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Seismic Retrofit

SPOKE 4 – Reactivation of wood value chain for construction and innovation in modular systems for energy and seismic retrofit

DELIVERABLE DN. 20

Version history

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Glossary

	Definition
Hub Coordinator (HC)	The Hub Coordinator represents the single point of contact for the implementation of the innovation ecosystem towards the MUR. It carries out the management and coordination activities of the innovation ecosystem, receives the fundings, verifies, and transmits to the MUR the reporting of the activities carried out by the Spoke and their affiliates.
National Recovery and Resilience Plan (NRRP)	This document uses the Italian acronym for the NRRP, which is PNRR (Piano Nazionale della Ripresa e Resilienza)
Research Program Manager	The person who will be the responsible for the overall scientific contents of the NODES project. The NODES will appoint the Research Program Manager. It refers to “Responsabile del Programma di Ricerca” in the MUR’s Call of proposal for “Ecosistemi di Innovazione”
NODES’ Research and innovation program	NODES’ Research and Innovation program is articulated in specific programs for each Spoke, with the aim to promote and support applied research on topics consistent with the Intelligent Specialization Strategy, with the guidelines of the 2021-2027 partnership agreement scheme, with regional operational plans and regional and national research and innovation priorities. Although NODES’ Spokes are concentrated on different themes, they will organize their activities and actions within a common framework – NODES’ Booster Methodoloy
Spoke Coordinator	The University in charge of coordinating the Spoke’s ecosystem. It refers to “Spoke” in the MUR’s Call of proposal for “Ecosistemi di Innovazione”
Spoke Data Manager	The person who will be the responsible for the monitoring and management of data generated at the Spoke level. The Spoke Coordinator will appoint the Spoke Data Manager.
Spoke Partner	The entity associated to the Spoke Coordinator. It can be an Innovation Cluster, Competence Center, Research Center related to the Spoke’s ecosystem and contributes to achieve objectives and impact under the Spoke’ leadership and management. It refers to “soggetti affiliati” in the MUR’s Call of proposal for “Ecosistemi di Innovazione”.
Spoke Project manager	The person who will be the responsible for the management, coordination and progress of the project at the Spoke level. The Spoke Coordinator will appoint the Spoke Project Manager.
Spoke research and innovation program	NODES’ Research and Innovation program is articulated in specific programs for each Spokes. The spoke will leverage a consolidated collaboration with leading private and public companies and will focus the applied research activity on technological domains and applications that can favour the integration of SMEs into new value chains.
Spoke Scientific and Technical Manager	The person who will be the responsible for the overall scientific contents of the project at the Spoke level. The Spoke Coordinator will appoint the Spoke Scientific and Technical Manager.
Spoke Stakeholders Committee (SC)	Consultation structure formed by relevant stakeholders (Government, universities, companies, civil society, third sector, etc.)
Spoke Thematic	General target focus and domain of the Spoke research.
Spoke Topics	Specific areas/lines of development within the Spoke.
Spoke Work Package Leader	At the Spoke level, Work Packages (WPs) will be organized by WP leaders, who will be responsible for performance evaluation and reporting.

Flagship Project	Main research project at the Spoke level with the goal of prototyping, testing, demonstrating the research activities towards higher TRLs.

EXECUTIVE SUMMARY

The research on energy and seismic construction and retrofit plans the demonstration of offsite retrofit elements. The demonstrators and prototypes set medium to high TRL for either tests in real environments or in controlled ones with interfaces for continuous monitoring.

Task 4.4. Seismic retrofit.

A deep transformation of the building retrofit sector and the concept of building renovation is driven by metamaterial technology. That can support EU's and National's ambitious environmental sustainability targets. The Tasks 4.4 and 4.5 have addressed the following goals:

- drive the innovation in seismic+energy retrofit solution by means of wooden-based components;
- develop the analysis of structural-seismic capabilities;
- develop the assessment of the expected safety levels for the case-project in Aosta, Casa Benedino;
- adapt the solutions so that they deal and preserve local architectures and heritage buildings;
- bring EDMP technology to the market, pursuing the model of collaborative project delivery with industries.

A) Energy-dissipating meta-panel (EDMP)

Mechanical metamaterials with negative stiffness are effective tools for dissipating elastic energy. This is achieved through the activation of a snap-through mechanism and bistability. Specifically, energy absorption arises from the oscillation of the metamaterial between its two stable static configurations when subjected to dynamic loading. Such mechanisms can be obtained by optimizing the geometry of the metamaterial.

In light of these recent developments, an analysis has been initiated to assess the feasibility of creating a meta-panel that can be applied to existing buildings to achieve integrated seismic and energy retrofitting. The term *meta-panel* refers to a panel composed of a vibrating mass and an inner layer characterized by a geometry that exhibits two stable equilibrium configurations. Therefore, the meta-panel can dissipate seismic energy through two mechanisms: (i) oscillation of the vibrating mass positioned as the outermost layer of the meta-panel, leveraging the *tuned mass damper* effect, and (ii) oscillation of the meta-layer between its two stable static configurations.

