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# Smart Materials for Seismic Control: Performance of Cu- and Fe-Based Shape Memory Alloys in Structural Applications

Betty Heleen*, M Abubakar**
*(Department of Metallurgical and Materials Engineering, and USA
Email: Lawalsanisco14@gmail.com)
** (Department of Metallurgical and Materials Engineering, and Nigeria
Email: Sanisco92@gmail.com)

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## Abstract:

This review examines the potentials and applicability of cost-effective Cu- and Fe-based shape memory alloys (SMAs) for vibration control in civil structures. Seismic devastation is accentuated by the tremor-induced collapse of buildings, and NiTi-based SMAs—despite excellent damping properties—pose prohibitive cost barriers, particularly for developing nations. This paper advances the case for Cu- and Fe-based SMAs by examining their structural applications, damping characteristics, and comparative performance. These fundamental material insights directly inform understanding of the magnetic and electronic behaviour underpinning the functional performance of Fe-containing SMA and SMA-adjacent systems in structural applications. The findings confirm that Cu- and Fe-based SMAs are technically viable, simply implementable, and sustainable alternatives for structural vibration control in buildings and civil infrastructure.

*Keywords* — **Shape memory alloys, Structural vibration, Damping, Fe–Cu metastable alloys, Ferromagnetism, Seismic control, Civil structures**

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## I. INTRODUCTION

Conventionally, buildings and engineering structures in seismic-prone regions are designed using seismic codes that allow appreciable resistance to ground vibrations. These structures absorb earthquake energy through localized damage of their supporting members. However, documented evidence shows that many such structures still record catastrophic collapse under intense seismic vibrations [71]. This has propelled research into vibration mitigation strategies that can increase the resistance of civil structures to seismically induced ground motion. The dynamic response of civil structures is highly dependent on the presence of vibration control units when subjected to external loading [12]. Shape memory alloys (SMAs) have emerged as particularly promising smart materials for this purpose, owing to their high energy absorption, damping capacity, superelasticity, and re-centering ability [13]. Among SMAs, NiTi-based alloys have dominated research and practical application; however, their prohibitive production costs and the requirement for controlled processing environments limit their sustainability, particularly for developing nations [13]. Against this background, the use of cheaper Cu- and Fe-based SMAs represents an important and underexplored avenue for structural vibration control. This review builds upon the foundational work of Alaneme et al. [1] and incorporates recent findings from Zhang et al. [106], who investigated the magnetic and electronic properties of mechanically alloyed Fe–Cu metastable solid solutions ($Fe_{20}Cu_{80}$). The structural and magnetic characterisation of this Fe–Cu system provides fundamental material-science context for understanding Fe-containing alloys relevant to the SMA family, particularly with respect to phase transformation, ferromagnetic behaviour, and defect-induced property modifications.

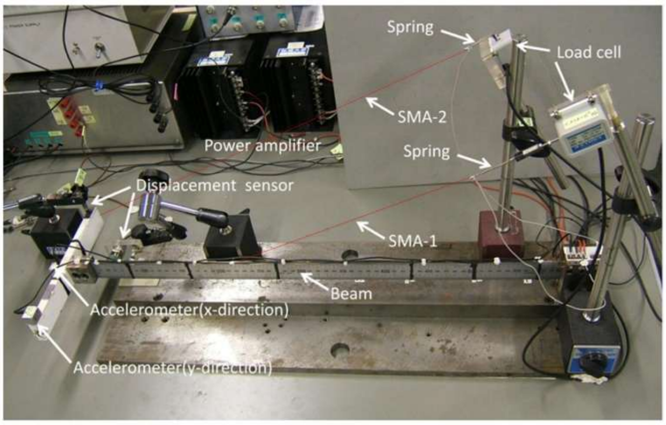
## II. Structural Vibration Control Systems

Several vibration control approaches have been developed, broadly classified as passive, active, hybrid, and semi-active systems [11].

### *A. Passive Control*

Passive systems use the structure's own motion to impart control forces through energy dissipation or base isolation, requiring no external power. Examples include viscoelastic fluid and solid dampers, friction dampers, and tuned mass dampers [7]. These are well-established but have limited adaptability.

