Dissipative properties of timber diaphragms strengthened with plywood panels

Mirra, Michele; Ravenshorst, Geert; van de Kuilen, Jan Willem

Publication date
2021

Document Version
Accepted author manuscript

Citation (APA)
Mirra, M., Ravenshorst, G., & van de Kuilen, J. W. (2021). *Dissipative properties of timber diaphragms strengthened with plywood panels*. Paper presented at World Conference on Timber Engineering 2021, WCTE 2021, Santiago, Chile.

WCTE 2021
WORLD CONFERENCE ON TIMBER ENGINEERING
SANTIAGO, CHILE | 9 - 12 AUGUST

DISSIPATIVE PROPERTIES OF TIMBER DIAPHRAGMS STRENGTHENED WITH PLYWOOD PANELS

Michele Mirra[1], Geert Ravenshorst[1], Jan-Willem van de Kuilen[1,2]

ABSTRACT: In the field of seismic retrofitting, a common intervention to improve box-like behaviour in an existing building is the strengthening and stiffening of existing timber floors and roofs. However, these retrofitting methods should be carefully applied, because they change the static scheme and the buildings' response to earthquakes. Strengthening solutions with high reversibility and light weight have therefore to be preferred, and in this context the overlay of plywood panels on existing floors can improve their characteristics in terms of strength and stiffness, but also enhance their energy dissipation, already at a very limited deflection. This strengthening technique was adopted and tested within an experimental campaign aimed at assessing the seismic response of timber diaphragms with typical characteristics from the Groningen area, located in the northern part of the Netherlands. In that region, human-induced earthquakes take place due to gas extraction and the existing buildings are not suitable to safely withstand these seismic events. This paper presents a summary of the results of the experimental campaign on as-built and retrofitted timber diaphragms, and evaluates the beneficial damping properties of floors strengthened with plywood panels, connected only to the underlying planks and not directly to the joists. The results are compared with the data available in literature and provide new reference values for the coming version of the Dutch seismic standard.

KEYWORDS: Timber diaphragms, Plywood panels, Damping, Existing buildings, Retrofitting

1 INTRODUCTION

Human-induced earthquakes have recently started to take place in the region of Groningen, in the northern part of the Netherlands, due to gas extraction. Since these events were unknown until a few years ago, the current building stock cannot safely withstand the expected seismic actions. These buildings are mainly composed of unreinforced single-leaf or double-wythe brick masonry walls, and timber diaphragms (floors and roofs). Masonry walls are slender and have poor characteristics, while timber diaphragms are composed of small structural elements, and are therefore very flexible in their plane. In this context, a characterization of as-built timber diaphragms took place, and retrofitting measures were defined afterwards: given the vulnerability of the building stock, it was decided to adopt a strengthening technique which could not only increase strength and stiffness of the floors, but also improve their energy dissipation, even with a limited deflection. Such a dissipative contribution could therefore be beneficial to the seismic response of a whole building.
A literature survey has shown that an overlay of plywood panels fastened to the existing sheathing proves to be quite effective in combining all these desired properties. In [1], as-built and strengthened floors were studied with a view to the US context, and the influence of panels' blocking was discussed as well. In addition, both existing and retrofitted timber diaphragms with features from New Zealand were studied in [2]. In [3], the tests focused also on the orthotropic behaviour of the diaphragms. All Authors reported a great improvement in strength, stiffness and energy dissipation of the floors after strengthening them with plywood panels.
In this work, the seismic response of timber diaphragms with Dutch features is analysed, focusing especially on their dissipative properties after retrofitting them with plywood panels screwed to the sheathing around their perimeter. Unlike the previous research studies, the panels do not have large dimensions and are placed only accounting for the underlying layer of planks, without having to consider also joists' spacing and thus allowing an easier installation. This produces a lower stiffening effect on the floor, but the resulting slightly larger deflection allows higher friction among panels and plasticization of screws, with great energy dissipation.
Firstly, a summary of the conducted experimental campaign will be presented: after extracting original samples from existing houses, replicated specimens were constructed, and cyclic tests were performed on as-built and retrofitted full-scale diaphragms [4]. Secondly, a value of equivalent damping ratio [5] was quantified for the strengthened floors, and validated afterwards by means of numerical analyses. These results were then compared to both the values calculated from data available in literature, and the current suggested values in the Dutch seismic standard NPR 9998 [6].

[1] Michele Mirra, M.Mirra@tudelft.nl
Geert Ravenshorst, G.J.P.Ravenshorst@tudelft.nl
Jan-Willem van de Kuilen, J.W.G.vandeKuilen@tudelft.nl
Delft University of Technology, Faculty of Civil Engineering and Geosciences, Biobased Structures and Materials, P.O. Box 5048, 2600 GA Delft, The Netherlands
[2] Jan-Willem van de Kuilen, vandekuilen@hfm.tum.de
Technical University of Munich, Wood Technology, Winzererstrasse 45, 80797 Munich, Germany

2 MATERIALS AND METHODS

2.1 MATERIALS

After a survey in the most common typologies of traditional timber diaphragms in the Groningen area, four representative samples were extracted from existing detached houses (built between 1890 and 1930) to be demolished: three of them were wooden floors, while the fourth was part of a pitched roof.

