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Behavior of Smart Beams Reinforced with Superelastic Shape Memory Alloy Rebar (SMA)Subjected to Repeated Loading

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ABSTRACT

A reinforced concrete beam with shape memory alloy rebar (SMA) is a novel form of smart beam used in smart seismic structural systems to reduce the effects of earthquakes while keeping nearly the same load-carrying capability as conventional concrete beams. The experimental research investigation is carried out to study beams' flexural behavior by replacing some steel rebars with shape memory alloy rebars (SMAs) in the longitudinal reinforcement zone. The experimental program included testing three beams to investigate the effects of the replacement of longitudinal steel rebar by shape memory alloy rebar on the flexure behaviour of beams. The beams were tested by the repeated load. The study was focused on determining ultimate load, maximum deflection, and load-deflection behaviour. Experimentally, the flexure behaviour beams are significantly affected by changing the number of reinforcing bars with shape memory alloys (SMA) longitudinal direction. However, for using one rebar of shape memory alloy as a longitudinal reinforcement, the replacement of one bar and two bars of shape memory alloy SMA beams have less yield load than the control beam by about (12.5%) and (37.5%) respectively. The replacement of one bar and two bars of shape memory alloy SMA beams having less ultimate load compared with reference beam by about (9.82%) and (21.94%) respectively. Because of its superelasticity quality, the introduction of superelastic SMA bars to the beam shows excellent recentering ability.

1. Introduction

Conventionally, the seismic performance of concrete structures reinforced with traditional steel is assessed by the amount of energy dissipated in via the yielding of steel reinforcing bars, which is done for safety reasons. It is true that plastic deformation can help disperse seismic energy and save a building from collapsing, but this comes at the expense of leaving more permanent residual deformation that compromises the building's safety and usefulness [1]. SMA can be controlled in accordance with the phase transition behaviour of the material. This is because the alloy possesses two qualities that are characterized as being different. The shape memory effect (SME) refers to the ability of shape memory alloys to return to their normal shape after being subjected to significant stresses by means of heating. The superelastic effect (SE) refers to the ability of shape memory alloys to return to their original shape after the stress has been removed from the material while it is in the stressed state [2].

SMA has been frequently utilized in orthodontic aerospace before. Unique atomic bonding causes significant changes in mechanical properties and crystalline structure forms, so the demand for this alloy is expanding rapidly, with a wide range of applications,

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especially in controlling immoderate deflection for civil engineering structures and closing concrete cracks [3]. Dolce et al. suggested and evaluated the three different types of (SMA) Nitinol wire-based devices, which are as follows: supplemental recentering device (SRCD), recentering device (RCD), and non-recentering device (NRD), as well as the usage of SMA and SRDC isolation devices in structure [4].

However, only a small amount of study has been done on the behaviour of reinforced concrete structures that use superelastic shape memory alloy as a partial replacement for steel rebar. Previous research published in earlier papers by Debbarma (2013) and M. Saiidi et al. (2007) found that Ni-Ti alloy (Composed of nickel and titanium elements) was employed as a partial replacement for steel in reinforced concrete beams [5,6]. But the research conducted by Shrestha et al. (2013) used Cul-Al-Mn. SMA is used to limit deflection due to its capacity to recover and reduce permanent deformation when used with concrete [7]. The obtained result demonstrates that Ni-Ti can be utilized to potentially reduce residual deformation or just close concrete cracks due to its recovery forces as in the S. Giorgio Church Bell-Tower in Italy and a reinforced concrete bridge in Michigan. However, research on the effects of SMA as extra reinforcement for steel rebar in concrete is limited and has not been investigated [8].

The amount of experimental research that involves SMAs in concrete structures is quite restricted, and the focus of this study has typically been on new construction. It encompasses exploratory study on (small scale) beams reinforced by either embedded or externally anchored nickel titanium, as well as the seismic behaviour of columns reinforced with SMA bars and engineered cementitious concrete in the plastic hinge region as a technique to reduce damage and pre-stressing tendons for concrete elements [9,10]. In addition, this includes the seismic behaviour of columns reinforced. Although many different kinds of SMAs have been suggested, the superplastic Ni-Ti material, which is a nickel-titanium-based SMA, has been discovered to be the most suitable for applications in civil engineering. It has a high recoverable strain, durability, and superior corrosion resistance [11]. Over the last few years, technological advancements have resulted in greater quality and dependability, energy dissipation capability, high / low cyclic fatigue resistance, the recentering ability of SMAs under cyclic loading, good resistance to corrosion and a significant drop in price have made it particularly appealing for usage in a variety of structures to improve seismic performance through the use of bolted connections, bracing processes, dampers, prestressing strands, and, lastly, reinforcing bars [12].

