SAHC2014 – 9th International Conference on
Structural Analysis of Historical Constructions
F. Peña & M. Chávez (eds.)
Mexico City, Mexico, 14–17 October 2014

COLLAPSE AND REBUILDING OF A MEDIEVAL CITY WALL – AN ASSESSMENT OF THE STRUCTURE AND MATERIAL

Carl Thelin[1], Kristin Balksten[2] and Folke Höst[3]

[1] Tyréns AB
Storgatan 40, SE-352 31 Växjö, Sweden
e-mail: carl.thelin@tyrens.se

[2] Department of Art History,
Uppsala University – Campus Gotland, SE-621 67 Visby, Sweden
kristin.balksten@konstvet.uu.se

[3] Tyréns AB
Ideon Science Park, Scheelevägen 17, SE-223 70 Lund, Sweden
e-mail: folke.host@tyrens.se

Keywords: City wall, masonry structure, structural behaviour, lime mortar, two-leaf masonry wall.

Abstract. *In February 2012, a part of the medieval city wall of Visby collapsed. The wall was constructed in several stages in the 13th and 14th centuries. It was decided that the collapsed part of the wall should be rebuilt. To determine a procedure for the rebuilding and to secure a safe work site, it was necessary to define the construction and structural behaviour of the wall. Furthermore, the cause of the collapse needed to be identified, in order to assess and predict the risk of future damage to other parts of the wall. An investigation into the construction of the wall was carried out through archival research and on-site examinations. Laser scanning made it possible to describe and study the geometry of the wall and the damage in detail, and a structural analysis was carried out. The results show that the wall was built in two stages, making its construction complicated. The structural analysis indicates that there is a concentration of forces to the outer masonry leaf of the lower part of the wall. The collapse was most likely triggered by freezing of the water contained in the masonry. The combination of high stress levels in the outer masonry leaf, due to the construction of the wall, with a loose core, thin outer masonry leaf and insufficient binding stones and weak adhesion in the bedding lime mortar in the lower part of the wall, resulted in a domino effect that explains the extent of the collapse. To secure the wall during dismantling, a temporary steel structure was constructed. The medieval types of construction and material in a two-leaf masonry wall have proven to be durable if correctly implemented, with sufficient binding stones and a core in order, and will therefore be used for the rebuilding.*

1 INTRODUCTION

In February 2012, a part of the medieval city wall of Visby collapsed. The city wall is a part of the UNESCO World Heritage Site of the Hanseatic Town of Visby and is exceptionally well preserved. The damage caused by the collapse resulted in the loss of irreplaceable cultural values. At the same time, the collapse opened up a unique opportunity to understand the construction and the material of a medieval city wall.

Originally, the wall was approximately 3.6 km long, and 3.44 km are still standing today. The wall once had 29 large towers and 27 smaller towers that rode on top of the wall. Of those, 27 large towers and 9 of the smaller towers remain [1]. There is limited knowledge about the erection of the wall, but we know that it was built in several periods. The part of the wall running along the seafront, called “the sea wall,” was built before the rest of the wall, called “the land wall.” It is believed that the land wall was constructed during two major periods, the first in the 13th century, before 1288, and the second between 1289 and 1361 [2]. The construction material is local limestone. The section built during the first period was about six metres high, with crenellations and a rampart walk built on arches on the inside. In the second period, the wall was raised by 2-4 metres and the wall towers were added; see Figure 1. It was completed before 1361 when the Danish king Valdemar Atterdag conquered Visby.

Over the years, several parts of the wall have collapsed and been repaired or rebuilt in different ways. Several collapses were probably triggered by the wall towers, as they add a significant load to an already stressed wall.

