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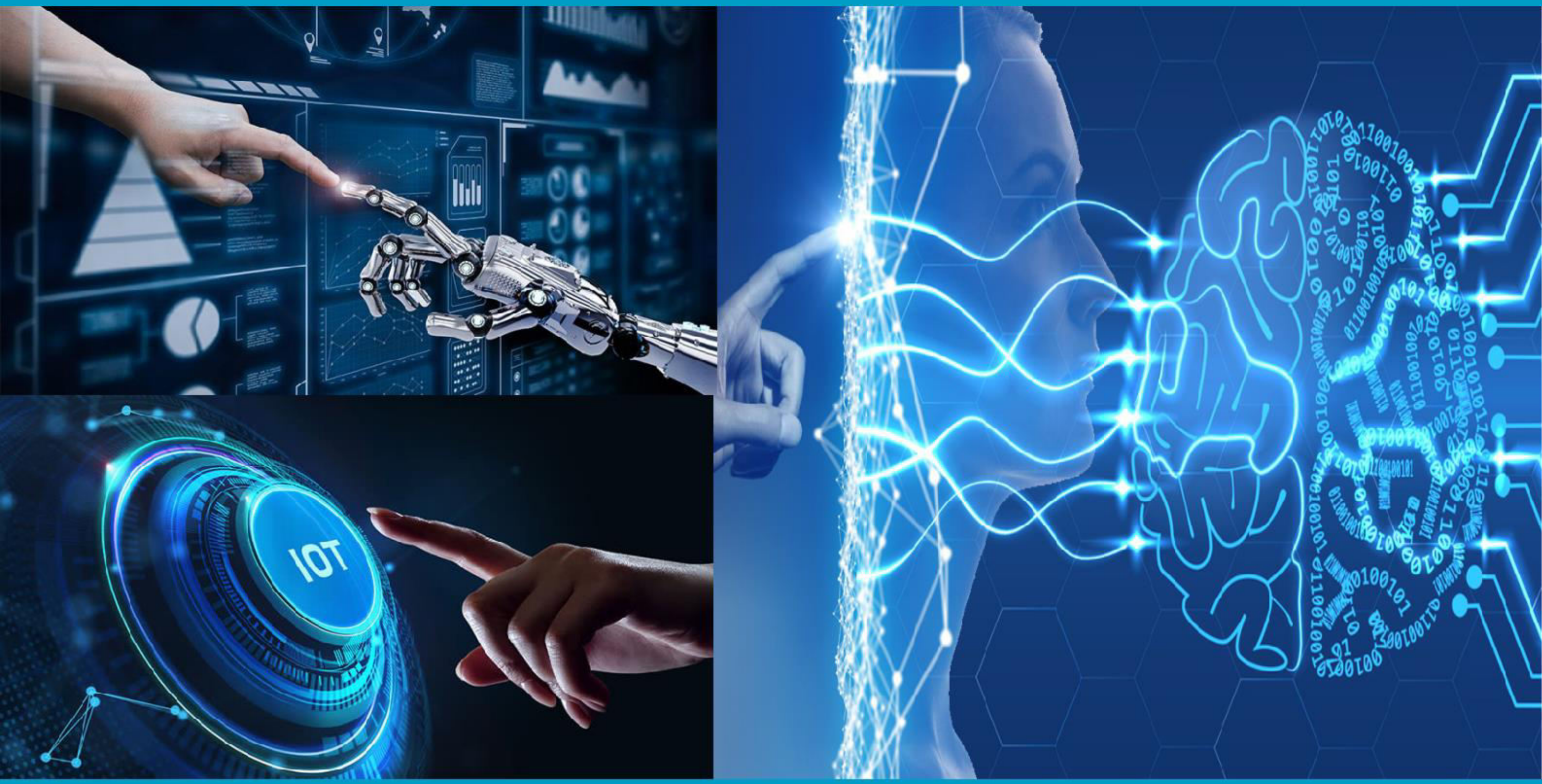

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Development of Smart Materials for Structural Applications

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ABSTRACT: With advancements in materials and technology, the field of civil engineering has witnessed the introduction of numerous innovative materials that address the challenges of deteriorating infrastructure. Among these, smart materials have emerged as a promising solution that warrants extensive research and application. These materials exhibit unique properties due to their two distinct crystal structures, Austenite and Martensite, which vary with temperature. Unlike conventional steels, smart materials possess two remarkable characteristics: shape memory and super-elasticity, making them highly suitable for diverse civil engineering applications such as prestressing bars, self-rehabilitation mechanisms, and two-way actuators. The primary objective of this research is to explore the potential applications of smart materials in civil engineering by conducting an extensive literature review, gathering fundamental information, and analyzing their basic mechanical properties. Through axial tension tests, the force-extension and stress-strain curves of shape memory and superelastic materials were separately measured, providing crucial validation of previous research findings. Additionally, four beam experiments were carried out to assess the flexural performance of beams reinforced with superelastic materials. Parameters such as the load-displacement relationship at midspan, surface strains on the concrete beam, and crack width under varying loads were systematically recorded and analyzed. While this study serves as an initial step in evaluating the viability of smart materials in structural engineering, further large-scale experiments involving bigger beams are planned to deepen the understanding of their behavior and potential implementation in real-world structures.

KEYWORDS: Smart Materials, Structural Applications, Piezoelectric Materials, Shape Memory Alloys, Adaptive Structures, Durability, Sustainable Construction