The stratigraphy of the meta-panel is shown in Fig. 1. A thin wooden panel is used to connect the meta-panel to the existing structure, followed by the meta-layer, which consists of one or more sinusoidal beams, and is in turn connected to the vibrating mass. To achieve both seismic and energy retrofitting, the vibrating mass is composed of two layers: (i) a 3-layer XLAM wooden panel (5.7 cm) and (ii) a 10 cm layer of rock wool to ensure thermal insulation.

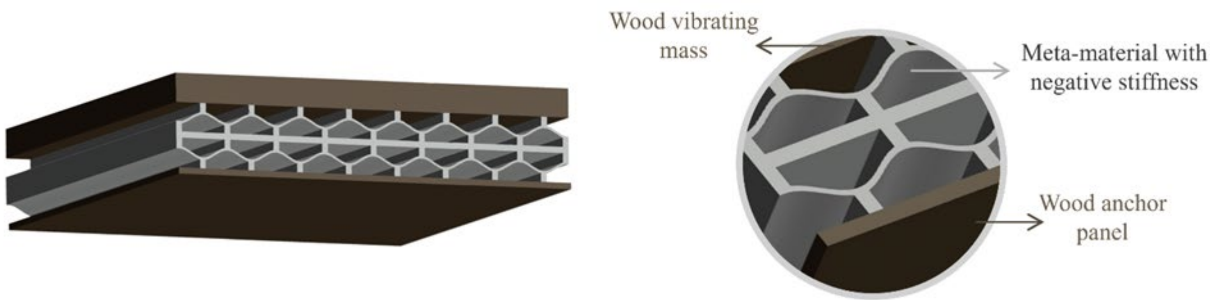

Figure 1

To study the meta-panel and define its optimal geometry, it was necessary to develop a parametric study. A single strip of the meta-panel was modelled as a bistable oscillator, as shown in Fig. 2.

Initially, the geometry of the sinusoidal beam was defined, which can be described by the following equation:

$$y = h/2(1 + \cos(2\pi l/L))\; l \,\epsilon\, [-L/2, L/2]$$

where h/2 represents the amplitude of the sinusoid and L is the span of the sinusoid.

Next, a bistable oscillator was modelled, composed of two inclined springs with properties representative of the two sinusoidal portions of length l_0. This bistable oscillator is governed by the following equation:

$$m\ddot{x} + c\dot{x} + k_1 x + k_3 x^3 = -m\ddot{u}_g$$

where m is the vibrating mass, c the linear damping, k1 and k3 the negative linear and positive nonlinear contributions to the stiffness of the system, respectively, and $m\ddot{u}_g$ the external excitation applied to the system.

The force-displacement profile of the oscillator, symmetric and bistable, is given by:

$$F = k_1 x + k_3 x^3$$

where:

$$k_1 = 2k(1 - (2l_0)/L) < 0$$

$$k_3 = (8kl_0)/L^3 > 0$$

The stiffness k of the sinusoidal portion of length l_0 is given by:

$$k = EI = (Ebt^3)/12$$

where b is the length of the panel strip and t the thickness of the sinusoidal beam.

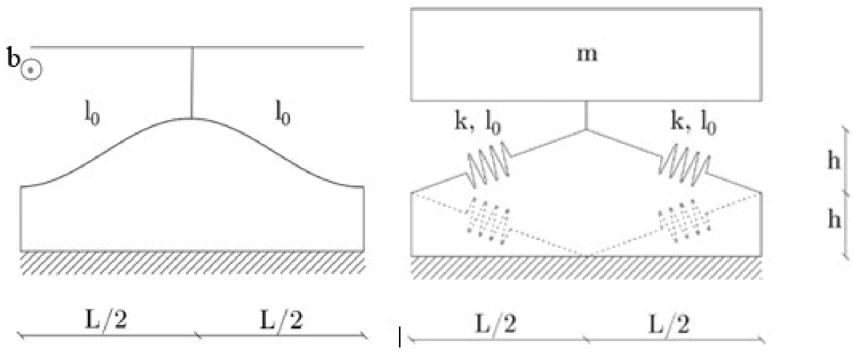

Figure 2

B) Finite Element Simulations

In this section, the modelling process of the device is described. The device is designed to optimally respond to dynamic loads, such as those induced by seismic events. The system consists of a sinusoidal steel panel coupled with an XLAM wooden panel.