NiTi SMA crystalline structure includes two stable phases: first, high temperature with low stress phase called as austenite, which is extremely symmetric and has a body-centered cubic atomic structure, (Figure 1 (a)) as well as the phase called martensite, which is stable and has a rhombic form and exists at low temperatures and high stresses. Based on the crystal orientation direction, Martensite can exist in one of two forms: twinned (twin variations) or detwinned (single favored variation), as shown in Figure 1 (b) and (c), respectively [13]. Penar investigates the behavior of the beam-column connection using SMA tendons while the material is at the austenite phase. Tendons measuring 19.05 mm in diameter each. The tendon was cut with a smaller section diameter of 12.7 mm and then machined into the shape of a dog bone. The results indicated improved recentering ability compared to the connection using steel tendons used as a reference [14]. Gelan and Ali used the superelasticity effect (SE) of Nitinol alloy to enhance the structural characteristics of steel building; they used analytically six models of HS-shape frames for three frequencies; the first is equipped with 100% steel bars, the second is equipped with 50% steel bars and 50% nitinol (superelastic SMA), and the third is equipped with 100% nitinol bars. The results showed that the residual roof displacement for the steel building equipped with 50% SMA bars and 50% HS steel bars and the steel building furnished with 100% SMA bars, respectively, recovered by 82.7%, 152.72%, and showed moderate energy dissipation. Generally, the frame built with 50% superelastic SMA bars and 50% HS steel bars performed better during earthquakes [15]. Maha and Ali found that by reinforcing concrete beam-column joints with Nitinol bars with a replacement ratio of (25%, 50%, and 75%) of the reinforcing steel and by the method of repeated test, the ultimate failure value will be decreased by (20.7%, 10.7%, 9.3%) respectively, while the deflection increased by (9.6%), 5.28%, 10.9%) respectively [16].

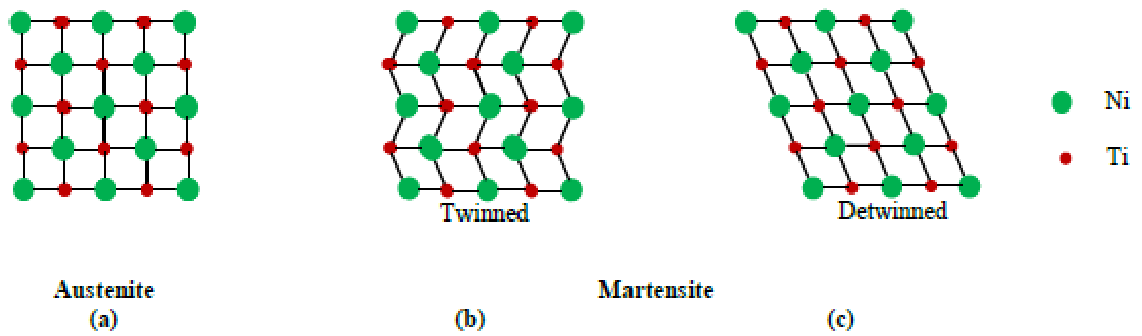

Figure 1. Austenite and Martstenite stages of SMA (2D)

For earthquake-resistant design applications and structures retrofit, superelastic shape memory alloys are desired due to their possessing several features that make them attractive choices. These characteristics include the following:

a) Hysteretic dampening of the system.
b) Having a high elastic strain range, which ultimately results in recentering capabilities.
c) Outstanding qualities concerning low- and high-cycle fatigue.
d) Strain hardening when subjected to large strains.
e) A stress plateau serves to provide constraints on the force transfer.

A summary of the mechanical characteristics of shape-memory alloys made from NiTi can be found in Table 1.[17]

Table 1: Properties of NiTi shape memory alloys

Property	**NiTi SMA**	
	Austenite	**Martensite**
Physical Properties		
Density	6.45 g/cm	
Mechanical Properties		
Recoverable Elongation	up to 8%	
Young’s Modulus	30-83 GPa	21-41 GPa
Yield Strength	195-690 MPa	70-140 MP
Ultimate Tensile Strength	895-1900 MPa	
Elongation at Failure	5-50% (typically 25%)	
Poisson’s Ratio	0.33	
Chemical Properties		
Corrosion Performance	Excellent (similar to stainless steel(	

Previous research concentrated on dealing with structural joints that were more likely to collapse during earthquakes and explosions. These joints included columns and connecting points between columns and beams. In addition to this, it concentrated on the behavior of concrete beams that were reinforced with SMA bars, both theoretically and practically, through the use of the ABAQUS and ANSYS programs, as well as studies that tested models through the application of the three-point loading method. The method of the four-point loads is the method of laboratory structural test that comes the closest to representing these loads. The gravity of the beam during earthquakes is in the way that it carries the enormous dead and live load represented by the weight of the roofs, and this is why the method of the four-point loads is used.

2. Experimental Work

2.1 Materials

2.1.1 Shape Memory Alloy Rebar (SMA)

A machine called Metalic materials tensile testing (ISO6892) in the engineering lab of Diyala university was used to determine the tensile strength of the shape memory alloy material (SMA) for two specimens 8 mm in diameter. The results showed that the material had a yield strength of 200 MPa and ultimate strength of 800 MPa, as depicted in figure 2 and 3.