I. INTRODUCTION

Reinforced concrete structures must be designed to meet the requirements of both strength and serviceability limit states to ensure structural integrity and long-term performance. However, designing for serviceability is particularly challenging because predicting the behavior of composite beams under sustained service loads is complicated by time-dependent deformations such as creep and shrinkage of concrete. These deformations result in progressive strains as the concrete ages, significantly impacting the overall structural performance by causing excessive deflections and altering stress distribution within the material. Additionally, sustained loading induces dimensional changes in the concrete, further affecting the stability and durability of the structure. Given these challenges, it is crucial to develop an intelligent system for reinforced concrete structures that can effectively minimize internal and external disturbances, thereby enhancing structural safety and extending service life. Although Shape Memory Alloys (SMAs) have been known for several decades, their application in civil structures has only gained momentum in recent years. While significant research efforts have been dedicated to exploring their potential, many studies remain at the laboratory stage, with only a few implementations in real-world field applications demonstrating effectiveness. SMAs, also referred to as memory metals, possess unique mechanical properties that make them highly suitable for smart structural applications. These materials have the remarkable ability to undergo large recoverable strains—typically in the range of 8%—while exhibiting hysteresis behavior. One of the defining characteristics of SMAs is their ability to "remember" their original geometry, even after being subjected to deformation. When heated or, in certain cases, when unloaded at higher ambient temperatures, the material returns to its initial shape due to a stress- and temperature-dependent phase transformation. This transformation involves a shift from a low-symmetry crystallographic structure to a highly symmetric phase, allowing the material to self-recover from deformations. Given these extraordinary properties, SMAs offer a promising solution for mitigating the effects of long-term deformations in reinforced concrete structures, making them a valuable innovation in enhancing durability and serviceability in civil engineering applications.

II. LITERATURE REVIEW

The concept of smart materials has evolved significantly over the years, with extensive research focusing on their mechanical properties, applications, and long-term durability. A review of existing literature provides insights into the progress made in the field of SMAs and other adaptive materials used in structural applications.

2.1 Research and Development of Smart Structural Systems (2000) By Shunsuke Otani, Hisahiro Hiraishi, Mitumasa Midorikawa, Masaomi Teshigawara- The study titled "Research and Development of Smart Structural Systems" by Shunsuke Otani, Hisahiro Hiraishi, Mitumasa Midorikawa, and Masaomi Teshigawara (12WCEE, 2000) marked a significant milestone in the advancement of adaptive structural technologies. Initiated as a part of the U.S.-Japan cooperative research efforts, this five-year project under the Japanese Ministry of Construction aimed to develop smart materials and structural systems capable of autonomously adjusting their properties in response to external disturbances and environmental changes. This pioneering initiative laid the groundwork for integrating smart technologies into civil engineering by addressing challenges such as real-time structural monitoring, enhanced resilience, and energy efficiency. The research emphasized the need for innovative approaches in designing adaptive systems that could mitigate the impacts of seismic events, optimize performance, and ensure long-term structural integrity. This project not only advanced the understanding of smart materials and their applications but also strengthened international collaboration in the field of structural engineering.

2.2 Dynamic smart material and structural systems (2002) By A.B Flatau, K.P Chong- The paper "Dynamic Smart Material and Structural Systems" by A.B. Flatau and K.P. Chong (Engineering Structures, 2002) examines the transformative potential of smart materials and structural systems in improving the functionality, serviceability, and durability of civil and mechanical infrastructure. The authors discuss NSF-funded projects that emphasize the innovative use of high-performance sensors, actuators, and smart materials in the renewal and maintenance of infrastructure. By integrating these advanced technologies, structures can dynamically adapt to changing environmental conditions, mitigate damage, and extend their service life. The paper highlights the application of these materials in monitoring and controlling structural responses, such as vibration suppression, load redistribution, and damage detection. This research underscores the significance of smart material systems in addressing the challenges of aging infrastructure and promotes their adoption as a sustainable and efficient solution for infrastructure management.

2.3 Applications of Smart Materials in Structural Engineering (2003) By Cai, C.S.;Wu, Wenjie;Chen, Suren;Voyiadjis, George Z.- The study "Applications of Smart Materials in Structural Engineering" by Cai, C.S., Wu, Wenjie, Chen, Suren, and Voyiadjis, George Z. (ROSAP, 2003) investigates the potential of smart materials in the field of civil engineering. The primary focus of the research is to provide a comprehensive review of the existing literature, collect foundational information, and analyze the basic mechanical properties of smart materials. The authors emphasize the role of these materials in enhancing the performance and adaptability of structural systems by integrating their unique properties, such as sensing, actuation, and environmental responsiveness. The study also examines how these materials can address challenges such as structural health monitoring, seismic resilience, and energy efficiency in construction. By laying a solid foundation for understanding the mechanics and applications of smart materials, this work contributes to advancing their use in civil engineering and paves the way for future innovations in adaptive structural systems.

2.4 Nanotechnology and Smart Structures (2019) By Mudit Mishra, Arohan Maggo, Priyadarshi Mukesh
The paper "Nanotechnology and Smart Structures" by Mudit Mishra, Arohan Maggo, and Priyadarshi Mukesh (International Journal of Engineering Research & Technology, 2019) explores the synergistic integration of nanotechnology and smart materials in the development of advanced structural systems. The study highlights how nanotechnology enhances the properties of smart materials, such as increased strength, improved durability, and superior responsiveness to environmental stimuli. Applications of nanomaterials, such as carbon nanotubes, nanocomposites, and nanosensors, are discussed in the context of structural health monitoring, self-healing systems, and energy-efficient designs. The authors also emphasize the role of nanotechnology in miniaturizing devices for precision control and monitoring in smart structures. By leveraging these advancements, the paper underscores the potential of nanotechnology to revolutionize smart structures, enabling adaptive, sustainable, and resilient engineering solutions. The research concludes by advocating for continued interdisciplinary efforts to overcome challenges related to scalability, cost, and long-term performance of nanotechnology-enabled smart materials.

2.5 Structural Monitoring using Smart Materials and Internet of Things (IoT) (2021) By Vaishnavi M Gowda, Vedanth A, Sanjay S, Vimal A, Dr. Neethu Urs- The paper "Structural Monitoring using Smart Materials and Internet of Things (IoT)" by Vaishnavi M. Gowda, Vedanth A., Sanjay S., Vimal A., and Dr. Neethu Urs (International Journal of Engineering Research & Technology, 2021) explores the integration of smart materials and IoT technologies

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in structural health monitoring (SHM). The study emphasizes how IoT, through sensors and cloud computing, facilitates real-time data collection and analysis to detect structural deterioration, even in challenging environmental conditions. This approach enables timely corrective measures, thereby enhancing the durability and safety of concrete structures. The paper also introduces advanced concepts such as Ambient Intelligence, insidious computing, and omnipresent computing, illustrating how these technologies contribute to a deeper understanding of real-time structural behavior. By leveraging IoT's capabilities, the research highlights significant advancements in SHM, emphasizing its role in creating smarter, more adaptive, and sustainable infrastructure systems.

