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An integrated approach for seismic design and modelling of plywood-retrofitted timber floors

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Abstract

The application of timber-based strengthening solutions to existing wooden and masonry structures, combines several benefits, such as reversibility, compatibility, lightness, sustainability, affordability, and effectiveness. With specific reference to existing timber floors, the superposition of plywood panels fastened to the sheathing has proved to be an excellent method to enhance the seismic response of such structural components, combining a great improvement of in-plane strength and stiffness, with a considerable increase in their hysteretic energy dissipation. In order to promote the use of this retrofitting method in practice, this work firstly presents the implementation of calculation tools supporting the design and advanced numerical modelling of timber diaphragms strengthened with plywood panels. The suite of tools allows to first estimate the full nonlinear, cyclic in-plane response of the strengthened diaphragms, starting from the geometrical and material properties of the existing sheathing and the plywood overlay, as well as the mechanical characteristics of the fasteners. In a second step, it is possible to transform such estimated in-plane response into a constitutive law for finite element modelling and perform advanced numerical simulations, by means of a user-supplied subroutine developed for DIANA FEA software. Relevant calculation examples show the accuracy and potential of this integrated approach, which also found application in an ongoing research study on the evaluation of the influence of retrofitted diaphragms' stiffness on the seismic out-of-plane response of masonry gables, as part of the ERIES-SUPREME project, supported by the Engineering Research Infrastructures for European Synergies (ERIES).

Keywords: Timber floors; Plywood; Numerical modelling; Architectural conservation; Seismic retrofitting

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1. Introduction

Unreinforced masonry constructions featuring timber floors as horizontal structural elements, constitute a large part of the building stock in numerous seismic-prone architectural contexts. The observed damage to these buildings already for moderate earthquakes, has highlighted their vulnerability to seismic actions, mainly due to poor-quality masonry, excessive in-plane flexibility of timber floors, and absence of effective connections among structural elements. In this framework, several research studies on seismic characterisation and retrofitting of timber diaphragms (Branco et al. 2015, Brignola et al. 2012, Giongo et al. 2013, Gubana and Melotto 2018, Mirra et al. 2020, Peralta et al. 2004, Pozza et al. 2021, Wilson et al. 2014) and timber-masonry connections (Dizhur et al. 2018, Lin and LaFave 2012, Mirra et al. 2022, Moreira et al. 2012, Riccadonna et al. 2019) have been conducted in the recent years, progressively focusing on more reversible techniques, because of their lower impact on existing buildings, especially when they are monumental or protected (Gubana 2015). In particular, the overlay of plywood panels on the existing sheathing has proved to be a valid and versatile strengthening method, as demonstrated by several investigations and practical applications in different contexts, e.g. in the United States (Peralta et al. 2004), New Zealand (Brignola et al. 2012, Wilson et al. 2014), the Netherlands (Mirra et al. 2021a,b,c), and Italy (Gerardini et al. 2024, Giuriani and Marini 2008, Mirra et al. 2023a,b, Pozza et al. 2021).

Besides improving in-plane strength and stiffness of the existing floors, the plywood-based retrofitting also provides additional capacity in terms of ductility and energy dissipation (Gubana and Melotto 2018, Mirra and Ravenshorst 2021), mainly because of the yielding of the numerous fasteners, provided that effective connections are realized between timber and masonry structural elements (Lin and LaFave 2012, Mirra and Ravenshorst 2022, Mirra et al. 2022, Moreira et al. 2012). Along with such advantages, this strengthening method also features practical benefits from the professional engineering perspective, such as affordability, ease and rapidity of application, compatibility with the existing structure, reversibility, sustainability, and effectiveness (Mirra and Gerardini 2024).

In light of the aforementioned investigations and findings, to promote timber-based seismic retrofitting techniques and facilitate the adoption and application of this strengthening method among professional engineers, this work presents an integrated approach for the design and modelling of plywood-retrofitted diaphragms, through a set of tools developed for this purpose. First, a calculation tool (*ApPlyWood*) was implemented in *Python* programming language, providing an estimate of the full, cyclic in-plane response of the strengthened diaphragms, starting from the geometrical and material properties of existing floor, plywood overlay, and fasteners. Second, a user-supplied subroutine (*SimPlyWood*) for finite element software DIANA FEA (Ferreira 2023) was developed, enabling the numerical simulation of the retrofitted floors' in-plane response through a macro-elements approach, based on the results obtained from the first calculation tool. *ApPlyWood* and *SimPlyWood* are available as a single design and modelling tools collection at: https://doi.org/10.4121/8a09d423-2acc-4c7f-86af-90b5adca4660 (Mirra 2024).