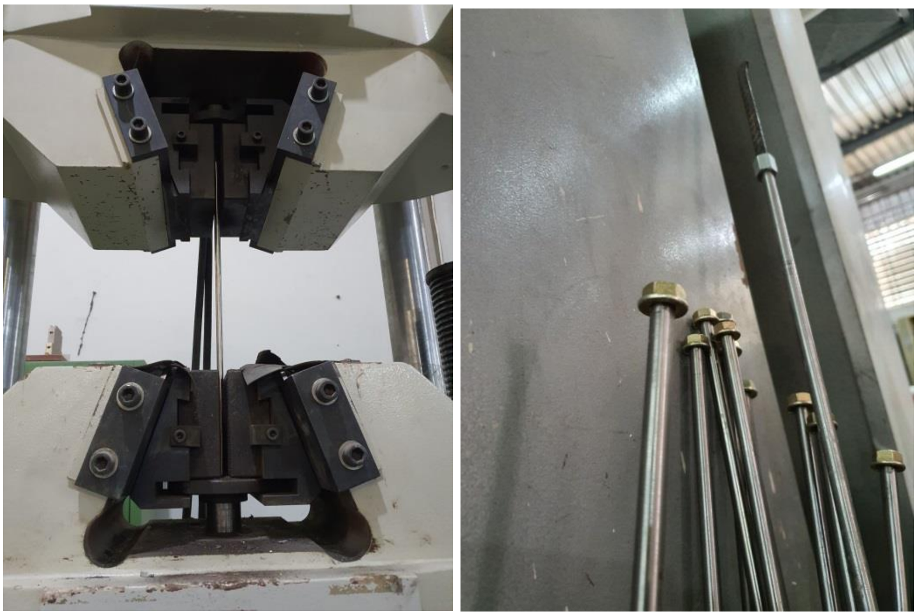

Figure 2. Tensile strength testing for shape memory alloy rebar (SMA)

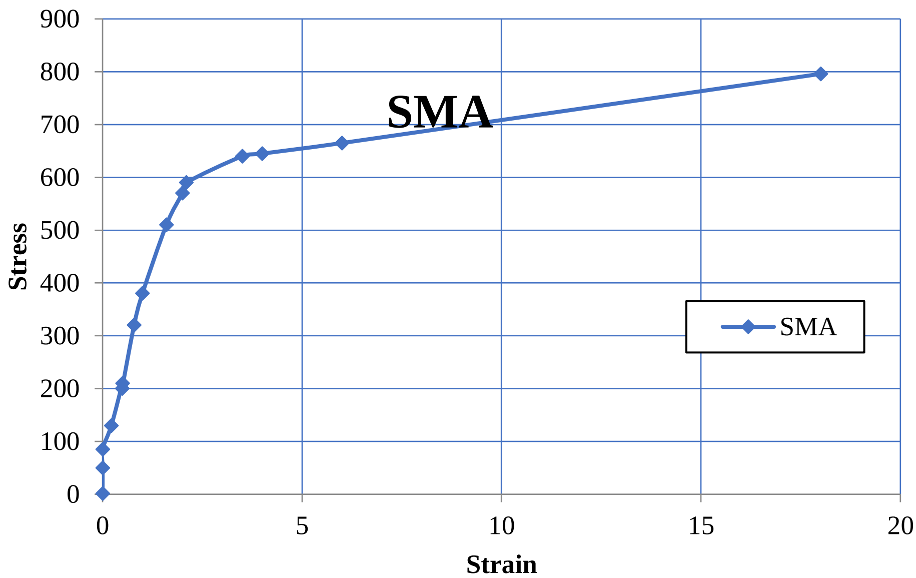

Figure 3. Stress-Strain relationship for SMA rebar by tensile testing

2.1.2 Steel

The tensile strength of steel was also evaluated by the same apparatus using two specimens with a diameter of 8 mm; the results showed a yield strength of 320 MPa and ultimate strength of 510 MPa, as shown in Figures 4 and 5.