2.6 Scope of Smart Materials in Future (2021) By Jaslok Pandey, Pranav Solanki- The paper "Scope of Smart Materials in Future" by Jaslok Pandey and Pranav Solanki (International Journal of Engineering Research & Technology, 2021) delves into the transformative potential of smart materials in futuristic applications, particularly in self-sustainable wireless sensor networks, vibration energy harvesting devices, and seismic resilience systems. The authors emphasize the unique properties of smart materials, such as piezoelectricity, shape memory, and electro-rheological/magneto-rheological fluid behavior, which allow these materials to mimic biological systems. By integrating these properties into engineering applications, smart materials can adapt to external stimuli, self-regulate, and enhance performance under varying conditions. The paper also explores the implications of these materials in creating sustainable and adaptive solutions across industries, particularly in infrastructure and energy systems. This study underscores the vital role of smart materials in addressing future technological and environmental challenges, paving the way for innovative applications that blend functionality with sustainability.

2.7 Smart Materials- Types & Applications (2022) By Anusuri Uma Maheswari, Anusuri Lavanya, E. Vinay- The paper "Smart Materials - Types & Applications" by Anusuri Uma Maheswari, Anusuri Lavanya, and E. Vinay (IJRASET, 2022) provides an overview of various types of smart materials and their diverse applications across multiple industries. The authors categorize smart materials based on their functionalities, including piezoelectric materials, shape memory alloys, magnetorheological and electrorheological fluids, and self-healing materials. The study focuses on the practical applications of these materials in fields such as construction, aerospace, automotive, healthcare, and energy systems. Smart materials are highlighted for their ability to adapt to external stimuli, such as temperature, pressure, electric fields, and mechanical forces, allowing them to perform functions like actuation, sensing, and energy absorption. The paper also discusses the challenges in the commercialization of these materials, such as high costs, material limitations, and integration complexities. Despite these challenges, the authors emphasize the transformative potential of smart materials in advancing technologies that are more efficient, adaptive, and sustainable.

2.8 Development and Prospect of Smart Materials and Structures for Aerospace Sensing Systems and Applications (2023) By Wenjie Wang ,*ORCID,Yue Xiang,Jingfeng Yu andLong Yang- The study "Development and Prospect of Smart Materials and Structures for Aerospace Sensing Systems and Applications" by Wenjie Wang, Yue Xiang, Jingfeng Yu, and Long Yang (published in Sensors, 2023) explores the advancements and future potential of smart materials and structures tailored for aerospace sensing systems. The research highlights how these materials, such as piezoelectric composites, shape memory alloys, and carbon nanotubes, enable enhanced sensing, adaptability, and self-repairing capabilities in aerospace applications. The authors emphasize the integration of multifunctional smart materials into structural systems, which can improve flight performance, structural health monitoring, and safety while reducing overall weight and energy consumption. Furthermore, the study discusses the challenges in developing these materials, including cost, reliability under extreme conditions, and scalability for real-world applications. By examining cutting-edge technologies and forecasting trends, this work provides a comprehensive framework for advancing smart systems in aerospace engineering, setting a benchmark for interdisciplinary innovations in sensing and structural applications.

2.9 Application of smart materials in civil engineering: A review (2023) By Abhilash, Deepmala- The paper "Application of Smart Materials in Civil Engineering: A Review" by Abhilash and Deepmala (Materials Today, 2023) provides a comprehensive overview of the diverse range of smart materials available and their applications in civil engineering. The authors categorize smart materials such as piezoelectric materials, shape memory alloys, self-healing concrete, and electrochromic glass, emphasizing their roles in enhancing structural performance, durability, and energy efficiency. The review also delves into the innovative materials that have the potential to revolutionize the construction industry, such as bio-inspired composites and nanomaterials. Furthermore, the study discusses the advantages of these materials, including their adaptability, sustainability, and ability to reduce maintenance costs, as well as the limitations, such as high costs, limited awareness, and integration challenges in real-world scenarios. By examining their applicability under various conditions, the paper highlights the transformative impact of smart materials on the construction industry and suggests future directions for research and practical implementation.

2.10 A Review on Applications of Smart Materials (2023) By K. Sreelatha, C.S. Ananda Kumar, P.Srinivasa Sai- The paper "A Review on Applications of Smart Materials" by K. Sreelatha, C.S. Ananda Kumar, and P. Srinivasa Sai (International Journal of Novel Research and Development, 2023) explores the transformative potential of smart materials across various industries, including construction, aerospace, healthcare, and electronics. The review highlights how the integration of smart materials enables the development of efficient, adaptive, and sustainable technologies by leveraging their unique properties, such as self-sensing, actuation, and adaptability to external stimuli. While the authors underline the significant advancements in this field, they also discuss the persistent challenges, particularly related to material cost, long-term durability, and scalability for widespread application. Future research directions identified in the paper focus on addressing these limitations, improving material performance, and broadening the range of applications to meet the growing demand for innovative and sustainable solutions in modern engineering and technology.

III. HISTORY OF SMART MATERIALS

The first recorded observation of a smart material transformation was made in 1932 when researchers discovered phase changes in a gold-cadmium alloy. This early finding indicated the potential for metals to exhibit unusual mechanical behaviors under specific conditions. A few years later, in 1938, a similar phase transformation was observed in brass, specifically in copper-zinc alloys, further advancing the understanding of these unique material properties. However, it was not until 1962 that the most significant breakthrough in smart materials occurred when Beehler and his colleagues at the Naval Ordnance Laboratory identified the shape memory effect in a nickel-titanium alloy. They named this revolutionary material "Nitinol," derived from "Nickel-Titanium Naval Ordnance Laboratory." This discovery marked a turning point in the development of smart materials, as Nitinol exhibited exceptional properties such as shape memory and superelasticity, which distinguished it from previously known alloys. Following the discovery of Nitinol, researchers identified several other alloy systems capable of demonstrating the shape memory effect. Despite the enthusiasm surrounding these materials, early attempts at product development faced significant challenges, primarily due to the high cost and scarcity of exotic elements required in many of these smart materials. Among the various alternatives explored, copper-based shape memory alloys emerged as the only commercially viable competitor to the Nitinol family due to their relatively lower cost and ease of production. The 1980s and early 1990s witnessed a surge in interest and commercialization of Ni-Ti-based smart materials. Several companies began manufacturing and supplying Nitinol-based materials and components, leading to an increasing number of practical applications. Among the most notable advancements during this period were the integration of smart materials into the medical field, where their shape memory properties were harnessed for biomedical devices such as stents, orthodontic wires, and surgical instruments. The continuous evolution of smart material technology has since expanded its applications beyond medicine, influencing various industries, including aerospace, robotics, and civil engineering, making them a cornerstone of modern material science.

