Shape Memory Alloy Fiber-Reinforced Mortar

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Abstract

Shape memory alloys (SMA) exhibit a property called pseudo-elasticity, which allows the material to ‘remember’ its original shape after being subjected to heavy loads. When SMA fibers are embedded in concrete or mortar, the pseudo-elasticity of the fibers translates to a self-centering property that allows structures to recover from deformation after being exposed to strong cyclic loads. This research focuses on the flexural and self-centering impacts of randomly distributing nickel-titanium alloy (NiTi) fibers throughout specimens with different fiber volume fractions and fiber lengths. These characteristics were explored using 3-point bending tests and the results show that the 30 mm fibers were significantly more effective at self-centering than the 20 mm fibers. The 0.5% volume fraction specimens decreased in strength compared to the 0.3% (30 mm) specimens, but had better residual deformation values. The 1.0% volume fraction specimens maintained the highest strength and should be tested further to explore their self-centering properties.
Concrete is a readily available and affordable tool for building large and reliable structures. It can be molded on-site into a variety of shapes. However, concrete has a relatively low tensile and flexural strength. It is prone to cracking. The cracking jeopardizes the long-term viability of such structures. One method of improving these weaknesses is to reinforce the concrete with fibers. Popular fibers currently established for use in industry include synthetic, natural, glass, and steel.

These fibers are commonly used in structures to improve the flexural strength, fatigue resistance, ductility, and impact resistance of concrete. However, the long-term viability of such structures is significantly reduced in areas prone to seismic events. Of the current solutions, steel fibers are able to withstand the heaviest loads, but the strong cyclical loading of earthquakes causes permanent deformation to structures made of steel fiber reinforced concrete (SFRC); this is because steel fibers are unable to recover their original shape after a heavy load is removed. There are, however, a group of materials with this property. A primary characteristic of shape memory alloys (SMA) is pseudo-elasticity. This property, made possible by the polymorphic nature of the crystal structure, allows the material to return to its original shape via stress-induced phase transformation. When SMA fibers are incorporated into a concrete or mortar mixture, the pseudo-elastic property of the fibers translates to a self-centering property for the structure. SMAs have other significant properties including high ductility, energy dissipation, and the shape memory effect (SME). SME is a property akin to pseudo-elasticity that is heat-dependent instead of load-dependent.

This study tests the flexural strength of pseudo-elastic NiTi fiber reinforced mortar beams at volume fractions of 0.3%, 0.5%, and 1% and at lengths of 20 mm (0.79 in) and 30 mm (1.8 in). For each specimen, the fibers are randomly distributed to provide self-centering properties throughout each specimen.

**Literature Review**

An abundance of steel-short-fiber research has also been done with regard to regular reinforced concrete as well as high performance concrete. SFRC is more suited for applications involving heavy loads than glass fiber-reinforced concrete (GFRC) or most synthetic fibers. Perumal conducted compressive, flexural, and splitting tensile tests with steel fiber volume fractions ranging from 0.5% to 2.0%. The steel fibers were 36 mm in length. The flexural performance of the beams was directly proportional to an increase volume fraction [10].

![Figure 1](image-url)
Kim et al tested the mechanical properties of steel fiber reinforced concrete (SFRC) with volume fractions of 0.25%, 0.5% and 1%. Four different maximum temperatures, ranging from room temperature to 700 degrees C were used to measure the compressive and tensile strength. As the maximum temperature increased and the volume fraction decreased, the SFRC weakened.

Abu-Lebdeh et al used four different geometries of short steel fibers in very-high-strength concrete to measure the bond strength of the various fibers via a pullout test. The results showed that flat-end steel fibers had the highest peak load, though they ruptured at every length when pulled out at a high rate.

Similarly, Abaza et al modeled the first crack load as a function of the steel-fiber fraction in order to find an optimal volume fraction. The resulting flexure test suggested that 0.64% steel fibers did not cause a significant change in ‘first-crack strength’, but 0.89% and 1.28% showed a comparable and significant increase in strength. From this, Abaza et al concluded that a steel-fiber dosage ranging from 0.89% to 1.28% would be optimal. In a similar study, Wang et al found that a 3.0% volume fraction would be optimal.

Steel fibers significantly improve the performance of concrete and are able to withstand strong loads. However, as noted earlier, they are unable to recover their original shape, which means that in areas prone to earthquakes, areas where the strong loads will likely be cyclical, SFRC structures have a significantly decreased lifespan. SMA fibers are able to recover their shape and are, therefore, a compelling alternative to steel fibers.

