Application of shape memory alloys (SMA) as a retrofit and strengthening component on reinforced concrete columns: Review Paper

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Abstract. Concrete structure deterioration and design deficiencies are stated as serious problems that frequently occur in the construction industry. It may lead to the loss of strength, stiffness, durability, and ductility of the existing structure. Therefore, an immediate structural strengthening must be highly considered to improve and repair the structure performance due to which the structure may fail to serve its purpose. The aim of this paper is to provide review of the structure strengthening methods for reinforced concrete columns proposed by researchers in the past two decades. However, the scope of this review paper is limited only to reinforced concrete columns retrofit by using the material of shape memory alloy (SMA). At the end of this paper, a suitable SMA form will be proposed for the future direction of research into this strengthening method.

1. Introduction

Construction errors have continued to puzzle the construction industry for many decades. The safety of the building has been questioned and a threat that also can lead to life-threatening and property damage. Deterioration of reinforced concrete structures occurred as the reason of corrosion took place in the reinforcement. In brief, concrete structure deterioration affects significantly the loss of strength and reliability of the existing structure [1]. Moreover, according to many researchers, construction design deficiencies defined as deterioration of the construction units danger and affect the society regardless being patent or latent [2]. Throughout the service life, deficient design and omission error may cause design deficiencies significantly that lead to structure damage and fail to serve its purpose [3]. The problems have grown and became a serious issue that must be aware and taken into account within the construction industry itself.

Consequently, major earthquake that happened in Loma Prieta (1989) and Northridge (1994) in United States and in Kobe, Japan (1995) have caused huge damage to many existing reinforced concrete bridge columns and buildings. It is indicates that the reinforced concrete column built in the past two decades at that time unable to support adequate strength and seismic waves [4]. Bridge failure investigation was carried out and identified that the most crucial causes of the bridge failure during the earthquake were insufficient of bar lap length and lateral reinforcement [5].
Thus, an immediate structural strengthening must be highly considered to improve and repair the structure performance due to which the structure may face failure. Besides, it is highly suggested to instantly repair and restore the reinforced concrete bridge column after an earthquake with purpose to minimize the consequent failure. Over the past three decades, researchers have been struggling to find appropriate strengthening methods for reinforced concrete columns. The effort is put extensively in order to rebalance the structural requirement that will improve the strength and ductility [6]. According to Chai Y H et al. (1994), retrofitting reinforced concrete columns by using steel jackets technique were proved to be efficient and adequate to increase the strength and ductility of the structure. Conversely, steel jacketing technique has some weaknesses such as possible to corrode and hardly to install by using machine. The grouted region which is the gapping space between concrete space and the steel jacket is fills up and creates a column discontinuity [7].

In the 1961, Buehler and Wiley [8] came out with a series of nickel-titanium alloys that revealed a new effect in steel material which be named as shape-memory effect (SME) and the material named as shape-memory alloy (SMA). Few years later, they found out that it is not only produced the unique effect but also has a superelastic characteristic at sufficiently high temperature [9]. As a result of the superelastic behaviour, SMA was proposed to be involved in innovative application including construction industry. In recent years, SMA has been introduced and explored by some researchers as an innovative material for seismic retrofits and strengthening building structure. Several applications of SMA for bridges have been conducted successfully in many papers [10-12].

This paper provides a review of the structure strengthening methods for reinforced concrete columns proposed by researchers in the past two decades. However, the scope of this review paper is limited only to reinforced concrete columns retrofit by using the material of SMA. The author have reviewed the characteristic and effectiveness of SMA and also identified the most suitable SMA form for the future direction of research into this strengthening method.

2. Shape Memory Alloy (SMA) Overview

Shape memory alloys display two distinct crystal structures or phases. The temperature and internal stresses determine the phase that the SMA will be at whether in martensite or austenite state. In martensite state at lower temperature, SMA can easily be deformed into any shape. But when SMA is heated, it goes through the transformation form martensite to austenite state. In the austenite state, SMA will remember and store the shape it had before it was deformed. The effect named shape memory effect (SME).

In recent years, SMA has been used as an innovative material for the retrofit and strengthening method for bridges and building. The alloys also have the potential for seismic application based on their unique mechanical behaviour, as SME and superelastic. Several studies for retrofitting and strengthening RC structures using SMA have been conducted. Researchers have been conducted various types of studies to test the effectiveness of the material such as on beam, foundation, as frame and column. Based on the studies from previous researchers, the author will be review and summarize the structure SMA strengthening methods for concrete cylinder and RC columns proposed by researchers in the past two decades. Refer to Table 1, the author have been tabulated all the data from previous papers for better understanding.

