Review of Shape Memory Alloys applications in civil structures, and analysis for its potential as reinforcement in concrete flexural members

Debbarma S.R¹, Saha S²
1- Senior Scientist, CSIR-Central Mechanical Engineering Research Institute, Durgapur 713209, West Bengal, India
2- Professor, Civil engineering Department, National Institute of Technology, Durgapur 713209, India
debbarma@yahoo.com
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ABSTRACT

This paper synthesizes information on the properties of Shape Memory Alloys (SMAs) and its useful aspect towards utilization in civil engineering structures. A basic description of their highly non-linear material behavior in terms of shape memory effect, superelasticity, martensite damping and variable stiffness is presented in this article. The load-deflection behaviors of SMA reinforced concrete (RC) beams have been analyzed using prediction model codes. The effects of the cross-sectional area, reinforcement ratio, yield strength of rebar, and span of beams were considered. Effective moment of inertia, cracking moment, instantaneous and long-term deflections under variable load on beams were analyzed using ACI 318 (2005), Eurocode 2 (CEN 2002), AS 3600 (2001) and CEB (1993) codes. Deflections of SMA reinforced beams were compared with deflections of similar beams reinforced with conventional steel to present the potential of SMAs in restricting instantaneous & long-term deflections. Finally, a new scope of experimental research work is proposed utilizing SMAs as reinforcement in RC flexural members to minimize instantaneous & long-term deflections.

Keywords: Shape memory alloy, Superelasticity, instantaneous deflection, time dependent deflection, reinforced concrete beam.

1. Introduction

Reinforced concrete structures must be designed to satisfy the requirements of both the strength and serviceability limit state. The design for serviceability, however, is not straightforward, since the prediction of behavior under sustained service loads is complicated by time-dependent deformations in the composite beams due to creep and shrinkage of concrete. It exhibit strains with age of concrete and causes considerable impact on its performance results in deflection as well as affecting stress distribution. It also causes dimensional change in the material under the influence of sustained loading.

Occurrence of creep & shrinkage in concrete members depend upon the uncertainties of inherent material variations as well as modeling. Studies of uncertainties in creep & shrinkage effects were performed by Bazant ZP, Diamantidis D., Madsen HO, Li Cq., Choi BS. As per Bazant the variation of creep and shrinkage properties is caused by various factors commonly classified as internal and external factors. The internal factors are the variations in quality and mix composition of the materials used in the concrete and the internal reinforcement where as external factors are the changes in environmental conditions, such as humidity, temperature etc. Studies on the various individual time effects due to creep
and shrinkage in simple supported composite concrete structures can be found in the work of Gilbert, Bradford and Gilbert. Despite all these studies and great advances in theories, the time dependent effects in RC structures due to creep and shrinkage have not been controlled rationally.

Therefore it is very important to develop a smart system for reinforced concrete structures, which can minimize internal and external disturbances for structural safety and extension of its service life. Although SMAs have been known for decades, they have not been used much in the civil structures until rather recently. Many research activities are at laboratory stage towards use of SMA in civil structures, but few have been implemented for field applications and found effective. The complete understanding and control of their extraordinary properties and of the associated metallographic process are still under investigation. Most of the research works conducted in RC structures uses properties of shape memory effects & damping of SMA. However, research findings on the instantaneous and time-dependent deflection behavior of SMA RC flexural members are scare in literature. In this article the results of analytical studies for these deflections in SMA RC flexural members are presented and compared with similar steel RC flexural members. Four different prediction model codes were used to analyze deflections of RC beams. It was found that SMA RC beams have more potential to restrict growth of instantaneous and long-term deflections in comparison to similar conventional steel RC beams under similar load.

2. Basis about Shape Memory Alloys

2.1 Discovery of SMA & its types

The reversible phase transformation in gold-cadmium (AuCd) was observed in 1923 by Chang and Read, which was the first record of shape memory transformation. In 1962 Buechler and co-researchers discovered the shape memory effect (SME) in nickel-titanium in Naval Ordinance Laboratory.

