Project

«Überprüfung und Ertüchtigung bestehender Holz-balkendecken in Altbauten bezüglich Erdbeben»

Final report

Submitted by:

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Abstract

Many existing unreinforced masonry buildings are built with timber slabs, which are very flexible in their plane and poorly anchored into the walls. Under earthquake loading, such features can lead to premature out-of-plane failure of walls and limit the redistribution of forces between walls. For this reason, timber floors have often been replaced by reinforced concrete slabs, which have a higher in-plane stiffness. The aim of this project is to investigate experimentally and numerically the seismic behaviour of unreinforced masonry buildings with timber slabs and the effect of retrofit measures, which aim at maintaining the integrity of the timber slabs. For this purpose, this project (i) investigates the friction force between timber beams and walls in the original configuration; (ii) conducts pull-out tests on injection anchors in stone masonry walls and investigates the influence of the anchor configuration and overburden stress on the pull-out resistance; (iii) presents an equivalent frame modelling approach for the nonlinear analysis of URM buildings with timber slabs, which can represent diaphragm flexibility and sliding of the timber beams on their supports in the wall as well as capture in-plane and out-of-plane failure modes of masonry walls. The results highlight that the friction forces transferred by the original floor-wall connections are often not sufficient to prevent out-of-plane failures of masonry walls. For the case study building analysed, strengthening the diaphragm alone does not lead to an improved behaviour but strengthening the floor-wall connection by means of anchors is essential to improve the integrity of the building during earthquake loading.

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Introduction[1]

Many existing unreinforced masonry buildings have been constructed with timber slabs, which consist of timber beams spanning in one direction connected by planks that are nailed to the beams (e.g. [1]–[3]). Such timber slabs have often a very small diaphragm stiffness when compared to modern floor typologies such as reinforced concrete (e.g. [4]–[6]). In addition, the timber beams are often simply supported on recesses in the masonry wall or on sills that result from reducing the wall thicknesses from storey to storey [7]. The forces that are transferred between floor and wall are therefore limited to the friction forces (i) between timber beam and timber beam if a trimmer beam is inserted for distributing the loads transmitted from the slab to the wall (Figure 1a) and (ii) between timber beam and mortar if the timber beam lies directly on the masonry construction (Figure 1b) [8]. As a result of the limited diaphragm stiffness and poor floor-wall connections, a box-type behaviour, which leads to a global building response, can often not be achieved for such unreinforced masonry construction and local out-of-plane failures are common (e.g. [9]).

Retrofit techniques address these two weak points of traditional construction and increase on one hand the diaphragm stiffness and on the other hand the connection between slab and wall [1], [10]. It is not uncommon that such improvements are obtained by replacing the timber slab by a reinforced concrete slab. However, this bears several disadvantages. First, the weight of the slab is significantly increased and therefore typically also the seismic forces that the unreinforced masonry structure needs to carry. Second, in historical buildings the timber slab might constitute a structural element that should be preserved from a structural heritage point of

[1] This report is a summary report. It reuses text and figures from the project proposal [23] and publications produced as part of this research project. These are the publications [8], [13], [15], [24].

view. In newer buildings for which conservation aspects do not play a role, timber as a construction material might be preferred to concrete because it is a more sustainable construction material.

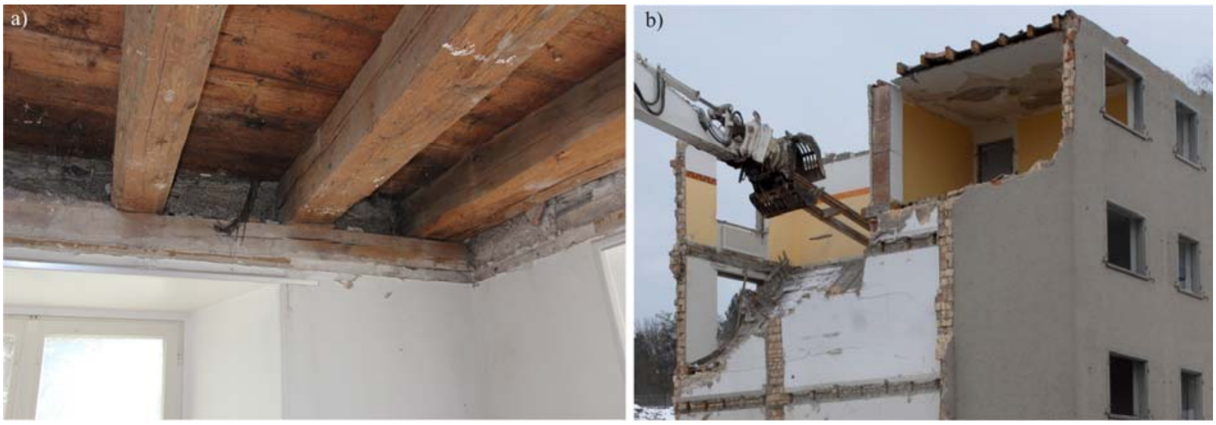


Figure 1 Examples of floor-wall connections in existing masonry buildings in Switzerland: a) with trimmer beam in the historical mathematical Institute in Basel, b) embedded in the wall in a residential building constructed around 1940 in Zürich-Wiedikon [7].

