A Thesis

Entitled

PRESTRESSING OF SIMPLY SUPPORTED CONCRETE BEAM WITH NITINOL SHAPE MEMORY ALLOY

By

Sreenath Kotamala

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Advisor: Dr. Mark A. Pickett

Graduate School

The University of Toledo

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The importance of advanced material systems is rapidly increasing. New demands are placed by our society and environment on the development of new technological systems. Smart material systems play an important role in innovative technology, providing materials that can act as both control elements and structural members. To address the problems of controlling the structural deflection, research is very essential on smart materials. Shape memory alloys (SMA) have been major elements of smart materials and structures. Shape memory alloys are novel materials that have the ability to return to a predetermined shape when subjected to the appropriate thermal procedure. SMAs are widely used for controlling the structural deflection.

This research addresses the use of Nitinol shape memory alloy to increase the flexural strength of simply supported concrete beams. The shape memory property of the Nitinol wire was used in prestressing the concrete beam. The prestressed Nitinol wire was placed in the concrete beam with an eccentricity. Electrical current was used to heat
that alloy to above its austenite finish temperature. When the temperature was raised high enough to cause the shape memory effect (SME) in Nitinol, the prestressing force was transferred to the beam. A total of ten concrete beams were tested for flexure strength in accordance with the ASTM C78. The flexural strength of the concrete beam was increased when prestressed Nitinol wire was placed in the concrete, when compared with the plain concrete beam and with un-prestressed concrete beam. Simple beam bending theory was used to determine how much prestress was transferred during the electrical heating of the Nitinol shape memory alloy.
DEDICATION

To my Mom and Dad for their everlasting support and love
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# TABLE OF CONTENTS

Abstract

Dedication

Acknowledgements

Table of Contents

List of Figures

List of Tables

I. INTRODUCTION

1.1. Shape Memory Alloys

1.1.1. General Characteristics of SMA

1.1.2. Shape Memory Effect

1.1.2.1. Thermally-Induced Transformation without Mechanical Load

1.1.2.2. Thermally-Induced Transformation with Applied Mechanical Load

1.1.3. Pseudoelasticity

1.1.4. Nitinol (NiTi Shape memory Alloy)

1.1.4.1. Thermomechanical Behavior of Nitinol

1.2. Prestressed Concrete

1.2.1. Methods of Prestressing

1.2.1.1. Pre-tensioned Concrete

1.2.1.2. Post-tensioned Concrete

II. OBJECTIVES
III. LITERATURE REVIEW

IV. EXPERIMENTAL PROCEDURE
   4.1. Selection of Appropriate Nitinol SMA wire for Prestressing
   4.2. Selecting the Appropriate Size of the Specimen
   4.3. Selecting the Correct Mix-Design Proportions
      4.3.1. Properties of the Coarse Aggregate
      4.3.2. Properties of the Fine Aggregate
      4.3.3. Mix-Design Proportions (Non-Air-Entrained)
   4.4. Calculating the Prestressing Force
      4.4.1. Checking the Compressive and Tensile Strength Limits due to the Prestress
      4.4.2. Prestressing Force
   4.5. Test Procedure to Strain the SMA Wire
   4.6. Electrical Heating of Nitinol SMA wire to Introduce the SME
   4.7. Making and Curing the Specimens
      4.7.1. Sample Data in Making Cylindrical and Flexural Specimens
   4.8. Experimental Tests on the Specimens
      4.8.1. Compressive Strength of the Concrete
      4.8.2. Flexural Strength of the Concrete
         4.8.2.1. Calculation of Modulus of Rupture

V. RESULTS
   5.1. Experimental Results from Tensile Test
   5.2. Test Results of Compressive Strength of Concrete
5.3. Test Results of Flexural Strength of Concrete Specimens. 51

5.4. Analysis of Test Results 56

5.4.1. Force in the SMA wire 56

5.4.2. Prestress Transferred through the Wire 56

5.4.2.1. Moment of Resistance of Plain Concrete Beam without any Reinforcement 56

5.4.2.2. Moment of Resistance of Concrete Beam with Un-Prestressed SMA Reinforcement 57

5.4.2.3. Moment of Resistance of Concrete Beam with Pre-Stressed SMA Wire 58

5.4.3. Percentage Loss in Prestress 59

5.4.4. Development Length 59

VI. CONCLUSION & FUTUREWORK 61

VII. REFERENCES 63
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Different Phases in SMA</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>Transformation versus Temperature</td>
<td>5</td>
</tr>
<tr>
<td>1.3</td>
<td>Temperature-Induced SME in SMA without Mechanical Loading</td>
<td>7</td>
</tr>
<tr>
<td>1.4</td>
<td>Thermally Induced SME in SMA with Applied Mechanical Loading</td>
<td>8</td>
</tr>
<tr>
<td>1.5</td>
<td>Pseudoelastic Behavior of SMA</td>
<td>9</td>
</tr>
<tr>
<td>1.6</td>
<td>Thermo-mechanical Behavior of Nitinol</td>
<td>12</td>
</tr>
<tr>
<td>1.7</td>
<td>Load-Deflection Behavior of Conventional Reinforced and Prestressed</td>
<td>13</td>
</tr>
<tr>
<td>1.8</td>
<td>Methods of Pretensioning</td>
<td>15</td>
</tr>
<tr>
<td>4.1</td>
<td>Details of the Concrete Specimen</td>
<td>24</td>
</tr>
<tr>
<td>4.2</td>
<td>Prestressed Rectangular Beam with Zero Eccentricity</td>
<td>29</td>
</tr>
<tr>
<td>4.3</td>
<td>Tenius Olsen Tensile Machine</td>
<td>33</td>
</tr>
<tr>
<td>4.4</td>
<td>Jaws &amp; Test Setup in Tensioning the Wire</td>
<td>34</td>
</tr>
<tr>
<td>4.5</td>
<td>Electrical Heating of Nitinol (SM495) Wire</td>
<td>37</td>
</tr>
<tr>
<td>4.6</td>
<td>Compressive Strength of Cylindrical Concrete Specimen Test Setup</td>
<td>39</td>
</tr>
<tr>
<td>4.7</td>
<td>Graphical Representation of Third-Point Loading</td>
<td>40</td>
</tr>
<tr>
<td>4.8</td>
<td>Flexural Strength Test Setup</td>
<td>41</td>
</tr>
<tr>
<td>4.9</td>
<td>Concrete Beam in Third-Point Loading Test</td>
<td>42</td>
</tr>
<tr>
<td>4.10</td>
<td>Figure Showing Cracks in the Middle-Third of Span Length</td>
<td>43</td>
</tr>
<tr>
<td>4.11</td>
<td>Electrical Heating of Embedded SMA wire</td>
<td>44</td>
</tr>
<tr>
<td>4.12</td>
<td>Flexural Test of Prestressed Concrete Beam</td>
<td>45</td>
</tr>
<tr>
<td>Figure 5.1</td>
<td>Load-Elongation Behavior of Nitinol SMA wire at Zero Degrees Centigrade</td>
<td>47</td>
</tr>
<tr>
<td>Figure 5.2</td>
<td>Load-Elongation Behavior of Nitinol SMA wire at Room Temperature</td>
<td>48</td>
</tr>
<tr>
<td>Figure 5.3</td>
<td>Load-Elongation Behavior of Nitinol SMA wire in-between 60-70 Degrees Centigrade (Austenite Finish) Temperature</td>
<td>49</td>
</tr>
<tr>
<td>Figure 5.4</td>
<td>Comparison of Three Tensile Test Results</td>
<td>50</td>
</tr>
<tr>
<td>Figure 5.5</td>
<td>Mean Compressive Strength of Cylindrical Specimens</td>
<td>53</td>
</tr>
<tr>
<td>Figure 5.6</td>
<td>Flexural Strength of Prestressed Beam Vs Plain Concrete</td>
<td>55</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 4.1</td>
<td>Physical, Mechanical, Shape Memory Properties, and Composition of SM495 Wire</td>
<td>23</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>Test Results of Fine-ness Modulus of Fine Aggregate</td>
<td>25</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>Test Results from the Tensile Machine at Room Temperature</td>
<td>35</td>
</tr>
<tr>
<td>Table 4.4</td>
<td>Concrete Proportions Used in Preparing the Test Specimens</td>
<td>38</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>Tensile Test Results at Zero Degrees Centigrade</td>
<td>47</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Tensile Test Results at Room Temperature</td>
<td>48</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>Tensile Test Results at Austenite Finish Temperature</td>
<td>49</td>
</tr>
<tr>
<td>Table 5.4</td>
<td>Compressive Strength of Cylindrical Concrete Specimen at 7, 14, and 28 Days</td>
<td>52</td>
</tr>
<tr>
<td>Table 5.5</td>
<td>Mean Compressive Strength of Cylindrical Specimen</td>
<td>52</td>
</tr>
<tr>
<td>Table 5.6</td>
<td>Flexural Strength of the Concrete Beam</td>
<td>54</td>
</tr>
<tr>
<td>Table 5.7</td>
<td>Mean Flexural Strength of the Concrete Beam</td>
<td>55</td>
</tr>
</tbody>
</table>
Chapter One

INTRODUCTION

The importance of advanced material systems is rapidly increasing as ever more stringent demands are placed by our society and environment on the development of new technological systems. Smart material systems play an important role in innovative technology, providing materials that can act as both control elements and structural members (such as piezoelectrics, shape memory alloys, or magnetostrictive materials). These materials consequently offer great possibilities for self-controlling structures, enabling these structures to adapt themselves to various loading conditions in the sense of structural optimization (Brinson et. al., 1996).

