REINFORCED CONCRETE: APPLICABILITY OF SMART MATERIALS

By

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ABSTRACT

With aging infrastructure, not only in the United States, but worldwide, we look toward designing structures which can withstand the test of time. Creating structures that can adapt to changes in the environment and provide better performance is at the forefront of current research. Reinforced concrete, one of the most widely used materials, can be reinvented using this philosophy.

In this thesis, smart materials are classified as materials which can provide sensing, actuation or self-repair. Three different smart materials were studied including self-healing concrete which provides self-repair, shape memory alloys as reinforcement for reinforced concrete which provides actuation and carbon fiber reinforced concrete which provides sensing. It was found that each smart material had potential to improve the performance of reinforced concrete structures. Factors that affect larger scale implementation are discussed.

Thesis Supervisor: Jerome Connor
Title: Professor of Civil and Environmental Engineering

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I am deeply thankful for being at M.I.T and all that I have achieved this year!

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My Family: Thank you for your love and support!

Justin: Thank you for your patience and support throughout this entire year! Couldn't have done it without you! Love you!

Table of Contents

ABSTRACT **2**

TABLE OF CONTENTS **4**

TABLE OF FIGURES **5**

1.0 INTRODUCTION **6**

2.0 SELF-HEALING CONCRETE **9**

2.1 INTRODUCTION 9

2.2 AUTOGENIC HEALING 10

2.3 ENCAPSULATION 12

2.3.1 Introduction *12*

2.3.2 Healing Agents *15*

2.4 MICROBIAL CONCRETE 17

2.4.1 Introduction *17*

2.4.2 Developments in Microbial Concrete *18*

2.5 IMPLEMENTATION 22

3.0 SHAPE MEMORY ALLOYS **23**

3.1 WHAT ARE SHAPE MEMORY ALLOYS? 23

3.2 SMA WIRES IN REINFORCED CONCRETE 26

3.3 EXPECTED SEISMIC PERFORMANCE OF SMAS IN REINFORCED CONCRETE 29

3.4 IMPLEMENTATION 34

4.0 CARBON FIBER REINFORCED CONCRETE **35**

4.1 INTRODUCTION 35

4.2 CARBON FIBER REINFORCED CONCRETE'S ABILITY TO SENSE DAMAGE 36

4.3 IMPLEMENTATION 40

5.0 CONCLUSION **42**

6.0 REFERENCES **44**

Table of Figures

Figure 1: Possible Causes of Autogenic Self-Healing [28] 10
Figure 2: Example of epoxy-filled glass tube [28] 13
Figure 3: Basic microcapsule approach (i) cracks form (ii) microcapsule is ruptured releasing healing agent (iii) healing agent contacts catalyst, polymerization occurs closing crack [28] 14
Figure 4: Schematic of crack healing by concrete-immobilized bacteria [28] 17
Figure 5: Decomposition of Urea [25] 20
Figure 6: Tensile and Compressive Strength of Specimens Containing Organic Substrate [15] . 21
Figure 7: Temperature Induced Martensite Transformation [22] 24
Figure 8: (a) Shape Memory Effect (b) Superelasticity, [8] 25
Figure 9: Stress-Strain for Constrained SMA [17] 26
Figure 10: Potential Deflection Control System for Beam [7] 27
Figure 11: Potential Reinforcement of a beam using SMAs [5] 28
Figure 12: Relationship between overstrength & ductility [2] 30
Figure 13: Capacity/Demand Ratio in terms of Base Shear & Roof Drift [2] 31
Figure 14: Untreated (left) and Ozone treated Fibers (right) [6] 38

1.0 Introduction

Currently in the United States, there are a lot of issues surrounding the maintenance of infrastructure, most of which is less than a century old. Maintenance and inspection, especially of concrete structures, is quite expensive, however it must be done in order to ensure public safety. In the United States, the quality of our infrastructure is directly related to the cost of doing business. It is estimated that in less than 10 years, deficient infrastructure will cost businesses almost $430 billion in transportation costs. This drives up expenses, which leads to a decrease in company profits. People recognize the need for a strong, healthy infrastructure however; repairs are just not enough [13]. Infrastructure must be modernized. With major technological developments, especially in the construction industry, focus should be placed on designing structures that will withstand the test of time.

Bridges, tunnels, roads and buildings all represent vital infrastructure. Reinforced concrete can be used in all these structures. For simplicity, reinforced concrete essentially has two main parts: the concrete matrix and the reinforcing bars. Concrete itself is one of the most commonly used construction materials. It is strong, durable and relatively inexpensive. Concrete is a quasi-brittle material which is strong in compression, but weak in tension. In order to give reinforced concrete structures more tensile capacity, steel reinforcing bars are used. The use of reinforcement allows for the transfer of tensile stress from the concrete to the steel, thereby increasing its load capacity.

One of the major problems with reinforced concrete is that it tends to crack easily, especially under tensile loading. The formation of cracks is considered an inherent feature of reinforced concrete. Microcracks are almost unavoidable in reinforced concrete. This combined with cracks due to loading, may reduce the overall durability of the reinforced concrete structure. If the cracks (marco- and micro-cracks) form a continuous network, the permeability may increase significantly. This will reduce the concrete's resistance against the ingress of aggressive substances and may lead to the corrosion of the reinforcing steel. Corrosion of the reinforcing steel is the major reason for premature failure of concrete structures [20], [27]. The prevention of cracks or devising a mechanism to heal cracks is essential to maintaining healthy reinforced concrete structures.

Another issue with reinforced concrete structures is the ability of the structure to withstand seismic forces. This is most directly related to the design of the reinforcement within the reinforced concrete structure. Members designed for seismic loading must perform in a ductile fashion and dissipate energy in a way that will not compromise the strength of the structure. This is usually done by providing adequate transverse and longitudinal reinforcement as well as adequate concrete confinement. Many reinforced concrete structures have failed under seismic loads in the past due to insufficient reinforcement. Being that seismic loading is becoming increasingly important in the design of structures, it is important that reinforcement be designed appropriately to prevent catastrophic damage.

Finally, the monitoring of structures is becoming ever more important. Extreme events reveal the inadequacies of past structures. Finding ways to monitor structures, and predict their life span can play an important role in preventing the failures of structures. Monitoring techniques for reinforced concrete include visual inspections and nondestructive methods such as ultra sound and other wave propagation methods. However, these methods tend to be labor intensive and may not provide the most accurate results. More recently, the addition of embedded sensors into concrete structures and the addition of piezoelectric materials have become popular for structural health monitoring. Each of these techniques has its own advantages and disadvantages. Finding a way to monitor the reinforced concrete structure for damage could help extend the life-span of the structure.

Finding solutions to these issues could potentially enhance the service life of concrete structures. The increase in service life will reduce the demand for new structures. However, the increase in service life means that the structure will probably encounter new loads and conditions and must still be serviceable. In the past, structures were designed to meet predefined specifications at the start of their lives. However, scientists and designers have begun looking at a more active approach where a structure is able change its performance based on these new loads and conditions. Systems that can automatically adjust structural characteristics in response to external disturbances in order to improve performance thereby extending the structure's life time and serviceability are known as smart systems or structures. An important development needed to produce smart structures is the development and implementation of smart materials. Smart materials are engineered materials that are able to provide a unique beneficial response when a

particular change occurs in the surrounding environment [20]. Smart materials can provide self-repairing, actuation and/or sensing capabilities. Smart materials can be integrated into structures and provide functions such as sensing, actuation and information processes needed for monitoring [22].

Using this new philosophy of building structures that react to the environment, let us explore the applicability of smart materials to the most basic building material; reinforced concrete. Smart materials such as self-healing concrete, shape memory alloys for use as reinforcement and carbon fiber reinforced concrete for damage sensing are explored. Their applicability to the civil engineering field is discussed.

2.0 Self-Healing Concrete

2.1 Introduction

Self-repair of materials is still in the early stage of development. However, the development of such materials could drastically reduce or eliminate the need for regular inspection or monitoring since the material would be able to repair itself once damage has been inflicted. In order for a material to possess a self-repair capability, it must have the following three attributes. First, the material must have the means for internal storage of the repairing material. Secondly, the material must have some way of releasing the repairing material when needed and lastly, the material must repair itself (i.e. the repair agent must work) [18]. Self-repairing has been studied in polymers, coatings and composites.

Cracks due to shrinkage and external loading are unavoidable in reinforced concrete structures. However, care must be taken to limit the propagation of such cracks. Cracks have the potential to facilitate the ingress of aggressive and harmful substances into the concrete therefore significantly reducing the durability of the structure. Although, the presence of cracks does not necessarily represent a safety issue, they are undesirable for many reasons including aesthetics, increased permeability and functional issues. Finding a mechanism in which these cracks can be successfully healed can increase the service life of the structure.

In concrete, two types of self-repair have been studied: autogenic and autonomic. Autogenic healing refers to the ability of a material to repair itself without any external trigger. Cementitious materials have an innate ability to repair themselves. The most common reason is due to water reacting with pockets of unhydrated cement in the matrix [20]. Autonomic healing refers to healing due to the release of an internally embedded healing agent. Two commonly used methods are encapsulation and the incorporation of bacteria. Both of these methods can be effective in healing cracks, but each has some limitations to implementation.

The main idea behind self-healing concrete is that upon the emergence of small cracks, the concrete will begin repairing itself, therefore the structure will regain its original or close to original level of performance. This process will continue through time thereby increasing the life-span of the structure. Even though the implementation of such a material will lead to higher initial costs, it is believed that having a high quality material will result in the postponement of

repairs, thus the overall reduction in the costs associated with maintenance and repair will begin yielding a financially positive situation for the owner [20]. Enhancing the longevity of our infrastructure in a way that is environmentally friendly and financially sound will undoubtedly become increasingly important in the future.

2.2 Autogenic Healing

Autogenic healing is a natural phenomenon that has been known for many years. It is most closely associated with old concrete structures which have lasted centuries due to the healing of cracks, preventing their propagation and extending the longevity of the structure. The advantage of autogenic healing over autonomic healing is that the healing material is inherent in the structure and requires no additional consideration. As long as there is unreacted cement and water, the healing can occur.

Self-healing of cracks in cementitious materials is considered to be based on chemical, mechanical and physical processes. The figure below shows some of the possible causes of the self-healing phenomenon. These include: a. formation of calcium carbonate or calcium hydroxide, b. blocking cracks by impurities in the water and loose concrete particles c. further hydration of the unreacted cement or cementitious materials and d. expansion of the hydrated cementitious matrix in the crack flanks (swelling of C-S-H) [20], [28].