| Ref. | Cylinder/Column | Material | $M_a$, $M_f$, $A_s$, $A_f$, Temp, ε, $\sigma_{rec}$, $\sigma_{res}$, E, $f_y$ |
|------|----------------|----------|--------------------------------------------------|--------------------------------------------------|-------------|----------------|-------------|----------------|-------------|
| [7]  | Ø150x300       | Ti49.7Ni | 30.3, 46.2, 8.3, 25.0, 26.4, 25.0, 1-6 | 110                                              |             |             |             |               |             |
|      | Wire Ø1.0mm    | Ti50.3Ni | 25.0, 45.1, 11.1, 25.0, 26.0, 25.0, 1-8 | 240                                              |             |             |             |               |             |
### 3. Research Methodology

The research approach influences findings and provides an opportunity to consider benefits and limitations of various approaches available. Three types of approaches are available in reviewing paper – narrative, best evidence and systematic review. Narrative review focusing on comparing and summarizing selected studies on the basis of the author’s experience, existing theories and models. Results are based on a qualitative rather than a quantitative level. Meanwhile, systematic review is the findings analysed statistically by strict procedures from various individual studies. Meta-Analyses are used to pool the results of individual studies. In this paper, the author used best evidence review as the medium by select relevant studies and combined it all with systematic methods of study-selection and result exploration.

| No. | Description | NiTiNb Wire Ø1.0mm | NiTi Wire Ø1.0mm | NiTi Wire Ø3.0 | NiTi Rebar 20.0x450 | NiTi Rebar 25.2mm | NiTi Nb Spiral Ø2.0mm | NiTi Nb Spiral Ø1.9mm |
|-----|-------------|---------------------|------------------|-----------------|---------------------|-------------------|----------------------|---------------------|
| 13  | Ø150x300    | -30.3 -25.0 8.3 -25 26.4 -25.0 5 -340 94 -90 | -46.2 -11.1 45.1 -25 56.0 -25.0 5 -223 27 -10 |  |  |  |  |  |
| 14  | Ø150x300    | -30.3 -25.0 8.3 -25 26.4 -25.0 5 -340 94 -90 | -46.2 -11.1 45.1 -25 56.0 -25.0 5 -223 27 -10 |  |  |  |  |  |
| 15  | Ø400x1400   | 33.7 -25.0 -9.5 -25 22.0 -25.0 5 354 216 -325 | 65.9 -11.1 45.1 -25 56.0 -25.0 5 223 27 -325 |  |  |  |  |  |
| 16  | Ø152x305    | 59.2 -31.8 41.1 -25 80.1 -25.0 130.0 -865 - - - - |  |  |  |  |  |
| 17  | Ø150x300    | 33.7 -65.9 -9.5 -25 22.0 -25.0 6 246.9 147.1 - - - |  |  |  |  |  |
| 18  | Ø254x305 (damaged) | -50 - - - - - 108 6 565.4 171 - - - |  |  |  |  |  |
| 19  | Ø100x200 Ø150x300 | - - - - - 15.0 108 6 565.4 - 62.5 401 |  |  |  |  |  |
| 20  | Ø150x300    | 30.3 -25.0 8.3 -25 26.4 -25.0 5 -340 94 -90 | -46.2 -11.1 45.1 -25 56.0 -25.0 5 -223 27 -10 |  |  |  |  |  |
| 21  | Ø203x1029 (wrapped 305mm) | <=105 <=105 68 76 - 6.4 574 447 197 531 |  |  |  |  |  |
| 22  | Ø1000x5000  | - - - - - - - 475 - 200 150 |  |  |  |  |  |
| 23  | Ø152.4x305  | - - - - - 6 550 - 17.9 150 |  |  |  |  |  |

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4. Discussion

4.1 Material types
There are various type of SMA that can be consider in construction industry but the most widely used material is NiTi alloy based. According to these studies, there are two (2) types of SMA material used; NiTi and NiTiNb. Most of the studies used both materials in their experiment for comparing the strength and ductility purposes. It is shown in study [13-15,20]. The researchers prepared Ni_{47.4\text{–}Ti_{37.86\text{–}}NB_{14.69} and Ni_{53.85\text{–}}Ti_{46.15}} SMA wires of Ø1.0mm to be used for specimen confinement. Thus, in study [7,16,19,22] were used only NiTi compound as their SMA material while in study of [17,18,21], and [23], the researcher focus only on NiTiNb material. The researcher’s objective is not to compare between two or more SMA material but it is more focusing on the behaviour and feasibility of the SMA confining method.

4.2 Material form
NiTi or Nitinol is readily available in the form of wire, rod, and bar stock with transformation temperature in the range of -100° to +100° Celsius. All of the different form will need for different purposes and methods. In the wire form, researcher from study [7,13,14,15,17,20] used wires of Ø1.0mm for specimen confinement. Figure 1. and Figure 2. illustrates how SMA wires were wrapped around the specimen.

