Confinement of Reinforced Concrete Columns Using Shape Memory Alloy Plates

E. M. Atia, M. A. Alkersh, A. M. Hilal, M. Abdelrazik

Abstract—Strengthening of columns is of great importance in maintaining the structural health of partially deficient structures. The purpose of this study is to propose a new equation determining the strength of circular columns strengthened with shape memory alloy (SMA) plates subjected to tension force. Moreover this study proposes a new method that can be used to confine reinforced concrete circular columns using SMA plates. The experimental program consists of three groups including. Fifteen circular concrete columns specimens (100 mm diameter, 700mm height). The parameters studied in the experimental program are the spacing between external stirrups, applied tension force to the external stirrups and type of confinement (active or passive). The SMA possesses unique characteristic properties ability to such as undergo large deformations and return back to their original shape through heating. This strain energy can be used to generate prestressing force on concrete, which is able to increase the strength of the circular concrete columns under axial compressive load. Finite element models on the well-known software ABAQUS ware performed to verity the experimental results. The results of the finite element models showed good agreement with experimental results. Anew equation pretending the increase in circular columns capacity due to repair using SMA ware deducted based on the results of the program. The results also showed that; increase in tension force applied to external stirrups caused increase in the strength of confined concrete at failure, and the increase in the external stirrups spacing in case of both passive and active caused decrease of the capacity of columns strengthened with (SMA).

Index Terms— Active Confinement, Capacity, Columns Strengthened, External Stirrups, Passive Confinement, Prestressing Force, Reinforced Concrete, Tension Force.

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1. INTRODUCTION

REINFORCED concrete elements are designed to satisfy safety, serviceability and economy. Strengthening of reinforced concrete columns with Smart Materials is important nowadays and useful for increasing strength especially with existing buildings over the world. The need of strengthening or retrofitting is due to several factors, such as additional load, functional change and design errors.

1.1. Active and passive confinement

Concrete confinement techniques are divided into two main types, passive and active. Figure 1(a), (b) show schematics of cross sections of passively and actively confined concrete cylinders, respectively[1,2]. The main difference between both techniques is the lateral confining pressure which is exerted on the section previous to axial loading at the case of active confinement. In the passive confinement method the confinement pressure is exerted only as a direct result of the side dilation of concrete. Therefore, in order for the passive confinement system to be totally engaged, the concrete has to experience some of damage. The unconfined concrete experiences volumetric compaction in the elastic zone, after which it starts increasing quickly until reaching failure. In the same way, under axial stress, the volume of a passively confined concrete decreases in the elastic region and the passive confining pressure assists in delaying the point where the concrete starts increasing volumetrically. In the active confinement case, the confinement pressure which is applied to prestress the concrete element laterally prior to loading exerts an initial volumetric strain due to compaction [3]. In order to overcome the effect of this strain, extra axial stress and strain are needed. The failure point of the concrete is more delayed compared to the passively confined concrete.

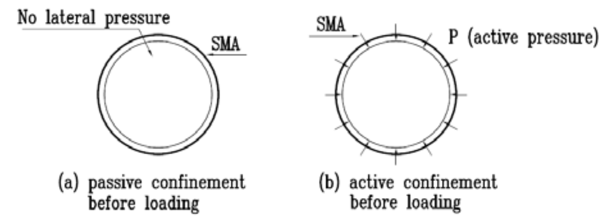

Fig. 1.(a and b).Schematics of the cross section of confined before loading.

