Energy efficient buildings by use of reinforced masonry walls

An experimental study

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Energy efficient buildings by use of reinforced masonry walls

An experimental study



Miklós Molnár   Jonas Niklewski   Ívar Björnsson

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Preface

The present report presents the results of the research and development project "Energy efficient buildings by use of reinforced masonry walls". The project has been carried out at Lund University, during 2018-2021, involving J. Niklewski, P-O. Rosenkvist, I. Björnsson and M. Molnár (project leader), all of them from the Division of Structural Engineering.

In the project, knowledge concerning energy and resource efficient masonry external walls is developed. The objective was to develop a new generation of energy efficient masonry walls without further increasing the total thickness of the walls. This objective was achieved by reducing the thickness of the load bearing layer by use of externally bonded reinforcement, which makes it possible to increase the thickness of the insulation layer.

The energy saving potential on building level is estimated to 20 – 30 %. On a national scale, the energy saving potential in newly built dwellings and commercial buildings is estimated to 25 – 30 GWh/year, with an increasing positive trend due to a more energy efficient building stock.

The project has been financed by the Swedish Energy Agency's research and innovation programme E2B2, through grant 37582-3. The following industry actors contributed with expertise, materials, labour force and dissemination of the project's results:

- J. Andersson and K. Nyman, Weber Saint-Gobain AB;
- A. Planensten, Fasadgruppen (earlier Randers Tegel AB);
- O. Jäderlund, Combimix AB;
- M. Persson, Tegelmäster AB;
- H. Johansson, Joma AB;
- T. Gustavsson, TG konstruktioner AB;
- M. Karling, Karling Fasad AB;
- K. Karlsson, Nyströms Cement AB;
- C. Hansson, Brukspecialisten AB;
- F. Almfeldt, Kåver & Mellin AB;
- Å. Nordlund, Tyréns (earlier WSP)
- T. Hemberg, Adfors Saint-Gobain.

We gratefully acknowledge the support from all the mentioned actors. We would further like to acknowledge J. Hiller and R. Andersson, brick-layers and P. Brynk, undergraduate student, for their help with the construction and strengthening of the walls.

Lund, in March 2021

Miklós Molnár Jonas Niklewski Ívar Björnsson

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1 Introduction

1.1 Background

In Sweden, the housing sector stands for approximately 30 percent of the energy use. Although the energy performance of newly built buildings in Sweden has steadily improved, the implementation of the Energy efficiency directive of the European Union 2012/27/EU puts new, sharper demands on the energy performance of the building envelope of new buildings.

Traditionally, the energy performance of the building envelope has been improved by use of building materials with better energy performance, often in combination with thermal insulation – the later applied in ever increasing thicknesses. Accordingly, modern Swedish building envelops usually have a thickness above 400 millimetres and external walls with a thickness of 500 millimetres are not seldom encountered.

Following the same trend is a feasible option, yet afflicted with the drawback that an increase of the wall thickness will reduce the useable area of the building. Thus, a continued increase of the thickness of the building envelope will entail a major economic drawback. Furthermore, increasing the thickness of the walls will require more building materials, which increases costs and the use of natural resources and generates more emissions contributing to climate change.

1.2 Thinner masonry walls by use of externally bonded reinforcement

In the present project, introduction of thinner masonry walls is investigated by use of externally bonded reinforcement. The technique of externally bonded reinforcement has previously been investigated mainly with the objective to improve the seismic performance of masonry, see Papanicolaou et al (2011), Valluzzi et al (2014). Use of externally bonded reinforcement as a means to improve the load bearing capacity of walls subjected to bending and axial load are more limited, see Bernat et al (2013), Jönsson and Molnár (2018).

Externally bonded reinforcement is normally applied to the external surface of the masonry and embedded in a render layer. The latter is used as a means of anchoring the reinforcement to the masonry and by that assuring full composite action between the wall and the reinforcing layer.

Much of the development concerning externally bonded reinforcement has focussed on the use of glass fibre mesh or similar products, associated with ease of application of the reinforcing mesh. Yet, steel products such as welded mesh, masonry reinforcement (called bistål in Swedish) or individual bars have also been considered.

Since the load bearing capacity of traditional masonry walls subjected to bending and axial load is often limited by the lack of useable bending strength of masonry, the opportunity to reinforce masonry walls seems promising - reinforced walls are expected to be less vulnerable with respect to buckling.

In a research and development project carried out at Lund University during 2016-2018, the behaviour of reinforced clay brick masonry walls subjected to eccentric axial loading was investigated experimentally, see Jönsson and Molnár (2018). By use of reinforcement, the axial load bearing capacity of the clay walls lay brick walls was improved by 30 – 100 percent. The results from the mentioned project gave rise to the idea to explore the practical limits for minimizing the thickness of masonry walls by use of externally bonded reinforcement.

An opportunity arose in 2018 through funding granted by the Swedish Energy Agency, through the research and innovation programme E2B2 (grant number 37582-3), to a project with the main objective to improve the energy performance of masonry based external walls.

1.3 The objectives of the project

The overall objective of the project was to improve the energy performance of masonry based external walls without further increasing the total thickness of the walls compared to the present state of the art. The more in-detail objectives were as follows:

- Experimentally develop at least two types of reinforced masonry walls with a thickness of around 100 millimetres.
- Optimize the use of materials and work methods, so that the new type of walls could be produced without an increase in use of resources or price.
- Reduce energy usage in newly built single family houses and commercial premises by 20 – 30 percent, without further increasing the thickness of external walls.
- Test the new walls in pilot projects.

Possible exterior wall sections with improved thermal performance are shown in Figure 1.1

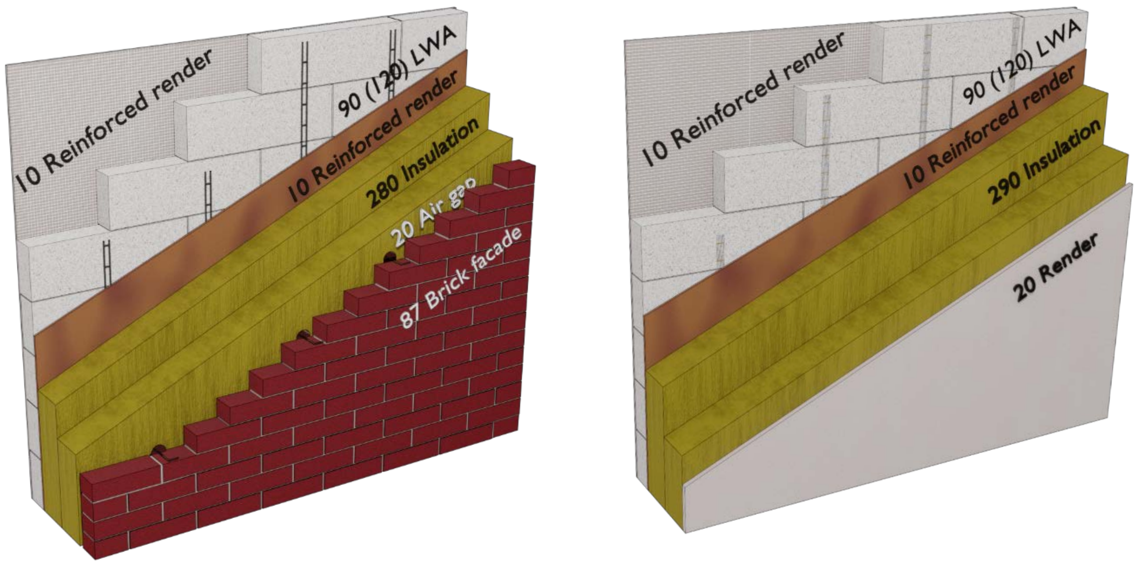

Figure 1.1 Exterior walls with improved thermal performance.

1.4 The focus of the present report

The main objective of the present report is to document the work that was carried out in the project, with focus on the experimental studies connected to the behaviour of full scale masonry walls strengthened with externally bonded reinforcement. Thus, Appendix 1 gives a more in detail summary of the results from the 36 full scale wall experiments. The report itself presents a summary of the test setup, the materials and methods that have been used (Chapter 2) and the most important results (Chapter 3). In Chapter 4, guidance is given to structural designers interested in using masonry wall strengthened with externally bonded reinforcement in practice.

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2 Experimental investigations

2.1 General

The experimental studies presented in this chapter have been carried out with the main objective to create a reliable knowledge base concerning the behaviour of masonry walls strengthened with externally bonded reinforcement, subjected to bending and axial vertical loading. Thus, 36 full scale walls were tested in the Laboratory of Structural Engineering (in Swedish V-labbet) at the Faculty of Engineering (LTH), Lund University. The testing of the walls was carried out in a rig developed in precursor to the present project, see Molnár et al (2018) and Jönsson & Molnár (2018).

In order to enhance the understanding of the wall behaviour, complementary studies were carried out on masonry components and strengthening materials.

2.2 Masonry materials

Two types of masonry – clay brick and light weight aggregate concrete (LWA) – has been used to erect the walls. In each case, a premixed dry mortar type M 2,5 from Weber Saint-Gobain was used. The thickness of the joints was 13 mm in the case of clay brick masonry and 10 mm in the case of LWA block masonry.

Clay brick masonry type 1 (BM1)

Six (6) of the studied walls in series 1 were erected using solid clay bricks with length*width*height = 228*87*56 mm from Tegelmäster AB. The bricks were manufactured in Denmark. No supplier information is available on the properties of the bricks. The following average mechanical properties of the masonry have been determined in the project:

- Compressive strength f = 9,7 MPa, CoV = 14 %;
- Peak compressive strain $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %;
- Limiting compressive strain $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;
- Modulus of elasticity E = 2480 MPa, CoV = 14 %.

The stress-strain relationship of brick masonry type 1 is shown in Figure 2.1

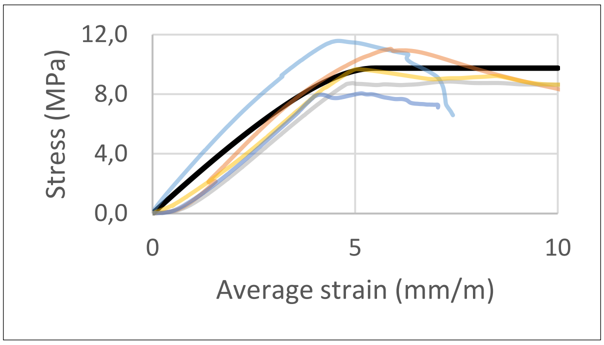

Figure 2.1 Stress – strain relationship brick masonry type 1.

Brick masonry type 1 was used for erection of 6 (six) walls in test series 1. In Appendix 1, walls of this type are named B1_W1 – B1_W6.

Clay brick masonry type 2 (BM2)

Nine (9) of the studied walls in series 3 were erected using perforated clay bricks with length*width*height = 287*87*87 mm from Wienerberger Sweden AB, see Figur 2.2 (left). The bricks were manufactured in Finland, commercial name IF Blandade M87 MH FT III. Declared compressive strength 35 MPa, water absorption 5 %. The following average mechanical properties of the masonry have been determined in the project:

- Compressive strength *f* = 14,8 MPa, CoV = 16 %;
- Peak compressive strain $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %;
- Limiting compressive strain $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;
- Modulus of elasticity E = 13000 MPa, CoV = 10 %.

The stress-strain relationship of clay brick masonry type 2 is shown in Figure 2.2 (right).

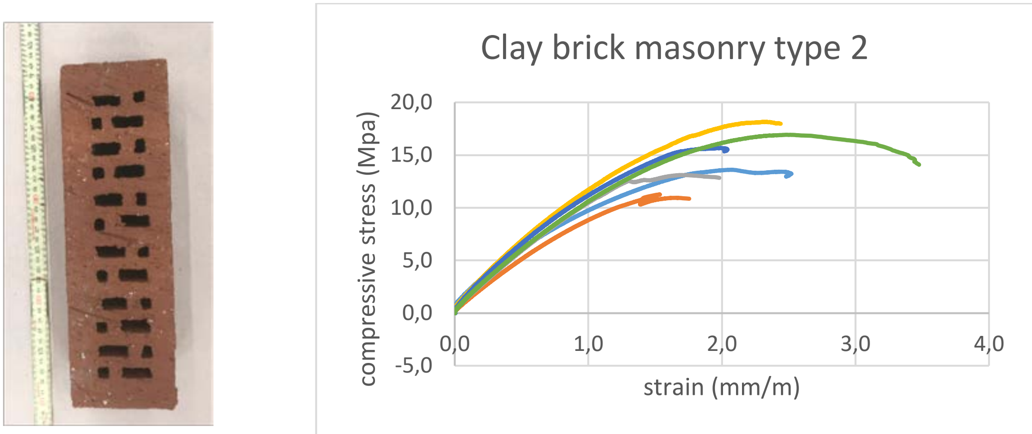

Figure 2.2 Clay brick masonry type 2. Perforated bricks (left); stress – strain relationship (right).

Brick masonry type 2 was used for erection of 9 (nine) walls in test series 3. In Appendix 1, walls of this type are named B3_W1 – B3_W9.

LWA block masonry type 1 (LWAM1)

Six (6) of the studied walls in series 1 were erected using solid light weight aggregate concrete blocks with length*width*height = 590*90*190 mm from Weber Saint-Gobain AB. The blocks were manufactured in Sweden, commercial name Leca Murblock 9 typ 5, having a declared compressive strength of 5 MPa. The following average mechanical properties of the masonry have been determined in the project:

- Compressive strength *f* = 3,3 MPa, CoV = 11 %;
- Peak compressive strain $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %;
- Limiting compressive strain $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

- Modulus of elasticity E = 2700 MPa, CoV = 4 % (Adjusted, estimated value taking into account that the strain measurement has been carried out over a length of 100 mm, while the representative length for LWA masonry is 200 mm (=block height 190 + joint height 10 mm).

The stress-strain relationship of LWA block masonry type 1 is shown in Figure 2.3.

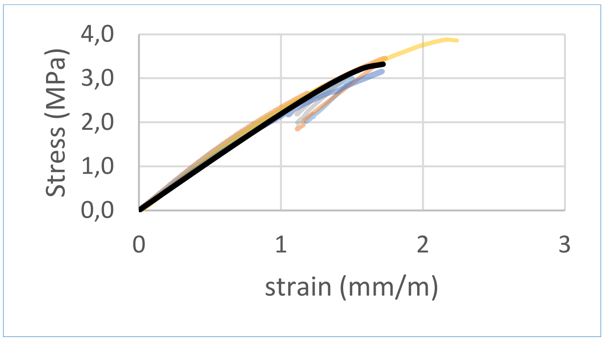

Figure 2.3 Stress – strain relationship of LWA block masonry type 1.

LWA block masonry type 1 was used for erection of 6 (six) walls in test series 1. In Appendix 1, walls of this type are named LWA1_W1 – LWA1_W6.

LWA block masonry type 2 (LWAM2)

Twelve (12) of the studied walls in series 2 were erected using solid light weight aggregate concrete blocks with length*width*height = 498*90*198 mm from Weber Saint-Gobain AB. The blocks were manufactured in Sweden, commercial name Leca Block 90, having a declared compressive strength of 3 MPa. The following average mechanical properties of the masonry have been determined in the project:

- Compressive strength f = 3,7 MPa, CoV = 7 %;
- Peak compressive strain ε_{m1} = 1,3 mm/m, CoV = 16 %;
- Limiting compressive strain ε_{mu} = 1,3 mm/m, CoV = 22 %;
- Modulus of elasticity E = 3400 MPa, CoV = 20 %

The stress-strain relationship of LWA block masonry type 2 is shown in Figure 2.4.

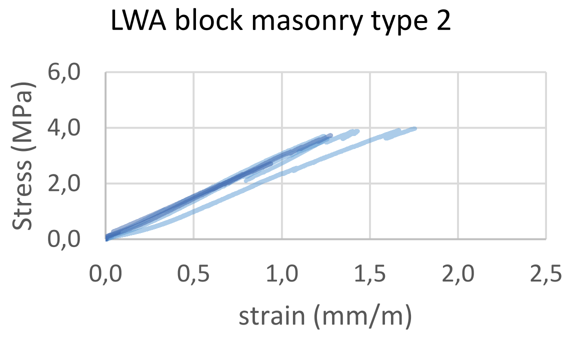

Figure 2.4 Stress-strain relationship LWA block masonry type 2

LWA block masonry type 2 was used for erection of 12 (twelve) walls in test series 2. In Appendix 1, walls of this type are named LWA2_W1 – LWA2_W12.

2.3 Strengthening renders

Strengthening render type 1

Strengthening render type 1 consisted of a cement rich render of type CS IV (older Swedish nomenclature “grundningsbruk typ A”). Two brands were used – one from Combimix AB and one from Weber Saint-Gobain AB. The following mechanical properties of the render were determined in the project:

- Dynamic modulus of elasticity E_{dyn}= 13000 MPa
- Static modulus of elasticity E_{stat}= 10000 MPa (estimated value)
- Flexural strength f_{fl} = 2,9 MPa
- Compressive strength f_c = 15,0 MPa

Strengthening render type 2

Strengthening render type 2 type CS IV mortar (older Swedish nomenclature “putsbruk B grov”), from Combimix AB. The following mechanical properties of the render were determined in the project:

- Dynamic modulus of elasticity E_{dyn}= 10400 MPa
- Static modulus of elasticity E_{stat}= 8000 MPa (estimated value)
- Flexural strength f_{fl} = 2,2 MPa
- Compressive strength f_c = 10,1 MPa

2.4 Strengthening materials

Masonry reinforcement (bistål)

The masonry reinforcement of type “bistål” is constituted of two bars welded at 95 mm distances with a perpendicular bar – all bars in the same plane in order to easily fit in a masonry bed joint. The masonry reinforcement was produced by Joma AB, commercial name Bi 40 fz, quality 700 – fz stands for surface coating with zinc, while 700 indicates the strength of the steel. The masonry reinforcement had the following properties:

- Strength f_y =717 MPa (determined experimentally in the project);
- Modulus od elasticity E = 210 (declared by the manufacturer);
- Percentage plastic extension at maximum force A_g =1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.
- Reinforcement area $A_s = 25$ mm^2 (two bars with Φ = 4 mm)

A load – deformation curve from one of the tests carried out to determine the strength and the percentage of plastic deformation at maximum force is shown in Figure 2.5. Observe that the axial deformation is measured by the LVDT embedded in the MTS testing machine and thus should not be used to determine the elastic modulus of the bar.

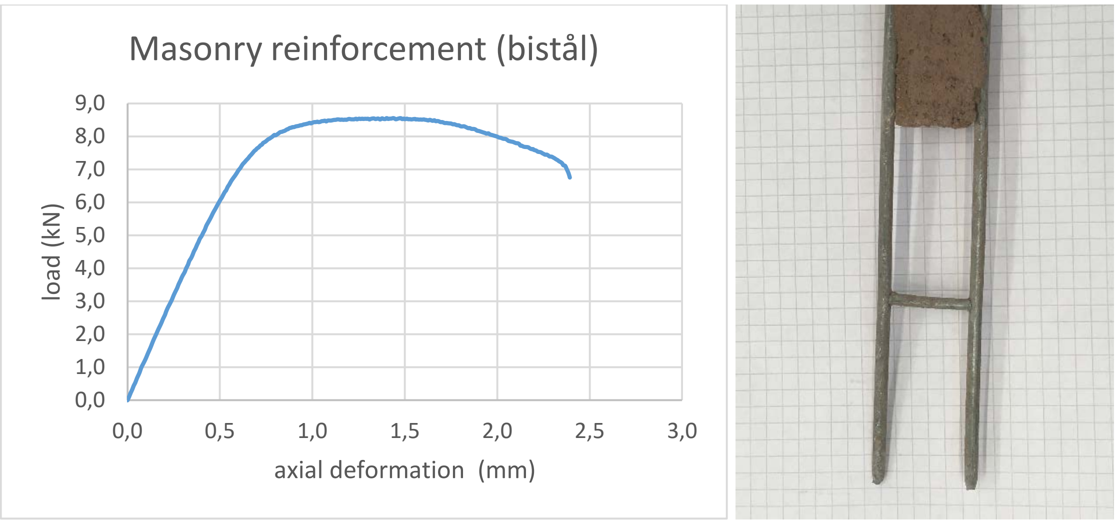

Figure 2.5 Masonry reinforcement (bistål). Load – axial deformation curve for one masonry reinforcement bar with A_s=12,5 mm^2 (left); ruptured masonry reinforcement (right).

High strength steel wire strips

This product is constituted of seven (7) wire threads of high strength stainless steel, assembled to a strip by use of perpendicular glass fibre threads, see Figure 2.6. The commercial name of the product is Leca murverksarmering 35 RF from Weber Saint-Gobain. The product is manufactured by Bekaert. The following mechanical properties have been declared by the manufacturer:

- Characteristic strength $f_{yk} = 1525\ MPa$;
- Modulus of elasticity $E = 150\ GPa$;
- Ductility class normal;
- Reinforcement area $A_s = 4{,}83$ mm^2

Figure 2.6 High strength steel wire strips before embedment in strengthening mortar.

Welded steel mesh

The welded carbon steel mesh, normally used in concrete construction, was purchased in the building materials' shop. The commercial name of the steel mesh is 6150, denoting that the bars have a diameter of 6 mm and the centre distance between the bars is 150 mm in both directions. The bars cross each other at different levels, making the nominal thickness being 12 mm. According to the shop, the steel mesh had the following properties:

- Characteristic strength $f_y = 500\ MPa$ (quality NK500AB-W);
- Modulus of elasticity *E* = 200 GPa (assumed value in the project);

Steel strips

The steel strips were cut out from steel sheets with thickness 2 mm in a mechanical workshop. The steel had the following mechanical properties:

- Characteristic strength $f_{yk} = 235\ MPa$ (according to the supplier);
- Rupture strength $f_u = 332\ MPa$ (determined in the project);
- Modulus of elasticity *E* = 210 GPa (assumed value in the project);
- Gross area $A_{gr} = 80$ mm^2
- Net area $A_{net} = 68$ mm^2 (after deduction of the hole diameter).