The wall is protected as an ancient monument since 1805 and several restorations have been carried out since then; however, a lack of finances has followed the modern history of the wall. The restorations in the 19th century aimed at reinforcing the wall. Iron struts were put in place to reinforce two wall towers, the top of the wall was partly covered with concrete and retaining walls and buttresses were built in several places to support the wall. The restorations in the 20th century mainly focused on repointing the wall. This was generally done with cement mortar in the 1930-1970s, according to the philosophy and technique of the time [3, 4]. Some reinforcements using concrete and steel ties were also carried out, as some parts of the wall were found to be close to collapsing [5].

Figure 1: Visby City Wall seen from the outside and the inside. The smaller wall towers ride on top of the wall. Old collapses as well as different kinds of reinforcing structures can be seen in many places.

The collapse in 2012 and the following dismantling during 2013 have provided a unique opportunity for researchers in different fields to document and study different aspects of the construction and material in the land wall. The National Heritage Board of Sweden decided to rebuild the collapsed part of the wall. The different options and conservation principles for rebuilding are discussed elsewhere [6]. The decision to rebuild the wall gave rise to further questions and the National Heritage Board launched a research project to study the wall and different methods to rebuild, reinforce and maintain the wall, in parallel with the actual project of rebuilding and reinforcing it. The research project aims at answering the following questions: How is the wall constructed and what materials were used? What is the structural behaviour of the wall? Why did it collapse? How can it be dismantled in a safe way? How should it be rebuilt? What knowledge can be gathered for use in the future maintenance of the wall and other similar structures?

2 METHODS

A combination of archival research and visual inspections of the wall, both in general and at the location of the collapse, has been carried out to describe the construction and materials of the wall. The dismantling of the wall made it possible to view the structure of the wall in detail and to collect material samples from different parts of the masonry.

The part of the wall around the collapse site was documented with laser scanning, which is a powerful tool to examine and describe the 3D geometry of the wall and the collapsed parts [7]. The laser scan was used to extract sections of the wall to analyse the stability of the remaining parts and to determine the geometry of temporary supporting structures with an exact fit. The laser scan also provided a 3D model of the collapsed part of the wall.

Structural analyses and computations of the structural stability of the supporting structure and to define the need for binding stones as well as reinforcements of adjacent parts of the wall were carried out.

The dismantling and rebuilding of the wall is a case study with respect to building methods, materials and the craftsmanship required to construct a long-term, durable medieval-type masonry wall. The work is being documented as it progresses.

Thin section specimens were prepared from the historic mortar. A UV fluorescent epoxy resin was used for the vacuum impregnation of the samples before they were polished down to a thickness of approx. 3 μm and studied with an Olympus BH-2 Polarisation Microscope. The mortar of the wall was also studied in situ together with masons in order to describe its performance with regard to adhesion to the limestone.

The study is mainly limited to the part of the wall that collapsed but the results are expected to be relevant to the rest of the city wall of Visby, as well as to other similar structures.

3 RESULTS

3.1 Construction of the wall

The city wall of Visby is about eight to ten metres high, about two metres wide at the base and about 0.7 metres wide at the coping. Basically, it is a two-leaf wall with a rubble core, but since it was built in at least two different stages it has a more complicated structure.

Earlier investigations indicate that the wall has varying foundations [2, 5]. In many places it probably rests directly on the bedrock but in some places it stands on soil. At the location of the collapse the foundation bed of the wall is soil. A geotechnical investigation showed that the distance to the bedrock from the ground surface is between 0.5 to 1 metre at the outside of the wall, and a minor test excavation showed that the depth of the foundation is shallow; approximately 30-50 cm below the ground surface. Below the foundation stones, the soil is mixed with limestone chips, as also seen in other parts of the wall in earlier investigations [5]. At the site of the collapse the ground level is about two metres higher at the inside of the wall.