After briefly describing the developed tools and their application (Section 2), the presented integrated approach is adopted in a first calculation example (Section 3), where a reference plywood-retrofitted floor is designed and modelled. Section 4 presents a second example of application of the tools, which were employed in an ongoing research study for evaluating the influence of (retrofitted) diaphragms' stiffness on the seismic out-of-plane response of masonry gables, as part of the ERIES-SUPREME project (ERIES 2024), supported by the Engineering Research Infrastructures for European Synergies (ERIES). Finally, Section 5 reports the concluding remarks of this work.

2. Developed calculation tools

2.1. Design tool (ApPlyWood)

The first step of the integrated approach presented in this work, is the design of the plywood-based retrofitting of the floors. To this end, a calculation tool (*ApPlyWood*, Mirra et al. 2024) was implemented in *Python* programming language, allowing to display the full, cyclic nonlinear in-plane response of the strengthened diaphragms. The software is based on analytical models describing the plastic response of the fasteners joining the plywood panels and the sheathing, and reported in detail in previous studies (Mirra et al. 2021a,c); the implementation and validation of the tool is presented in Mirra (2024). Based on the input values provided by the user, the software determines the in-plane response of a diaphragm (Fig. 1) constructing its backbone curve and deriving the internal pinching cycles.

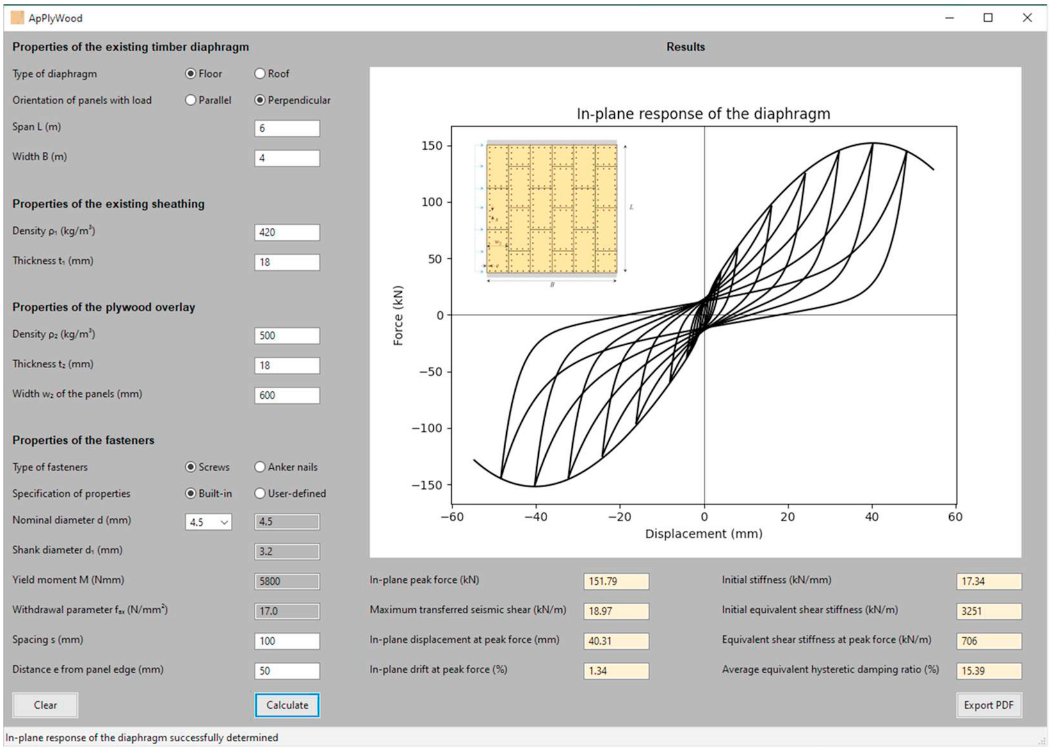

Fig. 1. Example of plywood-based retrofitting design for a 4×6 m^2 floor in *ApPlyWood* calculation tool.

The user needs to first specify the type of diaphragm (floor or roof; the latter case refers to in-plane loaded pitches, where the span to be specified is their inclined length), the panel orientation with respect to the load (parallel or perpendicular), and the main dimensions L and B. During the selection, the user is aided by a schematic picture of the diaphragm showing all required parameters. Next, the material and geometrical properties of both existing sheathing and plywood panels have to be inserted, followed by the characteristics of the fasteners. In this case, the user can specify the utilization of screws or Anker nails, and can refer to built-in properties based on available technical data (Rotho Blaas srl 2023), or user-defined ones, to be manually input. Finally, the spacing and distance from panel edge of the selected fasteners have to be inserted (Fig. 1; Mirra et al. 2024). By pressing the *Calculate* button, on the basis of the analytical formulation in Mirra et al. (2021a), the software plots the estimated nonlinear, cyclic in-plane response of the designed diaphragm, following ISO 16670 (2003), along with a miniature of the selected static scheme. Should an input parameter be missing for any reason, the bottom status bar will indicate it. Otherwise, the bottom status bar displays the statement *In-plane response of the diaphragm successfully determined*, and the button *Export PDF* is enabled. This allows the user to save a one-page PDF report of the graph with the main output values. Finally, the button *Clear* allows to clear all fields and start another calculation (Fig. 1).