Table 1: Some of the Alloys exhibiting Shape Memory Effect

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition (atomic %)</th>
<th>Transformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu-Al-Ni</td>
<td>28-29Al, 3.0-4.5 Ni</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Cu-Sn</td>
<td>15.5n</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Cu-Zn (brass)</td>
<td>38.5-41.5 Zn</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Cu-Zn-X</td>
<td>(X=Si, Al, Ga, Sn) few %X</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Fe-Cr-Ni-Mn-Si</td>
<td>9 Cr,5 Ni,14 Mn, 6 Si</td>
<td>Non- thermoelastic</td>
</tr>
<tr>
<td>Fe-Mn-Si</td>
<td>28-33 Mn, 4-6Si</td>
<td>Non- thermoelastic</td>
</tr>
<tr>
<td>Fe-Ni-C</td>
<td>31 Ni, 0.4C</td>
<td>Non- thermoelastic</td>
</tr>
<tr>
<td>Fe-Ni-Co-Ti</td>
<td>33 Ni, 10 Co, 4 Ti</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Fe-Ni-Nb</td>
<td>31 Ni, 7 Nb</td>
<td>Non- thermoelastic</td>
</tr>
<tr>
<td>Mn-Cu</td>
<td>5-35 Cu</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Ni-Al</td>
<td>36-38 al</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Ni-Ti</td>
<td>49-51 Ni</td>
<td>Thermoelastic</td>
</tr>
<tr>
<td>Ni-Ti-Cu</td>
<td>8-20 Cu</td>
<td>Thermoelastic</td>
</tr>
</tbody>
</table>

Up to date thirty different types of shape memory alloys have been discovered. Among them, the three main types of SMA are the copper-zinc-aluminum-nickel, copper-aluminium-nickel
and nickel-titanium (NiTi) alloys. The atomic composition and type of transformation for some alloys exhibiting shape memory effects are listed down in Table-1.

From the literature of Hodgson, D.E., it is found that cold-worked alloys respond more reliably to the shape setting heat treatment than the hot worked alloys. Out of all the Shape Memory Alloys that have been discovered so far, Nickel-Titanium (Ni-Ti) SMA alloys have been found to be the most flexible and beneficial in engineering applications due to its superior thermo-mechanical and thermo-electrical properties. It can recover from large amount of bending and torsional deformations as well as small amount of strain. The process of deformation and shape recovery can be repeated millions of times.

2.2 Crystal Structures and its Behavior

Like all other metals and alloys, SMAs have more than one crystal structure which is known as polymorphism. The prevailing crystal structure or phase in polycrystalline metals depends on both temperature and external stress. It exists in two different temperature dependent crystal structures, known as martensite at lower temperature and austenite at higher temperature or parent phase. In austenite phase, i.e at higher temperature, SMAs is stronger and stable and in martensite phase i.e at lower temperature it is weaker. These two phases differ in their crystal structures. The austenite has a body-centered cubic crystal structure, while the martensite has a parallelogram asymmetric structure having upto 24 variations. When, SMA in martensite phase is subjected to external stress, it deformed through a detwining mechanism and transforms different crystal structure variations to a particular one variation which can accommodate maximum elongation. Due to parallelogram structure, the martensite phase is weak and can be easily deformed. In austenite phase, the high temperature causes the atoms to arrange themselves into the most compact and regular pattern possible, resulting in a rigid cubic arrangement and have relatively stronger resistance to external stress. The special property that allows shape memory alloys to revert to their original shape on increase in temperature is that their crystal transformation is fully reversible. The transition temperature of SMAs varies from, about –50 deg C to 166 deg C depending upon their compositions. Simplified two-dimensional representation of the materials crystalline arrangement is shown in figure 1.

2.3 Material phenomena

SMAs have two unique properties, Shape Memory Effects (SME) and Superelasticity. The SME refers to the phenomenon that SMAs return back to their predetermined shape upon heating. For example if a straight bar of austenitic phase SMA is allowed to cool below the phase transition temperature, the crystalline structure will change to martensite. If the bar is subsequently deformed by bending, and then reheated above the transition temperature again, it will return to its original straight configuration as shown in figure 2.

Superelasticity refers to the phenomenon that SMA can undergo a large amount of inelastic deformations and recovers their shape after unloading. On increasing the external stress without thermal actuation the phase transformation of SMA may occur from austenite to martensite which causes superelasticity or pseudoelasticity. A mechanical stress occurs in the material if this deformation recovery is restrained. This recovery stress can be used for introducing forces in concrete structures to improve its resistance towards growth of creep.
shrinkage and thermal strains. Due to presence of superelasticity property the SMAs can be used in civil applications as a passive structural control, isolation device and energy dissipation devices.

