Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2025) 424- 4 2

ECCOMAS
Proceedia

COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

TWO-STAGE OPTIMIZATION FRAMEWORK FOR THE OPTIMAL DESIGN OF TIMBER EXOSKELETONS

R. Cucuzza[1,2], M. Domaneschi[3,2], K. Gao[4], Y. Jun[5] and G. Marano[3]

[1] College of Civil Engineering, Henan University of Technology, Zhengzhou, Henan Province, China
[2] School of Civil Engineering, Southeast University, Nanjing, China
e-mail: raf.cucuzza@gmail.com

[3] Dipartimento di Ingegneria Strutturale, Edile e Geotecnica (DISEG), Politecnico di Torino, Corso Duca Degli Abruzzi, 24, Turin, 10128, Italy
[2] School of Civil Engineering, Southeast University, Nanjing, China
e-mail: marco.domaneschi@polito.it

[4] Key Laboratory of Concrete and Prestressed Concrete Structures of the Ministry of Education, School of Civil Engineering, Southeast University, Nanjing, China
e-mail: gaokang@seu.edu.cn

[5] State Key Laboratory of Mountain Bridge and Tunnel Engineering, Chongqing Jiaotong University, Chongqing, 400074, China
e-mail: yangjun@cqjtu.edu.cn

[3] Dipartimento di Ingegneria Strutturale, Edile e Geotecnica (DISEG), Politecnico di Torino, Corso Duca Degli Abruzzi, 24, Turin, 10128, Italy
e-mail: giuseppe.marano@polito.it

Abstract. *In European seismic-prone countries, most of the buildings have been constructed before the implementation of rigorous seismic and environmental regulations, therefore there is currently a pressing need to rehabilitate the existing built heritage by adopting efficient, sustainable and cheap retrofitting approaches. In this paper, an automatic approach for the optimal design of 2D trussed perpendicular exoskeletons for retrofitting existing R.C. structures is proposed. In particular, starting from a case study of an existing building made of R.C., a Two-stage performance-based optimization framework is implemented through a modified Genetic algorithm in order to determine (i) the optimal sizing and position of Timber exoskeletons around the building (first stage) and (ii) the optimal sizing of steel connections at the joints of the timber exoskeleton members (second stage). According to the preliminary results, the algorithm shows efficient convergence capability and a reasonable reliability level of the optimal solution intended as a promising solution towards mitigation of the built environment seismic vulnerability.*

Keywords: structural optimization, timber, seismic performance-based design, connections

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.1266 .2545

1 INTRODUCTION

The built heritage in seismic-prone countries was generally erected before the current anti-seismic regulations. Moreover, it has largely exceeded the expected lifespan, presenting structural safety problems [1]. In this context, it is necessary to intervene to reduce the structural vulnerability. Traditional retrofitting approaches require an invasive approach for the local repairing of building's structural elements [2], consisting of the interruption of the activities carried out within strategic buildings [3] and the considerable economic costs and technical constraints that can arise. In recent decades, exoskeletons have gained significant attention, being non-invasive and time-efficient techniques. These structures, which can be either 2D or 3D systems, can be connected perpendicularly or in parallel to the facade of the existing building. They provide an increment of both stiffness and resistance of the structure against horizontal loads [4]. However, the stiffness-based approach proposed by European and American standard regulations leads to an overestimation of the resistent capacity of the exoskeletons even for the most critical damage limit state of the existing building [5]. Aiming to optimize the structural response of the exoskeletons, the authors proposed a paradigm shift toward a performance-based approach where the inter-story drift is selected as a control parameter of the exoskeleton design process [6]. By imposing a damage state of the existing building in terms of maximum allowable floor displacement, an optimization procedure has to be developed to explore all the possible sizing configurations and positions of the retrofitting system while satisfying structural verifications according to current standards. Despite previous works, this optimization procedure will be applied for the optimal design of timber exoskeletons aiming to explore the engineering feasibility of the proposed retrofitting solution. By adopting a well-customized evolutionary algorithm [7, 8], the design of each exoskeleton dynamically changes until the satisfaction of the assumed performance criteria. Once the first stage optimization is completed, the algorithm will automatically move to the second stage of the optimization framework, accounting for the refinement of the first stage optimal solution in which different bolded connection details are explored at the level of the timber members. The connection between the different structural timber elements is achieved by means of dowel-type fasteners and auxiliary steel elements such as metal sheets.