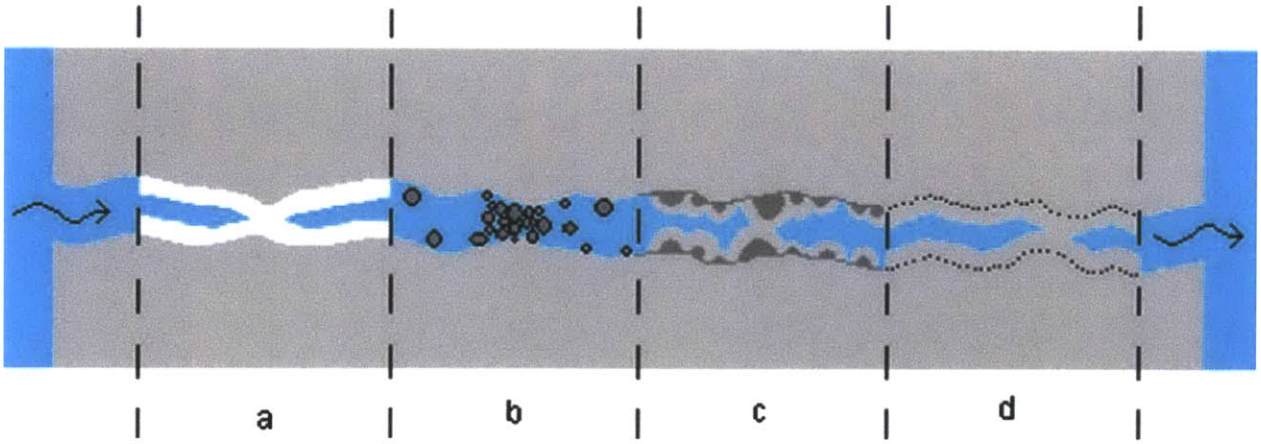

Figure 1: Possible Causes of Autogenic Self-Healing [28]

Some researchers have investigated the mechanism of self-healing in water filled cracks and concluded that further hydration of unhydrated cement and the nucleation of calcite were the main contributions of self-healing in cementitious materials. If concrete cracks and water

penetrates into the crack, further hydration of unhydrated cement will take place in the cracks. The formation and growth of hydration products will eventually heal the cracks.

In a series of studies, the healing of cracks in concrete specimens through submersion in water was studied. Specimens were formed with a crack opening up to 50 μm. A compressive force was applied to the specimens, before being submerged completely in water for two weeks and then strength tested. It was found that when the specimen is not loaded in compression there is nearly no strength increase. Additionally, the amount of compressive stress does not significantly influence strength gain. Other experiments have shown that the age of the specimen upon the first cracks can influence the strength recovery of the specimen. The earlier the cracking, the more strength was recovered. Finally, it was shown that in order for the healing to take place, water had to be present. Specimens stored in an environment of 60% and 95% relative humidity showed almost no increase in strength even after extended periods of time.

In another experiment carried out by Zhong and Yao, the degree of damage on the self-healing of concrete was examined. In this study, both normal and high strength concrete specimens were made and cured. To study the effect of age, the samples were deteriorated by compression tests after different lengths of time. After deterioration, the normal strength samples were cured for an additional 30 days, while the high strength samples were cured for another 60 days. The samples were then tested for compressive strength again after healing.

Degree of damage is defined below. In the equation D represents the degree of damage, v is the ultrasonic pulse velocity after peak loading and v_o is the ultrasonic pulse velocity before loading. The self-healing ratio is also defined below. In that equation, H is the self-healing ratio, S_h is the compressive strength after self-healing and S is the compressive strength at loading [30].

$$\boldsymbol{D = 1 - \frac{v}{v_0}} \qquad \textbf{[1]}$$

$$\boldsymbol{H = \frac{S_h - S}{S}} \qquad \textbf{[2]}$$

It was found that the self-healing of the concrete is influences by the degree of damage. It was also found that there exists a threshold where self-healing will become less effective. As the damage degree is increase, the self-healing ratio will increase. This is due to the exposure of unhydrated cement particles as new cracks are formed. If the degree of damage is too small, the

exposed number of unhydrated particles will be small and therefore the rehydration of the particles is not helpful. However, if the damage is too large, the new hydration products cannot bridge the gap and therefore the self-healing ratio decreases. The point where the self-healing ratio decreases is the threshold. It was found that this threshold value was higher for normal strength concrete than that for high strength concrete most likely due to the material makeup. This type of study is important for characterizing the amount of self-healing which can be expected for cracked concrete structures [30].

Autogenic healing properties are limited to small cracks and are only effective when water is available inside the crack. The amount of unreacted cement left in the matrix plays a great role in the autogenic healing of cracks. Today much finer cement grains are used so there is less unreacted cement available. This implies that the autogenous healing mechanism is less efficient [23]. This, along with the fact that not all concrete structures are or can be submerged in water has turned attention towards autonomic healing where all necessary components are contained within the matrix.

2.3 Encapsulation

2.3.1 Introduction

As mentioned previously, the autogenic healing of concrete requires that the cracks be entirely filled with water. With autonomic healing, the healing agent, along with any necessary components, is embedded within the concrete matrix. The idea behind this system is that the healing agent will be release upon the formation of damage, as needed, to heal cracks. As such, the healing agent is usually carried inside some kind of capsule to prevent the unexpected release or contact with the matrix. In order for self-healing to be effective, the healing agent should be cost effective and readily available. Additionally, the healed cracks should have mechanical properties after curing that are equal to or greater than that of the matrix. The healing agent should also have sufficient longevity and compatibility with the cementitious matrix over the lifetime of the structure [28].

There are a variety of encapsulation techniques that have been discussed and tried in literature. The three major ways to promote autonomic self-healing is through an external supply system, internal encapsulation and microcapsule. Each system has its own advantages and disadvantages.

In an external supply system, glass supply lines are use to deliver chemicals through the use of a vacuum pressure system. For an external supply system, the major advantage is the additional supply of healing agent that is available and therefore a large amount of healing agent can be handled, which ensures its effectiveness under multiple damage events. However, with this system the casting of concrete can become difficult [28]. This method does not seem practical for commercial use.

The next method is internal encapsulation. In this method, tubes or hollow fibers are used to store healing agent and are embedded within the concrete. This is simpler than external supply system. They can be integrated into the cement matrix and when damage or fracture occurs, rupture and heal the cracks. As long as there is healing agent remaining in the system, it is possible to have healing following repeated damage.

There are many types of internal encapsulation systems that can be used, however, hollow fibers is one of the most common. Hollow fibers or capsules, made from glass, are used to encapsulate the chosen healing agent. Because the fibers tend to be fragile, the fragmentation and subsequent dispersion of the contents begins as soon as cracks appear. Upon rupture, the encapsulated agent is released into the crack and heals it. Most researches make use of air-curing 1-component healing agents such as cyanoacrylate or epoxy. Once they are released, these agents harden upon contact with air [23]. This has been done with some successes and failures.

Figure 2: Example of epoxy-filled glass tube [28]

In studies using tubes, in particular glass tubes, it has been found that the healing agent had not been sufficiently drawn into the crack. The is believed to be due to the capillary attractive force of the crack and the gravitational force of the fluid mass were unable to overcome the negative pressure generated at the sealed ends of the tube. This means that a large amount of healing agent remains inside the tubes following their complete fracture [28]. Additional research needs to be performed to determine a tube which can adequately release the healing agent and has a good

bond with the concrete. The research on this topic can be quite scattered and random therefore it cannot yet be used reliably to self-heal cracks.

Finally, microencapsulation is explored. Microencapsulation is the process of enclosing micron-sized particles of solids, droplets of liquids or gases in an inert shell. The shell isolates and protects them from the external environment. These microcapsules (20 to 70μm) are manufactured and mixed into the cement matrix. In this healing process, cracks form and rupture the microcapsules. The healing agent is then released and heals the cracks. A schematic of this process can be seen in the figure below.

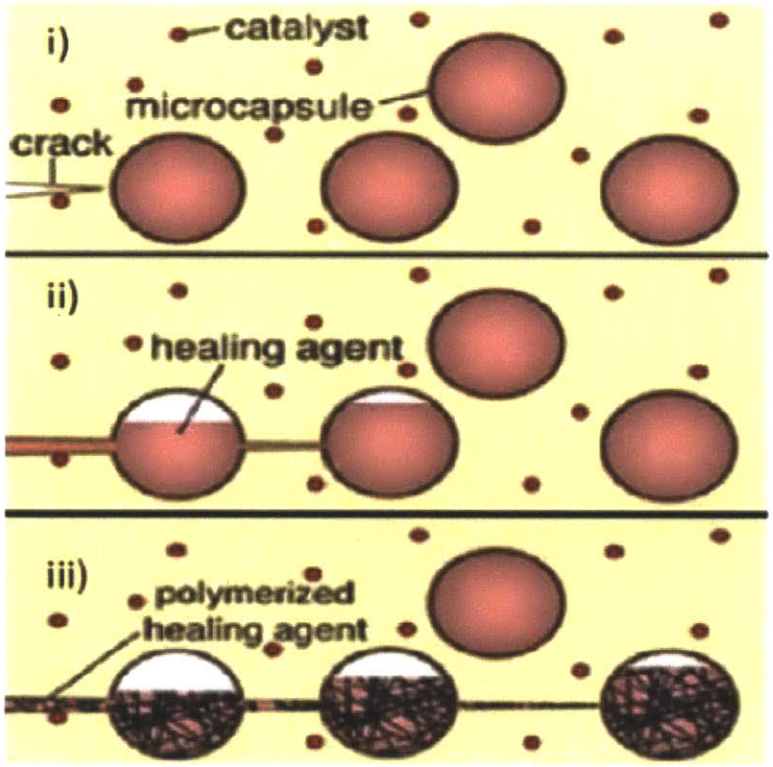

Figure 3: Basic microcapsule approach (i) cracks form (ii) microcapsule is ruptured releasing healing agent (iii) healing agent contacts catalyst, polymerization occurs closing crack [28]

The shape of the embedded capsule is a factor that should be considered. A spherically shaped capsule will provide a more controlled and enhanced release of the healing agent upon breakage. It will also reduce the stress concentrations around the void left from the empty capsule. A tubular capsule however, will require a larger internal area of influence on the concrete, while still only containing the same volume of healing agent as the spherically shaped capsule. The

potential release of the healing agent upon cracking will also be reduced since localized and multiple cracking may occur, thus preventing the effective distribution of the healing agent. More research on this topic must be done to propose an efficient shape.

