# Sustainable Structural Damping through Smart Shape Memory Alloy Systems

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**Abstract.** Advancements in structural engineering for effective vibration control is focusing significantly on smart technologies. Owing to unique properties like super elasticity and energy dissipation capability, smart materials are now becoming one of the primary choices of the engineering community for damping. Although considerable research has been carried out to control earthquake induced vibrations, less attention is given towards vibrations resulting from underground blasts. Such blast-induced ground motions (BIGM) are characterized by high-frequency, large-amplitude short duration impulse waves, which differ from earthquake-induced ground motions. The current study proposes a complete overview of non-linear (hysteretic) behaviour of SMAs and the nature of underground BIGM. The various sustainable aspects of SMA as a damper is also highlighted. A simulation-based analysis is performed on a double-storeyed steel frame installed with SMA wire bracings of varying configurations (diagonal, K-type and concentric type). The structural response is obtained for varying blast distances from the charge center and intensity. The peak response (with SMA damping devices), uncontrolled bare frame and installed with tradition steel bracing is illustrated. The study highlights the potential application of SMA bracings as a sustainable damping device in mitigating the structural response.

**Keywords:** SMAs, underground blasts, impulse, sustainable

## 1 Introduction

Underground mining operations and blast-intensive construction activities pose significant risk to adjoining structures from underground blast loads. Such ground motions possess unique characteristics including large-amplitude, high-frequency waves behaving like short duration impulse load. BIGM is different from earthquake ground motions in terms of amplitude, duration and frequency content. Hence, special mitigation strategies beyond the conventional seismic design methods become very necessary. In this context, smart material technologies have become a very promising aspect. SMAs are a prominent class of smart materials which provide several unique mechanical and thermal properties which make them extremely suitable as vibration control devices. SMAs possess two main characteristics, i.e., the shape memory effect (SME) and super elasticity. SME enables the SMA to regain its original configuration

R. Mehta et al. (eds.), *Proceedings of the International Conference on Infrastructure Development and Sustainability (ICIDS 2025)*, Atlantis Highlights in Sustainable Development 9,
https://doi.org/10.2991/978-94-6239-685-2_28

after deformation through thermal activation. On the other hand, super elasticity enables it to recover from large strains at a constant temperature owing to stress-induced phase transformation.

Nitinol (Ni-Ti) is the most commonly used SMA owing to its superior thermo-mechanical properties. Excellent re-centering capability, large energy dissipation, high strength, corrosion resistance and fatigue endurance are some of the remarkable material behaviours which make them suitable for advanced vibration control applications. [1] explored the applications of SMAs for seismic isolation. [2] have demonstrated substantial promise of SMAs in seismic applications. [3] has shown encouraging results, particularly in improving structural resilience and reducing residual displacements under earthquake loading. Several seismic applications of SMAs were reviewed by [4]. However, in spite of their suitable applications in seismic retrofitting and damping applications, the use of SMAs in mitigating BIGMs remain highly unexplored. There is only a limited number of studies related to full scale blast tests or field demonstrations to establish the device performance and actual reduction in ground motion owing to BIGM. SMA devices designed for seismic applications focus mainly on cyclic hysteresis and self-centering recovery. On the other hand, in BIGM applications SMA devices need to perform under extremely rapid loading with high strain-rate domination. Impulse mitigation and filtering of shock are the two main aspects of BIGM whereas residual drift control and energy dissipation are being prioritized in seismic applications. Typically, lesser materials by weight are utilized by SMAs and hence it offers stable hysteretic performance and thus contributes to reduced functional environmental impact per unit mass over time. Performance indicators such as reduction in residual drift, damage minimization and extension in the service life also enhances the sustainability claim of SMAs. The re-centering capability of SMAs significantly reduces repair volumes, demolition waste and downtime after occurrence of extreme events. In this context, the current study explores the applicability of SMA as a sustainable damping device due to BIGM on framed structures. Akin to the previous study by the author [5] where SMA was explored as a damping device for diagonal and X-bracing configuration, the current work aims to investigate the application of SMA in mitigating structural response for other different type of bracing configurations such as K-type and concentric type subjected to BIGM.