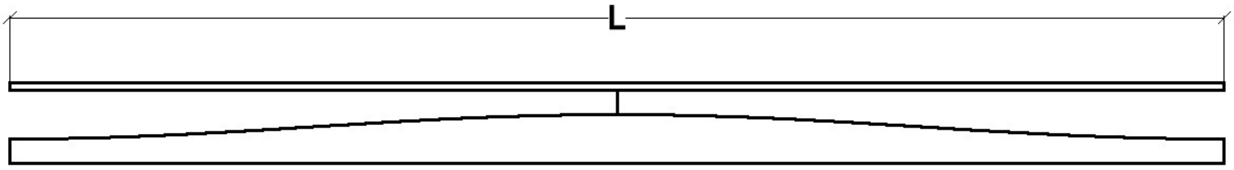

Figure 3

Table 1

Table 1. Geometric Values		
Parameters	Numerical Value	Units
Width L	20-50-100	cm
Height h	2	cm
Thickness XLAM	5.7	cm
Thickness t	1	mm
Length b	3	m

The selection of materials for the device was made considering the requirements of stability, mechanical strength, and energy dissipation capacity necessary for the proper functioning of the device in seismic contexts.

Below are the materials and the corresponding mechanical properties considered in the modelling:

1. For the vibrating mass, an XLAM wooden panel was considered with the following properties:

E=11000 N/mm2

ν=0.3

γ=600 kg/m3

2. For the sinusoidal panel and the connecting walls, steel was considered with the following properties:

E=210000N/mm2

ν=0.3

γ=7850kg/m3

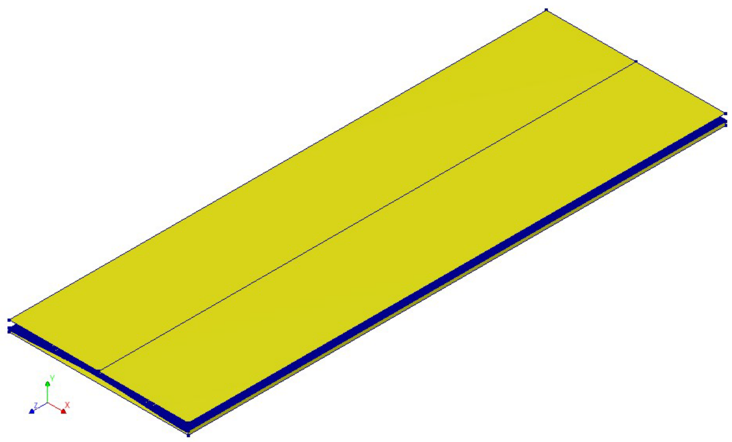

Figure 4

The nonlinear dynamic analyses were conducted using as input the recording of the 1940 El Centro earthquake.

The parametric analysis of the device yielded positive results, highlighting clear bistability for a geometry characterized by the values presented in Table 1, with a panel width L of 100 cm.

In the figure below, the time-displacement plot for the node connecting the XLAM panel with the sinusoidal panel is shown.

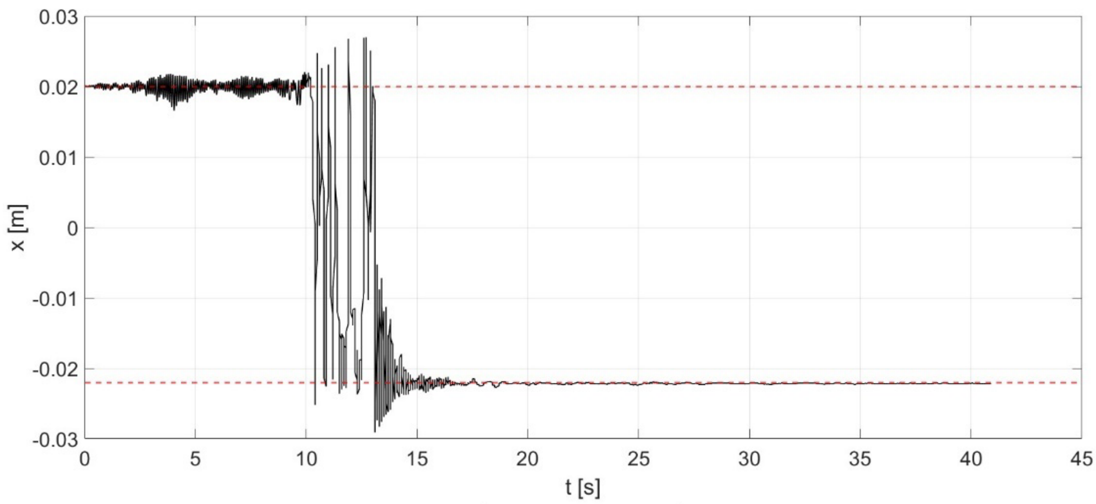

Figure 5

The plot illustrates the dynamic behavior of the device in terms of displacement x over time t, highlighting the presence of two distinct equilibrium states: one at x = 0.02 m and the other at x=−0.02m, which are typical of a bistable system. Specifically, during the first ten seconds, the device oscillates around the initial equilibrium position of 0.02m, showing small-amplitude oscillations known as intrawells. These reduced-amplitude oscillations reflect the device's ability to maintain a stable configuration.

