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EVALUATION OF THE INTER-STORY ISOLATION SYSTEM APPLIED TO AN EXISTING RC SCHOOL BUILDING

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Abstract

Inter-story Isolation System (IIS) is an interesting technique for the mitigation of the seismic risk of buildings. In existing buildings, this technique can also be effectively used, when properly designed, to add extra stories while reducing the seismic response of the structure, representing an innovative retrofitting strategy. Therefore, IIS is particularly advantageous when it is desired to both increase the volume of the building and improve its seismic behaviour.

In this paper, the IIS is used to rise an existing reinforced concrete school building, while improving its overall seismic behaviour. First, a specific superstructure is chosen and the optimization approach for deriving the optimal IIS parameters is presented. Then, based on the optimal results obtained, the IIS is designed, and its effectiveness is investigated by performing Time History analysis, using a set of spectrum-compatible natural records and a fiber modelling of the structure, and comparing the results obtained with and without the IIS.

Keywords: Inter-story isolation system, Tuned mass damper, Seismic isolation, Seismic retrofit, Structural optimization

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1 INTRODUCTION

Inter-story isolation system (IIS) is a technique that consist in inserting a seismic isolation system between two stories of the structure. Applied to high rise buildings, the technique allows a great architectural freedom, as the structural parts can have different architectural and structural characteristics (e.g., different geometries, materials, etc) [1, 2, 3, 4, 5].

IIS can be also effective in raising existing buildings, allowing for an increase in usable space, without burdening land consumption. This aspect is beneficial, especially in densely populate areas [1]. Moreover, if properly designed, the IIS can improve the seismic performances of the existing structure, in fact, it can act as a non-conventional Tuned Mass Damper (TMD) for the substructure [6, 7, 8, 9].

In general, the dynamic behaviour of the IIS combines the function of seismic isolation and mass damping [10,11], and different approaches need to be considered according to the specific case. Studies evaluating the technique acting as a seismic isolation system generally use models with three or more degrees of freedom (e.g., [3, 4, 5, 10, 12, 13, 14, 15]); on the other hand, when the IIS acts as a TMD system for the substructure, two-degree-of-freedom (2-DOF) systems have been used ([6, 7, 16, 17, 18, 19, 20]).

In this context, a large number of theoretical studies on IIS and TMD system are available in the literature, but only few investigations and optimization of the IIS for seismic retrofit of existing buildings [8, 9, 21, 22, 23].

This paper presents an application of the IIS for the raising of an existing building. First, the case study structure and its Finite Element model, are presented. Then, the optimization of the IIS is performed in frequency domain, considering a simplified 2-DOF model, representative of the dynamic proprieties of the structure (an approach widely used in the literature for the optimization of TMD systems).

The effectiveness of the technique was assessed through bi-directional Time History analysis on the 3D finite element model, comparing the results obtained without and with IIS, and evaluating, in the latter case, different damping values.

2 CASE STUDY

As a case study, a standard school building that well represents the macro-class of the reinforced concrete two-stories schools built in Italy in the 1960s has been chosen.

The building, which houses an elementary school, consists of a two-stories bidirectional frame designed in 1966 against gravity loads only. As commonly conceived when considering only vertical loads, the frame is characterized by a weak-column/strong-beam configuration. Indeed, schools tend to have longer spans and higher accidental loads than residential buildings, which often results in beams of significant height.

The selected school has an irregular L-shape plan and an area of approximately 800 m^2. Along the main direction, the school is 52 m long, whereas the façade in the perpendicular direction has a maximum length of 22 m. The façades present a significant portion of openings, as common in this type of buildings, to ensure an adequate amount of natural lighting in classrooms. Thus, only five bays per story results entirely infilled (Figure 1).

Original project documentation, retrieved from municipal archives, provided important information regarding dimensions and steel reinforcements of each structural element. Although this information is affected by uncertainties related to the actual realization of the structure, construction details were assumed in the structural modelling. Figure 2 shows some examples of reinforcement details for beams and columns.

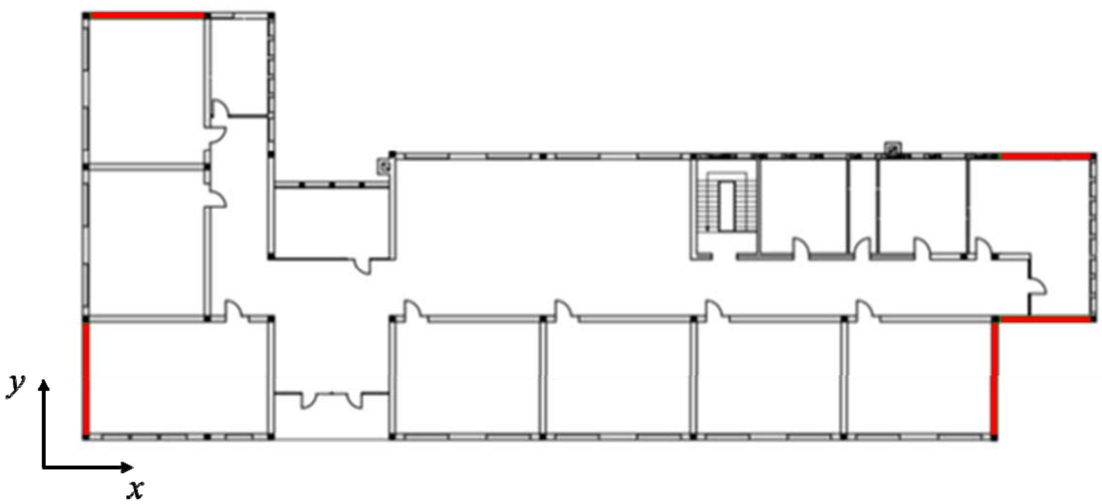

Figure 1: Floor plan of the existing structure (infilled wall highlighting).