The technological advantages of each class of these materials, over traditional materials, arise from special capabilities due to unique microstructure or molecular properties. However, these unique properties necessarily add complexity to the experimental analysis, the constitutive description and the structural implementation of these materials. These issues must be addressed and understood before the full potential of smart structures can be realized. This research focuses on Shape Memory Alloy (SMA) materials and provides a technique to prestress a simply supported concrete beam using the shape memory effect of nitinol (NiTi, Shape Memory Alloy) to control the structural deformation.
1.1 Shape Memory Alloys

The term Shape Memory Alloys (SMA) is applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature, will return to their shape prior to the deformation. Materials that exhibit the above kind of properties at different temperatures are called Shape Memory Alloys. A material that shows shape memory only upon heating is referred to as having a one-way shape memory. Some materials also undergo a shape change upon cooling. These materials are called Shape Memory Alloys having two-way shape memory.

Shape Memory Alloys are novel materials that have the ability to return to a predetermined shape when heated above their transformation temperature. When a SMA is cold, or below its transformation temperature, it has a very low yield strength and it can be deformed quite easily into any new shape and it will remain in that shape at that low temperature (Lagoudas, 1992). However, when that material is heated to above its transformation temperature, it undergoes a change in crystalline structure, which causes it to return to its original undeformed shape. If the SMA encounters any resistance during this transformation, it will apply a force on the resisting member. This phenomenon can be used as a remote actuation mechanism.


An SMA has two stable phases. One is called martensite and the other one is called austenite. The high temperature phase is austenite and the low temperature phase is martensite. In addition, the martensite can be one of two forms: twinned or detwinned
as shown in Figure 1.1. The phase transformation which occurs between these two phases upon heating/cooling is the basis for the unique properties of the SMAs. The key effects of the SMAs associated with the phase transformation are \textit{Pseudoelasticity} and \textit{Shape Memory} effect (Lagoudas, 1992).

The martensitic transformation is a shear-dominant diffusionless solid-state phase transformation occurring by nucleation and growth of the martensitic phase from a parent austenite phase. When an SMA undergoes a martensitic phase transformation, it transforms from its high-symmetry, usually cubic, austenite phase to a low-symmetry martensitic phase, as shown in Figure 1.1.

\textbf{Austenite}
- High temperature phase
- Cubic Crystal Structure

\textbf{Martensite}
- Low temperature phase
- Monoclinic Crystal Structure

\textbf{Twinned Martensite} \hspace{5cm} \textbf{Detwinned Martensite}

\textbf{Figure 1.1} Different Phases in SMA (source: Lagoudas, 1992).

The martensitic transformation possesses well-defined characteristics that distinguish it among other solid-state transformations:
It is associated with an inelastic deformation of the crystal lattice with no diffusive process involved. The phase transformation results from cooperative and collective motion of atoms over distances smaller than the lattice parameters. The absence of diffusion makes the martensitic transformation almost instantaneous.

Parent and product phases coexist during the phase transformation, since it is a first order transition, and as a result there exists an invariant plane, which separates the parent and product phases.

Transformation of a unit cell element produces a volumetric and a shear strain along well-defined planes. The shear strain can be many times larger than the elastic strain of the unit cell. This transformation is crystallographically reversible.

The martensitic phase has lower symmetry than that of the parent austenitic phase; several variants of martensite can be formed from the same parent phase crystal.

Stress and temperature have a large influence on the martensitic transformation. Transformation takes place when the free energy difference between the two phases reaches a critical value.

1.1.1 General Characteristics of SMA:

The martensitic transformation that occurs in the shape memory alloys yields a thermoelastic martensite and develops from a high-temperature austenite phase. The martensite typically occurs as alternately sheared platelets, which are seen as a herringbone structure when viewed metallographically as shown in Figure 1.1. The
usual way of characterizing the transformation and naming each point in the cycle is shown in Figure 1.2 (http://www.sma-inc.com/html/_shape_memory_alloys_.html). The transformation also exhibits hysteresis in that the transformations on heating and on cooling do not overlap (Fig. 1.2).

Figure 1.2 Transformation versus Temperature. (T₁: transformation hysteresis; Ms: Martensite start; Mf: Martensite finish; As: Austenite start; Af: Austenite finish).

The loading path and the thermomechanical history of the SMA material determine the key attributes of the SMA associated with the martensitic transformation, such as pseudoelasticity and shape memory effect (one-way and two-way memory effects). The characteristics associated with these attributes, or classes of behavior, are presented below.
1.1.2 Shape Memory Effect:

An SMA exhibits the *Shape Memory Effect (SME)* when it is deformed from austenite phase to martensite phase with (or without) applied mechanical load, by lowering the temperature below the martensitic finish temperature ($M^f_0$) as shown in Figure 1.3. If it is subsequently heated above the austenite finish temperature ($A^f_0$), it will regain its original shape by transforming back into the parent austenite phase.

http://herkules.oulu.fi/isbn9514252217/html/ (accessed on 03/04)

*1.1.2.1 Thermally-Induced Transformation without Mechanical Load:*

Upon cooling in the absence of an applied load, the material transforms from austenite into twinned (self-oriented) martensite. Upon heating the material in the martensitic phase, a reverse phase transformation occurs and the material transforms to austenite phase. This process is illustrated in Figure 1.3.

Martensitic start temperature ($M^{0s}$) is the temperature at which the material starts transforming from austenite to martensite. Martensitic finish temperature ($M^0f$) is the temperature at which the transformation is complete and the material is fully in the martensitic phase. Austenite start temperature ($A^{0s}$) is the temperature at which the reverse transformation from martensite to austenite initiates. And austenite finish ($A^0f$) is the temperature at which the reverse transformation is completed and the material is in austenite phase (Lagoudas, 1992).
**Figure 1.3** Temperature-Induced SME in SMA without Mechanical Loading

(M$_{0f}$: Martensite finish temperature; M$_{0S}$: Martensite start temperature; A$_{0f}$: Austenite start temperature; A$_{0S}$: Austenite finish temperature). Source: (Lagoudas, 1992).

1.1.2.2 Thermally-Induced Transformation with Applied Mechanical Load:

If the mechanical load is applied to the material in the twinned martensite state (low temperature) it is possible to detwin the martensite. Upon releasing the load, the material remains deformed. A subsequent heating of the material to a temperature above austenite finish, A$_{0f}$, will lead to complete reverse phase transformation from detwinned martensitic phase to parent austenite phase as shown in Figure 1.4 (http://smart.tamu.edu/overview/smaintro/detailed/detailed.html).
The above described phenomenon is called \textit{one-way shape memory effect} because the shape recovery is achieved only during heating. If shape recovery occurs during cooling also, then it is called \textit{two-way shape memory effect}.

1.1.3 Pseudoelasticity:

The \textit{Pseudoelastic} behavior of SMA is associated with recovery of the transformation strain upon unloading. This behavior is observed during loading and unloading above $A_{0s}$, and is associated with stress-induced martensite and reversal to austenite upon unloading. When this loading and unloading occurs above $A_{0s}$, partial strain recovery takes place. When the loading and unloading of SMA occurs above $A_{0f}$, full recovery upon unloading takes place.
Such loading path in the stress-temperature space is graphically shown in Figure 1.5. Initially, the material is in the austenite phase (A). Upon loading the SMA wire, it will go into the complete martensite phase (C). Upon unloading without external heat, the reverse transformation starts at D. At the end of unloading path (E), the material is again in the austenite phase (http://www.unipv.it/dms/auricchio/Research/Sma/sma_what.htm).