IV. CRYSTAL STRUCTURES AND THEIR BEHAVIOR

Like all metals and alloys, Shape Memory Alloys (SMAs) exhibit polymorphism, meaning they can exist in multiple crystal structures depending on external conditions. The dominant crystal structure or phase in polycrystalline metals is influenced by both temperature and applied stress. SMAs specifically exist in two distinct temperature-dependent crystal structures: martensite at lower temperatures and austenite at higher temperatures, also referred to as the parent phase.In the austenite phase, which occurs at higher temperatures, SMAs exhibit a stronger and more stable structure. Conversely, in the martensite phase at lower temperatures, they become weaker and more deformable. These two phases differ significantly in their crystal configurations. Austenite adopts a body-centered cubic (BCC) structure, which provides greater rigidity and resistance to external stress due to its compact atomic arrangement. In contrast, martensite has a parallelogram-like asymmetric structure with up to 24 different variations, allowing for significant deformation under applied stress. When an SMA in the martensite phase experiences external stress, it undergoes deformation through a detwinning mechanism, in which different martensitic variants realign into a particular configuration that accommodates the maximum possible elongation. Due to its less compact and more irregular structure, martensite is mechanically weaker and can deform more easily. In contrast, in the austenite phase, elevated temperatures cause atoms to reorganize into the most regular and compact arrangement possible, forming a rigid cubic structure that offers superior resistance to external forces. A remarkable property of SMAs is their ability to revert to their original shape when heated, a phenomenon made possible by their fully reversible crystal transformation. This unique characteristic, known as the shape memory effect, enables SMAs to recover their initial form once they transition back into the austenite phase upon heating. The transition temperature of SMAs varies widely, typically ranging from –50°C to 166°C, depending on their specific composition. This temperature-dependent transformation makes SMAs particularly useful in applications requiring adaptive materials, including biomedical devices, aerospace engineering, and smart structural systems in civil engineering.

V. MATERIAL PHENOMENA

SMAs have two unique properties,
1. Shape Memory Effects (SME)
2. Superelasticity

The Shape Memory Effect (SME) refers to the remarkable ability of Shape Memory Alloys (SMAs) to return to their predetermined shape when subjected to heating. This phenomenon is based on a reversible phase transformation between the martensite and austenite phases. For instance, if a straight SMA bar in the austenitic phase is cooled below the phase transition temperature, its crystalline structure transforms into martensite, making it more pliable. If this martensitic bar is then deformed by bending and subsequently reheated above the transition temperature, it will automatically return to its original straight shape. This self-recovery characteristic is widely utilized in various engineering applications, including actuators, biomedical devices, and adaptive structural systems. In contrast, superelasticity (also known as pseudoelasticity) is a unique property of SMAs that allows them to undergo large inelastic deformations and recover their original shape upon unloading, without requiring thermal activation. This property arises when an SMA experiences an external stress that induces a phase transformation from austenite to martensite. Upon removing the stress, the material spontaneously reverts to its original austenitic phase and regains its initial shape. However, if the deformation recovery is constrained, a mechanical stress is generated within the material, known as recovery stress. This recovery stress can be effectively utilized in civil engineering applications, particularly in reinforced concrete structures, to counteract the effects of creep, shrinkage, and thermal strains. The presence of superelasticity makes SMAs suitable for use as passive structural control systems, seismic isolation devices, and energy dissipation components in infrastructure. By incorporating SMAs into civil structures, engineers can enhance their resilience against external disturbances, improve durability, and extend service life, making them a promising innovation for the future of smart materials in construction.

5.1. Shape Memory Effect (SME)

Shape Memory Effect (SME) is one of the key properties of Shape Memory Alloys (SMAs), allowing them to return to their original shape after deformation when subjected to a temperature change. This unique behavior is a result of a reversible phase transformation between the **martensite** and **austenite** phases.

When an SMA in its **twinned martensite phase** is exposed to an external stress, it undergoes a transformation into the **detwinned martensite phase**, as illustrated in **Procedure 1**. This transformation occurs without any temperature change and allows the material to deform significantly under applied loads.

Upon **heating**, the **detwinned martensite** transitions into the **austenite phase** (**Procedure 2**), during which the material regains its original shape. When the temperature is lowered once again (**Procedure 3**), the SMA reverts from **austenite** back to **twinned martensite**, completing the cycle.

There are four critical temperature points that define this transformation process:

- **Mf** (Martensitic finish temperature) – The temperature at which martensitic transformation is complete.
- **Ms** (Martensitic start temperature) – The temperature at which austenite begins transforming into martensite.
- **As** (Austenitic start temperature) – The temperature at which martensite begins transforming into austenite.
- **Af** (Austenitic finish temperature) – The temperature at which austenitic transformation is complete.

Throughout **Procedures 1, 2, and 3**, SMAs experience changes in external stress, temperature increase, and temperature decrease, ultimately returning to their original **twinned martensite** state. However, if constraints are imposed during **Procedure 3**, when austenite transitions back to martensite, a significant **recovery force** is generated. This recovery force can be harnessed for numerous **civil engineering applications**, including:

- **Self-repairing concrete structures**, where SMAs can close cracks autonomously upon heating.
- **Reinforcement bars in prestressed concrete**, where recovery stress improves durability.
- **Seismic-resistant structures**, where SMAs enhance resilience by absorbing and dissipating earthquake-induced energy.

By leveraging the Shape Memory Effect, SMAs offer innovative solutions for improving the performance, safety, and longevity of infrastructure, making them a valuable advancement in modern civil engineering.