![Materials crystalline arrangement during Shape Memory Effect](image1)

**Figure 1:** Materials crystalline arrangement during Shape Memory Effect

![Demonstration of shape-memory effect](image2)

**Figure 2:** Demonstration of shape-memory effect

3. Overview of SMA application in Civil Structures

The properties for which SMAs can be integrated in civil structures are:

1. The large force generated upon returning to its original shape is a very useful property.
2. Repeated absorption of large amounts of strain energy under loading without permanent deformation.
3. SMA has excellent damping characteristics at temperature below the transition temperature range.
4. Excellent property of corrosion resistance (comparable to series 300 stainless steels) and nonmagnetic in nature.
5. SMA has low density and high fatigue resistance under large strain cycles.
6. It has the ability to be heated electrically for recovery of shape.

3.1 Vibration control of structure using SMA

Vibration control of a structure is possible through adaptability to change citation frequency or changing eigen frequency of the same. It generally occurs when there is change in the
static load of the structure or the state of the structural system changes. Nae et al. proposed the control of the superelastic stress-strain curve of thin SMA wires for vibration up to 5 Hertz. Resistance heating and forced convection cooling were used for temperature control. This is one method of active dumping using damping capacity and tuning functionality of SMA.

Shahin et al. presented a model for an individual bay of a multistoried building with crossed tension bracings made of SMA rods and also used as actuators. Williams et al. presented a model with adaptive spring in which stiffness of a SMA cantilever spring was tuned by resistance heating. The cantilever end with mass was acting as an adjustable damping system with variable eigenfrequency. The information regarding design of SMA springs for active vibration control can be found in paper of Liang, C. This concept of spring with adaptive stiffness can be used to design adaptive tuned mass dampers for civil structures. A general illustration of the idea of an adaptive tuned mass damper employing SMA springs is shown in Figures 3 and 4.

**Figure 3:** Concept for active vibration control of a str. by an adaptive tuned mass damper using SMA spring

**Figure 4:** Concept for more insensitive adaptation of an adaptive tuned mass damper using an assembly of two-level stiffness SMA springs

### 3.2 Application of SMA as an Actuator

SMAs can function as actuators due to its shape memory effects which can be realized either by exerting forces on the structure or by changing its shape as shown in figure 5. Upon heating, SMA actuators embedded or installed in structures will increase the stiffness of the parent structure so that the natural frequency of the structures can be actively tuned. By active frequency tuning the behavior of the structure can be controlled. Mc.Gavin G., reported a proof-of-concept on real-time experiment in which the frequency of a steel structure is adjusted using SMA wire actuator. They achieved about 32% change of natural frequency.

Song G., proposed the concept of Intelligent Reinforced Concrete (IRC) using actuation property of SMA. Martensite SMA wires were used in IRC for post-tensioning as shown in figure 6. The strain distribution inside the concrete was obtained by changing the electrical
resistance of SMA wires. The occurrence of cracks in IRC due to explosions or earthquakes can be minimized by electrical heating of SMA wires, where wire strands contract and reduce the cracks.

Figure 5: Function of an actuator for the un-activated mood (u) and the actuated mode (a).

Upon electric heating, the SMA wire strands contract and reduces the crack.

Figure 6: Intelligent reinforced concrete specimen

3.3 Application of tensioning properties of SMA utilizing shape memory effect

3.3.1 SMA as a tendon in concrete structure

In concrete members shape memory alloy bars or cables can act as tendons. Studies of Deng, Z., and Krstulovic-Opara, N., presented the use of SMA as a tendon in concrete members. SMA tendons have several advantages over conventional steel tendons. There are no frictional losses due to development of uniform tension force along the total length of the tendon during initiation of shape memory effects. It is very suitable for curved concrete member or where tendon profile is much curved. Using SMA prestressing tendon, there is no need of anchors. This can be used for tensioning extremely thin concrete members.