The advantage of using microcapsules is that multiple cracks can be healed simultaneously since the healing agent is mixed throughout the matrix. However, the manufacture of microcapsules for application in cementitious materials can be difficult and therefore such a system will be more expensive. Also, in this system there is less healing agent than with other systems since the microcapsules are small. This means that only smaller cracks can be healed. There are also several concerns with the capsules themselves. First of all, if the strength of the capsule wall is higher than the bond strength, the microcapsules will not rupture after the initiation of the cracks and therefore no healing action will occur [28]. Finding a capsule which can survive the mixing process but will rupture upon the formation of cracks is essential. Another concern is that the additional amount of healing agent contained within this system is severely limited [20]. Including too many capsules in the concrete matrix has the potential to reduce the mechanical properties and therefore a careful balance must be struck. Most likely, this system prove effective only when there are microcracks.

2.3.2 Healing Agents

A variety of healing agents have been proposed and tested in studies on the self-healing of concrete. The main materials suggested have been epoxy resins, cyanoacrylates and alkali-silica solutions. The ability of the agent to enter the cracks is dependent on the capillary forces dictated by the crack width and the viscosity of the repair agent [20]. Finding a material that can be easily encapsulated, and will penetrate the cracks when released is essential in making sure the healing is done successfully.

Currently low viscosity epoxy resins are being used in the remediation of critical concrete floors and bridge decks. Epoxy resins are durable materials that generally have good thermal, moisture and light resistance. They are available in either one or two part systems: a one part epoxy is activated by the presence of heat and a two-part epoxy is cured by the presence of both a hardener and resin component. The main problem with the application of two-part epoxy resins with regards to the autonomic healing of concrete is that both the components have to be

simultaneously present at a crack location. This is very unlikely, especially when encapsulated separately. Encapsulating the mixture of both the agents will cause the agent to remain liquid for only the duration of the "pot life". This is only on the order of hours [20]. Because of this, epoxy resins can be tricky to use as an encapsulated healing agent.

Unlike the two-part system mentioned above, cyanpacrylates (superglues) are one-part systems that react to the presence of moisture and are noted for their ability to cure rapidly. They have the ability to provide good bond strength with the matrix. Furthermore, they have low viscosities and therefore are better able to penetrate and heal small cracks. Cyanpacrylates, because they are acidic, will be neutralized upon contact with the concrete due to its alkalinity. This results in the neutralization of the glue and a quicker setting time [20]. These have been used with some success, however, the mechanical properties of the cyanpacrylates has been called into question.

Another healing agent is alkali-silica solution in the presence of oxygen causes hydration, thereby bonding the original crack faces together. The strength of this bond is less than that of glue. The use of an alkali-silica based healing material in concrete is also less likely to cause material compatibility problems than its polymer-based counterparts [20].

Other agents such as polyurethane have been tested in both mortar and concrete. This type of healing agent has two components, the first is a prepolymer of polyurethane that begins foaming and expanding in moist surroundings, the second compound is an accelerator that shortens the reaction time. The use of this expanding agent may help the agent leave the capsule more efficiently and allows for larger cracks to be healed. It was found that use of this healing agent, encapsulated in ceramic tubes, resulted in the both strength and stiffness regain similar to that of manually repaired cracks.

In conclusion, the choice in the type of encapsulation method and the selected healing agent should not be taken lightly. It is important that the method produces the desired amount of self-healing and that the healing agent has a positive, not negative, overall effect on the cement matrix. There are a lot of possibilities and currently there is no one method which is better than another.Continued research on the topic can improve the performance of encapsulated systems and reveal a healing agent which is both effective and economical.

2.4 Microbial Concrete

2.4.1 Introduction

The premise behind bacteria based concrete is that dormant, but viable bacterial spores can be immobilized in the concrete matrix. Once water enters freshly formed cracks, the spores will become metabolically active and the cracks will be quickly filled and sealed by the metabolically produced microbial calcium carbonate precipitation [15]. This healing process can be seen in the schematic below.

Concrete is highly alkaline and can be a hostile environment for most microorganisms. However, it has been found that some alkalophillic *Bacillus* species can not only survive in this environment, but also produce calcite ($CaCO_3$), filling in the cracks in the concrete (Knoben). Bacterial spores are specialized cells which have the ability to endure extreme mechanical- and chemical- stresses. In particular, *Bacillus* spores are known to remain viable for up to 200 years [15].

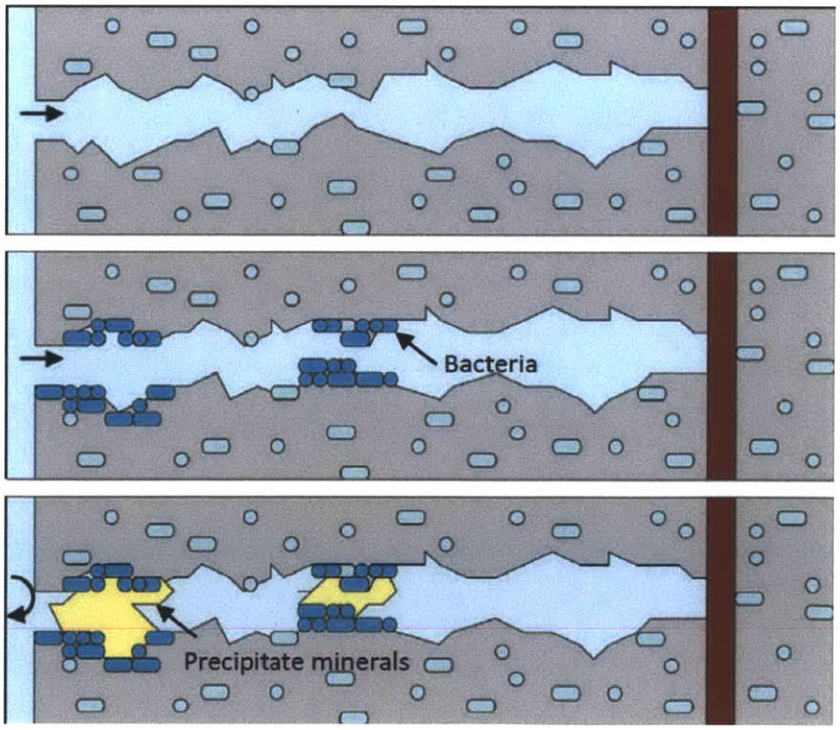

Figure 4: Schematic of crack healing by concrete-immobilized bacteria [28]

The bacteria used in microbial concrete produce urease, which catalyzes the hydrolysis of urea into ammonium and carbonate. The carbonate then spontaneously hydrolyses to form ammonia and carbonic acid. The products subsequently form bicarbonate and ammonium and hydroxide ions. The last two reactions produce a pH increase, which shifts the bicarbonate equilibrium. This results in the formation of carbonate ions. The following equations show these reactions [24].

$$\mathbf{CO(NH_2)_2 + H_2O \rightarrow NH_2COOH + NH_3} \quad [3]$$

$$\mathbf{NH_2COOH + H_2O \rightarrow NH_3 + H_2CO_3} \quad [4]$$

$$\mathbf{H_2CO_3 \leftrightarrow HCO_3^- + H^+} \quad [5]$$

$$\mathbf{2NH_3 + 2H_2O \leftrightarrow 2NH_4^+ + 2OH^-} \quad [6]$$

$$\mathbf{HCO_3^- + H^+ + 2NH_4^+ + 2OH^- \leftrightarrow CO_3^{2-} + 2NH_4^+ + 2H_2O} \quad [7]$$

The bacteria draw cations from the environment since their cell wall is negatively charged. These cations include Ca^{2+} which is deposited on the surface of the cell. These Ca^{2+} ions react with the CO_3^{2-} ions forming $CaCO_3$.

$$\mathbf{Ca^{2+} + Cell \rightarrow Cell - Ca^{2+}} \quad [8]$$

$$\mathbf{Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3} \quad [9]$$

In the following section, the development of microbial concrete will be discussed along with its potential in the civil engineering field.

2.4.2 Developments in Microbial Concrete

Microbial concrete is highly desirable because it is natural and pollution free. When used in concrete, the bacteria can continuously precipitate calcite. However, in order for microbial concrete to be effective two things must happen. First, the bacteria must be able to survive once incorporated into the concrete Secondly, there must be a suitable substrate that can be converted into calcium carbonate. It is important that this substrate can be incorporated into the concrete without negatively affecting the performance of the concrete.

There are numerous diverse microbial species which participate in the precupiation of mineral carbonates. These include *Bacillus pasteurii*, *Bacillus cohnii*, *Bacillus lentus* and *Bacillus sphaericus* [24]. In a study conducted by Chahal et al., different strains of ureolytic bacteria were isolated and the productivity of their production of urease was tested. It was found that there were several strains that had a high degree of calcite precipitation and could survive as higher pH levels [chahal, Rajor, Siddique 2011]. Any one of these strains could potentially be used in microbial concrete for the promotion of self-healing.

Being that this self-healing mechanism is imposed in order to obtain healing throughout the life span of the structure, it is important that the bacterial spores have a life-span equal to that of the structure. In a couple of studies the survival of bacterial within concrete, along with the optimum concentration of cells was obtained. It was found that bacteria can survive within the concrete for extended periods of time but functioned better when embedded in some kind of filler material. The activity of the bacteria did not decrease even after 70 days. Next, the optimal concentrations of bacterial cells, urea and Ca^{2+} were determined in order to obtain a maximum amount of $CaCO_3$ precipitation. It was found that a higher concentration of bacterial cells can decompose more urea with increasing concentrations of urea. This can be seen in the graph below. It was found that the concentrations of urea and Ca^{2+} cannot be too high in order to prevent large amounts of urea to be left in the cement matrix. The effect of such an event is unknown. A high concentration of Ca^{2+} will decrease bacterial activity. A suitable concentration of urea and Ca^{2+} might be 0.5M [25].