After the first ten seconds, the graph shows a rapid shift to the other equilibrium state, located at −0.02m. This jump, characteristic of bistable systems, indicates that the energy accumulated, or the force applied to the system has reached a critical threshold, sufficient to overcome the barrier separating the two equilibrium states. Subsequently, the system exhibits oscillations between the two equilibrium states.

Finally, a gradual attenuation of the oscillations is observed, indicating that the system is stabilizing around the second equilibrium state at −0.02m. The ability of the device to settle in this new equilibrium position, without returning to the initial point, demonstrates that the system can indefinitely maintain this stable configuration until a force is applied again to reverse the process.

This bistable behavior offers significant advantages in practical applications. The ability to alternate between two stable equilibrium states makes the device ideal for systems requiring seismic isolation or damping, as it can quickly adapt to changes in external conditions and absorb the energy from seismic stresses. Moreover, the distance between the two equilibrium states provides a measure of the energy required to trigger the transition, a critical parameter for defining the device's performance in practical contexts.

In summary, the plot not only confirms the presence of bistability but also highlights the device's effectiveness in maintaining stability in two distinct positions, offering great potential for energy control and dissipation in structural applications.

To optimize the bistable behavior of the device, an analysis of the geometry was necessary. The figure below shows a plot of three different geometrical configurations that were analyzed. It is evident that bistability occurs only for values of L equal to 100 cm. For values smaller than the optimal size, the displacements oscillate around the first equilibrium position at x=0.02 m.

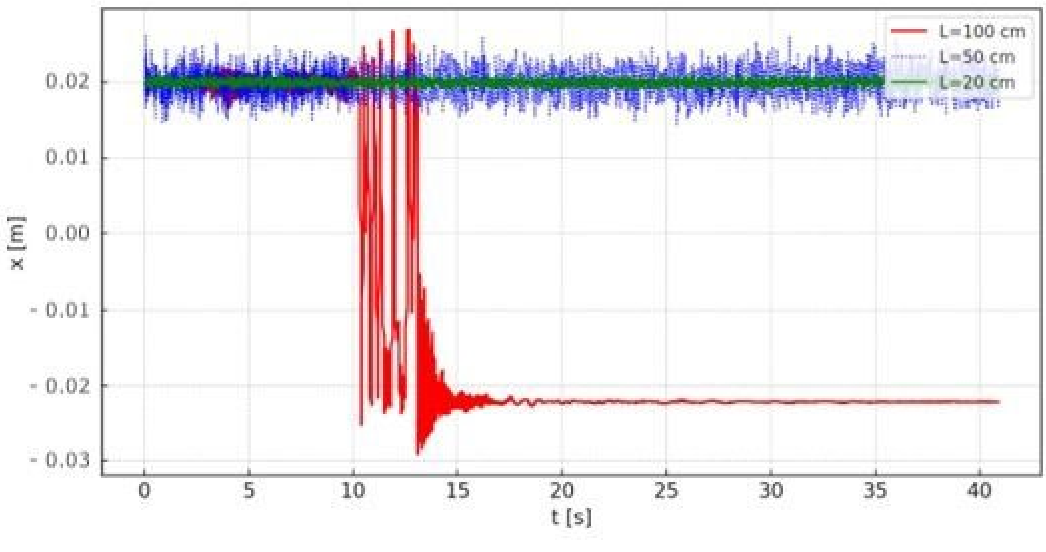

Figure 6

The same results are highlighted in the Force-Displacement diagram shown below. The diagram exhibits a nonlinear curve, indicative of nonlinear and bistable behavior. This type of response suggests that the system possesses significant nonlinear characteristics.

The shape of the graph, with loops, indicates the presence of hysteresis cycles. This behavior is typical of bistable systems that can oscillate between two equilibrium states. In other words, the system can have two stable states and requires a sufficient amount of energy to transition from one state to the other.

The hysteresis cycles also imply that the system dissipates energy during each loading-unloading cycle. The presence of loops indicates that, during loading and unloading, the system does not follow the same force-displacement path, leading to energy dissipation in the form of heat or deformation.