On the basis of the detected material properties of the extracted samples, replicated specimens were built accordingly and compared to the original ones, also in terms of cyclic response of nailed plank-joist connections [4]. As can be noticed from Table 1 and Figure 1, both material properties and cyclic behaviour of connections proved to be quite similar between extracted and replicated samples. Thus, good accuracy in the replication was achieved, and the tested diaphragms' response was representative for the existing floors' one.

Figure 2 shows the geometry and characteristics of the tested replicated diaphragms. The samples were constructed to be tested in a vertical configuration and in two directions, parallel and perpendicular to the joists. Four specimens were floors and one was a roof pitch: Table 2 reports the adopted nomenclature and testing direction. All structural elements were made of spruce (*Picea Abies*) timber with strength class C24 [7]. The diaphragms were retrofitted with 18-mm-thick plywood panels screwed to the existing sheathing; the shear transfer was also improved with additional fasteners (samples *DFpar-1s* and *DFpar-2s*) or elements (timber blocks for sample *DFpar-4s*, steel angles for specimen *DRpar-5s*). Further details can be found in [4].

Table 1: *Average material properties of timber structural elements of extracted and replicated samples [4]; in parentheses the coefficient of variation is shown*

Property	Extracted samples	Replicated samples
Density (kg/m^3)	481 (0.10)	474 (0.10)
Elastic modulus (MPa)	12990 (0.18)	11830 (0.21)
Moisture content (%)	9.2 (0.02)	11.3 (0.16)

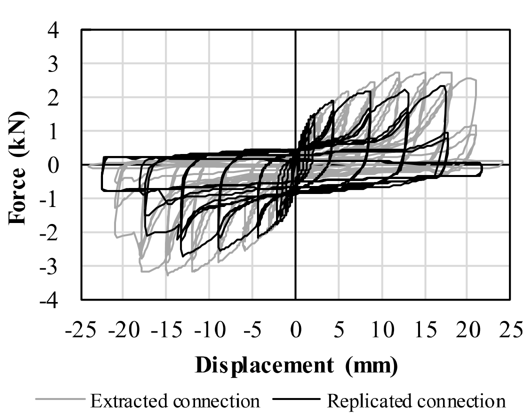


Figure 1: *Comparison between the cyclic response of extracted and replicated plank-joist connections [4]*

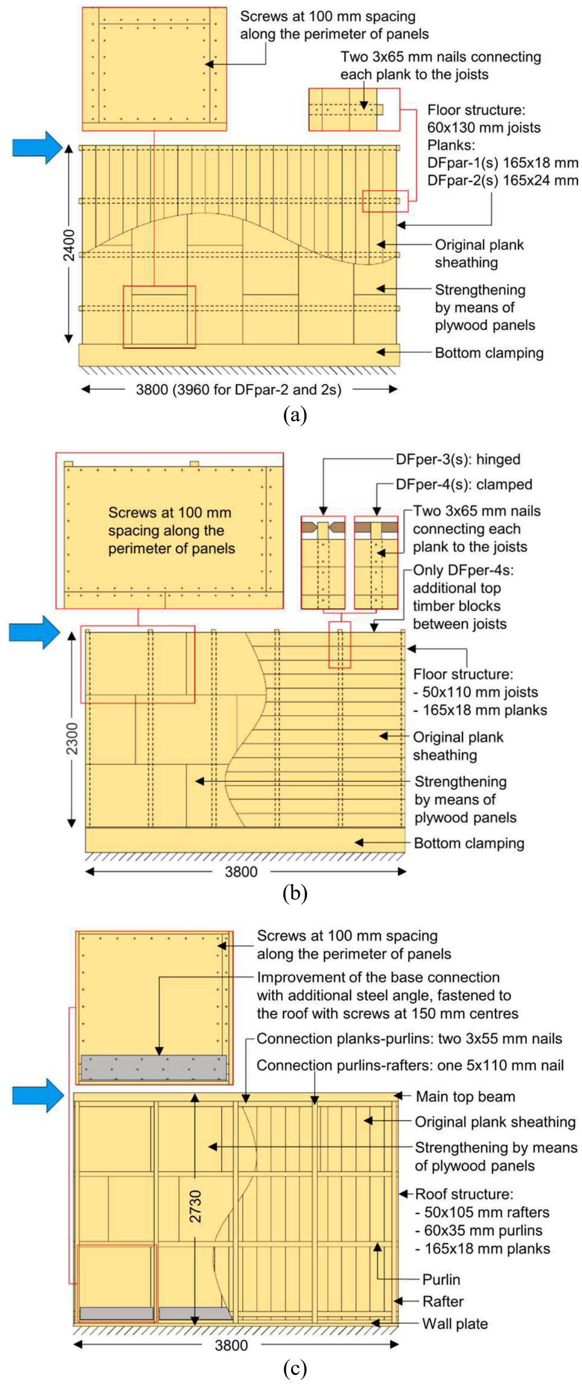


Figure 2: *Tested timber diaphragms: (a) parallel to the joists, (b) perpendicular to the joists, (c) roof sample [4]; all reported dimensions are in mm*