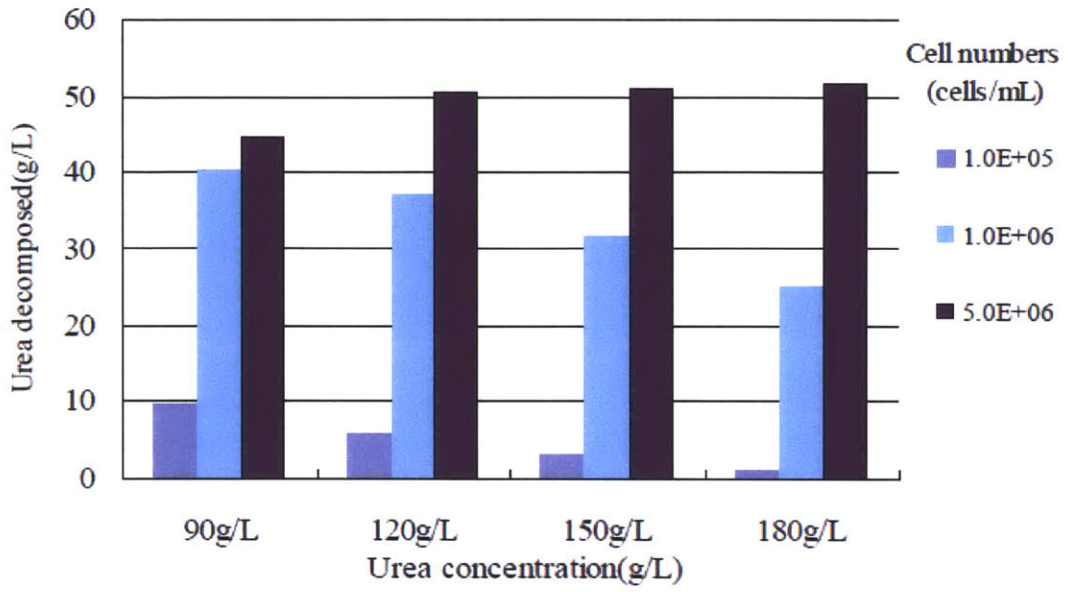

Figure 5: Decomposition of Urea [25]

Next, the incorporation of several organic substrates into the cement matrix were tested. In a study carried out by Jonkers et al., different organic substrates were dissolved in water and added to the concrete mix along with bacterial cells suspended in tap water. The organic substrates included Na-aspartate, Na-glutamate, Na-polyacrylate, Na-gluconate, Na-citric acid and Na-ascorbic acid. These specimens were cured for 28 days and then tested for both tensile and compressive strength. The results were compared against a control specimen (without bacteria or organic substrate) and a specimen which contained only the bacteria *S. pasteurii* (no organic substrate). There was no significant difference found in flexural tensile and compressive strength between control-, bacterial- and amino acid (aspartic acid and glutamic acid)- containing concrete bars. However, concrete which contained polyacrylic acid and citric acid had significant decrease in strength. The concrete which contained Na-gluconate and Na-ascorbic acid did not develop any strength [15].

Type of concrete:	Tensile strength (N/mm^2):	Compressive strength (N/mm^2):
Control	7.78 ± 0.38	31.92 ± 1.98
S. pasteurii	7.45 ± 0.45	34.78 ± 1.52
Na-aspartate	7.33 ± 0.37	33.69 ± 1.89
Na-glutamate	7.16 ± 0.19	28.52 ± 3.56
Na-polyacrylate	6.42 ± 0.47	20.53 ± 4.50
Na-citrate	3.48 ± 1.72	12.68 ± 1.82
Na-gluconate	0	0
Na-ascorbate	0	0

Figure 6: Tensile and Compressive Strength of Specimens Containing Organic Substrate [15]

Knowing that all the necessary components for microbial concrete can be successfully integrated into the concrete matrix, the process must be optimized. One thing that was noted was that the bacteria could survive better when immobilized into a filler material. When bacteria are used in concrete, the highly alkaline pH restricts the growth of the bacteria. Use of a filler material protects the bacteria from the alkaline environment [24]. Filler materials can include silica gel, polyurethane and expanded clay.

In a study conducted by Wiktor and Jonkers, a bio-chemical two-component self-healing agent consisting of a mixture of calcium lactate and bacterial spores were both embedded in expanded clay particles. Two cracked mortar specimens (one control and one bacteria based) each having a high number of individual cracks with varying crack widths, were immersed horizontally in tap water and monitored over the course of 100 days. It was found that the width of completely healed cracks was significantly larger in bacteria-based specimens (0.46 mm) compared to the control specimens (0.18mm). The addition of this healing significantly enhanced mineral precipitation on crack surfaces. The deposited minerals are likely calcium carbonate-based and were formed due to bacterial metabolic conversion O_2 consumption is, even several months after casting, substantial in bacteria-based specimens but only insignificant in control specimens. This proves that the bacteria remain viable and functional several months after concrete casting. In addition, as the metabolically active bacteria consume oxygen, the healing agent may act as an oxygen diffusion barrier protecting the steel reinforcement against corrosion [27].

2.5 Implementation

Self-healing of cracks is a common occurrence in concrete. The healing process allows for decreased permeability along with the regain of mechanical properties such as strength. The processes including encapsulation, use of bacteria and autogenic healing, are effective but have yet to be perfected.

One problem with autogenic healing is that the cracks need water in order to begin the healing process. This type of healing may be effective for undersea or underground reinforced concrete structures where the structure is often exposed to larger amount of water. Some have proposed wetting concrete structures in order to promote this type of healing but it is not practical for large scale structures. Encapsulation has the advantage of being able to release a compound on necessity. The healing agent could be chosen specifically for the needs of the structure and therefore there is much flexibility and potential for this method. However, encapsulation systems can be difficult to cast and could result in having a negative impact on the cement matrix if too many are used. Furthermore, the healing of the concrete is limited since the healing agent cannot be replaced once used. Lastly, microbial concrete was considered. This mechanism when used to heal cracks is natural and efficient. However, it is a lengthy process and cannot be used easily in the commercial setting. The strains of bacteria have to be harvested properly, immobilized and then introduced into the cement matrix in a way that will facilitate their survival. This process must be done carefully, and therefore, this method could be expensive.

Even though the idea of self-healing concrete does not seem viable for commercial use right now, this should not inhibit further research on the topic. Self-healing can be of great use especially in places like tunnels and underground structures where inspection is costly and difficult. It is clear that self-healing is possible, it is just a matter of finding a good way of incorporating it into structures. In the future, more research should be done on microbial concrete and the different ways the bacteria can be immobilized within the concrete. Placing bacteria into alternative aggregates could make this process more appealing. As for encapsulation more research needs to be done on how to best encapsulate healing agents. Since economy is everything, the healing agent must be cheap, effective and the capsules must be easy to manufacture and implement. Overall, this field has some work to do but it seems to hold a great deal of potential moving forward.

3.0 Shape Memory Alloys

3.1 What are Shape Memory Alloys?

Shape memory alloys (SMA) are alloys that, if deformed inelastically at room temperature can return to their original shape once heated above a certain temperature. SMAs have two unique properties: shape memory effect (SME) and superelasticity. The shape memory effect refers to the phenomenon that shape memory alloys return to their original shape upon heating. This phenomenon began to get attention when Buechler discovered the property in nickel-titanium. This material became known as Nitinol. Being that Nitinol has superior thermomechanical and thermoelectrical properties, it remains as the most commonly used shape memory alloy despite numerous discoveries of other alloys. The table below shows the properties of Nitinol compared to that of traditional steel [7]. The superelasticity property associated with shape memory alloys refers to its ability to undergo a large amount of inelastic deformation and recover their shape after loading [22].

Table 1: Properties of Nitinol SMA vs. Steel [7]

Property	NiTi shape memory alloy	Steel
Recoverable elongation	8%	0.2%
Young's modulus	8.7E4 MPa (Austenite), 1.4–2.8E4 MPa (Martensite)	2.07×10^5 MPa
Yield strength	200–700 MPa (Austenite), 70–140 MPa (Martensite)	248–517 MPa
Ultimate tensile strength	900 MPa (fully annealed), 2000 MPa (work hardened)	448–827 MPa
Elongation at failure	25–50% (fully annealed), 5–10% (work hardened)	20%
Corrosion performance	Excellent (similar to stainless steel)	Fair

The ability of shape memory alloys to return to their original shape is due to their structure. Shape memory alloys have two crystal phases: a strong austenite phase which is stable in higher temperatures and a weaker martensite phase which is stable in lower temperatures. Austenite, the stronger phase, has a body-centered cubic crystal structure which has only one possible orientation. Martensite has a parallelogram structure which can have up to 24 variations. This parallelogram structure allows for easy deformation. When martensite is subjected to external stress, the structure deforms through a detwining mechanism which converts it to a particular variation which can support maximum elongations. Austenite, on the other hand, has a relatively strong resistance to external stress due to the fact there is only one possible orientation [22].

The transformation between martensite and austenite can be temperature induced. The figure below represents a typical stress-free temperature-induced martensitic transformation. As shown in the figure there are four transition temperatures in the transformation loop. These are the martensite start temperature (M_s), the martensite finish temperature (M_f), the austenite start temperature (A_s) and the austenite finish temperature (A_f). These temperatures represent the beginning and the end of the forward and inverse transformations [22].

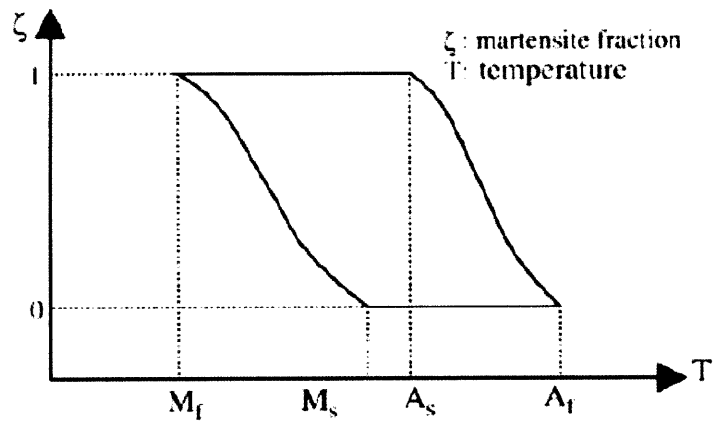

Figure 7: Temperature Induced Martensite Transformation [22]

The two figures below are stress-strain curves representing the shape memory effect and the superelastic properties. On the left is a typical stress-strain curve of an SMA specimen at constant low temperature ($T < M_f$). When martensite is subjected to tension, it will first deform elastically and then have a large increase in strain corresponding to almost constant stress. When the specimen is unloaded, the elastic strain recovers resulting in some residual strain caused by the martensite reorientation. If the deformation exceeds the maximum value which martensite can sustain through the martensite reorientation mechanism, then permanent plastic deformation takes place [22]. Heating the unloaded specimen above the austenite start temperature (A_s) starts the phase transformation from martensite to austenite. This results in the removal of the residual strain and the recovery of the initial shape [7].