Studies conducted on SMA fibers in concrete or mortar have explored various pre-treating techniques, fiber geometries, and fiber concentrations. Many journal articles published about SMAs in recent years focus on pre-stressing and the shape memory effect. Moser et al look in to the effects of pre-stressed SMA short fibers in mortar and found that the temperatures during the third and fourth cycles of employing the shape memory effect the risk of internal damage in a theoretical field application is relatively low.

Choi et al explored crack-recovery and deflection recovery of SMAs in mortar beams. The cold-drawn fibers for this experiment were of two geometries: straight and dog-bone shaped. Some of the fibers’ mid-sections were wrapped in paper, so that only the exposed ends were able to bond with the mortar. The paper-wrapped fibers showed greater crack-closing capacity and the dog-bone shaped fibers performed better in both tests than the straight fibers. A second study by Choi provides similar claims and concurred that pre-strained dog-bone fibers will be most practical for field application. An experiment by Sun et al draws a similar conclusion about bond length and crack repair: increasing un-bonded length of an embedded fiber is directly proportional to the crack-repair ability of the specimen.

When paired with engineering cementitious composites (ECC), SMA fibers exhibited full recovery of the original shape from flexural loading damage, with high energy dissipation capacity, and minimal residual deformation at a volume fraction of 1.8%. This is one of the highest volume fractions employed in recent publications.
A common SMA is nickel titanium alloy (NiTi), which possesses both pseudo-plasticity and pseudo-elasticity via martensitic/austenitic phase transformation. Shajil et al. [12] measured this using a metric called the self-centering factor, which describes the ratio of the difference between the maximum and permanent deflections and the maximum deflection. This study showed that under equal fiber volume conditions, steel fibers exhibited a self-centering factor of 0.1, whereas NiTi fibers showed 0.7.

Shajil et al [11] tests the re-centering and ductility of SMA fiber reinforced mortar beams using three point bending test. Volume fractions of 0, 0.25%, and 0.5% were tested. A volume fraction of 0.5% and a fiber length of 40mm was determined as the optimal reinforcement for a 40 x 40 x 160 mm prism. Much like steel fibers, SMA fibers are most effective when randomly distributed and act as three dimensional reinforcement [5].

**Methods**

This study tests the flexural strength and self-centering properties of randomly distributed NiTi fiber reinforced mortar beams at varying volume fractions and lengths (figure 2).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fiber Volume Fraction (%)</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-3</td>
<td>Control Specimen</td>
<td>Control Specimen</td>
</tr>
<tr>
<td>4-6</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>7-9</td>
<td>0.3</td>
<td>30</td>
</tr>
<tr>
<td>10-12</td>
<td>0.5</td>
<td>30</td>
</tr>
<tr>
<td>13-15</td>
<td>1.0</td>
<td>30</td>
</tr>
</tbody>
</table>

The test matrix was determined using the results of a selection of relevant studies published within the last few years. These studies are referenced in the literature review section. The goal was to minimize residual deflection and increase re-centering in specimens with randomly distributed fibers. The volume fractions fall within the range of previously tested amounts, however the fibers are randomly distributed throughout the specimen and not concentrated at the tension face. The fiber lengths were determined based past research and scaled to the capacity of a 40x40x160 mm (1.57 x 1.57 x 6.30 in) specimen.

**NiTi Wire Characterization**

The pseudo-elastic NiTi wire used in this experiment had a diameter of 0.35 mm (0.0138 in), a tensile strength of 1538 MPa (223 ksi) and a yield strength of 400 MPa (58 ksi). The wire was composed of six individual wires wound together. The hope of using type wire instead of a single, thicker stand to was the increase the surface area, thereby increasing the bond strength of the fiber with the mortar. The fibers were cut from a 213 meter (700 ft) wire using the centimeter marks on a standard ruler. To minimize fraying, the fibers were cut using titanium electrician’s scissors.
Specimen Preparation

The cement mortar proportions were calculated using ASTM standard C109. This standard gives the proportions for 50 x 50 x 50 cm cubes and each prism contains the volume of two cubes. The fine aggregate was sifted through a number 10 sieve. The cement mortar for all the specimens was mixed at the same time and then separated into five batches based on fiber length and volume fraction. The five batches were poured into 4 x 4 x 16 cm sections of a 54.9 x 37.7 x 4 cm (21.63 x 14.85 x 1.57 in) wooden form and allowed to cure for 28 days.

3-Point Bending Test

The flexural strength and self-centering capability were tested using a 3-point bending test. A materials testing system (MTS) machine was used to apply load to the specimens. A displacement rate of 0.016667 mm/second. This rate was extrapolated based on a test conducted on an extra control specimen from the same batch as the other fifteen specimens. The specimen was allowed to cure for 20 days and tested to failure using a force control.