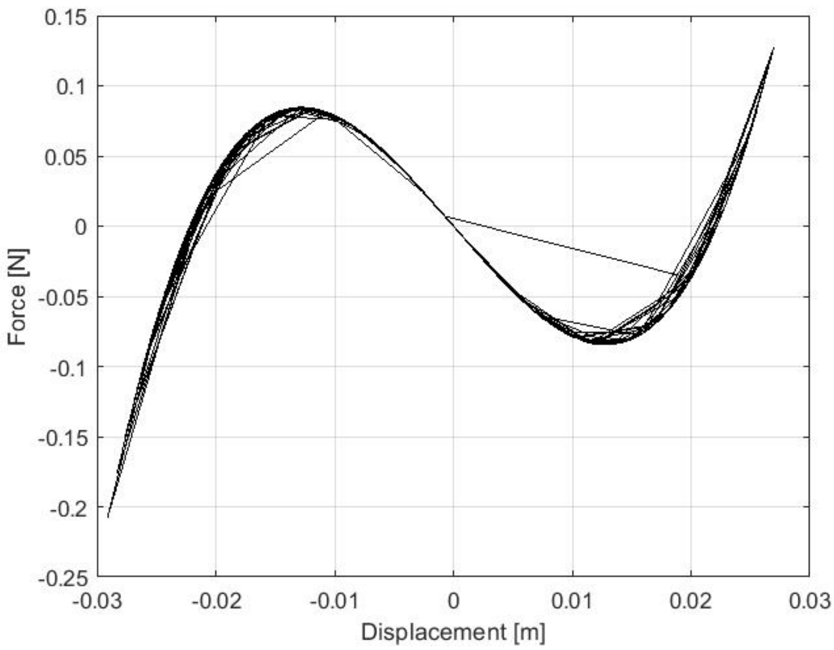

Figure 7

C) Application of the EDMP to an existing building

Current Condition

Casa Benedino is a building located in the city of Aosta, granted on loan to the Region of Valle d'Aosta. It is managed by the Caritas Diocesana of Aosta and serves as a fundamental shelter facility. This dormitory offers a comprehensive service that includes overnight accommodation, dinner, and breakfast, providing a safe and comfortable refuge for those in need.

Currently, the structure has eight rooms available for guests to rest and shared bathrooms, carefully maintained to ensure hygiene and comfort. The building, comprising one basement and two above-ground floors, offers a net usable area of approximately 70 m^2 per floor, excluding walls, staircases, and elevator space. It underwent a conservative restoration, and various structural reinforcements carried out in 1996/97. The structure features floors made of steel beams and clay bricks, filled with mixed mortar and blast furnace slag. The load-bearing walls are 40 cm thick brick masonry, while the spine wall is 25 cm thick brick masonry.

Figure 8

Modelling in DIANA FEA

The building, constructed in masonry, exhibits the typical seismic vulnerabilities of historical buildings in the region.

To address this, a global model of the building was created using the DIANA FEA software, on which a modal analysis was conducted to identify the modes of vibration and natural frequencies of the structure.

In parallel, local models were developed to study in detail the interaction between the masonry wall panel and the bistable panel, composed of a wooden layer preceded by a layer of elastomeric material. Special attention was given to the snap-through phenomenon, analysed in the intermediate layer through a parametric study of its shape (sinusoidal), thickness, and mechanical properties.

Global Model

To analyse the seismic behaviour of the building, a global model was created using DIANA FEA. The modelling included all geometric and constructional details of the building. The load-bearing masonry, floors, and thrusting roof were modelled with accurate geometry to reflect the structure's reality.

The mechanical properties of the materials were determined based on the values provided in Table C8.5.I of the Explanatory Circular No. 7 dated January 21, 2019, accompanying the 2018 Technical Standards for Construction. Typical values of compressive strength, modulus of elasticity, and Poisson's ratio were considered for the masonry.

The floors were assumed to be infinitely rigid. The wall panels were assumed to be fixed at the base. The model's geometry was defined using the building's historical drawings, allowing the inclusion of openings and other constructional features. The model was discretized using a three-dimensional finite element mesh.

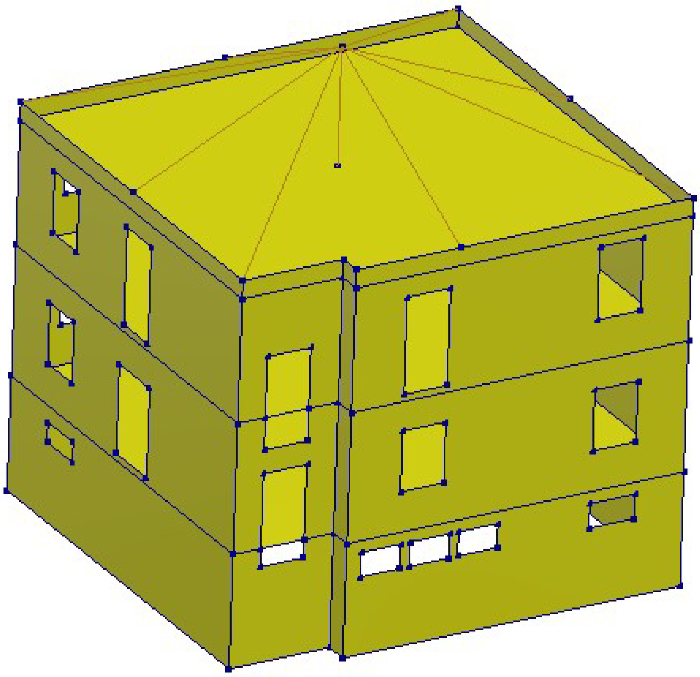

Figure 9

Retrofit vs No-Retrofit

The primary objective of the analyses was to compare the differences in the behaviour of the structure in its existing state and the structure with the implemented retrofit.