Figure 4. Tensile strength testing for steel used

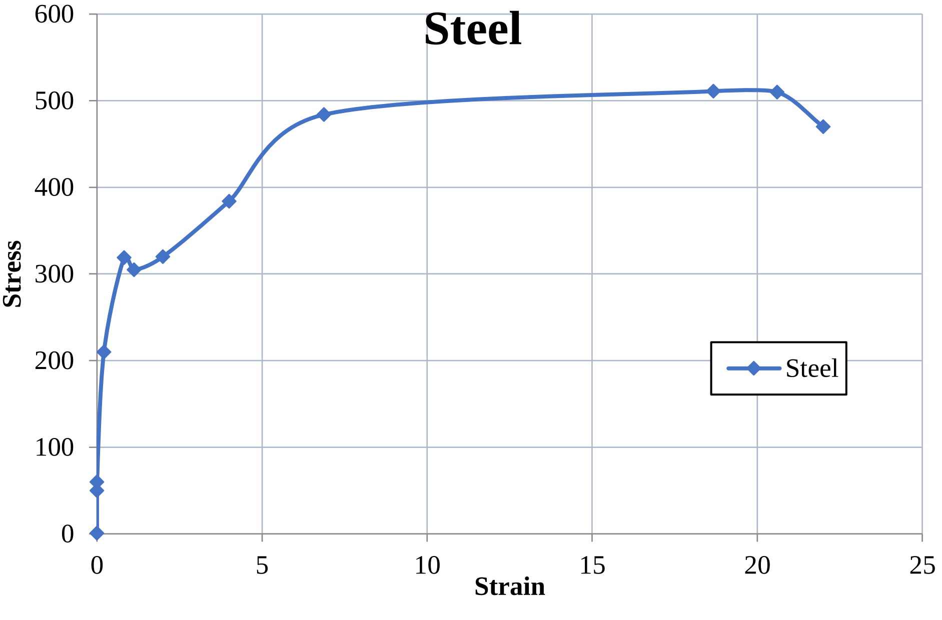

Figure 5. Stress-Strain relationship for steel rebar by tensile testing

2.1.3 Cement

Using Ordinary Portland cement (type I) was produced in Iraq.

2.1.4 Fine aggregate

The grading of the fine natural sand that was used; the used sand has a particle size showed in Table 2.

Table 2: Grading of fine aggregate

Sieve size	Passing %	Iraqi specification No. 45/1984 for Zone (2)
4.75 mm	93	90-100
2.7mm	78.5	75-100
1.18mm	67	55-90
600μm	52.3	35-59
300 μm	19.8	30-8
150 μm	1.2	0-10
Pan	zero	zero

2.1.5 Coarse aggregate

Natural coarse material was utilized for a thickness of no more than 12 mm and shown in Table 3.

Table 3: Grading of coarse aggregate

Sieve size (mm)	%Passing	Iraqi specification No. 45/1984
12.5	100	90-100
10	84	50-85
4.75	4	0-10
Pan	zero	zero

2.2 Test matrix

In this study, three test specimens of beams are used. The first beam acted as a reference, and the bottom longitudinal direction was reinforced with four steel rebars, each having an 8 mm diameter. The second beam has three steel rebars and one shape-memory alloy (SMA) rebar in the bottom longitudinal direction; this means that 25% of the longitudinal steel reinforcement is replaced with SMA rebars. The third beam will be reinforced with two rebars made of steel and two rebars made of shape memory alloy (SMA) in the bottom longitudinal direction, which represents a replacement rate of 50 %. For the three beams, the shear reinforcement must be a steel rod with a diameter of 6 mm per 100 mm, as shown in Figures 6,7 and two rebars with a diameter of 6 mm in the longitudinal direction to pin reinforcement. Design of reference beam by according to ACI 318m-19.

The dimensions of concrete specimens were (1450*250*150) mm. The concrete beams were cast with a mixing ratio of (400 cement: 750 sand: 780 gravel: 232 water) kg / m^3, which provided us with a compressive strength of 25 MPa (and the mixture, after being poured several times, provided us with the strength of 25 Mpa); additionally, six cylinders and three prisms were run, as shown Figure 8. The following day, the molds were opened, and the models were put in the treatment basins. Regarding the concrete beams, the mold was opened, and a 28-day treatment period commenced.