## 2 SMA as a sustainable damping device

SMA as a damping device aligns well with the principles of sustainable engineering. It contributes to long-term resilience and also minimizes environmental footprint which is mainly associated with structural damage, repair and rehabilitation. Excellent fatigue performance of SMAs make them suitable for long-term applications which leads to lesser replacements or maintenance. Nitinol SMA also maintain their functionality and integrity in harsh marine environment, thus reducing the need for protective coatings or replacement. After experiencing large deformations during an earthquake event, SMA dampers can regain their original configuration, eliminating the residual displacements which are common with traditional systems which lead to a reduced post-event repair cost. SMA damping devices also function passively without any external power source. These smart materials are also capable of reducing the lifecycle emissions associated with repairs and material waste. The non-zero operational energy requirement and high durability of SMAs play a pivotal role in the long-term economic benefit and result in a reduced lifecycle energy consumption when compared to traditional steel and other viscous dampers. Recent studies have also shown that SMA devices can curb damage while recentering multi-story frames.

# 3 Formulation and Methodology

A simulation study which demonstrates the impact of BIGM on a double-storied steel structural frame using a finite element (FE) model is carried out. The blast load is modelled as a time-domain exponential function characterized by parameters like TNT charge weight (Q), distance from the charge center (R), wave velocity ($C_p$) and chamber volume (V) which influences the resulting ground acceleration. The frame employed in the study features a compact steel structure braced with both traditional steel and SMA dampers [2]. Such damping devices (both steel and Ni-Ti SMA) are installed in the form of different bracing configurations as shown in Figure 1 with clamped or fixed boundary conditions.

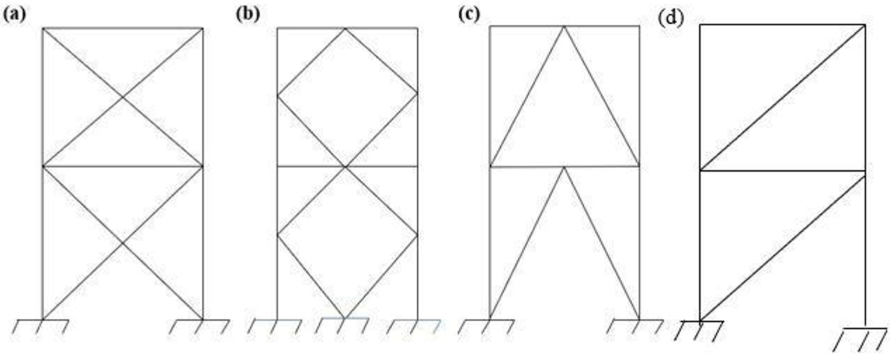

**Fig. 1.** Different bracing configurations of SMAs (a) X-type, (b) K-type and (c) concentric and (d) diagonal

The results clearly indicate that nonlinear modelling of SMA provides a more reliable reflection of its actual performance in blast mitigation.

The BIGM model, proposed by Carvalho and Battista (2003) is adopted in the current study as shown in Equation 1.

$$\dot{u}_g(t) = -\left(1/t_d\right) PPV^s e^{\left(-1/t_d\right)} \tag{1}$$

where $t_d$ is the time of arrival and $C_p$ is the wave velocity while propagating through rock. The average empirical attenuation relation for peak particle velocity $PPV^s$ on the ground surface is shown in equation 2 where $f_1^s$ is the decoupling factor for $R$ and $Q$ .

$$PPV^s = 2.981 f_1^s \left(R/Q^{0.33}\right)^{-1.3375} \tag{2}$$

An explicit model setup is also illustrated in Figure 2 with X-type bracing configuration employing Nitinol (Ni-Ti) damping device.

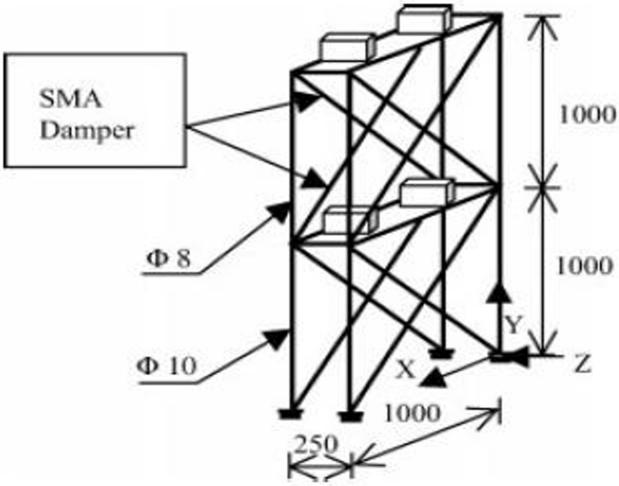

**Fig. 2.** Double storied frame (all dimensions are in mm)

The time history for ground acceleration is derived using key parameters such as R, Q, $C_p$ and V. The distance from the explosion center is varied and results are compared among three different configurations: installed with SMA dampers, steel bracings (1 mm and 0.8 mm) and uncontrolled bare frame.

