduced half for the same loading condition in the case of girder replacing by 25% steel bars with SMA bars. The load carrying capacity could also be increased. The failure mechanism of a reinforced concrete girder is modelled quite well using FEA, and the failure load predicted was very close to the failure load measured during experimental testing.

A.R. Khaloo et al. [15] studied different properties like displacement, stiffness of cantilever beam reinforced with SMA bars. Behaviour of cantilever beam reinforced with SMA bars was studied using FEA. Different ratios of steel and smart rebar had been used for reinforcement and the behaviour of these models under lateral loading, including their load-displacement curves, residual displacements, and stiffness were studied. Different grade of concrete with different steel to smart rebar ratio and different displacement produced depending upon the applied lateral loading was used for casting and the results were analyzed by plotting load vs displacement graph and comparing residual displacement and stiffness. Diagnostic results showed that due to replacement of steel bars with smart rebar area under hysteresis curve got reduced. Load displacement curve was divided into five zones and showed that smart bars can sustain more loading without yielding till zone 4. Increase in the ratio of steel bars to smart bars reduces the stiffness and residual displacement up to zone 3. Even though SMA reduces residual displacements in RC beams due to its recoverability, it reduces energy absorption capacity of the structure.

Yachuan and Jinping [16] investigated experimentally the closure of cracks formed in the concrete structures due to applied loading. In this paper, superelastic effect of SMA and the cohering characteristic of adhesive was used for strengthening of concrete beams. After formation of cracks and the mobile loads were removed, the super elasticity of SMA wires will recover the deflections and deformations of the structural members. At the same time, the switch of the repairing vessel containing adhesives was turned on and repairing adhesives flow out from the broken open fibers, to fill the crack. Five beams with different area and of SMA bars and adhesive-filled brittle fibers were casted experimentally. Outcomes of this experiment was compared with concrete beams reinforced with SMA wires, the smart beam reinforced with SMA wires and brittle fibers containing adhesives performed better in repairing concrete after damage occurs.

L. Janke et al. [17] gave a basic description of SMA highly non-linear material behaviour in terms of shape memory effect, super elasticity, martensite damping and variable stiffness. It is followed by a brief introduction to Ni-Ti and Fe-Mn-Si SMAs. Preexisting and new applications in the fields of damping, active vibration control and prestressing or posttensioning of structures with fibers and tendons are being reviewed with regard to civil engineering. Furthermore, the relatively high costs and the problem of retaining posttensioning forces when using some types of SMAs are named. In this regard is Fe-Mn-Si-Cr discussed as potential low cost SMA. A simple model for calculating the activation times of resistive heated SMA actuators or springs is presented. The results and measured data lead to further constrictions. Finally, new ideas for using SMAs in civil engineering structures are proposed such as an improved concept for the active confinement of concrete members.

E. Choi et al. [18] studied the effect of using welded SMA rings on column for the properties like strength. SMA rings was used as a type of lateral reinforcement for concrete columns. SMA bars with diameter of 3mm and length of 446mm were prepared and strained to 7% before yielding. 3 of the 6 confined cylinders were heated to 2000C to introduce the recovery stress in SMA rings. Behaviour of 2 welded bars with the resulting diameter of 6mm were tested and compared with that of continuous SMA bar without welding. Experimental result stated that the average peak strength and strain was higher than the plain concrete case. The strength of the confined concrete decreased abruptly upon the fracture of SMA rings in a step wise manner but the decrease of strength will not affect the practical structure because the strain that initiated stepping behaviour were 6 to 7 times larger than peak strain of plain concrete. The strength of concrete confined by lateral reinforcement showed lower strength as compared to column jacketed by SMA wires.

Billah and Alam [19] investigated experimentally the seismic performance of concrete columns reinforced with hybrid SMA and FRP bars. Use of different combinations of SMA and FRP with SS in concrete column was carried out. In the RC column replacement of steel with SMA-FRP, SMA-SS, SS-FRP and SS-SMA was carried out. Replacement was done in plastic hinge region. The columns were subjected to elastic push over analysis and dynamic time history analysis. Test resulted showed that the residual displacement in columns with SE SMA was high. Also, SS reinforced column has high energy dissipation capacity as compared to SMA reinforced column.

CONCLUSION

A large number of researches that study the behavior of Fe–Mn–Si alloys have been performed, but some aspects are still not clearly understood, and more research is needed on specific topics. For example, most of the research on thermomechanical treatments during the production process has focused on improving the recovery strain, whereas the recovery stresses are the true key point for the application of the SMAs as prestressing reinforcements. Therefore, a systematic study on the optimization of the recovery stresses for different alloy compositions is needed. Additionally, with respect to the material properties, relaxation and fatigue properties have not been studied in-depth. More information can be found on the corrosion behavior, although for prestressing applications, it would be necessary to know the corrosion characteristics under the alkaline environment of concrete. Large-scale production also needs research to allow having the large amounts of materials that are needed in civil engineering applications. For the development of some products or devices, it is also necessary to improve the knowledge on weldability. Different papers address the weldability properties of the iron-based SMAs in the austenite phase, but it would be very useful to know the temperature affected zone in a welded alloy in martensite for different welding technologies. At the application level, most of the research that was conducted during recent years for Ni–Ti alloys exploiting the SME and the damping capacity can be adapted for iron-based shape memory alloys. In this paper, some pilot experiences on the application of Fe–Mn–Si alloys have been highlighted, but many others could be conducted in the near future. For many concrete applications, it would be necessary to have more information about the bond strength reduction due to the temperature increase of the embedded SMA.