**Figure 1. Vibration control of flexible beam structure [23].**



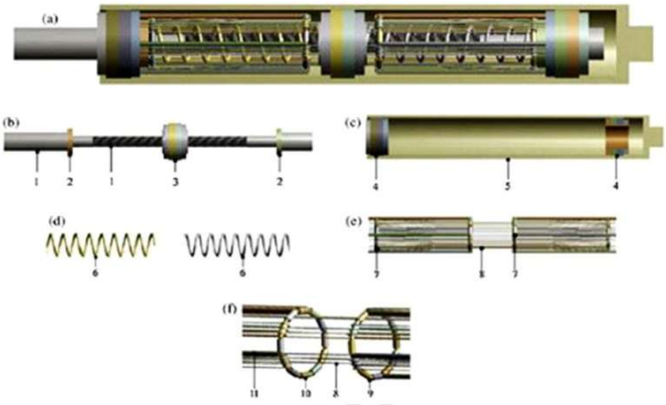
### *B. Active and Hybrid Control*

Active control systems rely on external power to operate actuators providing real-time control forces [8]. Examples include active mass dampers and tendon controls. Hybrid control combines passive and active mechanisms, inheriting limitations of both.

### *C. Semi-Active Control and Smart Materials*

Semi-active systems merge the best features of passive and active approaches with minimal energy requirements [13, 16]. Their success has driven the adoption of smart materials—including SMAs, piezoelectric, and magnetorheological materials—as the basis for next-generation vibration control devices [19].

**Figure 2. Schematic diagram of a building's SMA insulation system [13].**



## III. Shape Memory Alloys: Key Properties for Structural Application

### A. Damping Capacity

Damping capacity describes the ability of a material to absorb or suppress vibrational energy through dissipation of elastic strain energy [74]. In SMAs, damping arises primarily from high internal friction during martensitic transformation—energy loss due to movement between martensite variant interfaces and parent–martensite habit planes [41, 50].

### B. Energy Dissipation and Absorption

Energy dissipation capacity is the effectiveness with which a material redistributes externally induced energies to maintain structural stability [98]. SMA-based energy-dissipating devices are incorporated as braces, connectors, and retrofitting devices in civil structures [19].

## C. Re-Centering Ability

Re-centering ability describes the tendency of a material to return to its original geometry during excitation, preventing accumulation of inelastic deformations [68]. SMAs' superelastic behaviour enables structures to eliminate residual drifts after seismic loading, an advantage over conventional linear-elastic backup systems [13].

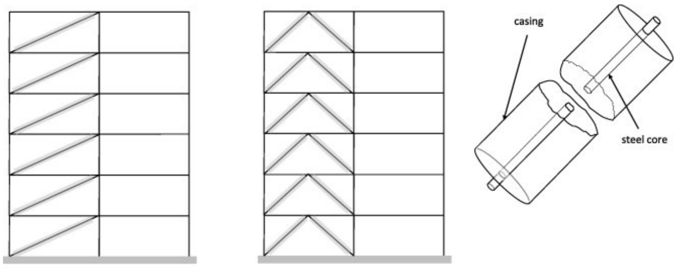
## IV. Low-Cost SMAs for Civil Structures: Cu and Fe Based Systems

### *A. Copper-Based SMAs*

Cu-based SMAs (principally Cu-Al-Be, Cu-Al-Mn, and Cu-Zn-Al) are considered the most practically attractive alternatives to NiTi because they are less expensive and easier to synthesise [8]. Their good ductility, damping characteristics, superelasticity, self-centering capability, and acceptable fatigue resistance make them suitable for structural applications [10, 92].

### A. a. Structural Braces

Cu-Al-Be SMA wires of 0.5 mm diameter have been successfully incorporated in bracings of a three-storey steel rigid frame model, providing effective passive damping [4]. The comparative cost advantage and acceptable superelasticity of Cu-based SMAs are expected to drive wider adoption in structural bracing systems.



(a) Protected building frames

(b) Detail of a device

### A. b. Seismic Isolation

The high energy dissipation capability, fatigue resistance, high stiffness, and superelasticity of Cu-Al-Be SMAs make them suitable for seismic isolation bearings [7, 9]. Combined NiTi and Cu-Al-Be SMA isolation bearings have demonstrated reduced earthquake damage on isolated highway bridges under moderate-to-strong ground accelerations [3].