Glass fibre mesh type 1

One of the glass fibre mesh products used were manufactured/delivered by Adfors (Saint-Gobain), commercial name R267 A101. The following mechanical properties were specified by the manufacturer:

- Nominal ultimate strength, weft $F_{ru,0}$ = 126 kN/m (strong direction)
- Ultimate strength, weft $F_{ru,\infty}$ = 94 kN/m (28 days strength according to ETAG test)
- Modulus of elasticity E = 80 GPa; (source – Wikipedia: "glass fibre")
- Strain at failure $\varepsilon_{ru} = 40$ mm/m.
- Net area in the weft direction of the mesh $A_r = 40$ mm^2/m (estimated as $A_r = F_{ru,0}/(E \cdot \varepsilon_{ru})$
- Square dimension warp/weft 8,5/6,5 mm

Glass fibre mesh type 2

The second one of the glass fibre mesh products used were manufactured/delivered by Adfors (Saint-Gobain), commercial name R451 A101. The following mechanical properties were specified by the manufacturer:

- Nominal ultimate strength, weft $F_{ru,0}$ = 164 kN/m (strong direction)
- Ultimate strength, weft $F_{ru,\infty}$ = 98 kN/m (28 days strength according to ETAG test)
- Modulus of elasticity E = 80 GPa; (source – Wikipedia: “glass fibre”)
- Strain at failure ε_{ru} = 45 mm/m.
- Net area in the weft direction of the mesh A_r = 46 mm^2/m (estimated as $A_r = F_{ru,0}/(E \cdot \varepsilon_{ru})$
- Square dimension warp/weft 5/5 mm

2.5 Wall specimens and experimental plan

In total, 36 full scale walls were manufactured by two professional bricklayers in the laboratory. In order to facilitate handling, the walls were manufactured in a frame. The bottom perpend of the frame consisted of a rectangular steel profile, with the cavity filled with concrete. This solution facilitated testing of the walls, since they could be placed in the testing rig without the need of removing the bottom perpend. Figure 2.7 shows pictures from manufacturing of the LWA block walls in series 2 (left) and the clay brick walls in series 3 (right).

Figure 2.7 Manufacturing of the LWA block walls in series 2 (left); clay brick walls in series 3 (left).

The frame’s two vertical sides were manufactured of glulam, thus facilitating lifting of the walls into the testing rig by a traverse crane. The vertical sides of the frame served also as guidance for compaction and regulation of the thickness of the strengthening render.

Before strengthening, the wall specimens had the following nominal dimensions:

- Brick walls, series 1 – L*W*H = 470*87*2400 mm
- LWA walls, series 1 – L*W*H = 590*90*2400 mm

- LWA walls, series 2 - L*W*H = 498*90*2400 mm
- Brick walls, series 3 - L*W*H = 587*87*2400 mm
- LWA walls, series 3 - L*W*H = 590*90*2400 mm

After manufacturing, the walls were cured for three weeks. Strengthening was carried out using materials presented in section 2.3 and 2.4. In series, the strengthening was applied in fresh render. This procedure was abandoned in series 2, since it was anticipated that large savings in terms of work time and strengthening render could be achieved. Finally, it was concluded that the steel-based strengthening products could be applied directly on the dry masonry, with subsequent embedment in strengthening mortar. The project arrived at the conclusion the glass fibre meshes should be applied in fresh render, tooled for full embedment and finally covered with additional strengthening mortar. The strengthening mortar was applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Figure 2.8 shows work steps involved in strengthening of the walls. The QR-code in Figure 2.9 links to a Youtube video showing work steps involved in strengthening and testing of one wall.

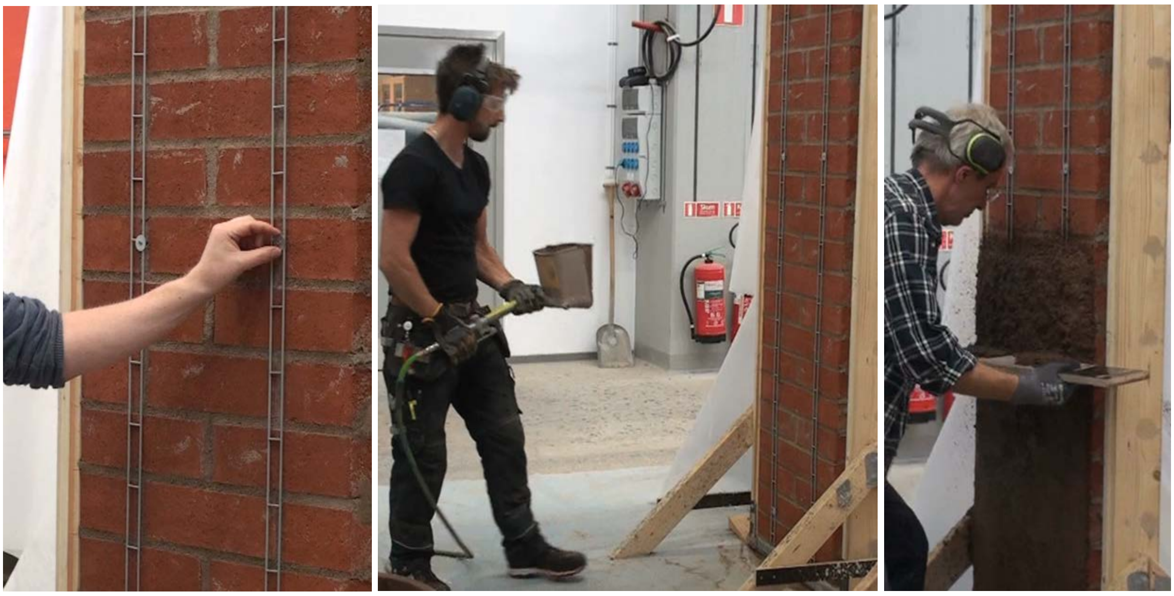

Figure 2.8 Attachment of the reinforcement (left); spraying of the strengthening render (middle); compacting and levelling of the render (right).

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SCAN ME

Figure 2.9 QR-code to Youtube video showing strengthening and testing of a wall.

An overview of the strengthening scheme is presented in Table 2.1. Further details are presented in Appendix 1.

Table 2.1 Strengthening scheme of the walls, see footnote for denotations concerning the masonry materials. For further details, e.g. the denotation of the walls, see Appendix 1.

Wall	Steel mesh	Masonry reinforcement (bistål)	Steel strips (mechanically fastened)	High strength steel wire	Glass fibre mesh type R267	Glass fibre mesh type R451	Render only	No render, no strength.
B1_W1	BM1							
B1_W2		BM1						
B1_W3			BM1					
B1_W4				BM1				
B1_W5					BM1			
B1_W6						BM1		
LWA1_W1	LWAM1							
LWA1_W2		LWAM1						
LWA1_W3			LWAM1					
LWA1_W4				LWAM1				
LWA1_W5					LWAM1			
LWA1_W6						LWAM1		
LWA2_W1					LWAM2			
LWA2_W2		LWAM2						
LWA2_W3					LWAM2			
LWA2_W4				LWAM2				
LWA2_W5				LWAM2				
LWA2_W6					LWAM2			
LWA2_W7		LWAM2						
LWA2_W8				LWAM2				
LWA2_W9				LWAM2				
LWA2_W10					LWAM2			
LWA2_W11					LWAM2			
LWA2_W12							LWAM2	
B3_W1		BM2						
B3_W2		BM2						
B3_W3				BM2				
B3_W4				BM2				
B3_W5					BM2			
B3_W6					BM2			
B3_W7							BM2	
B3_W8							BM2	
B3_W9								BM2
LWA_W1					LWAM1			
LWA_W2							LWAM1	
LWA_W3								LWAM1

Denotations: BM1 – clay brick masonry type 1; BM2 – clay brick masonry type 2; LWAM1 – lightweight aggregate concrete block masonry type 1; LWAM2 – lightweight aggregate concrete block masonry type 2;

2.6 Test rig

The test rig used to subject the walls to bending and vertical axial load in this project was the same as the rig presented in Jönsson and Molnár (2018). The rig was built as a self-equilibrating 3D-structure, mainly consisting of I-shaped cross section, steel elements. A schematic of the test rig is shown in Figure 2.10.

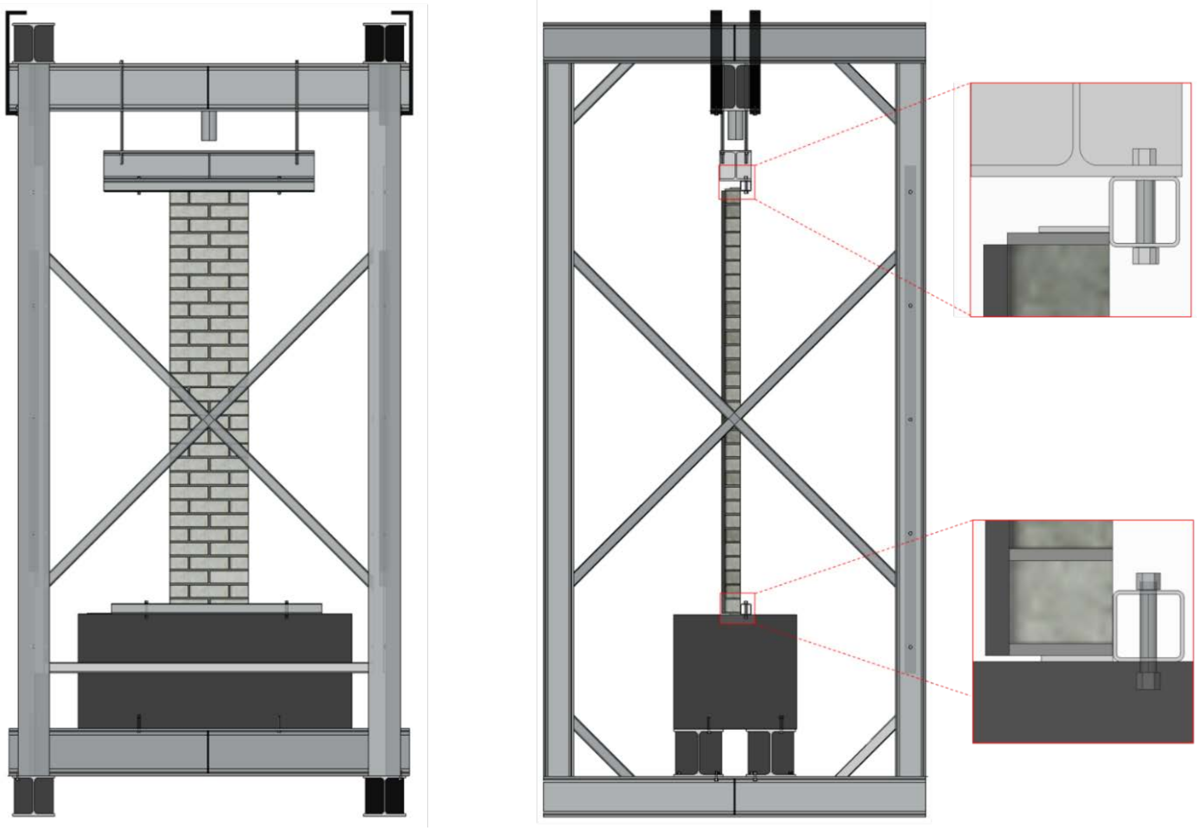

Figure 2.10 Rig for testing walls in bending and vertical axial loading.

The vertical axial load was generated with a hand controlled hydraulic pump, with a maximum capacity of 500 kN. The vertical axial load was introduced with eccentricity using a steel plate of width 60 mm at both supports. In this way, the walls were subjected to a combined vertical load in combination with a constant bending moment along the entire height of the walls. The relative eccentricity of the walls, calculated as the ratio between the resulting eccentricity and the thickness of the wall, varied between 0.16 – 0.20. Thus, the resulting bending moment introduced a certain tensile bending stress on the strengthened side of the walls.

This loading made that the walls deflected in a controlled manner, facilitating protection of the research crew and the technical equipment.

The bottom support of the wall is considered to be close to full restraint, while the top is considered to be simply supported.

2.7 Measurements

The vertical axial load was measured with a load cell placed between the top loading beam and a transverse beam. Displacements have been measured as follow:

- Transversal displacement at mid-height of the wall (potentiometer);
- Vertical axial deformations measured at five positions according to Figure 2.11 (LVDT).

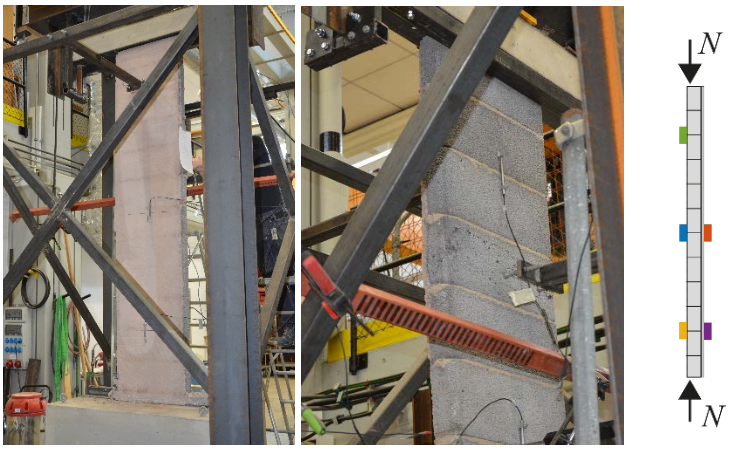

Figure 2.11 Measurement of the vertical axial deformations.

3 Results

3.1 Load bearing capacity of walls subjected to bending and vertical axial loading

In total 36 full scale walls have been tested by subjecting them to combined bending and vertical axial loading according to a procedure described in section 2.6. Thus, it should be remembered that that walls are subjected to a vertical load acting in the axial direction and that the load is introduced in a way to generate a constant moment along the wall. The results are summarized in Figure 3.1 and 3.2. More details are presented in Table 3.1 and Appendix 1.

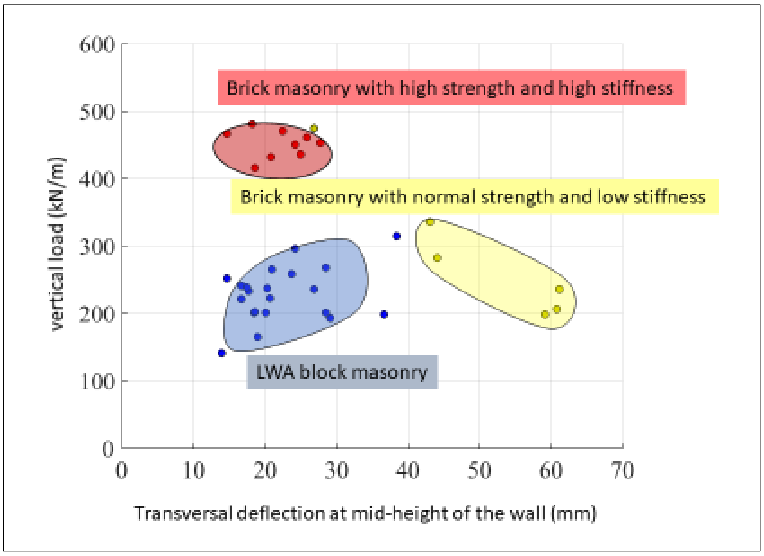

Figure 3.1 Load bearing capacity of the walls subjected to combined bending and vertical axial load.

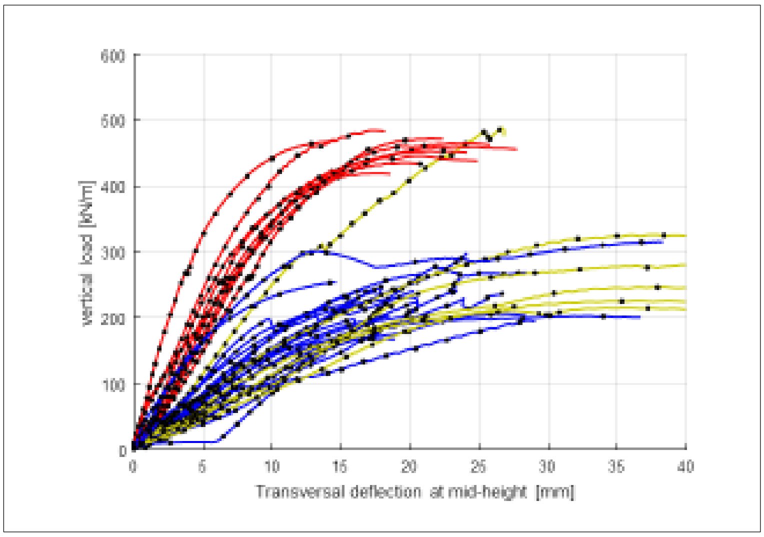

Figure 3.2 Load versus transversal deformation curves for 36 walls. The colour scheme is identical to that used in Figure 3.1.

Table 3.1 Structural response of 36 masonry walls. For further details, see Appendix 1.

Wall	Masonry material	Type of strengthening	Failure mode	Vertical load at failure (kN/m)	Transversal deflection at failure (mm)
B1_W1	BM1	Steel mesh – A_s=180 mm²/m	Crushing at support	487	27
B1_W2	BM1	Masonry reinf. - A_s=106 mm²/m	Yielding of the reinf.	294	44
B1_W3	BM1	Steel strips - A_s=340 mm²/m	Yielding of the reinf.	215	59
B1_W4	BM1	High strength steel wire - A_s=21 mm²/m	Rupture of the reinf.	247	38
B1_W5	BM1	Glass fibre R267 – A_r=40 mm²/m	Rupture of the glass f.	238	61
B1_W6	BM1	Glass fibre R451 – A_r=45 mm²/m	Flexural compr. mas.	238	61
LWA1_W1	LWAM1	Steel mesh – A_s=180 mm²/m	Crushing near support	203	20
LWA1_W2	LWAM1	Masonry reinf. - A_s=85 mm²/m	Flexural compr. mas.	195	29
LWA1_W3	LWAM1	Steel strips - A_s=540 mm²/m	Flexural compr. mas.	166	18
LWA1_W4	LWAM1	High strength steel wire - A_s=25 mm²/m	Crushing near support	278	22
LWA1_W5	LWAM1	Glass fibre R267 – A_r=40 mm²/m	Flexural compr. mas.	205	26
LWA1_W6	LWAM1	Glass fibre R451 – A_r=45 mm²/m	Flexural compr. mas.	203	32
LWA2_W1	LWAM2	Glass fibre R267 – A_r=40 mm²/m	Flexural compr. mas.	168	14
LWA2_W2	LWAM2	Masonry reinf. - A_s=100 mm²/m	Flexural compr. mas.	314	21
LWA2_W3	LWAM2	Glass fibre R267 – A_r=40 mm²/m	Crushing near support	233	10
LWA2_W4	LWAM2	High strength steel wire - A_s=19 mm²/m	Crushing near support	273	20
LWA2_W5	LWAM2	High strength steel wire - A_s=19 mm²/m	Flexural compr. mas.	239	19
LWA2_W6	LWAM2	Glass fibre R267 – A_r=40 mm²/m	Crushing near support	293	16
LWA2_W7	LWAM2	Masonry reinf. - A_s=100 mm²/m	Flexural compr. mas.	265	21
LWA2_W8	LWAM2	High strength steel wire - A_s=14 mm²/m	Crushing near support	352	24
LWA2_W9	LWAM2	High strength steel wire - A_s=14 mm²/m	Flexural compr. mas.	282	17
LWA2_W10	LWAM2	Glass fibre R267 – A_r=28 mm²/m	Flexural compr. mas.	240	19
LWA2_W11	LWAM2	Glass fibre R267 – A_r=28 mm²/m	Crushing near support	232	16
LWA2_W12	LWAM2	Render on the tension side	Crushing near support	206	17
B3_W1	BM2	Masonry reinf. - A_s=85 mm²/m	Rupture of the reinf.	448	25
B3_W2	BM2	Masonry reinf. - A_s=85 mm²/m	Rupture of the reinf.	453	24
B3_W3	BM2	High strength steel wire - A_s=17 mm²/m	Rupture of the reinf.	425	20
B3_W4	BM2	High strength steel wire - A_s=17 mm²/m	Rupture of the reinf.	462	23
B3_W5	BM2	Glass fibre R267 – A_r=40 mm²/m	Bond failure overlap	451	23
B3_W6	BM2	Glass fibre R267 – A_r=40 mm²/m	Bond failure overlap	442	21
B3_W7	BM2	Render on the tension side	Mechanism at 2/3rd h.	417	18
B3_W8	BM2	Render on the tension side	Mechanism	464	16
B3_W9	BM2	Plain wall	Mechanism	481	18
LWA_W1	LWAM1	G.F. R267 – A_r=40 mm²/m; rend. backs.	Crushing near support	315	13
LWA_W2	LWAM1	Render on the tension side	Mechanism at ½ h.	222	17
LWA_W3	LWAM1	Plain wall	Mechanism at ½ h.	253	15

Denotations: BM1 – clay brick masonry type 1; BM2 – clay brick masonry type 2; LWAM1 – lightweight aggregate concrete block masonry type 1; LWAM2 – lightweight aggregate concrete block masonry type 2;

From Figure 3.1 it can be seen that brick masonry walls generally had a larger load bearing capacity than LWA block masonry walls, mainly due to the formers' higher compressive strength – approximately 10 – 15 MPa for brick masonry compared to around 3,5 MPa for LWA block masonry.

Two other significant features shall be observed, both related to the stiffness of masonry materials. In spite of a distinct difference in compressive strength between the LWA block masonry (3,5 MPa - blue cluster) and the brick masonry with compressive strength around (10 MPa - yellow cluster), the load bearing capacity of the walls was similar – mainly in the interval 150 – 300 kN/m. Thus higher stiffness of the LWA walls (E = 2700 MPa for LWAM compared to 2500 MPa for BM1) compensated for lower compressive strength.