3.3.2 SMA as an external tensioning material in concrete structure

The deficit in load bearing capacity and the risk of large deformation occurs in concrete structures due to increase in load and time dependent effects of concrete. With age of the concrete structure, it often develops cracks that lead to shortening in its service life. Adding external tensioning element is a well accepted strategy today for counteracting such problems in concrete structures. Materials like steel and Fiber Reinforced Plastic (FRP) are commonly used for these purposes. In comparison to these materials, SMAs have the ability of being stressed without any tensioning devices, like hydraulic jacks etc. After mounting and anchoring of martensite SMA along the external surface of structure, they need to be heated to initiate shape memory effect. As deformation recovery is restrained due to anchorage with structure, a tension force builds up. Soroushian et al, presented an example of realization of an external post tensioning. Corrosion resistant Fe-Mn-Si-Cr rods were used to enhance the
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shear resistance of a cracked region of a reinforced concrete bridge girder. Resistance heating was applied at a current of 1000Ampere.

3.4 Retrofitting of structure using superelastic properties of SMA

The superelastic behavior of SMA has attracted the attention of civil engineers. Its major field of application is retrofitting structures in an earthquake design. Graessser E.J successfully used Ni-Ti SMA for damping of seismic loads. The work of Wittig, P.R., used Cu-Zn-Al for torsion, bending and tension dampers. Cardone. D., compare in their work the superelastic bracing of RC-frames with classic steel bracings.

A real scale application of a superelastic SMA device is the earthquake resistant retrofit of the Basilica San Francesco at Assisi, Italy Castellano, M.G., and Brite E., . The historic gable was connected with the main structure by device using SMA rods (Figure 7). The Ni-Ti SMA rods were subjected to tension, although they were designed to take tension and compression forces. Another project was executed to retrofit the earthquake resistant bell tower of the Church of San Giorgio, Italy (Figure 8). Steel tendons were added to increase its tilt resistance with intermediary superelastic SMA devices to act as load limiters to prevent the masonry from compression failure, Indirli, M., and ISTECH . DesRoches, R., proposed increasing the position stability of Simply Supported bridges in earthquake prone regions through connection between the bearings of the bridge and the bridge deck slab using superelastic bars (Figure 9).

Figure 7: Shape memory alloy device for earthquake suitable connection of the historic gable and the main structure of the Basilica San Francesco in Assisi, Italy (taken from [25])

Figure 8: Earthquake suitable retrofitting of the bell tower of the Church of San Giorgio, Italy (taken from [26])

Figure 9: A proposal for increasing the position stability of simple supported bridge using superelastic SMA rod (taken from [29])
The result shows that the SMA restrainer reduces effectively the relative hinge displacement at the abutment whereas with conventional steel restrainer cable the elastic deformation range in compression was large. In-addition, the SMA restrainer extremely limits the response of bridge deck to near field ground motion. Sakai et al. carried out research work on self-restoration of a concrete beam using superelastic SMA wires. The results revealed that the mortar beam with SMA wires recovers almost completely after incurring an extremely large crack. University of Houston developed a more efficient way to use superelastic SMA wires to achieve a larger restoration forces in the form of standard cable Otero K.. A concrete beam (24 in. x 4 in. x 6 in.) was reinforced with fourteen 1/8 in. diameter superelastic stranded cables with 2% pre-strain. Each cable had seven strands and each strand had seven superelastic wires. Special clamps were used to hold the superelastic strands without slippage. There was appearance of large cracks in the test beam under 11000 lbs load. On removal of load the crack on the beam was closed under the elastic restoration force of superelastic SMA. This research also demonstrates that the effective way to use SMAs for civil application is in form of stranded cable.

3.5 Application of SMA as a connectors between structural components

Connections of different structural components are more likely to get damaged on occurrence of earthquake. SMA connectors have been designed to provide damping and resist relatively large deformations. Tamai, H., has proposed an exposed type column base with SMA anchorage for seismic resistance. The SMA anchorages were made of Nitinol SMA rods in 20-30 mm diameter and steel bars. The results obtained from the loading test and numerical simulation shows that SMA rods were very effective in dissipating energy and reducing the vibration of building under severe seismic ground motion. It was observed that, in comparison to the accumulated deformation and residual strain in ordinary anchorage, the SMA anchorage can recover their original shape after cyclic loadings. Resistance performance of SMA connectors was kept same to prevent plastic deformation and damage in the structural columns.