2 OPTIMIZATION FRAMEWORK

The optimization process follows two steps: firstly, the optimizer determines the optimal number and position of exoskeletons around the building, along with the size of the elements, that minimizes the structural weight while ensuring structural safety. Then, the obtained optimal solution is refined, and proper connections among a wide range of possible solutions are identified. Following the same approach, the safety at the building level as well as at the connection level is addressed through specific structural verification account for bending, shear, buckling verifications of the timber members and traction or slip checks for the bolds according to Eurocode Standard. Additionally, the performance level of the building is governed by imposing a Total Lateral Drift (TLD) threshold related to an admissible level of damage. For the implementation of the optimization problem, the real-coded Genetic Algorithm (GA) proposed by Olivo et al. [6] has been adopted. The mathematical formulation of the optimisation problem can be described as follows.

First-stage Optimization

$$\textbf{min}\ f_1(\mathbf{x}) \ = \ \left[N_{Ex} \cdot \rho \cdot \sum_{i=1}^{N_{El}} A_i \cdot l_i \right] \cdot \phi_1(D_i) \cdot \phi_2(S_i) \tag{1}$$

$$\mathbf{x} \ = [\ x_1\ ,\ \dots\ ,\ x_i\ ,\ \dots\ ,\ x_n{}^{\text{Positioning DV}},\ x_{n+1}\ ,\ \dots\ ,\ x_{n+j}\ ,\ \dots\ ,\ x_{n+m}{}^{\text{Size DV}}\ ]$$

subjected to :

$$x_i \ = \begin{cases} 0 \\ 1 \end{cases} \quad ; \qquad x_{n+j}^{lower} \ < \ x_{n+j} \ < \ x_{n+j}^{upper}$$

where

- **x**: design variables accounting for exoskeletons' position and sizing;
- N_{Ex} : total number of exoskeletons;
- N_{El} : number of elements of the single exoskeleton;
- ρ : density of steel grade S355;
- A_i : area of the i^{th} exoskeleton element;
- l_i : length of the i^{th} exoskeleton element;
- ϕ_1, ϕ_2 : penalty functions accounting for displacement and stress verifications;

In accordance with the proposed design criteria, the first design constraint is related to a maximum allowable inter-storey drift imposed. This is intended to ensure the structural integrity of the building in the elastic field and to minimize the damage to structural (e.g. columns and beams) and non-structural (e.g. internal infills) elements. An allowable limit drift δ_{allow} is defined as the storey height divided by a factor β, which should be calibrated for each specific case study according to the expected building performance. The actual inter-storey drift, denoted by δ_j, is evaluated at each pair of nodes of the structural columns of the building. After comparing the aforementioned parameters, their ratio must respect the constraint defined as $D_i < 1$.

$$D_j \ = \ \frac{\delta_j}{\delta_{allow}} \ < \ 1 \qquad \forall\, j \ = \ 1\,, \dots,\, N_{col} \qquad ; \qquad \delta_{allow} \ = \ \frac{H}{\beta} \tag{2}$$

where

- δ_j : inter-storey evaluated at the j^{th} column;
- δ_{allow} : allowable inter-storey drift;
- N_{col} : total number of columns of the existing structure;
- H : height of the storey;
- β : allowable inter-storey drift factor;

Second-stage Optimization

$$\textbf{min}\, f(\mathbf{x}) \;=\; \left[\sum_{i=1}^{n} w_i \cdot j_i\right] \cdot \phi_1(N_{dif}) \tag{3}$$

$$\mathbf{x} \;=\; [\, x_1 \,,\, \ldots \,,\, x_i \,,\, \ldots \,,\, x_n \,]$$

subjected to :

$$x_i^{lower} \;<\; x_i \;<\; x_i^{upper}$$

where

- **x**: design variables accounting for connection variables;
- x_i : index of selected connection layout in catalogue of group i;
- n : number of groups defined in the first phase of automatic routine;
- N_{dif} : number of different layouts present in the solution;
- ϕ_1 : penalty function;

The term within brackets of the OF represents the weight of all the connections present in all the nodes the exoskeletons installed. Accordingly, w_i is the weight of the selected layout for the group i, and j_i is the number of nodes which are inside that group.

