Database of connections: characteristics and properties

Messali, F.; Ravenshorst, G.J.P.

Publication date
2019

Document Version
Final published version

Citation (APA)
Messali, F., & Ravenshorst, G. J. P. (2019). *Database of connections: characteristics and properties*. Delft University of Technology.

Project number	CM1B05
File reference	CM1B05-WP1-2.3
Date	3 December 2019
Corresponding author	Francesco Messali (f.messali@tudelft.nl)

Physical Testing and Modelling – Masonry Structures

DATABASE OF CONNECTIONS: CHARACTERISTICS AND PROPERTIES

Authors: Francesco Messali, Geert J.P. Ravenshorst

***Cite as**: Messali, F., Ravenshorst, G.J.P. Database of connections: characteristics and properties. Report No. CM1B05-WP1-2.3, 3 Deecmber 2019. Delft University of Technology.*

This research work was funded by NAM Hazard and Risk stream.

Contents

1 Introduction

The present document includes a list of common connections present in unreinforced masonry (URM) buildings in the Groningen province, and of possible retrofitting measures. The list has been created on the basis of the data collected from past experimental campaigns performed at TU Delft, of the communication with the engineering companies working on field and participating to the CVW regular knowledge meetings (particularly VIIA and BORG), and on the data available online on the 'Maatregelen catalogus' [1].
The dataset has been integrated by the results of the tests performed at the laboratory of TU Delft in 2019 (in two phases: phase 1 was held in March-May, phase 2 in July-September) to determine the resistance of a number of as-built and retrofitted connections, and presented in [2]. It should be noted that the experimental campaign included tests performed according to both quasi-static and high-frequency dynamic protocols. However, since the interpretation of the latter typology of tests has not been provided yet, the results of the high-frequency dynamic tests have not been considered in this report. They can be added in a later version of this document, once a thorough interpretation study is provided.

The report is structured as follows:

- Section 2 includes a summary table listing the identified connection types.
- Section 3 presents a synthetic description of each of the identified connection typologies, both as-built and retrofitted. The indicative strength values of the connections available from previous experimental campaigns and/or reports are also reported.

2 Summary table

No.	Type of connection	Indicative strength?	Characteristic strength?(1)	Section/ Page	Retrofitting option(s)	Indicative strength?	Characteristic strength? (1)	Section/ Page
Connection of floors to URM walls								
#01	Timber joists pocketed in masonry walls	✔	✔(2)	3.1.1 / p.5	- Addition of (i) hook anchors, (ii) L-shaped anchors, (iii) transversal timber beams below the joist, or (iv) timber blocks next to the joist - Maatregelen catalogus measure: L2-005	✔	✔(2)	3.1.2 / p.7
#01b	Timber joists pocketed in masonry walls with an anchor masoned in the wall and nailed to the joist	✔	✔(2)	3.2.1 / p.13	Similar to connection type #01	✘	✘	3.1.2 / p.7
#02	Timber joists parallel to masonry walls	✔ (null)	✔ (null)	3.3.1 / p.15	- Chemical anchors passing through the timber joist anchored in masonry walls - Maatregelen catalogus measure: L2-011	✔	✔	3.3.2 / p.15
#03	Concrete floor on inner leaf of cavity walls (only calcium silicate brick masonry)	✔	✔	3.4.1 / p.18	Steel angles and anchors (similar to Maatregelen catalogus measure: L2-018)	✘	✘	3.4.2 / p.19
#03b	Hollow core / NeHoBo floor on masonry walls	✘	✘	3.5.1 / p.20	Similar to connection type #03	✘	✘	3.5.2 / p.20
Connection of roof rafters to URM walls								
#04	Rafter seated on solid or cavity walls	✘	✘	3.6.1 / p.21	Maatregelen catalogus measures: L2-001; L2-012	✘	✘	3.6.2 / p.21
#04b	Rafter seated on single leaf of cavity wall with anchor	✘	✘	3.7.1 / p.23	Similar to connection type #04	✘	✘	3.7.2 / p.23
Connection URM walls to foundations								
#05	Masonry walls on foundation strips	✘	✘	3.8.1 / p.24	Maatregelen catalogus measures: L2-003; L2-019	✘	✘	3.8.2 / p.24
Connection outer- to inner-leaf in cavity walls								
#06	Wall-wall connection in cavity walls	✔	✔	3.9.1 / p.26	Mechanical anchors connecting inner and outer leaves of a cavity wall	✔	✔	3.9.2 / p.26
Connection of non-load bearing walls								
#07	Non-loadbearing masonry walls disconnected to the above floor	✔ (null)	✔ (null)	3.10.1 / p.28	Maatregelen catalogus measure: L2-037	✘	✘	3.10.2 / p.28
#08	Wall-wall not cross masoned in the corner (shear friction between masonry walls is zero)	✔ (null)	✔ (null)	3.11.1/ p.29	Maatregelen catalogus measure: L2-025	✘	✘	3.11.1/ p.29

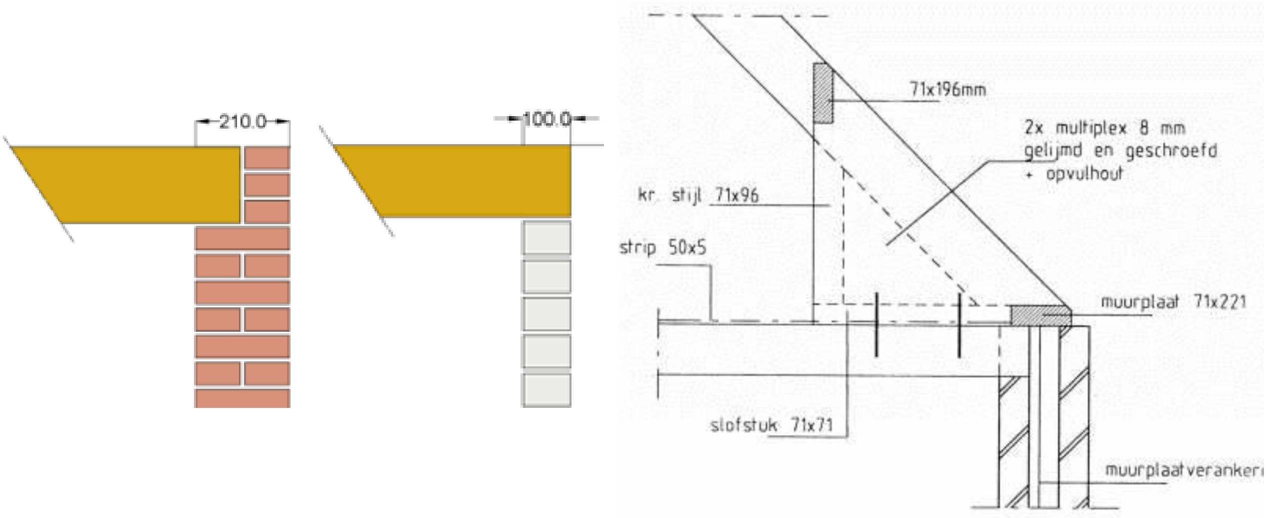
(1) the characteristic values, when available, should be intended only for the specific anchors and configurations tested (see related sections). For the values, please refer to the related sections.
(2) available for joists pocketed in single wythe solid clay brick masonry walls only.

3 Short description of each type of connection

3.1 Timber joist pocketed in masonry walls (#01)

3.1.1 As-built conditions

The connection simply consists of timber joists supported in masonry pockets. This solution is very commonly adopted both in case of single or double wythe solid clay brick masonry walls, and of cavity walls. In the latter case the joist is supported on pockets created in the inner leave, commonly made of calcium silicate brick masonry.



(a) (b) (c)

Figure 1. Examples of technical drawings for timber joists pocketed in masonry walls. Figures (a) and (b) from the 2018 TU Delft testing campaign [3]; figure (c) kindly provided by VIIA.

(a) (b)

Figure 2. Examples of pictures of timber joists pocketed in masonry walls. Images kindly provided by VIIA (Z015A).

Figure 3. Examples of connections tested during the 2019 TU Delft testing campaign [2].