The surface deformation and strain contours of each specimen were captured in two methods: digital image correlation (DIC) and laser displacement scanning. DIC is a camera software system that calculates the change in deformation and strain based on the movement of a random network of points that cover the one face of the specimen. In this case, the DIC was used to record data on the strain distribution throughout the cyclic loading process. Laser scanning was used to monitor the mid-span displacement of each specimen throughout the cyclic loading process.

Experimental Results

Due to a lack of consistency in the results of the replicates (figure 4), the specimen with the least structural desirability was chosen to represent each category.

Figure 3

Figure 4
Specimens 1-3: Control

![Figure 5](image)

The control specimen, which was plain mortar and contained no fibers, had a heavy stress concentration through the middle of the beam (figure 5). Reaching a maximum force of 1478 N (337 lb-f), the specimen failed soon after the initial crack (figure 6).

Specimens 4-6: 0.3% VF and 20 mm length

![Figure 7](image)

Specimen 6 had 0.3% SMA fiber volume fraction of 20 mm fibers. The strain contour (figure 7) shows a more prominent distribution of strain throughout the specimen. The 20 mm specimen withstood a maximum force of 1581 N (355 lb-f), which is 103.8 N more than the control (figures 8&9). The residual displacement of the beam was 0.77 mm (0.03 in). Self-centering is evident, though not as prominent as the following specimen, which contained 30 mm long fibers and the same 0.3% volume fraction.
Specimens 7-9: 0.3% VF and 30 mm length

Specimen 9 had 0.3% SMA fiber volume fraction of 30 mm fibers. The strain contour (figure 10) shows a more prominent distribution of strain throughout the specimen and a smaller central concentration of strain than Specimen 6. This specimen withstood a maximum force of 1661.9 N (373.6 lbf), which is 80.1 N greater than Specimen 6 (20 mm) and 183 N greater than Specimen 3 (control) (figures 11 & 12). The residual displacement of the beam was 0.71 mm (0.28 in). The self-centering properties of this specimen are much more evident than Specimen 6, which contained the same volume fraction, but used 20 mm fibers.

Specimens 10-12: 0.5% VF and 30 mm length

Figure 13
Specimen 11 had 0.5% SMA fiber volume fraction of 30 mm fibers. The strain contour (figure 13) shows a more prominent distribution of strain throughout the specimen and less strain on the entire specimen overall. This specimen withstood a maximum force of 1532.4 N (344.5 lb-f), which is 54.4 N greater than Specimen 3 (control), but 129.5 less than Specimen 9 (0.3%, 30mm). It should be noted that all 0.3% volume fraction, 30 mm specimens withstood more force than all 0.5% volume fraction specimens (figures 14 &15). This result is unexpected, however the residual displacement of the specimen 11 beam was 0.53 (0.21 in) and all of the residual displacement values for the 0.5% volume fraction specimens were lower than the 0.3% volume fraction specimens. This is reflected in the self-centering properties (figure __ b) of this specimen are much more evident and show greater recovery than specimens with smaller volume fractions.

Specimens 13-15: 1.0% VF and 30 mm length

Specimen 14 had 1.0% SMA fiber volume fraction of 30 mm fibers. The strain contour (figure 16) shows a more prominent distribution of strain throughout the specimen and the strain is significantly reduced in comparison to lower volume fractions. This specimen withstood a maximum force of 1702.3 N (382.7 lb-f), which is 40.4 N more than Specimen 9 (0.3%, 30 mm) and 224.3 N more than the control specimen (figure 17). The 1.0% volume fraction specimens exhibited the least residual displacement (figure 18). Specimen 14 had a residual displacement of 0.60 mm (0.024 in) at the end of the 13th cycle. The self-centering properties are less evident in the 1.0% specimen. This may be because the specimen reaches its maximum load at the end of the test and, as seen in specimens 6, 9, and 11, self-centering was most evident after the
maximum load has been reached. It is recommended that further testing be completed on the 1.0% volume fraction specimens, as the self-centering properties may become more evident after the 13th (final) cycle of this project.

**Conclusion**

In this study, the flexural strength and self-centering properties of NiTi fiber-reinforced mortar were tested at varying lengths and volume fractions. The 30 mm fibers were significantly more effective at self-centering than the 20 mm fibers. The 0.5% volume fraction specimens decreased in strength compared to the 0.3%, 30 mm specimens, but had better residual deformation values. The 1.0% volume fraction specimens maintained the highest strength and should be tested further to explore their self-centering properties.

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**References**


