

Optimal Design of Bistable Meta-Panels for Energy Dissipation in Buildings Under Seismic Excitation

Original

Optimal Design of Bistable Meta-Panels for Energy Dissipation in Buildings Under Seismic Excitation / Cavanni, V., Scussolini, L., Caneparo, L., Ceravolo, R.. - ELETTRONICO. - 676:(2025), pp. 761-769. (11th International Conference on Experimental Vibration Analysis for Civil Engineering Structures (EVACES 2025)) Porto (PO) 2-4 July 2025) [10.1007/978-3-031-96114-4_78].

Availability:

This version is available at: 11583/3004107 since: 2025-10-16T09:50:09Z

Publisher:

Springer

Published

DOI:10.1007/978-3-031-96114-4_78

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

Springer postprint/Author's Accepted Manuscript

This version of the article has been accepted for publication, after peer review (when applicable) and is subject to Springer Nature's AM terms of use, but is not the Version of Record and does not reflect post-acceptance improvements, or any corrections. The Version of Record is available online at: http://dx.doi.org/10.1007/978-3-031-96114-4_78

(Article begins on next page)

Optimal design of bistable meta-panels for energy dissipation in buildings under seismic excitation

Valeria Cavanni ¹[0009-0002-0043-2244], Linda Scussolini ¹[0000-0001-7883-111X], Luca Caneparo ²[0000-0002-1170-3233], and Rosario Ceravolo ^{1,3}[0000-0001-5880-8457]

¹ Department of Structural, Geotechnical and Building Engineering,
Politecnico di Torino, 10129 Torino, Italy

² Department of Architecture and Design, Politecnico di Torino, 10125
Torino, Italy

³ Responsible Risk Resilience interdepartmental Centre (R3C),
Politecnico di Torino, 10129 Torino, Italy

valeria.cavanni@polito.it

Abstract. Metamaterials, which are engineered materials exhibiting mechanical properties superior to the ones existing in nature, have gathered significant attention in the last years. Of particular interest are bistable mechanical metamaterials with negative stiffness, which have proven remarkable energy absorption properties. This encouraged their implementation with the purpose of absorbing and dissipating part of the seismic energy impacting existing buildings. An energy dissipating meta-panel (EDMP) can be outlined combining the fundamental concepts of passive vibration control system, as a tuned mass damper (TMD), and bistable metamaterials. The unit cell of the EDMP is comprised of a meta-layer linked to a vibrating mass. The meta-layer, designed as a cosine-shape beam (CSB), should have properly calibrated geometric properties to achieve bistable behaviour. Despite a proper calibration of the unit cell, the dissipation performance may be affected by the overall number of cells used to form the meta-panel. This paper investigates the impact of varying the number of cells per layer. This is conducted by numerical simulations on a calibrated EDMP. The aim is to understand how different configurations affect the overall performance of the meta-panel to gain fundamental insights necessary for designing the optimal solution tailored to each application.

Keywords: Negative stiffness metamaterials, geometric nonlinearity, seismic energy dissipation.

1 Introduction

Mechanical metamaterials (MM) can exhibit unique mechanical properties by carefully designing their structures [1]. Among them, negative stiffness (NS) metamaterials being particularly useful for dissipating and absorbing energy [2, 3].

NS metamaterials are typically designed using repeated unit cell geometries, consisting of tilted, arched, or curved beams [4], and they are typically referred to as NS because their geometric design allows them to exhibit bistability, meaning they have two stable positions and one intermediate unstable position. When the force-displacement profile is analysed through a quasi-static displacement-control test, it can be observed that the curve has a negative slope at the unstable position, which is where the name originates. This bistability is the result of a geometric nonlinearity. When subjected to a dynamic excitation, a bistable system can exhibit two distinct oscillatory regime: interwell and intrawell regimes [5]. Interwell oscillations occur when the mass moves between the two stable equilibria, crossing the unstable equilibrium. In contrast, intrawell oscillations involve motion around a single stable equilibrium.