A retrofit strategy that maintains the timber slab would therefore often be desirable. However, the lack of clear design and evaluation guidelines for such a retrofit strategy hinders its application in engineering practice. In particular, knowledge on the force transfer between slab and wall in the unretrofitted configuration was missing. Second, information on the forces that can be carried by injection anchors in stone masonry were missing. Third, modelling recommendations for the unretrofitted and retrofitted configurations on the building level were required to design such retrofit measures effectively and demonstrate. The objective of this research project was to contribute to the deployment of such a retrofit strategy through new experimental and numerical research addressing these open questions. The following chapter summarises the main results of this research project. The final chapters present the conclusion and an outlook on future research work.

Main results of this project

The main results of this research project were derived from two experimental campaigns and one numerical study. The first experimental campaign addressed the force transfer of original floor-wall connections through cyclic friction tests. In the second experimental campaign the force transfer of strengthened floor-wall connections was addressed. The floor-wall connections were strengthened with injection anchors and the resistance of this connection was determined through pull-out tests. Finally, modelling recommendations for the analysis of unreinforced masonry buildings with original and strengthened floor-wall connections and floor diaphragms were formulated and the effect of these retrofit measures illustrated by analysing a case study building. In the following, these studies are briefly described and the main results summarised.

Force transfer of original floor-wall connections

Under seismic loading, timber floors are solicited mainly through in-plane forces, i.e., the timber floors act as a diaphragm. The forces that are transferred between floor and wall are limited to the friction forces (i) between timber beam and mortar if the timber beam lies directly on the masonry construction or (ii) between timber beam and timber beam if a trimmer beam is inserted for distributing the loads transmitted from the slab to the wall [8]. Timber-timber contacts exist also at intermediate supports of long spanning floor beams (a).

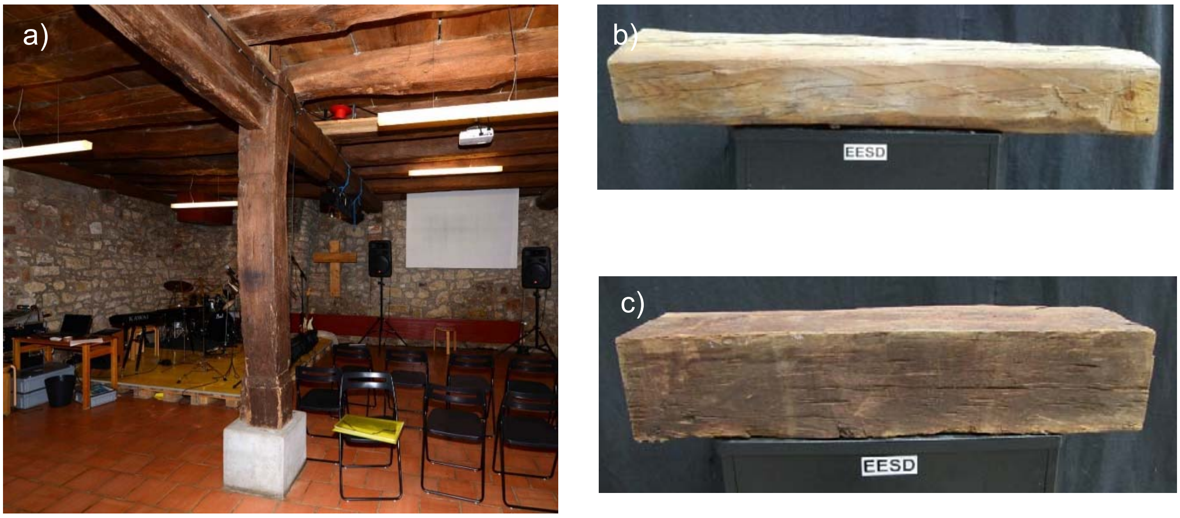
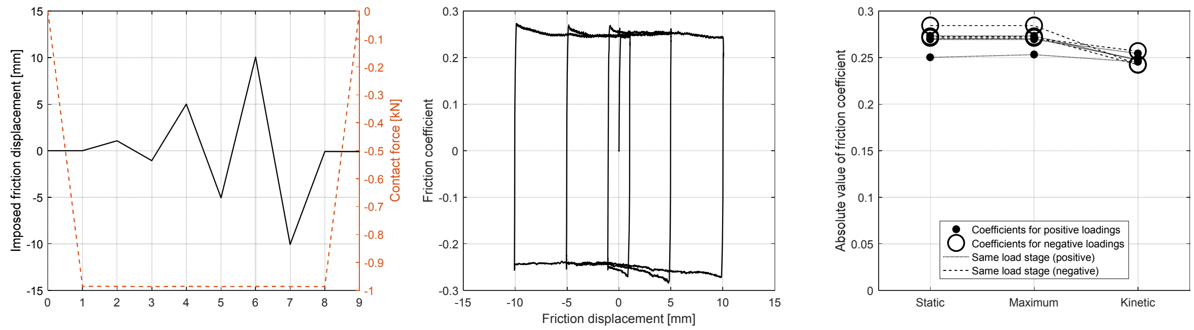


Figure 2 (a) Intermediate timber column and beam serving as mid-span support for floor beams spanning between two masonry walls, in the city of Basel. Hand-carved spruce (b) and oak (c) timber beams from the 16th century used for the experimental campaign [12].