The penalty function, denoted by ϕ_1, is a function of the number of different layouts present in an individual's chromosome. Solution characterized by high diversity in connection details (i.e. number and diameter of bolds, dimension of metal sheets) are penalized in order to encourage a standardization in connection design combined with a complexity reduction in situ.

3 CASE STUDY AND NUMERICAL MODEL DEFINITION

The selected case study corresponds to a scholastic complex located in the Italian city of Naples. The resisting structure of the buildings is provided mainly by unidirectional R.C. frames. In figure 1, the SAP2000 numerical model is depicted.

Geometric information of the building was obtained from the historical survey, while the definition of the mechanical properties was identified through visual inspections in situ and a comprehensive experimental campaign on R.C. columns and beams of the building according to Italian and European regulations.

Specifically, the high in-plane stiffness of the slabs was conveniently simulated by means of rigid floor constraints. Since the slab's elements correspond to a ribbed one-way type, they were modelled as loads directly transferred to the longitudinal beams. Following the same criteria, non-structural permanent loads were calculated according to the Italian standard regulation and applied to the main longitudinal beams. Finally, gravitational actions such as live loads at the level of the floors, snow and maintenance loads on the roof have been modelled, taking into account the specific building activities and environmental boundaries. Horizonal actions intended as wind load and seismic action were simulated through static equivalent load perpendicular

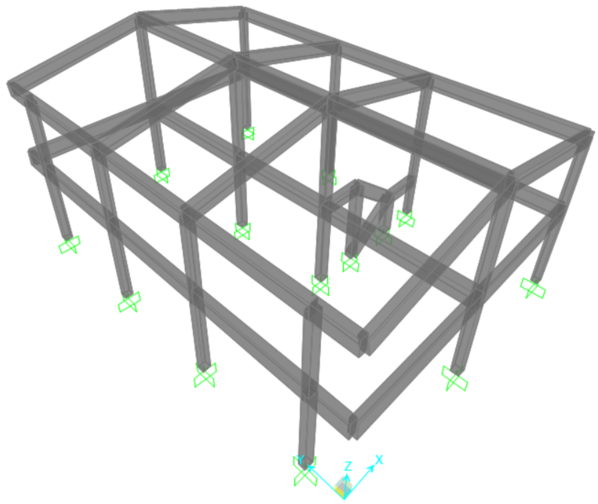

Figure 1: Axonometric view of the structural model.

to the longest facade (critical configuration) and by performing a Response Spectrum analysis, respectively. Exposure, pressure and dynamic coefficients of the wind, as well as the seismic parameters, have been calculated according to the specific location of the building and characteristics of the site (e.g. Elastic Response Spectrum) following the CNRR Italian regulation and Eurocode suggestions, respectively.

With specific respect to the modeling criteria adopted for the retrofitting structures, the graphical scheme, reported in figure 3, has been adopted.