The same trend can be observed when the load bearing capacity of the brick walls built with high strength and high stiffness (E = 13000 MPa - red cluster) and normal strength and low stiffness (2500 MPa – yellow cluster) are compared. Difference in stiffness between the two types of brick masonry is also reflected by larger transversal deformations of the walls – between 10 – 30 mm for the walls with BM2 masonry versus 40 – 60 mm for the walls with BM1 masonry.

3.2 Behaviour at failure

The walls failed in three distinct modes – flexural compression, rupture of the reinforcement and crushing of the masonry at the upper support, below the steel plate that was used to introduce the vertical load.

Flexural compressive failure, occurred mostly close to the mid-height of the walls or over this level. This failure mode was most frequent in the walls built with LWA block masonry and can be explained by the relatively low compressive strength (3,5 MPa) and limited deformation capacity (limiting compressive strain around 1,5 mm/m) of the LWA block masonry. A typical flexural compressive failure is shown in Figure 3.3. As a result of the flexural compressive failure, the load dropped, yet without triggering collapse the walls.

Figure 3.3 Flexural compressive failure in an LWA block wall.

Rupture (tensile failure) of the strengthening was mostly registered in the brick walls. This failure mode was in most cases the result of yielding and excessive deformation of the strengthening materials – mainly of the steel based strengthening products. Rupture of masonry reinforcement and high strength steel wire strips is shown in Figure 3.4. Rupture of the strengthening triggered immediate collapse of the walls.

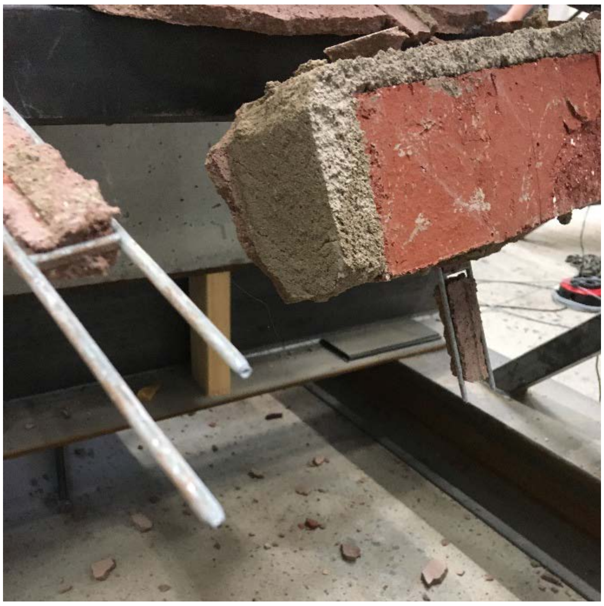

Figure 3.4 Tensile failure of strengthening, followed by collapse of the brick walls. Masonry reinforcement (left), high strength steel wire strip (right).

Tensile failure in walls strengthened with glass fibre mesh occurred either due the rupture of the mesh alternatively due to bond failure in the overlap zone between adjacent pieces of glass fibre mesh. Figure 3.5 shows the two later named failure modes in strengthening consisting of glass fibre mesh.

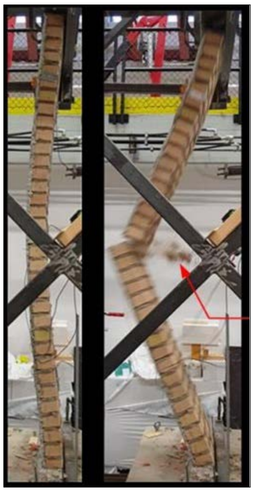

Figure 3.5 Failure in glass fibre mesh strengthening. Tensile failure of the glass fibres triggers collapse of the wall (left); bond failure in the overlap zone between to pieces of glass fibre mesh (right).

Many of the walls built with clay brick masonry type BM2, i.e. a masonry having high compressive strength (15 MPa) and high modulus of elasticity (13 000 MPa), failed in a violent way, especially when the walls where not strengthened. This behaviour can be explained by the large strain energy accumulated in the walls at load levels between 400 – 500 kN/m. The failure of these walls exhibited a behaviour that one might expect at buckling of an ideal column.

Crushing at or in the vicinity of the upper support was observed in walls built with clay brick masonry of type BM1 and LWA block masonry, most frequently in the latter. In some cases, a combined crushing and splitting of the masonry was observed, as shown in Figure 3.6.

Figure 3.6 Crushing and splitting of masonry in the vicinity of the upper support.

Crushing of the masonry triggered a drop of the load, yet without causing collapse of the walls. In some cases, the walls recovered and could carry larger loads than those registered before crushing. In the understanding of the authors, the ability of the walls to recover after crushing of the upper support was caused by a rotation towards the vertical axis of the loaded area. Thus, the rotation caused a reduction of the eccentricity of the vertical axial load. An example illustrating this behaviour is shown in Figure 3.7, where crushing occurred at a load level of 116 kN. After a smaller drop, the load peaked at 140 kN.

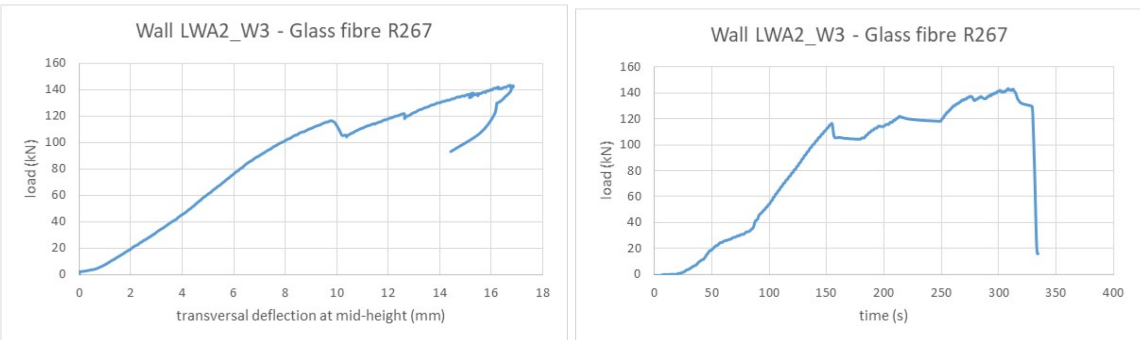

Figure 3.7 Recovery of the vertical load after crushing failure. Load vs. transversal deflection at mid height (left); load vs. time (right).

3.3 Cracking of the strengthening render

Two type of cracks were observed in the strengthening render – shrinkage cracks and cracks caused by flexural tensile stresses.

Shrinkage cracks were observed in approximately 25 % of the walls. Typical locations of the shrinkage cracks were in the vicinity of the strengthening (vertical cracks) and the vertical edge of the walls (horizontal cracks).

Visible cracks caused by flexural tensile stresses were observed in approximately 50 % of the walls. Typically, these cracks appeared at high loads, just before failure of the walls. For security reasons, the cracks could not be inspected during the ongoing experiment. Instead, a video recorder focussing the central, strengthened side of walls was used to register the behaviour of the walls.

In many cases no identifiable cracks could be detected, which might be explained by the fact that the relative eccentricity of the vertical axial load was in the range 0,16 – 0,20, making that the flexural tensile stresses might have been limited. Since the flexural strength of the render was 2,9 MPa and the modulus of elasticity around 10 000 MPa, see section 2.3, cracks might be expected at tensile strain levels close to 0,3 mm/m. These strain levels were in many cases registered at high loads, see Figure 3.8.

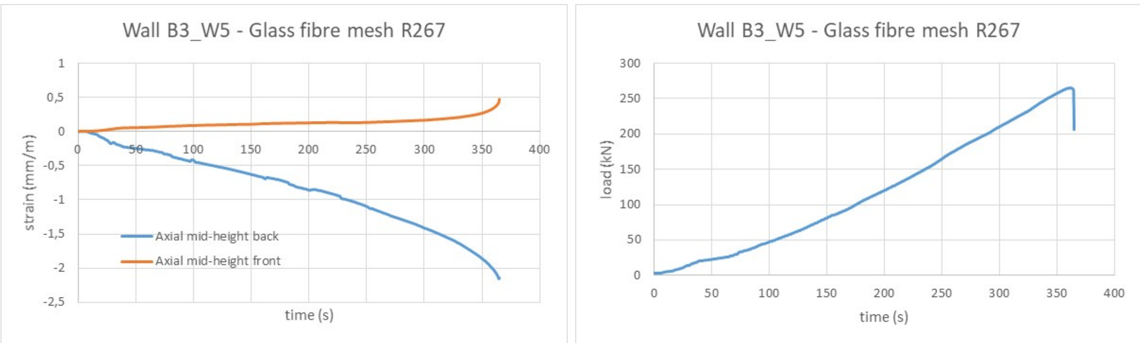

Figure 3.8 Strains at mid-height of a clay brick masonry wall (left) and corresponding loads (right).

3.4 Practical aspects

As mentioned in section 2.5, the work effort can be reduced by applying masonry reinforcement and high strength steel strips directly on the dry wall. Yet, glass fibre mesh should be applied in several steps – first by spraying a render layer of thickness between 3 – 5 mm, second by attaching the glass fibre mesh and tooling it for optimal adhesion to the substrate, third by spraying additional render to the desired thickness, fourth tooling the second render layer for optimal compaction.

When using glass fibre meshes, overlap joints should be avoided, since it is difficult to obtain adequate adhesion of the mesh to the masonry substrate. The denser the mesh, the higher the risk of low bond strength. Thus, meshes with high distance between warp/weft are preferable.

The masonry substrate might need be pre-wetting before application of the strengthening. The render used for embedment of the strengthening should be applied by a spraying tool and subsequently compacted. For the strengthening materials used in the project, a render thickness of 10 mm was considered sufficient. Yet, based on the type of the strengthening products and functional requirements such as durability, fire safety and acoustics, the thickness of render layer might be adjusted upwards or downwards.

Instalments such as electric ducts and coupling boxes might require sawing of chases and drilling of larger holes. These works should preferably be carried out before application of the strengthening. When chases are sawn after the application of the strengthening, consideration shall be taken in order to avoid damage. In this aspect, sawing of horizontal chases might be most critical.

3.5 Fire protection

Externally bonded strengthening is vulnerable with respect to fire, since a thin render layer has more limited ability to delay rising of the temperature to critical levels. In this respect, the two following strategies might be practical:

- Protection by use of gypsum render alternatively light weight render. If needed, these renders might be applied on top of a base render with cement binder. The total thickness of the render is estimated to be 15 – 20 mm.
- Instead of using externally bonded strengthening, individual reinforcement bars might be placed in vertical chases. This solution is more work intensive than application of externally bonded reinforcement.

Using gypsum render or placing reinforcement in vertical chases might normally be necessary on wall surfaces facing inwards. Reinforcement facing outwards might get sufficient protection from the thermal insulation normally required in external walls.

3.5 Acoustics

The acoustics performance of walls is closely connected to the walls' thickness and mass. Thin and light walls perform worse than thick and heavy walls. In this regard, the strengthened walls developed in the present project are expected to perform worse than similar walls with higher percentage of masonry materials. Gap and cracks can further deteriorate acoustics.

The light weight aggregate concrete walls studied in this project might pose some acoustics related problems since the density of LWA block masonry is around 750 kg/m^3. Furthermore, block masonry is often built with open head joints, a drawback from acoustics point of view. Thus, application of a render layer on both sides of a thin masonry walls is beneficial.

4 Design recommendations

The behaviour of strengthened masonry walls subjected to bending and vertical axial loads depends on the magnitude of the loads and the characteristics of the wall section such geometry and the strength of the masonry and the reinforcement. Other important parameters are the slenderness of the wall, imperfections related to the execution and uncertainties concerning the application of the loads.

Design of reinforced masonry can be carried out according to EN 1996-1-1, in combination with methods established for section and buckling analysis of reinforced concrete sections and members subjected to bending (M) and vertical axial load (N).

4.1 Section analysis

Consider a cross section of the masonry wall subjected to a centric axial load (N) and a moment (M); see Figure 4.1. The centric axial load causes a uniform compressive strain while the moment, before cracking, induces a curvature resulting in a linear strain distribution with compression and tension on either side of the section. The overall strain in the section is the sum of these two effects.

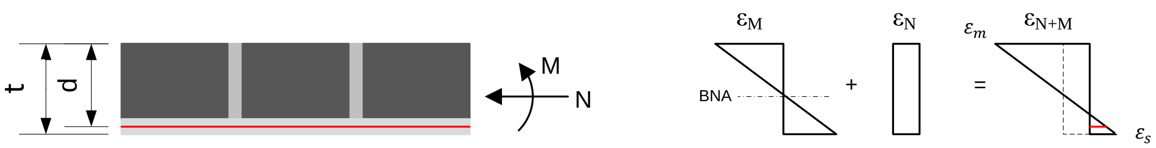

Figure 4.1 Strains in a strengthened wall section subjected to a combination of axial force (N) and moment (M); BNA = bending neutral axis.

Failure modes

Normally, there are two[1] different failure modes to be considered:

1. Tensile failure of the reinforcement, $\varepsilon_s \geq \varepsilon_{su} = 0{,}01$
2. Compressive failure of the masonry, $\varepsilon_m \geq \varepsilon_{mu}$

The limiting compressive strain ε_{mu} can be taken as 0,0035 for clay brick masonry and 0,002 for light weight aggregate (LWA) concrete masonry.

In the ultimate limit state, the strength of the render and the tensile strength of the masonry are neglected and thus set to zero. The compressive stresses are normally assumed to have reached the compressive strength of the masonry over an area equivalent to 80 percent of the compressed zone, i.e. 80 percent of the zone above the bending neutral axis, see Figure 4.2

[1] Disregarding possible anchorage failure of the strengthening or de-bonding of the render from the masonry substrate

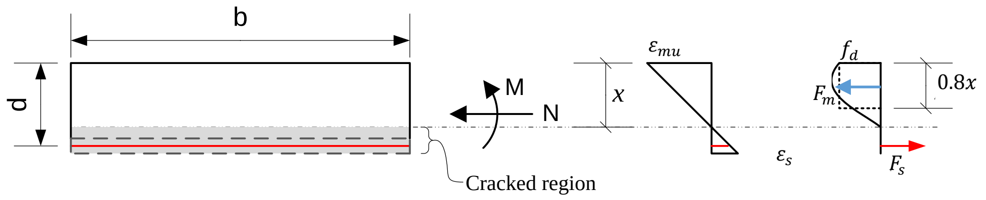

Figure 4.2 Strains and stresses in a strengthened wall section subjected to a combination of axial force (N) and moment (M) – uniform stress over the compression zone.

When the deformation capacity of the masonry is limited, see Figure 2.3 and 2.4 in this report, a more conservative assumption can be employed by considering that the stresses in the compressed masonry does not achieve the compressive stress of the masonry over the entire compression zone. Thus, a triangular stress distribution can be adopted, see Figure 4.3.

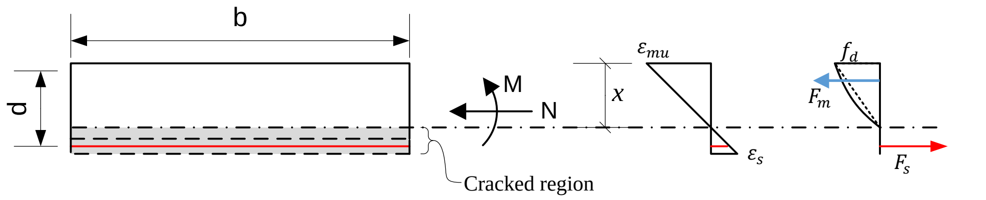

Figure 4.3. Linear stress distribution over the compression zone.

Analysis

The capacity of the strengthened wall section can be analysed using three equations:

- Equilibrium of forces;
- Equilibrium of moments;
- Strain compatibility.

If departed from the stress distribution shown in Figure 4.2, the three equations can be written as follow

$$\sum F = 0;\ N = F_m - F_s; \quad N = 0{,}8x \cdot b \cdot f_d - \sigma_s \cdot A_s; \tag{1}$$

$$\sum M = 0;\ M = F_m \cdot \left(\frac{t}{2} - 0{,}4x\right) - F_s \cdot \left(d - \frac{t}{2}\right); \quad M = 0{,}8x \cdot b \cdot f_d \cdot \left(\frac{t}{2} - 0{,}4x\right) - \sigma_s \cdot A_s \cdot \left(d - \frac{t}{2}\right); \tag{2}$$

$$\frac{\varepsilon_s}{d-x} = \frac{\varepsilon_s + \varepsilon_{mu}}{d} = \frac{\varepsilon_{mu}}{x} \tag{3}$$

Notations are according to Figure 4.2. Further, note that the moment equilibrium is taken around the central axis of the cross section. The potential unknown variables include the axial force (N), the moment (M) and the depth of the neutral axis (x).

If departed from the stress distribution shown in Figure 4.3, the three equations can be written as follow

$$\sum F = 0;\ N = F_m - F_s; \quad N = 0{,}5x \cdot b \cdot f_d - \sigma_s \cdot A_s; \tag{4}$$

$$\sum M = 0;\ M = F_m \cdot \left(\frac{t}{2} - \frac{x}{3}\right) - F_s \cdot \left(d - \frac{t}{2}\right); M = 0{,}5x \cdot b \cdot f_d \cdot \left(\frac{t}{2} - \frac{x}{3}\right) - \sigma_s \cdot A_s \cdot \left(d - \frac{t}{2}\right); \tag{5}$$

$$\frac{\varepsilon_s}{d-x} = \frac{\varepsilon_s + \varepsilon_{mu}}{d} = \frac{\varepsilon_{mu}}{x} \tag{6}$$

The notations are identical to those used in equations (1) – (3).

In design, one may use the loads M_E and N_E as input and then check whether the capacity N_R and M_R are adequate. The moment capacity is then a function of the applied normal force and vice versa. Alternatively, the capacity of a cross section can be described by a failure surface showing every possible combination of M and N for which failure occurs.

A straightforward procedure for determining this curve is by assuming different values of x and calculating the corresponding values of N and M. Since tensile normal forces (uplift) are of little practical relevance for masonry walls, the lower limit of x can be determined by setting N = 0.

Example 1: N-M diagram for light weight aggregate block wall with masonry reinforcement

Determine N - M interaction diagrams for a LWA block masonry wall section strengthened with masonry reinforcement on one side of the wall. Section geometry and material parameters are given in Table 4.1.

Table 4.1. LWA block masonry wall - section geometry and material properties

Wall breadth	b	1000 mm
Wall thickness, including 10 mm render	t	100 mm
Reinforcement area	A_s	50, 100, 200 mm²
Effective depth	d	92 mm
Masonry design compressive strength	f_d	1,7 MPa
Masonry limiting compressive strain	ε_{mu}	0,002
Reinforcement design tensile strength	f_{yd}	530 MPa
Reinforcement modulus of elasticity	E	210 GPa
Reinforcement yield strain	ε_{sy}	0,0025
Reinforcement limiting tensile strain	ε_{su}	0,010

We start the analysis by assuming that the normal force $N = 0$, i.e. the section is in pure bending. The stress distribution in the compressed zone is assumed to be according to Figure 4.2 and the tensile stress in the reinforcement is $\sigma_s = f_{yd}$. The position of neutral axis x is calculated using eq. (1)

$$N = 0{,}8x \cdot b \cdot f_d - \sigma_s \cdot A_s;$$

$$0 = 0{,}8x \cdot b \cdot f_d - f_{yd} \cdot A_s;$$

$$0 = 0{,}8x \cdot 1 \cdot 1{,}7e6 - 530e6 \cdot 50e - 6$$

$$\rightarrow x = 0{,}0195\ m$$

Using eq. (3) it is found that the tensile strain in the reinforcement is $\varepsilon_s = 0{,}0074$, which indicates that the reinforcement is yielding ($\varepsilon_{sy} = 0{,}0025$). Next, the bending moment M is calculated using eq. (2)

$$M = F_m \cdot \left(\frac{t}{2} - 0{,}4x\right) - F_s \cdot \left(d - \frac{t}{2}\right);$$

$$M = 0{,}8x \cdot 1 \cdot 1{,}7e6 \cdot \left(\frac{0{,}1}{2} - 0{,}4 \cdot 0{,}0195\right) - 530e6 \cdot 50e - 6 \cdot \left(0{,}092 - \frac{0{,}1}{2}\right);$$

$$M \cong 2.2\ kNm$$

Thus the first point in the N – M interaction diagram is $(N, M) = (0;\ 2{,}2)$.

A similar calculation using twice the amount of reinforcement, i.e. $A_s = 100\ mm^2$, gives $x = 0{,}039\ m,\ \varepsilon_s = 0{,}0027$ and $(N, M) = (0; 4{,}1)$. The value of the strain indicates, that the reinforcement is close to the yielding limit, indicating that an increase of the normal force N will decrease the stress. The section will be in a state of over-reinforcement, a term used to characterize a section where the tensile stress in the reinforcement is less than the yield strength.

A next point is calculated assuming that the reinforcement is at the limit between the elastic phase and yielding – so called balanced reinforcement. Thus, the reinforcement strain

$$\varepsilon_s = \varepsilon_{sy} = 0{,}0025$$

The position of the neutral axis is calculated using eq. (3)

$$x = 0{,}041\ m$$

Knowing x and that the reinforcement stress is equal to the yield strength, N and M are calculated using eq. (1) and (3) respectively. $N = 28{,}9\ kN$ and $M = 3{,}0\ kNm$ gives the next point $(N, M) = (28{,}9;\ 3{,}0)$.

In the case when the amount of reinforcement is $A_s = 100\ mm^2$, the stresses in the reinforcement will be lower than the yield strength. The reinforcement stress σ_s is then given by

$$\sigma_s = \varepsilon_s \cdot E_s \cdot A_s = \varepsilon_{mu} \cdot \frac{d-x}{x} \cdot E_s \cdot A_s \tag{7}$$

To determine the next point on the interaction curve, a larger value for the position of the neural axis can be chosen. If x = 0,045 mm, we obtain $\varepsilon_s = 0{,}0021$ and $(N, M) = (20; 3{,}8)$.