**Figure 1.5** Pseudoelastic Behavior of SMA

1.1.4 Nitinol (NiTi Shape Memory Alloy):

The most common shape memory material is an alloy of nickel and titanium called Nitinol. This particular alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance. As an actuator, it is capable of up to 5% strain recovery and 50,000 psi restoration stress throughout many cycles. For example, a Nitinol wire 0.020 inches in diameter can lift as much as 16 pounds. Nitinol also has resistance properties, which are suitable for actuation electrically by joule heating. When
an electric current is passed directly through the wire, it can generate enough heat to cause the phase transformation. In most cases, the transition temperature of the SMA is chosen such that room temperature is well below the transformation point of the material. Only with the intentional addition of heat can the SMA exhibit actuation. In essence, Nitinol is an actuator, sensor, and heater all in one material.

*Physical Properties of Nitinol:*

- Density: 6.45gms/cc
- Melting Temperature: 1240-1310° C
- Resistivity (hi-temp state): $82 \times 10^{-6}$ ohm-cm
- Resistivity (lo-temp state): $76 \times 10^{-6}$ ohm-cm
- Thermal Conductivity: 0.1 W/cm-° C
- Heat Capacity: 0.077 cal/gm-° C
- Latent Heat: 5.78 cal/gm; 24.2 J/gm

*Mechanical Properties of Nitinol:*

- Ultimate Tensile Strength: 754 - 960 MPa or 110 - 140 ksi
- Typical Elongation at Fracture: 15.5 percent
- Typical Yield Strength (hi-temp): 560 MPa, 80 ksi
- Typical Yield Strength (lo-temp): 100 MPa, 15 ksi
- Approximate Elastic Modulus (hi-tem): 75 GPa, 11 Mpsi
- Approximate Elastic Modulus (lo-temp): 28 GPa, 4 Mpsi
- Approximate Poisson's Ratio: 0.3
1.1.4.1 Thermomechanical Behavior of Nitinol:

The mechanical properties of shape memory alloys vary greatly over the temperature range spanning their transformation. This is seen in Figure 1.6, where simple stress-strain curves are shown for a nickel titanium alloy that was tested in tension, below, in the middle of, and above its transformation temperature range. The martensite is easily deformed to several percent strains at quite a low stress, whereas the austenite (high temperature phase) has much higher yield stress. The dashed line on the martensite curve indicates that upon heating, after removing the stress, the sample remembered its unstrained shape and reverted to that shape as the material transformed to austenite. No such shape recovery is found in the austenite phase upon straining and heating, because no phase change occurs.

An interesting feature of the stress-strain behavior is seen in Figure 1.6. When the material is tested at slightly above its transformation temperature ($T_2$), martensite can be stress-induced. It then immediately strains and exhibits the behavior of increasing strain at constant stress, as seen in AB. Upon unloading, though, the material reverts to austenite at a lower stress, as seen in line CD, and shape recovery occurs, not upon the application of heat, but upon a reduction of stress. This effect, which causes the material to be extremely elastic, is known as pseudoelasticity. Pseudoelasticity is nonlinear. The Young's modulus is therefore difficult to define in this temperature range, as it exhibits both temperature and strain dependence.

1.2 Prestressed Concrete:

“There is probably no structural problem to which prestressed concrete cannot provide a solution and often a revolutionary one” (Krishna Raju, 1997).

Prestressed concrete is basically concrete in which internal stresses of a suitable magnitude and distribution are introduced, so that the stresses resulting from external loads are concentrated to a desired degree. The prestress is commonly introduced by tensioning the steel reinforcement in the concrete member. Prestressing involves the application of an initial compressive load on a structure to reduce or eliminate the internal tensile forces and thereby control or eliminate cracking. The initial compressive load is imposed and sustained by highly tensioned steel reinforcement reacting on the concrete. Prestress may also impose internal forces which are opposite to the external loads and may therefore significantly reduce or even eliminate deflection. Typical load-deflection behavior of reinforced and prestressed concrete beams is shown in Figure 1.7. The application of permanent compressive stress to a material like concrete, which is strong in
compression but weak in tension, increases the apparent tensile strength of that material, because the subsequent application of tensile stress must first nullify the compressive prestress (Gilbert, et. al. 1990).

![Load-Deflection Behavior of Conventional Reinforced and Prestressed Concrete Beams](image)

**Figure 1.7** Load-Deflection Behavior of Conventional Reinforced and Prestressed Concrete Beams (Krishna Raju, 1997).

1.2.1 Methods of Prestressing:

As mentioned in the above section, prestress is usually imparted to a concrete member by highly tensioned steel reinforcement (wire, strand, or bar) reacting on the concrete. The high-strength prestressing steel is most often tensioned using hydraulic
jacks. The tensioning operation may occur before or after the concrete is cast and, accordingly, prestressed members are classified as either \textit{pretensioned} or \textit{post-tensioned}.

1.2.1.1 Pretensioned concrete:

In the pretensioning system, the tendons are first tensioned between rigid anchor-blocks cast on the ground or in a column or unit-mould type pretensioning bed, prior to the casting of the concrete in the moulds. The typical pretensioning system is shown in Figure 1.8. The tendons comprising individual wires or strands are stretched with constant eccentricity as shown in (a) or variable eccentricity as in (b) with tendon anchorage at one end and jacks at the other. With the forms in place, the concrete is cast around the stressing tendon.

When the concrete attains sufficient strength, the jacking pressure is released. The high-tensile wires tend to shorten but are restrained by the bond between concrete and steel. In this way, the prestress is transferred to the concrete by bond, mostly near the ends of the beam, and no special anchorages are required in the pretensioned members, except for single wires of larger diameter (exceeding 7mm). Wires less than 7mm diameter anchor themselves satisfactorily with the help of the surface bond and the interlocking of the surrounding matrix in the microindentations on the wires. The bond of prestressing wires may be considerably improved by forming surface indentations and by helical crimping of the wires.
1.2.1.2 Post-tensioned Concrete:

In post-tensioning, the concrete units are first cast by incorporating ducts or grooves to place the tendons. When the concrete attains sufficient strength, the high tensile strength wires are tensioned by means of a jack bearing on the end face of the member and anchored by wedges or nuts. The forces are transmitted to the concrete by means of the end anchorages and, when the cable is curved, through the radial pressure between the wires and the duct. The space between the tendons and the ducts is generally grouted after the tensioning operation.
Chapter Two

OBJECTIVES

In any structural engineering issue, one of the main problems is controlling the deflection of the structure. There are many different methods available to control the deflection in order to increase the life of the structure. One of the methods is prestressing the structural steel in a concrete beam. The main aim of this method is to internally induce the compressive forces to counteract the effects of tensile forces. Concrete is weak in tension. Consequently, prestressing is applied to the beam to decrease the tensile forces. This method can be used to increase the load carrying capacity of the structure, without increasing the section of the members. By means of prestressing, we can control the deflection very effectively.

The main aim of this research was to increase the load carrying capacity of a simply supported beam using a Shape Memory Alloy wire as a prestressed tendon. Instead of steel tendon, a pre-strained Nickel Titanium (NiTi) shape memory alloy wire was used to prestress the concrete beam. The shape memory effect of the NiTi wire was used to prestress the concrete beam. The concrete mix-design was prepared according to ACI 211.1-81. ASTM C39/C 39M-99 was used to find the compressive strength of the concrete, and third-point loading (ASTM C78-94) was used to find out the flexural strength.
Chapter Three

LITERATURE REVIEW

Smart materials and structures have the ability to modify their shape and properties in response to the thermomechanical environment. Shape memory alloys have been major elements of smart materials and structures. Actuators for the control of structures have been designed on the basis of their unique thermomechanical behavior. Because of their shape memory effect, SMAs are very widely used as force and displacement actuators in many fields and applications. These actuators undergo change in shape, stiffness, position, natural frequency, or other mechanical properties when they are subjected to temperature or electromagnetic field (Otsuka et al, 1998).

The first reported steps towards the discovery of the shape memory effect were taken in the 1930s, and in 1951 the shape memory effect was observed in a bar of Gold and Cadmium (AuCd). In the 1960’s, Buehler and Wiley, at the U.S. Naval Ordinance Laboratory, discovered the shape memory effect in an equiatomic alloy of nickel and titanium (www.sma-inc.com). Following is the information about the research already performed on SMA.