Table 2: *Overview of the tested samples [4]*

As-built sample	Strengthened sample	Testing direction
DFpar-1	DFpar-1s	// to joists
DFpar-2	DFpar-2s	// to joists
DFper-3	DFper-3s	⊥ to joists
DFper-4	DFper-4s	⊥ to joists
DRpar-5	DRpar-5s	// to purlins

2.2 METHODS

2.2.1 Experimental tests on timber diaphragms

As can be noticed from Figure 2, it was chosen to test in a vertical configuration half of a diaphragm, according to the principle of symmetry, by clamping its bottom part (centre of symmetry of the floor). In this way, the applied force corresponded to the reaction that the floor was able to bear. The test setup is shown in Figure 3: each diaphragm was glued to a bottom steel beam, connected directly to the laboratory floor. The horizontal cyclic displacement was introduced by means of a laminated veneer lumber (LVL) I-beam, fastened to the top joist, when loading parallel to the floor's beams, or to the wooden blocks shown in Fig. 2b, for the orthogonal direction. Out-of-plane displacements of the LVL I-beam were prevented with vertical steel elements, covered with Teflon to allow low-friction sliding.

The testing protocol for cyclic loading according to ISO 21581 [8] was adopted, with a variable rate to achieve the ultimate displacement between 1 and 30 minutes. As-built samples were firstly tested without bringing them to failure; then, the plywood panels overlay was applied and the diaphragms were tested again in their retrofitted configuration [4].

2.2.2 Analytical evaluation of damping properties

The tested as-built samples exhibited an approximately linear elastic response, with limited energy dissipation and a low in-plane stiffness, as reported in Section 3.1. On the contrary, all strengthened diaphragms displayed a relevant improvement in these characteristics. The potential beneficial effect of dissipative retrofitted floors was quantified in terms of an equivalent damping ratio ξ, evaluated with the energy loss per cycle method [5]:

$$\xi = \frac{E_d}{2\,\pi\,E_e} \tag{1}$$

In Equation (1), E_d is the energy dissipated in one full cycle, i.e. the area enclosed in it, and E_e is the corresponding elastic energy, as shown in Figure 4.

The adopted testing protocol [8] consisted of several displacement steps to be applied, each one composed of three cycles. In order to thoroughly characterize the diaphragms' dissipative properties, E_d was evaluated for all three cycles, and for each step until a drift of approximately 1%, corresponding to a 25 mm diaphragm's deflection. This allowed to analyse, within a reasonably limited drift range, the effect on ξ of progressive strength and stiffness degradation. Besides, such a testing protocol, with several displacement steps very close to each other, led to a conservative estimation of ξ, because during a short, induced earthquake, a timber diaphragm is expected to undergo only a limited number of large-amplitude cycles, thus with lower degradation compared to the performed quasi-static tests. Based on the results of this analytical calculation, a single average ξ value was derived for the tested diaphragms. This was compared to the values calculated from literature [1–3] and to the one prescribed in the current Dutch seismic design standard NPR 9998 [6], assigning $\xi = 0.06$ to timber floors.

Figure 3: Setup for in-plane tests on timber diaphragms

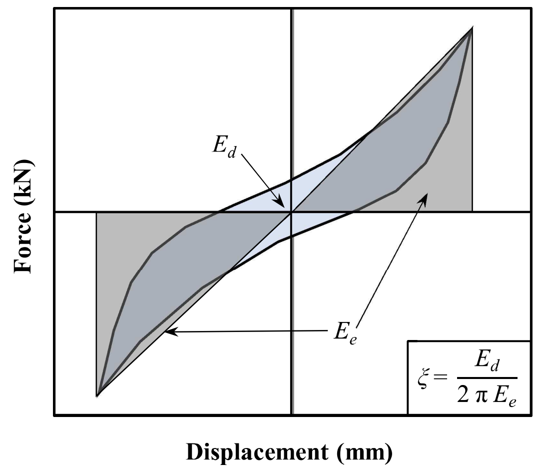


***Figure 4:** Determination of the equivalent damping ratio from the energy dissipated in one full cycle and the corresponding elastic energy*

2.2.3 Numerical validation of damping values

After having determined an average reference damping value for the tested diaphragms, numerical time-history analyses were performed to validate it. A procedure similar to the one presented in [9] was adopted. Two numerical models were created: a first one including the full nonlinear properties of the diaphragms; the other one with linear elastic equivalent characteristics, i.e. the calculated ξ value, and the stiffness at a reference drift of 0.5%. The analytically found ξ value was validated by comparing the responses obtained with the two modelling strategies. In fact, if the results of the simplified equivalent model are very similar to those of the more refined nonlinear one, and all relevant properties of interest are properly captured (peak force and displacement, among others), then the calculated ξ can be considered a reliable value, because it correctly represents the energy dissipation provided by the retrofitted floors during seismic loading.