Along with the graph of the in-plane response of the retrofitted diaphragm, the tool provides as output the global peak force $F_{max,floor}$; its associated transferred seismic shear $v = F_{max,floor}/(2B)$; the corresponding displacement $d_{max,floor}$ along with the drift γ; the initial stiffness $K_{0,floor}$ and corresponding initial equivalent shear stiffness $G_{d,0}$; the equivalent shear stiffness at peak force G_d, and the average equivalent hysteretic damping ratio ξ_{av} (calculated with the energy loss per cycle method) over all pinching cycles (Fig. 1). These output parameters can be adopted to expeditiously design or assess a retrofitting intervention on a timber floor or roof in an existing building, or as input for numerical models. Besides, the tool can also be employed to assess different retrofitting configurations and optimise the design as a function of desired in-plane strength/stiffness in combination with available budget (Gerardini et al. 2024). *ApPlyWood* is downloadable as *Python* script (optimized for Windows and Mac OS) or standalone executable (for Windows only) at https://doi.org/10.4121/10125465-64bf-46f3-a2e3-d7ce7ae78cf8, and is provided under the GNU General Public License (GPLv3).

2.2. Numerical modelling tools (SimPlyWood)

The developed package of tools for the floors' numerical simulation (*SimPlyWood*), allows to transform the in-plane response of a retrofitted diaphragm estimated with *ApPlyWood* calculation tool into a set of input values for an implemented user-supplied subroutine for DIANA FEA software. DIANA FEA is widely used to assess the structural and seismic response of (existing) masonry structures, and allows utilizers to provide user-supplied materials. In light of the frequent presence of wooden floors and roofs in masonry buildings, an additional tool for the advanced modelling of the seismic response of retrofitted timber diaphragms is beneficial for a more complete structural assessment within the same software. The subroutine was developed considering a macro-element approach as numerical simulation strategy for retrofitted diaphragms, also adopted in previous studies (Scotta et al. 2018, Mirra et al. 2021c, Mirra and Ravenshorst 2021). These macro-elements consisted of quadrilaterals of rigid truss elements, surrounding two diagonal truss elements, in which the nonlinear in-plane behaviour of the floor was implemented adopting the proposed analytical model (Fig. 2). Such modelling strategy proved to be accurate and efficient, enabling to simulate the in-plane response of the diaphragms by means of uniaxial constitutive laws. The macro-elements can also be combined with linear elastic orthotropic plate elements for simulating the out-of-plane (static) response of the floors (Mirra et al. 2021c, Mirra and Ravenshorst 2021).

In order for the user-supplied subroutine to be compatible with the DIANA FEA environment, the constitutive laws for the diagonal trusses of the macro-elements were implemented adopting FORTRAN 90 programming language. Three types of input variables are required by a DIANA FEA subroutine: user-specified initialization variables (not changing within the calculations performed in the subroutine); initial state variables (varying during the calculations performed in the subroutine, for instance to determine loading and unloading points); initial indicator variables (not applicable for this case and set to 0). As output, DIANA FEA requires user-supplied subroutines to provide the stress-strain relation of the material, to be adopted at every calculation step. The subroutine needs four relevant initialization variables as input: the strain ε_{max} at peak stress σ_{max}, the peak stress σ_{max} itself, the initial elastic modulus K_0 (Fig. 2), and a *FASTENER* variable that identifies the fastener type (0 = nails, 1 = screws; based on this, a different yielding stress σ_y is considered: $\sigma_y = 0.4\sigma_{max}$ for nails; $\sigma_y = \sigma_{max}/8$ for screws). These variables are known, once the diaphragm's retrofitting has been designed according to the expected seismic loads, with the support of *ApPlyWood* calculation tool (Mirra 2024). Besides, ten initial state variables were adopted, necessary for describing all loading and unloading branches; their initial value is set to 0. With reference to Fig. 2, these parameters are the maximum strains ever reached in tension and compression ($\varepsilon_{t,max}$ and $\varepsilon_{c,max}$, respectively); the stress-strain coordinates identifying the end of the loading and unloading branches in tension, i.e. points ($\varepsilon_{t,l}$, $\sigma_{t,l}$) and ($\varepsilon_{t,ul}$, $\sigma_{t,ul}$), respectively; the stress-strain coordinates identifying the end of the loading and unloading branches in compression, i.e. points ($\varepsilon_{c,l}$, $\sigma_{c,l}$) and ($\varepsilon_{c,ul}$, $\sigma_{c,ul}$), respectively. Further details on the implementation and the adopted constitutive laws can be found in Mirra et al. (2021c) and Mirra (2024).