These NS mechanical metamaterials may be used to develop a seismic energy dissipation device. This is attributed to the fact that the viscous dissipation depends not only on the damping coefficient but also on the velocity. During the interwell oscillations, the bistable element transitions between two stable configurations, resulting in increased velocity due to the snap-through phenomenon. This behaviour makes these metamaterials particularly valuable, as activating an interwell regime significantly enhances energy dissipation. To achieve this, the concept of nonlinear tuned mass damper (TMD), commonly referred to as nonlinear energy sink (NES) is employed. For a more in-depth understanding of this topic, readers may refer to [6–12]. Specifically, an energy dissipating meta-panel (EDMP) can be created by coupling a steel cosine-shaped beam (CSB) with NS mechanical metamaterials properties to a vibrating mass. This configuration forms a viscously damped single-degree-of-freedom (SDoF) auxiliary system with geometric nonlinearities, designed to connect to a primary structure.

The structure of the paper is outlined as follows: *Section 2* frames the general concept behind the design of the seismic energy dissipation device details the assumptions made to simulate its response. *Section 3* reports the numerical analyses performed to evaluate the effects of varying the number of cells in parallel and the device width. Finally, *Section 4* summarizes the key findings, conclusions, and future work developments.

2 Meta-panel: Conceptual framework

Buildings across Europe face dual vulnerabilities: insufficient energy insulation and inadequate seismic safety. Romano et al. 2023 [13] proposed a score-based approach to identify EU nations most in need of combined seismic and energy retrofiting solutions. The analysis identifies Italy, Romania, Croatia, Greece,

Bulgaria, and Germany as the most critical nations requiring attention. Addressing these issues requires a cohesive approach to retrofitting that improves both seismic safety and energy efficiency, safeguarding architectural heritage and advancing sustainability.

2.1 Integrated retrofitting

Integrated retrofitting interventions aim to address the two primary challenges of existing buildings: insufficient energy insulation and inadequate seismic safety. By combining external thermal insulation composite system (ETICS) with innovative mechanical metamaterials, these interventions provide a comprehensive solution to enhance buildings performance.

In this approach, ETICS is added to the façade to improve energy efficiency, while the integration with a mechanical metamaterial layer enhances the seismic safety. The metamaterial layer dissipates seismic energy impacting the building, reducing structural displacement, and mitigating damage. This dual functionality ensures that both energy efficiency and seismic safety are effectively targeted within a single intervention.

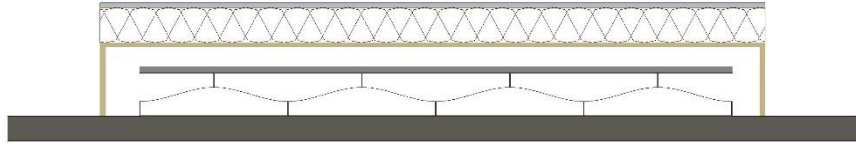


Fig. 1. Schematic representation of the panel designed to be anchored to existing buildings for seismic and energetic retrofitting.

Fig. 1 illustrates the conceptual configuration of the meta-panel for integrated retrofitting. The panel comprises an external thermal insulation coupled with an advanced layer placed in contact with the building wall. This advanced layer houses an EDMP, a device developed using NS metamaterials. These metamaterials leverage the snap-through phenomenon, characterized by rapid change of configuration, to dissipate seismic input energy efficiently. However, in order to ensure effective thermal insulation, it will be necessary to fill the cavities left by the EDMP with very low-density insulation materials (e.g. foams).

Fig. 2 presents some potential applications of this interventions across different structural configurations. The external thermal insulation coupled with the EDMP, is strategically placed only in selected locations, while the remaining areas are covered with ETICS only. Taking into account the constraints posed by the presence of windows, the integrated retrofitting can be implemented at the level of floor slabs or extended to cover the entire inter-storey space adjacent to the windows. Additionally, finite element (FE) analysis may help determine whether this intervention is required across all the floors or only at the top floor, where higher displacement occur.