The numerical models were developed using the software *OpenSees* [10], due to its good nonlinear representation of the diaphragms' behaviour, especially in terms of pinching phenomenon. Figure 5a depicts the adopted modelling strategy, analogous to [11]: the floor was discretized in macro-elements, each one composed of a quadrilateral of rigid truss elements, and a diagonal spring containing the diaphragms' properties. In the nonlinear model, for these springs the *Pinching4* material [12] from OpenSees library was implemented, while for the linearized equivalent model, the springs were simply linear elastic elements.

By knowing the force-displacement relation of the whole diaphragm, the constitutive law for the single diagonal spring was defined according to geometrical considerations: the correct calibration of the model was verified by performing a cyclic analysis on the floor, and comparing the response with the experimental results. Figure 5b shows an example of calibration of the nonlinear model for sample *DFpar-1s*: good accuracy in representing the floors' response is observable, also in terms of energy dissipation.

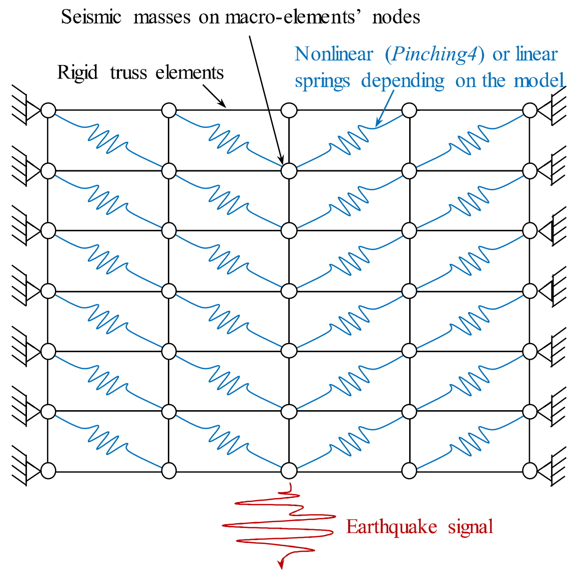
After this first step, time-history analyses were performed for both nonlinear and linearized models. Seismic masses were assigned to the nodes of the macro-elements, and were computed accounting for the self-weight of both floor and surrounding masonry walls, and for 30% of the live load, according to the usual seismic load combination of EN 1990 [13]. The chosen seismic signal (Figure 5c) corresponded to the recorded human-induced shallow earthquake occurred in Zeerijp (NL), in 2018. This signal was properly scaled in order to bring each diaphragm at a 0.5% drift, where also the equivalent stiffness K_{eq} to be adopted in the linearized model was determined (see again Figure 5b). In this way, it was possible to assess the damping contribution of the timber diaphragms for reasonably limited deflections.

3 RESULTS

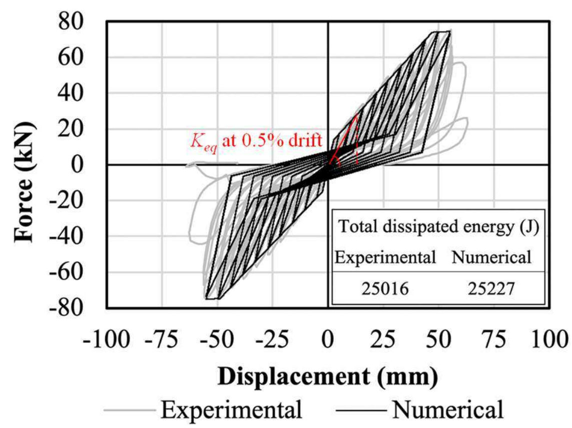
3.1 CYCLIC TESTS ON TIMBER DIAPHRAGMS

Five diaphragms were tested in their as-built and strengthened configurations, for a total of ten tests. The obtained results are reported in the graphs of Figure 6. The improvement in terms of in-plane strength and stiffness of retrofitted diaphragms is immediately noticeable, as well as their enhanced dissipative behaviour compared to as-built ones. Furthermore, the response changed from more flexural-related to shear-related after applying the plywood panels overlay, as thoroughly discussed in [4], and observed also in [2].