Strength:

The cyclic behaviour of timber joists pocketed in both double wythe clay brick masonry walls or in the calcium silicate (CS) brick masonry inner leaf of cavity walls was investigated at TU Delft in early 2018, and the results reported in [1]. Only one test per typology was performed and the results can be assumed as indicative only. For this reason only an indicative value of the strength of the connection could be defined.

The connection in single wythe solid clay masonry was more extensively studied in 2019, and also the characteristic value of the strength could be computed. The characteristic strength F_k was computed by following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests. In total, 7 values are considered: 1 value from the monotonic test and 2 values for each of the 3 cyclic tests. The coefficient of variation is assumed not be known from prior knowledge.

The strength of the connection loaded in parallel to the joist is reported for both cases in Table 1. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. This difference has a meaning only for the double wythe walls, while a symmetric behaviour is obtained for single wythe walls. For this reason, in the latter case, the results are averaged between the two loading directions. The compressive value in case of double wythe walls is much higher than the other cases because the joist reacts against the clay bricks (Figure 1a). The complete force-displacement curves are reported in [3] for the 2018 campaign and in [2] for the 2019 campaign.

Table 1. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2018	Double wythe clay brick masonry	0.70	6.30	n.a.	n.a.
2018	Single wythe CS brick masonry	0.53		n.a.	
2019	Single wythe clay brick masonry	0.61		0.28	

If the connection is assumed to behave on the basis of a frictional behaviour, it is possible to compute the friction coefficient and the initial shear strength of the connection on the basis of measured peak and residual forces, of the vertical reaction at the support, and of the contact area. For the joist pocketed in single wythe walls the values are computed as an average between the tensile and compressive direction. The values reported in Table 2 are obtained. It should be noted that the values of the initial shear strength f_{v0} in case of single wythe walls are extremely small and may be neglected.

Table 2. Derived values of initial shear strength (f_{v0}) and friction coefficient (μ).

Campaign	Masonry type	Average value		Characteristic value	
		f_{v0} (MPa)	μ (-)	f_{v0} (MPa)	μ (-)
2018	Double wythe clay brick masonry	0.06	0.60	n.a.	n.a.
2018	Single wythe CS brick masonry	0.03	0.70	n.a.	n.a.
2019	Single wythe clay brick masonry	0.02	0.95	0.01	0.61

3.1.2 Strengthening options

(1) **Application of a standard hook anchor nailed to the joist and glued to the wall**

The timber joists can be connected to the masonry with an hook anchor nailed to the joist and glued to the wall after being placed in a previously realised incision (Figure 4).This strengthening option consisted of a standard 240x240x14 mm hook anchor fastened to the joists by means of 4x55 mm nails and glued to the wall. The anchor was therefore embedded in the glue, which filled a 25x40 mm incision realized on the masonry.

(a) (b)

Figure 4. Example of a technical drawing (a) and picture of a detail for timber joists pocketed in single wythe solid clay walls, retrofitted with a standard hook anchors (from the 2019 TU Delft testing campaign [2]) (b).

Strength:
This strengthened connection was studied only when the joist was pocketed in single wythe solid clay masonry. In total, 7 values are considered: 4 values for the pulling/tensile force and 3 values for the pushing/compression forces. Given the number of he characteristic value of the strength could be computed, again following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests The coefficient of variation is assumed not be known from prior knowledge. The strength of the connection is reported in Table 4. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The measured strength is significantly larger than the unstrengthened case when no hook anchors are used. An additional comparison can be made with the presence of a standard hook anchor in as-built conditions, as presented in section 3.2.1. With respect to this condition, similar results in terms of pulling strength are obtained, but much larger capacity for pushing (compression) actions. This difference may be caused by the additional presence of the planks, which was not included in the tests presented in section 3.2.1.
The complete force-displacement curves are reported in [2].

Table 3. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2019	Single wythe clay brick masonry	5.40	12.94	3.10	10.69

(2) **Application of a L-shape steel angle below the joist**

The timber joists can be connected to the masonry with the insertion of additional a L-shape folded steel plate (Figure 5) that can provide a stronger connection between the joist and the masonry wall.

(a) (b)

Figure 5. Example of a technical drawing (a) and picture of a detail for timber joists pocketed in single wythe solid clay walls, retrofitted with L-shaped anchors (from the 2019 TU Delft testing campaign [2]) (b).

Strength:

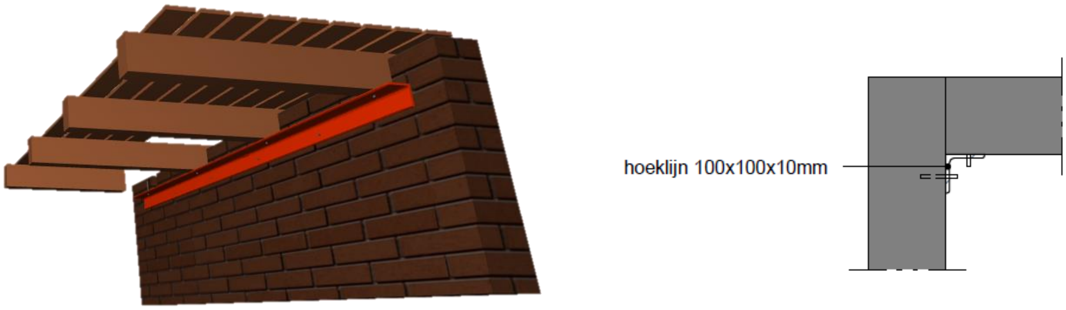
Similar to the unstrenghtened connection, the behaviour of strengthened timber joists pocketed in both double wythe clay brick masonry walls or in the calcium silicate (CS) brick masonry inner leaf of cavity walls retrofitted with L-shaped anchors was investigated at TU Delft in early 2018, and the results reported in [1]. Only one test per typology was performed and the results can be assumed as indicative only. For this reason only an indicative value of the strength of the connection could be defined.
The strengthened connection in single wythe solid clay masonry was more extensively studied in 2019, and also the characteristic value of the strength could be computed, again following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests. In total, 7 values are considered: 4 values for the pulling/tensile force and 3 values for the pushing/compression forces. The coefficient of variation is assumed not be known from prior knowledge. The strength of the connection is reported for both cases in Table 4. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The measured strength is significantly larger than the corresponding unstrengthened case.
The complete force-displacement curves are reported in [3] for the 2018 campaign and in [2] for the 2019 campaign.

Table 4. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2018	Double wythe clay brick masonry	10.3	15.5	n.a.	n.a.
2018	Single wythe CS brick masonry	5.6	10.5	n.a.	n.a.
2019	Single wythe clay brick masonry	6.18	8.85	4.48	6.87

Maatregelencatalogus:

The use of steel angles is reported in the Maatregelencatalogus [1], as measure L2-005 (Figure 6). This retrofitting solution has already been applied in VIIA projects (Figure 7). It should be noted that the measures of the steel angles are different from those used in the TU Delft tests.



(a) (b)

Figure 6. Sketch and technical drawing of the retrofitting measure (from the Maatregelencatalogus [1]).

(a) (b)

Figure 7. Example of application of retrofitting measure L2-005. The images are kindly provided by VIIA.

(3) Addition of a transversal timber beam below the joist

Alternatively to the steel angle, a timber beam transversal to the joists and parallel to the wall (Figure 8 and Figure 9). This solution may represent a suitable solution especially when the quality of the masonry just below the joint is poor, and the connection load must be spread on a wider surface.

(a) (b)

Figure 8. Timber joists pocketed in masonry walls retrofitted with additional timber beams, as tested in the 2019 TU Delft campaign [2].

(a)

(b)

Figure 9. Examples of pictures of timber joists pocketed in masonry walls retrofitted with additional timber beams. The images are kindly provided by VIIA (Testschool De Roemte).

Strength:

This strengthening method was investigated in 2019 at TU Delft for the case of single wythe solid clay brick masonry only. Similar to the case presented above, the characteristic value of the strength could be computed, again following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests. In total, 6 values are considered: 3 values for the pulling/tensile force and 3 values for the pushing/compression forces. The value of the monotonic test was excluded since early failure of the bolts occurred due to a not accurate installation [2]. The coefficient of variation is assumed not be known from prior knowledge.

The strength of the connection loaded in parallel to the joist is reported for both cases in Table 8. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The measured strength is significantly larger than the corresponding unstrengthened case. Besides, the strength for pushing and pulling is rather similar and closer with respect to the case of the application of steel angles.
The complete force-displacement curves are reported in [2] for the 2019 campaign.