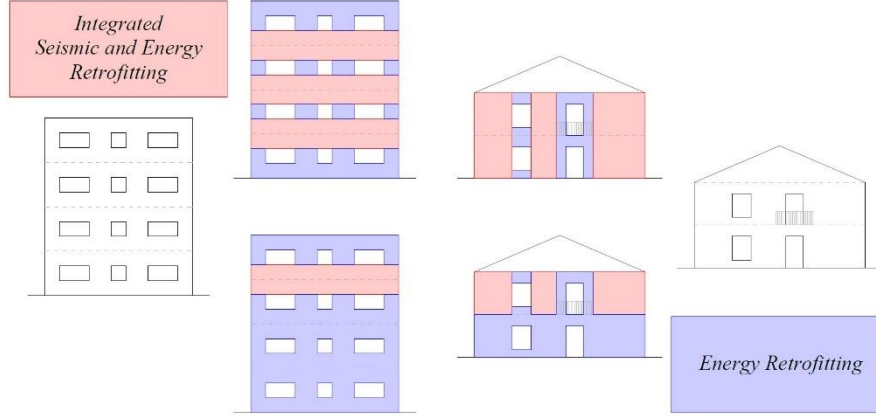


Fig. 2. Potential applications of integrated seismic and energy retrofitting for different structural configurations.

2.2 Design scheme for seismic energy dissipation device

This sub-section focuses on the EDMP, and the simplified model developed to analyse its response under real earthquake excitation. The primary objective of this study is to establish an initial set of results that can serve as a foundation for more detailed and advanced analyses.

This device is composed of NS metamaterials, which exhibit bistable behaviour under specific geometric configurations. In this study, a curved beam geometry ([3, 14]) is chosen to develop the device. In Fig. 3 a simplified scheme of a multi-cell EDMP is proposed. Each unit cell can be schematized through four characteristics, (i) negative linear stiffness k_1 , (ii) positive cubic stiffness k_3 , (iii) viscous damping c , and (iv) vibrating mass. Designed in steel, the device incorporates a CSB with a very thin thickness ($\leq 1 \text{ mm}$) to ensure sufficient deformability for reasonable earthquake scenarios. Increasing the thickness of the CSB leads to higher input energy requirements for initiating interwell oscillations. As the CSB is so thin, its mass is negligible when compared to the vibrating mass. As a result, the CSB contributes to the device stiffness and viscous damping, while the mass is an additional rigid body placed at the top of the CSB. The stiffness terms are influenced by the geometries of the unit cell, particularly the initial length of half CSB (l_0), the span (L), the amplitude ($h/2$), and the thickness (t) of the CSB. Hence, half CSB behaves as a spring of initial length l_0 , and stiffness $k = Ebt^3/l_0^3$, where b denotes the CSB width. Accordingly, the equation of motion for the seismic energy dissipation device becomes:

$$m_N \frac{d^2 y_N}{dt^2} + c_N \frac{dy_N}{dt} + k_L y_N + k_{NL} y_N^3 = -m_N \frac{d^2 u_g}{dt^2} \quad (1)$$

where m_N is the total vibrating mass given by Nm , and c_N is the equivalent viscous damping obtained as $2\zeta\omega_n m_N$. The linear negative stiffness term k_L is computed as the linear stiffness of the unit cell by the number of cells in parallel N :

$$k_L = Nk_1 = 2Nk \left(1 - \frac{2l_0}{L}\right) < 0 \quad (2)$$

Similarly, the nonlinear stiffness term k_{NL} is obtained by pre-multiplying the nonlinear stiffness of the unit cell by the number of cells in parallel, namely:

$$k_{NL} = Nk_3 = \frac{8Nkl_0}{L^3} > 0 \quad (3)$$

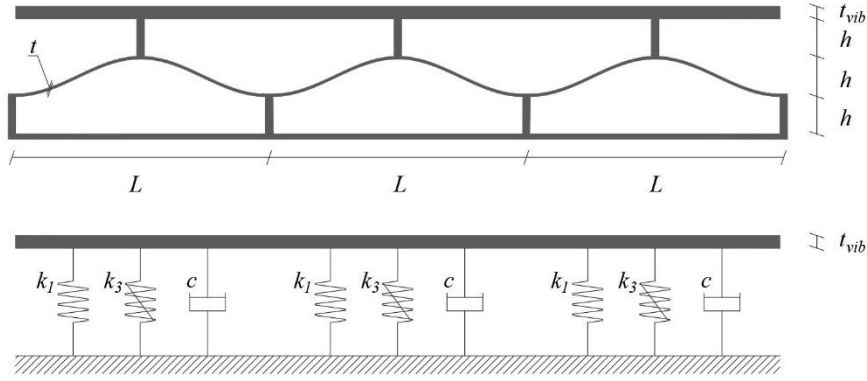


Fig. 3. Seismic energy dissipation device with three parallel cells, and a schematic representation using springs and dampers to simulate the device response.