A time history analysis was performed for the Casa Benedino case study to evaluate how the two models—one with and one without meta-panels—respond to seismic loads, examining the differences in their dynamic behaviour. This type of analysis, which simulates the effects of a real seismic event by applying forces sequentially over time, allows for a detailed study and comparison of the structural responses of the two models, monitoring displacements, deformations, and energy dissipation capacity throughout the duration of the seismic event.

Through the time history analysis, it is possible to observe not only the levels of displacement and deformation reached by the two models but also how each configuration dissipates the absorbed seismic energy. The approach enables the examination of the different phases of the structure's dynamic response, from the initial oscillations to the final stabilization.

The time history analysis serves as an effective tool for assessing the efficacy of meta-panels as seismic mitigation devices. This analysis provides detailed data on how seismic energy is transferred among different structural elements, highlighting how the meta-panels distribute stresses more evenly compared to the configuration without them.

The expected results of this analysis aim to demonstrate that integrating meta-panels improves the overall seismic response of the building, proving to be a crucial element not only for structural resistance but also for the preservation of historical buildings subjected to repeated seismic stresses.

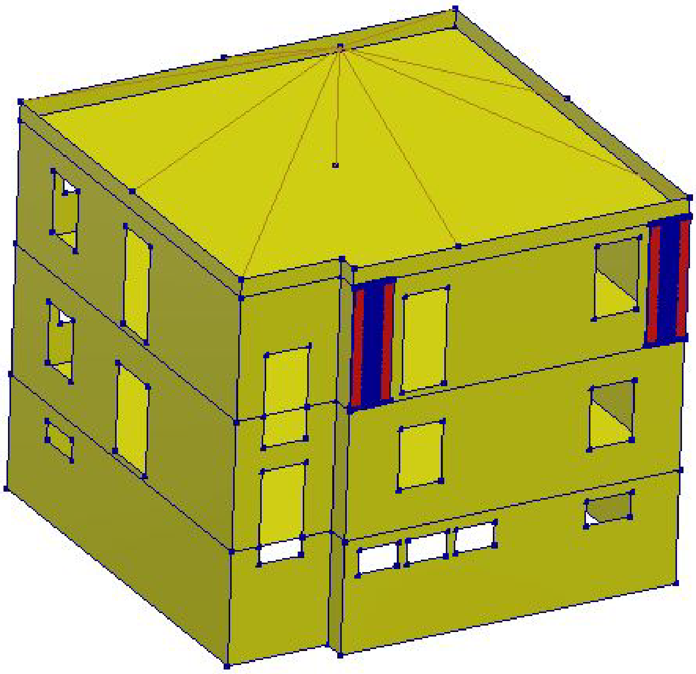

Figure 10

In the analysis conducted, the 1940 El Centro earthquake was used as the seismic input, a significant event frequently employed for seismic evaluations due to its intensity and the detailed nature of its recorded characteristics. The earthquake was applied in a specific direction, carefully chosen in relation to the configuration and arrangement of the meta-panels installed on the Casa Benedino structure.

The choice of direction was based on the orientation of the panels, which exhibit their y-direction out of plane. This orientation was considered optimal for maximising the effectiveness of the meta-panels in dissipating seismic energy and reducing horizontal deformations and stresses induced by the earthquake. By applying the seismic input along a direction perpendicular to the plane of the panels, the meta-panels are enabled to function more effectively as dissipation devices, promoting a dynamic response that minimises oscillations and preserves the structural stability of the building.

$E = 0.3E_x + E_y$

The first result analysed concerns the displacement in the y-direction, as a function of time, of the meta-panel applied to the case study during the simulated seismic event. For this evaluation, a key node was chosen, positioned at the point of connection between the sinusoidal panel and the vibrating mass associated with the system. This node plays a crucial role in transferring stresses between the meta-panel and the main structure, as it is located at the strategic interface between the dissipative device and the vibrating element.

The choice to analyse the displacements of this node was driven by the need to understand how seismic forces are distributed through the meta-panel and the specific contribution of the sinusoidal panel in mitigating oscillations. The representation of displacements over time allowed for the observation of the system's dynamic response in terms of oscillations and subsequent attenuations, providing a clear picture of the meta-panel's ability to absorb and dissipate seismic energy along the y-direction.