Table 5. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2019	Single wythe clay brick masonry	8.90	8.67	7.60	6.18

(4) Addition of transversal timber blocks next to the timber joist

Similar to the strengthening solution presented above at point (3), timber blocks can be added also next to the joint. This strengthening option was realized with 65x170 mm timber blocks placed on both sides of the joist (in practice they would be placed between each couple of joists). The blocks were firstly fixed to the existing joist by means of 5x70 mm screws drilled at an angle of 45 degrees, and then fastened to the masonry with 10x165 mm mechanical anchors. Since this intervention involves also the diaphragm, the same conditions were recreated: beside the presence of the planks, fixed to the joist with 3x65 mm nails, also an additional plywood panel overlay was placed and screwed through the planks inside the blocks. This ensured that all the elements of the connections that are involved in the transfer of the horizontal load were present.
Figure 10 shows the details of the strengthening solution as applied during the 2019 TU Delft testing campaign [2], including the sequence of operations to install thes strengthening blocks. Figure 11 shows an example of a strengthened wallet tested during the same testing campaign.

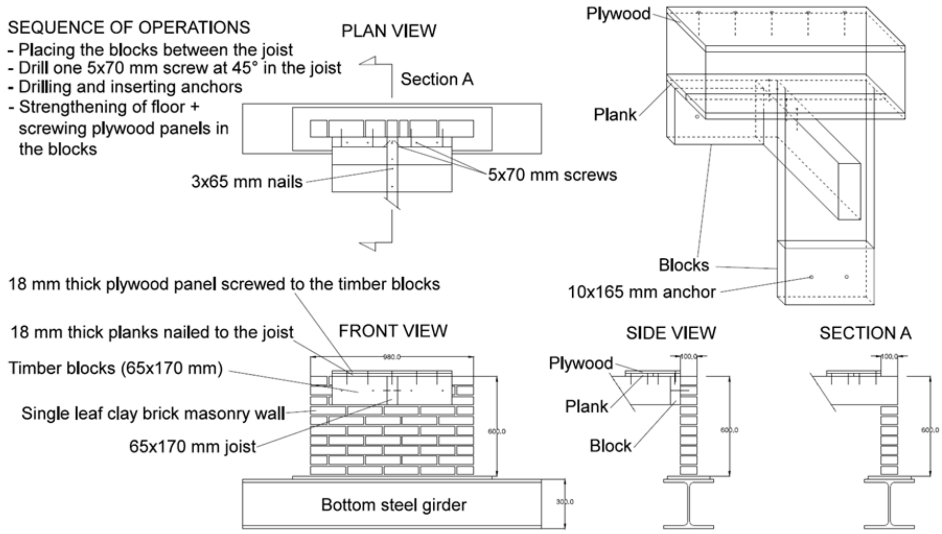


Figure 10. Technical drawing of the strengthening option consisting of timber blocks anchored to the masonry and screwed to the joist and to the plywood panel overlay (from the 2019 TU Delft testing campaign [2]).

(a) (b)

Figure 11. Pictures of the strengthened specimens: (a) front and (b) back of the connection (from the 2019 TU Delft testing campaign [2]).

Strength:
This strengthened connection was studied only when the joist was pocketed in single wythe solid clay masonry. In total, 7 values are considered: 4 values for the pulling/tensile force and 3 values for the pushing/compression forces. Given the number of he characteristic value of the strength could be computed, again following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests The coefficient of variation is assumed not be known from prior knowledge. The strength of the connection is reported in Table 6. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The measured strength is significantly larger than the unstrengthened case.
The complete force-displacement curves are reported in [2].

Table 6. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	**$F_{H,c}$ (kN)**	**$F_{H,t}$ (kN)**	**$F_{H,c}$ (kN)**
2019	Single wythe clay brick masonry	10.28	6.27	7.60	3

(5) Application of two inclined screws into the joist and fixed in the masonry with epoxy resin

Alternatively to the solutions presented in the points above, the strengthening can be obtained by connecting the joist to the wall by means of two inclined screws (Figure 12). These were inserted into the joist after drilling in the masonry proper holes, which were tehn filled with injected epoxy resin: the screws were therefore partly embedded in the glue and partly inserted in the joist. In this configuration 7x180 mm screws were used to connect the joist and the wall. The screws were placed at an angle of 45 degrees both in the vertical and horizontal plane, in order to reach a sounder part of the masonry. Before inserting the screws in the timber joist, 10 mm holes were drilled in the wall and then filled with injected epoxy. This intervention could be realized from outside: directly, in presence of gables, or just by removing a limited number of bricks from the outer leaf, for a cavity wall.

(a) (b)

Figure 12. Example of a technical drawing (a) and picture of a detail for the application of two inclined screws into the joist and fixed in the masonry with epoxy resin (from the 2019 TU Delft testing campaign [2]) (b).

Strength:
This strengthened connection was studied only when the joist was pocketed in single wythe solid clay masonry. In total, 7 values are considered: 4 values for the pulling/tensile force and 3 values for the pushing/compression forces. Given the number of he characteristic value of the strength could be computed, again following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests The coefficient of variation is assumed not be known from prior knowledge. The strength of the connection is reported in Table 7. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The measured strength is significantly larger than the unstrengthened case.

It should be noted that, unlike the other strengthening solutions, almost the same strength is obtained for both pulling and pushing actions.

The complete force-displacement curves are reported in [2].

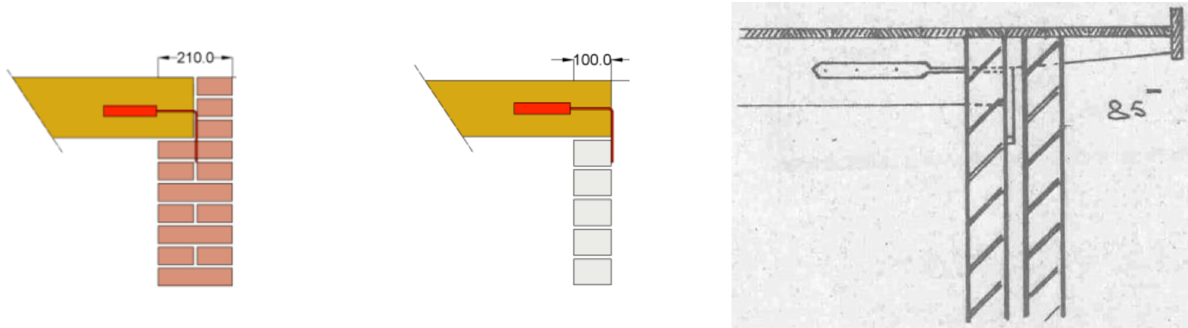
Table 7. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2019	Single wythe clay brick masonry	7.32	7.84	4.50	4.57

3.2 Timber joist pocketed in masonry wall with an anchor masoned in the wall and nailed to the joist (#01b)

3.2.1 As-built conditions

The connection is similar to the typology described in Section 3.1.1. In addition, a steel anchor with a hook is nailed to the timber joists and masoned in the wall. The hook is masoned in a mortar head joint for double wythe clay brick walls (Figure 13a), or lies on the external face of the CS inner leaf of a cavity wall (Figure 13b,c and Figure 14a,c) or of the single solid clay brick masonry walls (Figure 14b).



(a) (b) (c)

Figure 13. Examples of technical drawings for timber joists pocketed in masonry walls with an anchor masoned in the wall and nailed to the joist. Figures (a) and (b) available in the report [3] by TU Delft; figure (c) kindly provided by VIIA.

(a) (b) (c)

Figure 14. Examples of pictures of timber joists pocketed in masonry walls with an anchor masoned in the wall and nailed to the joist. Figure (a) comes from the 2018 TU Delft campaign [3] and figure (b) from the 2019 TU Delft campaign [2]; figure (c) kindly provided by VIIA (S049).

Strength:

The cyclic behaviour of timber joists pocketed in masonry walls with an anchor masoned in the wall and nailed to the joist was investigated at TU Delft in early 2018 for what concerns both double wythe clay brick masonry walls and calcium silicate (CS) brick masonry walls. The results are reported in [1]. Only one test per typology was performed and the results can be assumed as indicative only.