### A. d. Damping Devices

Cu-based SMAs (Cu-Al-Mn, Cu-Al-Be) fulfil the primary functional requirements for passive vibration control devices [17]. Experimental studies confirm that CuAlBe dampers effectively reduce earthquake impact, dissipating approximately 50% of absorbed seismic energy with performance comparable to NiTi systems [20].

### A. e. Structural Connectors and RC Columns

Prototype partially restrained connections using Cu-Al-Be SMA bars demonstrated superelastic behaviour and moderate energy dissipation with no strength degradation after cycles up to 3% drift [17]. Cu-Al-Mn bars used as rebars in engineered cementitious composite (ECC) tube columns achieved 91% recovery of permanent deformation under simulated seismic loading [11].

### *B. Iron-Based SMAs*

Fe-based SMAs are low-cost alternatives with promising structural applications. Fe-Mn-Si is the most extensively explored Fe-based SMA for civil structures, valued for its temperature-independent stress-induced martensitic transformation [5].

### B. a. Prestressing and Tensioning Applications

Fe-Mn-Si SMA tendons, wires, and fibres are pre-tensioned, embedded in concrete members, and activated by resistive heating (100–160°C) to generate compressive prestress, improving structural strength [14]. Near Surface Mounted (NSM) and shotcrete techniques further improve bonding, durability, and loading capacity of Fe-SMA reinforced beams [18, 19].

### A. c. Advanced Fe-Based Alloys: FeNCATB and FeNiCoAlTaB

Newer Fe-based SMAs, including FeNCATB (13.5% superelastic strain) and FeNiCoAlTaB, demonstrate exceptional performance as reinforcements in RC bridge columns and restrainers in isolated bridge systems [10, 15]. FeNCATB-reinforced bridge piers outperformed all other SMA-RC bridge piers at all damage states [10]. FeNiCoAlTaB SMA wires in a double-cross arrangement around Lead Rubber Bearings improved re-centering capability by reducing maximum shear strain by up to 46% [28]. A recent experimental study published provides valuable new fundamental insights into the structural, magnetic, and electronic properties of metastable Fe–Cu solid solutions synthesised by mechanical alloying [22]. This study on metastable Fe–Cu alloys provides useful insights for low-cost shape memory alloy applications in structural vibration control. The alloy exhibits clear ferromagnetic behavior, with ZFC–FC divergence indicating magnetic clustering and defect-induced anisotropy from mechanical alloying. The combined magnetic and transport characteristics highlight the role of defects, microstructure, and electron interactions, which are critical factors in tailoring Fe-based alloys for smart damping and vibration mitigation in civil infrastructure.[22]

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## V. Comparative Summary of SMA Systems

| Property | NiTi SMAs | Cu-Based SMAs | Fe-Based SMAs |
|---|---|---|---|
| **Shape Recovery** | ~8% | ~5% | ~4% |
| **Damping Capacity** | High | High | Moderate |
| **Superelasticity** | Excellent | Good | Moderate–Good |
| **Processing Cost** | High (vacuum melting) | Low–Moderate (casting/milling) | Low (milling / casting) |
| **Corrosion Resistance** | Excellent | Good | Moderate |
| **Primary Civil Application** | Isolation, braces, dampers | Braces, connectors, isolation | Prestressing, RC reinforcemen |

| Property | NiTi SMAs | Cu-Based SMAs | Fe-Based SMAs |
|---|---|---|---|
| | | | t |
| **Magnetic Behaviour** | Non-magnetic | Non-magnetic | Ferromagnetic (γ→α Fe) [22] |
| **Defect Sensitivity** | Low–moderate | Moderate | High — $\rho_0$ affected by milling [22] |
| | | | |

## VI. Conclusion

This review confirms the great promise of Cu- and Fe-based SMAs for structural vibration control in civil structures. The following conclusions are drawn: Cu-based SMAs (particularly Cu-Al-Be and Cu-Al-Mn) deliver damping and energy dissipation performance comparable to NiTi at significantly lower costs, making them ideal for developing nations in seismically active regions. Fe-Mn-Si SMAs excel in prestressing and tensioning applications for RC structures, while newer Fe-based systems (FeNCATB, FeNiCoAlTaB) demonstrate outstanding super elastic strains and re-centering capabilities for bridge columns and isolation systems. Adoption of low-cost SMAs in structural design codes for seismic-prone regions is both technically feasible and economically justified; large-scale experimental validation and standardized processing protocols are recommended to accelerate this integration.

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