The presented procedure is repeated to obtain a reasonable amount of points to be able to draw the N – M curve for the two cases with different amount of reinforcement. The calculations can be more efficiently carried out using a spreadsheet.

The results of the calculations are presented in Figure 4.4, for reinforcement areas $A_s = 50\ mm^2$, $100\ mm^2$ and $200\ mm^2$. All the curves have been calculated assuming a stress block according to Figure 4.2.

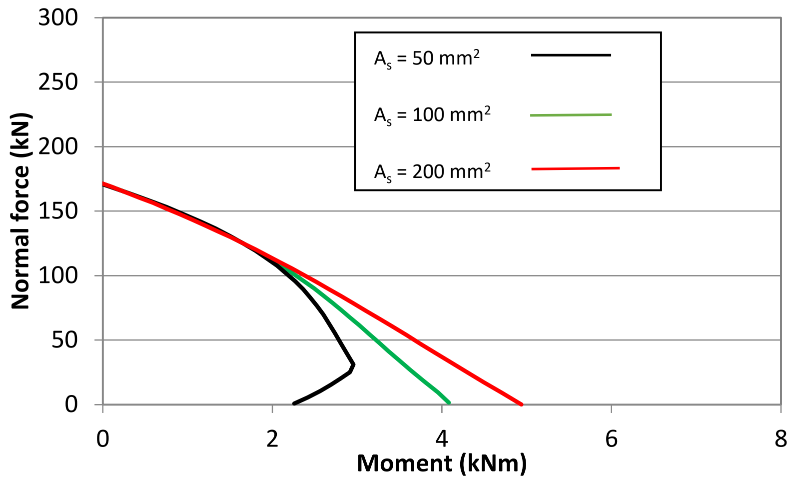

Figure 4.4 N – M interaction diagram for strengthened LWA wall, see Table 4.1.

From Figure 4.4 it should be observed that:

- Increasing the amount of reinforcement from 50 mm^2 to 100 mm^2 or more, the section gets over-reinforced, implying that the reinforcement will not be utilized in an optimal way. Yet, over-reinforcing a section might be necessary to obtain sufficient moment capacity, a situation that is often encountered in masonry columns subjected to large lateral loads, such as wind.
- At high levels of normal load, the load bearing capacity of the wall is mostly dependent on the compressive strength of the masonry, which is indicated by the convergence of the three N – M curves towards the sections' capacity at pure compression.

Example 2: N-M diagram for clay brick masonry wall with masonry reinforcement

The same task as in Example 1 is now carried out for a clay brick masonry wall section strengthened with masonry reinforcement on one side of the wall. Section geometry and material parameters are given in Table 4.2.

Table 4.2 Clay brick masonry wall - section geometry and material properties

Wall breadth	b	1000 mm
Wall thickness, including 10 mm render	t	97 mm
Reinforcement area	A_s	100, 150, 200 mm^2
Effective depth	d	89 mm
Masonry design compressive strength	f_d	4,5 MPa
Masonry limiting compressive strain	ε_{mu}	0,0035
Reinforcement design tensile strength	f_{yd}	530 MPa
Reinforcement modulus of elasticity	E	210 GPa
Reinforcement yield strain	ε_{sy}	0,0025
Reinforcement limiting tensile strain	ε_{su}	0,010

The analysis is carried out in a similar way to that shown in Example 1. The resulting N – M interaction diagrams are presented in Figure 4.5

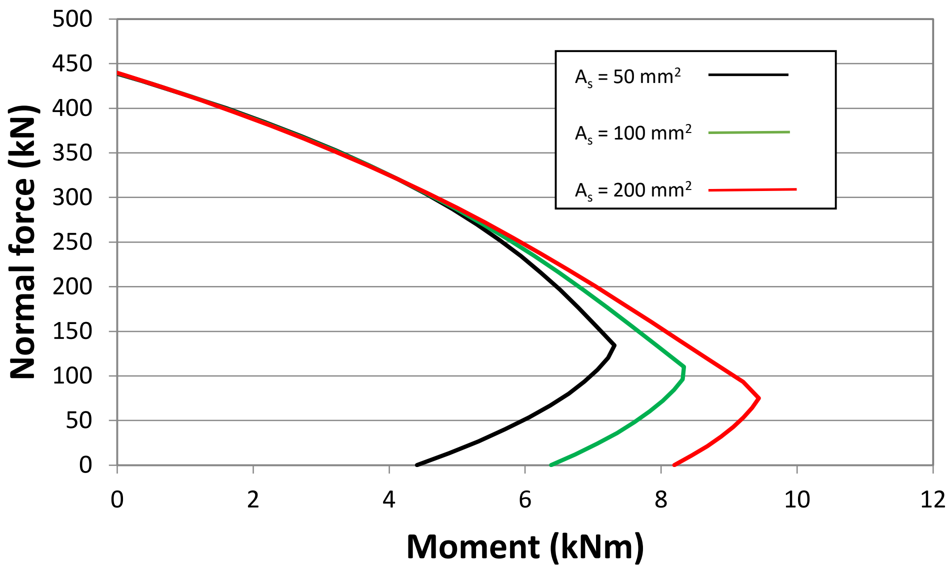

Figure 4.5 N – M interaction diagram for strengthened clay brick masonry wall, see Table 4.2.

From Figure 4.5 it should be observed that:

- At low levels of the normal force N, the sections are normal-reinforced
- At high levels of normal load, the load bearing capacity of the wall is mostly dependent on the compressive strength of the masonry, which is indicated by the convergence of the three N – M curves towards the sections' capacity at pure compression.
- Larger load bearing capacity with regard to bending moment could have been achieved by application of additional reinforcement.

4.2 Buckling analysis

Slenderness

Slender reinforced masonry walls subjected to bending and axial loading shall be designed by taking into consideration second order effects. According to EN 1996-1-1, the limiting value of the slenderness ratio, when second order effects shall be taken into account, is $\lambda_c \geq 12$. Th slenderness ratio is calculated as

$$\lambda_c = \frac{h_{ef}}{t_{ef}} \tag{8}$$

where

h_{ef} is the effective length of the wall, calculated according to general principles of structural analysis. Positive effects from restraint from confining structural elements should be taken into account according to EN 1996-1-1, 5.5.1.2.

t_{ef} is the effective thickness of the wall, calculated according to EN 1996-1-1, 5.5.1.3. For solid walls, $t_{ef} = t$.

Second order effects

Second order effects in slender reinforce masonry walls subjected to bending and axial loading are taken into account by increasing the value of the eccentricity at mid height of the wall e_{mk} calculated according to EN 1996-1-1, 6.1.2.2(1), by an additional eccentricity e_a, calculated according to EN 1996-1-1, 6.2.2 (7)

$$e_a = \frac{h_{ef}^2}{2000 \cdot t} \tag{9}$$

where

h_{ef} is the effective length of the wall;

t is the thickness of the wall.

Design bending moment

Thus, the design moment M_{ed}, adjusted for second order effects is calculated as

$$M_{Ed} = N_{Ed}(e_{mk} + e_a) \tag{10}$$

where

N_{Ed} is the design axial load;

e_{mk} is the eccentricity at the mid-height of the wall calculated according to EN 1996-1-1, 6.1.2.2 (1).

e_a is an additional eccentricity e_a, calculated according to EN 1996-1-1, 6.2.2 (7) and eq. (9) in this section.

In the light of the results of the present project, second order effects calculated according to eq. (9) might be on the safe side – especially in the case of walls, where the value of the support eccentricity e_N is less than 20 percent of the wall thickness. Furthermore, the present masonry Eurocode provisions do not consequentially take into consideration the effect of the masonry stiffness on second order effects. This makes that the positive stiffening effect of the strengthening mortar is usually not fully explored. In the draft version of the new generation of masonry Eurocodes, a more differentiated method for calculation of second order effects is proposed.

Calculation of the load bearing capacity

The load bearing capacity of a wall subjected to bending and vertical axial load is calculated by comparing the loads (N_{Ed}, M_{Ed}) calculated according to this section with the capacity of the wall section calculated according to section 4.1 in a way that

$$(N_{Ed}, M_{Ed}) \leq (N_{Rd}, M_{Rd}) \tag{11}$$

Example 3: Load bearing capacity of light weight aggregate block wall with masonry reinforcement

The external walls in a 1,5 – storey single family house are built with lightweight aggregate concrete masonry with externally bonded reinforcement. The properties of the wall section are identical to the wall section analysed in Example 1. For one of the masonry columns situated between two windows, the conditions presented in Table 4.3 apply. Determine the required amount of masonry reinforcement A_s needed to resist the combined action of axial load and bending moment.

Table 4.3 Masonry column properties and loads

Wall height (effective wall height)	h (h_{ef})	2600 (1950) mm
Wall breadth	b	1000 mm
Wall thickness, render on the tension side included	t	100 mm
Slenderness ratio	λ_c	$h_{ef}/t=19,5$
Design axial load	N_{Ed}	80 kN
Design value of eccentricity at the top of the wall	e_i	16 mm
Design value of the eccentricity at mid-height of the wall (without second order effects)	e_{mk}	14 mm

A) Check of the masonry column's capacity at the top edge

The load bearing capacity of the masonry column at the top edge is calculated according to EN 1996-1-1, 6.1.2.1 and 6.1.2.2 as

$$N_{Rd,i} = \left(1 - 2 \cdot \frac{e_i}{t}\right) \cdot f_d \cdot t \cdot b = \left(1 - 2 \cdot \frac{0{,}016}{0{,}100}\right) \cdot 1{,}7 \cdot 10^6 \cdot 0{,}1 \cdot 1 \cong 116\ kN$$

Since $N_{Rd,i} = 116 > N_{Ed} =$ 80 kN, the load bearing capacity at the top edge is sufficient.

B) Check of the masonry column's capacity with respect to buckling

Buckling of masonry walls supported at the bottom and top edge is usually controlled by analysing the wall section's capacity at mid height. When designing reinforced masonry walls, second order effects shall be taken into consideration if the slenderness ratio is $\lambda_c > 12$. Since $\lambda_c = 19{,}5$, second order effects shall be taken into account.

According to section 4.3 in this report, an additional eccentricity is calculated as

$$e_a = \frac{h_{ef}^2}{2000 \cdot t} = \frac{1950^2}{2000 \cdot 100} = 19\ mm$$

The design moment M_{ed}, adjusted for second order effects, is calculated using eq. (10)

$$M_{Ed} = N_{Ed}(e_{mk} + e_a) = 80\ \cdot (0{,}014 + 0{,}019) = 2{,}64\ kNm$$

It can be seen that the second order effects give rise to a larger bending moment than the eccentricity of the axial load.

The capacity of the masonry column can now be checked using the equilibrium equations presented in section 4.1. Alternatively, the N - M interaction diagram calculated in Example 1, see Figure 4.3, can be used. Thus the point (N_{Ed}, M_{Ed}) = (80; 2,64) is plotted into the N-M interaction diagrams shown in Figure 4.6 (reproduction of Figure 4.3) – see blue dot.

From Figure 4.6 it can be seen that the LWA wall has to be strengthened with masonry reinforcement having a total area of A_s = 100 mm^2.

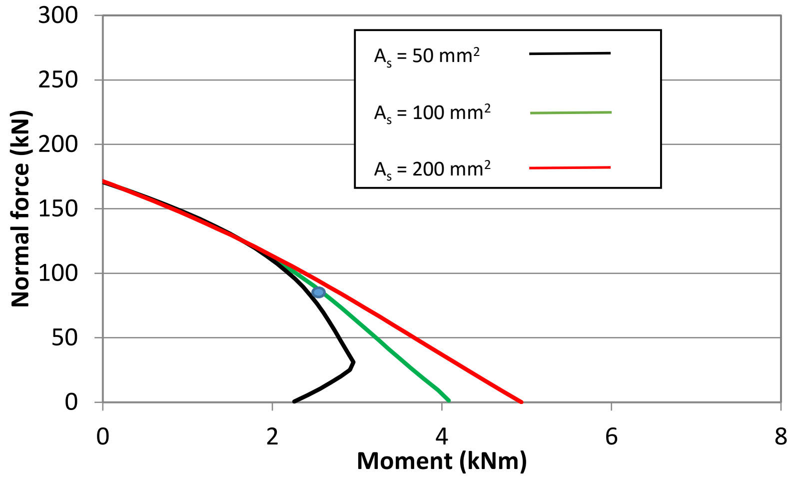

Figure 4.6 Check of the section capacity – LWA wall; see also Table 4.1.

Normally, also the column's capacity with regard to predominating transversal load shall be checked. This check is however not carried out here.

5 Conclusions

The project's main conclusions are as follow:

- Use of externally bonded reinforcement enables construction of masonry based external walls where the thickness of the load bearing part of the external wall is around 100 mm.

- The strengthening potential of externally bonded reinforcement is dependent on the compressive strength of the masonry and the strength and deformation capacity of the strengthening material.

- Design of masonry walls strengthened with externally bonded reinforcement can be carried out by using section and buckling analysis, according to methods established in the fields of masonry and concrete design.

- Light weight aggregate concrete (LWA) block walls subjected to bending and vertical axial load having a thickness of 100 mm can be designed for capacities in the range of 2 – 4 kNm/m (moment) and 80 – 120 kN/m (axial load).

- Clay brick masonry walls with design compressive strength around 4,5 MPa can be designed for capacities in the range of 4 – 8 kNm/m (moment) and 150 – 300 kN/m (axial load).

- The present Eurocode design recommendations in the masonry fields overestimate the so called second order effects, especially at low levels of bending moment.

- Steel based strengthening products, such as masonry reinforcement and high strength steel wire strips, can be applied on the dry masonry and embedded in strengthening mortar.

- The thickness of the strengthening mortar needed to anchor the strengthening to the wall can be limited to 10 mm, given that the thickness of the strengthening material is less than 5 mm.

- Glass fibre mesh should be embedded in mortar – thus not applied against the dry masonry. Glass fibre meshes should be applied without overlapping (seamless).

- Using the strengthened walls developed in this project, the U-value of a 400 mm thick external wall can be as low as 0,11 W/m^2K.

6 References

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Appendix 1 – Detailed test results

B1_W1 (Brick, series 1, wall 1) – brick and carbon steel mesh

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

Steel mesh Φ = 6 mm, at 150 mm centres (commercial name 6150)

Steel characteristic strength $f_y = 500\ MPa$ (quality NK500AB-W, according the supplier)

Reinforcement area $A_s = 85$ mm^2 (three bars Φ = 6 mm)

Way of application: The mesh was attached to the dry wall by screws, theoretically without gaps, with the longitudinal bars closest to the surface of the wall. However, due to normal deviations of the walls from a straight line, some gaps were present between the longitudinal bars and the wall. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm (gap) + 3 mm (radius) = 4 mm

Strengthening render Layer 1 – render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 3 – 8 mm, see Figure B1_W1_1 (left). Layer 2 – render quality CS III (Swedish commercial term “utstockningsbruk B”) – thickness between 14 – 17 mm.

Way of application: Both layers were applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4. Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 87 + 20 = 107 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 23.5 mm.

Test results

Maximum load 229 kN, corresponding to 487 kN/m; Transversal deflection at maximum load 27 mm – see Figure B1_W1_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure B1_W1_1 (right). No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: No visible cracks on the rendered (tensioned) side of the wall.

Figure B1_W1_1 Application of the first render layer, CS IV, thickness 3 – 8 mm (left); Failure at the upper loading plate (right).

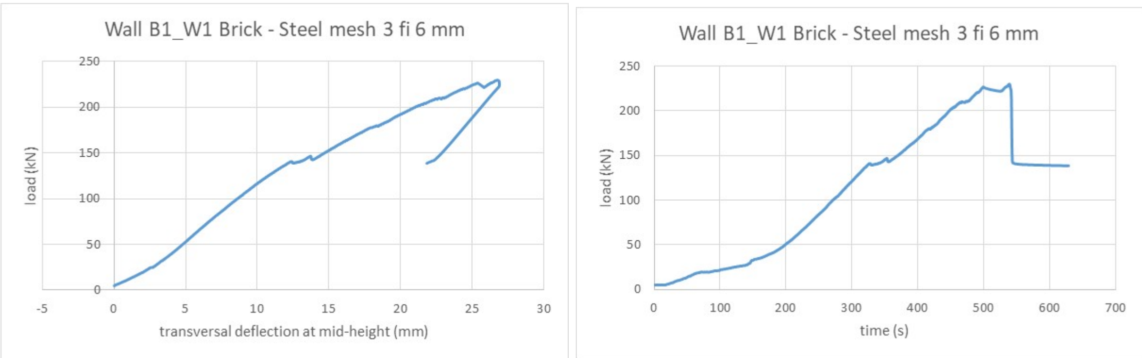


Figure B1_W1_2 Load vs lateral deflection at mid-height (left); Load vs time (right).

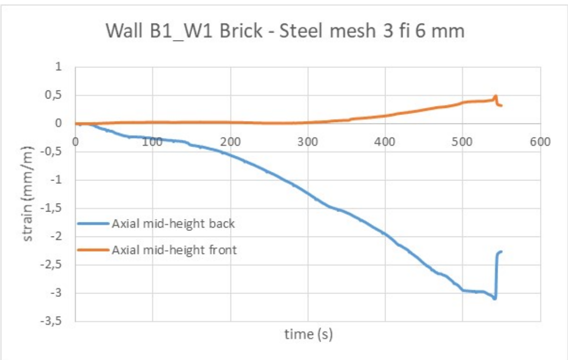


Figure B1_W1_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B1_W2 (Brick, series 1, wall 2) – brick and masonry reinforcement

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength f_y =717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force A_g=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s = 50$ mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached to renders strips with a thickness of 3-5 mm. This procedure was later abandoned, because it was difficult to keep the reinforcement sticking to the substrate. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 4 mm (render) + 2 mm (radius) = 6 mm

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 3 – 6 mm. Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 14 – 17 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 87 + 20 = 107 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 23.5 mm.

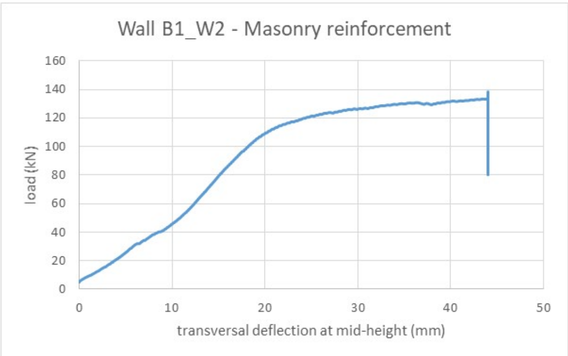
Test results

Maximum load 138 kN, corresponding to 294 kN/m; Transversal deflection at maximum load 44 mm, see Figure B1_W2_1.

Failure mode: Ductile failure, probably due to yielding of the reinforcement. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Cracks were observed on the rendered (tensioned) side of the wall.

Figure B1_W2_1 Brick wall with masonry reinforcement (bistål), before application of the second strengthening render layer.



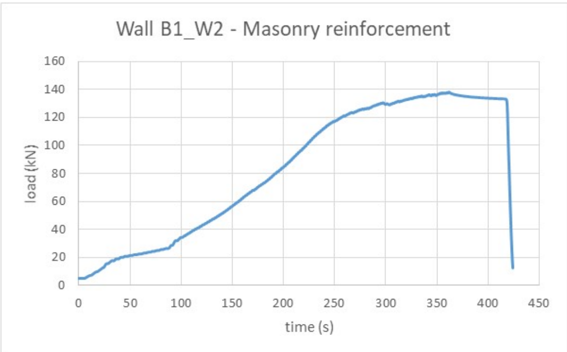


Figure B1_W2_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

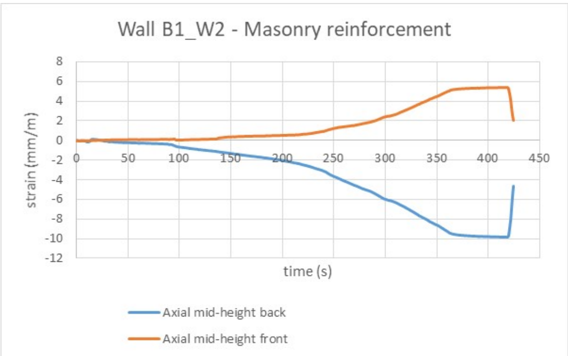


Figure B1_W2_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B1_W3 (Brick, series 1, wall 3) – brick and mechanically fastened steel strips

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

Steel strips (stålband), quality S235JR, 40*2 mm^2

Steel characteristic strength $f_{yk} = 235$ MPa; Rupture strength 332 MPa (tested in the project).

Reinforcement area $A_{s,gross} = 160$ mm^2 , $A_{s,net} = 144$ mm^2 (two strips).

Way of application: The steel strips were mechanically attached to the dry wall by concrete screws. The screws were fastened in pre-drilled holes in the bricks, see Figure B1_W3_1.

Strengthening render: No strengthening render was used. The compression face of the wall was untreated.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 11.5 mm.

Test results

Maximum load 101 kN, corresponding to 215 kN/m; Transversal deflection at maximum load 59 mm, see Figure B1_W3_2.

Failure mode: Ductile failure, probably due to yielding of the reinforcement. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Figure B1_W3_1 Testing of brick wall strengthened with mechanically fastened steel strips.

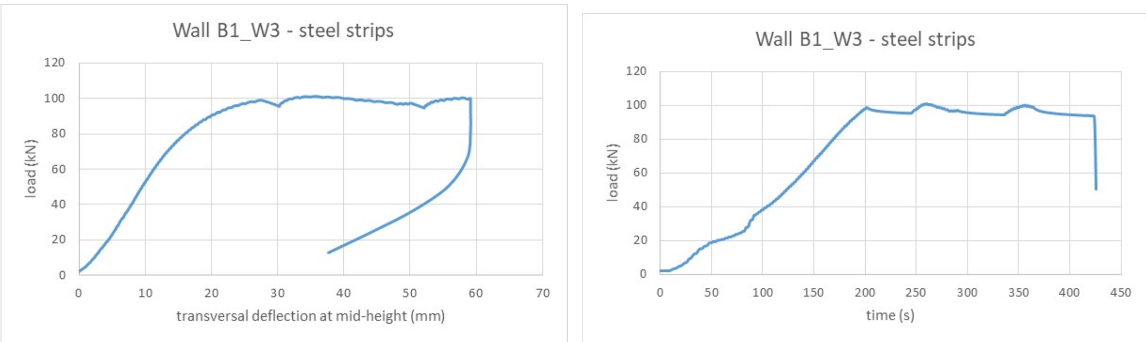


Figure B1_W3_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right).