Passive confinement is the first possible approach used for structural confinement and this method is by far the more common of the two approaches used to enhance the strength and ductility capacity of vulnerable members. The following relation for strength of passive confined concrete in the American code ACI 440.2R-08 (2008)[4]was proposed:

$$f'_{cc} = f_{co}\left(2.254\sqrt{1+\frac{7.94f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}} - 1.254\right)$$

$$f'_l = 1/2\, k_e \rho_s f_{yh}$$

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$$k_e = \frac{1-\left(\frac{s''}{2d_s}\right)^2}{1-\rho cc}$$

$$\rho_s = \frac{A_{sp}*\pi*d_s}{\frac{\pi}{4}{d_s}^2*s}$$

f'_{cc} = the strength of confined concrete at failure, f'_{co} = unconfined concrete compressive strength, f'_l= effective lateral confining pressure, f_{yh}= the yield strength of transverse reinforcement, k_e = the confinement effective coefficient, ρ_{cc} = the ratio of the area of the axial steel to the area of the core of the section, s'' = the clear spacing between the spiral, ρ_s = the transverse reinforcement ratio, A_{sp} = area of transverse reinforcement bar, d_s = the diameter of the spiral between bar centers, s = the spacing between the spiral.

Active confinement is the other possible approach used for structural confinement. While this method is far less commonly used, it does have some major advantages when compared to the passive confinement applications. In this study a new equation is proposed to determine the strength of circular columns strengthened with shape memory alloy (SMA) plates, knowing that SMA is subjected to tension force.

1.2. Background information on SMA

SMAs have the ability to take large deformations (up to 8%) and return to their original shape upon heating. These unique properties are primarily due to the back and forth transformation between the martensite phases and the austenite phases on the atomic level. The austenite and martensite phases are related to the high temperature and low temperature state of the material. The SMA's are dependent on two transformation temperatures, austenite finish temperature (Af) and martensite finish temperature (Mf) [5]. Figure 2 shows how the stress-strain behavior of the SMA changes with respect to temperature. At temperatures below Mf where the alloy is in its martensite phases, the SMA behaves plasticity. If the SMA is heated above the temperature Af, the alloy transforms to austenite and the SMA recovers its original shape (super-elasticity) as depicted in Figure (2). That phenomenon is known as shape memory effect[6]. 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, and the amount of prestrain.

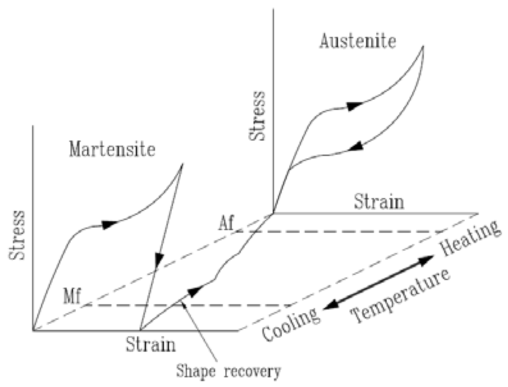

Fig. 2. Mechanical behavior of SMAs.

SMAs are a very unique group of metallic alloys that are capable of recovering apparent permanent strains when they are heated above a certain temperature, due to a reversible phase change that occurs within the atomic structure of the alloy. With these amazing alloys, a temporary deformed shape can be virtually held forever until the right stimulus (mainly temperature) is applied to trigger a shape recovery and return the alloy back to the original un-deformed shape [7]. Due to this reversible process, SMAs have an endless amount of possible applications and appear to be one of the main materials of the future.

SMAs have already been used for multiple applications within the biomedical field (eyeglasses, dental wires, and reinforcement for arteries and veins), and aerospace industries (fixed wing and rotary-wing components) in the past. Recently, they have also started to attract a lot of attention in other engineering fields due to the price decrease that has occurred over the past 10 to 15 years. This price decrease which is mainly due to enhanced manufacturing processes over this time frame is expected to continue within the future and should drastically decrease due to the eventual increase in both copper and iron based alloys, which has made previously large scale applications now realistically possible [8,9].

2. SMA PLATE

In study used SMA plate of Nickel (Ni) and Titanium (Ti) with an atomic percentage of 55% and 44%, respectively were used. The SMA plates could provide a linear strain recovery up to 8% when heated above the as temperature of 23°C. The SMA plates have been supplied by the manufacturer in its martensitic pre-strained. According to the manufacturer, the ultimate tensile strength, elastic modulus, and strain at failure of the SMA plate were 896MPa, 84821MPa, and 18%, respectively.