To quantify the resistance of these timber-timber and timber-mortar contacts, cyclic friction tests were carried out on mortar and timber triplets, and on timber and timber triplets. The timber specimens and mortar properties were chosen to be representative for pre-modern and contemporary construction periods (b, c). The test setup used is similar to the one in [11]. However, unlike in [11] where the contact pressure was applied by post-tensioned bars, the contact pressure was controlled actively by an actuator and maintained constant throughout a test. This actuator is the horizontal actuator in the test setup (Figure 3). A second actuator applied the shear displacements (vertical actuator in Figure 3). This actuator is part of the universal testing machine used for these cyclic tests. The friction forces were determined for various contact pressures to cover a range of normal forces foreseeable in building connections. Example results are shown in Figure 4.

Figure 3 (a) Overview of the test setup, with double-actuator testing machine on the right-hand side, control system on the left, and data acquisition software in the centre; (b) Close-up view [8].



(a) (b) (c)

Figure 4 Post-processed results of one friction test with timber units obtained from a 16th century oak beam ($\sigma \approx 0.08$ MPa) [8].

Mean, characteristic and examination values for the various timber-timber and mortar-timber tests are summarised in Table 1. The main findings resulting from these tests are as follows:

- The average static friction coefficient for the different materials varied between 0.6 and 0.8, including both mortar-timber and timber-timber tests. Mortar-timber friction was in average 15% larger than timber-timber friction. The only configuration which resulted in much lower friction coefficients was the timber-timber test with placed surface units, for which a static friction coefficient of 0.35 was obtained. The surface roughness appears therefore to be a governing factor to friction resistance. In particular, it appears that an increased local roughness (with flat surface) predominates over a more uneven surface but locally smooth.
- For practical applications, it can be assumed that the kinetic and static friction coefficients are similar, that the influence of the contact pressure on the friction coefficient can be neglected and that cumulative loading does not lead to a significant reduction in friction coefficients. For the range of velocities investigated, the loading speed did also not influence the results.

Table 1 Summary of friction coefficients for the mortar-timber and timber-timber tests [8], [13].

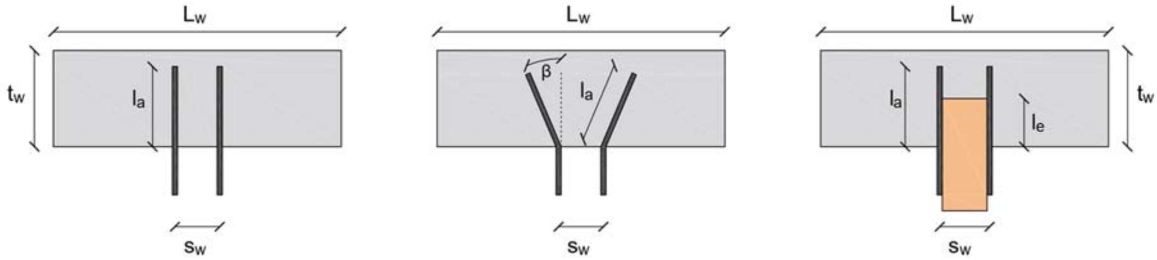
Friction coefficient	Timber on mortar			Timber on timber		
	Modern planed timber on mortar	Modern sawn timber on mortar	Antique timber on mortar	Modern planed timber on modern planed timber	Modern sawn timber on modern sawn timber	Antique hacked timber on antique hacked timber
Mean value	0.64	0.77	0.70	0.29	0.63	0.56
Standard deviation	0.07	0.08	0.09	0.08	0.09	0.08
Characteristic value	0.52	0.64	0.55	0.16	0.48	0.43
Design value	0.4	0.4	0.4	0.1	0.3	0.3

Pull-out tests on injected anchors

While guidelines for designing injection anchors in brick masonry are available, corresponding ones for rubble stone masonry walls are missing. Also experimental evidence of the resistance of injection anchors in rubble stone masonry are scarce [14]. To improve the experimental database, quasi-static pull-out tests were performed on injection anchors double-leaf rubble stone masonry walls of stone masonry class A. These tests are described in detail in the publication [15] and are summarised here. The objective of these tests were the following:

- Provide new test results for the resistance of injection anchors in stone masonry walls.
- Investigate the influence of anchor configuration and vertical overburden stress on the resistance.
- Collect data beyond the global force-deformation relationship in order to provide new insights into the mechanisms that contribute to the resistance of the injection anchor in the stone masonry.

The rods had a diameter of 16 mm and were spaced apart by s_w=140 mm (centre to centre, Figure 5). As per the manufacturer's recommendations, a 20 mm borehole was adopted for the selected rod diameter. The anchors were injected with a two-component epoxy (Hilti HIT-RE 500). Three different anchor configurations, each consisting of two anchors, were investigated in this study, namely (Figure 5): 1) two horizontal anchors parallel to each other; 2) two horizontal anchors each inclined at an angle of 23° to the vertical plane; and 3) two parallel, horizontal anchors with a timber joist.



(a) (b) (c)

Figure 5 Configurations of anchors for pull-out tests (the sketches show horizontal cuts through the specimens): (a) PA specimens; (b) IA specimens; (c) PAT specimens [15].