This type of connection in single wythe solid clay masonry was more extensively studied in 2019, and also the characteristic value of the strength could be computed. The characteristic strength F_k was computed by following the procedure reported in Annex D of EN 1990 [5], assuming a lognormal distribution of the tests. In total, 7 values are considered: 1 value from the monotonic test and 2 values for each of the 3 cyclic tests. The coefficient of variation is assumed not be known from prior knowledge.

The strength of the connection loaded in parallel to the joist is reported for both cases in Table 8. The horizontal force (F_H) is considered in tension ($F_{H,t}$) when it pulls out the joists from the wall, and in compression ($F_{H,c}$) when it pushes the joists through the pocket. The presence of the anchor usually provides a significantly larger strength to the connection, with the exception of the compression force for the connection to CS brick masonry walls: in that case the hook movement is not restrained and it does not provide additional capacity to the connection.
The complete force-displacement curves are reported in [3] for the 2018 campaign and in [2] for the 2019 campaign, respectively.

Table 8. Summary of test results.

Campaign	Masonry type	Average value		Characteristic value	
		$F_{H,t}$ (kN)	$F_{H,c}$ (kN)	$F_{H,t}$ (kN)	$F_{H,c}$ (kN)
2018	Double wythe clay brick masonry	5.0	12.9	n.a.	n.a.
2018	Single wythe CS brick masonry	5.3	1.4	n.a.	n.a.
2019	Single wythe clay brick masonry	6.10	1.25	3.90	0.73

3.2.2 Strengthening options

The same options presented in Section 3.1.2 may be considered when the strength of the connection is considered not to be sufficient. However, in this case the increase of strength is more limited and it varies from case to case. The values provided in Section 3.1.2 can be considered for a conservative approach, since the additional contribution of the anchor is not included.

3.3 Timber joist floor on masonry wall perpendicular to the span of the joists (#02)

3.3.1 As-built conditions

In this case a real connection between the timber joist and the masonry walls is in fact absent, since the joist runs next to the wall but the two elements are not connected.

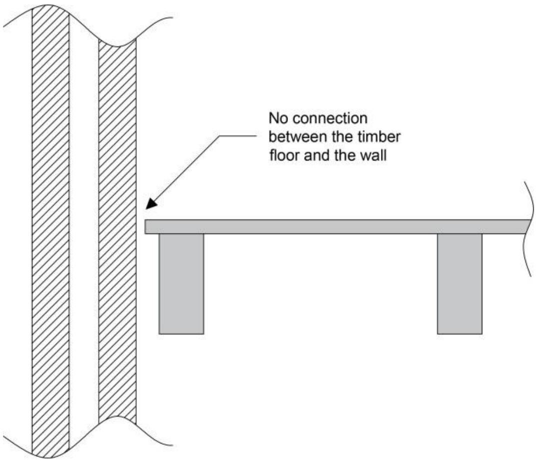


Figure 15. Examples of a technical drawing for timber joists next to a masonry wall.

Strength:
No experimental values are available. However, given the absence of connections zero strength can be assumed.

3.3.2 Strengthening option

Mechanical or chemical anchors can be drilled trough the timber joists and anchored into the masonry walls. The anchors can provide both axial (pull-out) and shear strength to the connection. In the following only chemical anchors (Figure 16) are discussed

(a) (b)

Figure 16. Examples of pictures of chemical anchors anchored in a solid clay brick masonry wall (from the testing report [4] prepared by Fischer Benelux for ARUP and kindly provided).

Strength:
The strength of this typology of connections strongly depends on both the tested anchors and the masonry where the connectors are anchored. The following description is obtained on the basis of the data reported in the testing report [4] prepared by Fischer Benelux for ARUP in 2014. Other types of anchors and/or of masonry require new tests to determine the strength of the connection.

Tests on chemical anchors "Fischer FIS A M12x210 ankerstang (90286)" with high-performance mortar "Fischer FIS V 360 S NL (94404)" were performed in 2014. Six series of five tests each were performed. Each series differs for the position of the anchors in the wall (mortar joints, long or short face of the bricks), the drilling direction, and the investigated strength (for axial or shear loads).
The tests were performed on site in a detached house in Loppersum. The walls were made of double wythe solid clay brick masonry. It should be noted that the strength of the connection strongly depends on the type of masonry, and the reported results cannot be generalized to every type of masonry. The mechanical properties of the masonry were not provided in the report.

The properties and the strength computed by each test series are reported in Table 9. The characteristic strength F_k was computed by following the procedure reported in Annex D of EN 1990 [5], assuming a normal distribution of the tests. The coefficient f variation it is assumed not be known from prior knowledge.

Table 9. Summary of the connection properties and of the measured mean and characteristic strength for the six testing series reported in [4].

	Tests type:	**Anchored in:**	**Drilling direction:**	**Position**	**No. tests**	**F_m (kN)**	**F_k (kN)**
A	Axial (pull-out)	Mortar joints	Horizontal	Top of the wall (small overburden)	5	12.60	5.89
B	Axial (pull-out)	Bricks, long side	Horizontal	Top of the wall (small overburden)	4*	13.50	7.24
C	Shear	Bricks, short side	Horizontal	Top of the wall (small overburden)	5	7.60	3.37
D	Axial (pull-out)	Bricks, short side	Horizontal	Top of the wall (small overburden)	5	11.20	8.16
E	Axial (pull-out)	Bricks, long side	22° downwards	Top of the wall (small overburden)	5	12.20	0.16
F	Axial (pull-out)	Bricks, short side	Horizontal	Foundation (large overburden, damped masonry)	4*	17.00	9.56

* = a test was excluded when computing the characteristic strength because premature failure due to the poor conditions of masonry occurred.

It should be noted that drilling the anchors in the bricks not horizontally increases the dispersion of the results and it is therefore not advised. Besides, almost one anchor out of five may not work efficiently due to the poor masonry conditions.

By grouping tests in group series with similar characteristics it is possible to derive more general strength values (without prejudice to the importance of the masonry mechanical properties), as reported in Table 10.

Table 10. Summary of the mean and characteristic axial (pull-out) and shear strength of the tested anchors.

Test type:	**Anchored in:**	**No. tests**	**F_m (kN)**	**F_k (kN)**
Axial (pull-out)	Bricks	13	13.69	7.55
	Mortar	5	12.60	5.89
Shear	Bricks	5	7.60	3.37

Maatregelencatalogus:
The use of connectors anchored in the masonry is reported in the Maatregelencatalogus [1], as measure L2-011 (Figure 17). The considered measure is visible on the left (named as 'variant 1') and highlighted by a red square.

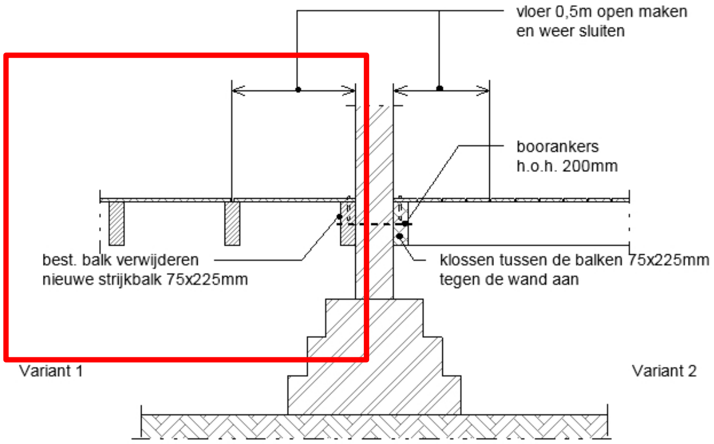


Figure 17. Technical drawing of the retrofitting measure (from the Maatregelencatalogus [1]). The considered measure is visible on the left and named as 'variant 1' (highlighted by a red square).

3.4 Concrete floor on URM walls (#03)

3.4.1 As-built conditions

In this section only the case of a concrete floor supported on the CS brick masonry inner leaf of a cavity wall is considered. This connection is characterised by an interface between the concrete slab and the internal leaf of a cavity wall. The masonry leaf is usually composed of either calcium silicate bricks and general purpose mortar or calcium silicate elements and thin layer mortar. Another wall may be supported on top of the concrete slab (intermediate floor). Accordingly, different compression forces may act on the interface.
The connection is governed by frictional behaviour.