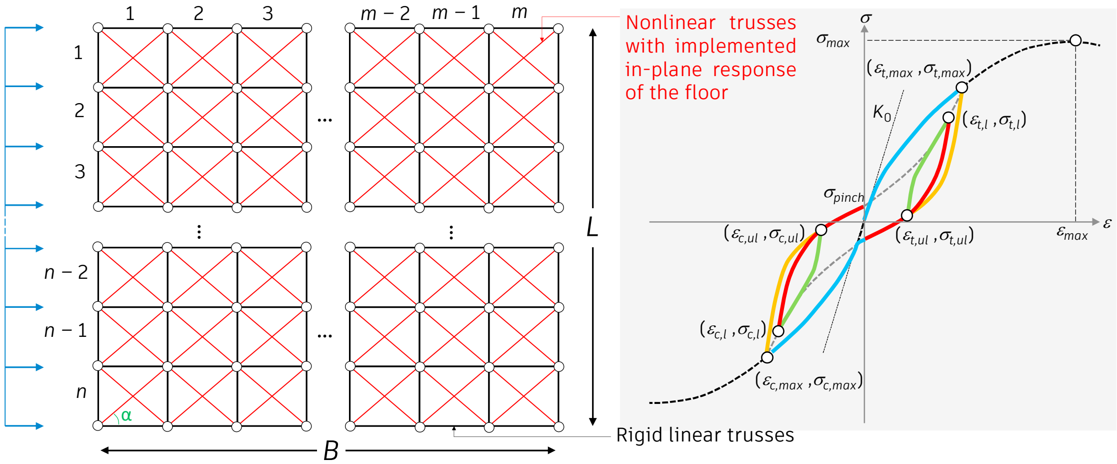

Fig. 2. Principle of the macro-element modelling strategy adopted for simulating the in-plane response of the diaphragms retrofitted with plywood panels. The constitutive laws of the nonlinear diagonal trusses implemented in the user-supplied subroutine are also shown.

The implemented subroutine, part of the *SimPlyWood* package, can be downloaded at the following link: https://doi.org/10.4121/b2588d43-7365-422f-8a73-8071e16c5e1c. Both the original script *SimPlyWood.f90* and the ready-to-use library *SimPlyWood.dll* to be provided in DIANA FEA, are included. Besides, a spreadsheet *SimPlyWood_input* is also present, to directly convert the in-plane response of the retrofitted diaphragm estimated with *ApPlyWood* calculation tool (Section 2.1), to the user-supplied variables to be input in DIANA FEA. In the worksheet, the following parameters from *ApPlyWood* calculation tool have to be inserted: displacement at peak force $d_{max,floor}$, peak force $F_{max,floor}$, initial stiffness $K_{0,floor}$, span L and width B of the diaphragm, fastener type. Next, the number of macro-elements along the span (n) and the width (m) have to be provided (Fig. 2). Assuming for convenience a unitary cross section (1 mm^2) of the nonlinear diagonal trusses, the spreadsheet provides the related user input parameters for DIANA FEA by considering geometrical relationships (Mirra et al. 2021c), based on the macro-elements layout (Fig. 2).

An overview of this workflow is shown in Fig. 3: the users first adopt *ApPlyWood* calculation tool to derive the main output parameters defining the in-plane response of the diaphragm (displacement at peak force, strength, initial stiffness and fastener type), starting from geometrical and material properties of floor and plywood, and mechanical characteristics of fasteners. Next, by means of the spreadsheet *SimPlyWood_input*, these output parameters can be converted into the input values for the user supplied subroutine, by specifying the geometry of the macro-elements' mesh to be modelled in DIANA FEA. Finally, such calculated values can be specified when defining the material properties of the diagonal truss elements in DIANA FEA, where nonlinear numerical analyses can be conducted.

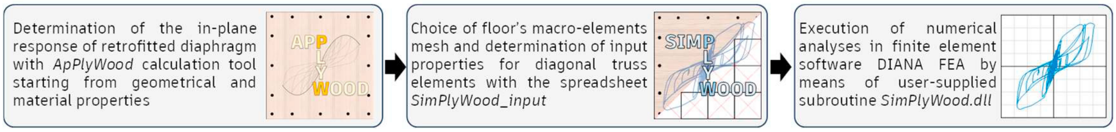

Fig. 3. Workflow of the presented integrated approach.

