Ministry of Higher Education
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# Structural Behavior Of Smart Beams Reinforced With Super Elastic Shape Memory Alloy Rebar (SMA)

**A Thesis Submitted to the Council of the College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Civil Engineering**

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بسم الله الرحمن الرحيم

# يَرْفَعِ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ
# وَالَّذِينَ أُوتُوا الْعِلْمَ
# دَرَجَاتٍ وَاللَّهُ بِمَا
# تَعْمَلُونَ خَبِيرٌ

صدق الله العظيم

المجادلة 11

## ***Dedication***

*To the spirit of my father dear and my dear mother*

*To my lovely wife which has been a constant source of support and encouragement during the challenges*

*To my brothers and sisters and friends .*

*To those who struggle for their freedom.*

*To those who pursue a meaning for their lives.*

*To mankind.*

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*Karrar Maallak Hannun*
*2022*

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# Abstract

Reinforced concrete beam with shape memory alloy rebar (SMA) is a new type of smart beam that is an important part of smart seismic structural systems developed to decrease the effects of earthquakes while maintaining approximately the same load carrying capacity as compared with conventional concrete beams. Shape memory alloy rebar has the ability to recover its normal shape after exposure to loads by removing loads or exposure to heat, and this property is so important in terms of enhancing seismic structural performance. In this thesis, an experimental investigation is carried out to study concrete beams for two effective types of loads, monotonous loads and repeated loads and the behaviour of normal reinforced concrete beams.

The experimental program tests eight normal beams with dimensions of 1450mm×250mm×150mm. The specimens are divided into three groups according to the percentage of SMA rebars that reinforced beams in bottom longitudinal direction. Each group included four beams, two as reference beams and two as variations which had reinforcing details similar to the other. The two reference beams are reinforced with steel bars in the longitudinal direction representing flexural reinforcement, which acts as control beams in the three groups. The first group has a percentage of the SMA rebars in flexural reinforcement, 25% of the total flexural reinforcement. The second group beam has a percentage of the SMA rebars in flexural reinforcement, 50% of the total flexural

reinforcement. The third group beam has a percentage of the SMA rebars in flexural reinforcement, 75% of the total flexural reinforcement. For the three groups, one beam was tested by monotonic load and compared to a reference that tested by monotonic load, and last beam is tested by repeated load within a specific protocol and compared by a reference beam that tested also by repeated load.

The experimental results showed that the ultimate load decreased by using SMA bars in (25%, 50%, 75% ) of total flexural reinforcement about (2.66,18.93, 44.66%) respectively, in the case of monotonic loading and (9.825%, 21.776%, 42.78 %) in case of repeated loading. The deflection increased by using SMA in (25%, 50%, 75% ) percentage of total flexural reinforcement about (14.45%, 19.18%, 3.491%) respectively, in case of monotonic loading and (18.8%, 6.213%, 3.084%) in case of repeated loading. The ductility increased by using SMA bars in (25%, 50%, 75% ) of total flexural reinforcement about (37.446%, 92.4%, 18.116%) respectively, in case of repeated loading, while in case of monotonic loading, ductility increased by using SMA bar in (25%, 50%, 75%) of total flexural reinforcement about (32.05%, 73.89%, 3.236%). The Absorbed energy increased by using SMA bars in (25%) of total flexural reinforcement about (5.15%, 12.24%) in case of monotonic and repeated loading, respectively, while by using SMA bars in (50%,75%) of total flexural reinforcement in case monotonic loading, Absorbed energy decreased about (9.26%, 42.48%), and in case of repeated loading it decreased about (14.55%, 28.08%). The Nitinol alloy had a positive effect in reducing distortions, as well as a relative return of the beams to its original place.