The test setup is shown in Figure 6 and Figure 7. A universal testing machine was used to apply a constant axial load throughout the test. This axial load was varied between the tests and corresponded to 0.1-0.3 MPa. The pull-out force was applied to the two bars using a loading system consisting of a horizontal beam and a bar, which was loaded by a hollow core jack. The force taken by the two anchors was measured by a load cell on top of the hollow core jack. The displacement of the anchors was measured by LVDTs that measured the slip of the anchors from the backside of the wall.

In addition to an instrumentation that measured the global force-displacement response of the pull-out tests, this experimental program aimed at providing detailed information on the failure mechanism and the load transfer from the anchor to the surrounding masonry. The anchors were designed to remain elastic. The failure therefore manifested itself through the formation of a mechanism in the stone masonry. The corresponding displacement field was recorded using Digital Image Correlation (DIC) measurements of the 3D displacement field of the stone masonry wall. Optical fibres placed in grooves along the length of the anchors measured the strain variation in the anchors. Because the anchors remained elastic, the strains can be related to axial stresses in the anchors and therefore to the stress transfer from the anchor to the surrounding masonry. The collection of this data is an investment into the future (see section on future research); its evaluation and interpretation is beyond the scope of this project.

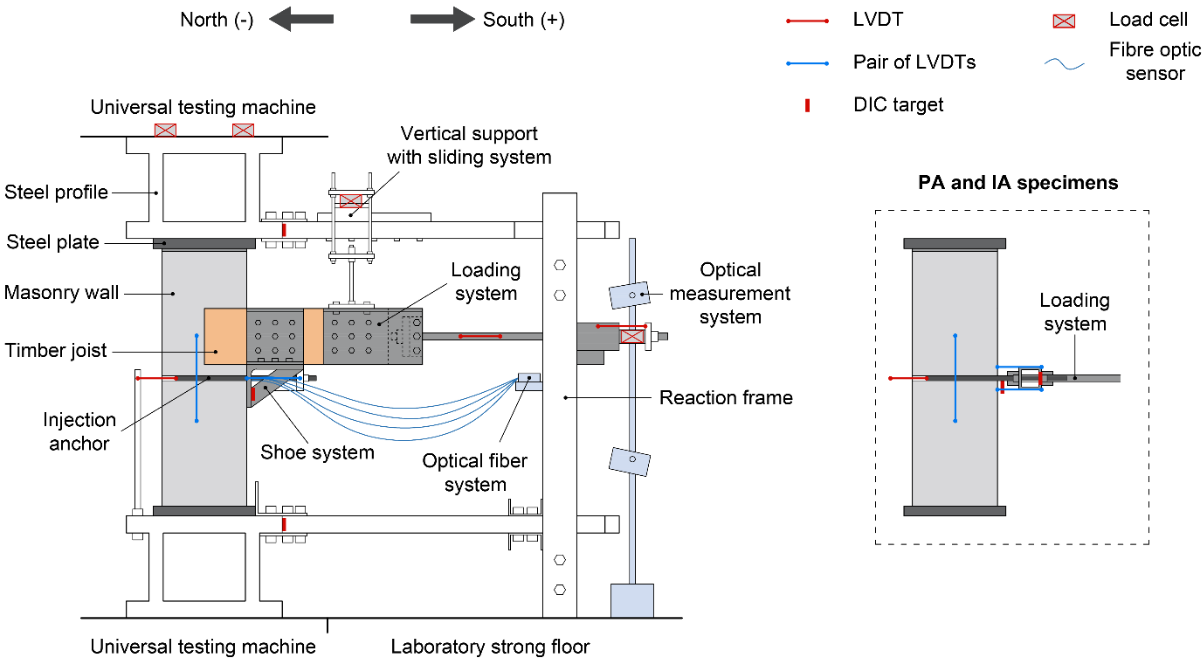


Figure 6 Test setup and instrumentation used for the pull-out tests: illustrative sketch [15].

Figure 7 Test setup and instrumentation used for the pull-out tests: photo [15].

An example of a curve showing the pull-out force F vs the anchor displacement d is shown in Figure 8a. No significant influence in terms of pull-out capacity was observed for specimens tested under the same value of overburden stress, independently on their anchoring detail (Figure 8b). For an overburden stress of 0.20 MPa, the mean value of pull-out capacity was 54.1 kN (CoV = 5%). On the other hand, a linear proportional increase in maximum pull-out force was observed with increasing overburden stress (R^2 = 0.88). The testing of the PAT specimens is still ongoing at the time this report is submitted.