3 Numerical analysis

The numerical analyses are conducted by varying the number of parallel cells, N , and considering two different values of panel width, b . The number of cells ranges from 1 to 40, a selection based on the varying available space between openings in real applications. The two values of b , 1.50 m and 3.00 m, are chosen to represent of the two possible configurations illustrated in Fig. 2: one where the device is implemented at the level of floor slabs (with a vertical spacing of approximately ~ 1.50 m between consecutive openings), and another where the device covers the entire inter-storey space adjacent to the openings (with a typical inter-storey of ~ 3.00 m).

To numerically analyse the response of the various EDMP configurations, the accelerogram of Kobe earthquake of 1940 (depicted in Fig. 4) is selected as the input excitation. This seismic event is considered because of its significant impact and the availability of detailed ground motion data, which can be accessed through the Strong Motion Center database (<https://www.strongmotioncenter.org/>). The

choice of this particular earthquake allows for an assessment of the multi-cell EDMP performance under a real and well-documented seismic event.

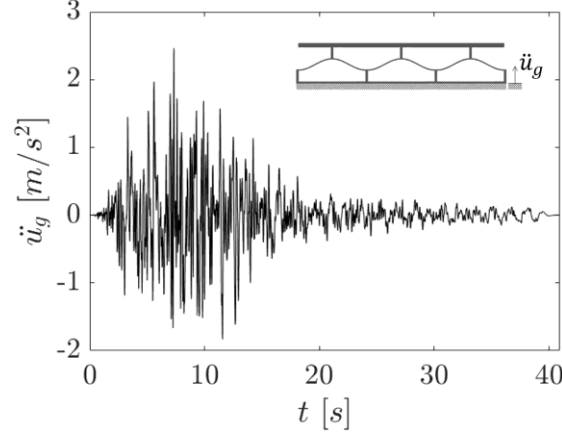


Fig. 4. Accelerogram of Kobe earthquake of 1940, recorded from the Kakogawa station, with a total duration $t_{end} = 40.94$ s and a sampling time $t_s = 0.01$ s.

Table 1 presents the geometric and material properties of the repeated unit cell. The material used is steel, and the geometry results from an optimization process that is beyond the scope of this article.

Table 1. Geometric and material properties of the unit cell.

Geometric properties		Material properties			
CSB thickness, t	0.001 m	Damping ratio, ζ	1	%	
CSB height, h	0.03 m	Density, ρ	7860	kg/m ³	
CSB span, L	0.50 m	Young's Modulus, E	2.1e11	Pa	
CSB length, b	1.50 ÷ 3.00 m				
Vibrating mass thickness, t_{vib}	0.005 m				

To determine the displacement time history response of the multi-cell EDMPs, Eq. (1) was solved using MATLAB *ode45*, a numerical solver based on an explicit Runge-Kutta (4,5) method. This method is useful for solving moderately stiff and no-stiff ordinary differential equations (ODEs), hence, to solve a second-order differential equation an equivalent system of first-order equations must be written. The system of equations is given by $dx_1/dt = x_2$ and $dx_2/dt = -d^2u_g/dt^2 - (c_N/m_N)x_2 - (k_L/m_N)x_1 - (k_{NL}/m_N)x_1^3$. Fig. 5a displays the displacement time histories for $N = 1, 2, \dots, 40$ cells in parallel with a panel width of 1.50 m, while Fig. 5b shows the same results for a width of 3.00 m. By solving the second-order differential equations, the velocity of the mass during motion is also determined, enabling the computation of the energy dissipated through viscous damping as:

$$E_{d,c_N} = c_N \int_0^{t_{end}} \left(\frac{dy_N}{dt} \right)^2 dt \quad (4)$$

where t_{end} is the duration of the input accelerogram, namely Kobe earthquake. Fig. 5c and Fig. 5d illustrates the cumulative dissipated energy for the two EDMP widths and for the $N = 1, 2, \dots, 40$ cells. Fig. 6 highlights the total dissipated energy for the two EDMP widths across the different number of cells in parallel.