On the right, is a typical stress-strain loop of a superelastic SMA specimen undergoing stress-induced transformation at constant temperature above that of the austenite finish temperature. As seen in the figure, the specimen will first behave elastically until it reaches a critical stress. Next a stress-induced martensite transformation takes place. This results in a large deformation with

little increase in stress. Upon the unloading of the specimen, the martensite becomes unstable and transforms back to austenite. This finishes with the recovery of the original undeformed shape [7]. Also seen in the figure is that there are four characteristic stress values which indicate the beginning and ending of the transformation. These stress values are temperature dependant. The temperature at unloading will dictate the amount of residual strain. Since this was a high temperature transformation, there was no residual strain [22].

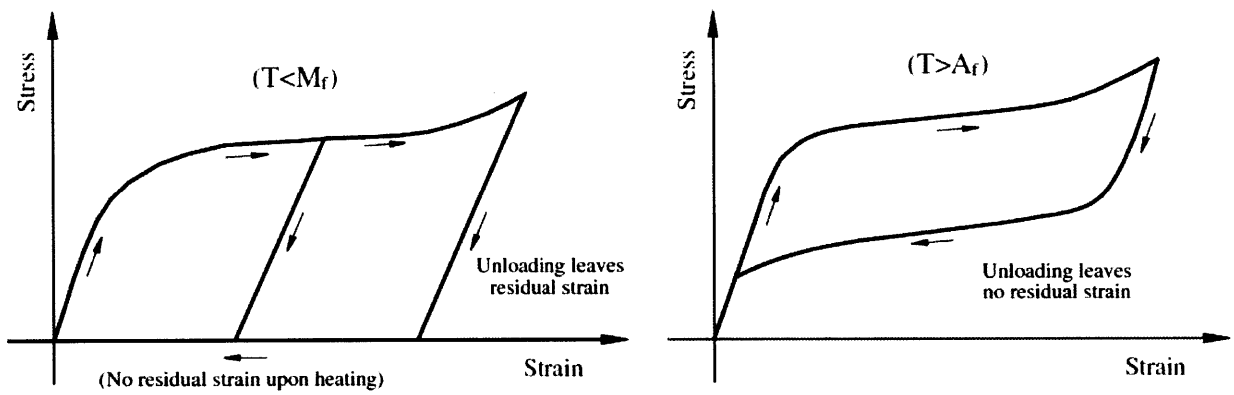

Figure 8: (a) Shape Memory Effect (b) Superelasticity, [8]

The above characterization is applicable to cases where the alloy is free to deform. These properties can be used to develop large internal forces which can be used as an actuator or for prestressing or posttensioning applications [11]. This will be especially important when used with concrete. Often, reinforced concrete structures use prestressing to eliminate possible tensile stresses that would have otherwise developed due to external loads. This prestressing is activated in shape memory alloys through a temperature change. The figures below show the constrained behavior associated with that of prestressing.

As the SMA specimen is heated from room temperature T_d past the austenite start temperature, A_s, the phase transformation from martensite to austenite begins. However, due to the constrained effect, the strain recovery from ε_p to ε_r is gradual. The actuation stress increase gradually from zero at the start of the transformation, to maximum value of σ_r at temperature M_d. This temperature is the maximum temperature at which martensite can still be stress induced. As the temperature rises, the actuation stress increases [17]. This is used to induce the prestressing of the reinforced concrete element.

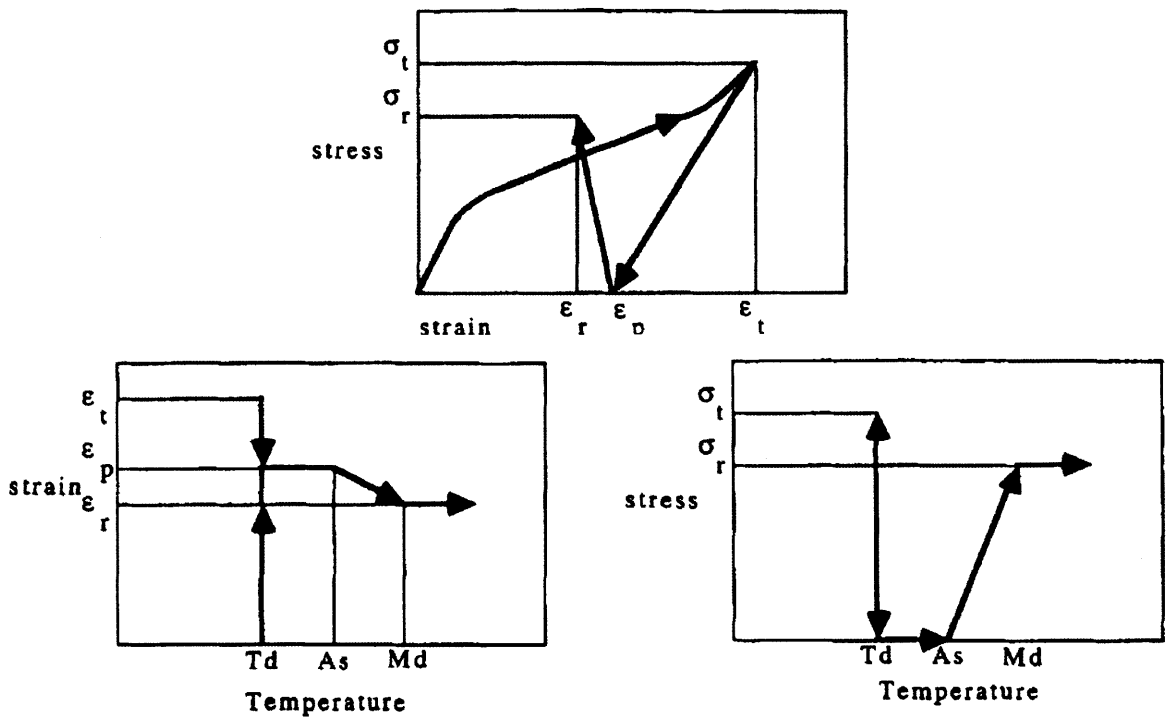

Figure 9: Stress-Strain for Constrained SMA [17]

The properties of shape memory alloys including the shape memory effect and the superelasticity holds a lot of potential for reinforced concrete design due to its sensitivity to tensile stresses and failure due to cracking. In the next sections, the use of shape memory alloys as reinforcement in reinforced concrete beams is analyzed. The results of such studies are taken one step further and analyzed under seismic loading where the ability to deform and maintain shape are especially important. It is important to note, that there are many applications for shape memory alloys including damping and isolation but only its application in reinforcing concrete will be examined.

3.2 SMA Wires in Reinforced Concrete

Reinforced concrete beams are common in many structures. Beams take bending and as such it is common for reinforced concrete beams to crack under the tensile stresses. Therefore one of the first applications of SMAs is in the idea of deflection control. In order for reinforced concrete beams to work, the steel and concrete must be bonded. Similarly, it was important to establish whether or not a bond can form between SMA wires and the cement matrix. Pull out tests were performed by Maji et al.. It was found that when individual wires were embedded in the

concrete, the surfaces of the wires were clean. This means that the bond between the wire and the hydration products was poor. However, when strands were formed from a bundle of wires and then embedded in concrete, the bond was better. When strands of SMA wires were pulled from the concrete, cement paste was found to adhere to the crevices in between the wires [17]. This means that for better performance, strands of wires should be used instead of individual wires. The bond between the strands and concrete demonstrates that there can be some form of composite action.

Knowing this potential, deflection control of beams using SMAs can be explored. It is suggested that a control system could be set up where the deflection of the concrete beam is measured using a sensor. When the deflection exceeds the allowed deflection, the system starts to supply current and actuate the SMA wires. This action continues to be performed until the deflection of the beam recovers just below the allowed deflection [7]. In order to counteract deflection, a force must be actuated by the change in temperature. This is possible only in the constrained condition.

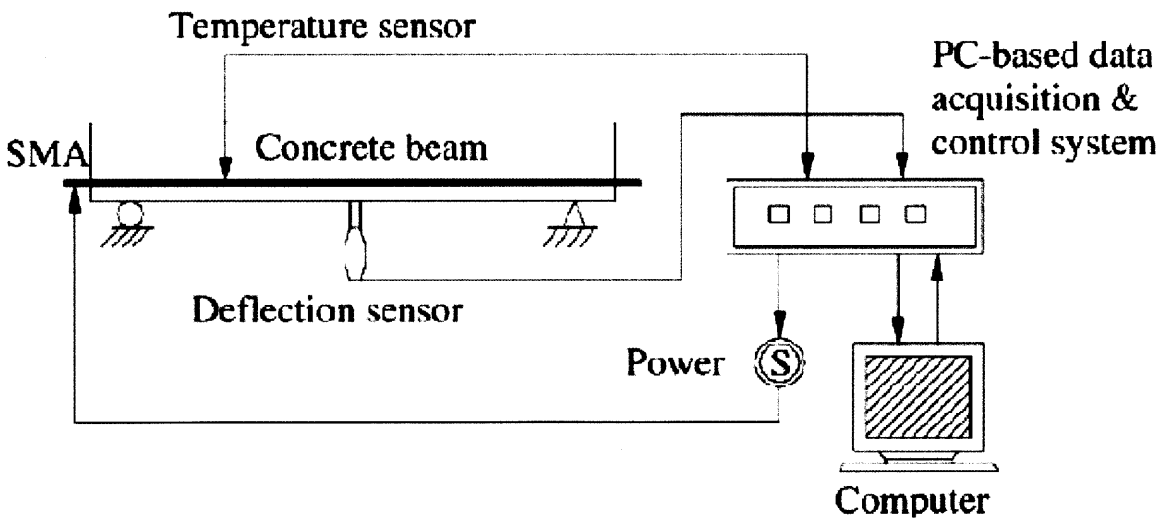

Figure 10: Potential Deflection Control System for Beam [7]

Prestressing SMA wires or strands in a reinforced concrete beams by residual stress can control deflection and crack-width at the loading state and close cracks during the unloading state. Designing a reinforced concrete member like that shown in the figure below can greatly improve performance. The horizontal SMA strands can control bending cracks while the diagonal wires can control diagonal cracks [5]. The rest of the beam element will act as normal.