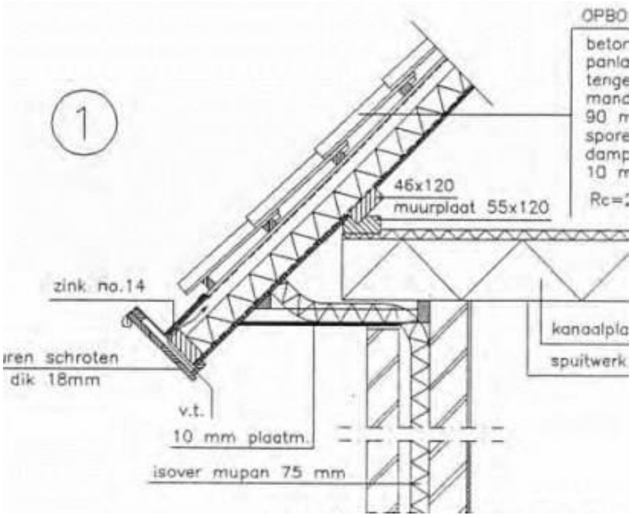
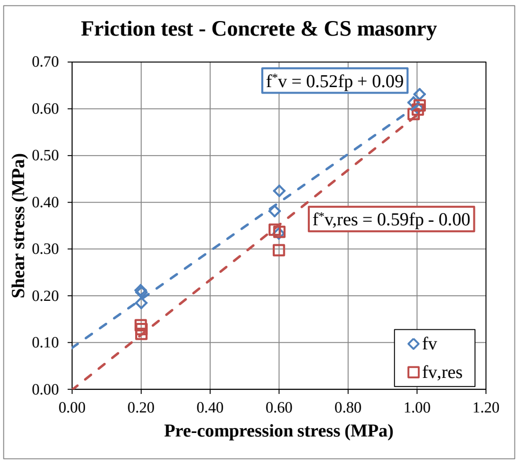


Figure 18. Examples of a technical drawing for a concrete slab supported on the inner leaf of a cavity wall (image kindly provided by BECA [6]).

Strength:
Only data on the frictional behaviour between a cast-in-situ concrete slab and a calcium silicate brick masonry wall are available. Nine triplets (Figure 19a) were tested in 2015 at the laboratory of the TU Delft University. The tests were performed in accordance with EN 1052-3 [6]. Three different levels of lateral precompression (0.2, 0.6, 1.0 N/mm^2) were applied, in order to define the initial and residual shear strength (f_{v0}, $f_{v0,res}$) and the initial and residual coefficient of friction (μ, μ_{res}). The average values are derived according to the outcomes of the tests, plotted in Figure 19b. The characteristic values are computed as 80% of the obtained average values, as recommended in [6]. The results are summarised in Table 11. A complete description of the tests is reported in [8].



(a) (b)

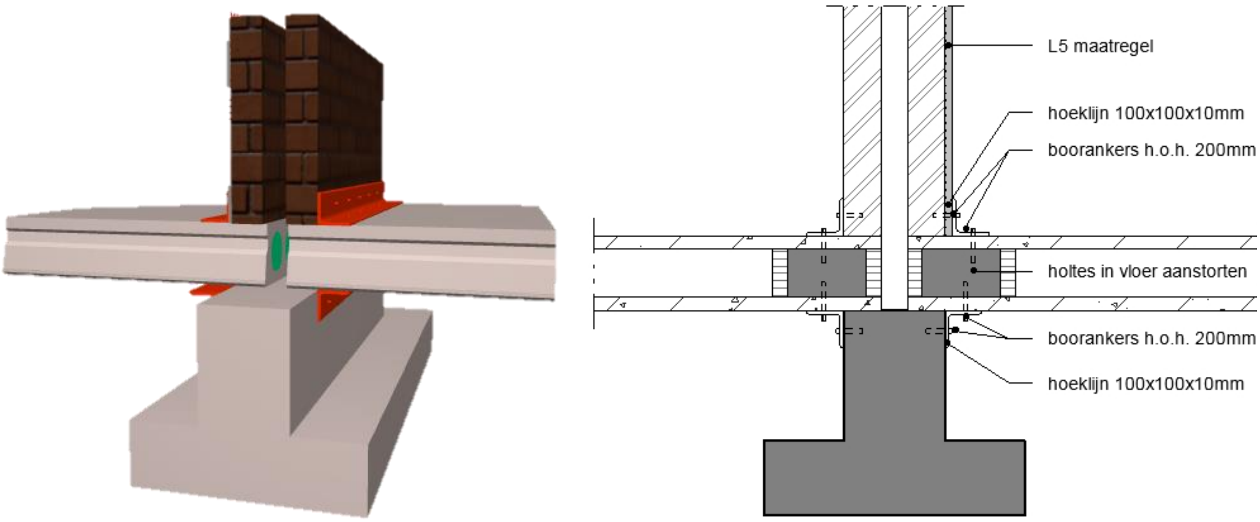
Figure 19. Shear compression tests: specimen and set-up (a) and individual shear strength against the normal compressive stress (b).

Table 11. Mean and characteristic frictional properties of the concrete-calcium silicate brick masonry connection.

Mean properties				Characteristic properties			
f_{v0}	μ	$f_{v0,res}$	μ_{res}	$f_{v0,k}$	μ_k	$f_{v0,res,k}$	$\mu_{res,k}$
(MPa)	(-)	(MPa)	(-)	(MPa)	(-)	(MPa)	(-)
0.09	0.52	0.00	0.59	0.07	0.42	0.00	0.47

3.4.2 Strengthening options

Maatregelencatalogus:
Measure L2-018 [1] allows connecting a solid/hollow concrete floor to either a URM wall or the foundations (Figure 20). The strength of the connection depends on the used connectors, the steel angle, and the embedment material (concrete or masonry). An indicative value of the strength of connectors embedded in masonry can be derived from the test reported in section 3.3.2.



(a) (b)

Figure 20. Sketch and technical drawing of the retrofitting measure L2-018 (from the Maatregelencatalogus [1]).

3.5 Hollow core / NeHoBo floor on masonry walls (#03b)

3.5.1 As-built conditions

This connection type can be compared to the previous category (section 3.4.1), since it is assumed to be governed by frictional behaviour. However, the frictional properties depend on the different materials (concrete-masonry for hollow-core concrete floors, masonry-masonry for NeHoBo floors).

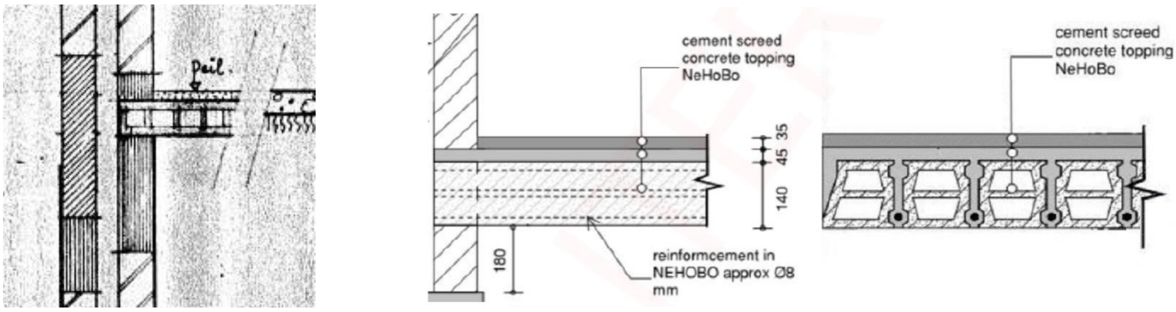


Figure 21. Examples of technical drawings for hollow-core concrete floors (a) or NeHoBo floors (b) supported on masonry walls. Figure (a) and (b) were kindly provided by VIIA and ARUP (and included in a TU Delft report [9]), respectively.

Strength:
The connection is assumed to be governed by frictional behaviour. The frictional properties depend on the different materials of the connection (concrete-masonry for hollow-core concrete floors, masonry-masonry for NeHoBo floors).
In case of hollow core floors supported on CS masonry walls, the properties reported in Section 3.4.1 may be used. For NeHoBo floors, no specific study has been carried out to investigate the behaviour of the masonry-masonry interface.