The original land wall was about six metres high and had a parapet with crenellations and a rampart walk on top of an arcade on the inside; see Figure 2. The contour of that wall can still be seen within the stonework of the current wall [8]. The wall has a thin outer leaf of bonded masonry, about 25-50 cm thick, and an arcade of pointed masonry arches, approximately 70 cm thick, on the inside. In between, there is a loose rubble core of stones varying in size and clay mortar. Except from the upper, thinner part of the wall, there are no through stones and a limited number of stones that bind the outer leaves to the core. The outer leaf and the arcade were built with lime mortar. The parapet wall was also built with lime mortar as a homogeneous wall, about 75 cm thick. Since the thickness of the parapet wall is greater than the outer leaf of the lower part of the wall, it stands partly on the core and partly on the outer leaf masonry.

When the wall was heightened by 2-4 metres, the parapet wall was used as an outer leaf and a bottleneck-shaped addition was built on the rampart walk, with an upwardly narrowing core of smaller stones and lime pressed against the parapet wall. Since the parapet wall was reused as an outer leaf, no binding stones exist in that part. The top part above the former parapet wall was built as a homogeneous solid wall.

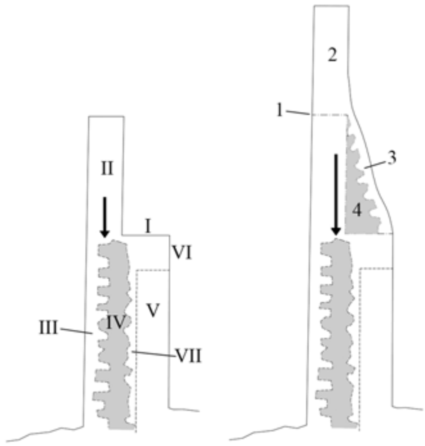

Figure 2: Simplified sections of the land wall. The section to the left shows the land wall before it was heightened and the section to the right shows it after the heightening and the structure today. The arrows show the eccentric loading of the outer leaf. I) Rampart walk. II) Parapet. III) Outer masonry leaf. IV) Core with clay mortar and no bond. V) Openings of inside arches. VI) Top of inside arches. VII) Thin masonry leaf inside arches. 1) The height of the original wall (left image). 2) Heightening of the wall in solid masonry. 3) Masonry leaf of bottleneck-shaped masonry. 4) Upper core inside former parapet wall.

Figure 3: Two photos showing the same part of the wall at two different stages of dismantling of the collapsed part. 1) Lower core with clay mortar and no bond. 2) Thin outer masonry leaf. 3) Former parapet, now outer leaf of the middle part of the wall. 4) Upper core inside the parapet wall. 5) Top with solid masonry.

3.2 Material used in the wall

The city wall was built of local limestone. The limestone of the island of Gotland is Silurian limestone. In the surroundings of Visby the limestone is very pure, consisting of ≥96% calcite [8]. The building stone quarried for the city wall mainly has a thickness of 10-30 cm, determined by the natural layers of the limestone.

The historic mortar present in the city wall is mainly of three different types and is related to the two main building phases. In the first building phase the bedding mortar in the outer leaf and in the arches on the inside are made of a pure and fat air lime mortar (a). It is a white, very lime-rich and rather homogeneous type of mortar that was used for the adhesion between the lumps of limestone. It is found up to the top of the former parapet. In the core below the rampart walk of the older part of the wall, clay mortar (b) was used as bedding mortar. It can be described as a brown clay mortar with a natural content of sand particles and, occasionally, a small lump of limestone can be found. As expected, the clay mortar dissolves into powder when dry and is stable when wet [9]. Due to the fact that the ground level is high on the inside of the wall, the clay mortar should have been moist for a long time.

In the second building phase, another pure air lime mortar (c) was used in the core as well as in the two leaves. This was not as rich in lime as the mortar from the first building phase. This mortar has the colour of sand rather than of white lime and it is slightly less homogeneous than the (a) mortar. Both types of lime mortar display very good adhesion to the limestone, but the (c) mortar from the 14th century is slightly stickier than the (a) mortar from the 13th century, despite the lower lime content.