The framed structure is subjected to BIGMs for R = 50m and 100m respectively with V=1000 $m^3$, $C_p$ = 5280 meter per second and Q=10 and 100 tons. Variation of input ground accelerations with time for varying R and Q is shown in Figure 3.

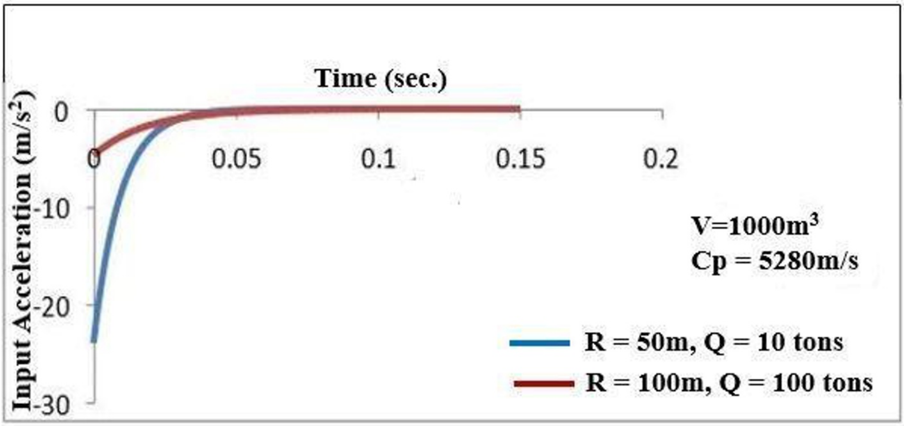

**Fig. 3.** Ground acceleration (input) versus time for (i) R = 50m, Q = 10 tons, (ii) R = 100m, Q=100tons with V=1000 $m^3$ and $C_P$= 5280 m/s.

The different mechanical properties of Nitinol considered in the study are density (ρ) = 6500 6500kg/$m^3$, Poisson's ratio (υ) = 0.33 and modulus of elasticity (E) = $62 \times 10^9$ N/$m^2$. SMA wire bracing of diameter 1mm and 0.8mm are adopted. The frame is 1m X 0.25m X 2m in dimension with diagonal bracing configuration of SMA dampers as shown in Figure 4.

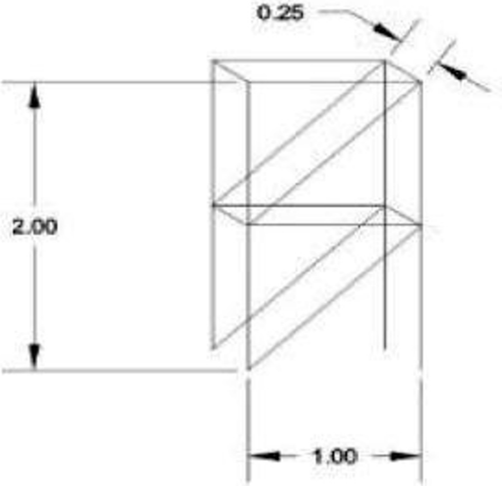

**Fig. 4.** Frame installed with SMA damper as diagonal bracing (unit; m)

The upper and the lower story in the frame comprises of circular columns and floor beams of 8mm and 10mm diameter respectively.

## 4 Non-Linear Hysteresis

A tension-only model for SMA is developed in 1D to accurately simulate the non-linear hysteretic behavior within the ANSYS material library [6] as shown in Figure 4. It is able to capture the typical force-deformation behaviour of super elastic SMAs under constant temperature conditions.