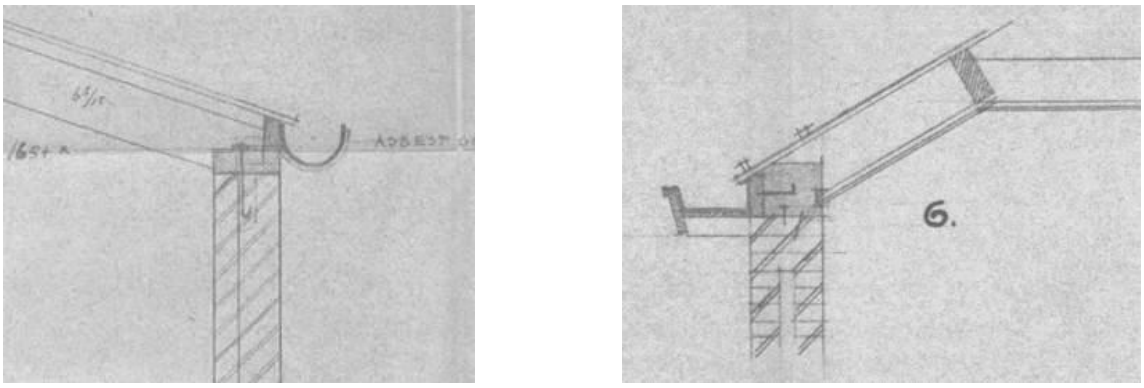
3.5.2 Strengthening options

The same options presented in Section 3.4.2 may be considered when the strength of the connection is considered not to be sufficient. Specific attention should be devoted to anchor the connectors in the strong parts of the floors, preferably in the concrete.

3.6 Rafter seated on solid or cavity walls (#04)

3.6.1 As-built conditions

This connection type can appear similar to the case of floor timber joists supported on URM walls (section 3.1.1). However, since the composition of the forces may lead to the "opening" of the roof and to the sliding of the rafter towards the outer face of the wall, the rafter is usually nailed to the masonry.



(a) (b)

Figure 22. Examples of technical drawings of a rafter seated on a solid (a) or on a cavity wall (b). The figures are extracted from the report [6] by BECA.

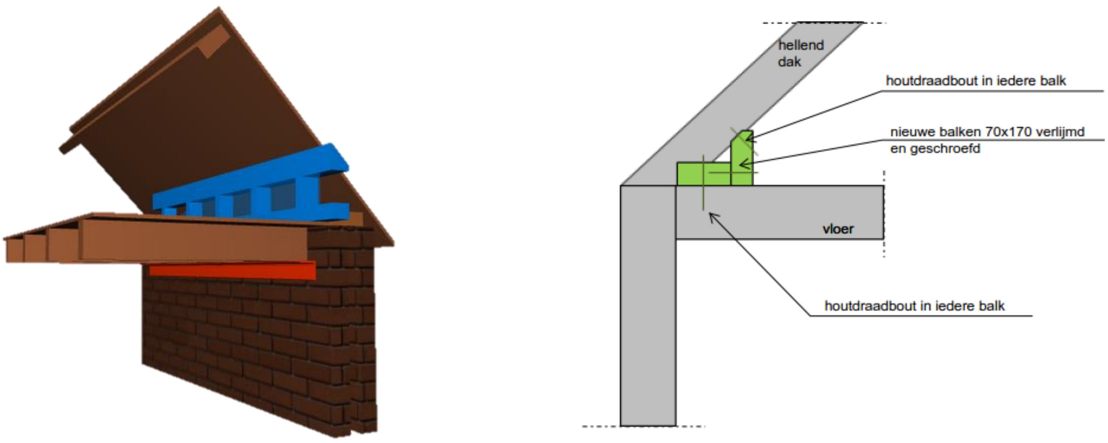
Strength:
No values available.

3.6.2 Strengthening option

Maatregelencatalogus:

Two different solutions are proposed in the catalogue:

- L2-001: the retrofitting measure connects the rafters of a timber roof to a timber floor via two nailed/glued timber beams as shown in Figure 23. This solution has already been applied in VIIA projects (Figure 24).
- L2-012: the retrofitting measure is similar to the previous one, but it differs for the details of the timber beams, that are of different size, placed in different positions and connected by different anchors (Figure 25).



(a) (b)

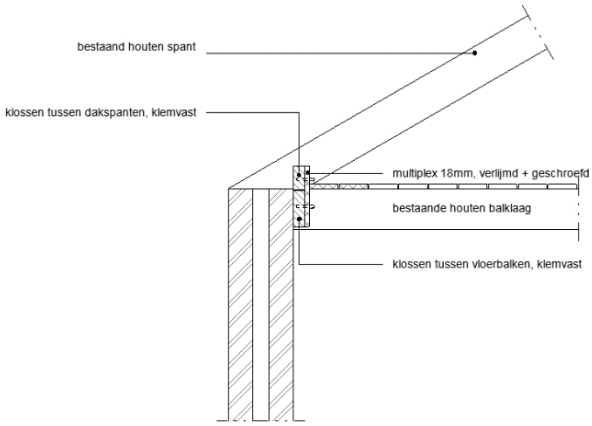
Figure 23. Sketch (a) and technical drawing (b) of the retrofitting measure L2-001 (from the Maatregelencatalogus [1]).

(a)

(b)

Figure 24. Example of application of retrofitting measure L2-001. The images are kindly provided by VIIA.

(a)



(b)

Figure 25. Sketch (a) and technical drawing (b) of the retrofitting measure L2-012 (from the Maatregelencatalogus [1]).

It should be noted that the two presented solutions do not match exactly with the unstrengthened conditions, because both the strengthening measures assume the presence of a floor at the roof level or immediately below.

Strength:
No values available.

3.7 Rafter seated on single leaf of cavity wall with anchor (#04b)

3.7.1 As-built conditions

This is similar to the previous case. However, given the short width of a single wythe wall, the presence of a strong anchor is required. The strength of the connection depends then mainly on the anchor.

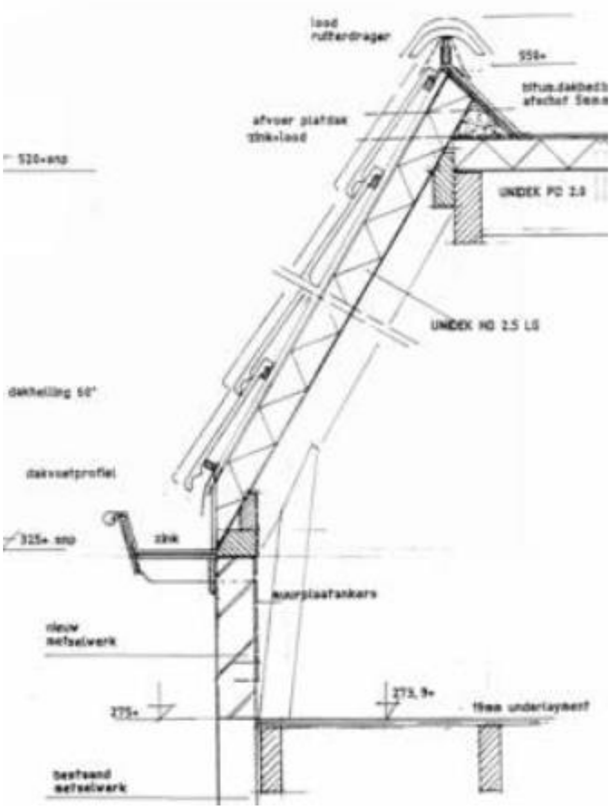


Figure 26. Example of a technical drawing of a rafter seated on the inner leaf of a cavity wall. The figure is extracted from the report [6] by BECA.

Strength:
No values available.

3.7.2 Strengthening options

The same options presented in Section 3.6.2 may be considered when the strength of the connection is considered not to be sufficient. However, in this case the increase of strength is more limited and it varies from case to case.

3.8 Masonry walls on foundation strips (#05)

3.8.1 As-built conditions

The connection efficiency depends on the bond and the friction between the wall and the foundation. When the used materials are similar, the description provided in section 3.4.1 for a RC floor supported on a URM may apply also to this case.