3. Calculation example: designing and modelling a timber floor retrofitted with plywood panels

As reference example for the utilization of the implemented modelling tools, a floor $B \times L = 4.0 \times 6.0$ m^2 retrofitted with plywood panels of width 600 mm, subjected to an in-plane distributed load perpendicular to their long side, is considered, featuring the properties previously shown in Fig. 1. The panels are fastened by means of 4.5 mm diameter screws (Fig. 1), but also the use of 4.0 mm diameter Anker nails is examined. The numerical model constructed in DIANA FEA 10.4 consisted of six macro-elements along the span and four along the width (Fig. 4a), composed of unitary-cross-section rigid and diagonal truss elements, the latter incorporating the in-plane response of the diaphragm (Section 2.2). The macro-elements were overlapped to linear elastic plate elements, having a thickness of 36 mm (sum of sheathing and plywood thicknesses from Fig. 1), a negligible in-plane stiffness (G_{xy} = 0.1 MPa), and a mass density of 4910 kg/m^3, corresponding to a seismic weight of 1.77 kN/m^2, which incorporated the self-weight of the floor elements, an additional dead load of 1.00 kN/m^2, and 30% of a 2.00 kN/m^2 live load, following the seismic combination of EN 1998-1:2004.

After calculating the in-plane response with *ApPlyWood* tool, the spreadsheet *SimPlyWood_input* was used. By inserting the relevant output values from *ApPlyWood*, the input parameters for DIANA FEA were determined (Fig. 4b, c) and adopted for the user-supplied material of the diagonal truss elements, considering either the retrofitting with screws or nails. The floor was hinged on the short sides and subjected to an earthquake signal, to assess the accuracy of the user-supplied subroutine in representing the diaphragm's in-plane seismic response. Nonlinear dynamic (time-history) analyses were performed, incorporating in the model the user-supplied subroutine library *SimPlyWood.dll*. The obtained floor's in-plane seismic response is reported in Fig. 4d for the configuration with screws, and in Fig. 4e for that featuring nails; the graphs show the seismic shear of the diaphragm against its midspan in-plane deflection. As can be noticed, the adopted modelling strategy and associated subroutine allow to accurately reproduce the full nonlinear behaviour of the strengthened diaphragm, including pinching phenomena. Therefore, the presented approach can support the effective (preliminary) design and advanced numerical modelling of timber diaphragms retrofitted with plywood panels, and has already been adopted in relevant case studies from engineering practice, presented in a companion paper (Mirra and Gerardini 2024).