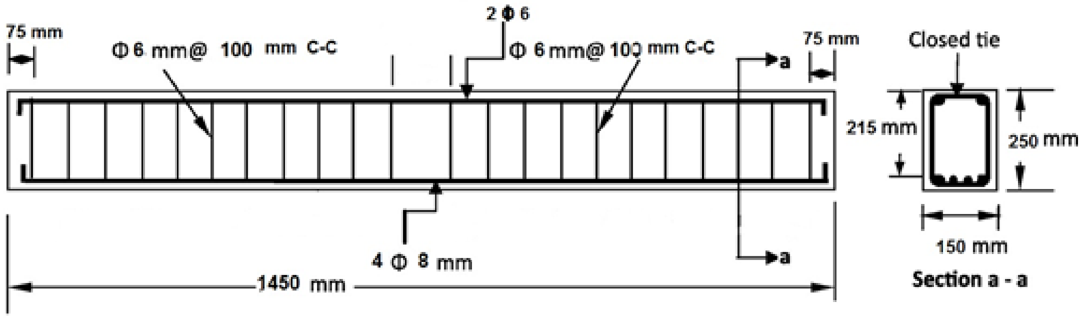

Figure 6. reinforcement details for specimens

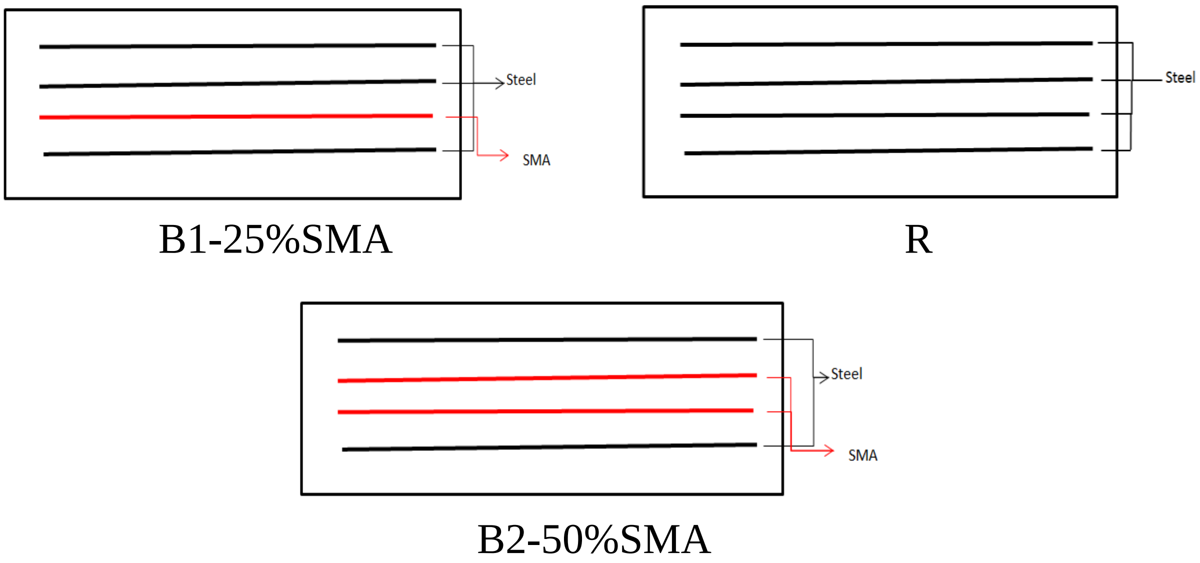

Figure 7. Arrangement of renforcing the bottom beams in the longitudinal direction

Table 4: Reinforcement of longitudinal direction of specimens

Specimen	Beam reinforcement	Replacement percent %	Steel rebar	SMAs rebar
R	Longitudinal reinforcement	0	4	0
B1-25%SMA	Longitudinal reinforcement	25	3	1
B2-50%SMA	Longitudinal reinforcement	50	2	2

Figure 8. Casting steps

2.3 Test setup

The beams were put through their paces by having them placed on a flexural test device and subjected to a load that was directed in a double (P / 2) style, with a distance of 75 mm between the bracket and the outer edge of the beam on both sides, the test was displayed in Figure 9. The gap between two double loads was 250 mm, while the net distance that separated the two supports was 1300 mm. To circumvent the issue of stress concentration, rubber pads were installed below the load-bearing sections (both the supports and the loads). The LVDT vertical distance measurement device was positioned in the center of the interior area, beneath the sill. The data locker device was connected to the strain gauges, and the connection was made for concrete and steel longitudinal and shear steel bars, in addition to shape memory alloy bars. The protocol load of repeated load, an increase rate of 0.2 kN/s was applied to each subsequent load. According to the same reference beam but with static load tests of beam load increment of 10% of the ultimate force, repeated load tests were load-controlled in terms of the measured displacement at mid span (Δ). In the load history, two cycles with the same displacement were assigned using the diagrammatic representation shown below in figure 10. Throughout their service life, beams may experience anywhere from a few thousand to a few million load cycles [18]. It is possible that the repeated load will consist only of compression (cyclic axial compressive loading) [19], or it may take the form of compression tension (reversed loading) [20]. Using the protocol above to be able to give an adequate and clearer picture of the resedual distortions and the ability of this type of beams to absorb the energy attached to it.

2.4 Test results

The result of the first beam considered as a reference R showed the result of load-deflection as in Figure 11, the yield failure occurred at 56 kN load for ten cycles first part, and the ultimate failure occurred at 74.3 kN load in the ten cycle second part.