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# List of Symbols, Abbreviations and Nomenclature

| Symbol | Definition |
|---|---|

| | |
|---|---|
| *Af* | Austenite finish temperature |
| *As* | Austenite start temperature |
| *Db* | bar diameter |
| *Dc* | concrete compressive damage |
| *Dt* | concrete tensile damage |
| *Ec* | concrete modulus of elasticity |
| *fc* | concrete compressive stress |
| *f' c* | concrete compressive strength |
| *fs* | stress in the reinforcement |
| *ft* | concrete tensile stress |
| *fu* | stress at ultimate |
| *fy* | yield stress |
| *Pcr* | cracking load |
| FEM | Finite Element Method |
| *M* | applied moment |
| *Mf* | Martensite finish temperature |
| N | Nitrogen |
| Ni | Nickel |
| O | Oxygen |
| P | applied load |
| PE | Psuedoelasticity Effect |
| RC | Reinforced Concrete |
| SMA | Shape Memory Alloy |
| SME | Shape Memory Effect |
| T | temperature |
| Ti | Titanium |
| w/c | Water to Cement Ratio |
| $\mu\Delta$ | displacement ductility |
| $\sigma$ | stress |
| $\sigma u$ | stress at ultimate load |
| $\psi$ | Curvature ductility |
| $\sigma ds$ | detwinning start stress |
| ρ | Ratio of Tension Reinforcement Equal to As /($b_w$d) |
| 2D | Two-Dimensions |
| 3D | Three-Dimensions |

# CHAPTER ONE
# INTRODUCTION

## 1.1 General

For safety purpose, concrete structures reinforced with traditional steel are typically designed so that seismic performance is determined by the amount of energy dissipated via the yielding of steel reinforcing bars. 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 **(Hossain, 2013)**.

Many buildings in the areas hit by the 1985 Michoacan (Mexico) and 1994 Northridge (United States) earthquakes had to be torn down and rebuilt after suffering substantial irreversible deformation beyond the scope of repair. More than one hundred RC bridge piers suffered permanent deformation of greater than (1.75 %) during the 1995 Hyogo-Ken Nanbu earthquake (Kobe, Japan), forcing the authorities to dismantle and rebuild the structures because of the difficulty of straightening them **(Ramirez and Miranda, 2012)**. In addition, 240,000 building structures suffered partial collapses, resulting in an estimated economic loss of between $50 to $100 billion (US) **(Comartin et al., 1995; Eguchi et al., 1998 )**.


**Figure (1-1):** Collapse of the RC 6story building (**Shiohara, 2017**)

There was another big earthquake in northern Chile in 2010 with a magnitude of 8.8 on the Richter scale and a related tsunami that damaged 80 out of 3000 buildings (>10 storey), resulting in an estimated $30 billion in economic loss **(Wen et al., 2011)**. In 2011, Japan was hit by the Tohoku earthquake, which had a magnitude of 9 on the Richter scale and caused powerful tsunami waves that caused 129,225 buildings to collapse, 254,204 buildings to "half collapse," and 691,766 buildings to be partially damaged **(National Police Agency of Japan 2012)**.

In 2017, an earthquake measuring 7.4 on the Richter scale occurred in Halabja city, located in the Sulaymaniyah province in Iraq, and its center was in the Iranian province of Kermanshah. The Iranian government announced that hundreds of infrastructure had collapsed and eight villages had been flattened, while the Iraqi government announced that a Darbandikhan dam had been damaged, and hundreds of buildings in the provinces of Sulaymaniyah and Diyala **(Wikipedia)**.

To prevent this kind of damage, there is an urgent need to construct smart structures; the academic and structural science community favored a performance-based seismic system design in which a building's seismic performance would stay within a range of defined limits even when ground motion excitation, protecting people inside (via large deformation) and restoring the building's original form and function via re-centering, **(Jason McCormick et al., 2008)**. The above performance-based seismic design would be focused on minimizing the residual sideways deformations by utilizing re-centering devices, such as post-tensioned re-centering sensors **(Priestley et al., 1999; Valente et al., 1999)**, passive energy dissipating devices, such as optimized mass and optimized liquid dampers **(Clark et al., 1995; Symans et al., 2008)**, and smart materials such as shape memory alloys (SMAs) **(Alam et al., 2009)**.