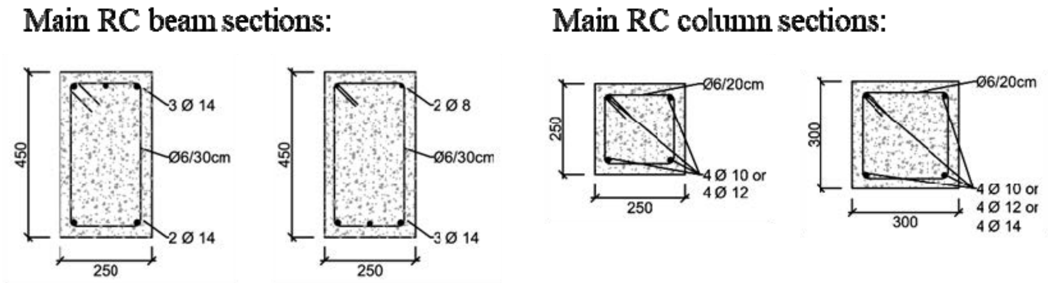

Figure 2: Details of RC beams and columns (some examples – 2nd floor).

Regarding material properties, the original project reported the class of smooth bars (i.e., AQ50), whereas no data were available on the class of the concrete. Thus, the cylindrical compressive strength of concrete was assigned according to the analysis of a large database of core tests carried out and recently presented by Masi et al. [24], which indicated a mean value of 20.08 MPa for the 1960s decade.

The original design reported an infill panel thickness of 13 cm. The type of clay bricks used for infilled panels was not available, hence it was assumed to be consistent with the panels of a coeval school built in the same municipality. The use of hollow clay bricks with modest void area (i.e., approximately 35%), typical of the period of construction, was assumed.

2.1 Intervention presentation

The proposed elevation consists of an isolated steel frame. The additional weight, provided by the new floor, is 67% of the weight of the existing structure.

To support the additional load provided by the superstructure, four additional columns were placed on the second floor of the existing building (as shown in Figure 3).

As concern the superstructure, IPE400 profiles were used for the main beams and IPE 360 for the secondary beams of the slab above the isolation system; on the roof, however, IPE400 profiles were used for the main beams and IPE270 for the secondary beams. HEB200 profiles were used for the columns. The type of steel used for the elements is S235. To achieve dynamic behaviour comparable to that of a rigid body, the superstructure was stiffened to horizontal actions through a bracing system.

The isolation system is realized with 8 isolators and 16 sliding bearing, arranged as shown in Figure 4, and modeled with linear springs and dashpots.

Figure 5 shows the finite element model of the structure, including the substructure and superstructure.

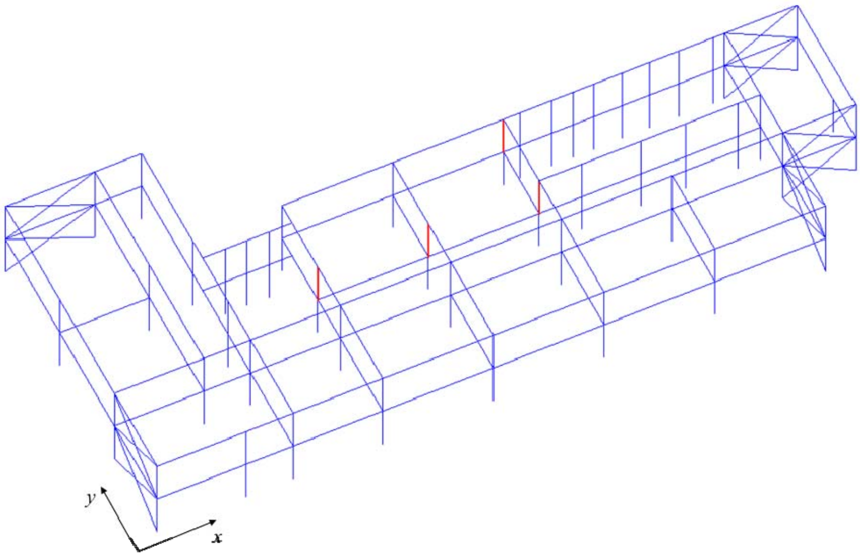

Figure 3: Model with added columns.

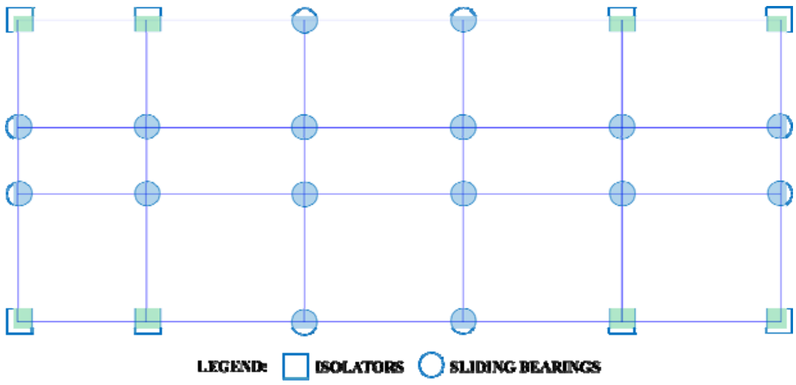

Figure 4: Plan layout of the isolation system.