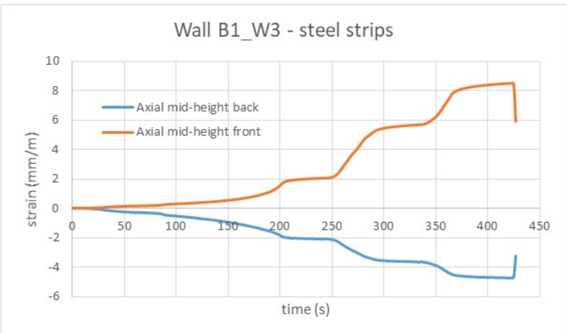


Figure B1_W3_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B1_W4 (Brick, series 1, wall 4) – brick and high strength steel wire strips

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 9{,}7$ mm^2 (two strips with 14 threads with Φ = 0,69 mm)

Way of application: The steel wire strips were attached to renders strips with a thickness of 3-5 mm, see figure B1_W4_1. This procedure was later abandoned, because it was difficult to keep the reinforcement sticking to the substrate. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 4 mm (render) + 0,5 mm (radius) = 4,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 3 – 5 mm. Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 15 – 17 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 87 + 20 = 107 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 23.5 mm.

Test results

Maximum load 116 kN, corresponding to 247 kN/m; Transversal deflection at maximum load 38 mm, see Figure B1_W4_2.

Failure mode: Exact failure mode unclear – the walls probably failed through rupture of the steel wire reinforcement. The wall collapsed.

Other comments: Multiple cracks were observed on the rendered (tensioned) side of the wall.

Figure B1_W4_1 Brick wall strengthened with strips of high strength steel wire, before application of the second layer of strengthening render (left); Crack pattern just before failure (right).

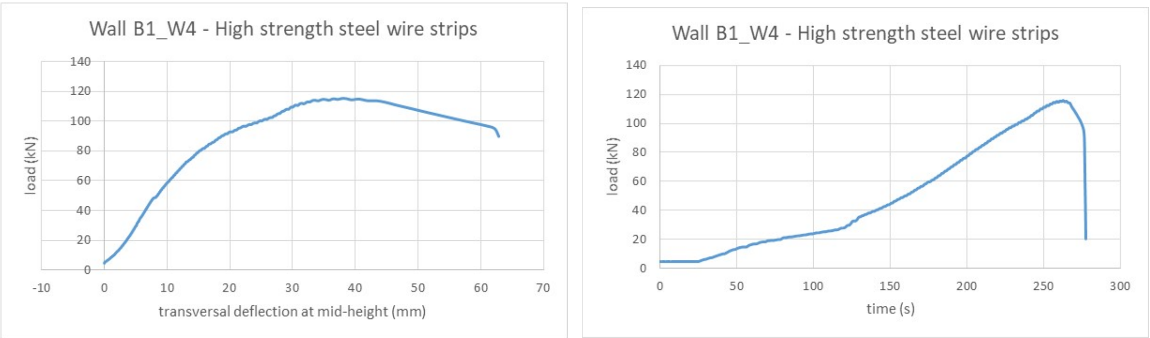


Figure B1_W4_2 Load vs. transversal deflection at mid-height (left); load vs time (right).

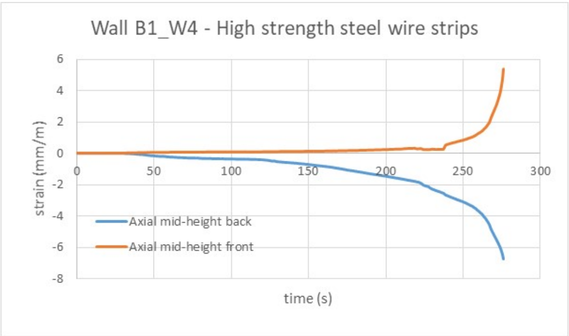


Figure B1_W4_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B1_W5 (Brick, series 1, wall 5) – brick and glass fibre mesh

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 57$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 42 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m.

Reinforcement area $A_r = 19$ mm^2 (when covering the entire length of the wall, i.e. 470 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 8 - 10 mm, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 9 mm (render) + 0,5 mm (thickness) = 9,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 8 - 10 mm. Layer 2 – render quality CS III (Swedish commercial term “utstockningsbruk B”) – thickness between 10 – 12 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 87 + 20 = 107 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 23.5 mm.

Test results

Maximum load 112 kN, corresponding to 238 kN/m; Transversal deflection at maximum load > 61 mm, see Figure B1_W5_1.

Failure mode: Exact failure mode unclear – the walls probably failed through rupture of the glass fibre reinforcement. The wall collapsed.

Other comments: Multiple cracks were observed on the rendered (tensioned) side of the wall just prior to failure, see Figure B1_W5_3.

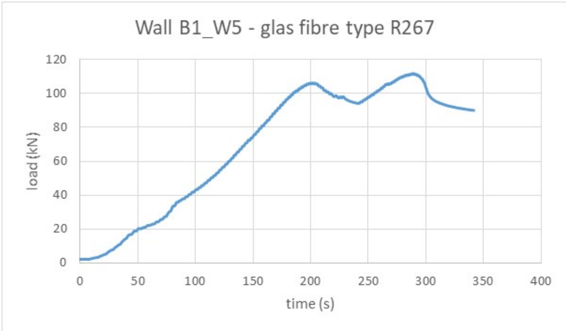


Figure B1_W5_1 Load vs. transversal deflection at mid-height (left); load vs. time (right).

Figure B1_W5_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

Figure B1_W5_3 Cracks at mid-height of the wall just before failure (left); Collapse of the wall (right).

B1_W6 (Brick, series 1, wall 6) – brick and glass fibre mesh

Wall properties:

Bricks L*W*H = 228*87*56 mm

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 9,7 MPa, CoV = 15 %;

Strains: $\varepsilon_{m1} = 5{,}5$ mm/m, CoV = 19 %; $\varepsilon_{mu} = 10$ mm/m, CoV = 35 %;

Modulus of elasticity E = 2480 MPa, CoV = 14 %

Wall geometry L*W*H = 470*87*2400 mm

Strengthening:

Glass fibre mesh, commercial name R451, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 74$ kN – the embedded strength should be taken as 60 % of the nominal strength, i.e. 45 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 45$ mm/m

Reinforcement area $A_r = 21$ mm^2 (when covering the entire length of the wall, i.e. 470 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 8 - 10 mm, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 9 mm (render) + 0,5 mm (thickness) = 9,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 8 - 10 mm. Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 10 – 12 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 87 + 20 = 107 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 23.5 mm.

Test results

Maximum load 167 kN, corresponding to 355 kN/m; Transversal deflection at maximum load > 43 mm, see Figure B1_W6_1.

Failure mode: Flexural compressive failure at mid-height of the wall. The wall did not collapse.

Other comments: Cracks were observed on the rendered (tension) side.

Figure B1_W6_1 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

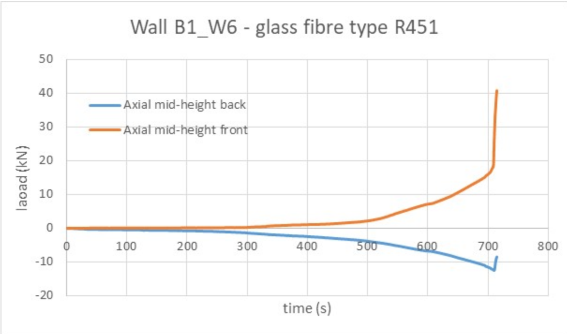


Figure B1_W6_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

Figure B1_W6_3 Flexural compressive failure at mid-height of the wall (left and upper right); Crack pattern before failure (lower right).

LWA1_W1 (Light weight aggregate concrete, series 1, wall 1) – LWA and carbon steel mesh

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Steel mesh Φ = 6 mm, at 150 mm centres (commercial name 6150)

Steel characteristic strength $f_y = 500\ MPa$ (quality NK500AB-W, according the supplier)

Reinforcement area $A_s = 113$ mm² (four bars Φ = 6 mm)

Way of application: The mesh was attached to the dry wall by screws, theoretically without gaps, with the longitudinal bars closest to the surface of the wall. However, due to normal deviations of the walls from a straight line, some gaps were present between the longitudinal bars and the wall. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm (gap) + 3 mm (radius) = 4 mm

Strengthening render Layer 1 – render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 3 – 8 mm, see Figure LWA1_W1_1 (left). Layer 2 – render quality CS III (Swedish commercial term “utstockningsbruk B”) – thickness between 14 – 17 mm.

Way of application: Both layers were applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 90 + 20 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 25 mm.

Test results

Maximum load 120 kN, corresponding to 203 kN/m; Transversal deflection at maximum load 20 mm – see Figure LWA1_W1_2.

Failure mode: Local crushing of the masonry at approximately 100 – 300 mm below the load application plate, at the upper edge of the wall, see Figure LWA1_W1_1 (right). No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: No visible cracks on the rendered (tensioned) side of the wall.

Figure LWA1_W1_1 Mesh reinforcement (left); Crushing below the load application plate (right).

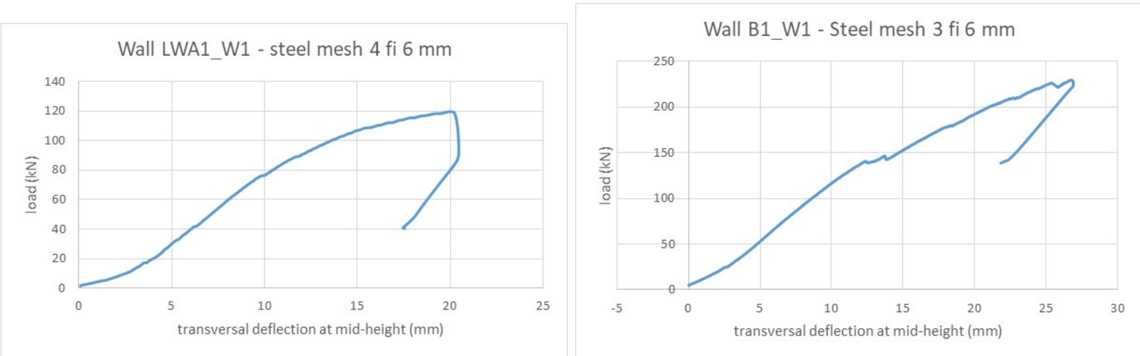


Figure LWA1_W1_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

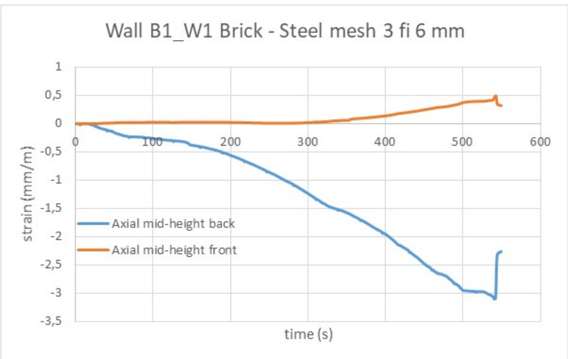


Figure LWA1_W1_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA1_W2 (Light weight aggregate concrete, series 1, wall 2) – LWA and masonry reinforcement

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength f_y =717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force Ag=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s = 50$ mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached to renders strips with a thickness of 3-5 mm. This procedure was later abandoned, because it was difficult to keep the reinforcement sticking to the substrate. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 4 mm (render) + 2 mm (radius) = 6 mm

Strengthening render Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 3 – 8 mm, see Figure LWA1_W2_1 (left). Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 14 – 17 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 90 + 20 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 25 mm.

Test results

Maximum load 115 kN, corresponding to 195 kN/m; Transversal deflection at maximum load 29 mm – see Figure LWA1_W2_2.

Failure mode: Flexural compressive failure at mid-height of the wall, see Figure LWA1_W2_1 (right). No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: No visible cracks on the rendered (tensioned) side of the wall before failure.

Figure LWA1_W2_1 Masonry reinforcement (left); Flexural compressive failure at mid-height of the wall (right).

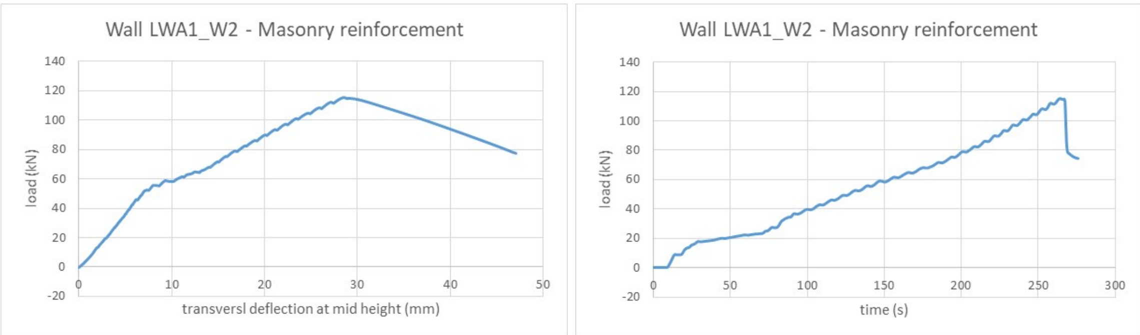


Figure LWA1_W2_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

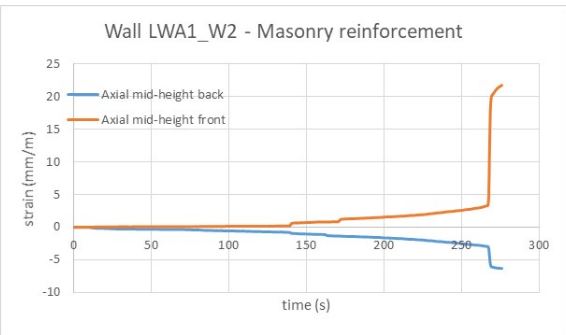


Figure LWA1_W2_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA1_W3 (Light weight aggregate concrete, series 1, wall 3) – LWA and steel strips

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Steel strips (stålband), quality S235JR, 40*2 mm^2

Steel characteristic strength $f_{yk} = 235$ MPa; Rupture strength 332 MPa (tested in the project).

Reinforcement area $A_{s,gross} = 320$ mm^2 , $A_{s,net} = 288$ mm^2 (four strips).

Way of application: The steel strips were mechanically attached to the dry wall by concrete screws, see Figure LWA1_W3_1.

Strengthening render: No strengthening render was used. The compression face of the wall was untreated.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 15 mm.

Test results

Maximum load 98 kN, corresponding to 166 kN/m; Transversal deflection at maximum load 18 mm – see Figure LWA1_W3_2.

Failure mode: Flexural compressive failure. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Partial composite action is expected.

Figure LWA1_W3_1 Mechanically fastened steel strips.

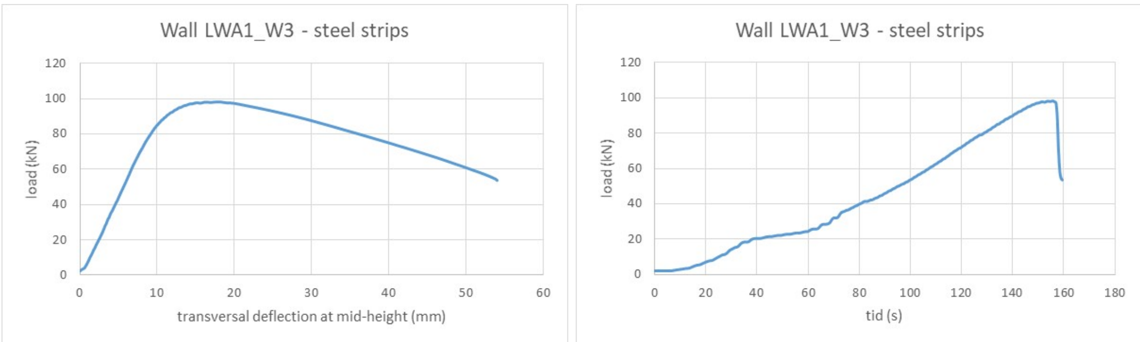


Figure LWA1_W3_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

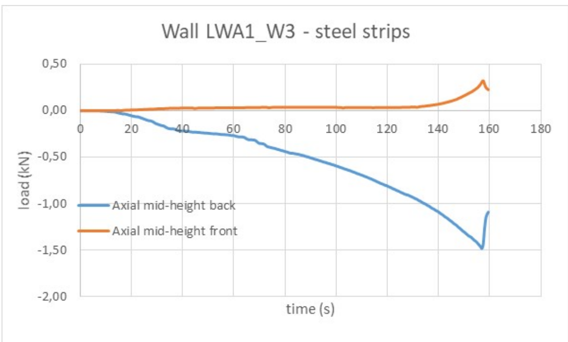


Figure LWA1_W3_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA1_W4 (Light weight aggregate concrete, series 1, wall 4) – LWA and high strength steel mesh

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 14{,}5$ mm^2 (three strips with 14 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached to renders strips with a thickness of 3-5 mm. This procedure was later abandoned, because it was difficult to keep the reinforcement sticking to the substrate. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 4 mm (render) + 0,5 mm (radius) = 4,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 3 – 5 mm. Layer 2 – render quality CS III (Swedish commercial term “utstockningsbruk B”) – thickness between 15 – 17 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 90 + 20 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 25 mm.

Test results

Maximum load 164 kN, corresponding to 278 kN/m; Transversal deflection at maximum load 22 mm – see Figure LWA1_W4_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure LWA1_W4_1(right). No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: No visible cracks on the rendered (tensioned) side of the wall.

Figure LWA1_W4_1 High strength steel strips (left); Crushing at the load application plate (right).

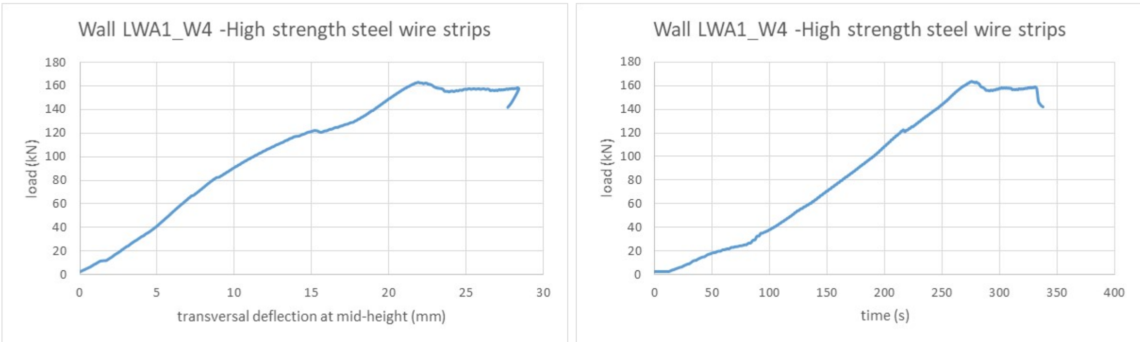


Figure LWA1_W4_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

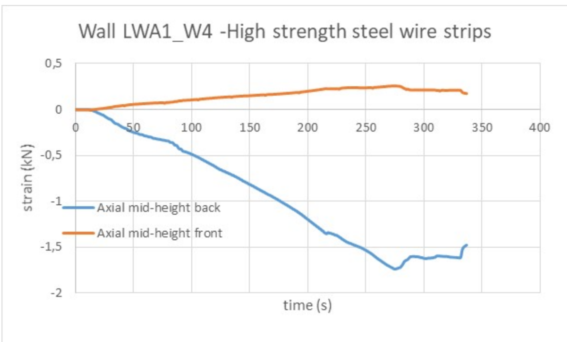


Figure LWA1_W4_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA1_W5 (Light weight aggregate concrete, series 1, wall 5) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}7$ mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 74$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 56 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 24$ mm^2 (when covering the entire length of the wall, i.e. 590 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 8 - 10 mm, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 9 mm (render) + 0,5 mm (thickness) = 9,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 8 - 10 mm. Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 10 – 12 mm. Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated. Total nominal thickness of the wall after strengthening 90 + 20 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 25 mm.

Test results

Maximum load 121 kN, corresponding to 205 kN/m; Transversal deflection at maximum load 26 mm – see Figure LWA1_W5_2.

Failure mode: Flexural compressive failure at 2/3-height of the wall, see Figure LWA1_W5_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments:

Figure LWA1_W5_1 Flexural compressive failure at 2/3-height of the wall.