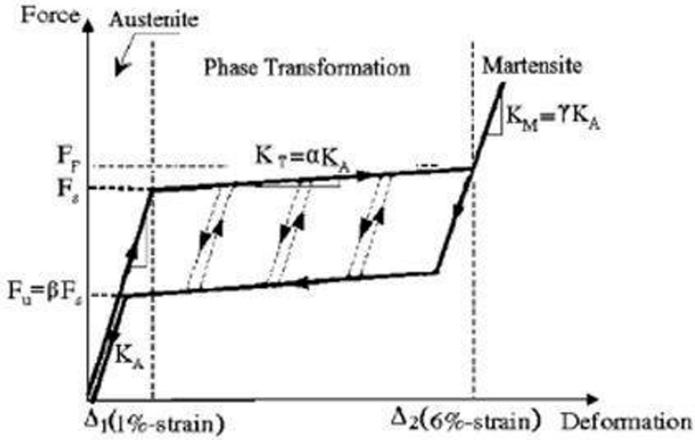

**Fig. 5.** Non-linear hysteretic behaviour of SMA under constant temperature

The time histories (for displacement) are illustrated through Figures 6.a – 6.c for R = 100m and Q = 100 tons

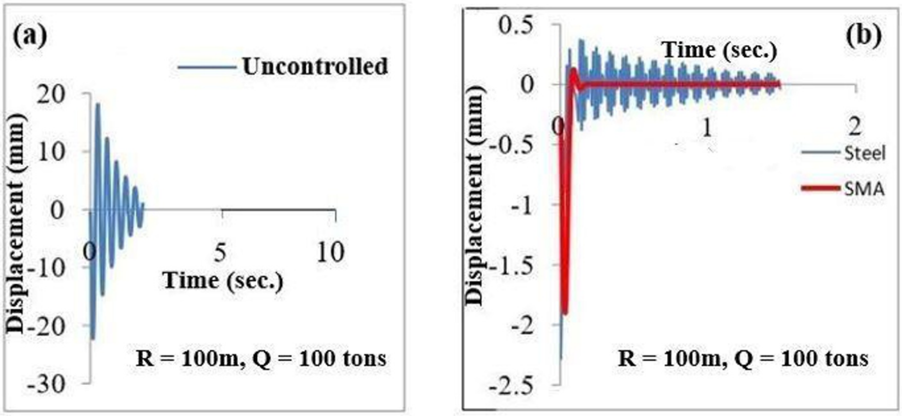

**Fig. 6.** Time history (displacement response) for (a) frame (without damper) and (b) frame with steel and SMA damper installed as diagonal bracing for R = 100 m and Q = 100 tons.

A parametric study showing the peak displacement responses for various bracing configurations are shown in Table 1.

**Table 1.** Peak response (displacement) for the frame installed with conventional steel and SMA dampers as different bracing configurations (R = 50 m, Q = 50 tons)

| Type of bracing | R (m) | Q (tons) | Peak displacement in mm (steel bracings) | Peak displacement in mm (SMA bracings) |
|---|---|---|---|---|
| Diagonal | 50 | 50 | 11.23 | 0.7 |
| X-type | 50 | 50 | 3.5 | 0.0031 |
| K-type | 50 | 50 | 5.56 | 0.081 |
| Concentric | 50 | 50 | 7.9 | 0.087 |

Significant improvement in peak response reduction is observed in case of SMA dampers over the conventional steel bracings. Amongst all the configurations, it is observed that when Ni-Ti SMA dampers are installed as X-type bracing configuration, the structure performs the best in terms of peak response (displacement) reduction.

## 5 Conclusion

Nitinol based SMAs have emerged as promising damping devices owing to their unique ability to dissipate energy. From sustainability point of view, SMAs are advantageous since they offer high recoverable strain (nearly up to 8%) and require nominal maintenance. SMAs possess immense applications in seismic mitigation of framed structures and vibration control of aerospace structures. Durability and fatigue resistance make the SMAs cost-effective over the entire structural life span. The study highlights the potential of Ni-Ti based SMA dampers in reducing structural vibrations due to BIGM. Framed structures installed with SMA dampers experience significantly reduced vibrations compared to both uncontrolled frames and those with ordinary steel bracing. The damper performance for various bracing configurations is also demonstrated. The SMA dampers offer a superior damping response over the conventional steel braces. Such observations establish the promising potential of such smart materials as damping devices for designing blast-resistant structures when installed judiciously and efficiently.

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