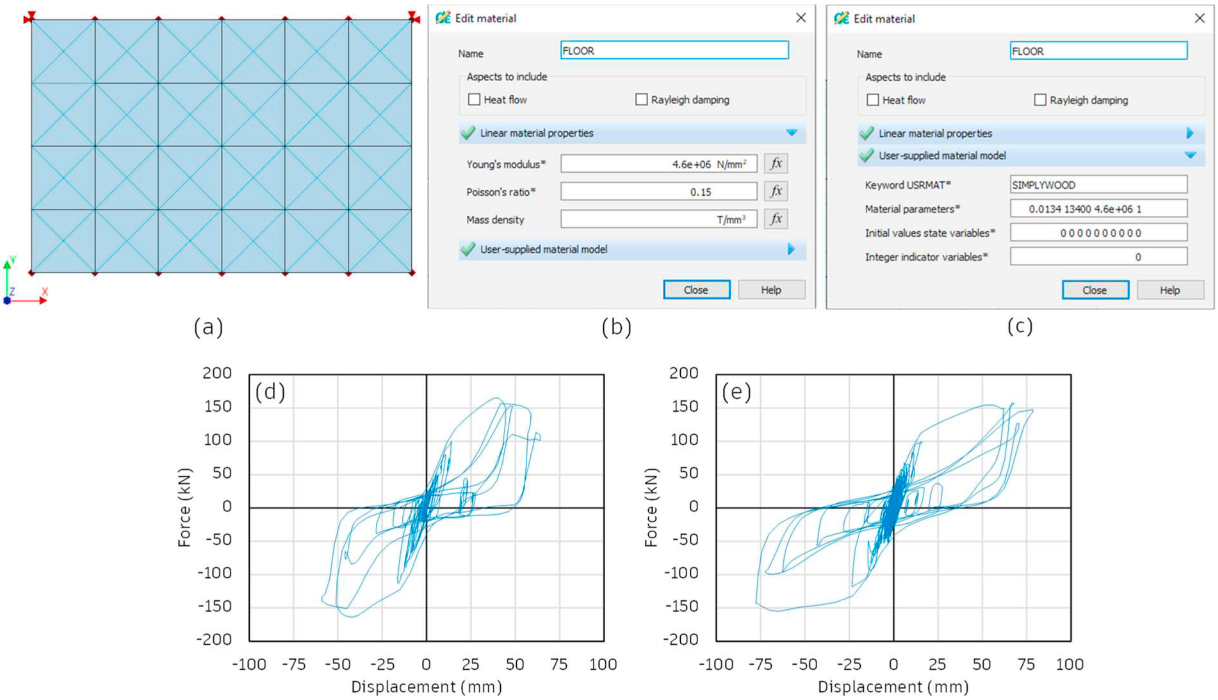

Fig. 4. (a) macro-element model of the reference floor in DIANA FEA; input of the linear material properties (b) and user-supplied material model parameters (c) needed for the user-supplied subroutine as determined from the spreadsheet *SimPlyWood_input*; in-plane seismic responses determined from time-history analyses in DIANA FEA of the floor featuring plywood panels screwed (d) or nailed (e) to the existing sheathing.

4. Utilization of the presented tools within the joint research project ERIES-SUPREME

Within the framework of the Engineering Research Infrastructures for European Synergies (ERIES), the project ERIES-SUPREME (Seismic oUt-of-Plane REsponse of Masonry gablEs), a joint initiative of Delft University of Technology, the Dutch Organisation for Applied Scientific Research (TNO), IUSS EUCENTRE and University of Pavia (ERIES 2024), involves the out-of-plane incremental dynamic testing of three full-scale clay brick masonry gables, considering also their interaction with the connected timber roof structure, which significantly affects their dynamic response. To this end, the 9D LAB facility in Pavia, Italy (EUCENTRE 2023), providing the possibility to apply different motions at two vertical levels, is employed. Although the testing campaign aims to investigate the response of the gables within a masonry building, i.e. connected to the roof structure, the roof diaphragm is not part of the specimen because of the limited dimension of the 9D LAB shake table: for this reason, the interaction with the roof is simulated by varying the input motions of the bottom and top platforms (ERIES 2024). The three tests account for the interaction of the gables with different typologies of roof diaphragms: a rigid roof, a flexible roof, and a semi-rigid retrofitted roof. In particular, the rigid roof configuration is obtained by imposing the same input seismic excitation at both top and bottom platforms of the 9DLAB, whereas the semi-rigid retrofitted and flexible roof configurations are reproduced by applying distinct input motions to the bottom and top platforms.

Such motions are defined based on the results of supporting numerical studies, designed to quantify the amplification of the seismic excitations through flexible as-built and semi-rigid roofs. Since the latter case is representative for roofs retrofitted with plywood panels, the benefits provided by this timber-based strengthening solution towards improving the out-of-plane seismic capacity of gables, can be quantified within this research project. Therefore, the approach presented in the present work is adopted for performing a detailed numerical modelling of the in-plane response of a semi-rigid plywood-retrofitted timber roof within a reference masonry buildings, to finally determine the seismic input motions at the top and bottom of the gable, to be applied in the experimental shake-table tests (Fig. 5, ERIES 2024).

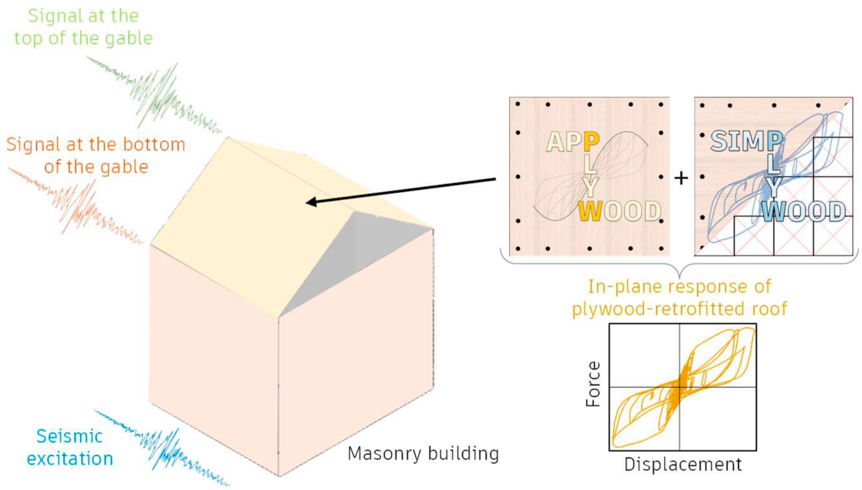

Fig. 5. Principle for the utilization of the developed design and modelling tools for the prediction of the seismic response of masonry gables in a building featuring a plywood-retrofitted timber roof, within the framework of the ongoing ERIES-SUPREME project.