Martensite SMA tendons were used by Leon et al. as a primary load transferring elements in steel beam-column connection as shown in Figure 13. Based on load test results of full-scale model it was concluded that the connection exhibits stable and repeatable hysteresis for rotation up to 4% and the SMA tendon was able to sustain up to 5% strain without any permanent damage.

4. Type of SMA, suitable for use in civil structures

However, not all the SMAs have the potential for being used in civil structures due to requirement of special mechanical properties, the specific temperature conditions in civil structures and last but not the least the cost involvement. Fe-Mn-Si-X alloys are low cost SMA with high superelastic properties and good shape memory effects. Comparing the market price of Ni and Ti on the one side and Fe, Mn, Si, Cr on the other side and consider their ratio, it will be a factor of about 8 to 12. So, in terms of cost an iron based SMA could only be a small fraction of that NiTi SMA. The study of Tamarat.K, shows that Fe-based SMA like Fe-Mn-Si-X, Fe-Ni-C and Fe-Ni-Co-Ti also referred to as shape memory steel or Ferrous SMA have the potential for use in civil structures. The shape memory effects in Fe-Mn-Si containing sufficient amount of Mn were detected in 1982 by Sato et al.. In last decades Fe-Mn-Si based alloys with several additional alloying elements were developed and tested. With lots of research work, the poor shape memory effects and inferior corrosion
behavior was improved. It was found that 60% to 65% ratio of iron in Fe-Mn-Si-X alloys combine low cost with high strength and high Young’s modulus. Corrosion behavior similar to that of stainless steel was achieved by Li, H.H., with addition of 10% chromium and nickel. From the literature of Farjami, S., Lin, C., and Baruj, A., it was found that addition of Al, C, Co, Cu, N, Nb, NbC, V, VN, and ZrC improves shape memory effect.

There is a wide scope of research towards uses of low-cost SMAs for initiating large-scale applications like civil structures. Low-cost SMA has been successfully implemented in bridge rehabilitation by Soroushian et al. Graesser, E. J., used Ni-Ti for the damping of seismic load successfully. Wittig, R.P., used Cu-Zn-Al for torsion, bending and tension dampers incorporated in bracings. Because of better workability and lower cost of ferrous SMAs, these are more attractive than Ni-Ti SMA’s for use in civil structures.

4.1 Procedure adopted for deflections Analysis of SMA R.C beams

4.2 Instantaneous deflection

The short-term or instantaneous deflection of RC beam may be calculated using the effective second moment of area of the member \(I_e\) and secant modulus of elasticity of concrete \(E_{cs}\). To consider possible material nonlinearities, rigidity is evaluated with the secant modulus of elasticity \(E_{cs} = 0.85 E_c\). The following effective moment of inertia expression was originally proposed by Branson (1965):

\[
I_e = \left(\frac{M_{cr}}{M_a}\right)^m \cdot I_{uncr} + \left(1 - \left(\frac{M_{cr}}{M_a}\right)^m\right) \cdot I_{cr}
\]

Where, \(M_{cr}\) is the cracking moment and \(M_a\) is the maximum moment in the beam. Branson’s effective moment of inertia expression is also adopted by ACI 318-05 (ACI 2005) [43] and AS 3600 (SAA 1994) [44] in the instantaneous deflection calculation of concrete beam. All of these codes set the values of \(m\) to 3 to obtain an average moment of inertia for the entire span of the beam. Eurocode 2 (2004) [45] proposed following expression for \(I_e\) for instantaneous deflection calculations:

\[
I_e = \frac{I_{cr}}{1 - \left(1 - \frac{I_{cr}}{I_{uncr}}\right) \left(\frac{M_{cr}}{M_a}\right)^2}
\]

When the maximum moment \(M_a\) in a beam does not exceed the cracking moment \(M_{cr}\), the beam is in the uncracked condition. It behaves homogeneously and elastically and the slope of the load deflection plot is proportional to the second moment of area of the uncracked transformed section, \(I_{uncr}\). The uncracked moment of inertia of a flexural member with no compression reinforcement is obtained from the following equation:

\[
I_{uncr} = \frac{bD^3}{12} + bD \left(y' - \frac{D}{2}\right)^2 + \left(n - 1\right)A_{st} \left(d - y'\right)^2
\]