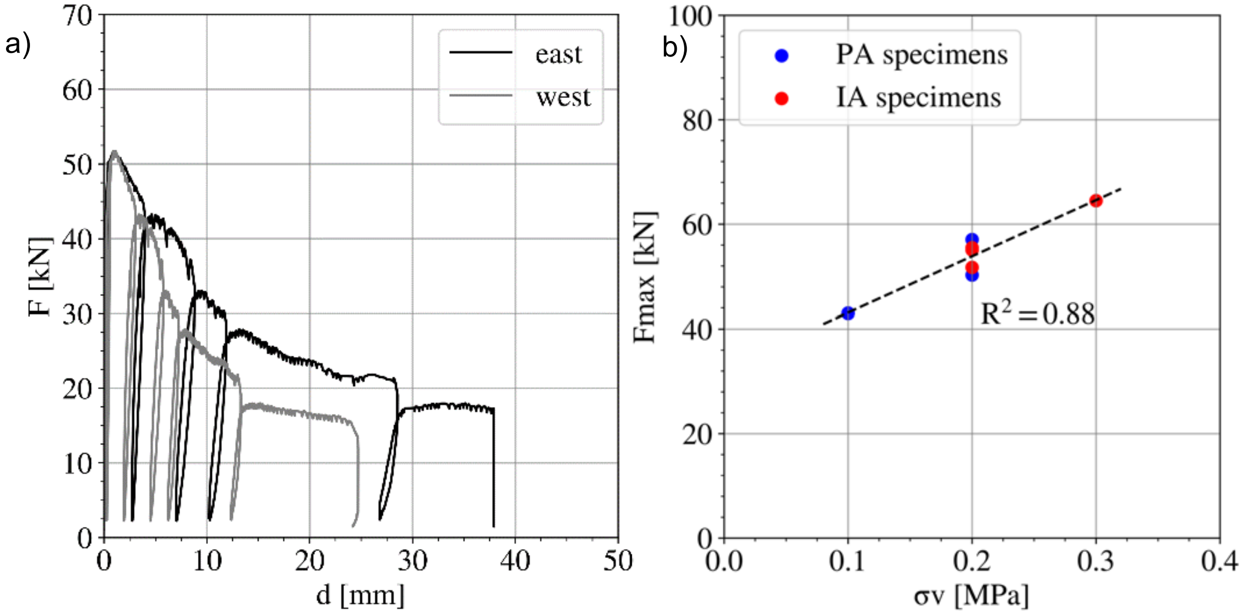


Figure 8 (a) Example of a curve of a pull-out force vs anchor displacement. The data plotted corresponds to specimen IA1; east and west refers to the east and west anchors. (b) Influence of the vertical overburden stress on the peak pull-out force [15].

Finite element simulations of unreinforced masonry buildings with original and strengthened timber floors and floor-wall connections

To assess the seismic behaviour of unreinforced masonry buildings in their original configuration and to design appropriate strengthening interventions, computationally efficient modelling approaches for the global response of the building are required. In this final part of the research project, we presented an approach for modelling URM buildings with original and strengthened timber floors and floor-wall connections numerically and investigated the influence of the strengthening interventions on the global behaviour of the building under earthquake loading.

In this project the unreinforced masonry buildings were modelled using equivalent frame models (e.g. [16]). This modelling approach was chosen because it represents a good compromise between accuracy and computational efficiency when analysing entire masonry buildings. This study sets itself apart from previous studies in two points: First, the equivalent frame models capture not only the diaphragm deformation but also the sliding of the timber beam on its support if the wall-slab connection is not retrofitted by anchors. Second, previous numerical studies on URM buildings with timber slabs focused on displacement demands induced by the flexible slabs (e.g. [17]) or used models that did not address the nonlinearity of the floor-wall connections [18], [19]. In this study, for the original configuration, the connection between floor and wall was modelled using non-linear springs, which simulate a Coulomb friction connection [20]. In addition, a new formulation of a macro-element was used [21], which cannot only capture the in-plane response of the masonry element but also simple, one-way spanning out-of-plane rocking modes.

The following modelling assumptions were made with regard to slabs and floor-wall connections in their original and strengthened configuration:

- In its original configuration, the slab consists of timber beams and a single layer of planks, which is nailed to the timber beams. The slab is modelled as an orthotropic elastic diaphragm. The properties of this diaphragm are determined according to [4].

- The floor diaphragm is retrofitted by adding a layer of planks to the existing floor, which lies at right angle to the first layer of planks (Figure 9). The increase in stiffness of the diaphragm is again calculated using the formulae provided in [4].
- The floor-wall connection in its original configuration transfers loads only via friction. Representative friction coefficients were determined in the first experimental campaign of this project [8]. In the finite element model, in tension, the connection was modelled as rigid until the friction force was attained and sliding occurred (Figure 10).
- It was assumed that the floor-wall connection was retrofitted by injection anchors, which were tested as part of this project [15]. These anchors are relatively stiff until the peak force is attained. For this reason, they were modelled as infinitely rigid with infinite force capacity. Using the force capacities attained in the pull-out tests, it was computed how many anchors would be necessary to transfer the forces between slab and wall, which were recorded for the numerical model. The anchor configuration investigated in the second experimental test series would have a suitable resistance for the case study building.