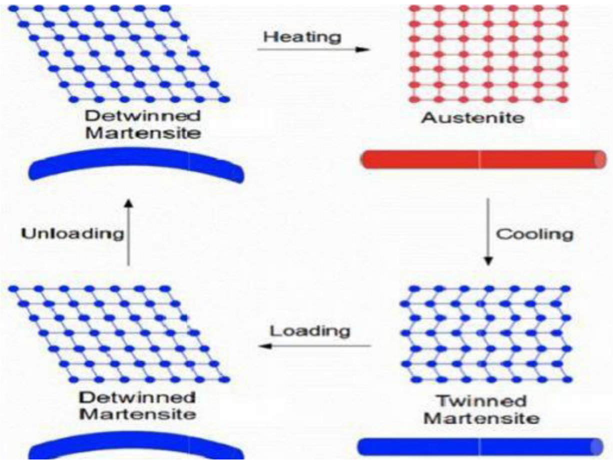


Fig.1: Transformations between different phases

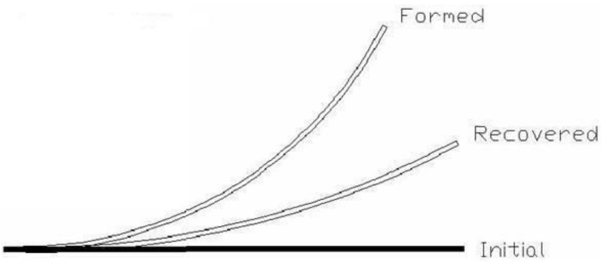


Fig.2: Demonstration of shape-memory effect

5.2. Superelasticity

Superelasticity is another remarkable property exhibited by Shape Memory Alloys (SMAs), making them highly valuable in structural applications. This phenomenon occurs when an SMA remains in its **austenite phase** at room temperature due to its **Austenite finish temperature (Af)** being relatively low.

In this state, when an **external stress** is applied, the SMA undergoes a **stress-induced phase transformation** from **austenite to detwinned martensite**. Unlike the Shape Memory Effect (SME), this transformation occurs purely due to mechanical loading, without the need for temperature changes. Once the stress is removed, the material **spontaneously reverts** from detwinned martensite back to its original austenite phase, recovering its shape almost instantly.

This reversible transformation is responsible for the unique **pseudoelastic behavior** of SMAs, allowing them to withstand large strains—**up to 8%**—without permanent deformation. This property results in an energy dissipation effect, which is particularly beneficial for applications requiring **shock absorption, flexibility, and durability**.

Application of Superelasticity in Civil Engineering:

Superelastic SMAs are widely used in **civil engineering** due to their ability to recover large deformations, dissipate energy, and enhance structural resilience. Some key applications include:

- **Seismic-resistant structures**: Superelastic SMA reinforcements can absorb seismic energy and reduce structural damage during earthquakes.
- **Bridge cables and dampers**: Used in bridges to withstand cyclic loading and prevent failure due to extreme stress variations.
- **Structural joints and connections**: SMAs provide flexible yet durable connections that can self-adjust under dynamic loads.
- **Rehabilitation of aging infrastructure**: SMA-based reinforcements improve the longevity of deteriorating structures by reducing stress concentrations.

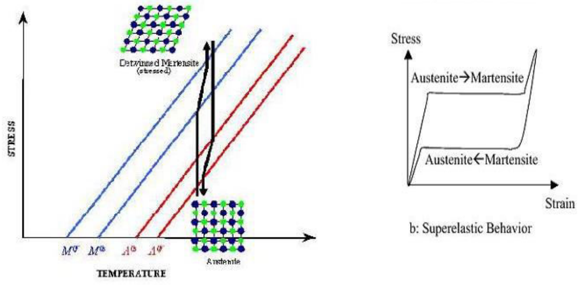


Fig.3: Stress-induced transformations of Austenite materials

The stress-strain behavior of superelastic Shape Memory Alloys (SMAs) is characterized by a distinctive hysteresis loop, as illustrated in Figure 3. This loop represents the phase transformation that occurs under mechanical loading and unloading.

- The upper plateau in the stress-strain curve corresponds to the stress-induced transformation from austenite to detwinned martensite. As external stress is applied, the material transitions from its original austenitic phase into a more deformable martensitic phase, allowing it to undergo large strains without permanent deformation.
- The lower plateau represents the reverse transformation, where the material returns from martensite back to austenite as the stress is released. This transformation enables the material to fully recover its original shape.

Key Features and Applications:
Superelastic SMAs possess several advantageous properties that make them ideal for civil engineering applications, particularly in reinforcement and rehabilitation of structures:

1. Self-Rehabilitation of Cracked Concrete
   - When used as reinforcement bars, superelastic SMAs can close cracks in concrete by exerting a recovery force as the stress is released. This property enhances the durability of reinforced concrete structures and minimizes maintenance needs.
2. Hysteretic Damping for Seismic Protection
   - The stress-strain loop indicates a hysteretic energy dissipation mechanism, making superelastic SMAs effective for seismic-resistant design. They absorb and dissipate earthquake-induced forces, reducing structural damage.
3. Reliable Energy Dissipation and Fatigue Resistance
   - Superelastic SMAs exhibit repeatable phase transformations, enabling them to withstand multiple loading cycles without degradation. This property makes them ideal for bridge cables, seismic dampers, and energy-absorbing devices.
4. Excellent Corrosion Resistance
   - Unlike conventional steel reinforcements, SMAs offer high resistance to corrosion, extending the service life of structures exposed to harsh environmental conditions.

VI. APPLICATION OF SMA IN CIVIL STRUCTURES

6.1 Overview
Shape Memory Alloys (SMAs) offer several properties that make them valuable for integration into civil structures:

1. The ability to generate large forces when returning to their original shape.
2. High capacity to absorb significant strain energy without permanent deformation.
3. Excellent damping characteristics below the transition temperature range.
4. Superior corrosion resistance, comparable to 300-series stainless steels, and non-magnetic properties.
5. Low density and high fatigue resistance under large strain cycles.
6. Capability for electrical heating to restore original shape.