By analysing the temporal trend of the node’s displacement, it is possible to understand how the meta-panel reacts to load variations and the degree of damping of oscillations, an essential element for assessing the panel’s effectiveness in reducing deformations transmitted to the structure. The behaviour of this node therefore provides a direct representation of the stabilising and dissipative effect of the meta-panel, highlighting the specific characteristics of the connection between the sinusoidal panel and the vibrating mass, and contributing to a better understanding of the benefits of the structural retrofit on Casa Benedino.

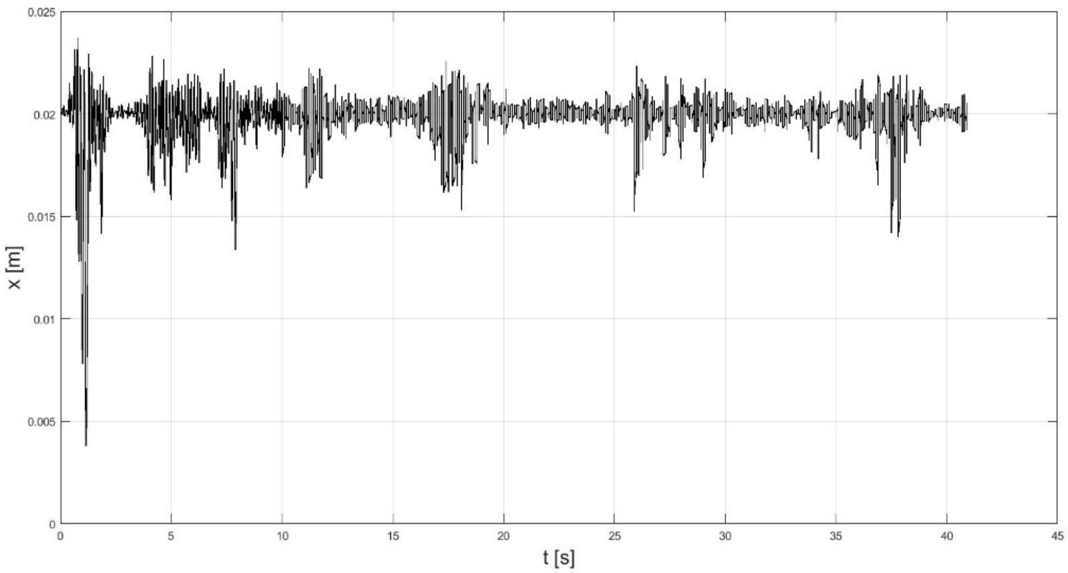

Figure 11

The plot above highlights significant displacements in the y-direction of the sinusoidal panel, which, however, fails to reach the bistable state. Despite the loading conditions being the same as those analysed in the previous chapter (where the bistability of the panel was achieved), in this case, the main structure partially damps the force transmitted to the meta-panel. This damping reduces the intensity of the dynamic input applied to the sinusoidal panel, preventing it from activating bistable behaviour.

The same displacement is plotted in the figure below to compare the displacement differences between the node of the panel, and the corresponding node located on the masonry. This comparison allows for an understanding of how the oscillations are distributed between the meta-panel and the masonry itself, providing insights into the differences in dynamic response and the effectiveness of the panel in reducing deformations transmitted to the structure. By analysing these variations, it is possible to assess the influence of the meta-panel on the stability and absorption of seismic forces compared to the masonry.