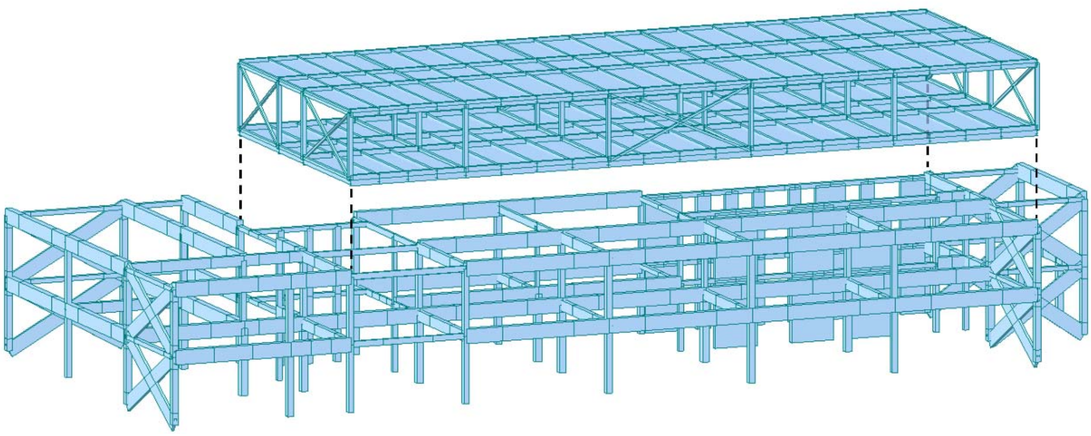

Figure 5: Finite element model of substructure and added superstructure.

2.2 Definition of the finite element model

The structure was modelled using the finite element (FE) software Midas Gen [25].

As the existing substructure, the main structural elements (i.e., beams and columns) were modelled through fiber sections, which allow for the evaluation of distributed plasticity (Fig. 6a). The Mander model [26] was assumed for the concrete, assuming different properties for the core and cover on the basis of the actual confinement, whereas the Menegotto and Pinto [27] model was assumed for steel bars, considering hardening behaviour.

The effect of masonry infills was simulated through a single-strut macro-model, whose equivalent section was calculated on the formulations proposed by Mainstone [28] and Stafford Smith [29]. The constitutive law of the infill struts was assumed according to Panagiotakos and Fardis [30], and it is shown in Fig. 6b.

As for the superstructure, it was modelled assuming a linear behaviour.

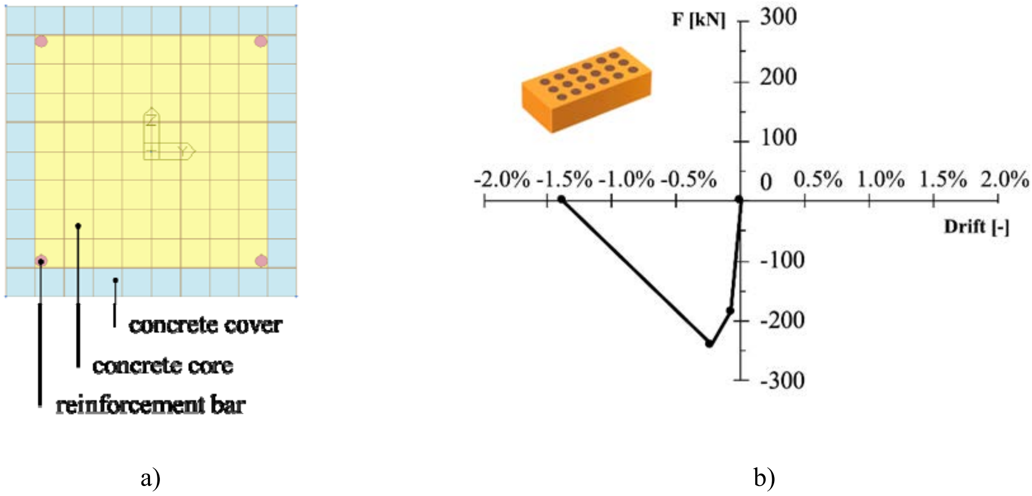

Figure 6: a) Example of a column fiber section and b) Panagiotakos and Fardis [30] model used for infills.

3 DEFINITION OF THE SIMPLIFIED DYNAMIC MODEL OF THE STRUCTURE

Structures with IIS can ideally be divided into three main parts, namely substructure, seismic isolation system and superstructure. Since a sufficiently rigid superstructure is designed (allowing the phenomenon of modal coupling to be avoided and neglecting the vibration modes of the superstructure [10]), it is possible to simplify the study by adopting the conventional 2-DOF system.

Therefore, the simplified system with IIS assumed in this study (Figure 7) consist of an equivalent 2-DOF model. In Figure 7, m_{Sub}, k_{Sub} and c_{Sub} represent the modal mass, stiffness and equivalent viscous damping coefficient of the substructure (primary structure), whereas m_{Is}, k_{Is} and c_{Is} represent the corresponding parameters of the isolated superstructure. Particularly, m_{Is} is the sum of the masses of the IIS and the superstructure, while k_{Is} and c_{Is} are the stiffness and damping of the isolation system. Then, ω_{Sub} and ζ_{Sub} are the angular frequency and equivalent viscous damping ratio of the substructure, whereas ω_{Is} and ζ_{Is} are the same parameters associated with the IIS.