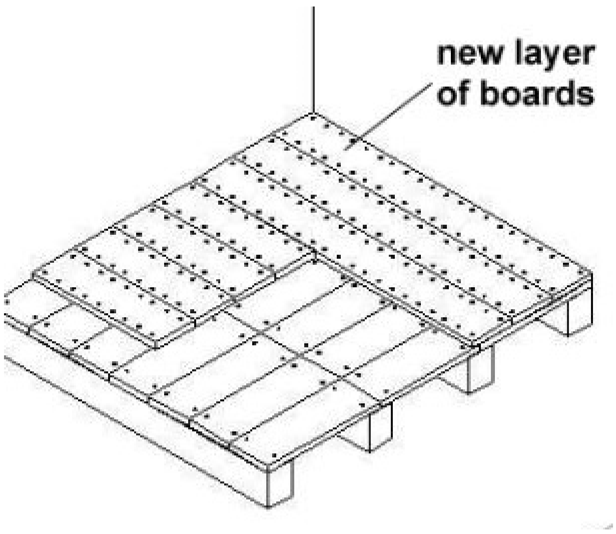


Figure 9 Timber slab retrofitted with a second layer of planks in order to increase the diaphragm stiffness [4].

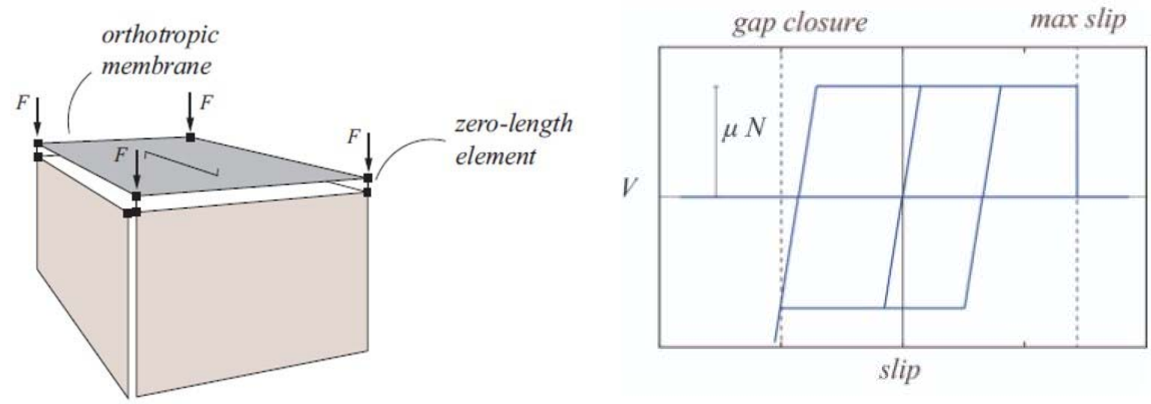


Figure 10 Numerical modelling of floor-to-wall connection [21].

The effect of the two retrofit interventions (strengthening of floor diaphragms and strengthening of floor-wall connections) were investigated by analysing a case study building. For the case study building, strengthening the diaphragm alone had little effect on the response. To improve the response, it was necessary to strengthen the floor-wall connections. The latter led to an increase in force and displacement capacity because the failure mode changed from an out-of-plane failure to an in-plane failure mode (Figure 12).

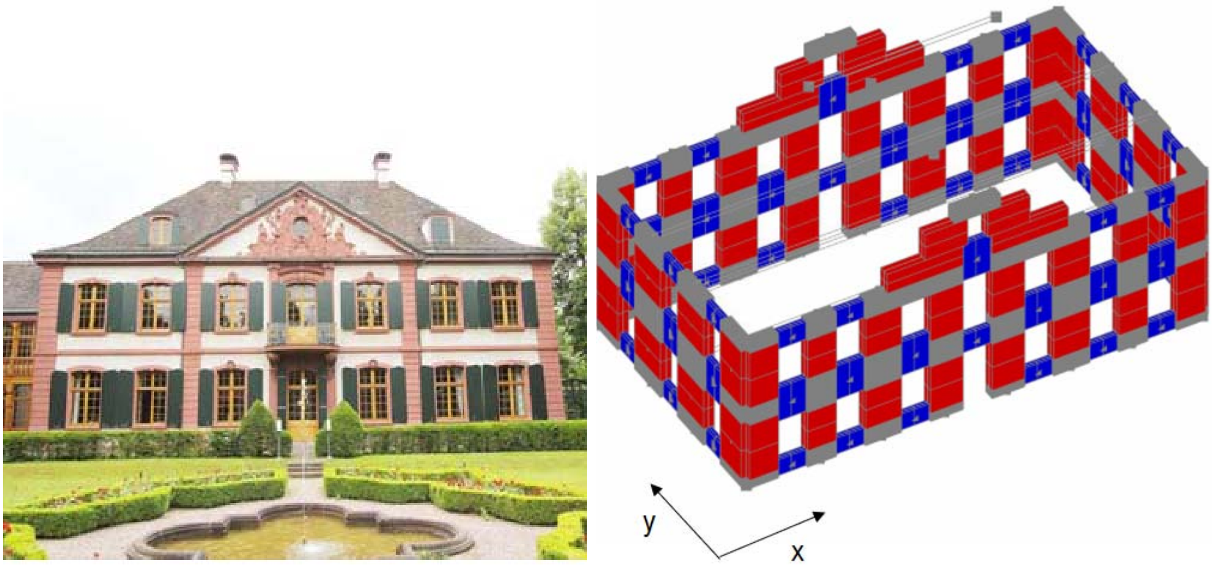


Figure 11 The case study building "Holsteinerhof" in Basel and its equivalent frame model [22].