## 1.2 Smart structures:

Smart structures are a new design concept made possible by technological and scientific advancements in the field of materials engineering. A structure is said to be smart if it is capable of sense or detect an applied load or displacement and then respond in such a way as to reduce the amount of deflection demand and the damage that results from this. A network of sensors and actuators is used to provide the intelligent structure with the ability to detect and respond to its environment. When compared to conventional servomechanisms, the hardware requirements and response times of this architecture are much more manageable **(Banks, et al., 1996)**. A variety of materials are utilized as actuators with smart system architecture. Most of these intelligent materials are **( Clarke, et al., 2009)**:

1- Piezoelectric (PZL) layers.
2- Electrostrictive (ER).
3- Magnetorostrictive (MR)
4- electrorheological fluids and solids.
5- shape-memory alloys (SMA), this is the subject of this thesis.

Recent studies investigate man-made and natural materials with unusual properties, known as smart materials, and systems that can spontaneously adapt to environmental changes, known as adaptive systems. This has led to the development of the smart structure concept, in which smart materials are integrated into a structure to make it smart **(Cheng, F. Y., et al. 2008)**.

## 1.3 Shape Memory Alloy:

SMA is a one-of-a-kind material due to its remarkable capacity to recover its original shape after being significantly deformed. By using SMAs as reinforcing bars in an RC construction, the building will be better able to absorb seismic forces and return to its original shape with minimal damage **(Alam et al., 2008; Saiidi and wang, 2006)**.SMA is one of the most useful parts of smart metals. Because of the development of the utilization area, SMAs, whose popularity is growing quickly, have become more easily accessible due to alloys like NiTi **(Youssef et al., 2008)**.

Nickel-Titanium Alloys (NiTi) are a special class of metal that exhibit a number of distinctive features, including the capacity to recover significant deformation with little permanence of the residual strain, by up-heating (shape memory effect) or unloading (superelasticity effect ). A form of SMA known as Superelastic Nitinol has the unusual capacity to withstand huge strains of up to 6–8%, as well as having great strength, significant fatigue resistance, and high damping. The superelasticity is one feature that makes these materials attractive for use in passive vibration control systems. When SMA is deformed, it transforms between its two stable phases, austinite and martensite, a phase change known as a "solid-to-solid" phase transformation. Typically, martensite is stable under high stress, but austenite is stable under low stress; nevertheless, when nitinol is loaded, austenite transforms into martensite. After being unloaded, the martensite will change back into its original parent phase, which is austenite **(DesRoches et al., 2004)**. The shape of the recovery indicated in Figure (1-2).

## 1.4 Optimum use of SMA in concrete beams:

Beam structures are an important type of building part that construction workers and some types of engineers need to know about. These structures are significant for transferring weight and ensuring that a building's foundation is firmly set in the ground. Overhanging, fixed, trussed, continuous, and simply supported beams are some of the most common types of beam structures**(Ballio, et al., 1983)** . The urgency of using smart