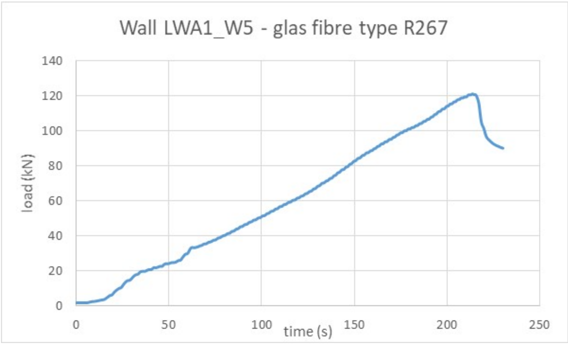


Figure LWA1_W5_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

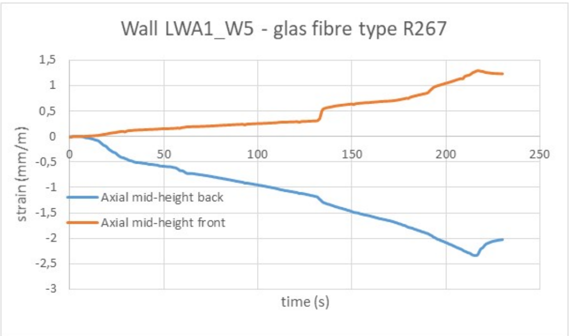


Figure LWA1_W5_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA1_W6 (Light weight aggregate concrete, series 1, wall 6) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,3 MPa, CoV = 11 %;

Strains: $\varepsilon_{m1} =$ 1,7 mm/m, CoV = 16 %; $\varepsilon_{mu} =$ 1,7 mm/m, CoV = 22 %;

Modulus of elasticity E = 2700 MPa, CoV = 4 %

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R451, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 97$ kN – the embedded strength should be taken as 60 % of the nominal strength, i.e. 58 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} =$ 45 mm/m

Reinforcement area $A_r = 27$ mm^2 (when covering the entire length of the wall, i.e. 590 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 8 - 10 mm, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 9 mm (render) + 0,5 mm (thickness) = 9,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 8 - 10 mm. Layer 2 – render quality CS III (Swedish commercial term "utstockningsbruk B") – thickness between 10 – 12 mm.

Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied 24 hours later, without pre-wetting. The second render layer was compacted and levelled in a way to achieve a total render thickness of 20 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 20 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 25 mm.

Test results

Maximum load 120 kN, corresponding to 203 kN/m; Transversal deflection at maximum load 32 mm – see Figure LWA1_W6_2.

Failure mode: Flexural compressive failure at mid-height of the wall, see Figure LWA1_W6_1 . No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Cracks observed in the render before failure.

Figure LWA1_W6_1 Flexural compressive failure

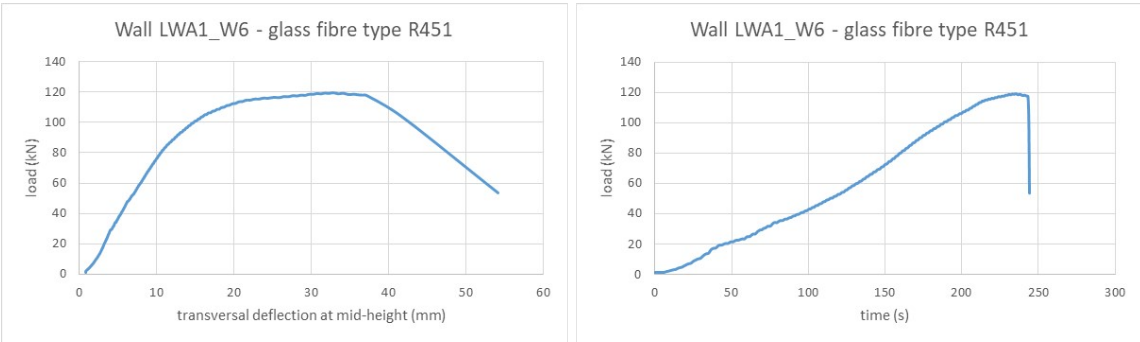


Figure LWA1_W6_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA1_W6_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W1 (Light weight aggregate concrete, series 2, wall 1) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 62$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 47 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 20$ mm^2 (when covering the entire length of the wall, i.e. 498 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 3 - 5 mm, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 4 mm (render) + 0,5 mm (thickness) = 4,5 mm.

Strengthening render: Layer 1 – render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 3 - 5 mm. Layer 2 consisted of the same render as in layer 1, thickness between 5 - 7 mm.

Way of application: Both layers were applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second layer was applied directly after the glass fibre mesh was attached to the wall. The second render layer was compacted and levelled in a way to achieve a total render thickness of 7 - 8 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 8 = 98 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 19 mm.

Test results

Maximum load 84 kN, corresponding to 168 kN/m; Transversal deflection at maximum load 14 mm – see Figure LWA2_W1_2.

Failure mode: Flexural compressive failure at 2/3-height of the wall, see Figure LWA2_W1_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Large displacement at the beginning of the test – not clear why.

Figure LWA2_W1_1 Flexural compressive failure at 2/3-height of the wall.

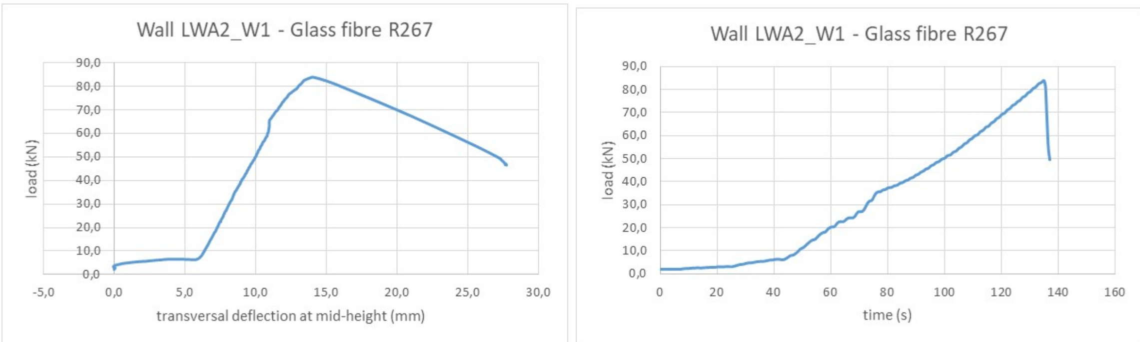


Figure LWA2_W1_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

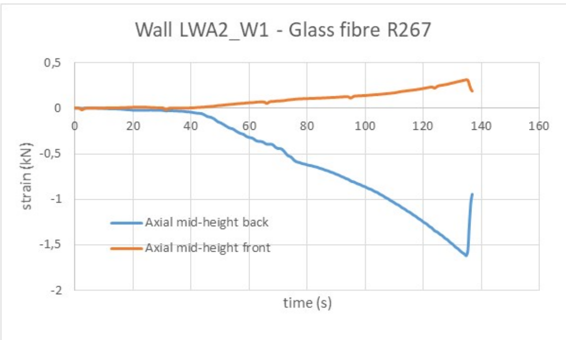


Figure LWA2_W1_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W2 (Light weight aggregate concrete, series 2, wall 2) – LWA and masonry reinforcement

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} =$ 1,3 mm/m, CoV = 16 %; $\varepsilon_{mu} =$ 1,3 mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength $f_y =$717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force Ag=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s = 50$ mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached directly to the masonry, i.e. not laid in mortar. This procedure increases productivity, without known detrimental effects on the vertical load bearing capacity. A reasonable distance between the centrum of the longitudinal bars and the wall surface is 1 mm gap + 2 mm (radius) = 3 mm

The strengthening render, quality CS IV (Swedish commercial term "rödgrund A"), was applied in one layer. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render was compacted and levelled to a total thickness of 8-10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 10 = 100 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 20 mm.

Test results

Maximum load 157 kN, corresponding to 314 kN/m; Transversal deflection at maximum load 21 mm – see Figure LWA2_W2_2.

Failure mode: Flexural compressive failure at 2/3-height of the wall, see Figure LWA2_W2_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: No visible cracks on the rendered (tensioned) side of the wall before failure.

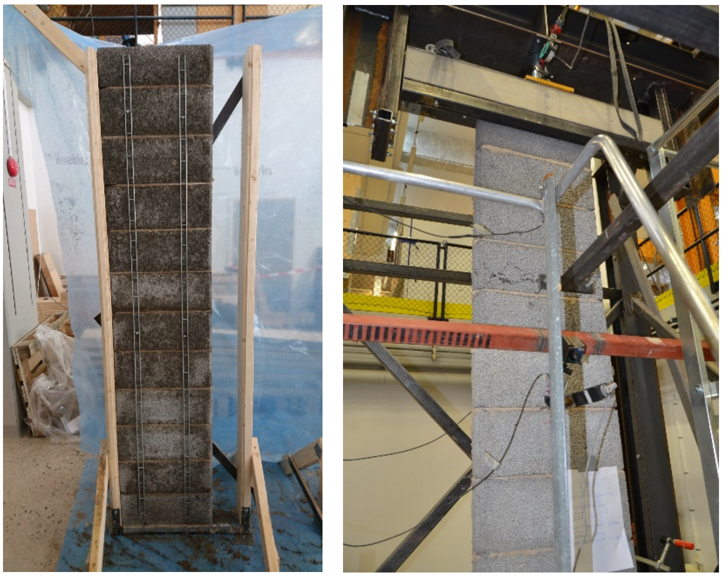


Figure LWA2_W2_1 Masonry reinforcement attached directly to the surface of the wall (left); Flexural compressive failure at mid-height of the wall (right).

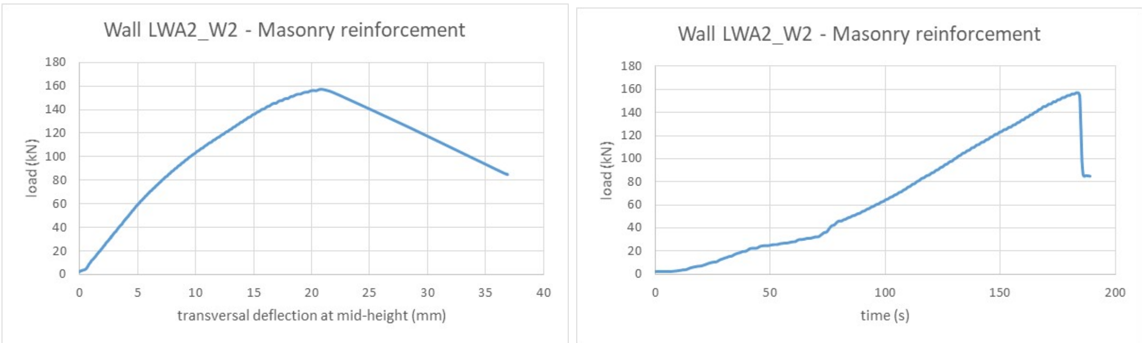


Figure LWA2_W2_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

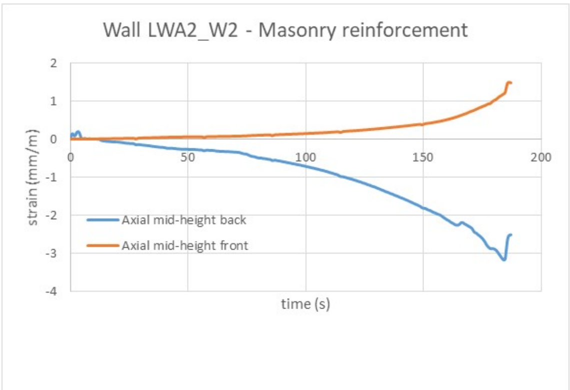


Figure LWA2_W2_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W3 (Light weight aggregate concrete, series 2, wall 3) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 62$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 47 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 20$ mm^2 (when covering the entire length of the wall, i.e. 498 mm).

Way of application: The glass fibre mesh was attached directly on the masonry with a staple gun, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 5 – 6 mm. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 5 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

Test results

Maximum load 116 kN, corresponding to 233 kN/m; Transversal deflection at maximum load 10 mm – see Figure LWA2_W3_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure LWA2_W3_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: After local crushing, the load could be sustained and also increased to 140 Kn.

Figure LWA2_W3_1 Glass fibre mesh attached directly to the surface of the wall (left); Local crushing at the upper loading plate (right).

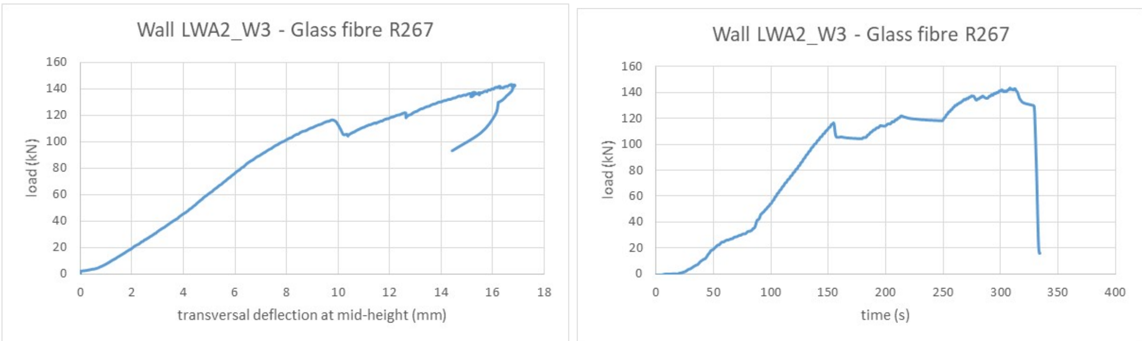


Figure LWA2_W3_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W3_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W4 (Light weight aggregate concrete, series 2, wall 4) – LWA and high strength steel wire

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 9{,}7$ mm^2 (two strips with 7 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 5 – 6 mm. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 5 – 6 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

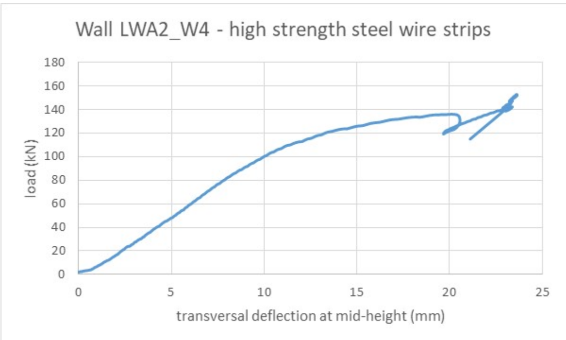
Test results

Maximum load 136 kN, corresponding to 273 kN/m; Transversal deflection at maximum load 20 mm – see Figure LWA2_W4_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure LWA2_W4_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments:

Figure LWA2_W4_1 Crushing at the load application plate.



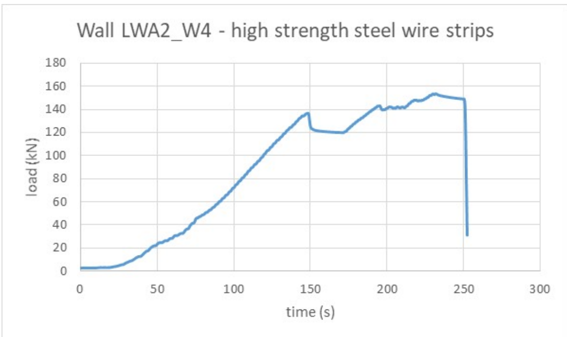


Figure LWA2_W4_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

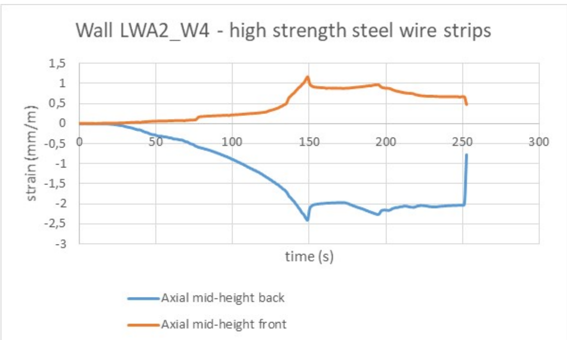


Figure LWA2_W4_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W5 (Light weight aggregate concrete, series 2, wall 5) - LWA and high strength steel wire

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 9{,}7$ mm^2 (two strips with 7 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 5 – 8 mm. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 5 – 6 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 6 = 96 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18 mm.

Test results

Maximum load 119 kN, corresponding to 239 kN/m; Transversal deflection at maximum load 19 mm – see Figure LWA2_W5_2.

Failure mode: Flexural compressive failure at mid-height of the wall, see Figure LWA2_W5_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Large crack on the rendered side.

Figure LWA2_W5_1 High strength steel wire strips attached directly to the wall (left); Compression failure at mid-height of the wall (right).

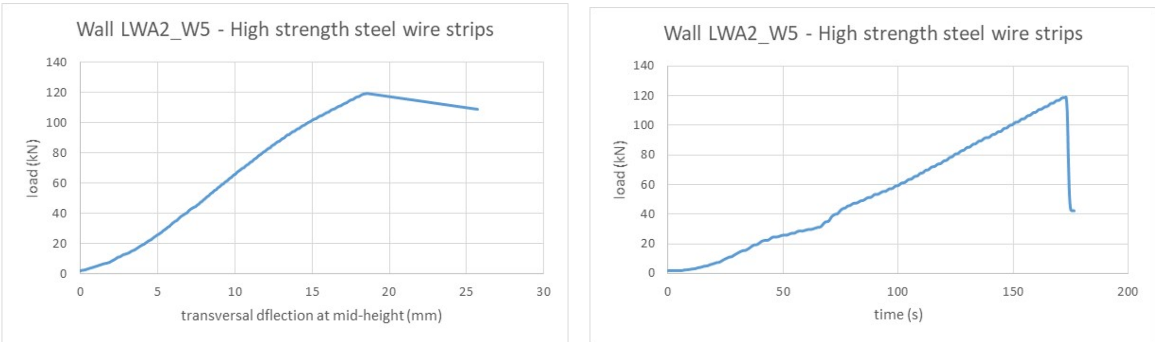


Figure LWA2_W5_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W5_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W6 (Light weight aggregate concrete, series 2, wall 6) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 62$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 47 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 20$ mm^2 (when covering the entire length of the wall, i.e. 498 mm).

Way of application: The glass fibre mesh was attached directly on the masonry with a staple gun, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 7 – 12 mm, due to irregularities of the wall. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 7 - 12 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 10 = 100 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 20 mm.

Test results

Maximum load 146 kN, corresponding to 293 kN/m; Transversal deflection at maximum load 16 mm – see Figure LWA2_W6_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure LWA2_W6_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: The load dropped somewhat at 80 kN, but recovered later.

Figure LWA2_W6_1 Local crushing at the upper loading plate.

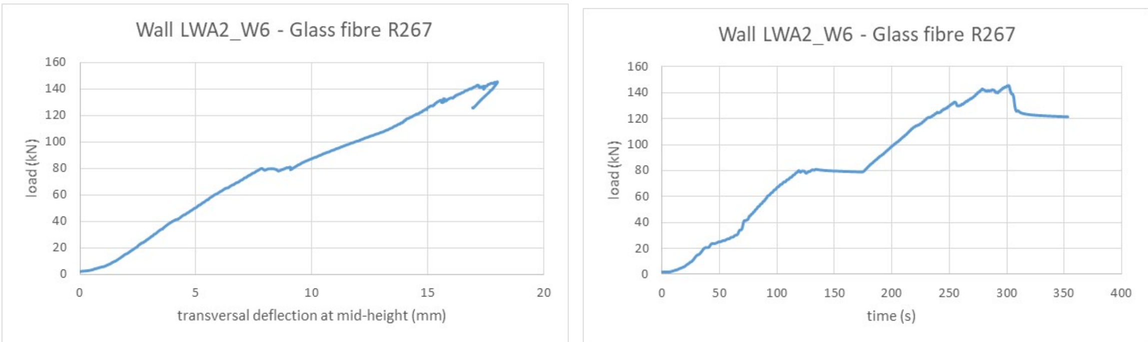


Figure LWA2_W6_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W6_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W7 (Light weight aggregate concrete, series 2, wall 7) – LWA and masonry reinforcement

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} =$ 1,3 mm/m, CoV = 16 %; $\varepsilon_{mu} =$ 1,3 mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength $f_y =$717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force Ag=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s =$ 50 mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached directly to the masonry, i.e. not laid in mortar. This procedure increases productivity, without known detrimental effects on the vertical load bearing capacity. A reasonable distance between the centrum of the longitudinal bars and the wall surface is 1 mm gap + 2 mm (radius) = 3 mm

The strengthening render, quality CS IV (Swedish commercial term "rödgrund A"), was applied in one layer. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render was compacted and levelled to a total thickness of 8-10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 7 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18,5 mm.

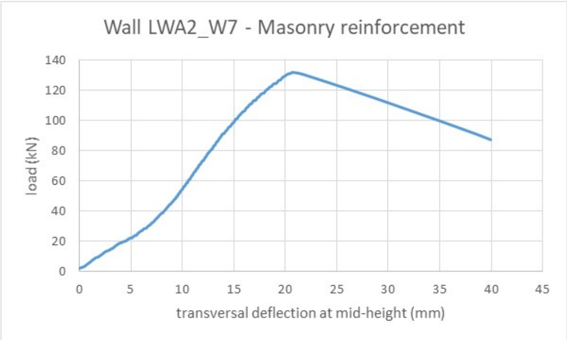
Test results

Maximum load 132 kN, corresponding to 265 kN/m; Transversal deflection at maximum load 21 mm – see Figure LWA2_W7_2.

Failure mode: Flexural compressive failure at mid-height of the wall, see Figure LWA2_W7_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: this wall is a replica of wall LWA2_W2.

Figure LWA2_W7_1 Flexural compressive failure at mid-height of the wall.



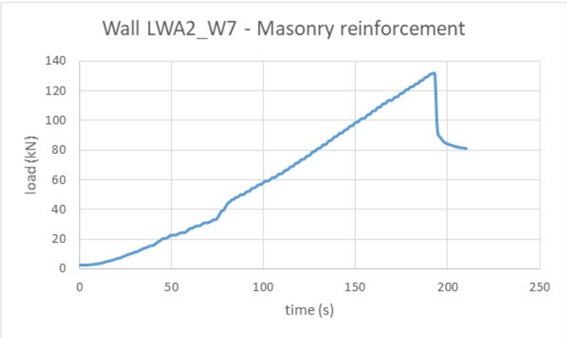


Figure LWA2_W7_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

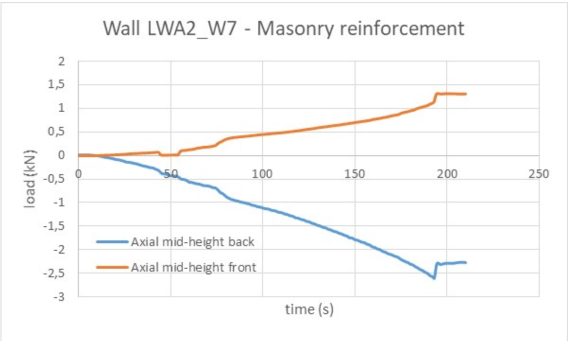


Figure LWA2_W7_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W8 (Light weight aggregate concrete, series 2, wall 8) – LWA and high strength steel wire

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 6{,}9$ mm^2 (two strips with only 5 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 5 mm. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 5 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

Test results

Maximum load 176 kN, corresponding to 352 kN/m; Transversal deflection at maximum load 24 mm – see Figure LWA2_W8_2.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall, see Figure LWA2_W8_1. The load dropped from 176 kN to 140 kN and was sustained on that level. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments:

Figure LWA2_W8_1 Local crushing at the upper loading plate.