Where, \(b\) and \(D\) are the width and depth of the flexural member respectively. \(y'\) is the depth of the centroid of the transformed uncracked cross-section from the compression face. \(n\) the modular ratio of reinforcement to concrete. \(A_{st}\) is the total cross-sectional area of the longitudinal reinforcement placed in tension zone. \(d\) is the effective depth of the tension reinforcement.
When the maximum moment ($M_a$) at a cross-section of beam reaches $M_{cr}$, vertical flexural cracks form in the outermost layers of the tension zone. The section becomes fully cracked, when the flexural cracks reach the neutral axis, rendering the entire tension zone ineffective in resisting the bending moment. The moment of inertia of the section in the fully cracked condition is determined from the following equation:

$$I_{cr} = \frac{1}{12} . b . x_{uu}^3 + n.A_{se} . (d - x_{uu})^2$$

(4)

Where, $x_{uu}$ is the Neutral Axis (N.A) depth of the fully cracked section from the compression face. Equation (3) assumes that the concrete in the compression zone has a linear elastic behavior up to the yielding of the tension reinforcement. The value of cracking moment in equation (1) may be obtained from the following equation with different modulus of rapture ($f_r$) expressions:

$$M_{cr} = \frac{f_r . I_g}{y_e}$$

(5)

Where, $y_e$ is the vertical distance of the extreme tension fiber from the NA. $I_g$ is the moment of inertia of gross concrete section about centroidal axis, neglecting reinforcement. ACI 318-05 (ACI 2005) presents the following empirical expression for the calculation of the modulus of rapture ($f_r$):

$$f_r = 0.623 \times \sqrt{f_c}$$

(6)

Where, $f_c$ is the mean compressive strength of concrete in MPa, obtained from the cylinder test. According to Section 3.1.9 of Eurocode 2 (CEN 2002) [46], the mean flexural tensile strength (modulus of rapture) of concrete is obtained from the following equation:

$$f_r = \max \left( f_{ctm} , \left( 1.6 - \frac{h}{1000} \right) . f_{ctm} \right)$$

(7)

Where $f_{ctm}$ is the mean axial tensile strength of concrete obtained from equation (7); and $h$ is the beam height in millimeters.

$$f_{ctm} = 2.12 . \ln \left( 1 + \left( \frac{f_c}{10} \right) \right)$$

(8)

Where $f_c$ is the mean compressive strength of concrete in MPa, obtained from the cylinder tests.

### 4.3 Long-term deflection

The deflection of RC flexural members under a constant load increases with time mainly due to time dependent cracking, reduction in tension stiffening, creep of concrete and shrinkage.
**ACI 318-05 (2005) approach** for long term deflection $\Delta W$, resulting from creep and shrinkage is obtained from:

$$\Delta W = \frac{\xi}{1+50\rho} W(t_0)$$  \hspace{1cm} (9)

Where $W(t_0)$ is the instantaneous deflection caused by the sustained load and $\rho' = A_s'/(bd)$ is the compression reinforcement ratio on the critical section. A critical section may be taken at mid-span for simple supported and continuous beams. The factor $\xi$ depends on the duration of the load. $\xi = 2.0$, for 5 years or more, and $\xi = 1.4$, for 12 months of duration of the load. Total deflection of the beam $W$, is given by, $W = W(t_0) + \Delta W$

**Eurocode 2 (2004) approach** for long term deflection calculations, for a member containing deformed bars the effective moment of inertia is given by

$$I_e = \frac{I_{cr}}{1-0.5\left(1-\frac{I_{cr}}{I_{uncr}}\right)(\frac{M_{cr}}{W_a})^2}$$  \hspace{1cm} (10)

The long-term elastic modulus is taken as: $E_{el} = E_{cm}/(1+\phi)$. Where, $E_{cm} = 28$-day tangent modulus $= 1.05 E_{cm}$, and $\phi =$ Creep factor.