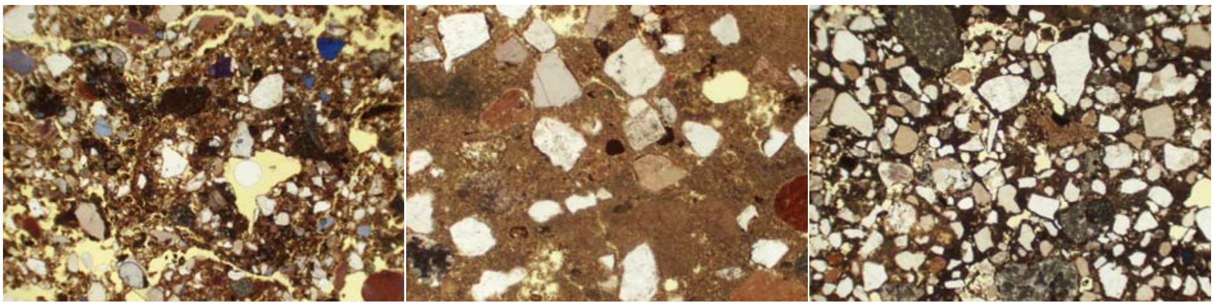

Figure 4: The first sample represents the clay mortar used in the wall core beneath the rampart walk. It is a clay soil type containing sand, resulting in a rather fat clay mortar. The second sample represents the type of fat lime mortar used in the first building phase of the wall, in the two leaves and in the compact masonry above the level of the rampart walk. This is a very fat lime mortar where the amount of lime is greater than the amount of sand. The third sample represents the type of lime mortar used in the second building phase. The yellow colour shows the pore system, the brown colour shows the binder and the other particles show minerals in the sand. The width of each thin section is equivalent to 4.5 mm of the sample.

3.3 Structural behaviour of the wall

The general structural behaviour and common pathology of two-leaf masonry walls have been described by Heyman [10] and Beckman and Bowles [11], and similar behaviour and problems apply to the city wall of Visby. The lower oldest part of the wall has a thin outer masonry leaf and a weak core of limestone and clay mortar. There are no through stones and few stones binding the leaf to the core. The arcade on the inside initially carries its own load plus the load of the rampart walk and provides an inner support for the core. The former parapet wall (now the outer leaf of the upper middle part of the wall) is thicker than the lower leaf and therefore stands both on the core and the outer leaf; see Figures 2 and 3. Since the lower core is weak and easily deformed under loading, the loads from the former parapet will be concentrated to the outer leaf of the lower part of the wall and the loading will be eccentric.

The heightening of the wall by 2-4 metres and the addition of an inner leaning part on top of the former rampart walk increased the load significantly. Since the parapet wall was used as an outer leaf in the heightening of the wall there are no binding stones at all in this part. To a great extent, the increased load needed to be carried by the thin outer leaf of the lower and older part of the wall.

The repointing of the wall, in parts with a stiff modern cement mortar, may have affected the loading situation further by providing a stiffer loading path at the outer part of the wall that concentrates the load further to the outside of the outer leaf.

Thus, a structural analysis indicates that there is a concentration of forces to the outer masonry leaf of the lower part, probably resulting in high stress levels in many parts of the wall. Even though many parts of the wall have been standing for at least 750 years, its condition implies that the margin for further loading is limited.