5. Conclusions

This paper has presented a set of tools supporting the design and advanced numerical modelling of plywood-based seismic retrofitting interventions on existing timber diaphragms. The developed calculation tool *ApPlyWood* allows the users to obtain an estimate of strength, stiffness, and dissipative properties of diaphragms retrofitted with plywood panels, as well as to visualize their nonlinear, cyclic response. The implemented user-supplied subroutine (*SimPlyWood*) for DIANA FEA software enables the numerical simulation of the in-plane seismic response of the retrofitted diaphragms, by means of a macro-element modelling strategy. Through a dedicated spreadsheet, the output values from *ApPlyWood* calculation tool can be transformed into the input parameters, to be provided in DIANA FEA, for the constitutive laws of the macro-elements simulating the in-plane response of the floors. The reported calculation example shows that the adopted modelling strategy can be utilized to effectively simulate the nonlinear seismic behaviour of the diaphragms, as proved by the presented results from time-history analyses conducted on a reference 4×6 m diaphragm retrofitted with screwed or nailed plywood panels.

In conclusion, the developed tools can be used to both obtain preliminary indications and calibrate the retrofitting interventions according to the specific needs of a building, supporting an integrated approach for design and modelling of the diaphragms, and relying on the adaptability and versatility of the plywood-based strengthening method. The presented approach has already been adopted in engineering practice, as reported in a companion paper (Mirra and Gerardini 2024), as well as in support of research project ERIES-SUPREME, funded by the Engineering Research Infrastructures for European Synergies (ERIES), and focusing on the evaluation of the influence of (retrofitted) diaphragms' stiffness on the seismic out-of-plane response of masonry gables. The collection of tools described in this paper can be downloaded at: https://doi.org/10.4121/8a09d423-2acc-4c7f-86af-90b5adca4660.

The outcomes of this work can contribute to the research framework supporting the use of timber-based techniques for the seismic upgrading and architectural conservation of existing and historical structures.

References

Branco, J. M., Kekeliak, M., Lourenço, P.B., 2015. In-Plane Stiffness of Timber Floors Strengthened with CLT. European Journal of Wood and Wood Products 73, 313-323.

Brignola, A., Pampanin, S., Podestà, S., 2012. Experimental Evaluation of the In-Plane Stiffness of Timber Diaphragms. Earthquake Spectra 28(4), 1–23.

Dizhur, D., Giaretton, M., Ingham, J.M., 2018. URM wall-to-diaphragm and timber joist connection testing. Proceedings of the 10th International Masonry Conference, Milan, Italy.