6.2 Application of Tensioning Properties of SMA Utilizing Shape Memory Effect
6.2.1 SMA as a Tendon in Concrete Structures
SMA bars or cables can function as tendons in concrete structures. Research by Deng Z. and Krstulovic-Opara N. highlights the advantages of SMA tendons over conventional steel tendons:

- No frictional losses due to uniform tension distribution along the tendon length.

- Suitable for curved concrete members and complex tendon profiles.
- No requirement for anchors, making them ideal for tensioning thin concrete members.

6.2.2 SMA as an External Tensioning Material in Concrete Structures

Over time, concrete structures experience load-induced deformations and cracking, reducing their service life. External tensioning elements, such as steel and Fiber-Reinforced Plastic (FRP), are commonly used to counteract these effects. SMAs offer an advantage as they do not require hydraulic jacks or other tensioning devices. After mounting and anchoring martensitic SMA rods, heating initiates the shape memory effect, generating tension within the structure.

A notable application by Soroushian et al. involved using corrosion-resistant Fe-Mn-Si-Cr SMA rods to enhance shear resistance in a cracked reinforced concrete bridge girder. Resistance heating was applied at 1000 Amperes to activate the SMA properties.

6.3 Retrofitting Structures Using Superelastic Properties of SMA

The superelastic behavior of SMAs has been widely studied for structural retrofitting, particularly in seismic applications. Research highlights include:

- Graesser E.J. successfully used Ni-Ti SMAs for seismic load damping.
- Wittig P.R. explored Cu-Zn-Al SMAs for torsion, bending, and tension dampers.
- Cardone D. compared SMA bracing of reinforced concrete frames with traditional steel bracing.

Real-World Applications

- **Basilica San Francesco, Assisi, Italy**: SMA rods were used to connect the historic gable to the main structure for earthquake resistance.
- **Bell Tower of the Church of San Giorgio, Italy**: Steel tendons with SMA devices improved tilt resistance and load limiting to prevent masonry failure.
- **Bridge Seismic Restraint**: DesRoches R. proposed using superelastic SMA bars to enhance stability in earthquake-prone simply supported bridges.
- **Concrete Beam Restoration**: Sakai et al. demonstrated self-restoration of a cracked concrete beam using SMA wires, showing significant recovery upon unloading.
- **University of Houston Study**: A reinforced concrete beam (24" x 4" x 6") with fourteen 1/8" diameter SMA-stranded cables showed effective crack closure after being subjected to an 11,000 lbs load.

6.4 Application of SMA as a Connector Between Structural Components

Structural connections are highly susceptible to damage during earthquakes. SMA connectors have been developed to provide damping and resistance against large deformations.

- **Seismic Resistant Column Bases**: Tamai H. proposed using exposed SMA anchorage systems with 20-30 mm Nitinol SMA rods. Load testing demonstrated superior energy dissipation and vibration reduction compared to conventional anchorage systems.
- **Steel Beam-Column Connections**: Leon et al. utilized martensitic SMA tendons as primary load transfer elements. Full-scale load testing showed stable hysteresis up to 4% rotation, with SMA tendons sustaining up to 5% strain without permanent damage.

These advancements in SMA applications continue to enhance structural resilience, longevity, and seismic resistance in civil engineering.

VII. Problems in Highways and Bridges

One of the significant challenges in highway and bridge infrastructure is differential settlement between bridges and pavements, leading to bumps or uneven joints at bridge ends. These irregularities create substantial impact loads, particularly for heavy trucks, resulting in accelerated deterioration of both pavements and bridges. The adverse effects include separation of pavement layers, joint spalling, fatigue cracking in pavements, and structural damage to bridges. Additionally, such conditions pose safety risks, potentially leading to vehicular accidents and increased maintenance costs. A related issue is the uneven settlement between bridge piers or approach spans. Differential settlement not only affects the rideability of bridges but also induces additional internal forces within the structure. Maintaining bridge joints presents an ongoing challenge for engineers and highway authorities. Traditional solutions have primarily focused on foundation design improvements, yet they have not completely resolved issues related to joint unevenness and settlement. Temperature variations and time-dependent factors such as creep and shrinkage further contribute to internal restraint forces in indeterminate structures. These forces, either independently or in combination with external loads, lead to cracking in structures and pavements. Addressing these effects often increases construction costs due to the need for larger section dimensions and enhanced material properties. Another critical issue pertains to the performance of bridge bearings. Malfunctioning bearings, caused by material deterioration, dirt accumulation, or mechanical failure, result in excessive stress concentrations near the bearing regions. This alters the intended force redistribution, compromising the structural integrity and increasing maintenance demands. Such issues are common contributors to bridge failures. An effective solution to automatically adjust forces among bearings would significantly mitigate these problems.

7.1. Concept of Smart Bridges

The integration of smart materials, particularly Shape Memory Alloys (SMA), offers an innovative approach to addressing these challenges. The two-way memory effect of SMA enables the development of actuators that can dynamically adjust their height, compensating for differential settlement and structural deformations. Additionally, SMA-based smart strands, embedded within concrete, can be activated through external heating or internal stress variations to provide self-repair and adaptive prestressing functionalities. Smart bearings utilizing SMA technology can autonomously adjust their height, counteracting issues related to settlement, time-dependent deformations (creep, shrinkage, relaxation of prestressed steel), and temperature fluctuations. This dynamic adaptability enhances structural resilience and reduces maintenance costs. Moreover, prestress forces can be modified as needed to control cracking in both positive and negative moment zones, ensuring optimal load distribution across the bridge structure. The combined application of smart bearings and smart strands facilitates real-time internal force adjustments, allowing the bridge to adapt to varying environmental and load conditions. This innovative approach enhances structural performance, prolongs service life, and improves overall safety by mitigating the adverse effects of differential settlement, temperature changes, and excessive vehicular loads.