To provide a dimensionless study, the dynamic characteristics of the isolated superstructure can be expressed as a function of the characteristics of the primary structure, through the mass (μ) and frequency (ν) ratios defined in Equation (1). These ratios, together with ζ_{Is}, are the dimensionless parameters that characterize the IIS and thus the variables of the optimization problem.

$$\mu = \frac{m_{Is}}{m_{Sub}} \quad ; \quad \nu = \frac{\omega_{Is}}{\omega_{Sub}} \tag{1}$$

Furthermore, the mass (**M**), damping (**C**) and stiffness (**K**) matrices of the 2-DOF reduced-order model can be normalized to the substructure characteristics, thus deriving $\mathbf{M}^{/}$, $\mathbf{K}^{/}$ and $\mathbf{C}^{/}$ as shown in Equations (2) to (4), which depend only on μ, ν, ζ_{Is} and ζ_{Sub}. In this study, ζ_{Sub} was set to 5%, as generally done in structural models of reinforce concrete (RC) buildings.

$$\mathbf{M} = \begin{bmatrix} m_{Sub} & 0 \\ 0 & m_{Is} \end{bmatrix} = m_{Sub} \begin{bmatrix} 1 & 0 \\ 0 & \mu \end{bmatrix} = m_{Sub}\mathbf{M}^{/} \tag{2}$$

$$\mathbf{C} = \begin{bmatrix} c_{Sub} + c_{Is} & -c_{Is} \\ -c_{Is} & c_{Is} \end{bmatrix} = m_{Sub}\omega_{Sub} \begin{bmatrix} 2\zeta_{Sub} + 2\mu\nu\zeta_{Is} & -2\mu\nu\zeta_{Is} \\ -2\mu\nu\zeta_{Is} & 2\mu\nu\zeta_{Is} \end{bmatrix} = m_{Sub}\omega_{Sub}\mathbf{C}^{/} \tag{3}$$

$$\mathbf{K} = \begin{bmatrix} k_{Sub} + k_{Is} & -k_{Is} \\ -k_{Is} & k_{Is} \end{bmatrix} = m_{Sub}\omega_{Sub}^{2} \begin{bmatrix} 1 + \mu\nu^{2} & -\mu\nu^{2} \\ -\mu\nu^{2} & \mu\nu^{2} \end{bmatrix} = m_{Sub}\omega_{Sub}^{2}\mathbf{K}^{/} \tag{4}$$

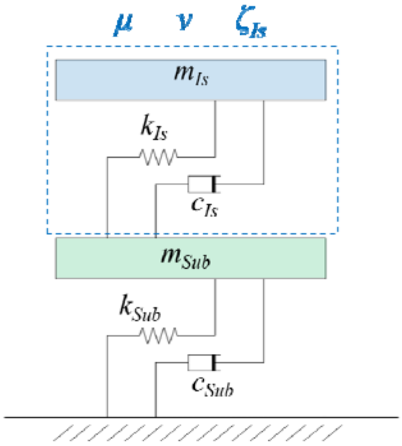

Figure 7: Reduced-order model of the structural systems with IIS.

4 OPTIMIZATION

4.1 Optimization approach

The optimization aims to minimize the dynamic response of substructure under seismic action, in term of displacement.

To model the stochastic nature of the seismic input, the Power Spectral Density (PSD) function of a zero-mean Gaussian stochastic process, $\mathbf{S}(\omega)$, is generally assumed; considering this type of process, random vibration theory produces the following displacement covariance matrix:

$$Cov[\mathbf{x}\mathbf{x}^{T}] = \int_{-\infty}^{\infty} \mathbf{H}(\omega)\ \mathbf{S}(\omega)\ \mathbf{H}(\omega)^{*T}\, d\omega \tag{5}$$

where **H**(ω) is the displacement frequency response function of simplified 2-DOF model and ω is the input frequency of the system. Furthermore, by also assuming seismic excitation as a white noise process, its PSD function no longer depends on ω ($\mathbf{S}(\omega)=S_0$); therefore, to obtain the optimal TMD parameters (i.e., ν, ζ_{Is}), the minimization of the integrals in Equation 5 is equivalent to the minimization of the integrals in Equation 6, where $\boldsymbol{\sigma}^2$ is the displacement variance.

$$\sigma^2/S_0 = \int_{-\infty}^{\infty} |\mathbf{H}(\omega)|^2 \, d\omega \tag{6}$$

Therefore, the objective of the optimization (J) is to find the optimal parameters ν, ζ_{Is} (ranging from 0 to 1) that minimize the integral in Equation 6. The optimization can be defined as follow:

$$J: \begin{cases} \min\limits_{\xi_{Is},\nu} \int_{-\infty}^{\infty} |\mathbf{H}(\omega)|^2 \, d\omega \\ \textit{subjected to} \begin{cases} 0 < \zeta_{Is} \le 1 \\ 0 < \nu \le 1 \end{cases} \end{cases} \tag{7}$$

4.2 Optimization of the case study building

To apply the optimization method to the specific case study, the first step is to define the mass ratio (μ), based on the modal analysis performed on the Finite Element model of the structure. The main vibration modes are shown in Table 1 and the modal shapes in Figure 8. For this case study, the 3rd mode in x-direction and 1st mode in y-direction were chosen.

Mode	ω_{Sub} *[rad/s]*	*m-Tx* *[%]*	*m-Ty* *[%]*	*m-Rz* *[%]*
1	**9.36**	**0.24**	**90.38**	**1.57**
2	10.68	27.23	1.66	63.97
3	**13.33**	**63.98**	**0.07**	**27.52**

Table 1: Modal analysis results: angular frequencies (ω_{Sub}) and % of participating mass (model without IIS).

From the calculation, the modal masses result to be 680.3 t along the x-direction and 701.6 t along the y-direction; therefore, the mass ratios in the two directions are 1.24 along x and 1.2 along y.

To identify the best parameters ν and ζ_{Is}, the optimizations were performed. Table 2 reports the results and includes information on the ideal stiffness (k_{Is}) and damping constant (c_{Is}) of the isolation system according to the vibration mode considered.

Direction	μ *[-]*	ν *[-]*	ζ_{Is} *[-]*	ω_{Sub} *[rad/s]*	K_{Is} *[N/mm]*	c_{Is} *[Ns/m]*
x	1.24	0.20	0.58	13.33	12400	974
y	1.21	0.21	0.56	9.36	6420	699

Table 2: Optimal isolation parameters.