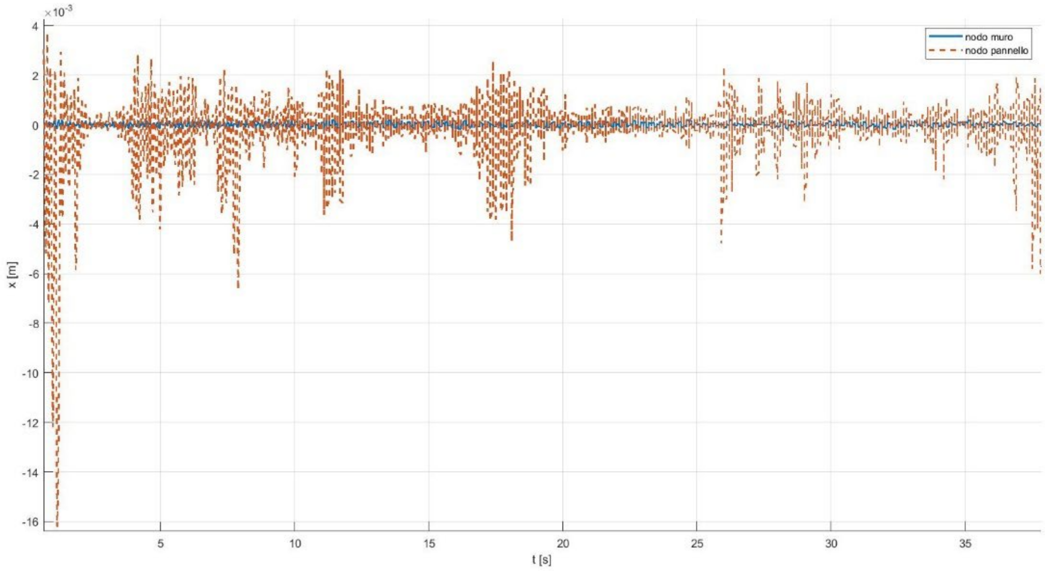

Figure 12

The simulations conducted have clearly demonstrated a significant reduction in oscillations of the structure during seismic events, thanks to the integration of the meta-panels specifically designed for this type of intervention. In particular, the data show a maximum reduction in displacement of 15.77%, a result that highlights the effectiveness of the meta-panels in mitigating the horizontal forces generated by seismic vibrations. This result exceeds the minimum 10% reduction considered necessary for the intervention to be deemed a seismic improvement. This decrease in displacement helps reduce the accumulation of stress in the masonry and other load-bearing components, contributing to extending the life of the structure. The panels absorb and dissipate seismic energy optimally, preventing extreme deformations that could compromise the architectural integrity of the historic building.

Furthermore, the intervention carried out on Casa Benedino represents a replicable and scalable model for other structures, offering an adaptable and versatile approach. Thanks to its ability to adapt to different contexts, this technology could be applied to a wide range of structural rehabilitation projects.

In conclusion, the application of meta-panels to Casa Benedino constitutes a valuable example of how technology can seamlessly integrate with existing buildings. The solution adopted not only preserves the aesthetic qualities of the building but also ensures effective protection against seismic forces, helping to reduce the risk of structural damage.

D) EDMP technology development

To bring EDMP technology to the market, the innovation has to pass the stages of innovation and to go through industrial development and commercialisation. Stephen K. Markham's [2002] pioneer study has recognised to "bridge the gap between the technical invention or market recognition of an idea and the efforts to commercialize it", […] "the series of discrete activities: recognize that his/her idea or research actually has commercial value, manifest the discovery as a product, communicate its potential through a compelling business case, acquire the resources necessary to realize that potential, use those resources to reduce risk, seek approval for formal development, and translate the project into the approval criteria."

The managerial approach highlights the challenges to securing resources at this stage. Paul Ellwood et al [2022] have studied the difficulties intrinsic to bridge the gap, despite of resources and support.

Industrial development and commercialisation

To address industrial development and commercialisation, the Task has adopted a processual- [Langley et al., 2013] and collaborative-approach [Townsend, 2014] as progress of interrelated flows of actions and as interaction between actors with disciplinary or complementary knowledge and know-how.

Have been assessed different industrial development and commercialisation pathways, for instance:

- intellectual property creation and spin-off company founding, e.g. in partnership with venture fund;
- strategic partnerships with start-up/spin-out incubation;
- collaborative projects with industrial companies.

Collaborative project delivery with industries

The Task adopted the model of collaborative project delivery with industries. Industry consultants have considered the EDMP technology not adequately industrial mature in order sell it to companies. The degree of industrial evolution is being considered apt to collaborative projects with companies already established in the supply of components for the retrofit of buildings.

The project-team initiated lab-based development work to deploy a panel product that can integrated within the manufacturing facilities of leading companies. The Task has identified different market segments in the supply of components for the retrofit, pertaining to the level of integration the components [Dupire et al., 1981]:

- semi-finished small panels – Saint-Gobain;
- stell prefabricated large panels – Permasteelisa Group;
- timber prefabricated large panels – Wolf Haus.

Current plans and next steps

Three project plans of lab work were initiated and are still ongoing in order to integrate the EDMP within the productive facilities of the three Companies: the industrial engineering projects aim to design the meta-layer functional to them. To support the engineering, in the Task have been implemented generative procedures to exhaustively explore the space of the solutions. All the feasible solutions were generated and analysed in terms of h/L , t/L and m (Figure 2). For each solution, the force-displacement law was numerically obtained and the energy absorbed as the area subtended by the same graph was evaluated. The exhaustive study of the solutions is supporting the expert engineers in the Companies to identifies the meta-layer configurations functional to their manufactory process. Configurations are plural since the bistable mechanism usually provides alternative configurations, whose definition can be profited in engineering and managerial terms.

Next planned steps in the industrial collaboration will address:

- defining EDMP in terms of innovative product in the Company's market, in which EDMP is to be placed and developed. In terms of marketing method, it may involve significant modifications in product placement, selling channel, product promotion, and support.
- developing a kit for the integrated retrofit seismic + energy. The kit demands for specific regulatory work and asseverated installation procedures.