**CEB –FIP (1990) [47] approach** for long term deflection due to load, including creep and shrinkage is given by,

$$W = (1-\eta)W_1 + \eta W_2$$  \hspace{1cm} (11)

Where $W_1$ and $W_2$ are the deflections calculated for un-cracked and fully cracked conditions, respectively. Coefficient $\eta$, allowing for tension stiffening effects, given by $\eta = 0$ if $M_a < M_{cr}$ or $\eta = [1-\beta (M_{cr}/M_a)]$ if $M_a \geq M_{cr}$ . $\beta$ is 1.0 for a single-time loading and 0.5 for sustained loads or many cycles of repeated loading. In long-term deflection calculation the influence of creep is included by using effective modulus of elasticity for concrete, $E_{ce} = E_c/(1+\phi)$.

The additional deflections $W_{cs.1}$ and $W_{cs.2}$ due to shrinkage for single span beam is calculated from

$$W_{cs.1} = \frac{L^2}{8} \chi_{cs.1}; \quad W_{cs.2} = \frac{L^2}{8} \chi_{cs.2}$$  \hspace{1cm} (12)

Where, $L$ is the span of the beam. Shrinkage curvature $\chi_{cs.1}$ for un-cracked section and $\chi_{cs.1}$ for cracked sections calculated from

$$\chi_{cs.1} = \varepsilon_{cs} \alpha_{es} S_1 \frac{S_1}{I_{uncr}}; \quad \chi_{cs.2} = \varepsilon_{cs} \alpha_{es} S_2 \frac{S_2}{I_{cr}}$$  \hspace{1cm} (13)

Where $\varepsilon_{cs}$ is the free shrinkage strain; $S_1$ and $S_2$ are the first moment of area of the reinforcement about centroid of the transformed section in the uncracked and cracked stages respectively; $\alpha_{es} = E_s/(0.85 E_{ce})$ is the effective modular ratio. The values of $W_{cs.1}$ and $W_{cs.2}$ are used in expression (11) to obtain the additional deflection caused by shrinkage.
AS 3600 (2001) [48] approach for long term deflection due to creep and shrinkage is calculated by multiplying the instantaneous deflection caused due to sustained load by a multiplier $K_{cs}$ given by

$$K_{cs} = \left(2 - 1.2 \left(\frac{A_{sc}}{A_{st}}\right)\right) \geq 0.8$$  \hspace{1cm} (14)

Where $A_{sc}$ is the area of steel in the compressive zone of the cracked section and the ratio $A_{sc}/A_{st}$ is at mid-span for simple supported beam.

5. Examples for deflection analysis of R.C beams

5.1 Description of concrete beams

The instantaneous and long-term deflection of eight numbers rectangular RC single span beams was studied. Among the eight beams four were reinforced with SMA bars and other four with conventional steel bars of grade Fe415. The deflections under various uniform loads in all the simple-supported concrete beams were predicted using available standard model codes. The details of the beams are shown in Table-2.

In the analysis the characteristic compressive strength of concrete was $f_{ck} = 35$ MPa. The characteristic yield strength & modulus of elasticity of conventional steel bars were $f_y = 415$MPa and $E_s = 200$ GPa respectively. The characteristic yield strength & modulus of elasticity of SMA bars were $f_{SMA} = 705$ MPa and $E_{SMA} = 110$KN/mm$^2$ respectively. In calculation of time-dependent deflections the creep coefficient was considered $\phi = 1.6$ and shrinkage strain $\varepsilon_{cs} = 300 \times 10^{-6}$.

Table 2: Details of beam specimens analyzed

<table>
<thead>
<tr>
<th>Identity</th>
<th>Nominal Dimensions Width x Height x Length (mm)</th>
<th>Type of Rebar</th>
<th>Number and size of Tension Rebar</th>
<th>% area of Rebar</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1-a</td>
<td>125x250x2000</td>
<td>Fe-415</td>
<td>4 nos, 8mm $\phi$</td>
<td>0.64</td>
</tr>
<tr>
<td>B1-b</td>
<td>125x250x2000</td>
<td>SMA</td>
<td>4 nos, 8mm $\phi$</td>
<td>0.64</td>
</tr>
<tr>
<td>B2-a</td>
<td>125x250x4000</td>
<td>Fe-415</td>
<td>4 nos, 8mm $\phi$</td>
<td>0.64</td>
</tr>
<tr>
<td>B2-b</td>
<td>125x250x4000</td>
<td>SMA</td>
<td>4 nos, 8mm $\phi$</td>
<td>0.64</td>
</tr>
<tr>
<td>B3-a</td>
<td>250x500x2000</td>
<td>Fe-415</td>
<td>4 nos, 20mm $\phi$</td>
<td>1.00</td>
</tr>
<tr>
<td>B3-b</td>
<td>250x500x2000</td>
<td>SMA</td>
<td>4 nos, 20mm $\phi$</td>
<td>1.00</td>
</tr>
<tr>
<td>B4-a</td>
<td>250x500x4000</td>
<td>Fe-415</td>
<td>4 nos, 20mm $\phi$</td>
<td>1.00</td>
</tr>
<tr>
<td>B4-b</td>
<td>250x500x4000</td>
<td>SMA</td>
<td>4 nos, 20mm $\phi$</td>
<td>1.00</td>
</tr>
</tbody>
</table>