During the confinement procedure, the SMA plate is initially utilized in its pre-strained martensite form. After which, the application of heat triggers the Shape Memory Effect of the SMA plate transforming the plate into its austenite state that actively confines the concrete specimen through a reactive force induced by restraining the SMA plate. Thus, the tensile characteristics of the SMA plate were determined in its martensite and austenite state.

3. EXPERIMENTAL PROGRAM

Sixteen RC columns with overall dimensions of 100 mm diameter, 700mm height were tested. The moulds were precisely cut from a polyvinyl chloride (PVC) plastic pipe, such that their inside surface was smooth and they were all very similar in geometry. The concrete mix was designed, aiming at a compressive strength about 22.5MPa at 28 days. The vertical longitudinal reinforcement of all specimen was 4 bars with diameter 10mm. The internal stirrups were 4mm diameter bars at 220mm from spacing, additional three stirrups and one layer of CFRP at 100mm beginning and end of column to avoid local failure. The external stirrups were (SMA plate U-shape) 2mm thickness, 20mm wide,380 mm length, 30mm beginning and end on the form of 90 degree angle and hole diameter 8mm in the center of the angle. The specific parameter of each specimen is described in Table (1).

The test specimens were divided into three groups and a column reference depending on spacing of transverse external stirrups as shown in Figure (3).

TABLE 1
SPECIFIC PARAMETER OF EACH COLUMNS

Group	Speci-ment	Spacing external stirrups (mm)	Temper-ture (℃)	Applie-d torque (N.mm)	Bolt preten-son force(N)
1	C11	60	≤15	0	0
	C12	60	≥23	0	0
	C13	60	≥23	3.2x106	2000
	C14	60	≥23	6.4 x106	4000
	C15	60	≥23	9.6 x106	6000
2	C21	90	≤15	0	0
	C22	90	≥23	0	0
	C23	90	≥23	3.2x106	2000
	C24	90	≥23	6.4 x106	4000
	C25	90	≥23	9.6 x106	6000
3	C31	120	≤15	0	0
	C32	120	≥23	0	0
	C33	120	≥23	3.2x106	2000
	C34	120	≥23	6.4 x106	4000
	C35	120	≥23	9.6 x106	6000

The torque (Ma) required to induce the pretensioning force (T) shell be calculated as follows:

Ma = k.d.T

Where: Ma = Applied torque, K = Coefficient (about 0.2 for all bolts diameters), d = Diameter of bolt, T = Bolt pretension force

Group (1) consisted of five columns, the spacing between external stirrups was @ 60mm. Column (C11) was passively confined and the temperature of external stirrups is smaller than 15℃. Column (C12) was passively confined and the temperature of external stirrups was bigger than 23℃. Column (C13, C14 and C15) is actively confined, the temperature of external stirrups higher than 23°Cand tension of external stirrups by 2000, 4000 and 6000 N respectively.

Group (2) consisted of five columns, the spacing between external stirrups was @ 60mm. Column (C21) was passively confined and the temperature of external stirrups is smaller than 15℃. Column (C22) was passively confined and the temperature of external stirrups was bigger than 23℃. Column (C23, C24 and C25) is actively confined, the temperature of external stirrups higher than 23and tension of external stirrups by 2000, 4000 and 6000 N respectively.

Group (3) consisted of five columns, the spacing between external stirrups was @ 60mm. Column (C31) was passively confined and the temperature of external stirrups is smaller than 15℃. Column (C32) was passively confined and the temperature of external stirrups was bigger than 23℃. Column (C33, C34 and C35) is actively confined, the temperature of external stirrups higher than 23°Cand tension of external stirrups by 2000, 4000 and 6000 N respectively.

