Experimental Design of Bistable Meta-panel for Dynamic Investigation

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Experimental Design of Bistable Meta-panel for Dynamic Investigation

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Abstract – Bistable metamaterials offer a promising solution for vibration mitigation in structural systems. This research presents the conceptualization of the experiments for a bistable meta-panel, which uses geometric nonlinearity and snap-through instability to enhance energy absorption and dissipation. A scaled prototype, produced via additive manufacturing, undergoes static and dynamic testing to assess its response. This work provides a foundation for further development of meta-material-based seismic protection systems.

I. Overview and Conceptualization of the Experiment

Civil structures are inherently at risk due to their location in hazard-prone areas, with seismic activity being a significant challenge to structural safety. To mitigate seismic risk, strategies focus on reducing structural vulnerability, either by base isolation or enhancing its ability to dissipate and absorb energy [1]. While dissipation involves hysteresis, plasticity, or viscous behaviours to dissipate energy through material properties, absorption utilizes deformation mechanisms to extract energy from the system. A common example is the tuned mass damper (TMD) [2], which uses a mass connected to the structure to absorb energy and reduce displacement amplitudes. TMDs are typically tuned to specific vibrational modes of the structure and, when incorporating nonlinear components, they are also known as nonlinear energy sinks [3]. To address challenges like mass and installation space, innovative behaviours such as snap-through instability [4] can be explored, offering a promising approach to passive energy absorption.

In this phenomenon, an instantaneous change in the position of a specific body occurs, resulting in a very high velocity. This high-velocity motion enables the use of smaller masses, allowing the TMD concept to be applied to more compact and easily installable systems, such as systems mounted on building walls instead of on the top of the building. This introduces the concept of *bistable elements*, systems capable of maintaining two stable structural positions and transitioning between them through a snap-through instability mechanism. It is important to emphasize that for a bistable element to function as intended, the system must retain its dual stability characteristics even after the snap-through event [5] to be classified as bistable element. Therefore, while snap-through is a necessary condition for bi-stability, it is not a sufficient one.

Several studies explore the parameters that determine whether bistable systems exhibit true bistability or a monostable snap-through transition. To simulate such behaviour, different methods have been proposed, including the use of plates, beams, or triply periodic minimal surface (TPMS) systems [6]. These approaches leverage metamaterial principles—using geometry and structural design rather than material composition—to achieve unique properties. By tuning geometry, meta-structures can exhibit features like *(i)* negative (apparent) elastic modulus, useful for wave control, energy absorption, and vibration damping; *(ii)* negative Poisson's ratio, beneficial for impact protection; *(iii)* other special properties, such as negative effective mass. Regarding meta-systems with a negative elastic modulus, one promising solution for vibration absorption and dissipation, involves beam-based systems with various geometric configurations [7], such as curved, tilted, and arched designs. Fig. 1 illustrates the geometric configurations of various systems used to achieve bistable behaviour.

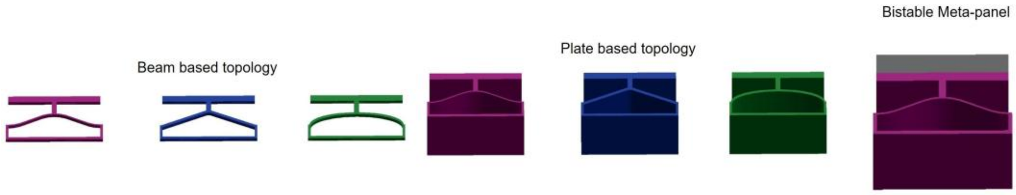


Fig. 1 Metamaterials solutions for energy absorbing.

This study explores the potential of using meta-panels designed as *cosine-shaped plates* (CSP) connected to a vibrating mass. The goal is to use interwell vibrations (oscillations between the two stable states) to absorb and dissipate energy from the structural system. The dissipation occurs through viscous effects, driven by the high velocity during the snap-through phenomenon, while absorption occurs because the meta-panel needs energy to pass from one stable point to the other. This reduces vibration amplitudes and lowers structural vulnerability.

To achieve this, an optimal design study of these meta-panels is necessary to prepare them for experimental testing. The first step involves defining key design parameters, such as plate thickness t, span L, length b, deflection height of the CSP h, Young's modulus E, and crucially, the vibrating mass m, which plays a fundamental role in determining the panel vibrational properties. Following an optimisation process guided by energy dissipation performance, the selected parameters are $h = 0.03$ m, $t = 0.001$ m, $L = 0.5$ m, $b = 3.0$ m, $E = 2.1\text{x}10^{11}$ Pa, and $m = 9.83$ kg. To simulate the meta-panel in a scaled version and explore its behaviour in an efficient way, a decision was made to create a sample of the selected meta-panel using 3D printing technology. The Bambu Lab X1 Carbon printer was used for this purpose, and the material selected for printing was PLA. The tested sample features the following geometry: h of 0.005 m, t of 0.001 m, L of 0.09 m, $b = 0.02$ m, E of $2.8\text{x}10^{9}$ Pa, and m varying between $47\text{x}10^{-3}$ kg and $71\text{x}10^{-3}$ kg.