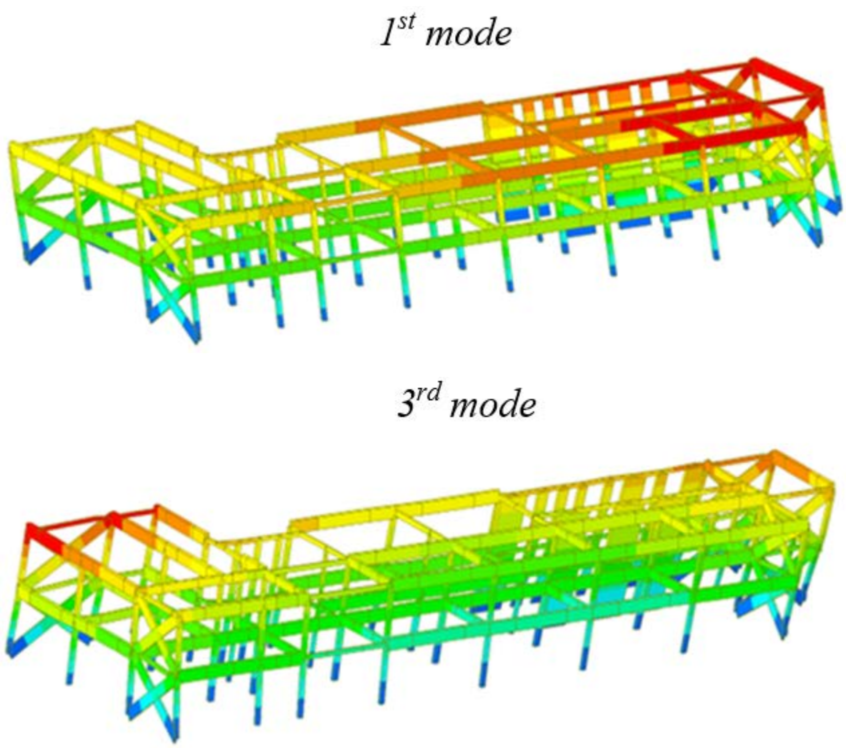

Figure 8: Graphical representation of the main vibration modes.

5 ASSESSMENTS THROUGH TIME HISTORY ANALYSIS

5.1 Seismic inputs

To assess the structural behaviour, Time History analysis of seven bidirectional natural records were performed. The seismic events were chosen from the SIMBAD Database [31] and were scaled to be compatible, on average, with the Type 1 elastic response spectrum of EC8 [32]. A bedrock acceleration (a_g) of 0.25 g and a type B soil were chosen, resulting in a peak ground acceleration of 0.3 g. The main details of these accelerograms are reported in Table 3.

Earthquake	Date	Mw	Epicentral distance [km]	Scale factor	
				X	Y
Eastern Fukushima Prefecture	2011/04/11	6.6	26.24	1.30	1.38
Imperial Valley	1979/10/15	6.5	24.68	1.59	1.48
S. Suruga Bay	2009/08/10	6.2	25.38	0.60	0.97
Friuli 1st shock	1976/05/06	6.4	21.72	0.79	0.72
Eastern Fukushima Prefecture	2011/04/11	6.6	27.56	2.33	1.41
Irpinia	1980/11/23	6.9	21.79	1.34	1.93
Irpinia	1980/11/23	6.9	18.85	1.43	1.58

Table 3: Selected bidirectional natural records.

5.2 Time History results

The average results obtained from Time History analysis, referring to the control point shown in Figure 9, are shown below. Results obtained without and with IIS were compared.

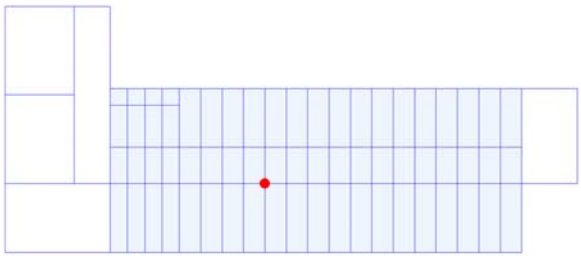

Figure 9: Point referenced in the results below.

Figure 10 shows the inter-story drift of the substructure. The results show that in the second story the drifts are higher. This effect results from the fact that the first story stiffness is greater. Globally, the results show that the IIS is effective in reducing the drift, allowing a reduction of 52% in the x-direction and of 43% in the y-direction.

Figure 11 shows the peak acceleration profiles, again IIS is effective in reducing this action, particularly in x-direction, where the substructure acceleration without IIS is higher.

The fiber stresses after the Eastern Fukushima Prefecture earthquake are shown in Figure 12. In particular, it is observed that performance improves only in the part of the structure below the IIS. The effectiveness is most noticeable at the base of the columns, where linear behaviour is generally maintained with the IIS.

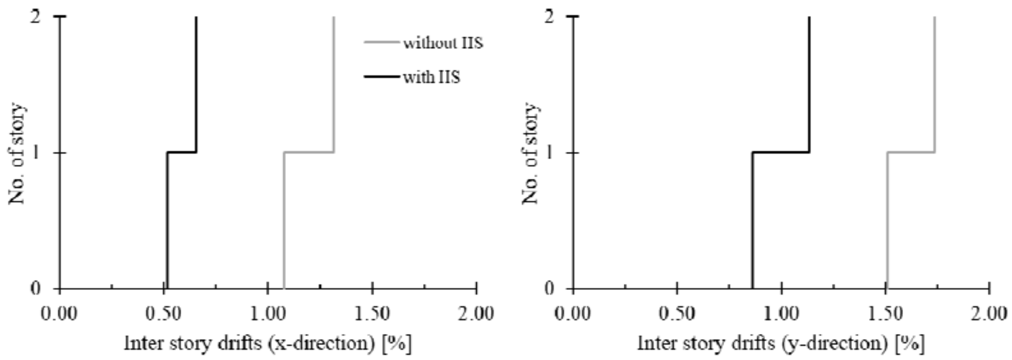

Figure 10: Inter-story drift for the structure with and without IIS, for x (left) and y (right) directions.