REFERENCES

[1] Duerig TW, Pelton AR. (1994) "Ti-Ni shape memory alloys". in Materials Properties Handbook: Titanium Alloys, Gerhard Welsch, Rodney Boyer, E. W. Collings (eds.) American Society for Metals. pp. 1035–48. ISBN 0-87170-481-1.

[2] Sato A, Chishima E, Soma K and Mori T (1982)," Shape memory effect in y transformation in Fe–30Mn–1Si alloy single cryst", Acta Metall, Vol. 30, pp. 1177–83.

[3] Maruyama T and Kubo H (2011), "Ferrous (Fe-based) shape memory alloys (SMAs): properties, processing and applications", Woodhead Publishing Limited., pp. 141– 59.

[4] Matthew, S. Speicher, Reginald. DesRoches, Leonb. Roberto, T. (2011) "Experimental results of a NiTi shape memory alloy (SMA)-based reentering beam-column connection", Engineering Structures, 33 (2011) 2448–2457

[5] Alam, M.S. Youssef, M.A. Nehdi, M. "Analytical prediction of the seismic behavior of super elastic shape memory alloy reinforced concrete elements", Engineering Structures 30 (2008) 3399_3411.

[6] Song G, Ma N and Li N M (2006), "Applications of shape memory alloys in civil structures", Engineering Structures, Vol. 28, pp. 1266-1274.

[7] Nehdi M, Shahria Alam M, Youssef M A. Development of corrosion-free concrete beam column joint with adequate seismic energy dissipation. Engineering Structures, 2009, 32(9): 2518–2528

[8] M.Sharia Alam., Moni, M., and Tesfamariam, S. (2012). "Seismic Over strength and Ductility of Concrete Buildings Reinforced with Superelastic Shape Memory Alloy Rebar," Engineering Structures, 34(1): 8-20.

[9] Cladera A, Weber B, Leinenbach C, Czaderski C, Shahverdi M and Motavalli M (2014), "Iron based shape memory alloys for civil engineering structures: An overview", Construction and building materials, Vol. 63, pp. 281-293.

[10] Czaderski, C., M. Shahverdi, R. Brönnimann, C. Leinenbach and M. Motavalli (2014). "Feasibility of iron-based shape memory alloy strips for prestressed strengthening of concrete structures." Construction and Building Materials 56: 94-105.

[11] José Sepúlveda, Rubén Boroschek, Ricardo Herrera, Ofelia Moroni, Mauricio Sarrazin (2014), "Steel beam–column connection using copper-based shape memory alloy dampers".

[12] S. Malagisi, S. Marfia, E. Sacco and J. Toti, "Modeling of Smart Concrete Beams with Shape Memory Alloy Actuators", Wccm – Eccm – Ecfd 2014 Congress.

[13] Alaa Abdulridha, Dan Palermo, Simon Foo and Frank J. Vecchio (2012). "Behavior and modeling of superelastic shape memory alloy reinforced concrete beams", Engineering Structures, Volume 49, April 2013, Pages 893–904.

[14] N. K. Paul, S. Saha (2011). "Improvement of Load Carrying Capacity of a RCC T-Beam Bridge Longitudinal Girder by Replacing Steel Bars with S.M.A Bars", World Academy of Science, Engineering and Technology 51 2011.

[15] A. R. Khaloo, I. Eshghi and P. Piran Aghl (2010). "Study of Behavior of Reinforced Concrete Beams with Smart Rebar Using Finite Element Modeling", International Journal of Civil Engineering. Vol. 8, No. 3, September 2010.

[16] Kuang Ya-chuan and OU Jin-ping (2008). "Passive smart self-repairing concrete beams by using shape memory alloy wires and fibers containing adhesives", J. Cent. South Univ. Technol. (2008) 15: 411−417.

[17] Janke L, Czaderski C, Motavalli M and Ruth J. (2005), "Applications of shape memory alloys in civil engineering structures – overview, limits and new ideas", Mater Struct; Vol. 38, pp. 578–92.

[18] Eunsoo Choi, Sun-Hee Park, Baik-Soon Cho, David Hui (2012). "Lateral reinforcement of welded SMA rings for reinforced concrete columns", Journal of Alloys and Compounds 577S (2013) S756–S759.

[19] Muntasir, Billah A.H.M. Shahria, Alam M. (2012) "Seismic performance of concrete columns reinforced with hybrid shape memory alloy (SMA) and fiber Reinforced polymer (FRP) bars", Construction and Building Materials, 28 (2012) 730–742.