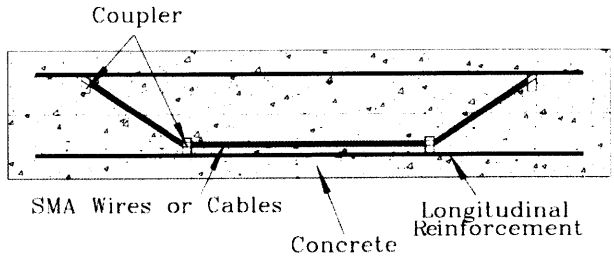

Figure 11: Potential Reinforcement of a beam using SMAs [5]

Shape memory alloy when used in this capacity, takes advantage of the superelasticity property and allows these members to recover from deformation [19]. In tests conducted by Sakai et al., it was found that reinforcing mortar beams with SMA wires can greatly increase the capacity of deformation. The range of deflection of the mortar beam reinforced with SMA wires was more than seven times that of the beam with steel. Also, after unloading of the member, the deflection returns to about one-tenth deflection compared with the maximum. This means that beams with SMA as reinforcement not only the potential to take a larger deformation but can also recover from it almost completely. However, it is important to note there is a weaker bond force between SMA and mortar. During increase loading, a large crack formed and the bond was broken. The SMA wires stretched in the axial direction [19].However, due to superelasticity, the wires were able to recover and the crack closed significantly.

Similar results were obtained for beams which contained pre-stressed SMA wires and the wires heated upon the formation of cracks. When the wires embedded inside the concrete are heated, the wire shrinks and imposes a compressive force upon the beam. This causes the deflection to become positive (tension along the top of the beam). The actuating of SMA wires can transform the tensile stress in the tensile zone to be compressive stress. This action will also close any cracks that may have formed upon loading. Furthermore, the load capacity of the beams increase after the actuating of the SMA wires even though the concrete was already cracked. It was found that the way the wires were heated had a significant effect on the deflection behavior of the concrete beam. The phase transformation of SMA depends on both the transient temperature and the phase transformation performing time. The longer the actuating time, the greater amount of martensite was transformed to austenite and therefore a larger compressive force was imposed on the beam. Furthermore, the pre-strain had a great influence on the recovery force. The larger the

pre-strain of SMA wire, the larger the bending deformation of the concrete beam that could be obtained [7], [16].

From the results obtained above, it is clear that SMA wire in reinforced concrete beams can have a positive effect on the performance of the beams. Deflections can be significantly decreased and even controlled if actuated properly. However, this is most applicable to new structures. It would be difficult to place SMA wires inside of structures when performing typical strengthening and repairing of structures. However, it is feasible to use SMA wires mounted outside of the structures in order to strengthen and repair existing structures through the generated recovery force [16]. This application will be discussed in the next section.

3.3 Expected Seismic Performance of SMAs in Reinforced Concrete

There is an increase in the amount of reported damages of reinforced concrete structures which are exposed to earthquakes. Traditional reinforced concrete structures are designed for safety against collapse through the dissipation of earthquake energy through the yielding of the steel reinforcement and inelastic deformation. Recently, the seismic design of structures has tended towards a performance based approach [2]. As such, the use of SMAs in reinforced concrete may provide the enhanced deformation capacity and ductility that is needed to withstand seismic forces.

One of the first applications studied is that of reinforced concrete frames. It has been found that structural overstrength plays an important role in preventing building from collapse. According to Alam et al., the overstrength factor (R_0) is defined as the ratio of the actual lateral strength (V_y) to the design lateral strength (V_d). Overstrength is the result of rounding of dimensions of structural elements, variation in actual yield strength from the minimum specified, and the strain hardening of steel. Ductility (μ) is defined as the ratio of displacement at actual capactity (Δ_{max}) to the displacement corresponding to V_y on the idealized bilinear curve (Δ_y) [2]. The object of the design is to increase the ability of the structure to take base shear.

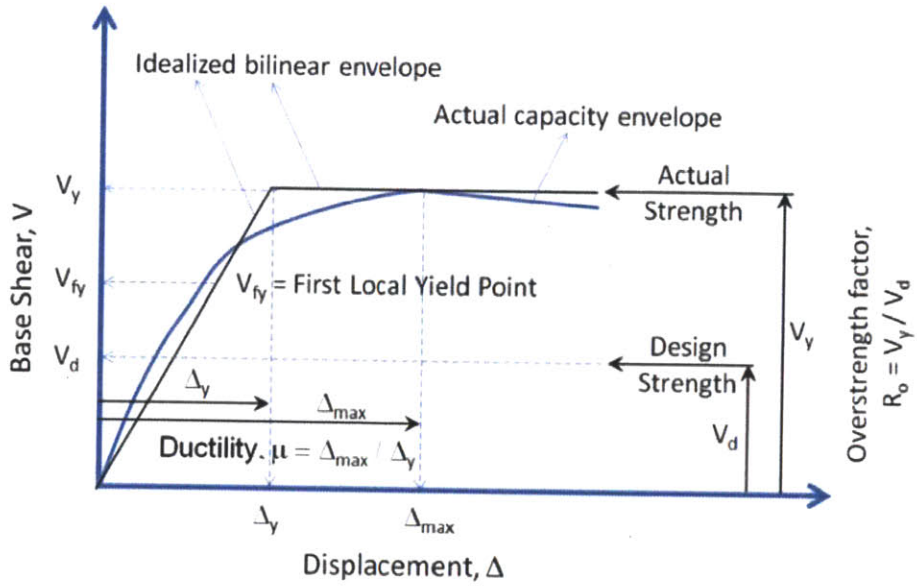

Figure 12: Relationship between overstrength & ductility [2]

Since the actual construction and testing of reinforced concrete frames is impractical, the effect of SMA as reinforcement in concrete frames was investigated analytically by Alam et.al.. In this investigation, three different types of reinforced concrete building of three different sizes were considered. For each building size, three different reinforcement detailing was used, (i) only steel reinforcement, (ii) Steel-SMA hybrid reinforcement where SMA is used in the plastic hinge region of the beams and steel in other regions, (iii) SMA reinforcement in the beams and steel in other regions. The sizes of the buildings are 3, 6 and 8 stories. Each building has five bays in both directions with a bay length of 5 m each. The story heights are 3 m for all three buildings. The seismic performance of these frames was investigated analytically using a finite element program. In order to determine the overstrength factor and ductility, inelastic pushover analyses were used. Additionally, nonlinear dynamic time history analyses were used to investigate the capacity demand ratio in terms of base shear and inter-story drift.

After performing the analyses the following was found. In the case of the capacity/demand ratio in terms of base shear, it was found that SMA frames performed slightly better in all three situations. In the case of the 6 and 8 story frames, the steel-SMA frames performed better compared to that of the steel frames. The capacity/demand ratio in terms of roof drifts showed that in the case of 6 and 8 story frames, Steel-SMA and SMA frames had comparable performances. Overall, for 3 story frames, SMA showed a better performance than both steel-

SMA and steel reinforced concrete frames in terms of both base shear and roof drift capacity [2]. The figures below show these results.

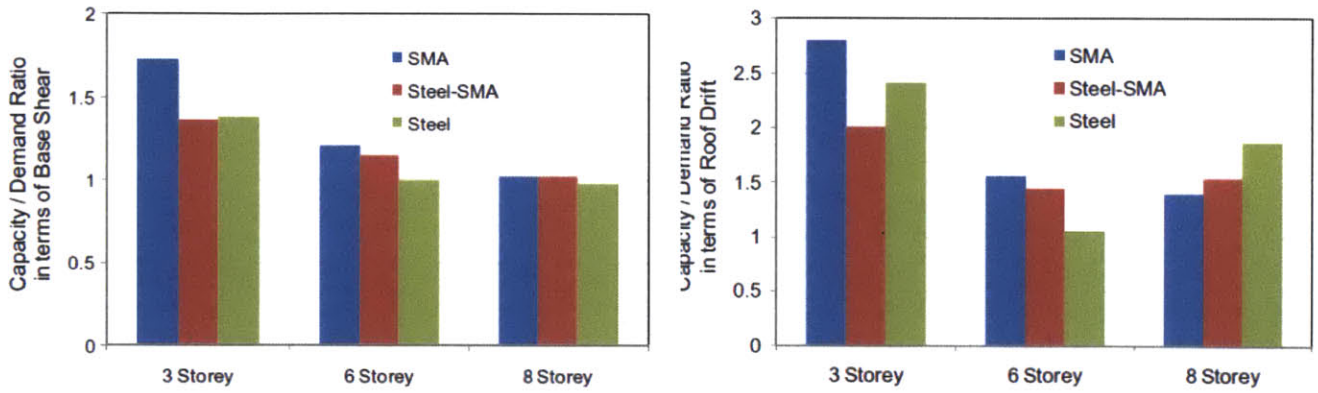

Figure 13: Capacity/Demand Ratio in terms of Base Shear & Roof Drift [2]

From the inelastic pushover analyses, it was found that the overstrength factor of the SMA frames were similar to the steel reinforced concrete frames. Due to SMA's lower modulus of elasticity and therefore reduced stiffness, the ductility of SMA frames was found to be at least 16% lower than that of steel reinforced concrete frames. Even though steel reinforced concrete frames were more effective in reducing inter-story drift for 8 story buildings, it is still possible that SMA reinforced concrete building may outperform the steel reinforced concrete building in seismic regions. This is due to the fact that SMA buildings have a higher base shear capacity compared to its seismic demand. It was found that the performance of steel-SMA frames and SMA frames were similar.

Since shape memory alloys are expensive materials, and the steel-SMA and SMA frames performed similarly, it may be preferred to use Steel-SMA reinforced concrete frames in seismic regions. However, it is important to note that these frames have higher inter-story drift compared to their steel counterparts and therefore they must be designed to limit non-structural damage. The design should be based on the reduced stiffness and effective moment of inertia of the SMA members. Such a design method should be further studied [2]. The use of SMA in frame elements, especially in the joints could potentially improve the seismic performance of the

structure. Future studies can help solidify these findings and provide an optimized design process for such structures.