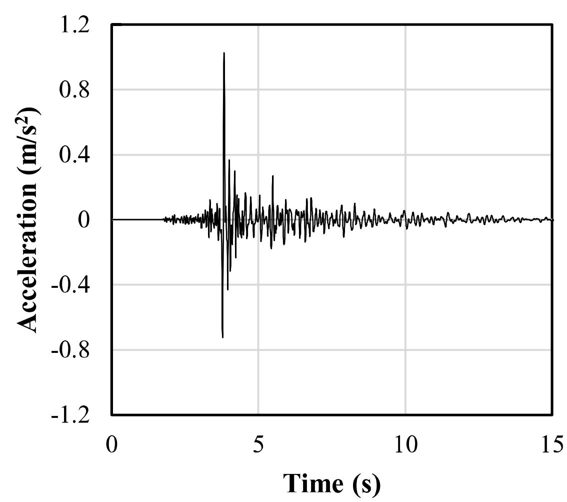
The hysteretic cycles of samples tested parallel to the joists are shown in Figure 6a. As-built diaphragms displayed an approximately elastic response, with very limited in-plane stiffness and energy dissipation; their behaviour was mainly related to the flexural stiffness of the planks. Strengthened diaphragms exhibited a great improvement in properties, and the stiffer response of sample *DFpar-2s* was related to both the effect of thicker planks and the more accurate panels' positioning and fastening, compared to specimen *DFpar-1s*. The test on floor *DFpar-2s* had to be ended prematurely, due to the failure of the glue layer at its bottom. Yet, the reached drift enabled a proper seismic characterization, even if the floor's ultimate strength was not activated.



(a)



(b)



(c)

Figure 5: *Adopted modelling strategy with macro-elements (a), results of the calibration of the nonlinear model for sample DFpar-1 (b), adopted seismic signal from 2018 human-induced Zeerijp earthquake (c)*

The in-plane behaviour of samples tested orthogonally to the joists is shown in Figure 6b. As-built specimens displayed a very flexible response, mainly related to the flexural stiffness of the joists. With both strengthened floors (samples *DFper-3s* and *DFper-4s*) a large improvement is noticeable, but the presence of timber blocks in specimen *DFper-4s* enabled to almost eliminate the otherwise orthotropic behaviour of the diaphragms: it was, in fact, possible to reach in-plane stiffness values similar to those obtained for the strengthened floors tested parallel to the joists.

Finally, the response of the roof pitch is depicted in Figure 6c. In this last case, the as-built sample was characterized by a very low stiffness, due to its particular structural configuration. The presence of the plywood panels overlay, as well as of the steel angles to increase the shear transfer, radically improved the in-plane behaviour of the sample. This is particularly relevant, because the roof could frequently be a weak part of existing buildings, and also for the Dutch context, where gables are often composed of single-leaf masonry walls.

Therefore, on the basis of the obtained results, the proposed retrofitting techniques appeared to be quite effective in improving the in-plane behaviour of timber diaphragms. Due to the high level of energy dissipation observed, further analyses were conducted to evaluate the damping characteristics of the retrofitted diaphragms. This aspect, discussed in section 3.2, is of relevance because the current provisions of NPR 9998 [6] assign only a very limited equivalent damping ratio to timber floors. The present value of $\xi = 0.06$ can be regarded as reliable for as-built diaphragms, because of their limited dissipative role, but constitutes a large underestimation when considering the high energy dissipation achieved with the proposed retrofitting technique.

3.2 EQUIVALENT DAMPING RATIO VALUES FOR THE RETROFITTED DIAPHRAGMS

3.2.1 Analytical calculation

By adopting the formulation presented in section 2.2.2, for each tested retrofitted diaphragm the equivalent damping ratio ξ was evaluated with Equation (1) for the initial displacement steps, up to approximately 1% drift. Since every step was composed of three cycles, the graphs of Figure 7 show the evolution of ξ in relation to the drift for each cycle.

As can be noticed, the dissipative contribution of the diaphragms is relevant, and especially in the initial displacement range, which can be of interest for buildings subjected to light, human-induced earthquakes. Values of ξ from 0.10 to 0.20 were calculated, with the effect of degradation becoming noticeable after 0.5% drift: ξ decreases not only by furtherly increasing the drift, but also among the three cycles within a same step. On the basis of the chosen displacement range, it was possible to define reference average values, displayed in Figure 8: up to 0.5% drift, $\xi = 0.15$ can be assumed, while up to 1% drift, $\xi = 0.14$ was obtained due to the larger effect of cyclic strength and stiffness degradation. These reference values are 2.5 times higher compared to the currently proposed ones in NPR 9998.