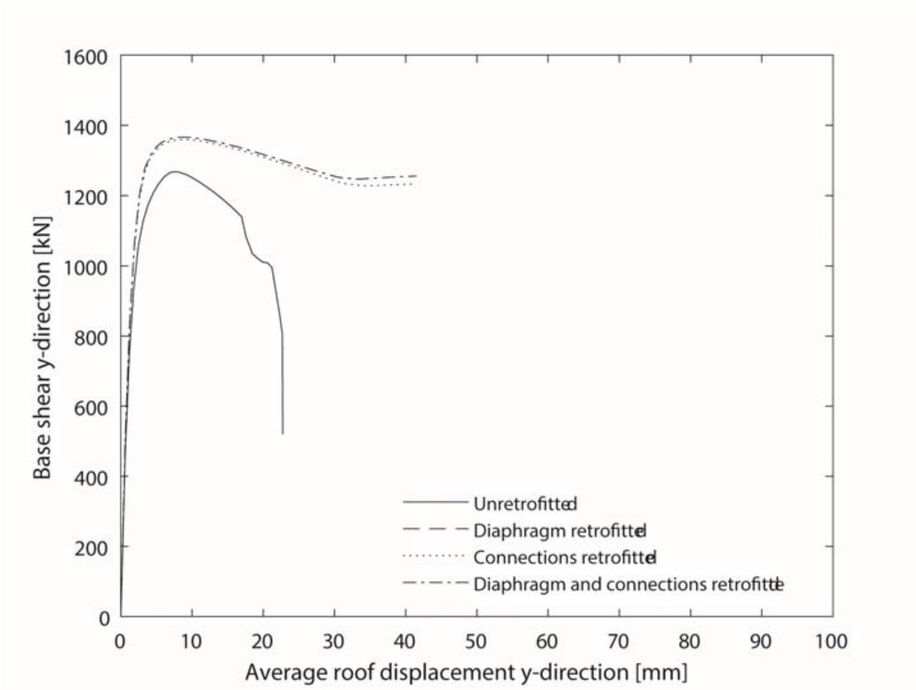


Figure 12 Holsteinerhof: Force-displacement response in y-direction

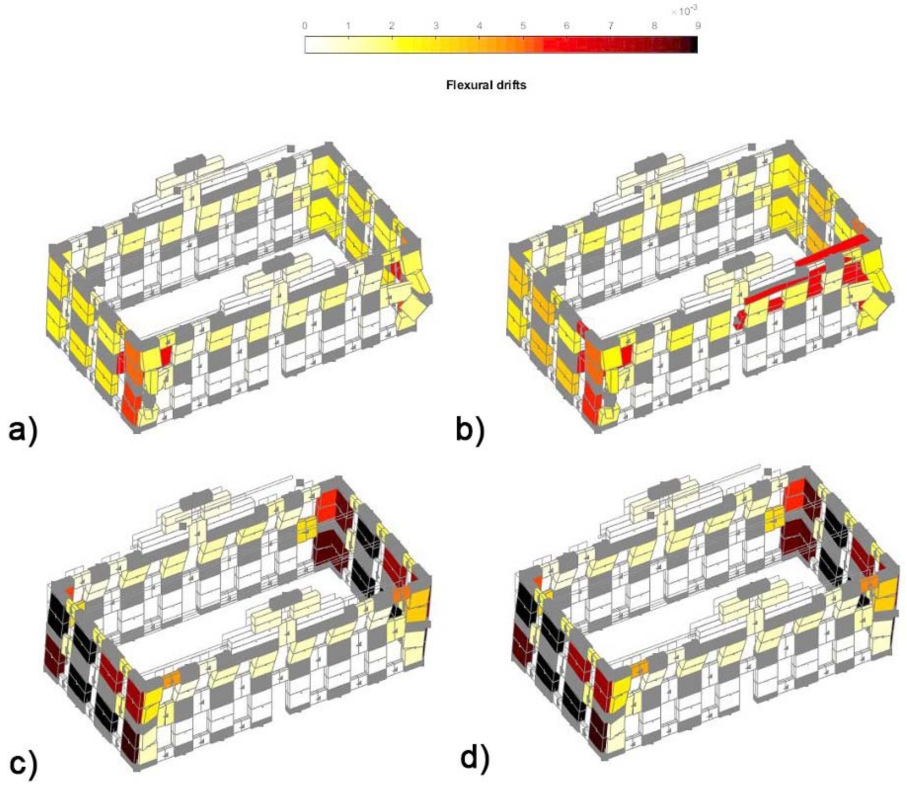


Figure 13 Holsteinerhof: Final deformation mode for loading in the y-direction for the following cases: a) Unretrofitted; b) Diaphragm retrofitted; c) Floor-wall connection retrofitted; d) Diaphragm and floor-wall connection retrofitted.