3.4 Deterioration patterns

With moisture present in masonry, several deterioration processes may occur; frost damage, leaching of lime binder, cracks and movement due to swelling and shrinkage, biological growth, both on the surface and with roots inside the joints, insects building nests, etc. [3]. The lime mortar in the Visby city wall was originally very fat and extremely compact, giving very good resistance to frost and little capillary transport. Due to the pore structure the deterioration has been a very slow process, occurring on the very surface of the joints, from the 13th century until the beginning of the 20th century, and still continues in the parts that were never repointed. If lime mortar is saturated with moisture for a very long time, the lime will slowly dissolve [12], followed by a loss of the binding effect in the mortar. If there is also a presence of salts, giving a lower pH, the solubility increases as acid-base reactions dissolve the lime. This is a common phenomenon in old masonry constructions and can be recognised as stalactites and flowstone as precipitation on the stone masonry. As the cement mortar used for repointing during the 20th century has lower vapour permeability than the original lime mortar [13], the moisture can now remain longer inside the joints than before [14]. On the city wall of Visby, the phenomenon with lime precipitation can only be seen where the joints have been repointed with cement mortar. Limestone, cement mortar and lime mortar all have different properties when it comes to swelling and shrinkage due to temperature and moisture [15]. The thermal expansion coefficient of cement mortar can be two to three times higher than that of limestone, and twice as high as that of lime mortar [15], at normal temperature. The effect often seen on old masonry repointed with cement mortar is stiff joints with cracks between the stone and the mortar, giving no or poor adhesion. As those cracks are thin, they lead water inside the wall by capillary transport and water accumulates in the wall.

3.5 A theory of collapse

The collapse in 2012 resulted in the falling down of approximately 90 m^2 of the outer masonry leaf. The upper part of the wall, consisting of solid masonry, did not collapse and remained as an arch above the damaged part; see Figure 5.

The cause of damage is complicated and can be attributed to several components:

- The construction of the wall in different stages and without through stones and, in parts, few or no binding stones.
- The stress levels in the outer masonry leaf, as described in the structural analysis presented above.
- Different ground levels at the location of the collapse. The ground level is approximately two metres higher on the inside of the wall.

- The weakening of the masonry within the wall due to repointing with low permeability cement mortar, as the higher moisture content leads to deterioration.
- High levels of moisture within the wall due the difference in ground level as well as a drainage (made in 2011) from the building on the inside leading local drainage water into the lower parts of the wall.
- Several freezing cycles in the weeks before the collapse

The collapse was most likely triggered by freezing of the contained water. The combination of high stress levels in the outer masonry leaf, due to the construction of the wall, with a loose core, thin outer masonry leaf, insufficient binding stones and weak adhesion in the bedding lime mortar in the lower part of the wall, led to a domino effect, causing the extent of the collapse.

Figure 5: Visby City Wall in 26th of February 2012, a couple of days after the collapse.

3.6 Methods and materials for rebuilding

The rebuilding will take place throughout 2014. The objective is to give the rebuilt part long-term stability and strength. The medieval materials and structural principles using limestone and clay and lime mortar will be used, as they have proven themselves for many centuries. The loose core and the lack of binding stones between the leaves and the core, as well as the use of cement mortar, will not be repeated in the rebuilding, since they lead to weaknesses of the wall structure.

Three different types of mortar will be used for the reconstruction: 1) As bedding mortar in the two-leaf construction, a lime mortar made of traditional Gotland lime will be used (Gotland lime is a very pure and fat Silurian air lime). The mortar will be made as hot lime mortar, slaking the lime inside the sand. This provides the possibility of using mortar that is as rich in lime as the mortar that was originally used, producing mortar that is as strong as this type of lime can be and that sets even in a wet environment. 2) In the lower parts of the rubble core, clay mortar with a small content of lime will be used, as lime is known by generations of masons to stabilise the clay mortar. Clay mortar is durable also in a wet environment and is not expected to disintegrate, as pure lime mortar would. 3) As pointing mortar on the leaning inner side of wall, more water-resistant mortar is needed. This pointing mortar will be made as a hot lime mortar from Öland lime (the Öland lime is an Ordovician limestone with a clay content of approx. 10 %, giving a sub-hydraulic lime). Other parts will be pointed with the same mortar as the bedding mortar. Practical tests were performed during 2013 by experienced masons. Workability, adhesion and authenticity were the most important aspects in these tests.

The wall will be rebuilt with the same shape as before but with a core in better order and with the use of binding stones and through stones to connect the outer leaves. To determine the number of binding stones needed, two hypothetical load cases where used: local buckling of the outer masonry leaf and earth pressure from the core [16]. Both load cases give rise to forces of approximately the same magnitude; see Figure 6. These load cases are based on a wall structure in bad condition, in contrast to the rebuilt part, and can therefore be presumed to have a satisfactory factor of safety.