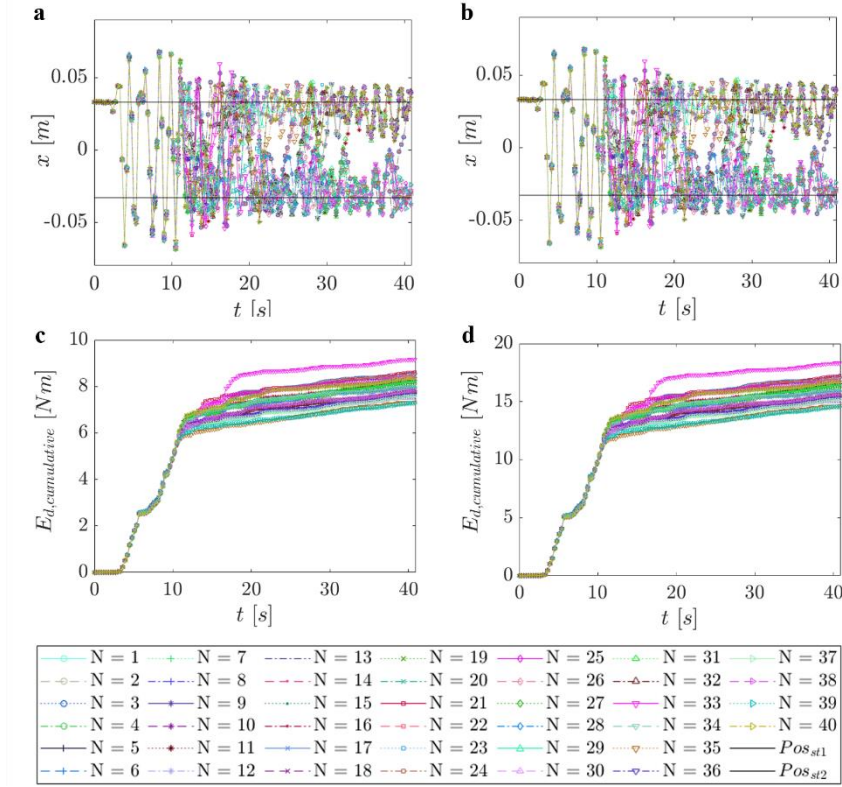


Fig. 5. Displacement time-history and cumulative dissipated energy for different number of cells in parallel with $b = 1.50$ m ((a), (c)), and $b = 3.00$ m ((b), (d)).

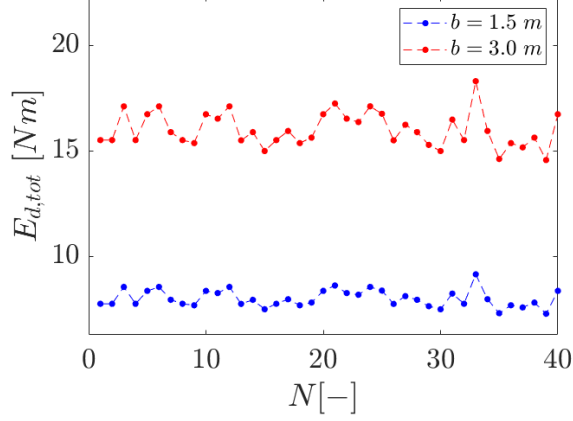


Fig. 6. Dissipated energy for $N = 1, 2, \dots, 40$ cells in parallel and for different width b .

4 Discussions and Conclusions

This study analysed the behaviour of a seismic energy dissipation device designed for future integration into an existing structure, focusing on the effects of the number of parallel cells and device depth b .

Results show that while the number of cells influences the displacement time history, depth b has a negligible impact, as it uniformly changes stiffness, damping, and mass. Furthermore, if the unit cell is designed for a bistable response under the given earthquake, adding multiple cells in parallel preserves this behaviour, with slight variations in interwell and intrawell oscillations.

Dissipation analysis reveals that while the number of cells has a minimal effect on total dissipation, depth b greatly increases dissipation due to the increase in vibrating mass and damping. It is also clear that for the first 10 s, dissipation remains consistent regardless of the number of cells in parallel, with the number of cells only slightly affecting dissipation after the earthquake peak.

In conclusion, the analyses provided valuable insights into the differences in dissipative capacity between the two potential applications of the device, as illustrated in Fig. 2: (i) applying the meta-panel to the height of the slab between openings, or (ii) placing it on the masonry walls between two floors. The results demonstrate that case (ii) offers greater dissipation due to the increased vibrating mass. Therefore, when both options are feasible, it is recommended to construct EDMP that span the entire inter-storey distance.

