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Experimental investigation of actively confined concrete using shape memory alloys

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ABSTRACT

This experimental study focuses on investigating the uniaxial compression behavior of concrete confined using an innovative active confinement technique. The thermally triggered recovery stress of prestrained Shape Memory Alloy (SMA) spirals is utilized to apply external active confining pressure to concrete cylinders. Thermo-mechanical tests are first conducted to determine the recovery stress and the prestrain losses of the spirals used. Next, the SMA spirals are utilized to confine concrete cylinders either solely or in conjunction with Glass Fiber Reinforced Polymer (GFRP) wraps. The confined cylinders are tested in compression and their behavior is compared with that of cylinders confined passively with GFRP only. The results of the study show that SMA spirals exhibit stable recovery stress under monotonic and cyclic loading. The amount of prestrain losses measured in the study is minimal and thus has no impact on the behavior of the confined cylinders. The compression test results indicate that the SMA spirals are effective in applying large and reliable active confining pressure on the tested concrete specimens. Additionally, the concrete cylinders confined with the SMA spirals show significantly higher ultimate strain and slightly higher strength compared to those of the GFRP passively confined cylinders.

1. Introduction

Among the major limitations of concrete as a construction material is its brittle behavior, which provides little warning prior to failure. Lateral confinement of concrete, which involves applying pressure on the concrete element perpendicular to the direction of loading, is a well known technique that is commonly used to improve the strength and ductility of reinforced concrete members. Among the early studies that reported the efficacy of concrete confinement is the study conducted by Richart et al. in 1928 [1]. Many studies have since been conducted to investigate the behavior of concrete with several confinement techniques.

Based on the method used in applying the confinement pressure, one can divide concrete confinement techniques into two main types, passive and active. Fig. 1(a), (b) show schematics of cross sections of passively and actively confined concrete cylinders, respectively. The major difference between both techniques is the lateral confining pressure which is exerted on the section prior to axial loading in the case of active confinement. In the passive confinement technique the confining pressure is exerted only as a direct result of the lateral dilation of concrete. Hence, in order for the passive confinement technique to be fully engaged, the concrete has to experience some sort of damage. Fig. 1(c) depicts typical stress versus volumetric strain behaviors of unconfined, passively confined, and actively confined concrete. The unconfined concrete experiences volumetric compaction in the elastic region, after which it starts expanding rapidly until reaching failure. Similarly, under axial stress, the volume of a passively confined concrete reduces in the elastic region and the passive confining pressure helps in delaying the point where the concrete starts expanding volumetrically. In the active confinement case, the confining pressure which is applied to prestress the concrete element laterally prior to loading exerts an initial volumetric strain ε_v^o due to compaction. In order to overcome the effect of this strain, extra axial strain and stress are need, and thus the failure point of the concrete is further delayed compared to the passively confined concrete.

Various methods have been used and studied to apply passive confinement on concrete elements. These methods vary from using internal transverse reinforcements in new structures (e.g. spirals, stirrups, etc.) to using external steel jackets or fiber reinforced polymer (FRP) sheets to retrofit old structures. There is a large body of literature discussing the analytical and experimental behavior of passively confined concrete. Many researchers examined the behavior of concrete confined internally with transverse steel reinforcements [2–6]. Different shapes of internal reinforcements such as rectangular hoops, spirals and circular hoops were investigated in these studies. On the other hand, studying the behavior of concrete confined with external steel jackets or FRP sheets has been also the focus of numerous studies [7–12]. Because of its superior effect on enhancing concrete behavior, a

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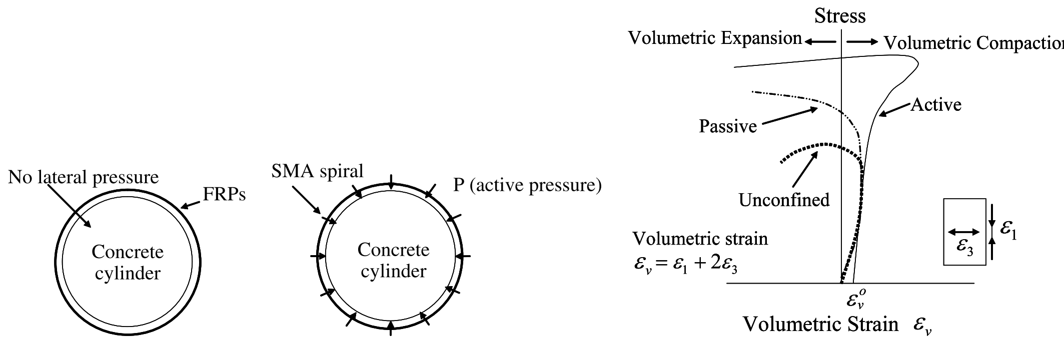
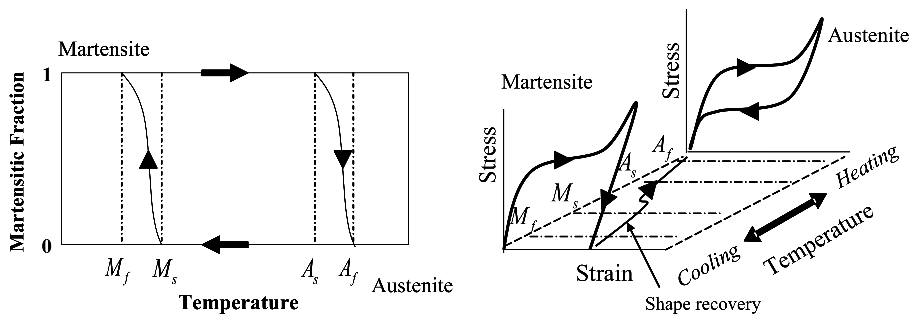