The following principles will be applied to the masonry work:

- The outer masonry leaves will be built with precise bonds to ensure that the stones are arranged to provide strength and stability. Vertical joints should not be continuous.
- Two to three binding stones per square meter will be used and in the upper part, where the wall is thinner, through stones will be used.
- A binding stone needs to have enough depth to bind to the core and connect with the stones there.
- Stones used in the core are placed in an orderly fashion, even though the demand on bonding is not as large as for the outer leaves. The stones should have varying fractions to fill out well and create sufficient support to the binding stones and through stones that are to be bonded to the core.

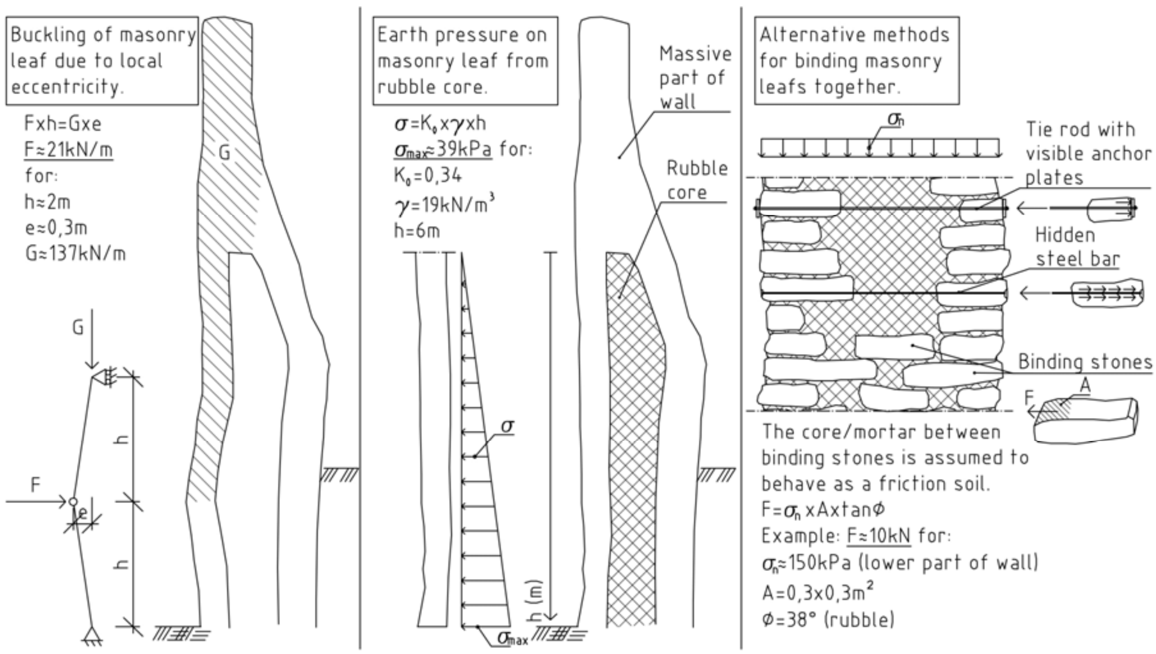

Figure 6: The hypothetical load cases used to design the number and placing of binding stones for the rebuilt part and reinforcing bars in the adjacent parts of the wall.