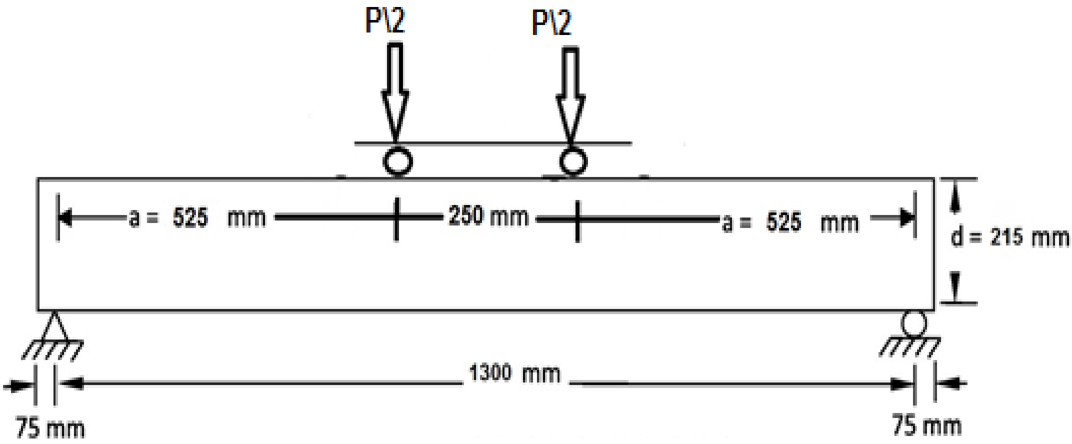

Figure 9. Testing setup

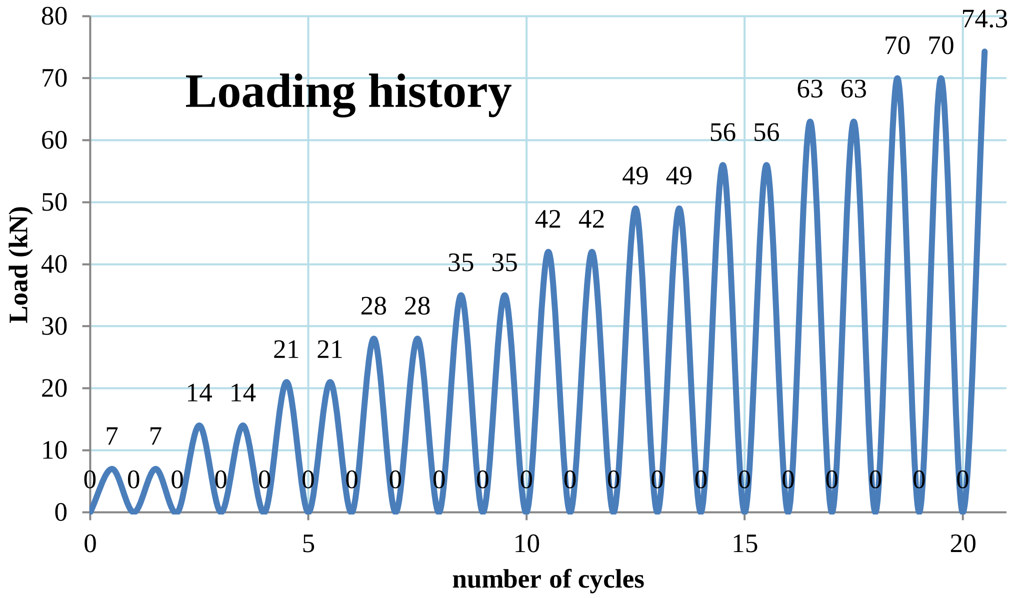

Figure 10. Cyclic displacement history

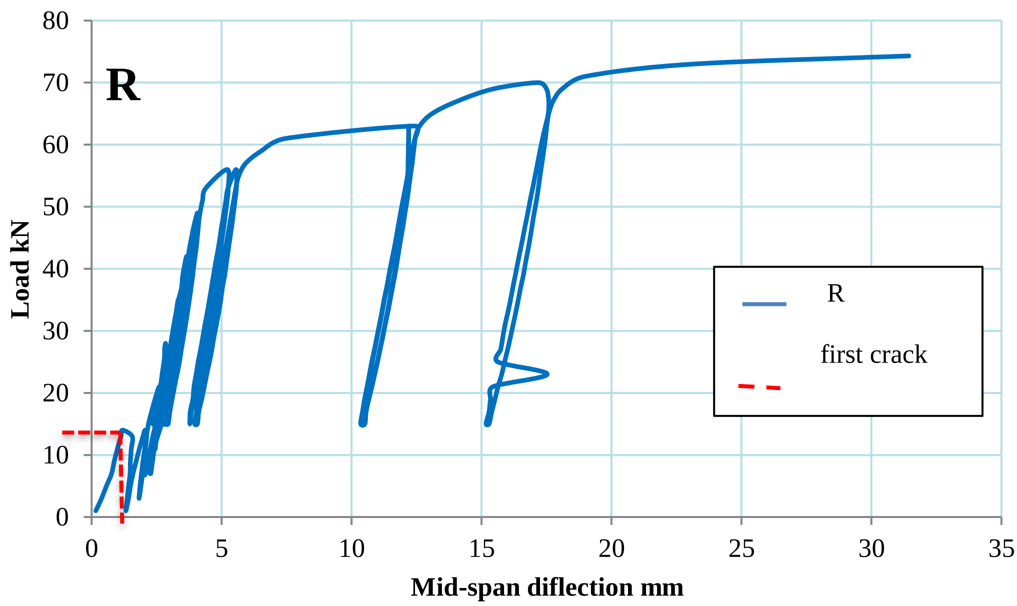

Figure 11. Load-deflection relationship for R

The result of the second beam B1-25%SMA showed the result of load-deflection as in Figure 12; the yield failure occurred at 49 kN load in the eight cycle second part, and the ultimate failure occurred at 67 kN load in the ten-cycle first part.