Besides reinforced concrete frames, shear walls are used frequently in buildings. Today, a significant number of existing structures utilize reinforced concrete shear walls as their lateral force resisting system. Shearing, bending, sliding and overturning damages are usually the four kinds of damage that occur in reinforced concrete shear walls during earthquakes. Damages could be mitigated if the reinforced concrete shear walls were able to maintain the majority of their initial shape. Being that SMAs have this ability, this study focused on the seismic response of shear walls with SMA reinforcement.

Two different concrete shear walls have been analyzed. The first wall was reinforced with SMA together with steel rebar. The other contained only steel rebar. Additionally, the behavior of two different concrete shear walls using SMA was investigated. One wall used pretensioned bars while the other did not. The reinforced concrete shear walls with SMAs considered in this study are only subjected to the conventional lateral loadings.

The effectiveness of the two different characteristics of SMA rebar in concrete shear wall was assessed separately. In the case of SMAs that have superelastic behavior, replacing steel more than 50% of steel rebar with SMAs results in a reduction in residual displacement, reduction in initial or primary stiffness and increase in strength of the concrete shear wall. Replacing steel rebar with SMAs that have memory effect behavior result in the reduction of the strength in the shear wall, a drop in residual displacement and decrease in initial stiffness, but not as much as SMA with superelastic case. However, energy dissipation is more with the shape memory effect when subjected to loading and then unloading. It was shown that the overall behavior of the wall system was improved by pretensioning the SMA rebar with the memory effect. A concrete shear wall with pretension SMA rebar is much stiffer and stronger than a concrete shear wall with ordinary SMA rebars. As a result there was a decrease in the residual displacements and increased wall strength [11]. Proper and careful detailing of both moment frames and shear walls using SMAs could greatly improve performance of concrete structures under lateral ground motion.

Besides buildings, reinforcing of concrete can be applied to any situation where drift is of concern, especially under seismic loads. Let's take bridges for example. Bridges are an important transportation method in modern cities. Damage to bridges could disrupt the flow of traffic and lead to disaster for local communities. Recent earthquake and hurricane damage has exposed the vulnerability of existing bridges under strong ground motion. There is several ways SMAs can be applied to bridges, including bridge bearings and cable vibration control, however, this investigation is restricted to their use in bridge columns and potential use in bridge beams.

Bridge columns are important for maintaining serviceability of the bridge after a seismic event. Limiting damage due to lateral ground motion can be done by using a reinforcement detail which will result in smaller residual drifts. In a study done by Zadeh et al., three different concrete bridge column models, with one-fifth scale were constructed. Each of the columns was round. The first column (RSC) was composed of conventional concrete and steel. This column served as a baseline measurement for the others. The second column (RNC) used conventional concrete together with NiTi SMAs in the plastic hinge region. The last column (RNE) used engineered cementitious composite (ECC) and SMAs in the plastic hinge region. Engineered cementitious composites are a new type of cement based engineering material that has properties such as high ductility and tight crack-width control [28]. It was found that residual drifts were reduced by 83 and 67% of the maximum drift for RNE and RNC respectively, as compared to the RSC, attributable to the SMA's recentering capability [8].

This thesis focuses on SMA as used in reinforcement of concrete structures; however it has been shown that SMA's can be used to rehabilitate reinforced concrete bridge beams lacking sufficient shear strength. As shown previously, installation of SMA rods, can lead to the development of a recovery force that can help successfully regain load-carrying capacity. This has lead to the idea of smart concrete beams for use in smart bridges. Basically, it is proposed that SMA bundles be used on the beams in the bridge in order to change the bridge's performance characteristics as needed. Activating the recovery force as needed could improve the bearing capacity and prevent overload of the bridge [8].

3.4 Implementation

Shape memory alloys can be used successfully in reinforced concrete structures. Using SMA as reinforcement can help structures obtain larger deformation capacity along with an ability to recover from such deformation. In seismic areas, SMAs can help structures withstand larger lateral forces. SMAs as reinforcement allow for adaptability to new conditions and loads. If applied correctly, the user could even control the performance of the structure. This could be useful in a variety of infrastructure projects from buildings to roadways and bridges.

However, there are some issues. Shape memory alloys are expensive and therefore, using them as reinforcement would be uneconomical. Also, only small scale beams have been tested with SMA reinforcement. Some of these test required the heating of the wire which would not be practical for large scale structures. Even though the potential outcomes can be great, there is not enough proof that this large initial cost would have a positive return. More research on design with SMAs, quantification of the energy requirements and larger scale testing needs to be done before SMA can be considered for reinforcing concrete structures.

4.0 Carbon fiber reinforced concrete

4.1 Introduction

Throughout history, structural materials have evolved dramatically. What initiated primarily as a need for mechanically strong materials has evolved into the need for both strong and lightweight materials and now strong and self-monitoring. Self-monitoring materials are materials which do not need the use of an embedded or attached sensor. The sensing of damage is valuable for service life predictions and structural health monitoring. The advantages of developing such a material over the use of sensors would be lower cost, increased durability, a large sensing volume and finally, the absence of mechanical degradation due to the embedding of the sensors [6]. One such self-monitoring material is carbon fiber reinforced concrete.

Concrete is known for having brittle failure, low tensile strength and a low strain capacity. In order to improve these properties, fiber reinforced concrete has been developed. The inclusion of fibers within the cement matrix has the ability to improve tensile strength, toughness and freeze-thaw durability. In particular, when carbon fibers are added to concrete, the electrical conductivity increases significantly. Carbon fibers are preferred over other conducting fibers such as steel fibers because they are low in density and they have a high strength to density ratio. Carbon fibers are inert in aggressive environments, abrasion-resistant and more chemically stable than glass fibers in alkaline environments (Vossoughi 2004). This electrically conducting concrete can be used as a smart material that is capable of non-destructive flaw detection.

The advantage of using carbon fiber reinforced concrete is that not only does a person get the flaw detecting advantages, but also the mechanical improvement due to the inclusion of the fibers. The capability of carbon fiber reinforced concrete is based on the notion that the volume electrical resistivity of concrete will increase upon the formation of flaws and decrease during the closure of cracks [4]. This allows for the real time detection of damage in concrete structures with simple and inexpensive electrical equipment.

Smart materials such as carbon fiber reinforced concrete are becoming increasingly popular because of their dual functions (mechanically strong and self-monitoring) at a low cost. This tends to be more economical than sensors or other structural health monitoring techniques.

Additionally, carbon fiber reinforced concrete does not bring about many extra construction difficulties and can be used in almost any structure.

4.2 Carbon Fiber Reinforced Concrete's Ability to Sense Damage

In CFRC damage can be monitored by measuring the change of electrical resistance generated by a change in the connectivity of the conduction path under an external load [3]. This change of electrical resistance is due to fiber push and pull. The stress required for fiber pull-out is consistant with the shear bond strength between carbon fiber and cement paste obtained through the pull-out testing of a single fiber.

Fibers in general have the ability to improve the performance of concrete. However, not all fibers will allow for a self-monitoring concrete. The sensing ability is present only when there is the addition of conducting fibers such as steel or carbon. The sensing ability is not present when there were no fibers or only non-conducting fibers (such as polyethylene) were used. In order for a material to a self-monitoring ability, at least one component has to be conducting. In the case of concrete, the carbon fibers serve to increase conductivity of the less conductive cement matrix.

In order for the carbon fiber reinforced concrete to be self-monitoring, a carbon fiber volume fraction as low as 0.2% can be used. Fiber addition has little effect on the concrete's volume electrical resistivity and therefore low carbon fiber volume fractions can be used if desired [6].

It has been found that the DC volume electrical resistivity of the concrete changes reversibly upon reversible strain. The gage factor is the fractional change in electrical resistance per unit strain. In carbon fiber reinforced concrete, the strain factor has been shown to reach up to 700 which is extraordinarily high when compared with conventional values around 2. This has been observed in concrete, mortar and cement paste in specimens under tension, compression and flexure. It is noted that the effect is greater in cement paste and mortar than in concrete [6].

The change in the fractional change in resistance is due to the external loading of the specimen. In compression the specimen becomes more compacted, decreasing the gap between fibers and therefore there is an increase in the chance for adjacent carbon fibers to connect to one another. New conductive networks are formed and therefore the conductivity increases or the resistivity

decreases with increasing stress. When the stress reaches a critical value, there is the formation of flaws within the specimen. Beyond this critical stress, there is breakage of the existing conductive networks and therefore a decrease in the conductivity or an increase in resistivity [3].

One of the first basic tests of carbon fiber reinforced concrete is the fractional change in resistance due to uniaxial loading and three-point bending. It has been found that under uniaxial compression, the fractional change in resistance decreased with increasing stress level. This is termed the negative pressure coefficient effect. At about 60% of the fracture stress a plateau appeared. The fractional change in resistance was kept almost constant. Shortly after that, the resistance increased rapidly with increasing stress. This is termed the positive pressure coefficient effect [3]. The same trend was found in other studies regarding compression. Upon compression up to failure, the resistance decreased monotonically. The opposite is true upon static tension up to failure. For tension, the resistance increased monotonically [6].

Once uniaxial compression and tension was understood, cyclic loading was studied. Under cyclic loading the behavior of the specimen will depend on whether the fibers used were ozone treated or not. Carbon fibers based on isotropic pitch are pretty inexpensive. However, their performance can be improved if they are surface treated with ozone. This will improve wetting with water, obtain better dispersion in the concrete, increase the bond strength between the fiber and cement matrix and increase tensile strength and ductility when compared to values obtain with fibers which have not been treated. The figures below show $\Delta R/R_o$, stress and strain during compressive cyclic loading. These figures show the difference between using treated and untreated carbon fibers.