(a) Passive confinement before loading. (b) Active confinement before loading. (c) Stress vs. volumetric strain of concretes.

Fig. 1. Schematics of the cross section of confined concrete before loading (a and b) and stress vs. volumetric strain curves of unconfined, passively and actively confined concrete (c).



(a) Thermal hysteresis. (b) Thermo-mechanical behavior.

Fig. 2. Thermal hysteresis and thermo-mechanical behavior of typical SMAs.

relatively few number of studies were focused on the application of active confinement. Gamble et al. [13] and Saatcigolu and Yalcin [14] attempted retrofitting reinforced concrete (RC) columns using prestressed steel strands. Krstulovic-Opara and Thiedmeman [15] and Hussain and Driver [16] conducted experimental tests on actively confined concrete using memory fiber mats and steel hollow structural section collars, respectively. Others investigated the behavior of RC columns using pre-tensioned FRP belts [17,18]. Most of the aforementioned studies used mechanically prestressed materials to provide active confinement. Applying active confinement by prestressing the jacket or strands around the concrete has proven to be problematic and would require excessive labor, time, and cost. Therefore, despite its superiority to passive confinement, the application of active confinement in real structures has been hindered. This study presents and examines an innovative method for applying active confinement without the need for mechanical prestressing. The confining pressure will be applied using a new class of materials known as Shape Memory Alloys (SMAs). In a previous paper, the authors explored this new technique analytically [19]. However, in this paper the technique is studied experimentally using concrete cylinders. Two new types of concrete wraps made with SMA spirals were developed and tested.

2. Shape memory alloy spirals

SMAs are a class of metallic alloys known for their unique thermo-mechanical characteristics including superelasticity and shape memory effect (SME). Due to these unique characteristics, SMAs have been adopted and studied in several engineering fields. For example, in the field of civil engineering, researchers have been interested in studying the feasibility of using SMAs for seismic applications including braces [20], base isolators [21], damage repair devices [22], and bridge restrainers [23], among other applications. The main reason for such interest in SMAs is their capability to recover their original shape after experiencing large deformations up to 8%-strain [24]. This unique characteristic is primarily due to the back and forth transformation between the martensite phase and the austenite phase on the atomic level, which is dependent on the alloy's four transformation temperatures (M_f, M_s, A_s and A_f). Fig. 2 shows how the stress–strain behavior and martensitic fraction of the SMA changes with respect to temperature. At temperatures below M_f (martensite finish temperature) where the alloy is in its martensite phase, the SMA behaves plastically as depicted in Fig. 2(b). If the SMA is heated above the temperature A_f (austenite finish temperature), the alloy transforms to austenite and the SMA recovers its original shape. This phenomenon is known as shape memory effect (SME). At high temperatures (above A_f), the SMA unloads with a zero residual strain, i.e. behaves elastically. The SME phenomenon is associated with large recovery stress if the alloy is restrained from restoring its original shape. This stress highly depends on the material composition, manufacturing procedure, and the amount of prestrain [25].

Fig. 3 shows a schematic describing the concept used in this paper for applying active confinement on concrete using SMA spirals. SMA wire is first prestrained to approximately 6% strain then wrapped around the element in the form of a spiral (see Fig. 3(a)). The SMA spiral is then heated to activate its shape recovery. However, since the spirals are fully constrained by the surface of the concrete element, large recovery stress (hoop stress) is developed in the spiral causing the application of large confining pressure on the wrapped element. It is important to note that not every type of SMAs is suitable for this application. This application requires an alloy with a relatively wide thermal hysteresis where the transformation temperatures M_s (martensite start temperature) and A_s (austenite start temperature) are significantly apart from each other. This is important to ensure that the alloy will not loose