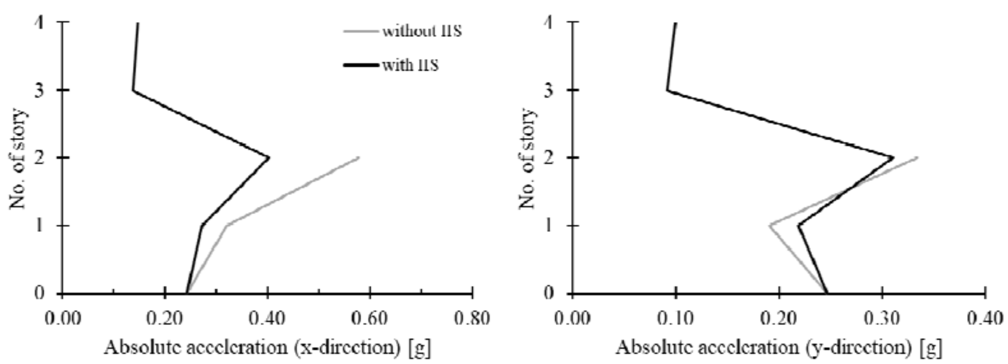

Figure 11: Peak floor acceleration for the structure with and without IIS, for x (left) and y (right) directions.

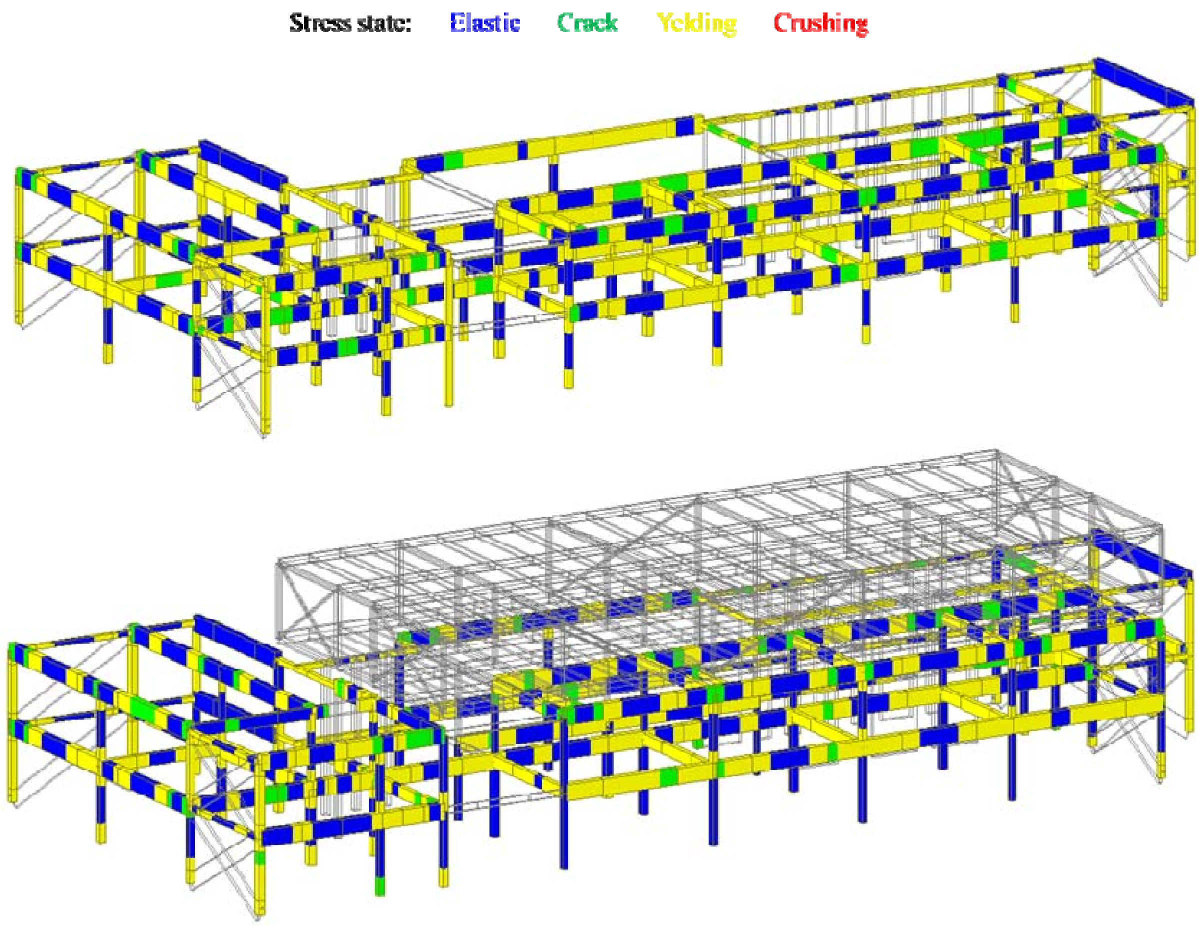

Figure 12: Comparison of the structural stress state: without (above) and with (below) IIS.

5.2.1. Effect of the isolation damping

In this section, the influence of ζ_{Is} on the seismic performance of the structure is analyzed. In particular, the results show how, moving away from the optimal results, damping affects the building response. Two values of ζ_{Is}, i.e., 0.15 and 0.25, were analyzed and compared with the optimal one. For all cases analyzed, the frequency of the isolation system was maintained the same as optimal.