Those alloys were designed and manufactured by high-frequency vacuum induction melting. The hot-rolled wires were deformed into a wire with a diameter of 1.0 mm by cold drawing without intermediate annealing. It is remains in the martensitic and austenitic state at room temperature, respectively. Refer to the Table 1, the material transformation temperature is slightly different between the studies. While, in study [16,18,21,23] were used wires of Ø1.9-3.0mm for specimen wrapping. The confined specimens were wrapped with SMA wire in the form of spiral loop. The spirals were attached to the cylinder with a closed loop of wire at the top and bottom. Prestrained SMA spirals are used to apply active confinement pressure on the cylinder and concrete column. Thus, in the studies, the researcher used SMA spirals to confine the plastic hinge of RC columns. Figure 3. and Figure 4. illustrates how SMA wires were wrapped around the plastic hinge.
According to this study [19], the experiment used NiTi SMA rebar as reinforcement to investigate the bond behaviour. Two types of shape memory alloys in the form of rebar with the thickness of 20.0mm and 32.0mm were used. All the Ni–Ti bars used in this study were 450mm long. The SMA bars were placed at the center of the concrete cylinder with a circular plate at the top having a 35 mm hole at the center as shown in Figure 5.

While in study [22], the SMA rebar were placed inside the concrete column as the reinforcement bar, reinforced in the plastic hinge region. The shape memory alloys in the form of rebar with the thickness of 25.2mm was used. Figure 6. illustrates the study experiment test set-up.
4.3 Specimen
There are two (2) types of specimen have been used by the researchers; concrete cylinder and reinforced concrete (RC) column. Mostly (66.67%) from the studies were using concrete cylinder as their specimen and the other were RC column.

4.4 Recovery and residual stress
The recovery stress of martensitic SMA wires can be used to confine concrete, and the confining effectiveness of the SMA wires was proved through experimental tests. The shape-memory effect produces recovery stress when deformed SMA wires are heated over $A_f$, where the transformation to austenite is completed, with restraining deformation. The developed or remaining recovery stress depends on the temperature of the wire and becomes zero when the temperature decreases to $M_s$, where the martensite starts. In [7,13,14,20] studies measured the recovery and residual stresses of samples subjected to different levels of prestrain of 1–7%. For the NiTiNb wire, the maximum recovery stress was 340MPa and the maximum residual stress was 94MPa at a prestrain of 5%. For the NiTi wire, the recovery and residual stresses were 223 and 27MPa, respectively, at 5% prestrain. While in [15,17], [18,19,23] studies were pretrained at 5% and 6%. All result were showed in the Table 1. The recovery stresses increase up to the maximum stress for both wires. However, after the maximum point, the stresses decreased slightly even with increasing prestrain. This strengthening method increased the ductile behaviour of the RC column with the support of lap splice. However, the residual stress developed was too small to generate an active confinement. In the study of [16], it is not state the exact prestrain value. A thermomechanical test using the 222 kN uniaxial hydraulic loading frame was conducted. In this test, a pretrained SMA wire was placed in the load frame and restrained at both ends by the loading frame grips. The average recovery stress after the temperature was fixed was 865 MPa. In study of [21], the wire reached a recovery stress of 574 MPa at an initial prestrain of 6.4%. After undergoing cycles of large inelastic strain, the wire experienced partial loss of its recovery stress (prestress) reaching a stress as low as 447 MPa upon returning to its origin position.

5. Conclusion
This paper presented a detailed overview of retrofitting and strengthening methods for concrete cylinder and RC circular column by using shape memory alloy (SMA). Throughout reviewing all the studies, there are two forms of SMA used in the proposed method such as (1) wire and (2) rebar. There are different techniques used as the effort to retrofit and strengthening the specimen such as (1) confining, (2) spiralling and work as (3) rebar in the column. The author found that there are two types of SMA material with NiTi compound used in the studies which (1) NiTi and (2) NiTiNb. Each form, method and type of the SMA material is discussed extensively noting the advantages and disadvantages. The review of the findings from various studies and researchers leads to a conclusion that can be benefit by future researcher in this particular field. Further, based on the review of various methods, the author are of the view that the most preferable SMA form used in the studies is in wire form. There are 10 out of 12 studies that showed the researchers used wire, while the other 2 are used rebar in their studies. In the context of technique, the author found that majority of the researcher will choose confinement technique which contributes some advantages such as resistance to corrosion, maintenance-free, suitable for automatic installation by a machine, easy to introduce recovery stress or post-tensioning stress and very large failure strain. Both SMA material increased the peak strength and the ductility of specimen satisfactorily. However, the NiTiNb SMA wires provided more confining pressure and increased the peak strength more than the NiTi SMA wires did. Moreover, NiTiNb SMA wires produced more recovery stress and residual stress compared to NiTi SMA wires. Thus, it can be concluded that NiTiNb SMA wires are more effective in protecting reinforced concrete structures against earthquake NiTi SMA wires.