3.1 Steven G Shu, Dimitris C Lagoudas, et. al. (1997):

In this research, they developed an electro-thermomechanical model to predict the structural response of a flexible cantilever beam with shape memory alloy wire actuators. A Nitinol SMA was attached externally with an offset at the end of the beam to control
the structural deflection. The SMA wire was pre-strained before being attached to the beam. Then the wire was heated to above its transformation temperature by passing electrical current through the wire. This caused the Nitinol wire to return to its original shape, thereby applying an actuation force on the beam. Experimentally they found that, if the beam deflection is 20% of the beam length, a linear model could approximate the deflection of the beam. For large deflections, non-linear beam model theory was necessary to predict the structural response.

3.2 Sup Choi, Jung Ju Lee (1998):

Tests were performed to study the control of the deflected shape of a composite beam with embedded SMA wire actuators. Experimentally they concluded that, electrical resistance heating of SMA actuators could control the deflected shape of a composite beam under compressive loading.

3.3 C. Liang, C. A. Rogers (1992):

A mathematical model was developed to design shape memory alloy force and displacement actuators, based upon their thermomechanical behavior. For their study, two types of spring actuators were considered. One type was a bias spring, which uses a spring to generate the restoring force. The second type was differential spring actuator, which includes an opposing SMA element, instead of a spring, to generate the restoring force. Based on the mathematical model, they determined the basic design parameters for the two widely used SMA force actuators. This case study gives information about the restrictions and design characteristics of the two types of actuators.
3.4 Andreas G. Mayer, et. al. (2000):

Tests were carried out on SMA wire specimens to determine the degradation of material properties, such as: shape memory effect (SME), and transformation temperature, when the specimen was subjected to a large number of thermal cycles. These tests demonstrated that, there was a change in material transformation temperature and in SMA throughout the thermal process. They concluded that this degradation of physical and mechanical properties of SMA wire can be controlled by appropriate microstructure design of SMA.

3.5 Hiroyuki Tamai, et. al. (2000):

In this research, a new type of the seismic resisting member, with the shape memory alloy wires, was proposed as a hysteretic damper for building structures. Pseudoelastic behavior of SMA was taken into account while conducting tests. The SMA wire was designed to produce pseudoelastic effect at room temperature. Loadings such as, pulsating tension loading tests with constant, increasing and decreasing strain amplitude were performed to investigate the restoring force characteristics of the wire. Based on the above test results, and using a numerical model, the restoring force characteristics of SMA wire under high speed dynamic loading, such as seismic loading, was predicted.

3.6 P Thomson, et. al. (1995):

An experimental test fixture of a cantilever beam constrained by shape memory (NiTi) wires was examined to investigate the application of shape memory alloys to
augment passive vibration dampers in structures. Experimentally, it was observed that,
damping increased significantly, when the shape memory wires were stressed such that
they lie within pseudoelastic hysteresis loop during loading and unloading. The tests
consisted of a cantilever beam with a mass, constrained at the free end by the SMA wires
eexternally. The base of the cantilever beam was excited sinusoidally in a direction
normal to the beam axis. Simulation was done to compare the experimental results with
theoretical.

3.7 S Saadat, et. al. (2000):

An overview of NiTi behavior, modeling and applications as well as their
limitations for structural vibration control and seismic isolation was presented.
Thermomechanical and thermodynamic modeling was used for structural applications
such as seismic and cyclic loading for controlling shape and vibration control.

3.8 A J Zak, et. al. (2003):

In this research, the major differences and similarities between three models
Tanaka, Liang and Rogers, and Brinson were presented and reinvestigated. After
examining the pseudoelastic behavior and shape memory effect (SME), they were able to
conclude that, at high temperatures, all three models agree well in their predictions of the
pseudoelastic behavior. However, at low temperatures, in fully martensitic phase, the
pseudoelastic behavior was not similar. From experimental results they found that, for
investigations of the SME and superelastic behavior of SMA components, the Brinson
model should be applied.
Chapter Four

EXPERIMENTAL PROCEDURE

Problem Statement:

The main aim of this research was to prestress a simply supported concrete beam using a Shape Memory Alloy (SMA). As said earlier, SMAs are materials, which are able to return to some previously defined shape or size when subjected to the appropriate thermal procedure. When a SMA is in the martenstic phase, it can be deformed into any predetermined shape, and it will remain in that shape. The original unstrained shape can be recovered, when the SMA is subjected to a temperature greater than the austenite finish temperature. This phenomenon is called Shape Memory Effect (SME). In this research, the SME of Nitinol SMA was used to prestress the concrete beam. Pre-strained Nitinol was placed in the concrete beam with an eccentricity. Electricity was used to heat that alloy, when the temperature was high enough to cause the SME in Nitinol, the prestressing force was transferred by the bond between the concrete and the alloy.

The experimental procedure listed below includes the step by step process starting from the selection of appropriate Nitinol wire for prestressing to the determination of the flexural strength of the prestressed concrete beam.
4.1 Selection of appropriate nitinol SMA wire for prestressing.

4.2 Selecting the appropriate size of the specimen.

4.3 Selecting the correct mix-design proportions.

4.4 Calculating the prestressing force.

4.5 Test procedure to strain the SMA wire.

4.6 Electrical heating of Nitinol SMA wire to introduce the SME.

4.7 Making and curing the specimens.

4.8 Experimental tests on the specimens.

4.1 Selection of Appropriate Nitinol SMA Wire for Prestressing:

The basic idea of this research project was to determine the prestressing effect of a SMA. Many researchers have used Nitinol as a good actuator because of its good shape memory property. In this experimental testing, SM495, a Nickel Titanium shape memory alloy suitable for shape memory applications, with transformation temperature in between 60-70 degree centigrade, was used.

In the Table 4.1, the physical, mechanical, shape memory properties, and composition of SM495 wire are listed. The diameter of the wire was 0.119 inches and length of the wire was 26 inches.
### TABLE 4.1- Physical, Mechanical, Shape Memory Properties, and Composition of SM495 Wire

<table>
<thead>
<tr>
<th>PHYSICAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point</td>
</tr>
<tr>
<td>Density</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MECHANICAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate Tensile Strength</td>
</tr>
<tr>
<td>Total Elongation (min)</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SHAPE MEMORY PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape Memory Strain (max)</td>
</tr>
<tr>
<td>Transformation Temperature (Aₗ)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel</td>
</tr>
<tr>
<td>Titanium</td>
</tr>
<tr>
<td>Oxygen (max)</td>
</tr>
<tr>
<td>Carbon (max)</td>
</tr>
</tbody>
</table>

In Table 4.1, a range is given for the Modulus of Elasticity, because it depends on the phase (austenite or martensite) of the wire and the temperature of the wire.
4.2 Selecting the Appropriate Size of the Specimen:

Based on the size of the wire and in order to determine the flexural strength of concrete in accordance with ASTM C78, the following dimensions were chosen for the concrete beam.

Height of the specimen = 6 inches.

Width of the specimen = 3 inches.

Length of the specimen = 20 inches.

Cross Sectional area of the specimen = 18 in$^2$.

![Figure 4.1 Details of the Concrete Specimen.](image)

4.3 Selecting the Correct Mix-Design Proportions:

ACI 211.1-81 (Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete) was used to design the correct mix. The following are the properties used in the design of the mix:

4.3.1 Properties of the Coarse Aggregate:

Size of the aggregate: 3/4 inch.

Moisture Content: 0.41%

Total Absorption: 1.88%

Dry-Rodded Density: 110 lb/ft$^3$. 
4.3.2 Properties of the Fine Aggregate:

- Moisture Content: 1.15%
- Total Absorption: 1.12%

Fineness Modulus of the Fine Aggregate: Sieve analysis was performed to determine the fineness modulus of the fine aggregate. Table 4.2 shows the calculations of fineness modulus.