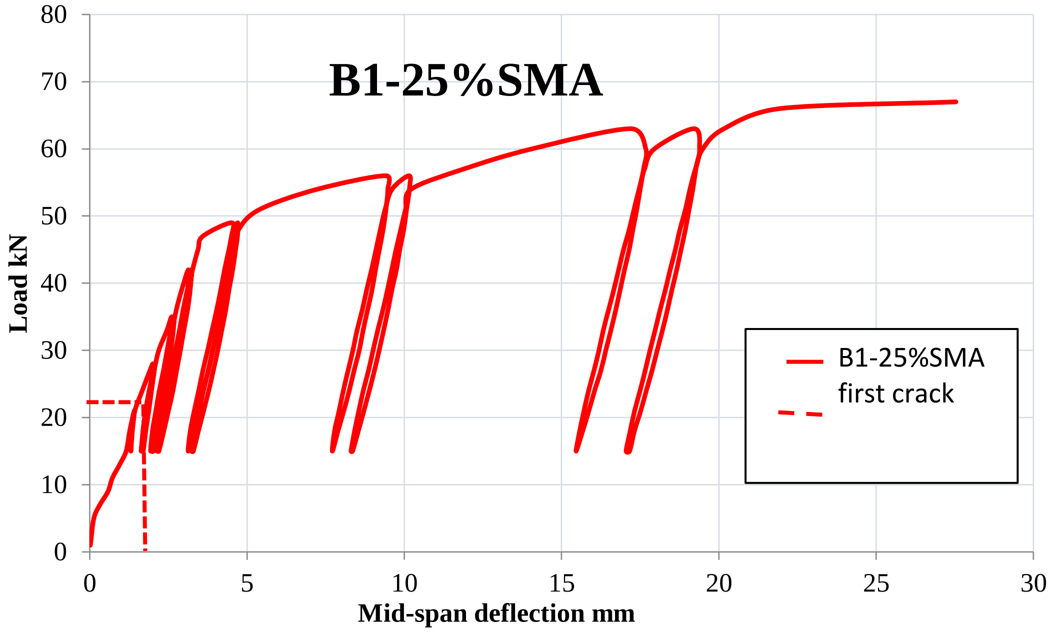

Figure 12. Load-deflection relationship for B1-25%SMA

The third beam B2-50%SMA showed the result of load-deflection as in Figure 13; the yield failure occurred at 35 kN load in the five cycles' first up part, and the ultimate failure occurred at 58 kN load in the eight cycles second up part.

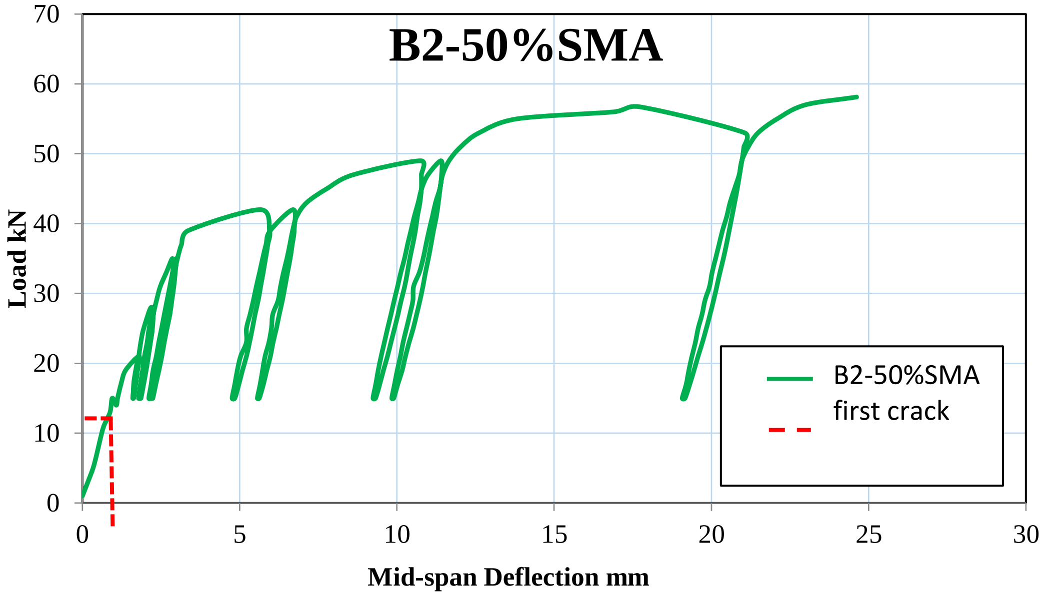

Figure 13. Load-deflection relationship for B2-50%SMA

Table 5: Experimental results

Name of sample	Pcr.(kN)	Py. (kN)	% diff. of Py	Pult. (kN)	%diff. of Pult.
R	14	56	-----	74.3	-----
B1-25%SMA	23	49	-12.5	67	-9.82
B2-50%SMA	15	35	-37.5	58	-21.94