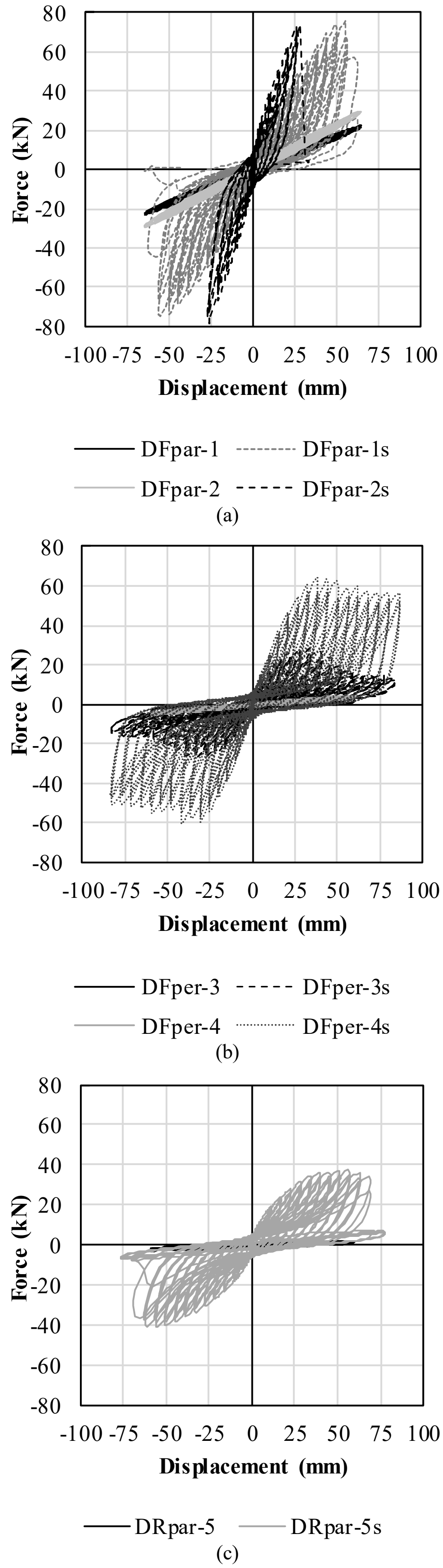


Figure 6: *Cyclic response of as-built and strengthened floors tested parallel (a) and perpendicular (b) to the joists, and of the roof pitch (c) [4]*

Another interesting observation is linked to the comparison of the calculated values for the tested diaphragms with the ones estimated from literature, both at 0.5% drift (Figure 9). Clear similarities are observable, and this confirms the great potential of the proposed technique, because high dissipation and improvement in strength and stiffness can be achieved even for light and very flexible diaphragms with small structural elements, like Dutch ones.
After determining average reference values as a function of the expected floors' drift range, these were numerically validated according to the methodology illustrated in section 2.2.3. The results of the validation are presented in section 3.2.2.

3.2.2 Numerical validation

The analytically obtained ξ values were validated through a comparison between time-history analyses carried out with two numerical models: a nonlinear one, in which the diaphragms' response was completely represented, and a linearized one, in which only the equivalent stiffness described the floors' behaviour, together with the evaluated reference ξ.
This comparison enabled to check, similarly to the procedure presented in [9], the reliability of the equivalent damping values. When ξ is correctly estimated, the time-history analysis with the linearized model should provide values of peak force and displacement that are very close to those derived from the analysis carried out with the nonlinear model.
An example of this evaluation is given in Figure 10, showing the response of floor *DFpar-1s* to the adopted seismic signal of the Zeerijp earthquake. The comparison between nonlinear and linearized model is shown in terms of force-displacement and displacement-time graphs. As can be noticed, the nonlinear model, in which the floor's dissipation is brought into play, displayed a response very similar to the linearized model, having the floor's equivalent secant stiffness at 0.5% drift and the derived average ξ value.
Thus, the estimation of the equivalent damping value appeared to be reliable, because both peak force and displacement were well captured by the linearized model. At the same time, the initial portion of mid-span displacement time-history, containing also the peak drift, was very similar for the two models, apart from the inevitable differences in terms of period: for the nonlinear model, this evolved throughout the analysis, while for the linearized one it was constant and linked to the stiffness at 0.5% drift.
These similarities in the time-history response of the nonlinear and linearized models, here reported for sample *DFpar-1s*, were observed for all other specimens, thus confirming for the retrofitted diaphragms the derived reference ξ value of 0.15 at 0.5% drift.