3.7 Dismantling and a safe working site

The rebuilding of the collapsed parts involves several difficult challenges. The location of the collapse and the particular way it fell down entailed complicated technical conditions that needed to be addressed to make the rebuilding possible and safe. The following issues needed attention:

- Masonry has to be built from the bottom upwards, layer by layer. To be able to start building, the rubble heap in front of the wall had to be removed; see Figure 5. Since the rubble heap acted as a buttress against the remaining parts it could not be removed.
- The top of the wall was retained in full and acted as an arch over the collapsed part. It loaded the remaining walls on both sides of the collapsed part with thrusting forces. The

weight of the masonry in that arch was approximately 2000 kg per meter. The arch was heavily cracked and occasionally parts of it fell down.
- If the remaining arching part was removed there was a risk that the structural behaviour of the adjacent parts of the wall would be affected.
- The collapse exposed the core of the wall that is not built with masonry bonds.
- Below the remaining arching part the wall was as thin as 20-30 cm.
- The lower parts of the exposed core was very loose and the risk of further collapse was evident, especially if stones where removed or affected in other ways. If the lower part of the core collapsed further, there was a great risk of the upper parts collapsing as well.
- The difference in ground level at the location of the collapse is unusually large. The ground is approximately two metres higher on the inside of the wall, resulting in the soil on the inside exerting pressure on the lower parts of the wall.
- There is a building close to the wall on the inside of the southern part of the collapse site.

The objective was to make sure that no further collapse occurred in the collapsed area or in the parts adjacent to it. At the same time it had to be possible to dismantle the damaged wall stone by stone in a safe working environment. Different options were examined and the most advantageous solution found was to construct a temporary steel framework to hold the wall together during dismantling.

The concept of the temporary structure was to restrain the wall from further collapse by counter-filling a formwork at the outside and placing wedges between the inside of the wall and the steel structure. The counter-fill on the outside created a passive pressure that was larger than the worst case of active pressure from a collapsing wall. Granulated foam glass was used as the filling material, as it is both light-weight and has high strength. The steel structure was held together at the top and through four holes drilled in the wall at the bottom. The structure also stabilised the adjacent walls on both sides of the collapse site; see Figure 7.

Since the ground level is about two metres higher on the inside of the wall and there was a pile of stone rubble on the outside, a new ground level had to be created for the temporary steel structure on the outside, through the use of concrete retaining walls and gravel. The steel structure also had to be adapted to fit in between the wall and the building close to the wall on the inside; see Figure 8.

As the dismantling progressed, the foam glass, the outer formwork and the wedging on the inside were taken down simultaneously.

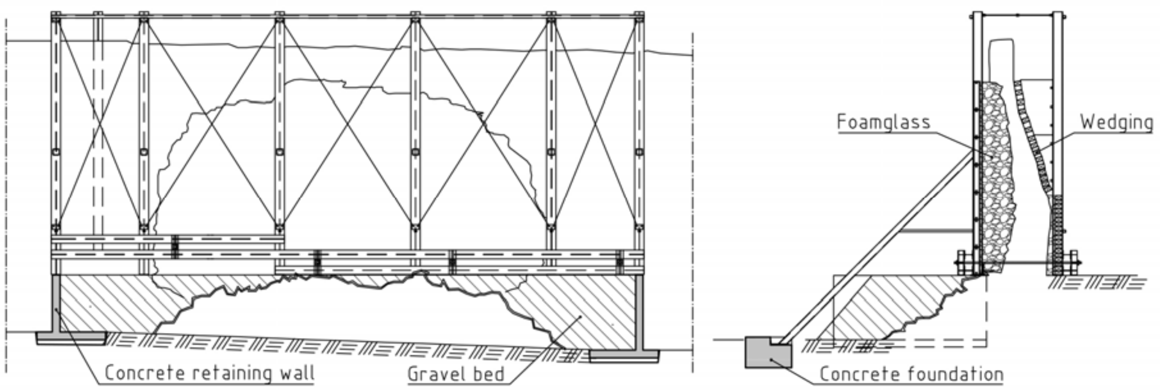

Figure 7: Drawings for the temporary supporting steel structure with counter-filling and wedging.

Figure 8: The temporary supporting steel structure, viewed from the outside during dismantling of the wall (left), and from the inside during erection (right).