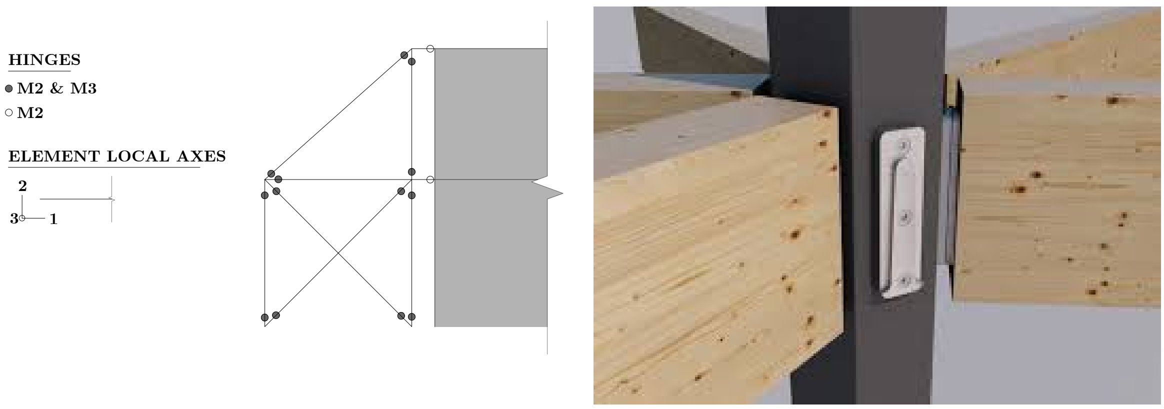

Figure 2: Modeling scheme and hinges properties of timber exoskeleton (on the left) and connection type (on the right).

The adopted bolded-steel connection makes reasonable the assumption of a pinned-pinned joint between timber members.

Finally, aiming to identify the effective vulnerability level of the existing building, a non-linear static analysis (Pushover) has been performed at the Life-safety (LS) and Collapse limit (CP) state. It was obtained at the LS state a vulnerability index equal to $\zeta_E = 0.79$ while it decreases to $\zeta_E = 0.54$ for CP state. Both analyses show weak seismic resistance to withstand horizontal actions and urgent needs for a seismic retrofitting intervention.

4 OPTIMIZED RETROFITTING CONFIGURATION

In this section, the results obtained from the two stages of the optimization process are shown. At first, the optimal retrofitting configuration intended as optimal number and positioning of exoskeletons around the building as well as optimal sizing is reported. In Figure 4, the top view of the retrofitting configuration is represented.

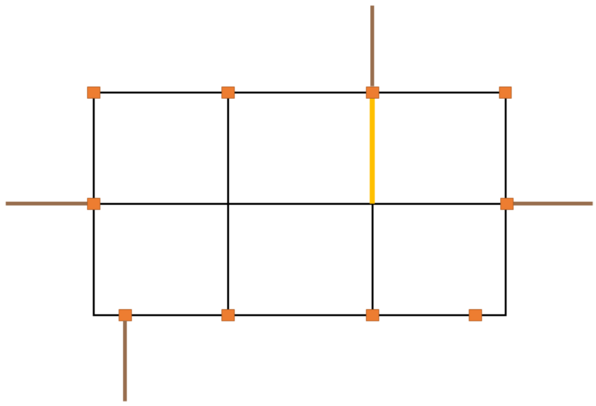

Figure 3: Top view of the optimal retrofitting solution coming from the first stage of the optimization process

As expected, the entire optimization design process is mainly controlled by the displacement target, which guarantees a certain performance level (imposed damage state) of the existing building. Even if the average demand-capacity ratio among all structural elements is far from the maximum strength capacity, the inter-storey drift is proximate to 1.

From the structural point of view, exoskeletons anchored to the central columns respect the geometric symmetry along the longitudinal direction, preventing shift in the centre of stiffness with an increase of torsion effects. On the transverse axis, the geometric symmetry is interrupted by the stairs, which produce a shift of the centre of stiffness with respect to the centre of mass. Both exoskeletons, perpendicular to the trasversal facade of the building, aim to mitigate the torsional effect.

The sizing of each timber element composing the exoskeleton system type is reported in Table 1.

Element	**b** $[mm]$	**h** $[mm]$
Col_1	0.35	0.42
Col_2	0.45	0.48
Beam	0.30	0.20
$Diag_1$	0.22	0.34
$Diag_2$	0.40	0.48

Table 1: Timber Exoskeleton's Cross-sections

The significant mitigation of the seismic vulnerability of the existing building produced by the retrofitting system can be observed both in terms of (i) reduction of the vulnerability index and (ii) shear base unloading ratio.