Figure 27. Example of a URM cavity wall standing on a RC concrete foundation. Image kindly provided by VIIA (Z015A).

Strength:
The frictional properties between CS bricks and concrete reported in Table 11 of section 3.4.1.

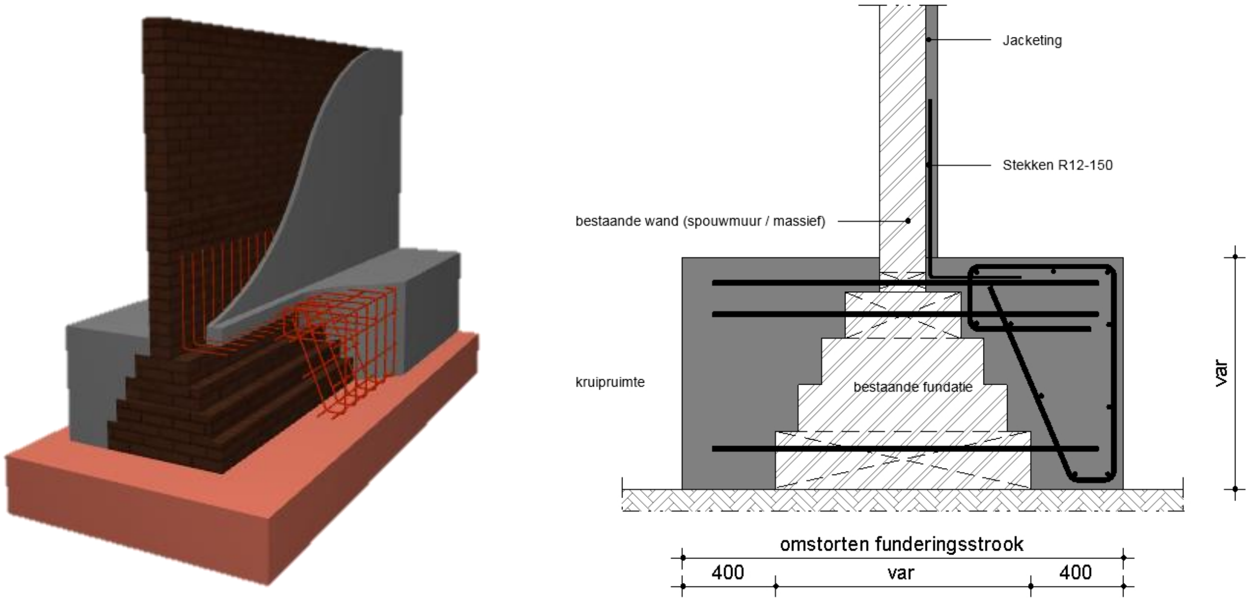
3.8.2 Strengthening options

Maatregelencatalogus:

Two different solutions are proposed in the catalogue:

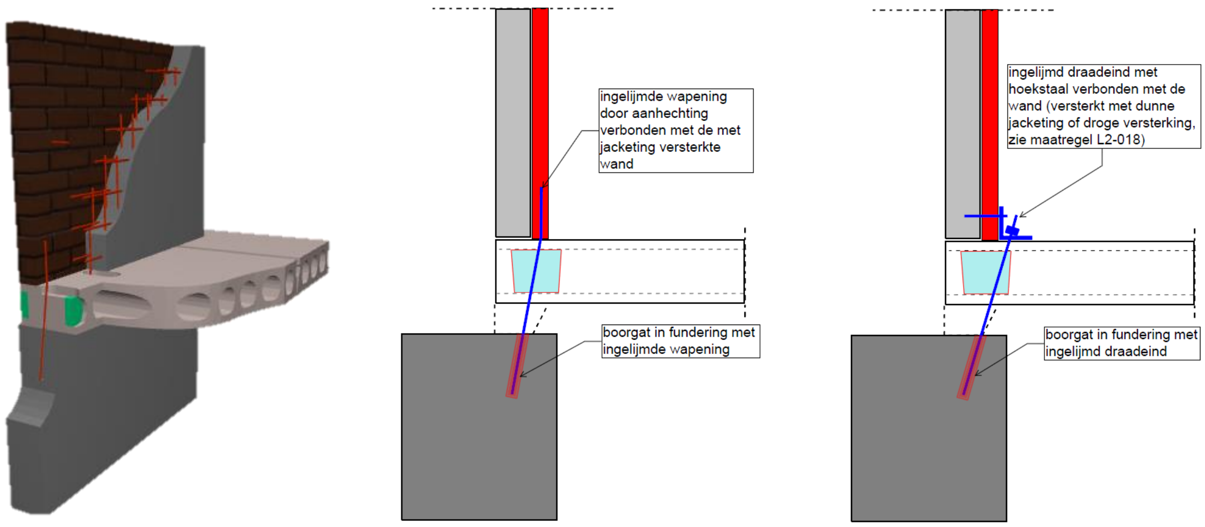
- L2-003: this measures considers the strengthening of both the URM wall (with jacketing) and of the foundation (by casting RC beams), as shown in Figure 28. The jacketing is connected to the foundation by steel reinforcement bars. Bars are drilled trough the existing foundation to connect the new casted RC beams to the existing foundation.

- L2-019: the measure connects a reinforced wall to strip foundations (Figure 29). The fixing of the anchor in the wall is given by the adhesion of the anchor to the jacketing, in case the jacketing is thick enough. In case of thin jacketing or dry reinforcement, the anchors should have threaded ends anchored above the floor to the wall by means of an L-shape steel plate fastened with mechanical anchors.



(a) (b)

Figure 28. Sketch (a) and technical drawing (b) of the retrofitting measure L2-003 (from the Maatregelencatalogus [1]).



(a) (b)

Figure 29. Sketch (a) and technical drawing (b) of the retrofitting measure L2-019 (from the Maatregelencatalogus [1]).

Strength:
The strength of the connection depends on the connectors, and the embedment material. Several values of anchors anchored in RC are provided by anchor suppliers.

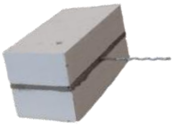
3.9 Wall-wall connections in cavity walls (#06)

3.9.1 As-built conditions

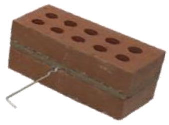
Wall ties are commonly adopted in cavity walls to ensure the connection between the internal loadbearing leaf and the external veneer, and prevent a premature out-of-plane failure of the latter. For this scope, the connection must provide a sufficient axial strength.
The following typologies of cavity walls were investigated:

- Internal loadbearing leaf: calcium silicate brick masonry;
- External veneer: perforated clay brick masonry;
- Ties: L-shaped ties with a diameter of 3.6 mm and a length of 200 mm.

A complete description of the tests is provided in [10].



(a)



(b)

Figure 30. Examples of wall ties embedded in CS brick (a) and perforated clay (b) couplets Pictures (extracted from [10]).

Strength:
The data reported in [10] have been re-analysed to define the mean and characteristic strength of the connection. The interpretation study is reported in Memo CM1B05-WP1-M1 [11]. The preliminary values are reported in Table 12.

Table 12. Mean and characteristic axial strength of wall tie connections in as-built conditions.

	F_m **(kN)**	F_k **(kN)**
Tensile strength (F_{mt})	1.18	0.84
Compressive strength (F_{mc})	0.55	0.47

3.9.2 Strengthening options

New wall ties are used to retrofit cavity walls either when the number of existing ties is not enough to provide an effective connection, or when old ties are corroded. Two different typologies of connectors are commonly adopted: mechanical (dry-fixed) or adhesive (resin bonded) connectors. In this section, only helical mechanical anchors are considered. Specifically, the mechanical anchors Helifix DryFix, 8mm diameter (supplied in the Netherlands by TotalWall) were tested in 2017 at the laboratory of TU Delft University. A complete description of the tests is reported in [12].

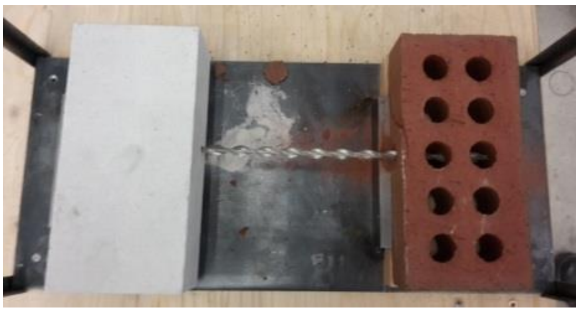


Figure 31. Retrofitting mechanical ties connecting a CS brick and a perforated clay brick (extracted from [12]).