Future work will involve finite element analysis to validate the effectiveness of this simplified model, along with an experimental campaign to support both numerical models.

References

1. Jiao P, Mueller J, Raney JR, Zheng X, Alavi AH (2023) Mechanical metamaterials and beyond. *Nat Commun* 14:6004. <https://doi.org/10.1038/s41467-023-41679-8>
2. Shan S, Kang SH, Raney JR, Wang P, Fang L, Candido F, Lewis JA, Bertoldi K (2015) Multistable Architected Materials for Trapping Elastic Strain Energy. *Advanced Materials* 27:4296–4301. <https://doi.org/10.1002/adma.201501708>
3. Chen S, Tan X, Hu J, Zhu S, Wang B, Wang L, Jin Y, Wu L (2021) A novel gradient negative stiffness honeycomb for recoverable energy absorption. *Compos B Eng* 215:108745. <https://doi.org/10.1016/j.compositesb.2021.108745>
4. Tan X, Wang B, Wang L, Zhu S, Chen S, Yao K, Xu P (2022) Effect of beam configuration on its multistable and negative stiffness properties. *Compos Struct* 286:115308. <https://doi.org/10.1016/j.compstruct.2022.115308>
5. Harne RL, Wang KW (2017) Harnessing bistable structural dynamics: for vibration control, energy harvesting and sensing. John Wiley & Sons
6. Shaw AD, Neild SA, Wagg DJ, Weaver PM, Carrella A (2013) A nonlinear spring mechanism incorporating a bistable composite plate for vibration isolation. *J Sound Vib* 332:6265–6275. <https://doi.org/10.1016/j.jsv.2013.07.016>
7. AL-Shudeifat MA (2014) Highly efficient nonlinear energy sink. *Nonlinear Dyn* 76:1905–1920. <https://doi.org/10.1007/s11071-014-1256-x>
8. Romeo F, Sigalov G, Bergman LA, Vakakis AF (2015) Dynamics of a Linear Oscillator Coupled to a Bistable Light Attachment: Numerical Study. *J Comput Nonlinear Dyn* 10:. <https://doi.org/10.1115/1.4027224>
9. Vakakis AF (2018) Passive nonlinear targeted energy transfer. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376:20170132. <https://doi.org/10.1098/rsta.2017.0132>
10. Vakakis AF, Gendelman O V., Bergman LA, Mojahed A, Gzal M (2022) Nonlinear targeted energy transfer: state of the art and new perspectives. *Nonlinear Dyn* 108:711–741. <https://doi.org/10.1007/s11071-022-07216-w>
11. Chen Y-Y, Su W-T, Tesfamariam S, Qian Z-C, Zhao W, Shen C-Y, Zhou F (2022) Experimental testing and system identification of the sliding bistable nonlinear energy sink implemented to a four-story structure model subjected to earthquake excitation. *Journal of Building Engineering* 61:105226. <https://doi.org/10.1016/j.jobbe.2022.105226>
12. Chen Y, Su W, Tesfamariam S, Qian Z, Zhao W, Yang Z, Zhou F (2023) Experimental study of magnetic bistable nonlinear energy sink for structural seismic control. *Soil Dynamics and Earthquake Engineering* 164:107572. <https://doi.org/10.1016/j.soildyn.2022.107572>

13. Romano E, Negro P, Santarsiero G, Masi A, Butenweg C (2023) Identification of European buildings most needing seismic and energy retrofit with a focus on the Italian context. Publications Office of the European Union
14. Qiu J, Lang JH, Slocum AH (2004) A Curved-Beam Bistable Mechanism. *Journal of Microelectromechanical Systems* 13:137–146. <https://doi.org/10.1109/JMEMS.2004.825308>

Acknowledgements

This publication is part of the project PNRR-NGEU which has received funding from the MUR-DM 118/2023. This publication is part of the Project NODES which has received funding from the MUR – M4C2 1.5 of PNRR funded by the European Union - NextGenerationEU (Grant agreement no. ECS00000036) from the Spoke 4 - Digital innovation toward sustainable mountain and from the Project ReSismico at Creation and Strengthening of Innovation Ecosystems, building Territorial R&D Leaders, Academic PoCs Call.