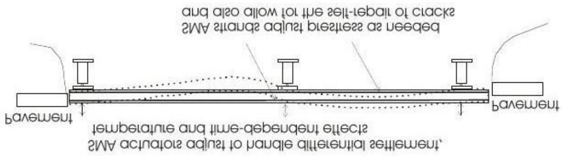


Fig.4: Sketch of a smart bridge

VIII. TYPE OF SMAs SUITABLE FOR USE IN CIVIL STRUCTURES

Not all shape memory alloys (SMAs) are suitable for civil structures due to specific mechanical property requirements, environmental temperature conditions, and cost considerations. Among various SMAs, Fe-Mn-Si-X alloys are a cost-effective option, offering high superelastic properties and good shape memory effects. When comparing the market prices of Ni and Ti with Fe, Mn, Si, and Cr, the cost factor is approximately 8 to 12 times lower for iron-based SMAs. This makes Fe-based SMAs a significantly more economical alternative to NiTi SMAs. Studies by Tamarat K. indicate that Fe-based SMAs such as Fe-Mn-Si-X, Fe-Ni-C, and Fe-Ni-Co-Ti, also known as shape memory steels or ferrous SMAs, have strong potential for applications in civil structures.

The shape memory effect in Fe-Mn-Si alloys containing sufficient Mn was first observed by Sato et al. in 1982. Over the past decades, extensive research and alloy modifications have improved their initially poor shape memory effects and corrosion resistance. It was found that Fe-Mn-Si-X alloys, with an iron content of 60–65%, offer an optimal balance of low cost, high strength, and high Young's modulus. Additionally, corrosion resistance comparable to stainless steel was achieved by Li H.J. through the addition of 10% chromium and nickel. Further literature from Farjami S., Lin C., and Baruj A. suggests that alloying elements such as Al, C, Co, Cu, N, Nb, NbC, V, VN, and ZrC enhance the shape memory effect. This highlights the potential for further research into low-cost SMAs for large-scale applications in civil structures. Several successful implementations of SMAs in structural applications have been documented. For example, Soroushian et al. used low-cost SMAs in bridge rehabilitation, while Graesser E.J. applied Ni-Ti SMAs for seismic damping. Additionally, Wittig R.P. incorporated Cu-Zn-Al SMAs into bracings for torsion, bending, and tension damping. Due to their better workability and lower cost, ferrous SMAs present a more attractive alternative to Ni-Ti SMAs for civil engineering applications. As research progresses, the development of low-cost SMAs will continue to open new possibilities for their widespread use in structural applications.

IX. EXISTING FIELD APPLICATION OF SMA

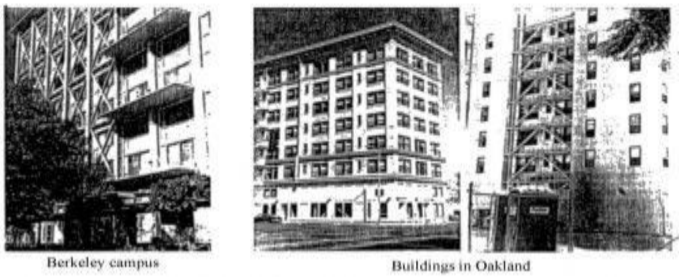
Retrofitting of the Basilica of San Francesco at Assisi, Italy

Retrofitting of the bell tower of the Church of San Giorgio at Trignano, Italy

(a) (b)

Unseating at in-span hinge during the 1994 Northridge earthquake for (a) an existing bridge and (b) bridge retrofit with SMA restrainer cables

Exterior of the Sherith Israel Synagogue retrofitted with SMA devices



Use of sma bars to seismically upgrade buildings in Berkley and Oakland

X. CONCLUSION

This paper presents a comprehensive review of the fundamental properties of Shape Memory Alloys (SMAs) and their applications in passive, active, and semi-active control of civil structures. Various experimental and analytical studies on SMA-based devices, such as dampers and base isolators, have demonstrated their effectiveness in enhancing structural resilience against extreme earthquake loading. In particular, the recentring capability of SMAs significantly reduces repair and retrofitting costs, making them a promising solution for structural safety and sustainability. Additionally, their application in prestressing offers a viable approach to accommodating additional loading and compensating for prestress losses over time. Furthermore, the self-repairing ability of superelastic SMAs can be leveraged to counteract preload losses in bolted joints and fasteners, thereby ensuring the necessary clamping force to maintain structural integrity. Despite substantial research on the use of SMAs in civil structures, the short- and long-term deflection behavior of concrete flexural members reinforced with SMAs remains an area requiring further experimental investigation. The analytical study conducted on SMA-reinforced concrete (RC) beams under various service loads revealed that SMA RC beams exhibit lower mid-span deflection compared to conventional steel RC beams of identical dimensions and material grades. The superior rigidity and superelastic properties of SMAs contribute to increased load-carrying capacity and reduced instantaneous and long-term deflections in RC flexural members. Additionally, an increase in the reinforcement ratio, cross-sectional area, and span of SMA RC beams enhances their resistance to deflection under service loads. However, these analytical findings necessitate validation through experimental studies to confirm their practical applicability in real-world structural scenarios.