**TABLE 4.2 Test Results of Fine-ness Modulus of Fine Aggregate**

<table>
<thead>
<tr>
<th>Sieve No.</th>
<th>Sieve Opening (mm)</th>
<th>Wt. Retain (lb)</th>
<th>% Retain</th>
<th>Cumulative % Retain</th>
<th>% Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.4</td>
<td>4.75</td>
<td>24.7</td>
<td>1.18</td>
<td>1.18</td>
<td>98.82</td>
</tr>
<tr>
<td>No.8</td>
<td>2.36</td>
<td>253.6</td>
<td>12.12</td>
<td>13.3</td>
<td>86.7</td>
</tr>
<tr>
<td>No.16</td>
<td>1.18</td>
<td>381.4</td>
<td>18.22</td>
<td>31.52</td>
<td>68.48</td>
</tr>
<tr>
<td>No.30</td>
<td>0.60</td>
<td>539.1</td>
<td>25.76</td>
<td>57.28</td>
<td>42.72</td>
</tr>
<tr>
<td>No.50</td>
<td>0.30</td>
<td>587.8</td>
<td>28.09</td>
<td>85.37</td>
<td>14.63</td>
</tr>
<tr>
<td>No.100</td>
<td>0.15</td>
<td>281.9</td>
<td>13.47</td>
<td>98.84</td>
<td>1.16</td>
</tr>
<tr>
<td>Pan</td>
<td></td>
<td>24.3</td>
<td>1.16</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Fineness Modulus of Fine Aggregate: 2.87
4.3.3 *Mix-Design Proportions (Non-Air-Entrained):*

Type of construction: Concrete Beam

Allowed Slump:

Max = 4 inches.

Min = 1 inches.

Nominal maximum size of the coarse aggregate = 3/4 inches.

Approximated mixing water (lb/yd$^3$) for indicated nominal size of the coarse aggregate for desired slump: (A)

Slump = 3 inches.

Nominal size of the coarse aggregate = 3/4 inches.

Weight of water for non-air-entrained concrete = 340 lb/yd$^3$.

Amount of entrapped air = 2%.

Water-Cement ratio:

Compressive strength of concrete (28 days) = 4000 psi.

Water-Cement ratio (W/C) for above strength of concrete = 0.57

Weight of Cement: (B)

$W/C = 0.57$

Weight of water = 340 lb/yd$^3$.

Weight of cement = 596 lb/yd$^3$.

Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of the fine aggregate:

Fineness moduli of fine aggregate = 2.87.

Unit weight of coarse aggregate = 110 lb/ft$^3$. 
Volume of coarse aggregate per unit volume of concrete = 0.613

Weight of Coarse aggregate: (C)

Coarse aggregate weight = 0.613*110*27

= 1821 lb/\text{yd}^3

Estimation of Concrete weight: (D)

Nominal size of the coarse aggregate = 3/4 inches.

Concrete weight based on 3/4 size aggregate = 3960 lb/\text{yd}^3.

Weight of Fine aggregate:

Weight of fine aggregate = D – (A+B+C).

= 1203 lb/\text{yd}^3.

Adjustment of mixing water:

Total moisture in coarse aggregate = 0.41%.

Coarse aggregate weight (wet) = 1821 * 1.004 = 1828 lb/\text{yd}^3.

Total moisture in fine aggregate = 1.15%.

Fine aggregate weight (wet) = 1203 * 1.0115 = 1217 lb/\text{yd}^3.

Percentage absorption of coarse aggregate = 1.88%.

Surface water contributed by the coarse aggregate = 0.41 - 1.88 = -1.41%.

Percentage absorption of fine aggregate = 1.2%.

Surface water contributed by the fine aggregate = 1.15 - 1.2 = -0.05%. 
The estimated requirement for added water = 340 - 1828*(-1.18%)-1217*(-0.05) = 362 lb/yd³.

Final Proportions (lb/yd³):

Weight of water = 362.
Weight of cement = 596.
Weight of coarse aggregate = 1828.
Weight of fine aggregate = 1217.

Batch Proportions (lb):

Batch percentage = 2.25 %.
Weight of water = 8.
Weight of cement = 14.
Weight of coarse aggregate = 42.
Weight of fine aggregate = 28.

4.4 Calculation of Prestressing Force:

As discussed earlier, prestressing was achieved by using the shape memory effect of SMA. The amount of prestressing force stored in the wire was calculated using the stress-strain relations of the SMA wire. Following procedure was used to find out the prestressing force.

The force in the wire was calculated using the following procedure.

Strain in the wire, $\varepsilon = 4\%$.

Modulus of Elasticity from experiments, $E = 3*10^6$ psi.

Stress due to 4% strain, $\sigma = E * \varepsilon = 120000$ psi.

Force in the wire, $P = \sigma * A = 1335 lb$. 
4.4.1 Checking the compressive and tensile strength limits due to the prestress:

Following are assumptions are used to find out the bending stresses in the beam.

- Beam is initially straight and unstressed.
- Plane cross sections remain plane after bending.
- Beam material is homogeneous and isotropic.
- Material properties are same in compression and tension

From the simple beam theory, bending stress in a beam can be calculated using Equation (4.1).

\[
\sigma = \frac{M \cdot I}{y}
\]  

(4.1)

M: Bending Moment due to loading.
I: Moment of Inertia of the beam.
y: Distance from extreme fiber to the neutral axis.

4.4.2 Prestressing force:

Consider a beam as shown in Figure 4.2. The beam was prestressed by a straight tendon carrying a prestressing force, P. The resulting stresses in concrete at any section were obtained by superimposing the effect of prestress and the flexural stresses developed due to the loads.

![Prestressed Rectangular Beam with Zero Eccentricity.](image)

**Figure 4.2** Prestressed Rectangular Beam with Zero Eccentricity.
Following is the procedure to find out the compressive and tensile limits.

Width of the beam = 3 inches.

Height of the beam = 6 inches.

Cross-sectional area of the beam $A_g = 18 \text{ in}^2$.

Moment of Inertia of the rectangular beam:

$$I = \frac{b \cdot h^3}{12} = 54 \text{ in}^4.$$  \hfill (4.2)

Distance from bottom fiber to the neutral axis:

$$y_{\text{bot}} = 3 \text{ inches}.$$  

Distance from top fiber to the neutral axis:

$$y_{\text{top}} = 3 \text{ inches}.$$  

Compressive strength of the concrete: (Experimental mean result in accordance with ASTM C 39/C at 28 days)

$$f_{ci} = 4470 \frac{\text{lb}}{\text{in}^2}.$$  

Unit-weight of the concrete:

$$w_c = 150 \frac{\text{lb}}{\text{ft}^3}.$$  

Length of the concrete beam (L) = 1.67 ft.

Self-weight of the beam:

$$w = A_g \cdot w_c = 19 \frac{\text{lb}}{\text{ft}}.$$  \hfill (4.3)
Moment due to self-weight:

\[ M_{DC1} = \gamma \cdot \left( \frac{w \cdot L^2}{8} \right) = 10lb\cdot ft \]  

(4.4)

Where, \( \gamma = 1.5 \) multiplying factor in handling stage.

Tensile strength limit in the concrete at extreme fiber (ACI 318: 18.4.1.b):

\[ f_{\text{tensile}} = 3 \cdot \sqrt{f_{ci}} = 201 lb/in^2. \]  

(4.5)

Compressive strength limit in the concrete at extreme fiber (ACI 318:18.4.1.a):

\[ f_{\text{comp}} = 0.6 \cdot f_{ci} = 2682 \frac{lb}{in^2}. \]  

(4.6)

Stress at the top fiber: Compression (without any prestress)

\[ f_{\text{top}} = \left( \frac{M_{DC1} \cdot \gamma_{\text{top}}}{I} \right) \]

\[ = \left( \frac{10 \cdot 12 \cdot 3}{54} \right) = 7 \frac{lb}{in^2} < f_{\text{comp}} \quad \text{OK} \]  

(4.7)

Stress at the bottom fiber: Tension (without any prestress)

\[ f_{\text{bot}} = \left( \frac{M_{DC1} \cdot \gamma_{\text{bot}}}{I} \right) = -7 \frac{lb}{in^2} < f_{\text{tensile}} \quad \text{OK} \]  

\[ \text{--ve sign for tension} \]  

(4.8)

Stresses at top & bottom fiber with prestressing force with an eccentricity of one inch:

\[ e = 1 \text{inch}. \]

\[ f_{\text{bot2}} = \left( \frac{M_{DC1} \cdot \gamma_{\text{top}}}{I} \right) + \frac{P}{A_s} + \frac{P \cdot e \cdot c}{I} . \]

\[ = \left( \frac{10 \cdot 12 \cdot 3}{54} \right) + \frac{1335}{18} + \frac{1335 \cdot 1 \cdot 3}{54} \]

\[ = 141 lb/in^2 < f_{\text{comp}} \quad \text{OK} \]  

(4.9)
From Equation (4.9), stress in the bottom fiber is compressive, and this stress is within the compressive limit.

\[
f_{top2} = \left( \frac{M_{pck} \cdot y_{top}}{I} \right) + \frac{P}{A_g} - \frac{P \cdot e \cdot c}{I} \\
= \left( \frac{12 \cdot 12 \cdot 3}{54} \right) + \frac{1335}{18} - \frac{1335 \cdot 1 \cdot 3}{54} \\
= 7 \frac{lb}{in^2} < f_{comp}\text{ OK (4.10)}
\]

Due to eccentricity, stress in the top fiber is compressive. And this compressive stress is also within the compressive limit.