5.2 Instantaneous and time-dependent deflection results

A study was conducted by analyzing typical beam sections with different $D$ (250mm & 500mm), tensile reinforcement ratio $\rho$ (0.64%, 1.0%), type of reinforcement (SMA, steel) span (2000mm, 4000mm) and uniform axial load level. Two identical beams a and b were
analyzed for each combination of parameters. The beam a was reinforced with steel bars and beam b was reinforced with SMA bars. Model codes used for prediction were ACI 318 (2005), AS 3600 (2001), CEB (1985) and Eurocode 2 (CEN 2000).

Figure 10: Load vs. deflection as per ACI 318 (2005)
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Figure 11: Load vs. deflection as per Eurocode 2 (CEN 2002)

Figure 12: Load vs. deflection as per CEB (1993)
The higher yield strength property of SMA bars results in increase in depth of neutral axis of the RC beam from its extreme compression fiber. This directly influences the cracking moment \( (M_{cr}) \) of the concrete beam section. The cracking moments of b specimens were more in comparison to a specimens. Increase in cracking moment of beam section results in increase of effective moment of inertia and causes lesser instantaneous and time-dependent deflections at mid-span due to applied load (or moment).

The mid-span instantaneous and long-term deflections under different uniform load condition for identical beams a and b using similar prediction model code were calculated and plotted together for comparison in figure 10, 11, 12 & 13. In these figures the dashed curved lines depict the calculated values for steel reinforced beams and solid curved lines for identical beams with SMA reinforcement. Under similar load, the effective moment of inertia was calculated higher in b specimens than in a specimens. Comparison of load vs. deflection of SMA reinforced and steel reinforced beams, it was observed that under similar load the growth of deflection was less in SMA reinforced beams. These differences of deflections were found more in RC beams with higher percentage area of reinforcement and in longer span. SMA as a reinforcement have the property to introduce strong driving force inside the concrete structure due to its high yield strength and superelastic properties which restrict the growth of instantaneous and time-dependent deflection.

### 5.3 Conclusion

This paper presents a review of the basic properties of Shape Memory Alloys and their applications in passive, active and semi-active control of civil structures. A number of experimental and analytical research works on SMA devices like dampers and base isolators are presented. They are proved to be effective in improving the response of civil structures to any extreme earthquake loading. In particular, the recentring capability of SMAs can be very efficient in reducing the cost of repairing and retrofitting of various structures. Other prospective use of SMAs is in prestressing, which can help the structure to actively accommodate additional loading or remedy prestress losses over time. The self-repairing capabilities of superelastic SMAs may be utilized to regain the preload drop in bolted joints or other type of fasteners, and thus necessary clamping forces can be provided to keep the joint members together. Although there has been substantial research work on civil structures utilizing SMAs, the short and long-term deflection behavior of concrete flexural members with SMAs are yet to be investigated through experimental program.
The analysis for deflection behavior of SMA & steel RC beams under various service loads had been carried out and their differences are presented. The analytical results show that, the mid-span deflection in SMA RC beams were less compared to steel RC beams of identical cross-section, length and grade. High rigidity and superelastic properties of SMA increase this load carrying capacity and reduces instantaneous and long-term deflections of SMA, RC beams. SMA act as a stiffener in the RC flexural members. Increase in percentage area of reinforcement, cross-sectional area and span of SMA RC beams results in increase of resistance to the deflection under service load. These analytical results are further required to be validated through experiments.

6. References


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