6. Research Gaps
The review also highlights potential research gap for future research such as considering SMA strip as
the material form for further investigation. In fact, there are researchers that using SMA strip in their study but the author found that is a gap in the effort of strengthens RC circular column or concrete cylinder for strip form.

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References
[1] Thoft-Christensen, P 2002 Deterioration of Concrete Structures Aalborg: Dept. of Building Technology and Structural Engineering Structural Reliability Theory. R0130 204
[2] W. K. Chong and S. P. Low 2006 Latent building defects: Causes and design strategies to prevent them J. Perform. Constr. Facil. 20 213–221
[3] P. E. D. Love, D. J. Edwards, Z. Irani, and D. H. T. Walker 2009 Project pathogens: The anatomy of omission errors in construction and resource engineering project IEEE Trans. Eng. Manag. 56 425–435
[4] B. Andrawes and M. Shin 2008 Seismic retrofitting of bridge columns using shape memory alloys Act. Passiv. Smart Mater. Struct. Integr. Syst. 6928, 69281K
[5] Y. H. Chai, M. J. N. Priestley, and F. Seible 1994 Analytical model for steel-jacketed RC circular bridge columns J. Struct. Eng. (United States). 120, 2358–2376
[6] S. Raza, M. K. I. Khan, S. J. Menegon, H. Tsang, and J. L. Wilson 2019 Strengthening and Repair of Reinforced Concrete Columns by Jacketing: State-of-the-Art Review Sustainability 11 3208
[7] E. Choi, T. H. Nam, S. C. Cho, Y. S. Chung, and T. Park 2008 The behavior of concrete cylinders confined by shape memory alloy wires Smart Mater. Struct. 17 6
[8] M. L. Heilig 1994 United States Patent Office ACM SIGGRAPH Comput. Graph. 28 131–134
[9] R. L. Taylor and J. Lubliner 1997 Computer methods in applied mechanics and engineering Shape-memory alloys: macromodelling and numerical simulations of the superelastic behavior Methods Appl. Mech. Engrg. 146 281–312
[10] M. Dolce, D. Cardone, and R. Marnetto 2000 Implementation and testing of passive control devices based on shape memory alloy wires Earthq. Eng. Struct. Dyn. 29 945–968
[11] R. DesRoches and M. Delemont 2002 Seismic retrofit of simply supported bridges using shape memory alloys Eng. Struct. 24 325–332
[12] Y. Zhang and S. Zhu 2007 A shape memory alloy-based reusable hysteretic damper for seismic hazard mitigation Smart Mater. Struct. 16 1603–1613
[13] E. Choi, T. H. Nam, S. J. Yoon, S. K. Cho, and J. Park 2010 Confining jackets for concrete cylinders using NiTiNb and NiTi shape memory alloy wires Phys. Scr. T 139
[14] E. Choi, Y. S. Chung, J. H. Choi, H. T. Kim, and H. Lee 2010 The confining effectiveness of NiTiNb and NiTi SMA wire jackets for concrete Smart Mater. Struct. 19 3
[15] E. Choi, D. H. Choi, Y. S. Chung, and R. DesRoches 2012 Seismic protection of lap-spliced RC columns using SMA wire jackets Mag. Concr. Res. 64 239–252
[16] B. Andrawes, M. Shin, and N. Wierschem 2010 Active confinement of reinforced concrete bridge columns using shape memory alloys J. Bridg. Eng. 15 81–89
[17] J. Park, E. Choi, K. Park, and H. T. Kim 2011 Comparing the cyclic behavior of concrete cylinders confined by shape memory alloy wire or steel jackets Smart Mater. Struct. 20 9
[18] M. Shin and B. Andrawes 2011 Emergency repair of severely damaged reinforced concrete columns using active confinement with shape memory alloys Smart Mater. Struct. 20 6
[19] A. H. M. M. Billah and M. S. Alam 2016 Bond behavior of smooth and sand-coated shape
memory alloy (SMA) rebar in concrete *ISTRUC* 5 186–195

[20] M. Kim 2016 Recovery and Residual Stress of Shape Memory Alloy Wires and Its Application 1–10

[21] D. Jung, J. Wilcoski, and B. Andrawes 2018 Bidirectional shake table testing of RC columns retro fitted and repaired with shape memory alloy spirals *Eng. Struct.* 160 171–185

[22] A. H. M. M. Billah and M. S. Alam 2018 Probabilistic seismic risk assessment of concrete bridge piers reinforced with different types of shape memory alloys *Eng. Struct.* 162 97–108

[23] P. S. Deogekar and B. Andrawes 2018 Hybrid confinement of high strength concrete using shape memory alloys and fiber-reinforced polymers *J. Struct. Integr. Maint.* 5314 1–11