For \( P = 1335 \text{ lb.} \) both tensile and compressive stresses were within the allowable stress limits.

**4.5 Test Procedure to Strain the NiTi SMA Wire:**

The maximum recoverable strain for the SMA495 wire is 8%. In order to induce the shape memory effect, depending on the prestressing force, 4% strain is necessary in the wire. Consequently 4% strain was induced in the wire using Tenius Olsen H50KS tensile machine as shown in Figure 4.3.
Figure 4.3 Tenius Olsen (H50KS) Tensile Machine.

The tensile machine consists of two heads. One is fixed and the other one is movable. It consists of one LCD screen, on which the results were shown. The unstrained NiTi SMA was placed in between two jaws, and the jaws were attached to the heads. The jaws and the test setup are shown in Figure 4.4. Tensile load was applied until the required strain in the wire was obtained.
Figure 4.4 Jaws & Test Setup in Tensioning the wire.

Load and the strain results are shown in Table 4.3. The load that was required in order to obtain the 4% strain was dependent on the temperature of the wire.
Table 4.3 Test Results from the Tensile Machine at Room Temperature.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Original Length of the Wire (inches)</th>
<th>Percentage of Strain</th>
<th>Length of the Wire after the Test (inches)</th>
<th>Load (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26</td>
<td>4</td>
<td>27.04</td>
<td>169</td>
</tr>
<tr>
<td>2</td>
<td>26</td>
<td>4</td>
<td>27.04</td>
<td>148</td>
</tr>
<tr>
<td>3</td>
<td>26</td>
<td>4</td>
<td>27.04</td>
<td>145</td>
</tr>
<tr>
<td>4</td>
<td>26</td>
<td>4</td>
<td>27.04</td>
<td>169</td>
</tr>
</tbody>
</table>

4.6 Electrical Heating of Nitinol SMA Wire to Introduce the SME:

At room temperature, SMA495 Nitinol wire is in the martensite phase. According to manufacturer (www.nitinol.com) specifications, the transformation finish or austenite finish temperature is 60 degrees centigrade. In order to induce the SME in the nitinol wire, the temperature of that wire was increased to 60 degrees centigrade.

There are many different heating methods available to increase the temperature of the alloy; one of them is the electrical heating method. Utilizing this method, electricity was allowed to pass directly through the wire until it reached the transformation finish or austenite finish temperature. This transformed the wire back to its original parent austenite phase.

At room temperature SM495 nitinol SMA has the following properties.

Coefficient of thermal expansion, \( \alpha \) : \( 6.6 \times 10^{-6} \text{ / C} \).

Electrical Resistivity, \( \rho \) : \( 30 \times 10^{-6} \Omega \text{ – in}. \)
Resistance of the nitinol wire was calculated using Equation (4.11).

$$R = \frac{\rho \cdot L}{A} \cong 0.07\Omega$$

Where \( L = 26\text{ inches} \),
\[ A = 0.011309\text{ in}^2. \tag{4.11} \]

The above resistance was calculated for room temperature (around 20 degrees centigrade). It is necessary to calculate the resistance of the wire when the transformation is completed at a temperature greater than the 60 degrees centigrade. Equation (4.12) was used to calculate the electrical resistance of the Nitinol SMA wire at temperature greater than the 60 degrees centigrade. For example, for a final temperature of 100 degrees centigrade, the resistance of the wire was calculated by Equation (4.12).

$$R_f = R_o (1 + \alpha (T - T_o))$$ \tag{4.12}

Where \( R_f \) = Resistance at 100 degrees centigrade,
\( R_o \) = Resistance at room temperature,
\( T \) = 100 degrees centigrade,
\( T_o \) = 20 degrees centigrade.

Therefore \( R_f = 0.07\Omega \).

Consequently, if the temperature of the wire was increased until it reached 100 degrees centigrade, there was no change in the electrical resistance.

In order for the SM495 Nitinol wire to induce the shape memory effect, approximately 20 amperes of current was allowed to pass through the wire. The experimental setup is shown in Figure 4.5, where a three-ohm resistor was connected in series with the wire to the power supply. In the experiment, the current was allowed to
pass through the wire for three minutes to reach the austenite finish temperature (60-70 degrees centigrade). An infrared thermometer was used to determine the temperature of the wire while heating. The shape recovery was completed when the wire temperature was reached to the austenite finish temperature.

Figure 4.5 Electrical Heating of Nitinol (SM495) Wire.

4.7 Making and Curing the Test Specimens:

Cylindrical specimens for compressive strength, and beam specimens for flexural strength were made according to ASTM C192 (Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory). The curing chamber was used to moisture cure the test specimens for the required age of the tests.
4.7.1 Sample Data in Making Cylindrical and Flexural Specimens:

The concrete mix was prepared according to ACI 211.1-81, cylindrical specimens and flexural specimens were made according to ASTM C192, ASTM C 39/C, and ASTM C78-94. Table 4.4 shows the concrete mix proportions used in the preparation of specimens.

**TABLE 4.3 Concrete Proportions Used in Preparing the Test Specimens.**

<table>
<thead>
<tr>
<th>Type of Test</th>
<th>Volume of Concrete (in³)</th>
<th>Concrete Mix Proportions (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Water</td>
</tr>
<tr>
<td>Compression</td>
<td>3</td>
<td>1017</td>
</tr>
<tr>
<td>Flexure</td>
<td>3</td>
<td>1080</td>
</tr>
</tbody>
</table>

4.8 Experimental Tests on the Specimens:

The test procedure used to prepare the cylindrical specimens for the compressive strength tests and the rectangular beam specimens for the flexural strength tests follows.

4.8.1 Compressive Strength of the Concrete:

ASTM C 39/C procedure was used to determine the compressive strength of the cylindrical concrete specimens. Compressive strength tests were carried out on cylinders of age seven, fourteen, and twenty-eight days. The compressive strength of the specimen was calculated by dividing the maximum load attained during the test by the cross-sectional area of the specimen.

\[
\sigma = \frac{P}{A}.
\]  

(4.13)
Where, $P =$ Maximum load attained during the test, lb,

$A =$ cross sectional area of the cylindrical specimen, $\text{in}^2$.

Figure 4.6 shows the test setup used to determine the compressive strength of a cylindrical concrete specimen.

![Figure 4.6 Compressive Strength of Cylindrical Concrete Specimen Test Setup.](image)

4.8.2 Flexural Strength of Concrete:

The flexural strength of the concrete was calculated according to the specifications of ASTM C78-94. Figure 4.7 shows the graphical representation of the third-point loading flexural strength test.
4.8.2.1 Calculation of Modulus of Rupture:

In accordance with ASTM C78, if the crack initiated on the tension surface within the middle third span length, the modulus of rupture was calculated by Equation (4.14):

\[
R = \frac{P \cdot L}{b \cdot h^2}. \quad (4.14)
\]

Where, \( R \) = Modulus of rupture, psi,

\( P \) = Maximum applied load indicated on the machine, lb,

\( L \) = Span length, in,

\( b \) = Average width of the specimen, in,

\( h \) = Average height of the specimen, in, at the fracture.

In accordance with ASTM C78, if the fracture occurred on the tension surface outside of the middle third of the span length, the modulus of rupture was calculated by Equation (4.15):

\[
R = \frac{3 \cdot P \cdot a}{b \cdot h^2}. \quad (4.15)
\]
Where, \( a = \) average distance between line of fracture and the nearest support, measured on the tension surface of the beam, in.

In this research, flexural capacity was calculated for the following conditions:

- Beam without any reinforcement.
- Beam with unstrained SMA reinforcement.
- Beam with strained (4%) SMA reinforcement.

Figure 4.8 & Figure 4.9 show the test setup of third-point loading and a specimen after failure (without any reinforcement).

**Figure 4.8** Flexural Strength Test Setup (Third-Point Loading).
Three specimens were tested without any reinforcement for flexural capacity. From Figure 4.10, it is clear that the cracks were initiated within the middle third of the span length. Figure 4.11 and 4.12 shows the test setup of the electrical heating of the embedded SMA wire in the concrete and the flexural test of the prestressed beam. Figure 4.12 shows that cracks were developed in the tension side during the loading process.