Strength:
The data reported in [12] have been re-analysed to define the mean and characteristic strength of the connection. The interpretation study is reported in Memo CM1B05-WP1-M1 [11]. The preliminary values are reported in Table 13.

Table 13. Mean and characteristic axial strength of mechanical anchors in cavity walls.

	$F_{R,m}$ **(kN)**	$F_{R,k}$ **(kN)**
Tensile strength (F_{Rt})	4.44	2.35
Compressive strength (F_{Rc})	4.28	2.68

3.10 Non-loadbearing masonry walls disconnected to the above floor

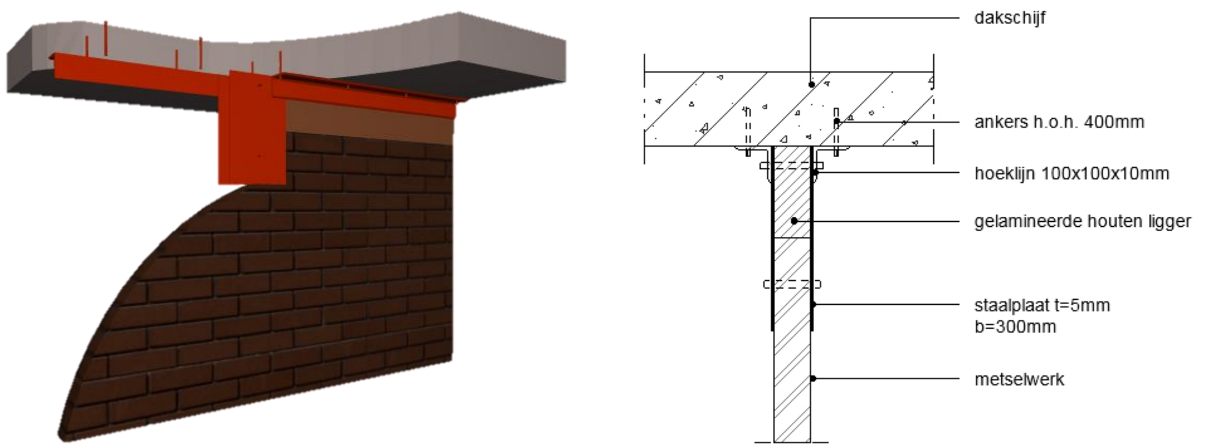
3.10.1 As-built conditions

In the majority of URM buildings the internal partition walls are not connected to the above standing floor. This condition makes the walls extremely vulnerable to out-of-plane failure, since the overturning of the wall (even lacking of top vertical load that may contribute to the wall stability) can easily activate.
In case of stiff RC floors, the floor may restrain the movement of the top section after the activation of the out-of-plane mechanism and the consequent uplifting of the top portion of the wall (if no gap exists between the wall and the floor).

Strength:
No connection between the non-loadbearing wall and the floor. Even though, as discussed above, some retaining can be provided by the floor to the out-of-plane failure of the wall in case of stiff RC floor, this effect is often neglected.

3.10.2 Strengthening options

Maatregelencatalogus:
Measure L2-037 [1] allows connecting a concrete floor to the top of a URM wall with steel angles and mechanical or chemical anchors (Figure 32). For strengthened timber floors, specific design of this retrofitting measure can be studied.



(a) (b)

Figure 32. Sketch (a) and technical drawing (b) of the retrofitting measure L2-037 (from the Maatregelencatalogus [1]).

Strength:
The strength of the connection depends on the used connectors, the steel angle, and the embedment material (concrete or masonry).
An indicative value of the strength of connectors embedded in solid clay brick masonry can be derived from the test reported in section 3.3.2.

3.11 Non-loadbearing masonry wall disconnected to transversal walls

3.11.1 As-built conditions

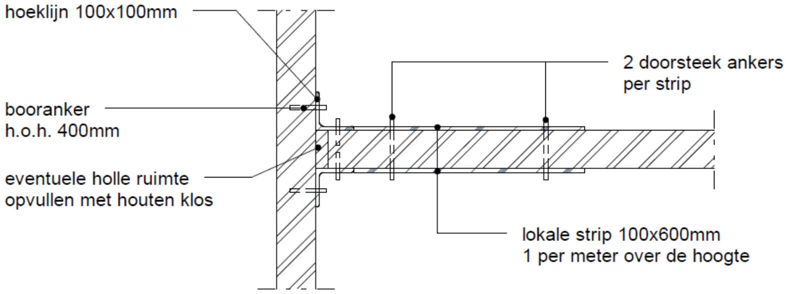
A large number of internal partition walls are not connected to the transversal loadbering walls. This condition increases the out-of-plane vulnerability of the wall. Additionally the connection between transversal walls can increase the overall in-plane capacity of the structure.

Strength:
The transversal walls are not connected. For this reason, the strength of the connection is usually assumed to be negligible.

3.11.2 Strengthening options

Maatregelencatalogus:
Measure L2-025 [1] is designed to connect two transversal URM walls with the use of steel angles and plates, and mechanical or chemical anchors (Figure 32).

(a)



(b)

Figure 33. Sketch (a) and technical drawing (b) of the retrofitting measure L2-025 (from the Maatregelencatalogus [1]).

Strength:
The strength of the connection depends on the used connectors, the steel angle and plates, and the masonry.
An indicative value of the strength of connectors embedded in solid clay brick masonry can be derived from the test reported in section 3.3.2.

Acknowledgements

This research was funded by NAM under contract numbers UI:67339 / 4610057386 "Structural upgrading of masonry structures in the Groningen area - TU Delft research program 2018/19".
The creation of the abacus was possible thanks to the discussion with the engineering companies working on field and participating to the CVW regular knowledge meetings (particularly Sander Meijers of VIIA and Han Krijgsman of BORG), that are kindly acknowledged.

References

[1] Catalogue of the strengthening measures: https://www.maatregelencatalogus.nl/

[2] Mirra, M., Ravenshorst G. J. P. (2019). Monotonic, cyclic and dynamic behaviour of timber-masonry connections. Delft University of Technology. Report number CS2B04WP2-3.3, 3 December 2019

[3] Ravenshorst GJP, Mirra M (2018). Test report on cyclic behaviour of replicated timber joist-masonry wall connections. Delft University of Technology. Report number C31B67WP4-11, version 02, 16th April 2018.

[4] Popma JT (2014). Groninger Preventie Structural Upgrading. Molenweg 32 Loppersum. Testresultaten 23-7-2014. Test report prepared by Fischer Benelux BV for Arup, 23 July 2014

[5] CEN, European Committee for Standardization (2002), Basis of structural design, Design Code EN 1990. Brussels, Belgium

[6] BICL(NL) BV (2018), Seismic Assessment Criteria (Basis of Assessment), Draft v.01, 23 January 2018

[7] EN 1052-3 (2002). Method of test masonry – Part 3: Determination of initial shear strength. Nederlands Normalisatie-instituit (NEN)

[8] Esposito R, Messali F, Rots JG (2016). Material characterization of replicated masonry and wall ties. Final report 18 April 2016, Delft University of Technology, Delft, the Netherlands

[9] Korswagen P, Meulman E, Mariani, V (2017). Testing, Characterisation, and Modelling of NeHoBo floors for Groningen Seismic Assessment. Report number C31B71WP0-1, Intermediate Report, version 3.3, January 2018.

[10] Messali F, Skroumpelou G, Esposito, R. (2017). Tests on existing wall ties: shear and axial tests. Delft University of Technology. Report number C31B67WP6-2, Version 01, 04 January 2017.

[11] Messali F (2018). Strength of as-built cavity wall ties and retrofitting anchors. Memorandum CM1B05-WP1-M1. Draft version 01, 23 March 2018, Delft University of Technology, Delft, the Netherlands

[12] Messali F, Paletti E (2017). Tests on retrofitting wall ties. Delft University of Technology. Report number C31B67WP6-4 Version 01, 01 August 2017.