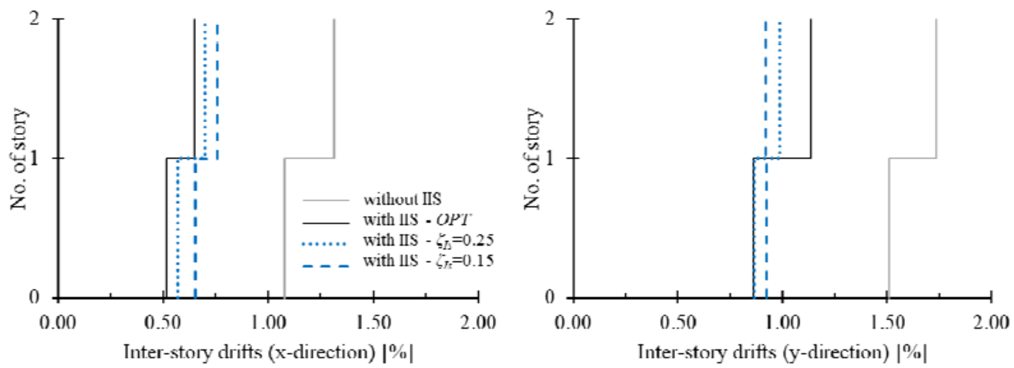

Figure 13: Inter-story drift for the structure without IIS and with IIS, considering different ζ_{Is} values.

Figure 13 shows the results in terms of drift. It is observed that by reducing the damping, the solution moves from the optimal one to the solution obtained without IIS; however, the IIS system is still effective, achieving maximum reductions of 39% and 47% in x-direction and 39% and 42% in y-direction (for ζ_{Is}=0.15 and 0.25, respectively). Finally, Figure 14 compares the same cases but in terms of peak acceleration. As with the drift, the best result is obtained with the optimized isolation system.

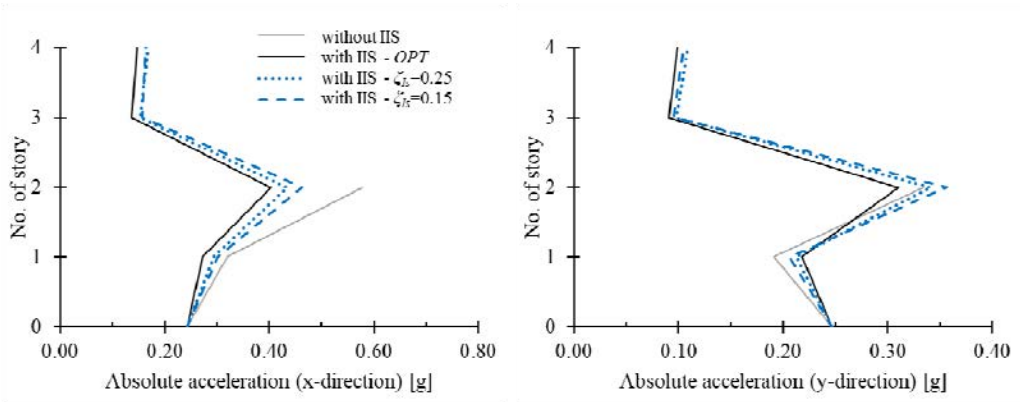

Figure 14: Peak floor acceleration for the structure without IIS and with IIS, considering different ζ_{Is} values.

6 CONCLUSIONS

The paper presents an application of IIS to improve the seismic performance of an existing school building. The intervention consists in raising the existing structure with a seismically isolated superstructure, designed to act as a non-conventional TMD for the substructure. The isolation parameters (frequency and damping) were optimized with the objective of minimizing the seismic response of the existing building.

The structural behaviour was assessed on the Finite Element model of the structure, through seven non-linear and bi-directional Time-History analysis. The main considerations can be drawn are:

- the IIS allow to improve the seismic response of the analyzed existing building;
- fiber stress analysis shows that the structural response improves, particularly in the part below the IIS;
- reducing the damping ratio of the isolation system from the optimal value (to evaluate a more economical solution), it could be still effective for the seismic improvement of the substructure.

REFERENCES

[1] F. L. Zhou, Seismic isolation of civil buildings in the People's Republic of China. *Progress in Structural Engineering and Materials* 1015 3(3):268-276. https://doi.org/10.1002/pse.85, 2001.

[2] M. Chey, J. Geoffrey Chase, J. Mander, A. Carr, Innovative seismic retrofitting strategy of added stories isolation system. *Frontiers of Structural and Civil Engineering*, 7, 13-23. https://doi.org/10.1007/s11709-013-0195-9, 2013.

[3] M. Donà, E. Bernardi, A. Zonta, P. Tan, F. Zhou, Evaluation of optimal FVDs for inter-storey isolation systems based on surrogate performance models. *Bulletin of Earthquake Engineering*, 2021.

[4] Y. Liu, J. Wu, M. Donà, Effectiveness of fluid-viscous dampers for improved seismic performance of inter-storey isolated buildings. *Engineering Structures* 169:276-292. https://doi.org/10.1016/j.engstruct.2018.05.031, 2018.

[5] M. Donà, E. Bernardi, A. Zonta, M. Minotto, F. da Porto, P. Tan, Effectiveness and optimal design of fluid-viscous dampers for inter-storey isolated buildings. *In Proc., XVIII ANIDIS Conf.,* Ascoli Piceno, Italy, 2019.

[6] E. Bernardi, M. Donà, F. da Porto, P. Tan, Investigations on inter-storey seismic isolation as a technique for adding upper storeys. *Proc. of 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN),* Athens, Greece, 2021.

[7] E. Bernardi, M. Donà, P. Tan, Multi-objective optimization of the inter-story isolation system used as a structural TMD. *Bulletin of Earthquake Engineering*, https://doi.org/10.1007/s10518-022-01592-9, 2023.