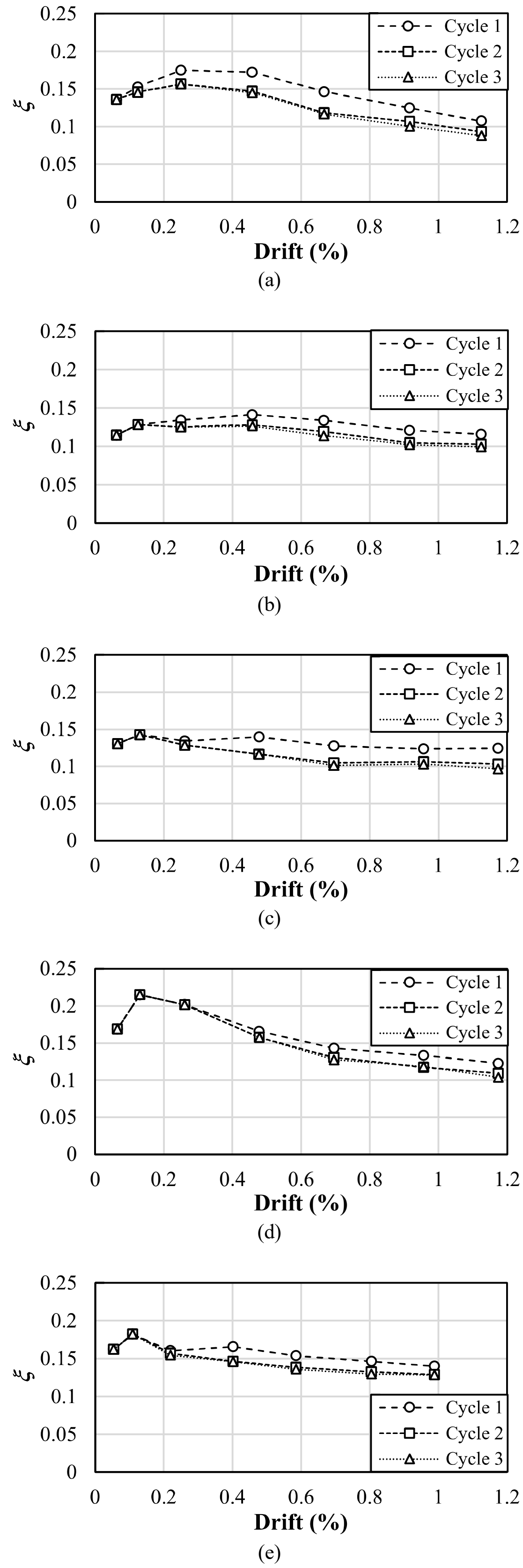


Figure 7: *Evaluation of equivalent damping ratio for the retrofitted timber diaphragms as a function of drift: sample DFpar-1s (a), DFpar-2s (b), DFper-3s (c), DFper4-s (d), DRpar-5s (e)*

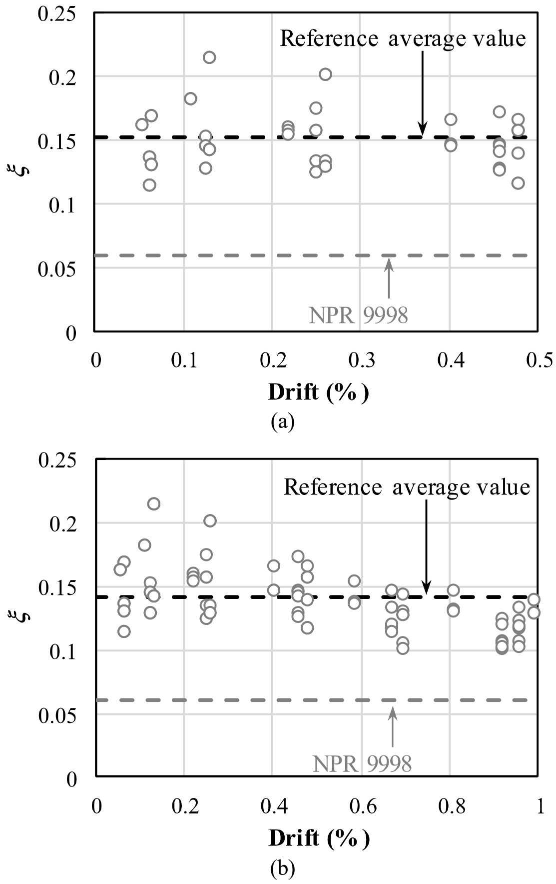


Figure 8: *Estimation of a reference average value of equivalent damping ratio up to 0.5% (a) and 1% drift (b), in comparison to the present value proposed in NPR 9998; the dots correspond to analytically calculated values*

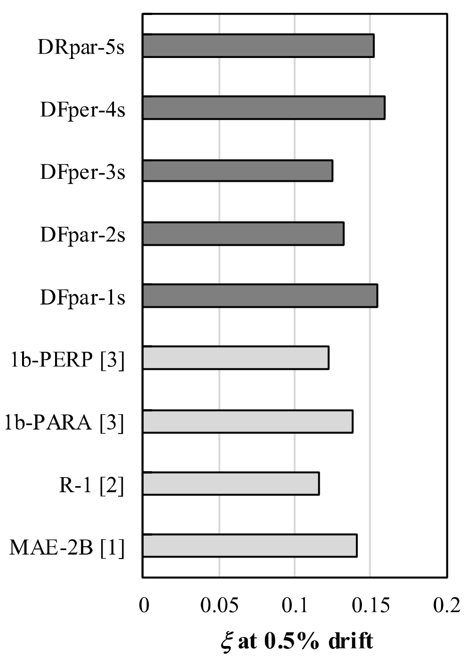


Figure 9: *Comparison at 0.5% drift between the values of equivalent damping ratio of the tested samples and the ones of specimens from literature*