**Figure 4.9** Concrete Beam in Third-Point Loading Test.
Figure 4.10 Figure showing Cracks in the Middle-Third of Span Length.
Figure 4.11 Electrical Heating of Embedded SMA wire.
Figure 4.12 Flexural Test of Prestressed Concrete Beam.
5.1 Experimental Results from Tensile Test:

Tensile tests were performed on the three different Nitinol SMA wires in order to determine the load-elongation behavior at different temperatures.

Dry ice was used to bring the wire temperature to nearly zero degrees centigrade. While at zero degrees centigrade, the Tenius Olsen tensile machine was used to pull the wire, until the wire reached its ultimate tensile strength. Table 5.1 shows the test results, and Figure 5.1 shows the load-elongation behavior at zero degrees.

A second wire was tested at room temperature. Tests results are in Table 5.2, and load-elongation behavior is shown in Figure 5.2.

Third wire was tested at the austenite finish temperature. Electricity was used to raise the temperature of the wire up to the austenite finish temperature of 60 degrees centigrade. Table 5.3 shows the test results, and Figure 5.3 shows the load-elongation behavior.

Comparison of three the tests are shown in Figure 5.4.
### TABLE 5.1 Tensile Test Results at Zero Degrees Centigrade.

<table>
<thead>
<tr>
<th>Length of the Specimen (in)</th>
<th>Maximum Load at Failure (lb)</th>
<th>Maximum Elongation (in)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1980</td>
<td>2.15</td>
<td>178</td>
<td>$3.1 \times 10^6$</td>
</tr>
</tbody>
</table>

Figure 5.1 Load-Elongation Behavior of Nitinol SMA wire at Zero Degrees Centigrade.
TABLE 5.2 Tensile Test Results at Room Temperature.

<table>
<thead>
<tr>
<th>Length of the Specimen (in)</th>
<th>Maximum Load at Failure (lb)</th>
<th>Maximum Elongation (in)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2000</td>
<td>2.1</td>
<td>180</td>
<td>3.0*10^6</td>
</tr>
</tbody>
</table>

Figure 5.2 Load-Elongation Behavior of Nitinol SMA wire at Room Temperature.
TABLE 5.3 Tensile Test Results at Austenite Finish Temperature.

<table>
<thead>
<tr>
<th>Length of the Specimen (in)</th>
<th>Maximum Load at Failure (lb)</th>
<th>Maximum Elongation (in)</th>
<th>Ultimate Tensile Strength (ksi)</th>
<th>Modulus of Elasticity (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2000</td>
<td>2.05</td>
<td>180</td>
<td>3.0*10^6</td>
</tr>
</tbody>
</table>

Figure 5.3 Load-Elongation Behavior of Nitinol SMA wire in-between 60-70 Degrees Centigrade (Austenite Finish) Temperature.
Figure 5.4 Comparison of Three Tensile Test Results.
5.2 Test Results of Compressive Strength of Concrete:

ASTM C 39/C was used to determine the compressive strength of cylindrical concrete specimens. Tests were carried on specimens of age seven days, fourteen days, and twenty-eight days. A total of nine specimens were tested. Three specimens were tested at age seven days. Three specimens were tested at age fourteen days, and three specimens were tested at age twenty-eight days. All nine specimens were made from same mix, but they are not from the same batch. Specimens A1, A2, A3 were from same batch. Specimens B1, B2, and B3 were from a different batch. Specimens C1, C2, and C3 are from a third batch. Table 5.4 shows the test results at different ages and Table 5.5 shows mean compressive strength of cylindrical specimens. Figure 5.5 shows mean compressive strength of the cylindrical specimens.

5.3 Test Results of Flexural Strength of Concrete Specimens:

ASTM C78-94 was used to determine the flexural strength of the concrete. A total of ten specimens were tested. Three specimens (D1 to D3) were made with plain concrete, without any reinforcement. Three specimens (E1 to E3) were made from a different batch with SMA wire that was not prestressed. Four specimens (F1 to F4) were made from a third batch with prestressed Nitinol SMA reinforcement. Details of flexural test are presented in Tables 5.6 and Table 5.7. Figure 5.6 shows the mean flexural strength of the concrete beam specimens.
### TABLE 5.4 Compressive Strength of Cylindrical Concrete Specimen at 7, 14, and 28 Days.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Age (Days)</th>
<th>Maximum Load (lb)</th>
<th>Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>7</td>
<td>79250</td>
<td>2800</td>
</tr>
<tr>
<td>A2</td>
<td>7</td>
<td>85000</td>
<td>3010</td>
</tr>
<tr>
<td>A3</td>
<td>7</td>
<td>90000</td>
<td>3180</td>
</tr>
<tr>
<td>B1</td>
<td>14</td>
<td>115000</td>
<td>4070</td>
</tr>
<tr>
<td>B2</td>
<td>14</td>
<td>117400</td>
<td>4150</td>
</tr>
<tr>
<td>B3</td>
<td>14</td>
<td>122000</td>
<td>4310</td>
</tr>
<tr>
<td>C1</td>
<td>28</td>
<td>124600</td>
<td>4410</td>
</tr>
<tr>
<td>C2</td>
<td>28</td>
<td>126500</td>
<td>4471</td>
</tr>
<tr>
<td>C3</td>
<td>28</td>
<td>127600</td>
<td>4510</td>
</tr>
</tbody>
</table>

### TABLE 5.5 Mean Compressive Strength of Cylindrical Specimens.

<table>
<thead>
<tr>
<th>Age (Days)</th>
<th>Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>3000</td>
</tr>
<tr>
<td>14</td>
<td>4180</td>
</tr>
<tr>
<td>28</td>
<td>4470</td>
</tr>
</tbody>
</table>
Figure 5.5 Mean Compressive Strength of Cylindrical Specimens
TABLE 5.6 Flexural Strength of the Concrete Beam

<table>
<thead>
<tr>
<th>Specimen Number</th>
<th>Description</th>
<th>Maximum Load Applied (lb)</th>
<th>Modulus of Rupture (psi)</th>
<th>Cracking Moment (Experimental) (lb-in)</th>
<th>Ultimate Moment (Theoretical) (lb-in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>Beam of Plain Concrete</td>
<td>4830</td>
<td>805</td>
<td>14490</td>
<td>NA</td>
</tr>
<tr>
<td>D2</td>
<td>Beam of Plain Concrete</td>
<td>4870</td>
<td>810</td>
<td>14580</td>
<td>NA</td>
</tr>
<tr>
<td>D3</td>
<td>Beam of Plain Concrete</td>
<td>4910</td>
<td>820</td>
<td>14760</td>
<td>NA</td>
</tr>
<tr>
<td>E1</td>
<td>Beam with Un-Prestressed SMA Wire</td>
<td>4730</td>
<td>790</td>
<td>14220</td>
<td>4210</td>
</tr>
<tr>
<td>E2</td>
<td>Beam with Un-Prestressed SMA Wire</td>
<td>4850</td>
<td>810</td>
<td>14580</td>
<td>4210</td>
</tr>
<tr>
<td>E3</td>
<td>Beam with Un-Prestressed SMA Wire</td>
<td>4900</td>
<td>820</td>
<td>14760</td>
<td>4210</td>
</tr>
<tr>
<td>F1</td>
<td>Beam with Pre-Stressed SMA wire</td>
<td>5300</td>
<td>885</td>
<td>15930</td>
<td>4210</td>
</tr>
<tr>
<td>F2</td>
<td>Beam with Pre-Stressed SMA wire</td>
<td>5300</td>
<td>885</td>
<td>15930</td>
<td>4210</td>
</tr>
<tr>
<td>F3</td>
<td>Beam with Pre-Stressed SMA wire</td>
<td>5400</td>
<td>900</td>
<td>16200</td>
<td>4210</td>
</tr>
<tr>
<td>F4</td>
<td>Beam with Pre-Stressed SMA wire</td>
<td>5500</td>
<td>920</td>
<td>16560</td>
<td>4210</td>
</tr>
</tbody>
</table>
**TABLE 5.7 Mean Flexural Strength of the Concrete Beam**

<table>
<thead>
<tr>
<th>Description</th>
<th>Modulus of Rupture (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam of Plain Concrete</td>
<td>810</td>
</tr>
<tr>
<td>Beam with Un-Prestressed SMA wire</td>
<td>805</td>
</tr>
<tr>
<td>Beam with Pre-Stressed SMA wire</td>
<td>900</td>
</tr>
</tbody>
</table>

![Mean Flexural Strength](image)

**Figure 5.6** Flexural Strength of Prestressed Beam Vs Plain Concrete.
5.4 Analysis of Test Results:

From the experimental results, it is clear that some prestress was transferred through the bond between the wire and the concrete, when the wire temperature reached the austenite finish temperature. Because of this prestress, the modulus of rupture increased some over the plain concrete beam without any prestressed wire.