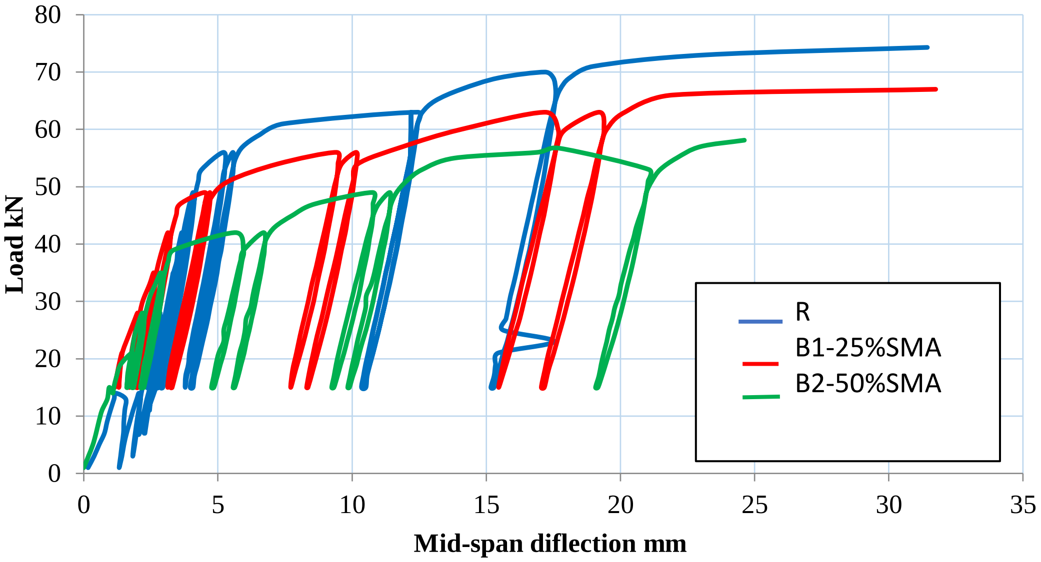

Figure 14. Load mid-span deflection of beams (R, B1-25%SMA, B2-50%SMA)

Compared to Karrar and Ali's research in which the samples are similar to those of our research in terms of reinforcement, tensile strength, compression strength to concrete and the rest of the details, it varies in the type of applied load, testing this research in a monotonous load method, while in our research the samples are tested in a repeated load method [21]. The ultimate strength and yield strength of beams subjected to monotonic loading is greater than that of beams subjected to repeated loading. The displacement at ultimate load for monotonic load specimens is greater than that of specimens of repeated load.

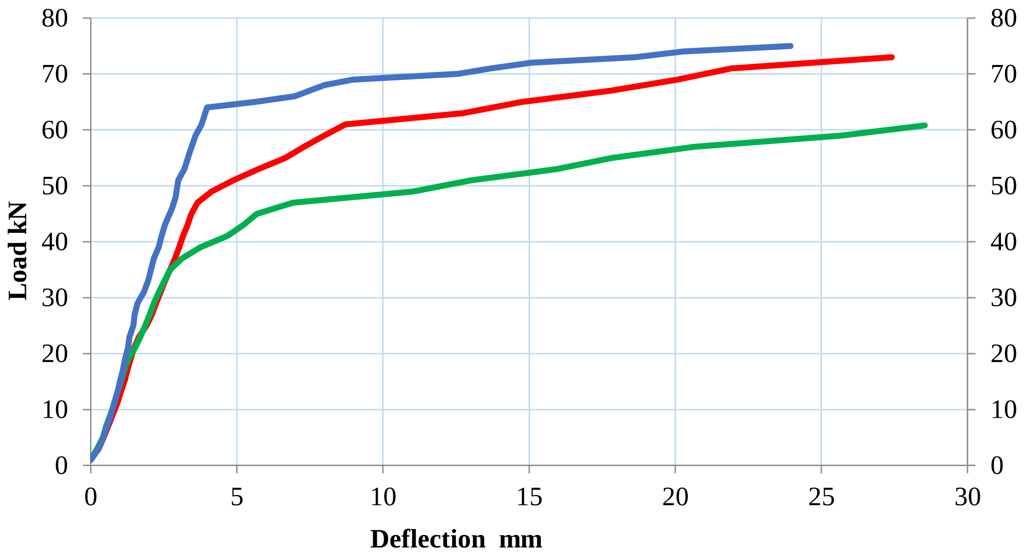

Figure 15. Load mid-span deflection of beams tested by ststic load [21]

3. Conclusion

The following is a summary of the conclusions and recommendations that can be taken from this body of work based on the results that were reported in this research and the observations that were obtained from the numerical analysis:

- The replacement of one bar of shape memory alloy SMA beams has less yield load than the control beam by about (12.5%) under repeated load. This gives the impression of the effectiveness of replacing the shape memory alloys for a single rod in that the result is very close to normal reinforcement.
- The replacement of two bars of shape memory alloy SMA beams has less yield load than the control beam by about (37.5%) under repeated load.
- The replacement of one bar of shape memory alloy SMA beams having high deflection at yield compared with reference beam by about (13.57%) under repeated load.
- The replacement of two bars of shape memory alloy SMA beams having high deflection at yield compared with reference beam by about (45.029%) under repeated load.
- The replacement of one bar of shape memory alloy SMA beams having an ultimate load lower than the reference beam by about (9.825%) under repeated load.
- The replacement of two bars of shape memory alloy SMA beams having ultimate load more down than the reference beam by about (21.776%) under repeated load.
- Because of its superelasticity quality, the introduction of superelastic SMA bars to the beam shows excellent recentering ability.
- Future studies recommend changing the placement areas of the SMA bars, changing the replacement ratios, and the mechanism of fixing the bars.
- Using a structural frame reinforced with smart materials and a different loading method and its application is more representative of earthquakes or other vibrations.

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