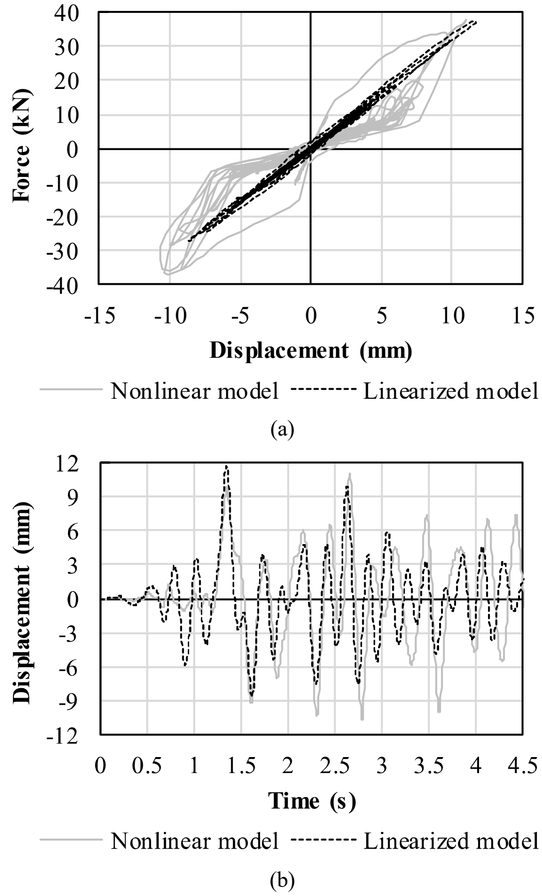


Figure 10: *Comparison between the responses of the nonlinear and linearized models for floor DFpar-1s, in terms of force-displacement (a) and displacement-time behaviour (b)*

4 CONCLUSIONS

Retrofitting timber diaphragms with small-size plywood panels screwed along their perimeter considerably improves their seismic performance and dissipative properties, if compared to the almost linear elastic behaviour of as-built floors. The position of the screws connecting the plywood panels to the planks does not necessarily have to correspond to the underlying joists: the planks are capable of transferring the shear force between adjacent panels.

This retrofitting technique showed good potential also in terms of energy dissipation, quantified by means of an equivalent damping ratio. For the Dutch context, the obtained ξ value was found to be similar to or larger than the ones derived for comparable retrofitted diaphragms in literature, and approximately 2.5 times higher than the one currently proposed in Dutch seismic standard NPR 9998.

This increased dissipative role could be, therefore, taken into account when assessing the seismic performance of an existing building after having retrofitted its timber diaphragms with the presented technique. The evaluated and proposed equivalent damping values could be also adopted in more simplified seismic analyses: for instance, when it is necessary to determine the seismic

demand in a pushover analysis, the overdamped response spectrum could be derived accounting for the dissipative behaviour of both masonry and retrofitted timber diaphragms.
This beneficial contribution of the diaphragms to the global seismic response of existing buildings is activated at already limited deflection, thus strengthening timber floors with a plywood panels overlay can be a generally recommendable technique, but particularly suitable also for those areas, like the Groningen region, subjected to light, human-induced shallow earthquakes.

ACKNOWLEDGEMENTS

The authors acknowledge NAM (Nederlandse Aardolie Maatschappij) for having funded the testing campaign.

REFERENCES

[1] Peralta D.F., Bracci M.J., Hueste M.B.D.: Seismic Behavior of Wood Diaphragms in Pre-1950s Unreinforced Masonry Buildings. Journal of Structural Engineering 130:2040-2050, 2004.
[2] Brignola A., Pampanin S., Podestà S.: Experimental Evaluation of the In-Plane Stiffness of Timber Diaphragms. Earthquake Spectra 28:1-23, 2012.
[3] Wilson A., Quenneville P.J.H., Ingham J.M.: In-Plane Orthotropic Behavior of Timber Floor Diaphragms in Unreinforced Masonry Buildings. Journal of Structural Engineering 140, 2014.
[4] Mirra M., Ravenshorst G.J.P., van de Kuilen J.W.G.: Experimental and analytical evaluation of the in-plane behaviour of as-built and strengthened traditional wooden floors. Engineering Structures 211, 2020.
[5] Clough R.W., Penzien J.: Dynamics of structures, McGraw-Hill New York, 1993.
[6] Nederlands Normalisatie-instituut: NPR 9998, 2018.
[7] CEN (European Committee for Standardization): EN 338 – Structural timber—Strength classes, 2009.
[8] International Organization for Standardization (ISO): ISO 21581–Timber structures–Static and cyclic lateral load test methods for shear walls, 2010
[9] Filiatrault A., Isoda H., Folz B.: Hysteretic damping of wood-framed buildings. Engineering Structures 25: 461-471, 2003.
[10] McKenna F., Fenves G.L., Scott M.H.: Open System for Earthquake Engineering Simulation. University of California, Berkeley, 2000. Link: http://opensees.berkeley.edu
[11] Scotta R., Trutalli D., Marchi L., Pozza L., Mirra M.: Non-linear time history analyses of unreinforced masonry building with in-plane stiffened timber floors. In *XVII ANIDIS Conference*, Pistoia, 2017.
[12] Mazzoni S., McKenna F., Scott M.H., Fenves G.L.: OpenSees Command Language Manual. University of California, Berkeley, 2006. Link: http://opensees.berkeley.edu/manuals/usermanual
[13] CEN (European Committee for Standardization): EN 1990 – Eurocode – Basis of Structural Design, 2002.