In preparing the testing setup, several challenges arise related to observing the bistable behaviour. Specifically, it is not possible to directly observe the vibrations of the meta-panel using contact sensors, as the sensor mass or the rigidity of the wiring could interfere with the dynamic behaviour of the meta-panel. To avoid resonance with modes of vibration other than the first translational mode of the meta-panel, it was decided to concentrate the mass at the centre of the plate. This is particularly useful to eliminate the possibility of the mass remaining stationary in its stable position during a rolling motion around its centre of mass. To prevent the plate supports from rotating, which could compromise the bistable behaviour, a support structure made of aluminium was designed to ensure an infinitely rigid constraint in the horizontal direction. Then, to prevent impact between the CSP and the rigid support, the height of the rigid walls was not assumed equal to h, but it was increased of a specific quantity designed with numerical simulations. The force application is carried out through an electromagnetic actuator, which directly applies force to the vibrating mass. Displacement is measured using position-sensitive detectors (PSDs) that detect the laser beam incident on the mass, enabling precise tracking of movement. Force control and displacement measurements allow detection of the force jump caused by the snap-through phenomenon. Fig. 2 displays the scaled meta-panel and the experimental setup used.

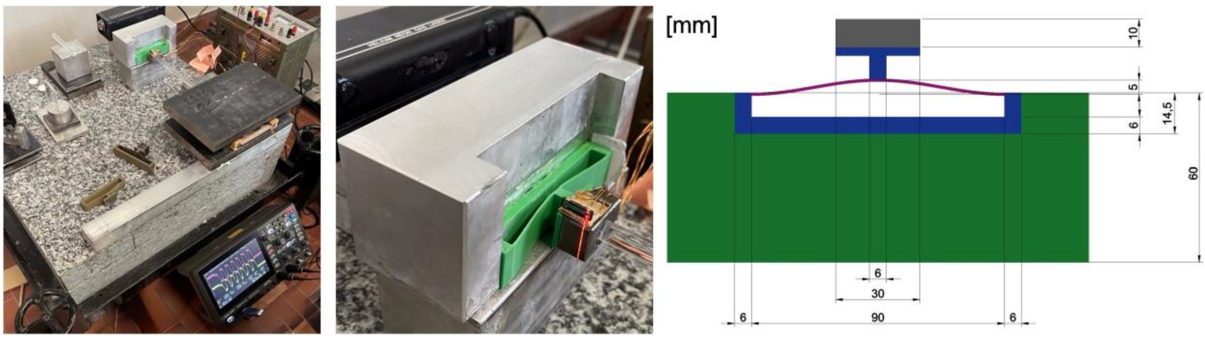
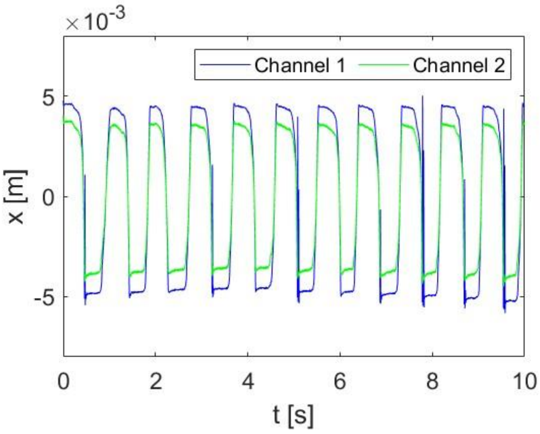


Fig. 2 Scaled meta-panel and the experimental setup employed for the experimental campaign.

Fig. 3 presents two response recordings of the bistable device. Two channels are employed to capture both the interwell/intrawell dynamic regimes and to detect any parasitic effects occurring during the mass vibration. To achieve this, two PSDs were used and installed at the two edges of the vibrating mass.



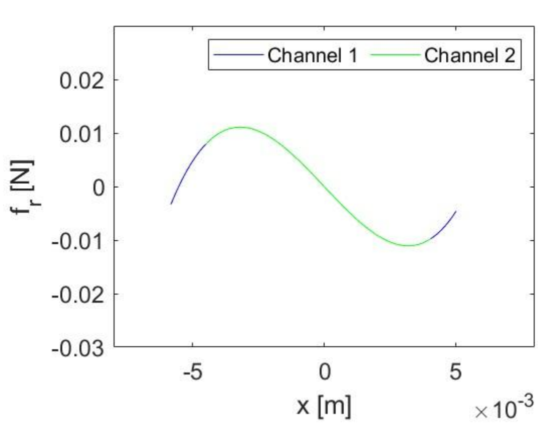


Fig. 3 Interwell response x [m] captured with the proposed experimental setup on the left and restoring force f_r [N] with respect to x [m] on the right.

II. Conclusion

The concept of the meta-panel presents a promising and innovative approach to energy absorption and dissipation, with the potential to significantly enhance the performance of structural systems. This study represents an initial step in the dynamic characterization of the meta-panel. The scaled experiments conducted provide valuable insights into its behaviour, serving as a foundational exploration for further development. Alongside numerical simulations, these results will inform the design of full-scale meta-panels, which will be tested and potentially integrated into existing structures. This work sets the stage for future advancements in seismic energy management, offering a novel solution to reduce the seismic vulnerability of civil structures.

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