[8] M. Donà, E. Bernardi, A. Zonta, E. Saler, F. da Porto, Assessment of the inter-story isolation technique applied to an existing school building. *The 8th International Conference on Structural Engineering, Mechanics and Computation. Cape Town*, SouthAfrica, 2022.

[9] D. Faiella, B. Calderoni, E. Mele, Seismic Retrofit of Existing Masonry Buildings through Inter-story Isolation System: A Case Study and General Design Criteria. *Journal of Earthquake Engineering,* DOI: 10.1080/13632469.2020.1752854, 2020.

[10] D. Faiella, E. Mele, Vibration characteristics and higher mode coupling in intermediate isolation systems (IIS): a parametric analysis. *Bulletin of Earthquake Engineering,* DOI:10.1007/s10518-019-00637-w, 2019.

[11] P. Tan, Y. Zhang, F. Zhou, Optimal design and control mechanism study on story isolation system. *The 14th World Conference on Earthquake Engineering*, Beijing, China, October 12-17, 2008.

[12] S. J. Wang, K. C. Chang, J. S. Hwang, B. H. Lee, Simplified analysis of mid-story seismically isolated buildings. *Earthquake Engineering and Structural Dynamics,* https://doi.org/10.1002/eqe.1004, 2011.

[13] S. J. Wang, J. S. Hwang, K. C. Chang, M. H. Lin, B. H. Lee, Analytical and experimental studies on midstory isolated buildings with modal coupling effect. *Earthquake Engineering and Structural Dynamics,* https://doi.org/10.1002/eqe.2203, 2013.

[14] D.C. Charmpis, P. Komodromos, M.C. Phocas, Optimized earthquake response of multistorey buildings with seismic isolation at various elevations. *Earthquake Engineering and Structural Dynamics*, https://doi.org/10.1002/eqe.218, 2012.

[15] D.C. Charmpis, M.C. Phocas, P. Komodromos, Optimized retrofit of multi-storey buildings using seismic isolation at various elevations: assessment for several earthquake excitations. *Bulletin of Earthquake Engineering*, https://doi.org/10.1007/s10518-015-9737-y, 2015.

[16] G.B. Warburton, Optimum absorber parameters for various combinations of response and excitation parameters. *Earthquake Engineering and Structural Dynamics*, 10(3):381-401, 1982.

[17] C. Moutinho, An alternative methodology for designing tuned mass dampers to reduce seismic vibrations in building structures. *Earthquake Engineering and Structural Dynamics*, https://doi.org/10.1002/eqe.2174, 2012.

[18] Q. Zhou, M.P. Singh, X.Y. Huang, Model reduction and optimal parameters of mid-story isolation systems. *Engineering Structures*, https://doi.org/10.1016/j.engstruct.2016.06.011, 2016.

[19] D. Pietrosanti, M. De Angelis, M. Basili, Optimal design and performance evaluation of systems with Tuned Mass Damper Inerter (TMDI). *Earthquake Engineering and Structural Dynamics*, https://doi.org/10.1002/eqe.2861, 2017.

[20] M. Yahyai, L. Zebarjad, M. Head, M. Shokouhian, Optimum Parameters for Large Mass Ratio TMDs Using Frequency Response Function. *Journal of Earthquake Engineering*, https://doi.org/10.1080/13632469.2019.1624228, 2019.

[21] D. Faiella, M. Argenziano, F. Esposito, G. Brandonisio, M. Fraldi, E. Mele, Effectiveness of isolated vertical extension of masonry buildings as nonconventional TMD. *Soil Dynamics and Earthquake Engineering*, Volume 165, 107675, ISSN 0267-7261, https://doi.org/10.1016/j.soildyn.2022.107675, 2023.

[22] D. Faiella, M. Argenziano, G. Brandonisio, F. Esposito, E. Mele, Intermediate isolation system for the seismic retrofit of existing masonry buildings. *The 8th International Conference on Structural Engineering, Mechanics and Computation. Cape Town*, SouthAfrica. doi:10.1201/9781003348443-311, 2022.

[23] E. Bernardi, M. Donà, S. Sut, E. Saler, A. Caprino, F. da Porto, Inter-story isolation system applied to an existing mansonry school. *Proc. of 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN),* Athens, Greece, 2023.

[24] A. Masi, A. Digrisolo, G. Santarsiero, Analysis of a large database of concrete core tests with emphasis on within-structure variability. *Materials* 12(12), 2019.

[25] Midas Gen, On-line manual. Korea: MIDAS Information Technology Co, Ltd; 2021. http://manual.midasuser.com/EN_Common/Gen/905/index.htm.2.1.

[26] J.B. Mander, M.J.N. Priestley, R. Park, Theoretical Stress-Strain Model for Confined Concrete. *Journal of structural engineering* 114(8): 1804–1826, 1988.

[27] M. Menegotto, P.E. Pinto, Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behaviour of elements under combined normal force and bending. *Proceedings of IABSE Symposium,* Lisbon, Portugal, 1973.

[28] R.J. Mainstone, Supplementary note on the stiffness and strength of infilled frames. *Building Research Station*, Garston, Watford, U.K, 1974.

[29] B.S. Smith, Methods for predicting the lateral stiffness and strength of multi-story infilled frames. *Building Science* 2(3): 247–257, 1967.

[30] T.B. Panagiotakos, M.N. Fardis, Seismic Response of Infilled RC Frames Structures. *In Proc. of 11th World Conference on Earthquake Engineering*, paper no. 225, 1996.

[31] I. Iervolino, C. Galasso, E. Cosenza, REXEL: computer aided record selection for code-based seismic structural analysis. *Bulletin of Earthquake Engineering* 8: 339-362, 2009.

[32] CEN Eurocode 8, Design of structures for Earthquake Resistance, European Standard, European Committee for Standardization, Brussels, 2004.