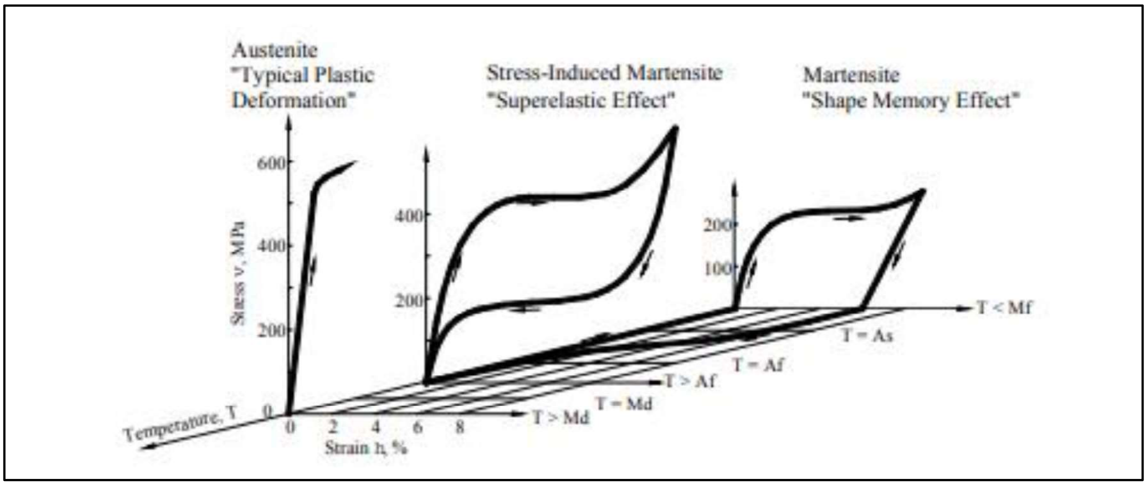


**Figure (1-2):** Three-dimensional stress,strain and temperature diagram showing the deformation and behavior of NiTi SMA **(DesRoches et al., 2004)**.

buildings has recently increased, with more resistance to unusual conditions such as earthquakes and explosions. Important parts of buildings on this side are columns, beams, slabs and areas of connection **(Song, et al., 2006)**.

The smart beam is one of the parts of the smart structure and the beam is considered smart when its internal or external structure is added parts that help it resist abnormal conditions. An example is the beam enhances the beam with the bars of the memory alloy to give a lengthy failure if it is exposed to a sudden load. As an example, the Pesoceramic Vibration Control Operator System is added and is a frequency field technique to achieve strong control performance and others **(Shahverdi, et al., 2016)**. An analytical study has shown that it works very well to mix super elastic SMA bars (nitinol bars) including some steel reinforcement in a reinforced concrete beam **(Bajoria, et al., 2016)**.

## 1.5 Repeated load

Offshore structures, bridge girders, foundations, Pile caps, and transfer girders in high-rise buildings are just a few examples of massive structural engineering applications that have been subjected to repeated load. Throughout their service life, beams may experience anywhere from a few thousand to a few million load cycles **(Teng, et al., 1998)** shown in Table (1-1). It is possible that the repeated load will consist only of compression (cyclic axial compressive loading) **(AlSulayfani, et al., 2010; Lam, 1979)**, or it may take the form of compression tension (reversed loading) **(Jurcevic, et al., 1990)** shown in Figure (1-3) and Figure (1-4).

**Table (1-1):** Fatigue cycles spectrum with corresponding structures (**Isojeh, et al., 2017)**

| **Low-Cycle Fatigue (0 – $10^3$ cycles)** | **High-Cycle Fatigue ($10^3$ – $10^7$ cycles)** | **Super-High-Cycle Fatigue ($10^7$ – 5 x $10^8$ cycles)** |
|---|---|---|
| - Structures subjected to earthquakes<br>- Structures subjected to storm | -Bridges<br>- Airport pavement<br>- Wind power plants<br>- Highway pavement<br>- Concrete railroad ties | - Mass rapid transit structures<br>- Sea structures<br>- Machine foundations |