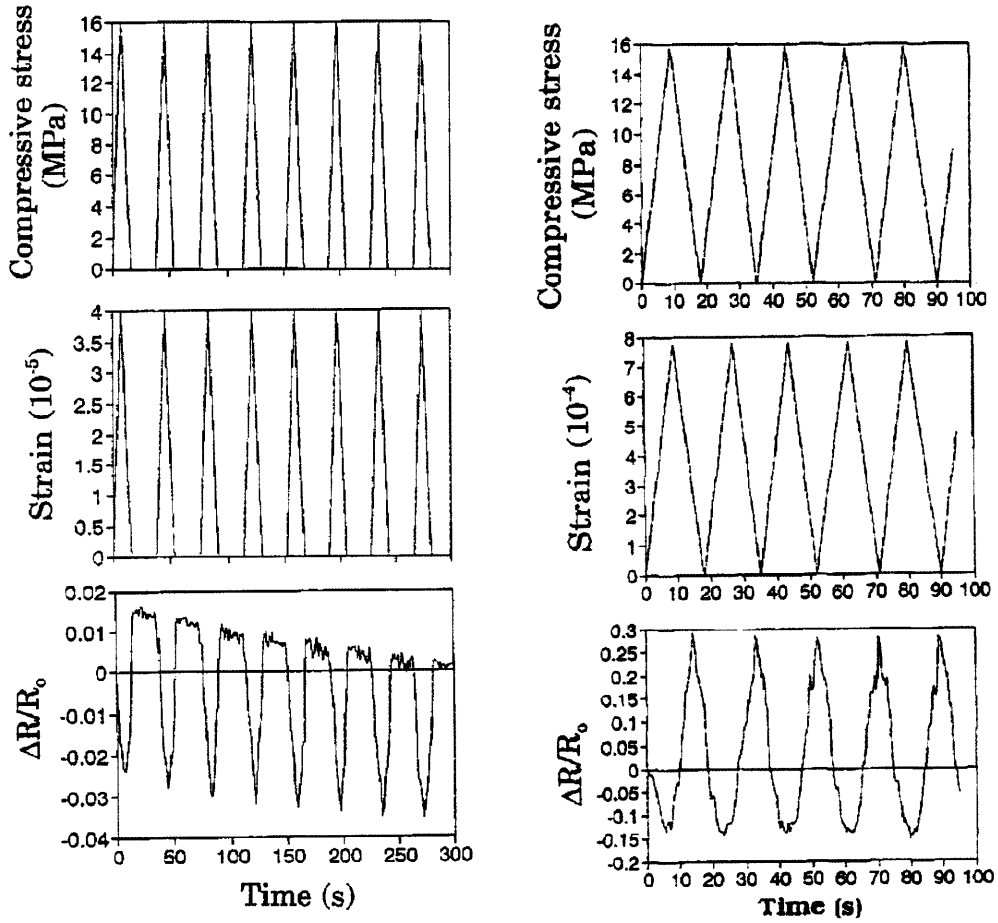

Figure 14: Untreated (left) and Ozone treated Fibers (right) [6]

In tests involving specimens containing ozone treated fibers it was found the $\Delta R/R_o$ increased during the tensile loading in each cycle and subsequently decreased during unloading in each cycle. This is caused by the pull-out of the fibers during the tensile loading and the push-in during the unloading process. The gage factor was found to be 700. At the end of each cycle the stress and strain returned to zero. It should be noted that at the end of the first cycle $\Delta R / R_o$ was positive rather than zero. This can be attributed to damage of the fiber-cement interface due to the fiber pull-out and push-in. Similar results were obtained for the compressive cyclic loading. The $\Delta R/R_o$ decreased during compressive loading in each cycle and increased during unloading in each cycle. The gage factor was found to be 560. The decrease is due to fiber push-in during loading and the subsequent fiber pull-out during unloading. Again, at the end of the first cycle $\Delta R/R_o$ was positive rather than zero due to damage of the fiber-cement interface. [6].

If the fibers are not ozone treated, the results are similar except that as cycling progresses both the maximum $\Delta R/R_o$ and the minimum $\Delta R/R_o$ in a cycle decrease for tension and compression respectively. This property can be attributed to the damage of the cement matrix se[erating adjacent fibers at their junction. The damage can increase the chance for adjacent fibers to touch one another and therefore the resistivity decreases. The decrease will persist from cycle to cycle for the first 120-350 cycles (10% fatigue life). After this point, the maximum and minimum $\Delta R/R_o$ do not change with cycling [6]. This can be called the baseline. A few cycles before fracture, the baseline will increase ever so slightly for a few cycles and then abruptly and greatly increase upon fracture. The slight increase in the $\Delta R/R_o$ baseline during a few cycles prior to fracture provides an indication (warning) of the impending fracture. However, due to the slightness of this increase the warning is not reliable [10]. In compressive cyclic loading, the damage of the cement matrix causes the initial decrease in the $\Delta R/R_o$ value. However, after a certain number of cycles, there is no further damage of this type and therefore it can be said it stabilized. This corresponds to the baseline. Knowing this information, a concrete structure can be monitored for fatigue.

In another study, fibers in the amount of 0.5% by weight of cement were used in mortar. Four different mortar specimens were used; one plain and the other containing a dispersion agent. It has been noted that in order for the carbon fiber reinforced concrete to have good self-monitoring abilities, the fibers must be well dispersed. Latex, methylcellulose and silica fume have all been used to aid in the dispersion of the fibers. In order to evaluate the effect of fiber addition alone, the dispersion agents were added regardless of whether the sample contained fibers. It was found the volume electrical resistivity increased irreversibly upon loading up to about 1/3 of the breaking load in the first loading cycle. In subsequent cycles, it reversibly increased upon unloading and reversibly decreased upon loading. This is consistent with the behavior described previously. In the case where there were no fibers, it was found that the resistivity was constant during loading and unloading. The use of the dispersion agent helped to develop a large fractional resistivity increase. By using methylcellulose with fibers, the fractional resistivity increased by 1040% [4].

This is the basic behavior of carbon fiber reinforced concrete. There are a variety of factors that can affect the self-monitoring ability of the concrete. One such factor is curing age. In a study on

the self-monitoring behavior of carbon fiber reinforced mortar it was found that the electrical resistance increased monotonically with increase compressive strain during the first loading at 7 days. However, at 14 and 28 days it decreased monotonically. This can be attributed to the weakening of the fiber-cement interface as curing progresses [10]. This should be considered when evaluating the self-monitoring ability of the concrete structure. Another factor to consider is the direction in which the resistivity is measured. In most studies the resistivity is measured in the stress direction. How resistivity changes in directions other than the stress direction can provide valuable insight on the mechanism behind the piezoresistive effect. In a study by Wen and Chung, it was found that the gage factor magnitude is comparable in the longitudinal and transverse directions [26]. This means measured direction is not of concern.

4.3 Implementation

Using carbon fiber reinforced concrete as an intrinsically smart material with the ability to self-monitor is obtainable. The carbon fibers are relatively cheap and easy to implement. They do not have negative effects on the concrete and ultimately help improve its performance. However, it seems that interest has been lost on this topic. Researchers are now investigating carbon fiber reinforced polymers to help with structures. Carbon fiber reinforced concrete has the ability to reduce crack width which is favorable in many areas. But, new materials like Engineered Cementitious Composites have similar abilities. Therefore, it seems that carbon fiber reinforced concrete has been replaced by new technology. Despite this, there are still several applications where this material could be useful.

One such application is in roads. The weighing of vehicles is needed to avoid damage to highways due to overweight vehicles. The monitoring of the weight of vehicles can be more convenient and effective if the weighing is done on the highway while the vehicle is moving. In this way, traffic is not affected and time is saved. In a study by Shi and Chung, a vertical wheel is allowed to rotate against the cylindrical surface of two horizontal concrete rollers. The speed of wheel rotation (corresponding to the speed of the car) and the force applied between the wheel and the concrete rollers (the force corresponding to the weight of the car) are systematically varied. The electrical resistance of the concrete near its surface is measured as the wheel rolls on it. It was found that self-monitoring concrete containing short carbon fibers is effective for traffic monitoring and weighing in motion. The resistance decreases reversibly with increasing stress up

to 1 MPa and is independent of speed up to 55 mph [21]. Such an application can be very useful especially when many current roads are in disrepair. The same idea can be applied to bridges with concrete decks. In this way, the life-span of these structures can be improved.

5.0 Conclusion

Reinforced concrete, one of the oldest building materials, can be modernized. Instead of building structures using traditional materials and then altering those to meet a performance standard, focus should be directed on making the material perform better. Let us reinvent an old material. In the case of reinforced concrete, there are several things that can be done to improve performance, increase concrete life-span and reduce the cost of maintenance and monitoring. First of all, the use of self-healing concrete can be used to help heal the inevitable microcracking and help heal cracking due to damage. This healing can reduce permeability and therefore increase the durability of the structure. Next, the use of shape memory alloys as reinforcement in reinforced concrete structures has the potential to limit deflections, improve ductility and increase the strength of shear walls if properly used. This can help improve a structure performance especially under seismic forces. Finally, carbon fiber reinforced concrete not only has great structural properties but its electrical conductivity can make the detection of damage easier. Each of these innovations can improve performance and cut down on the long term costs of maintenance and repair.

Even though reinforced concrete can have improved performance through the above mentioned methods, it is far from being widely implemented. One of the main barriers for implementing this type of technology is due to the inexpensiveness of concrete as a material. Maintenance of reinforced concrete structures also tends to be less than that of steel structures. Compared to other materials, concrete can easily be repaired or replaced. As such, people do not want to spend lots of extra money to improve its performance. Concrete must stay economical in order to remain as one of the leading building materials. All three innovations will increase the cost of building reinforced concrete structures. Until the cost of implementation and the savings from improved performance can be proven and quantified, it is unlikely that any will be adopted.

Another barrier preventing these improvements from being implemented is that the construction industry for the most part is adverse to change. Contractors like constructing structures with familiar materials and are therefore generally unwilling to use new smart materials. Designers have the ability to implement these innovations; however, it is unlikely that people will venture into this area due to the fact that large scale tests have not been performed for many of these improvements. In order to design a structure, the engineer must have a clear understanding of the

materials involved and how they will affect the performance of the structure as a whole. Since a lot of these applications are still in their infancy, designers will hesitate to use something that is not tried and true.

In conclusion, old materials can be reinvented. Although this thesis only focused on three innovations that can be used to improve the performance of reinforced concrete structures, it should be noted that there are a lot of new materials and technologies which can greatly improve the performance of structures. Self-healing concrete, use of shape memory alloys as reinforcement and carbon fiber reinforced concrete for damage detection all can improve the performance of reinforced concrete. Even though it is not clear whether all three innovations can be used together effectively, the potential each one holds is great. However, the construction industry is very price sensitive and the application of these smart materials will increase the initial cost of the reinforced concrete structure. Therefore it is unlikely that these smart materials will be put to use. In the future, further research, testing and development of these materials may make them more economical and therefore more applicable to the construction industry.

6.0 REFERENCES

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