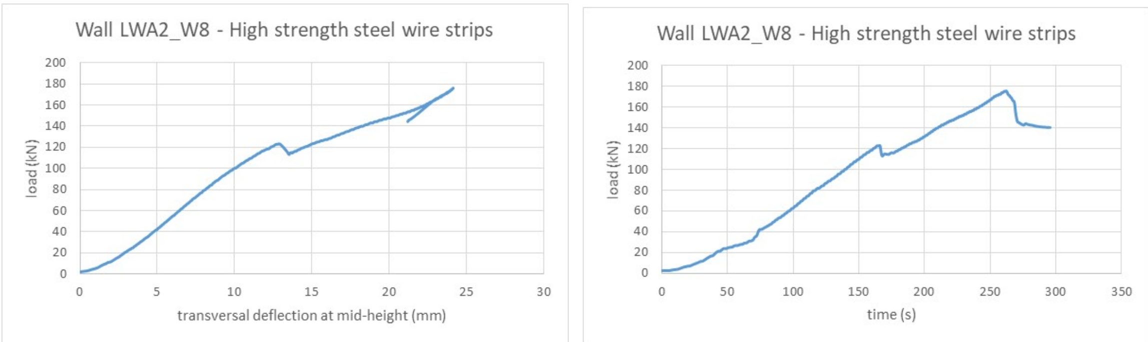


Figure LWA2_W8_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

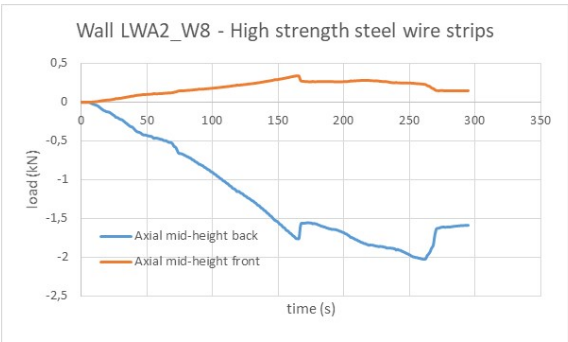


Figure LWA2_W8_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W9 (Light weight aggregate concrete, series 2, wall 9) – high strength steel wire

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 6{,}9$ mm^2 (two strips with only 5 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 5 mm. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled in a way to achieve a total render thickness of 5 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

Test results

Maximum load 141 kN, corresponding to 282 kN/m; Transversal deflection at maximum load 17 mm – see Figure LWA2_W9_2.

Failure mode: Flexural tensile failure of the reinforcement at around 2/3-height of the wall, see Figure LWA2_W9_1. The wall collapsed

Other comments: this wall is a replica of wall LWA2_W8.

Figure LWA2_W9_1 Flexural tensile failure of the reinforcement at 2/3-height of the wall.

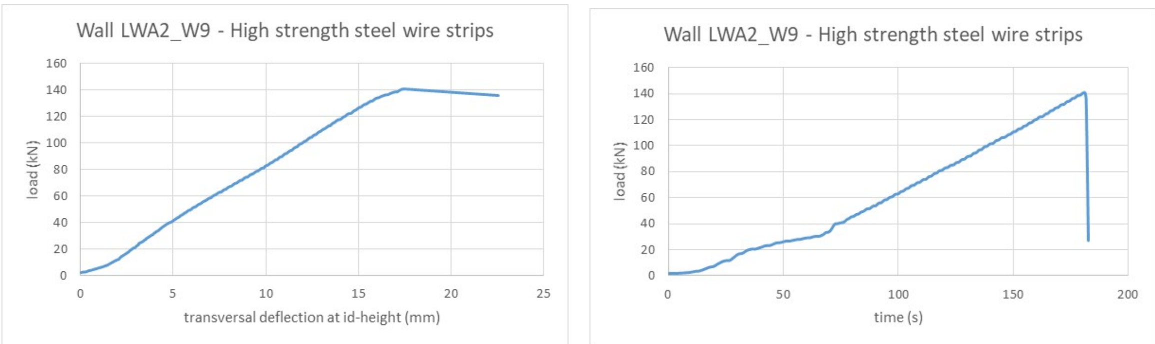


Figure LWA2_W9_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

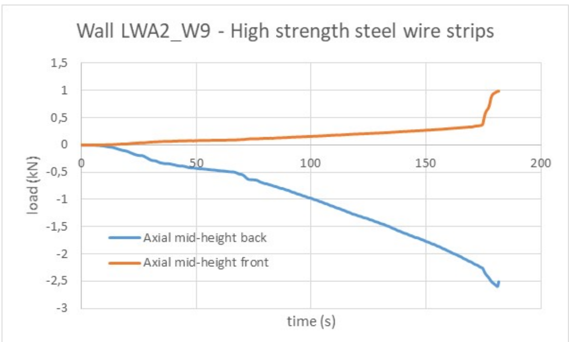


Figure LWA2_W9_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W10 (Light weight aggregate concrete, series 2, wall 10) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 45$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 34 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 14$ mm^2 – corresponding to two strips with width 180 mm/strip, that is 360 mm in total.

Way of application: The glass fibre mesh was attached directly on the masonry with a staple gun, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 3 - 7 mm, due to irregularities of the wall. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

Test results

Maximum load 120 kN, corresponding to 240 kN/m; Transversal deflection at maximum load 19 mm – see Figure LWA2_W10_2.

Failure mode: Flexural compressive failure at around 2/3-height of the wall, see Figure LWA2_W10_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: The load dropped to 84 kN and remained constant.

Figure LWA2_W10_1 Local crushing at the upper loading plate.

Figure LWA2_W10_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W10_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W11 (Light weight aggregate concrete, series 2, wall 11) – LWA and glass fibre mesh

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} = 1{,}3$ mm/m, CoV = 16 %; $\varepsilon_{mu} = 1{,}3$ mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 45$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 34 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 14$ mm^2 – corresponding to two strips with width 180 mm/strip, that is 360 mm in total.

Way of application: The glass fibre mesh was attached directly on the masonry with a staple gun, with the strong direction along the height of the wall. An overlap of 200 mm was used between the glass fibre strips. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm.

Strengthening render: Render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 3 - 7 mm, due to irregularities of the wall. Way of application: Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 5 = 95 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 17,5 mm.

Test results

Maximum load 116 kN, corresponding to 232 kN/m; Transversal deflection at maximum load 16 mm – see Figure LWA2_W11_2.

Failure mode: Crushing failure at the upper loading plate’s corner, see Figure LWA2_W11_1. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: Wall 11 is a replica of wall 10. After the crushing failure at the upper loading plate's corner, the load recovered to 140 kN.

Figure LWA2_W11_1 Local crushing at the upper loading plate, at the corner.

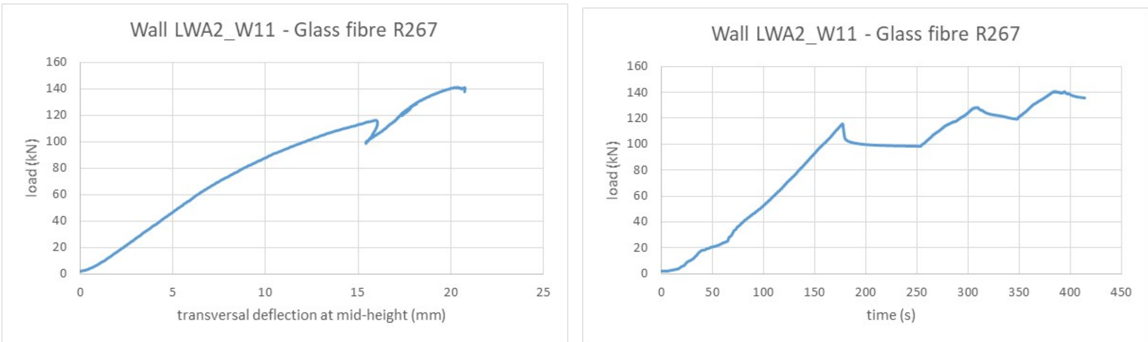


Figure LWA2_W11_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W11_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA2_W12 (Light weight aggregate concrete, series 2, wall 12) – LWA and one render layer

Wall properties:

Blocks L*W*H = 498*90*198 mm, commercial name LECA® BLOCK 90; strength class 3 (3 MPa)?

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,7 MPa, CoV = 7 %;

Strains: $\varepsilon_{m1} =$ 1,3 mm/m, CoV = 16 %; $\varepsilon_{mu} =$ 1,3 mm/m, CoV = 13 %;

Modulus of elasticity E = 3400 MPa, CoV = 20 %

Wall geometry L*W*H = 498*90*2400 mm; the wall was built without head joints.

Strengthening:

The wall was not strengthened – only a render layer was applied.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 5 - 10 mm, due to irregularities of the wall. Way of application: Before applying the render, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

render was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 8 = 98 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 19 mm.

Test results

Maximum load 103 kN, corresponding to 206 kN/m; Transversal deflection at maximum load 17 mm – see Figure LWA2_W12_2.

Failure mode: Crushing failure at the upper loading plate, see Figure LWA2_W12_1.

Other comments: After the crushing failure at the upper loading plate, the load recovered to 140 kN. Finally, the wall collapsed. Uneven impress indicates that the load was not uniformly distributed under the loading plate.

Figure LWA2_W12_1 Local crushing at the upper loading plate.

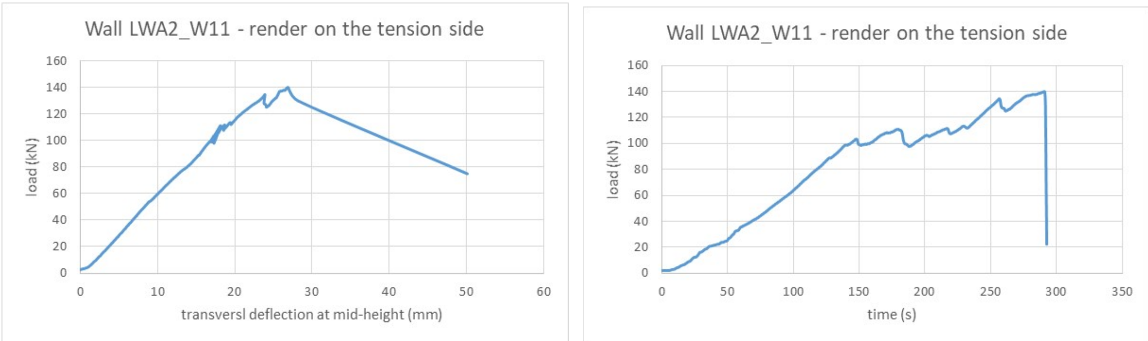


Figure LWA2_W12_2 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

Figure LWA2_W12_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W1 (Brick, series 3, wall 1) – brick and masonry reinforcement

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength f_y =717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force A_g=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s = 50$ mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached directly to the wall. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm (gap) + 2 mm (radius) = 3 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

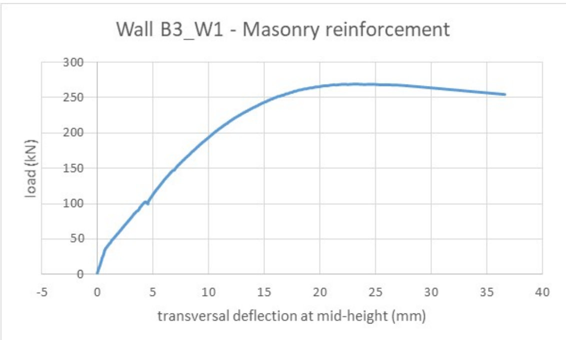
Test results

Maximum load 269 kN, corresponding to 448 kN/m; Transversal deflection at maximum load 25 mm, see Figure B3_W1_2.

Failure mode: Ductile tensile failure of the reinforcement at mid-height of the wall, followed by collapse.

Other comments: Cracks were observed along the masonry reinforcement bars.

Figure B3_W1_1 Masonry reinforcement bars that failed in tension.



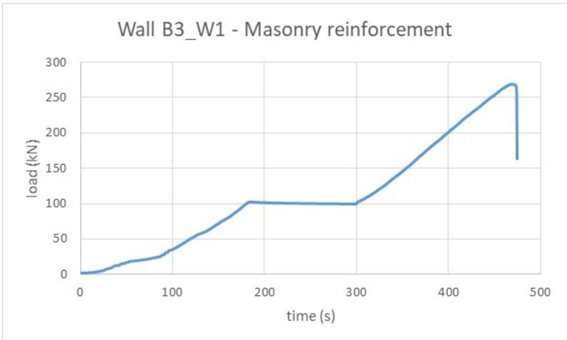


Figure B3_W1_2 Load vs transversal deflection at mid-height (left); Load vs time (right).

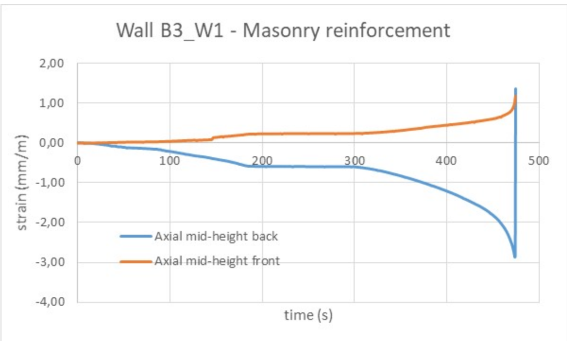


Figure B3_W1_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W2 (Brick, series 3, wall 2) – brick and masonry reinforcement

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

Masonry reinforcement (Swedish bistål), commercial name Joma Bi 40 fz, kvalitet 700

Steel characteristic strength f_y =717 MPa (determined experimentally in the project);

Percentage plastic extension at maximum force A_g=1,5 % (determined experimentally according to SS-EN ISO 6892-1:2016); guage length 100 mm; total length of specimens approx. 150 mm.

Modulus of elasticity: E = 210 GPa (supplier's information).

Reinforcement area $A_s = 50$ mm^2 (in total four bars with Φ = 4 mm)

Way of application: The bars were attached directly to the wall. A reasonable distance between the centrum of the longitudinal bars and the wall surface is set to 1 mm (gap) + 2 mm (radius) = 3 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

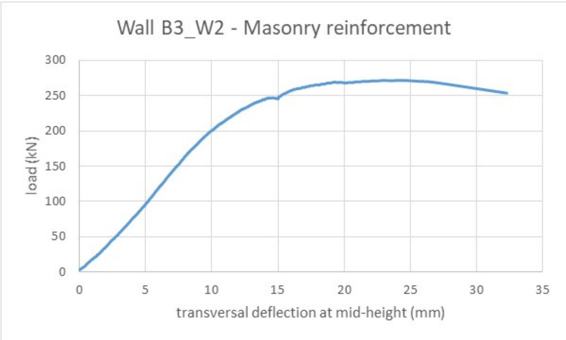
For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 272 kN, corresponding to 453 kN/m; Transversal deflection at maximum load 24 mm, see Figure B3_W2_1.

Failure mode: Ductile tensile failure of the reinforcement, followed by collapse.

Other comments: Cracks were observed along the masonry reinforcement bars.



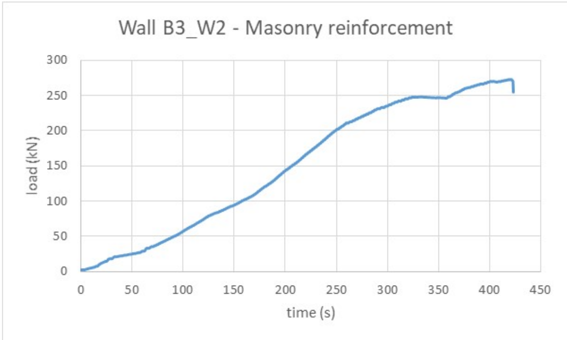


Figure B3_W2_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

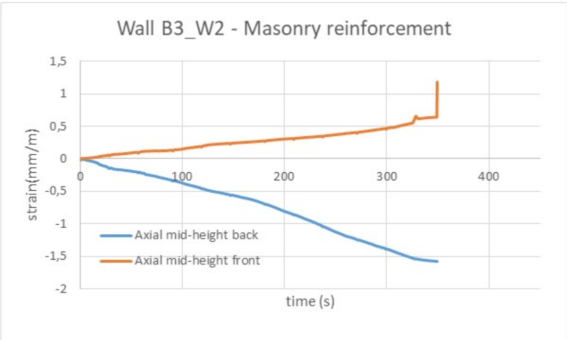


Figure B3_W2_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W3 (Brick, series 3, wall 3) – brick and high strength steel wire

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 9{,}7$ mm^2 (two strips with 7 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 2 mm.

Strengthening render: Render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 255 kN, corresponding to 425 kN/m; Transversal deflection at maximum load 20 mm, see Figure B3_W3_2.

Failure mode: Semi-ductile tensile failure of the reinforcement, followed by collapse.

Other comments: short horizontal cracks were observed at the edge of the wall. The wall had a camber of approximately 5 mm, with the untreated face on the convex side.

Figure B3_W3_1 High strength steel wires that failed in tension.

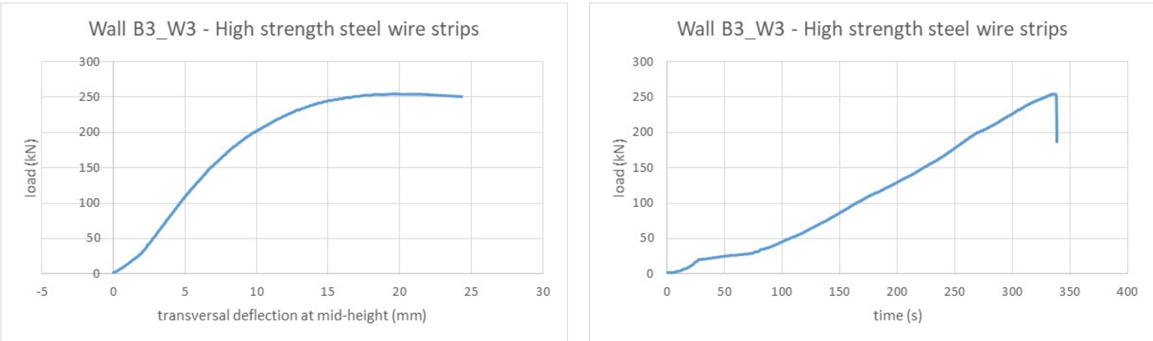


Figure B3_W3_2 Load vs transversal deflection at mid-height (left); Load vs time (right).

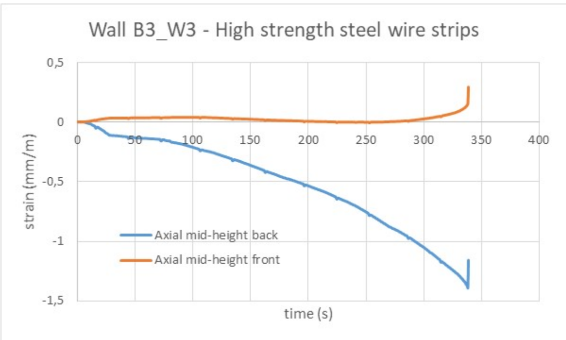


Figure B3_W3_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W4 (Brick, series 3, wall 4) – brick and high strength steel wire

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

High strength steel wire on strips, commercial name Leca murverksarmering 35 RF (manufactured by Bekaert)

Steel characteristic strength $f_{yk} = 1525\ MPa$; modulus of elasticity $E = 150\ GPa$; Ductility class normal.

Reinforcement area $A_s = 9{,}7$ mm^2 (two strips with 7 threads in each strip, thread Φ = 0,69 mm)

Way of application: The steel wire strips were attached directly to the masonry with staple gun. A reasonable distance between the centrum of the longitudinal threads and the wall surface is 2 mm.

Strengthening render: Render quality CS IV (Swedish commercial term “rödgrund A”) – thickness between 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

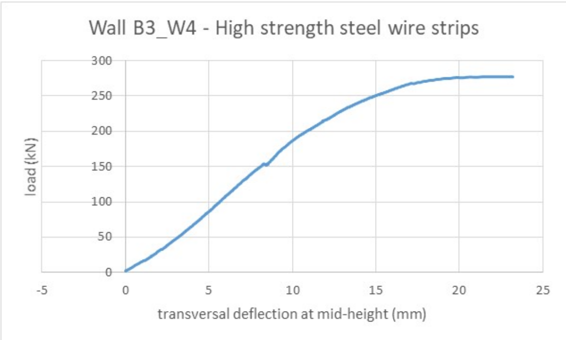
For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 277 kN, corresponding to 462 kN/m; Transversal deflection at maximum load 23 mm, see Figure B3_W4_1.

Failure mode: Ductile tensile failure of the reinforcement at mid-height of the wall, followed by collapse.

Other comments: The wall had a camber of approximately 5 mm, with the untreated face on the convex side.