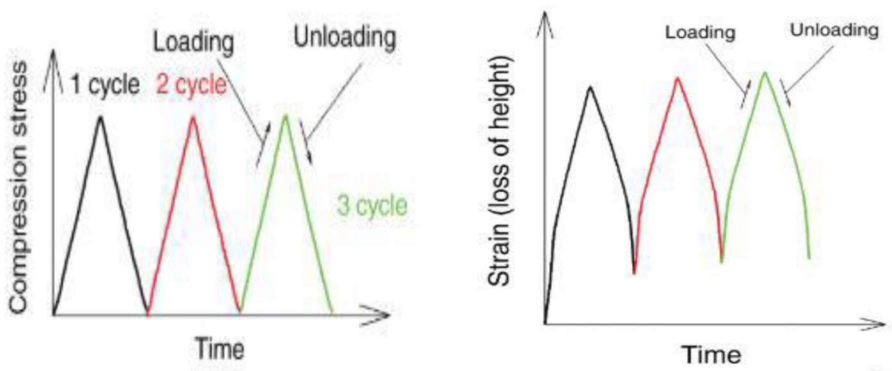


**Figure (1-3):** Load history for compression repeated load **(Zhang, et al., 2019)**

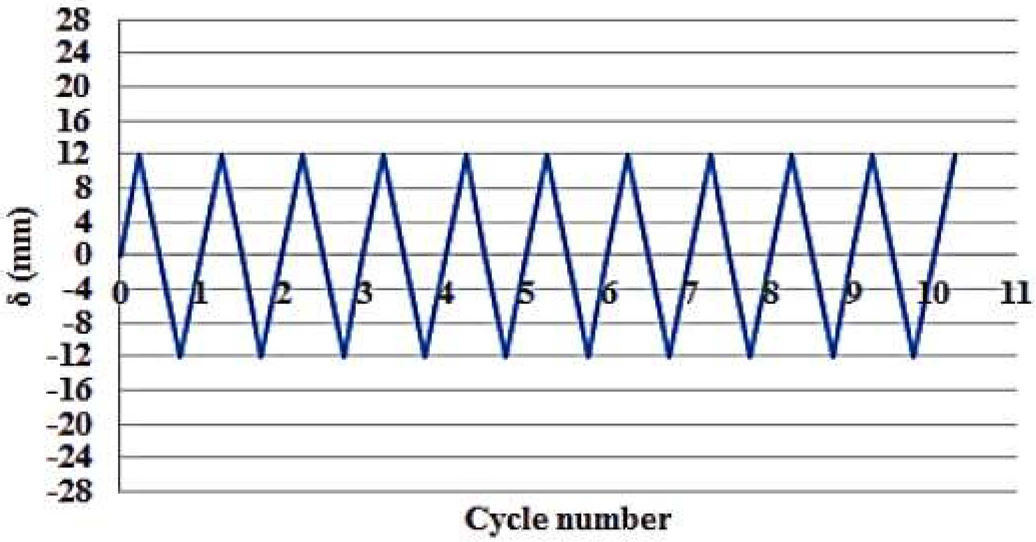


**Figure (1-4):** Load history for cyclic load **(Ibrahim and Abdulkhalik, 2017)**

## 1.6 Research Objectives

The overall objective of the research is to configure smart concrete beams reinforced with smart materials. To achieve this objective, the project has been subdivided as follows:

1- Review the developments in concrete beam systems over the coming years and the variables that affect how SMA material responds.
2- The exprementaI test involved casting reinforced concrete beams by partially replacing the normal reinforcement rebar with shape memory alloy rebar SMA.
3- Study the tested beam with different replacement ratios of (25%, 50%, and 75%) reinforcement rebar by SMA bars under monotonic loading.
4- To study the tested beam with different replacements of reinforcement rebar by SMA bar (25%, 50%, 75%) under repeated loading.

## 1.7 Research Justification

In the past, many studies were conducted on smart structure systems in seismic systems and smart materials such as SMA were used in analytical and theoretical ways, but most of them focused mainly on colomn-beam joints as well as columns. While studies related to the structural behavior of concrete beams are few and not comprehensive, most of them have used theoretical methods.

## 1.8 Layout of the Study

- **Chapter one** presents a general introduction about the smart structure and smart material. It also describes the aims of the study.
- **Chapter two** includes a summary of relevant literature, a description of the systems used in SMA design, an outline of the pseudo elastic reaction of SMA, and a discussion of the material's potential applications in building construction.
- **Chapter three** describes the methods employed and the characteristics of the materials tested. Information about the test beams, concrete, and apparatus, is provided as well.
- **Chapter four** presents an analysis and discussion of experimental data gathered from testing beams.
- **Chapter five** discusses some conclusions and makes some recommendations for future research.