As reported in Table 2, the effect of unloading on the existing building produced by the exoskeleton is demonstrated by the absence of elements that do not meet the structural verification. Additionally, the maximum stress experienced by the most critical elements is below the admissible Demand-Capacity safety threshold. As a consequence, the vulnerability index of the existing building shows a significant improvement with $\zeta_E > 1$.

		% Non-verif. elements	Max DCR col	Max DCR beam	ζ_E
Timber Exoskeletons	As-built	82.76	2.98	2.89	0.53
	after retrofitting: **S2**	0.00	0.87	0.93	1.1

Table 2: Results of the structural verifications of the existing buildings, in terms of percentage of non-verified elements and Demand-Capacity ratios of the most critical column and beam, before and after the retrofit.

The benefits obtained by adopting the proposed consolidation approach are demonstrated by an evident unloading effect in terms of shear base at the columns' foundation of the existing building.

Base Shear	**Unloading Ratio** [%]	**Carrying Load** [%]
$V_{r,x}$ timber ex	**-57.48**	**46.95**
$V_{r,y}$ timber ex	**-81.74**	**20.41**

Table 3: Unloading effect in both directions of the existing building.

Table 3 presents the structure unloading ratio and the percentage of load captured by the existing structure for both X and Y directions of the building.

The primary unloading of the structure is predominantly concentrated in the longitudinal direction. The elements installed in this direction appear to be more rigid with respect to the existing structure stiffness, allowing for a higher unloading ratio of the structure. This is evidenced by the fact that the existing structure just takes 20% of the base shear in that direction.

Concerning the transverse direction, a minor unloading ratio is observed in the exoskeleton intervention, which is consistent with the slight reduction in the exoskeleton's timber cross-sections along that direction. In this case, the structure takes approximately 50% of the base shear.

Finally, with specific regard to the connection design, the optimal connection pattern, intended as the optimal combination among all the possible connection layouts, identified by the optimizer is presented in Table 4. Furthermore, the number of required connections per typology is also provided.

The final solution comprises six distinct connection layouts, each identified with a unique ID corresponding to a specific timber element's joint position. Each connection is characterised by a specific bolt diameter employed $\varnothing$, inter-axis spacing of bolts a_1, number of rows of bolts n_r, and number of bolts per row n_b.

In Figure 4, an example of the optimal assignment processed by the optimizer for one exoskeleton along the X-direction is shown.

As reported in Table 4, the repetitiveness (*counting*) of each connection is strongly dependent on the penalty function level introduced in Eq. 4. The standardization criteria introduced in the optimization framework encourage the optimizer to adopt 4-times connection type 4 and 6.

Typology ID	t_p $[mm]$	$\varnothing$ $[mm]$	a_1 $[mm]$	n_r	n_b	Counting
1	14	16	80	4	4	2
2	14	16	80	4	2	2
3	14	16	80	2	3	1
4	14	20	100	4	2	4
5	14	16	80	7	3	0
6	14	16	80	7	2	4

Table 4: Design of the Connections Layout

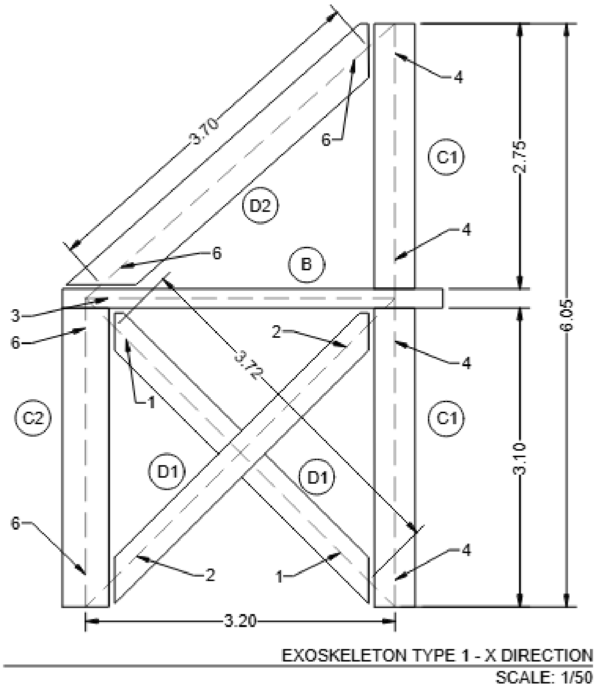

Figure 4: Example of the optimal connection layout assignment for the exoskeleton along X-direction

In the full-paper version, the authors will provide more details about the connection design process with comprehensive technical drawings of each connection typology and further discussion about the standardization philosophy ensuring at the connection design stage.