One hydraulic jack was used with capacity 100 Ton. Figure (4) shows the general setup and the test frame.

Fig. 4. Testing Frame.

3.1 Procedure for Strengthening columns with SMA in active confinement state

- The concrete surface was prepared using a hammer and blower to remove the weak parts on the concrete cover.
- The SMA plates ware rolled around column surface.
- Steel bolts ware put in opening of SMA plate and tie bolts by using applied force and torque mentioned Table 1.

4. EXPERIMENTAL RESULTS

Columns were tested under static load and results were verified by an analytical model. Test were performed in the Concrete Lab El Azhar University in Cairo. Figure (5) shows the crack pattern of (C11, C21 and C31).

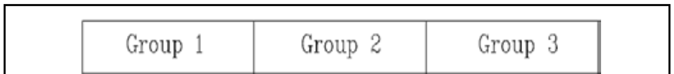

Fig. 5. crack pattern of (C11, C21 and C31).

5. THE FINITE ELEMENT PROGRAM

The computer program used in the analysis was ABAQUS. The analysis was based on the non-linear iterative secant stiffness formulation and merges the following described constitutive models for concrete, reinforcement and SMA. Concrete Damaged Plasticity model was used to describe the yield criterion of concrete as compressive behavior and tension behavior.

The reinforced concrete column was idealized by the finite element model using three types of elements. The concrete was represented by an eight-node solid element (C3D8R) with 24 degrees of freedom. The reinforcement was represented by a truss element (T3D2) with 6 degrees of freedom. SMA was represented by an eight-node solid element (C3D8R) with 24 degrees of freedom. The contact between concrete and SMA was represented by tie behavior. The verification of numerical model has shown good agreement with the experimental results. The results from ABAQUS strength of confined concrete at failure are compared in Table (2).

TABLE 2
COMPARISON BETWEEN THE EXPERIMENTAL AND ABAQUS STRENGTH OF CONFINED CONCRETE AT FAILURE

Group	Specimens	strength of confined concrete at failure f 'cc (N/mm2)	
		Experimental	FEA
1	C11	32.78	33.11
	C12	38.04	39.01
	C13	41.00	41.68
	C14	42.14	44.35
	C15	44.65	47.02
2	C21	27.96	28.74
	C22	31.71	31.82
	C23	33.02	33.19
	C24	33.77	34.40
	C25	35.46	35.70
3	C31	25.64	26.64
	C32	26.28	28.34
	C33	27.72	29.07
	C34	28.41	29.36
	C35	29.29	30.12

6. THE NEW PROPOSED EQUATION

In Table (2) the results of the finite element program(Abaqus) and the experimental strength of confined concrete at failure are compared. The main difference between results was small within 3%. The following equations to calculate strength of active or passive confined concrete at failure ware concluded.

$$f'_{cc} = f_{co}\left(2.26\sqrt{1+\frac{9.20f'_l}{f'_{co}}} - 2\frac{f'_l}{f'_{co}} - 1.254\right)$$

$$f'_l = 1/2\, k_e \rho_s f_{yh} F_S$$

$$k_e = \frac{1-\left(\frac{s''}{2d_s}\right)^2}{1-\rho cc}$$

$$\rho_s = \frac{A_{sp}*\pi*d_s}{\frac{\pi}{4}{d_s}^2*s}$$

$$F_s = 1+\frac{S_{SMA}}{f_{yh}} \quad \leq 1.5$$

$$S_{SMA} = \frac{T}{A_{sp}}$$

where;

f'_{acc} = the strength of active or passive confined concrete at failure, f'_{co} = unconfined concrete compressive strength, f'_l= effective lateral confining pressure, f_{yh}= the yield strength of transverse SMA plate, k_e = the confinement effective coefficient, ρ_{cc} = the ratio of the area of the axial steel to the area of the core of the section, s" = the clear spacing between the spiral, ρ_s = the transverse SMA plate ratio , A_{sp} = area of transverse SMA plate, d_s = the diameter of the spiral between SMA plate centers, s = the spacing between the SMA plate, F_s = the active confinement effective coefficient, S_{SMA}= Internal stress of external stirrups, T = tension of external stirrups.