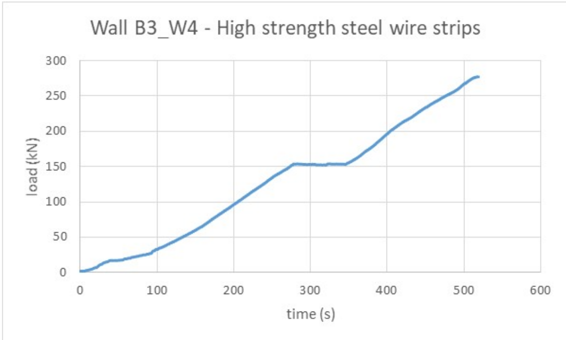


Figure B3_W4_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

Figure B3_W4_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W5 (Brick, series 3, wall 5) – brick and glass fibre mesh

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 72$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 54 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 23{,}5$ mm^2 (when covering the entire length of the wall, i.e. 590 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 3 – 5 mm, with the strong direction along the height of the wall. An overlap of 120 - 130 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 4 mm (render) + 0,5 mm (thickness) = 4,5 mm.

Strengthening render: Render quality CS IV (Swedish commercial term “rödgrund A”) – thickness 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish “putsspruta”) of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second render layer was applied directly after the application of the glass fibre mesh. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 266 kN, corresponding to 451 kN/m; Transversal deflection at maximum load 23 mm, see Figure B3_W5_1.

Failure mode: Bond failure in the upper overlap area, i.e. at around 1600 mm from the bottom edge of the wall. The wall collapsed.

Other comments:

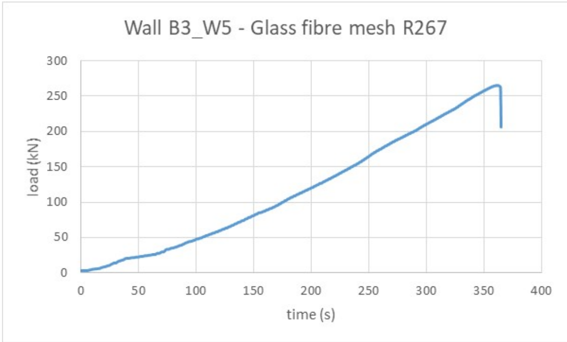


Figure B3_W5_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

Figure B3_W5_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W6 (Brick, series 3, wall 6) – brick and glass fibre mesh

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 72$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 54 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 23{,}5$ mm^2 (when covering the entire length of the wall, i.e. 590 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 3 – 5 mm, with the strong direction along the height of the wall. An overlap of 170 - 180 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 4 mm (render) + 0,5 mm (thickness) = 4,5 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second render layer was applied directly after the application of the glass fibre mesh. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 261 kN, corresponding to 442 kN/m; Transversal deflection at maximum load 21 mm, see Figure B3_W6_2.

Failure mode: Bond failure in the upper overlap area, i.e. at around 1600 mm from the bottom edge of the wall. The wall collapsed.

Other comments: This wall is a replica of wall B3_W5

Figure B3_W6_1 High strength steel wires that failed in tension.

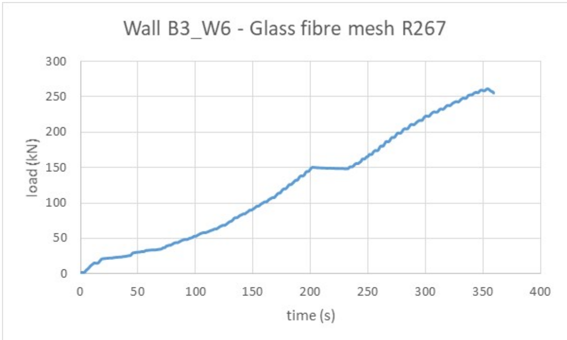


Figure B3_W6_2 Load vs transversal deflection at mid-height (left); Load vs time (right).

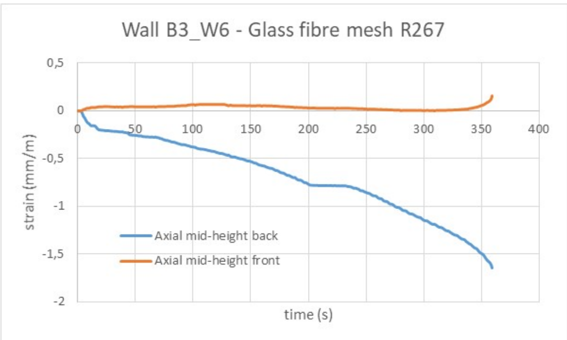


Figure B3_W6_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W7 (Brick, series 3, wall 7) – brick and one render layer

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

No strengthening was used, only render on the tension side of the wall

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the render, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 246 kN, corresponding to 417 kN/m; Transversal deflection at maximum load 18 mm, see Figure B3_W7_1.

Failure mode: The wall collapsed by formation of a mechanism approximately 1800 mm from the bottom edge of the wall.

Other comments: A tensile crack was observed at the position of the rupture plane prior to collapse.

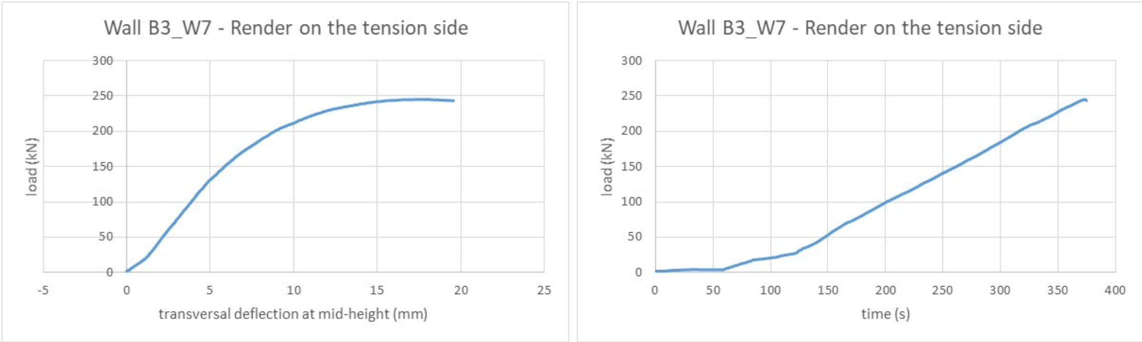


Figure B3_W7_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

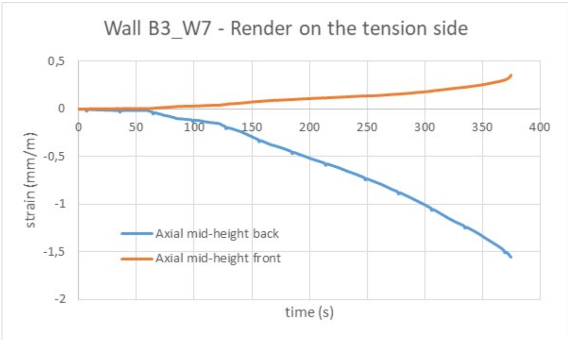


Figure B3_W7_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W8 (Brick, series 3, wall 8) – brick and one render layer

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} = 2{,}0$ mm/m, CoV = 18 %; $\varepsilon_{mu} = 2{,}2$ mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

No strengthening was used, only render on the tension side of the wall

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 10 mm.

Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the render, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Total nominal thickness of the wall after strengthening 87 + 10 = 97 mm.

Loading

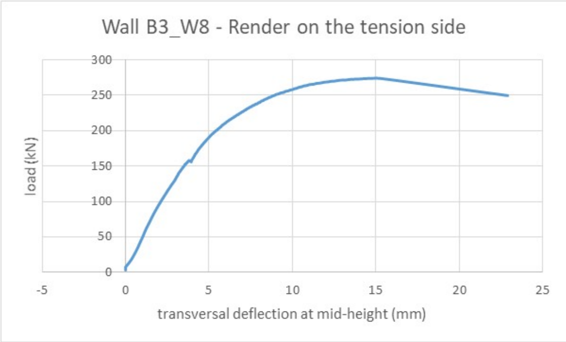
For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 18.5 mm.

Test results

Maximum load 274 kN, corresponding to 464 kN/m; Transversal deflection at maximum load 16 mm, see Figure B3_W8_1.

Failure mode: Very brittle, explosive buckling failure, followed by collapse of the wall.

Other comments:



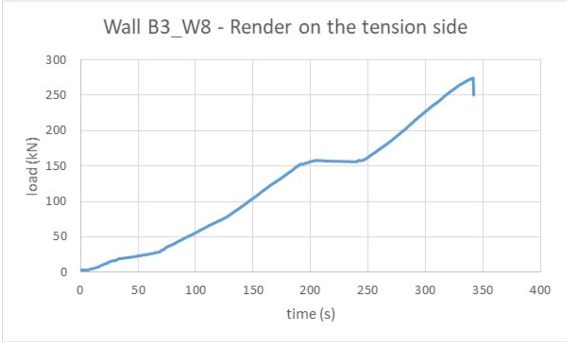


Figure B3_W8_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

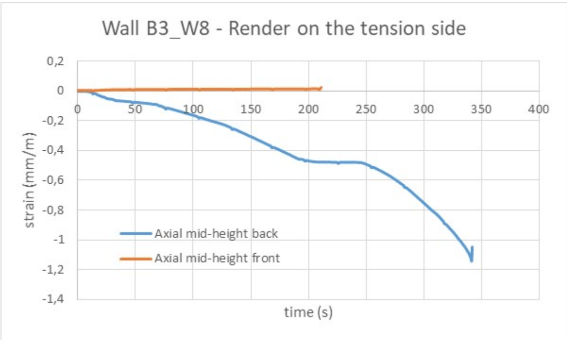


Figure B3_W8_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

B3_W9 (Brick, series 3, wall 8) – brick without any strengthening or render

Wall properties:

Perforated bricks L*W*H = 287*87*87 mm, commercial name IF Blandade M87 MH FT III, from Wienerberger Sweden. Declared compressive strength 35 MPa, water absorption 5 %.

Mortar type M2.5; joint thickness 13 mm

Average masonry compressive strength f_{av}= 14,8 MPa, CoV = 16 %;

Strains: $\varepsilon_{m1} =$ 2,0 mm/m, CoV = 18 %; $\varepsilon_{mu} =$ 2,2 mm/m, CoV = 40 %;

Modulus of elasticity E = 13000 MPa, CoV = 10 %

Wall geometry L*W*H = 587*87*2400 mm

Strengthening:

No strengthening was used, nor render

Total nominal thickness of the wall was 87 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 13,5 mm.

Test results

Maximum load 284 kN, corresponding to 481 kN/m; Transversal deflection at maximum load 18 mm, see Figure B3_W9_1.

Failure mode: Very brittle, explosive buckling failure, followed by collapse of the wall.

Other comments:

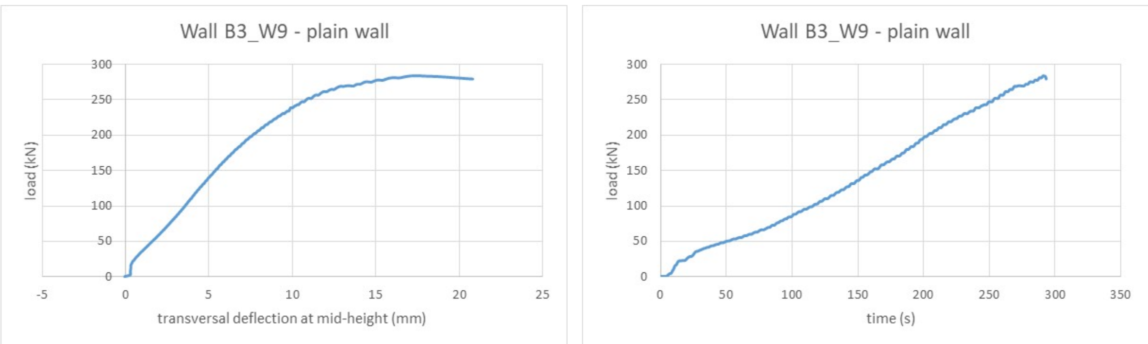


Figure B3_W9_1 Load vs transversal deflection at mid-height (left); Load vs time (right).

Figure B3_W9_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA3_W1 (Light weight aggregate concrete, series 3, wall 1) – LWA and glass fibre on both sides

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa. The lower 1000 mm of the wall was built with blocks used in series 1, for walls LWA1 W1-W6. The upper part of the wall was built with the same type of blocks, but from a separate batch.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,5 MPa (approximation, not determined)

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m; $\varepsilon_{mu} = 1{,}7$ mm/m (approximation, not determined)

Modulus of elasticity E = 3000 MPa (approximation, not determined)

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

Glass fibre mesh, commercial name R267, from Adfors (Saint-Gobain)

Nominal ultimate strength $F_{ru0} = 73$ kN – the embedded strength should be taken as 75 % of the nominal strength, i.e. 55 kN; modulus of elasticity $E = 80\ GPa$; failure strain $\varepsilon_{ru} = 40$ mm/m

Reinforcement area $A_r = 24$ mm^2 (when covering the entire length of the wall, i.e. 590 mm).

Way of application: The glass fibre mesh was applied into fresh render, thickness 3 – 5 mm, with the strong direction along the height of the wall. An overlap of 170 - 180 mm was used between the glass fibre strips. A reasonable distance between the centrum of the mesh and the wall surface is set to 4 mm (render) + 0,5 mm (thickness) = 4,5 mm.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness 10 mm. Way of application: The render was applied by a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. Before applying the first render layer, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The second render layer was applied directly after the application of the glass fibre mesh. The render was compacted and levelled in a way to achieve a total render thickness of approximately 10 mm. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4. Strengthening was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Inner render: The inner, compression side of the wall was rendered with a render quality CS III (Swedish commercial name grund-B). The render was reinforced with a glass fibre mesh normally used for limitation of crack widths (EF-nät from Weber Saint-Gobain Sweden). The thickness of the inner render layer was 10 mm.

Total nominal thickness of the wall after strengthening and application of the inner render layer was 10 + 90 + 10 = 110 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 22 - 25 mm.

Test results

Maximum load 178 kN, corresponding to 315 kN/m; Transversal deflection at maximum load 13 mm – see Figure LWA3_W1_1.

Failure mode: Local crushing of the masonry at the load application plate, at the upper edge of the wall. No collapse occurred – the wall could be removed from the rig by lifting it out by crane.

Other comments: The load dropped from 178 kN to 160 kN and recovered to 186 kN.

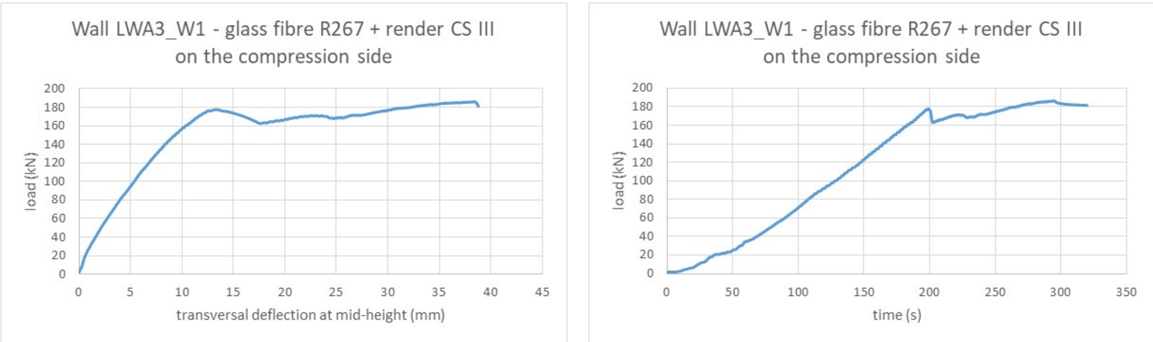


Figure LWA3_W1_1 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

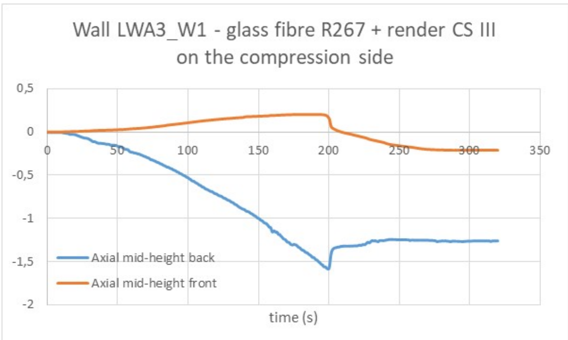


Figure LWA3_W1_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA3_W2 (Light weight aggregate concrete, series 3, wall 2) – LWA and one render layer

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa. The lower 1000 mm of the wall was built with blocks used in series 1, for walls LWA1 W1-W6. The upper part of the wall was built with the same type of blocks, but from a separate batch.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,5 MPa (approximation, not determined)

Strains: $\varepsilon_{m1} = 1{,}7$ mm/m; $\varepsilon_{mu} = 1{,}7$ mm/m (approximation, not determined)

Modulus of elasticity E = 3000 MPa (approximation, not determined)

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

The wall was not strengthened – only a render layer was applied.

Strengthening render: Render quality CS IV (Swedish commercial term "rödgrund A") – thickness between 5 - 10 mm, due to irregularities of the wall. Way of application: Before applying the render, the surface of the wall was pre-wetted by spraying approximately 1 liter water per sqm wall. The render was applied with a plaster sprayer (Swedish "putsspruta") of type Tiger Pro V, distributed by Målarkalk. The render layer was compacted and levelled. The render was cured for 7 days under plastic sheet, with wetting day 2 and 4.

Render was applied on one face of the wall only - to the face exposed to tensile bending stresses. The compression face of the wall was untreated.

Total nominal thickness of the wall after strengthening 90 + 10 = 100 mm.

Loading

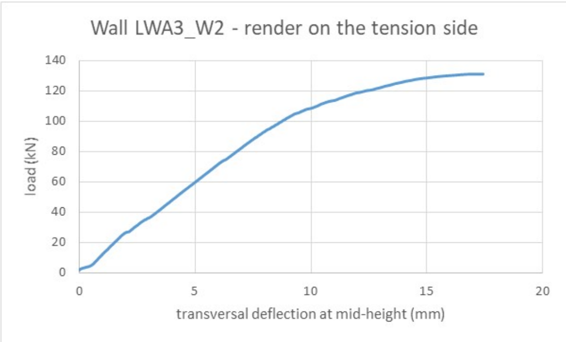
For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 20 mm.

Test results

Maximum load 131 kN, corresponding to 222 kN/m; Transversal deflection at maximum load 17 mm – see Figure LWA3_W2_1.

Failure mode: Buckling failure, with formation of a mechanism at mid-height of the wall. The wall collapsed.

Other comments: The wall was damaged during the installation in the test rig, causing a tensile crack on the rendered side at 2000 mm from the bottom edge of the wall.



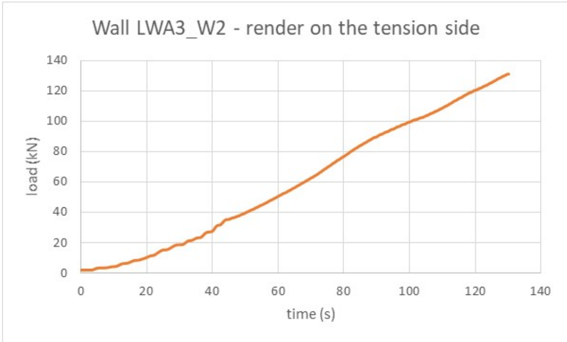


Figure LWA3_W2_1 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

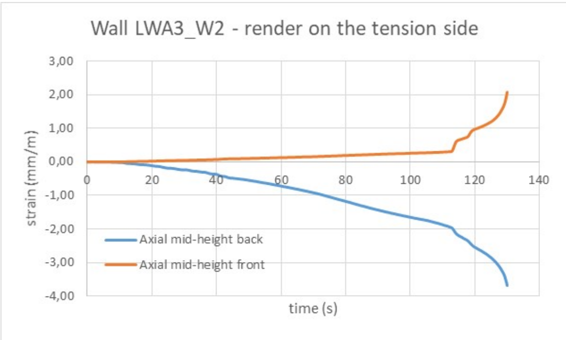


Figure LWA3_W2_2 Axial strains at mid-height vs. time – front (tension) and back (compression) side.

LWA3_W3 (Light weight aggregate concrete, series 3, wall 3) – LWA without any strengthening

Wall properties:

Blocks L*W*H = 590*90*190 mm, commercial name LECA® MURBLOCK 9 TYP 5; strength 5 MPa. The lower 1000 mm of the wall was built with blocks used in series 1, for walls LWA1 W1-W6. The upper part of the wall was built with the same type of blocks, but from a separate batch.

Mortar type M2.5; joint thickness 10 mm

Average masonry compressive strength f_{av}= 3,5 MPa (approximation, not determined)

Strains: $\varepsilon_{m1} = $ 1,7 mm/m; $\varepsilon_{mu} = $ 1,7 mm/m (approximation, not determined)

Modulus of elasticity E = 3000 MPa (approximation, not determined)

Wall geometry L*W*H = 590*90*2400 mm; the wall was built without head joints.

Strengthening:

The wall was not strengthened nor rendered

Total nominal thickness of the wall 90 mm.

Loading

For details on the testing rig, boundary conditions and introduction of the axial eccentric load, See Appendix 1. The eccentricity of the resulting axial force is estimated to 15 mm.

Test results

Maximum load 149 kN, corresponding to 253 kN/m; Transversal deflection at maximum load 15 mm – see Figure LWA3_W3_1.

Failure mode: Buckling failure, with formation of a mechanism at mid-height of the wall. The wall collapsed.

Other comments:

Figure LWA3_W2_1 Load vs. transversal deflection at mid-height (left); Load vs. time (right)

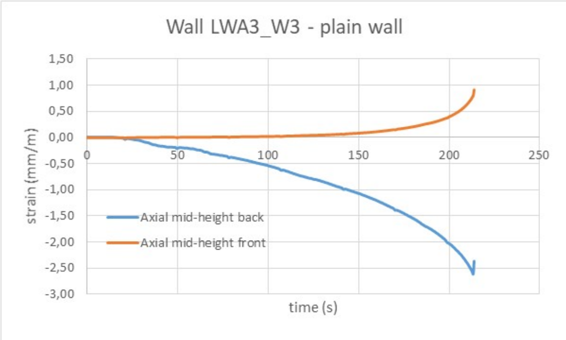


Figure LWA3_W2_3 Axial strains at mid-height vs. time – front (tension) and back (compression) side.