It is necessary to determine the amount of prestress transferred during the heating process. The following procedure was used to determine the prestressing force that helped to increase the flexural capacity of the beam.

5.4.1 Force in the SMA Wire:

The force in the wire was calculated using the following procedure.

Strain in the wire, $\varepsilon = 4\%$.

Modulus of Elasticity from experiments, $E = 3 \times 10^6$ psi.

Stress due to 4% strain, $\sigma = E \varepsilon = 120000 \text{ psi}$. (5.1)

Force in the wire, $P = \sigma A = 1335 \text{ lb}$. (5.2)

5.4.2 Prestress Transferred through the Bond:

Simple beam theory was used to find out the how much prestress was transferred.

5.4.2.1 Cracking Moment of Plain Concrete Beam without any Reinforcement:

Mean modulus of rupture, obtained experimentally, $\sigma_r = 810 \text{ psi}$.

Using the simple beam bending theory, the ultimate moment of resistance is calculated.
\[ M_r = \frac{\sigma_r * I}{(h/2)} \]

Cracking Moment, \[ = \frac{910 * 54}{3} \]

\[ = 14.6 \text{kip in} \]  

Where, \( h \) = total height of the beam, 6 in.  

\( I \) = moment of inertia, 54 in\(^4\).

5.4.2.2 Moment of Resistance (Ultimate Moment) of Concrete Beam with Un-Prestressed SMA Reinforcement:

Reinforced concrete beam moment of resistance was calculated by Equation (5.4).

The stress and strain distribution in a rectangular beam is shown in Figure 5.14.

**Figure 5.14** Stress and Strain Distribution in a Rectangular Beam.

\[ M_{ult} = A_s * f_y (d - \frac{a}{2}) \quad \text{or} \]

Ultimate moment of resistance  

\[ M_{ult} = 0.85 * f_c * b * a (d - \frac{a}{2}) \]  

(5.4)

Where, \( A_s \) = area of SMA wire, in\(^2\).

\( f_y \) = yield strength of SMA wire, ksi.
\( f_c = \) compressive strength of concrete, ksi.

d = distance from extreme compression fiber to the centroid of SMA wire, in.

c = depth of the neutral axis measured from extreme compression fibers, in.

\[ a = \beta_1 \times c \]

\( \beta_1 = \) compression zone factor given ACI 318-89

Therefore \( M_{ult} = 4.21 \text{kip.in} \)

Cracking moment (experimentally) \( M_{cr} = 14.9 \text{kip.in} \).

Ratio of cracking moment to ultimate moment \( \left( \frac{M_{cr}}{M_{ult}} \right) = 3.54 \).

5.4.2.3 Moment of Resistance of Concrete Beam with Pre-Stressed SMA Wire:

The cracking resistance of prestressed beam includes, moment of resistance of plain concrete and moment due to the prestressing force.

Experimental Mean Modulus of Rupture from Flexure theory \( \sigma_T = 900 \text{ psi} \).

Cracking Moment \( M_T = \frac{\sigma_T \times I}{(h/2)} = 16.2 \text{kip.in} \)

Considering the bottom fiber stresses in calculating the prestressing force;

\[ -\sigma_T = -\sigma_y + \sigma_p \]

\[ -\sigma_T = -\sigma_y + \left[ \frac{P \times e \times c}{I} + \frac{P}{A} \right] \]

(5.5)

Where, \( \sigma_T = 900 \text{ psi} \).

\( \sigma_y = 810 \text{ psi} \). (Experimental modulus of rupture from plain concrete)

e = eccentricity of SMA wire from neutral axis, 1 in.

c = distance from neutral axis to extreme compression fiber, 3 in.
A = cross sectional area of the concrete, 18 in\(^2\).

\[ I = \text{moment of inertia of the rectangular beam, 54in}^4. \]

Therefore, \( \sigma_p = \left[ \frac{P \cdot e \cdot c}{I} + \frac{P}{A} \right] = 90 \text{ psi.} \quad (5.6) \)

From Equation (5.6), \( P = 810 \text{ lb.} \)

Therefore, 810 lbs of force was transferred to the concrete beam in the prestressing process.

5.4.3 Percentage loss in prestress:

Prestressing force in the SMA wire \( P_p = 1335 \text{ lb.} \)

Actual prestressing force transferred to the beam \( P_a = 810 \text{ lb.} \)

Percentage loss of prestress \( = \frac{P_p - P_a}{P_p} = 39.32\% \). \quad (5.7)

Percentage transfer of prestress = 60.68\%.

From above results it is clear that, there was a significant loss in prestress transfer. If we can reduce the prestress loss by increasing the bond between the SMA wire and the concrete, we can significantly increase the flexure strength of the prestressed concrete beam.

5.4.4 Development Length:

In accordance with ACI 318:12.9.1, development length is calculated only for three or seven wire pretensioning strands not for plain wire. Assuming that if a three or seven wire strand was used in this research, the development length is calculated using Equation (5.8).
\[ l_d = \left( f_{ps} - \frac{2}{3} f_{se} \right) \cdot d_p \]
\[ = \left( 120 - \frac{2}{3} \cdot 72.8 \right) \cdot 0.119 \]
\[ = 8.50 \text{in.} \quad (5.8) \]

Where, \( l_d \) = development of length, in.

\( f_{ps} \) = stress in the prestressed wire, ksi.

\( f_{se} \) = effective stress in the prestressed wire after allowing all prestress losses, ksi.

\( d_p \) = diameter of the prestressed wire, in.

However, the actual length available in the experimental beam was only seven inches on each side of the region of the maximum flexural stress. Consequently, the wire had not developed its full capability at all locations where maximum stress was applied.
Chapter Six

CONCLUSION & FUTURE WORK

The application of prestressing to increase the flexure strength of the concrete beam was investigated in this research. A Nitinol shape memory alloy was used to prestress the concrete beam. The study focused on the shape memory effect of a Nitinol wire in prestressing the simply supported concrete beam.

In the tensile test, the Nitinol wire was tested at three different temperatures. It is evident that the ultimate tensile strength (UTS 180ksi) and the elongation (2.05 in) at UTS were not affected by temperature. From load-elongation curve the modulus of elasticity ($3\times10^6$psi) was calculated, and it was same for all three temperatures.

From experimental results it can be concluded that, the flexural strength of the concrete beam was increased when prestressed Nitinol wire was placed in the concrete. From this it is clear that, the prestress was transferred during the electrical heating of the Nitinol SMA wire.

The total prestress losses were found to be 39%. From this it can be concluded that, slippage occurred during the prestressing process. The total loss includes loss due to slip, loss due creep and shrinkage.

Heat of hydration during the curing process might be one of the reasons for the prestress loss.
The Flexural strength of the prestressed concrete beam can be significantly increased by increasing the bond between the concrete and the SMA wire.

The ultimate moment of the beam was always less than that the cracking moment. From this it can be concluded that the beam behaved elastically throughout the loading process, because the beam failed when it reached the cracking moment.

In this research, the prestressing was achieved using the shape memory property of the Nitinol wire. This property purely depends on the temperature of the wire. If the temperature of the wire decreased beyond the martensitic finish temperature, it can affect the load carrying capacity of the structure.

Recommendations:

In future, more research is needed to prevent the loss of bond and also more research needs to be done in this area before implementation in real life application.

In the tensile tests, the modulus of elasticity was calculated using the slope of the loading curve. Better results can be found if the modulus of elasticity was obtained for the slope of the unloading curve.

Care needs to be taken to decrease the development length by increasing the bond strength between the concrete and the wire.

Controlling the deflection is the key factor in the prestressing process, but in this research, it was not measured during the flexural test of the prestressed beam. The ultimate load is same for the prestressed and conventional reinforced beam, but the deflection at the ultimate load is different. For better results, deflection should be measured for both prestressed and conventional reinforced concrete beam.
REFERENCES


American Concrete Institute, “Structural Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete,” ACI 211.1-81, 1981.


http://www.sma-inc.com


http://smart.tamu.edu/overview/smaintro/detailed/detailed.html

http://www.unipv.it/dms/auricchio/Research/Sma/sma_what.htm

http://www.nitinol.com