7. PARAMETRIC STUDY

A more global parametric study for columns reinforced externally by SMA sheets was performed. This parametric study would help do deep explore the behavior of other different columns, not tested in the laboratory. The use of the limit element numerical model would help knowing the exact failure loads and strains for a larger number of specimen.

The parametric study was carried on a total number of 28 columns divided into two groups.

All columns where of cylindrical shape 400 mm diameter, 2800mm height. The vertical longitudinal reinforcement of all specimen was 8 bars with diameter 16mm. The internal stirrups were 10mm diameter bars at 1000mm spacing. The external stirrups were (SMA plate U-shape) 10mm thickness, 20mm wide and 400 mm inner diameter. The concrete compressive strength was about 22.5MPa.

The specific parameter of each specimen also theoretical (new proposed equation) and ABAQUS strength of active or passive confined concrete at failure for all columns was described in Table(3).

TABLE 3
SPECIFIC PARAMETER OF EACH COLUMN FOR PARAMETRIC STUDY AND COMPARISON BETWEEN THE THEORETICAL AND ABAQUS STRENGTH OF ACTIVE OR PASSIVE CONFINED CONCRETE AT FAILURE

Specimen	Spacing external stirrups (mm)	Temperature (℃)	Bolt pretension force(N)	strength of confined concrete at failure f'_{cc} (N/mm²)	
				Theoretical	FEA
C1-1	150	≤15	0000	29.27	28.92
C1-2	150	≥23	0000	32.61	32.72
C1-3	150	≥23	2000	32.97	33.10
C1-4	150	≥23	4000	33.33	33.46
C1-5	150	≥23	6000	33.69	33.82
C1-6	150	≥23	8000	34.04	34.17
C1-7	150	≥23	10000	34.38	34.53
C1-8	150	≥23	12000	34.73	34.88
C1-9	150	≥23	14000	35.07	35.24
C1-10	150	≥23	16000	35.41	35.59
C1-11	150	≥23	18000	35.74	35.94
C1-12	150	≥23	20000	36.07	36.29
C1-13	150	≥23	22000	36.40	36.64
C1-14	150	≥23	24000	36.73	36.99
C2-1	200	≤15	0000	27.08	26.96
C2-2	200	≥23	0000	29.41	29.42
C2-3	200	≥23	2000	29.67	29.69
C2-4	200	≥23	4000	29.92	29.92
C2-5	200	≥23	6000	30.18	30.15
C2-6	200	≥23	8000	30.43	30.38
C2-7	200	≥23	10000	30.68	30.61
C2-8	200	≥23	12000	30.92	30.84
C2-9	200	≥23	14000	31.17	31.06
C2-10	200	≥23	16000	31.41	31.29
C2-11	200	≥23	18000	31.65	31.51
C2-12	200	≥23	20000	31.89	31.73
C2-13	200	≥23	22000	32.13	31.95
C2-14	200	≥23	24000	32.37	32.17

From Table (3) the difference between results from finite element program and theoretical strength of confined concrete at failure ware small, consequently the results of the new equation have been confirmed and can be used in the case of active confinement.

8. CONCLUSIONS

The present study investigated the effect of active and passive confined external stirrups on the capacity of RC columns. The following summarizes the findings of this investigation:

1. Increase the spacing between passive and active external stirrups caused a decrease of the capacity of columns strengthened with SMA.
2. Increasing tension force in the external stirrups caused an increase of the capacity of columns strengthened with SMA.
3. Increase temperature external stirrups caused an increase of the capacity of columns strengthened with SMA.
4. Obtained by new proposed equation showed that it's convergence to the results by experimental and finite element program results.

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