EN 1998-1:2004. Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. Comité Européen de Normalisation (CEN), Brussels, Belgium.
ERIES, 2024. www.eriessupreme.com.
EUCENTRE, 2023. 9D LAB facility opening, https://youtu.be/iQ5h3lcCRSQ.
Ferreira, D., 2023. DIANA Finite Element Analysis Unser's Manual. DIANA FEA BV, Delft, The Netherlands.
Gerardini, A., Mirra, M., Boroni, A., 2024. Design strategies for seismic retrofit of an ancient masonry church with a dissipative timber system. World Conference on Earthquake Engineering, Milan, Italy.
Giongo, I., Dizhur, D., Tomasi, R., Ingham, J.M., 2013. In-plane assessment of existing timber diaphragms in URM buildings via quasi-static and dynamic in-situ tests. Advanced Materials Research 778, 495-502.
Giuriani, E., Marini, A., 2008. Wooden roof box structure for the anti-seismic strengthening of historic buildings. International Journal of Architectural Heritage 2, 226–246.
Gubana, A., 2015. State-of-the-Art Report on high reversible timber to timber strengthening interventions on wooden floors. Construction and Building Materials 97, 25–33.
Gubana, A., Melotto, M., 2018. Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors. Construction and Building Materials 191, 290–299.
ISO 16670:2003. Timber structures — Joints made with mechanical fasteners — Quasi-static reversed-cyclic test method, International Organization for Standardization (ISO), Geneva, Switzerland.
Lin, T.-J., LaFave J.M., 2012. Experimental Structural Behavior of Wall-Diaphragm Connections for Older Masonry Buildings. Construction and Building Materials 26, 180-189.
Mirra, M., 2024. A set of calculation tools supporting the design, modelling and application of plywood-based seismic retrofitting interventions on timber floors in existing buildings. Structures 63, 106378. https://doi.org/10.1016/j.istruc.2024.106378
Mirra, M., Gerardini, A., 2024. Design and modelling tools for timber-based seismic retrofitting: from research to practice. 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Salerno, Italy.
Mirra, M., Gerardini, A., Ghirardelli, S., Ravenshorst, G., van de Kuilen, J.W., 2023a. Combining architectural conservation and seismic strengthening in the wood-based retrofitting of a monumental timber roof: the case study of St. Andrew's Church in Ceto, Brescia, Italy. International Journal of Architectural Heritage. https://doi.org/10.1080/15583058.2023.2187726
Mirra, M., Gerardini, A., Ravenshorst, G., 2023b. Application of timber-based techniques for seismic retrofit and architectural restoration of a wooden roof in a stone masonry church. Procedia Structural Integrity 44, 1856–1863. https://doi.org/10.1016/j.prostr.2023.01.237
Mirra, M., Gerardini, A., Ravenshorst, G., 2024. Development of design tools for plywood-based seismic retrofitting of existing timber floors. World Conference on Earthquake Engineering, Milan, Italy.
Mirra, M., Ravenshorst, G., 2021. Optimizing Seismic Capacity of Existing Masonry Buildings by Retrofitting Timber Floors: Wood-Based Solutions as a Dissipative Alternative to Rigid Concrete Diaphragms. Buildings 11(12), 604. https://doi.org/10.3390/buildings11120604
Mirra, M., Ravenshorst, G., 2022. A seismic retrofitting design approach for activating dissipative behavior of timber diaphragms in existing unreinforced masonry buildings. Eighth International Conference on Structural Engineering, Mechanics and Computation (SEMC 2022), Cape Town, South Africa. https://doi.org/10.1201/9781003348443-312
Mirra, M., Ravenshorst, G., de Vries, P., Messali, F., 2022. Experimental characterisation of as-built and retrofitted timber-masonry connections under monotonic, cyclic and dynamic loading. Construction and Building Materials 358, 129446. https://doi.org/10.1016/j.conbuildmat.2022.129446
Mirra, M., Ravenshorst, G., van de Kuilen, J.-W., 2020. Experimental and analytical evaluation of the in-plane behaviour of as-built and strengthened traditional wooden floors. Engineering Structures 211, 110432. https://doi.org/10.1016/j.engstruct.2020.110432
Mirra, M., Ravenshorst, G., van de Kuilen, J.-W., 2021a. An analytical model describing the in-plane behaviour of timber diaphragms strengthened with plywood panels. Engineering Structures 235, 112128. https://doi.org/10.1016/j.engstruct.2021.112128
Mirra, M., Ravenshorst, G., van de Kuilen, J.-W., 2021b. Comparing in-plane equivalent shear stiffness of timber diaphragms retrofitted with light and reversible wood-based techniques. Practice Periodical on Structural Design and Construction 26(4). https://doi.org/10.1061/(ASCE)SC.1943-5576.0000602
Mirra, M., Sousamli, M., Longo, M., Ravenshorst, G., 2021c. Analytical and numerical modelling of the in-plane response of timber diaphragms retrofitted with plywood panels. 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2021), Athens, Greece. https://2021.compdyn.org/proceedings/pdf/18731.pdf
Moreira, S., Oliveira, D.V., Ramos, L.F., Lourenço, P.B., Fernandes, R.P., Guerreiro, J., 2012. Experimental study on the seismic behavior of masonry wall-to-floor connections. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, Portugal.
Peralta, D.F., Bracci, M.J., Hueste, M.B.D., 2004. Seismic Behavior of Wood Diaphragms in Pre-1950s Unreinforced Masonry Buildings. Journal of Structural Engineering 130(12).
Pozza, L., Marchi, L., Trutalli, D., Scotta, R., 2021. In-plane strengthening of masonry buildings with timber panels. Proceedings of the Institution of Civil Engineers – Structures and Buildings 174(5), 345–358.
Riccadonna, D., Giongo, I., Schiro, G., Rizzi, E., Parisi, M.A., 2019. Experimental shear testing of timber-masonry dry connections for the seismic retrofit of unreinforced masonry shear walls. Construction and Building Materials 211, 52-72.
Rotho Blaas Srl, 2023. Timber screws and deck fastening. Technical data catalogue, Cortaccia, Italy.
Scotta, R., Trutalli, D., Marchi, L., Pozza, L., 2018. Seismic performance of URM buildings with in-plane non-stiffened and stiffened timber floors. Engineering Structures 167, 683-694.
Wilson, A., Quenneville, P.J.H., Ingham, J.M., 2014. In-plane orthotropic behavior of timber floor diaphragms in unreinforced masonry buildings. Journal of Structural Engineering 140 (1).