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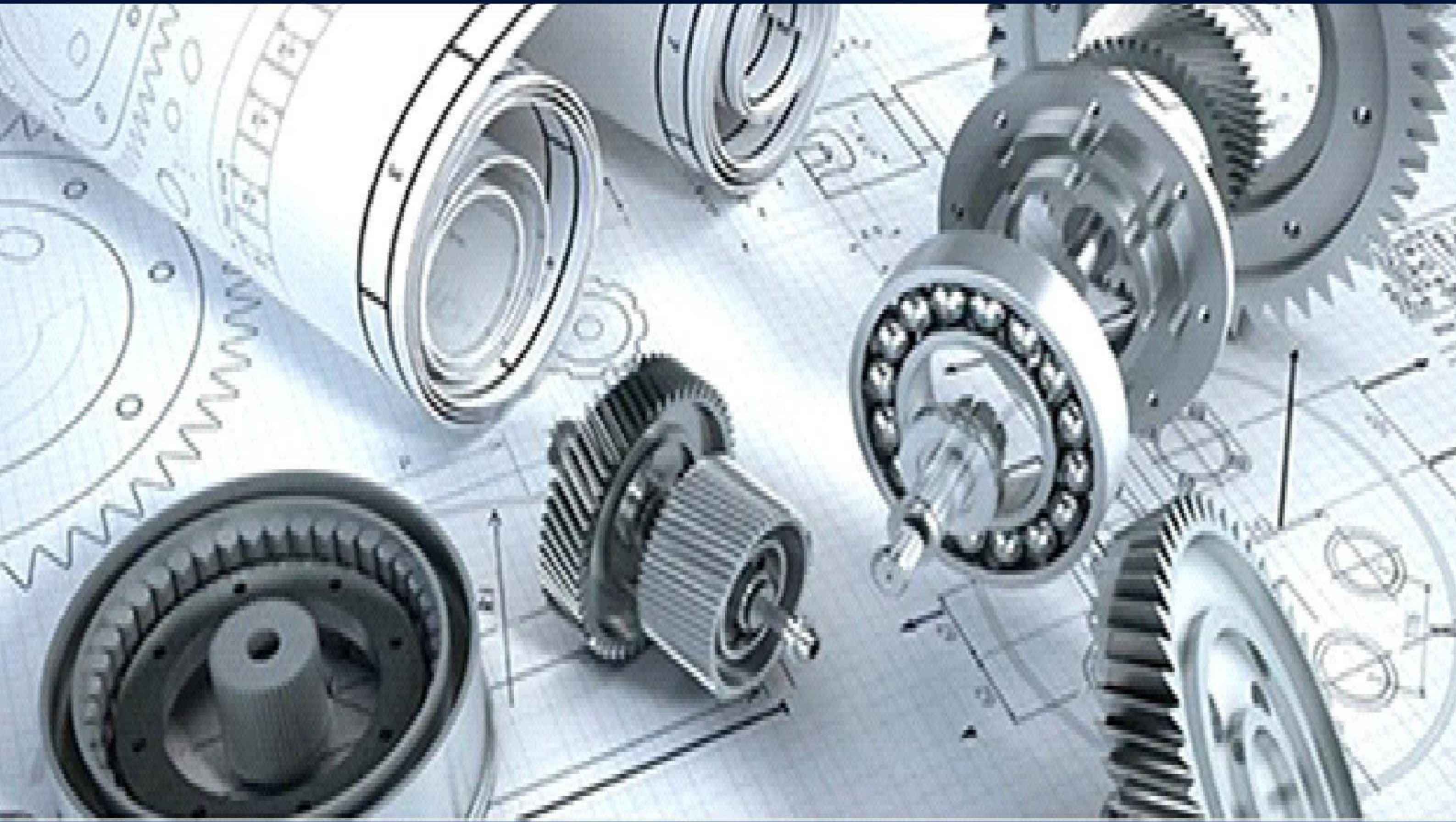
REFERENCES

1. Abhilash Mukherjee, Deepmala, Prateek Srivastava, Jasminder Kaur Sandhu, Application of smart materials in civil engineering: A review, Materials Today: Proceedings, Volume 81, Part 2, 2023, Pages 350-359, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2021.03.304.
2. A.B Flatau, K.P Chong, Dynamic smart material and structural systems, Engineering Structures, Volume 24, Issue 3, 2002, Pages 261-270, ISSN 0141-0296, https://doi.org/10.1016/S0141-0296(01)00093-1.
3. Arunkumar, M.P.; Bhagat, V.; Geng, Q.; Li, Y.M.; Pitchaimani, J. An exact solution for vibro-acoustic response of smart sandwich panels with MEE composite Layer. Compos. Struct. 2022, 286, 115201.
4. Bhalla, S., & Soh, C. K. (2004). Structural Health Monitoring by Piezo-Impedance Transducers. Earthquake Engineering & Structural Dynamics, 33(4), 491-511. DOI: 10.1002/eqe.361
5. Dolce, M., Cardone, D., & Marnetto, R. (2000). Implementation and Testing of Passive Control Devices Based on Shape Memory Alloys. Earthquake Engineering & Structural Dynamics, 29(7), 945-968. DOI: 10.1002/1096-9845(200007)29:7<945:AID-EQE947>3.0.CO;2-S
6. DesRoches, R., & Smith, B. (2003). Shape Memory Alloys in Seismic Resistant Design and Retrofit: A Critical Review. Engineering Structures, 25(3), 309-318. DOI: 10.1016/S0141-0296(02)00149-6.
7. K. Sreelatha, C.S. Ananda Kumar, P.Srinivasa Sai, P. Vijayalakshmi, Dr S.V.G.V.A. Prasad. (2023). A Review on Applications of Smart Materials. Dept of Physics, SVKP & Dr KS Raju Arts & Science College, Penugonda – 534320, A.P India. IJNRD
8. Review of Shape Memory Alloys applications in civil structures, and analysis for its potential as reinforcement in concrete flexural members Debbarma.S.R, Saha.S.
9. Seepersad, C.C.; Dempsey, B.M.; Allen, J.K.; Mistree, F.; McDowell, D.L. Design of Multifunctional Honeycomb Materials. AIAA J. 2004, 42, 1025–1033.
10. Seismic Control of Steel Structures with Shape Memory Alloys DesRoches, R., and Delemont, M.,
11. Seismic retrofit of simply supported bridges using shape memory alloys Engineering Structures, 24, 2002, 325?332. Hodgson, D.E., and Brown, J.W.
12. Vaishnavi M Gowda, Vedanth A, Sanjay S, Vimal A, Dr. Neethu Urs, 2021, Structural Monitoring using Smart Materials and Internet of Things (IoT), INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) NCACE – 2020 (Volume 09 – Issue 01)
13. Wang, W.; Xiang, Y.; Yu, J.; Yang, L. Development and Prospect of Smart Materials and Structures for Aerospace Sensing Systems and Applications. Sensors 2023, 23, 1545. https://doi.org/10.3390/s23031545
14. White, S. R., Sottos, N. R., & Geubelle, P. H. (2001). Autonomic Healing of Polymer Composites. Nature, 409(6822), 794-797. DOI: 10.1038/35057232
15. Yang, L.; Harrysson, O.L.A.; Cormier, D.; West, H.A.; Park, C.M.; Peters, K. Design of Auxetic Sandwich Panels for Structural Applications Design of Auxetic Sandwich Panels for Structural Applications. In Proceedings of the 2013 International Solid Freeform Fabrication Symposium, Austin, TX, USA, 12–14 August 2013.



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