5 CONCLUSION AND FUTURE DEVELOPMENT

In this paper, an optimized retrofitting approach for reducing the seismic vulnerability of existing R.C. buildings is introduced. A multi-stage optimization framework is proposed for the automatic design of timber exoskeletons, underscoring optimal sizing and placement of such a structural system moving toward a further automatic refinement of the connection design of timber members. The entire process is based on the minimization of the structural cost of the intervention.

Preliminary results reveal an acceptable level of reliability of the algorithm and a promising convergence capability, resulting in feasible engineering solutions at the different stages of the design process. In this sense, the optimal placement of the exoskeletons around the building enhances the seismic structural response of the retrofitted system through an efficient transferring of the shear base from the building. Additionally, timber elements adopted for the exoskeletons seem to be competitive with respect to traditional steel external structures. In future works, the benefits of adopting timber exoskeletons will be investigated both in terms of structural efficiency and environmental impact. Based on new and more complex case studies, comparisons between steel and timber exoskeletons will be conducted, aiming to identify the weakness and strength of each consolidation approach. Based on the authors' knowledge, this research firstly explores the possibility of using sustainable materials (e.g. timber) for such a retrofitting approach. Further investigations will be devoted to a comprehensive life-cycle cost (LFC) and life-cycle assessment (LCA) at the structural member and connection level of this system, where special attention to the foundation will be deserved.

REFERENCES

[1] 1. Iovane G, Sandoli A, Marranzini D, Landolfo R, Prota A, Faggiano B, Timber based systems for the seismic and energetic retrofit of existing structures. *XIX ANIDIS Conference, Seismic Engineering in Italy. Procedia Structural Integrity, vol. 44 (223), p. 1870-1876*, Torino, Italy, 11-15/09/2022.

[2] Reggio A, Restuccia L, Martelli L, Ferro GA , Seismic performance of exoskeleton structures. *Engineering Structures*, **198**, 109459, 2019.

[3] Di Lorenzo G, Colacurcio E, Di Filippo A, Formisano A, Massimilla A, Landolfo R , State-of-the-art on steel exoskeletons for seismic retrofit of existing RC buildings. *Ingegneria Sismica*, **37**, 1, 2020.

[4] Cucuzza, Raffaele and Aloisio, Angelo and Domaneschi, Marco and Nascimbene, Roberto, Multimodal seismic assessment of infrastructures retrofitted with exoskeletons: insights from the Foggia Airport case study. *Bulletin of Earthquake Engineering*, **22**, 6, 3323–3351, 2024.

[5] Cucuzza, R. and Olivo, J. and Bertagnoli, G. and Ferro, G. and Marano, G., Performance-based optimization of steel exoskeletons: An alternative approach to standard regulations. *Journal of Building Engineering*, 112177, 2025.

[6] Olivo, Jana and Cucuzza, Raffaele and Bertagnoli, Gabriele and Domaneschi, Marco, Optimal design of steel exoskeleton for the retrofitting of RC buildings via genetic algorithm. *Computers & Structures*, **299**, 107396, 2024.

[7] Cucuzza, Raffaele and Aloisio, Angelo and Rad, Majid Movahedi and Domaneschi, Marco, Constructability-based design approach for steel structures: From truss beams to real-world inspired industrial buildings. *Automation in Construction*, **166**, 105630, 2024.

[8] Cucuzza, Raffaele and Rad, Majid Movahedi and Domaneschi, Marco and Marano, Giuseppe C, Sustainable and cost-effective optimal design of steel structures by minimizing cutting trim losses. *Automation in Construction*, **167**, 105724, 2024.