Conclusions and future work

The aim of this project is to investigate experimentally and numerically the seismic behaviour of unreinforced masonry buildings with timber slabs and the effect of retrofit measures, which aim at maintaining the integrity of the timber slabs. The two experimental campaigns that were part of this research project made significant contributions to characterising quantitatively the resistance of original and strengthened floor-wall connections. Numerical simulations showed that floor-wall connections are key for ensuring the structural integrity of unreinforced masonry buildings with timber slabs under seismic loading. Strengthening of the slab alone often does not improve the seismic response of the building. Although improving the floor-wall connections is in general good practice, it might not always be the best solution for historical buildings in low to moderate seismic regions. For such buildings, striving to increase the structural robustness in general and the seismic resistance in particular vs maintaining the historical structure including its fabric can be contradictory objectives. For such buildings, numerical simulations of the seismic response of the entire masonry building like those presented in this project can help to differentiate between interventions that are necessary and those that are good practice for buildings that have no particular historical value. To disseminate the findings of this project in the engineering community, a Lignatec brochure will be published by the Lignatec partners of this project (Gunther Ratsch).

The obtained results show that it can be possible to obtain a good seismic response of existing unreinforced masonry buildings with timber floors if the resistance of the floor-wall connection is sufficient. This is often not the case if the resistance relies solely on a friction mechanism and a strengthening by means of anchors is necessary. The first project proposal aims at advancing the design guidelines for injection anchors. The second project proposals develops a timber floor system for new construction that satisfies the requirements of a high diaphragm stiffness and a good anchorage to the unreinforced masonry walls.

Force transfer mechanism from injection anchor to stone masonry wall

As outlined in the Section "Pull-out tests on injected anchors", the tests set themselves apart from previous work through the extensive instrumentation, which was designed to provide detailed information on the failure mechanism and the load transfer from the anchor to the surrounding masonry. The displacement field of the stone masonry wall was recorded using Digital Image Correlation (DIC) measurements and optical fibres placed inside the anchors measured the strain variation along the anchors. This data provides a valuable basis for further in-depth evaluations:

- to investigate how the force is transferred from the anchors to the surrounding masonry and how the pull-out cone forms in the stone masonry wall;
- to validate and extent equations for the pull-out capacity of injection anchors from stone masonry walls. Existing equations have been mainly developed for injection anchors in concrete and extended to masonry applications but their validation is based on very few tests, none of which used a similar set of instrumentation.

At present, the pull-out resistance of injection anchors in stone masonry can be extrapolated from the experimental tests, which have been conducted at full-scale using products and dimensions commonly found in real buildings. The proposed future project would be a further step towards understanding and designing such anchor connections based on a mechanically founded approach.

Development of a timber slab system for modern residential buildings

The results of this study have shown that unreinforced masonry buildings with timber floors can behave well under seismic loading provided the timber slab has a sufficient in-plane stiffness and is well anchored to the walls. This last point was highlighted by the results of this research project. It was further shown that the friction mechanism between timber beams and wall is often not sufficient to transfer the force from the slab to the wall but that an anchorage system is necessary.

Future research could apply these findings to new residential construction and develop a timber floor system that satisfies next to common non-seismic conditions also seismic design requirements with regard to its diaphragm stiffness and floor-wall connection. For the latter a module should be designed, which ensures the force transfer between slab and connection and which can be easily placed during the construction process. The seismic performance of this system should be validated through pull-out test on the anchorage system and a shake table test on a 2-storey residential URM building constructed with this new floor system. Such a building would combine the two natural building materials clay and timber for the construction and be an active contribution to the sustainable development of the built environment.

Scientific output

Scientific articles

Almeida, J. P., Beyer, K., Brunner, R., & Wenk, T. (2020). Characterization of mortar–timber and timber–timber cyclic friction in timber floor connections of masonry buildings. *Materials and Structures*, *53*(3), 51. https://doi.org/10.1617/s11527-020-01483-y

Ciocci, M.-P., van Nimwegen, S., Askari, A., Vanin, F., Lourenço, P. B., & Beyer, K. (2021). Experimental investigation of the behaviour of injection anchors in rubble stone masonry. To be submitted.

T. Wenk, R. Brunner, J. P. Almeida, and K. Beyer, "Ueberprüfung bezüglich Erdbeben von Holzbalkendecken in Bestandesbauten," *Der Bauingenieur*, vol. 95, no. 4, pp. S8–S13, 2020.

Conference presentation

R. Brunner, „Verankerung von Holzbalkendecken in Natursteinmauerwerkswänden“, Fachtagung der Basler Erdbebenkurse „Erdbebenüberprüfung und -ertüchtigung von Natur-steinmauerwerksgebäuden“, 12.9.2019, Basel.

Research reports

T. Wenk, K. Beyer and R. Brunner, „Überprüfung und Ertüchtigung von Holzbalkendecken in Bestandesbauten bezüglich Erdbeben“, Projektskizze prepared for the FOEN "Aktionsplan Holz", 2016.

J. P. Almeida, K. Beyer, R. Brunner and T. Wenk, „Überprüfung und Ertüchtigung von Holzbalkendecken in Bestandesbauten bezüglich Erdbeben“, Interim report prepared for the FOEN "Aktionsplan Holz", 2018.

K. Beyer, F. Vanin, I. Tomic, and I. Bozuliç, "Equivalent frame models for unreinforced masonry buildings with timber slabs," Technical report prepared for the FOEN "Aktionsplan Holz", 2020.

Experimental dataset, openly shared

Almeida, J. P., Beyer, K., Brunner, R., & Wenk, T. (2020). Data set: Characterization of mortar–timber and timber–timber cyclic friction in timber floor connections of masonry buildings. https://zenodo.org/record/3348328#.X6xULFAo-jE

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