3.8 Reinforcements of adjacent parts of the wall

The collapse had exposed several weaknesses in the structure of the wall clearly. A recurring problem, described in various records, is cavities in the core and between the core and the outer leaf. At several locations this has led to bulges in the outer masonry leaf. This problem was very evident at the northern side of the collapsed part, where large cavities between the outer masonry leaf and the core became visible; see Figure 3.

The decision to reinforce the wall on both sides of the collapse was made for the following reasons:

- The collapse exposed cavities and separation of the outer masonry leaf and the core.
- The collapse may have affected the adjacent parts of the wall and the dismantling of the collapsed part would have an effect on the structural action in those parts.
- To eliminate the risk of further collapse during the rebuilding and when the new parts were connected with the remaining adjacent wall parts.

The same load case as that used for determining the number of binding stones was used to design the reinforcements; local buckling of the outer masonry leaf and earth pressure from the core; see Figure 6. Three different methods were used to reinforce the adjacent parts of the wall. Above the inner ground level, where it was possible to drill through the wall, both hidden stitches of steel bars and tie rods with visible anchor plates were used, and below the level of the inner ground, grout-injected anchors from Cintec [17] were used. The size of the steel bars was adjusted to not be too stiff, which could cause other damage if future movement were to occur in the wall [18]. All the steel used is made from non-corrosive metal.

4 DISCUSSION AND CONCLUSION

The partial collapse of the medieval city wall of Visby provided a unique opportunity to investigate and understand its construction and component materials. The way the collapse happened, as well as the location of the collapse, meant that several problems had to be solved in order to make dismantling and rebuilding possible in a safe working environment. The safety of the personnel involved and the protection against further collapse have been crucial issues in the project.

The investigations and analyses of the wall have revealed a complex situation and exposed several weaknesses in the wall:

- The two building phases became evident, as well as how this impacts the structural behaviour.
- In parts, the wall is built surprisingly slovenly with few or no binding stones.
- The lower core is built in a disorderly manner without bonding and is loose.

- The outer masonry leaf of the lower older part is thin.
- There are cavities in the core and between the outer masonry leaf and the core.
- Bulging deformations of the outer masonry leaf.
- The leaning parts of the inside of the wall, as well as the angle of the stones, increase the amount of water leaking into the wall.
- The deterioration of the bedding mortar combined with strong pointing mortar of low permeability.
- The frost risk due to an increased moisture exposure from leaking water.
- Use of stiff modern cement mortar affecting the load paths of the wall.

With a load situation like the one in the city wall of Visby, the security margins against further loading or further deterioration are probably low in many places. If the stress situation changes, a collapse can be expected. If the bedding mortar loses some of its binding effect, the risk of shear failure increases, and as the outer masonry leaf is very thin there is a risk of buckling of the leaf. The restorations performed in the 20th century, with low-permeable and strong pointing mortar, may have had a negative effect, as the moisture content increases behind the pointing mortar at the same time as the surface of the masonry leaf becomes stiffer. Even though this deterioration process is slow it has to be brought to a halt to prevent a new collapse from taking place.

The weaknesses listed above are not due to the original materials used or the medieval principles of construction, which are very durable and have allowed the wall to stand for more than 700 years in most parts, in spite of its construction. The weaknesses are rather due to the two buildings phases, probably hasty and sloppy construction of the lower core and not using a sufficient number of binding stones, as well as poor and, in some cases, faulty maintenance throughout the years. For this reason, there are strong technical arguments in favour of using the same materials as the existing ones in the rebuilding of the wall, and to apply the basic structural principle of a two-leaf masonry wall but with an orderly core and with the use of binding and through stones.

The solution to provide a safe work site and to ensure that no further collapse occurred was to construct a temporary steel structure that held the wall together as a formwork that could be taken down at the same time as the wall was dismantled, and to reinforce the adjacent wall parts.

The knowledge gained on how the wall is constructed, its basic structural behaviour, its material properties, its weaknesses and possible causes of collapse can be used to investigate the rest of the wall to assess its structure and to develop a long-term maintenance plan to preserve the wall and to avoid future situations of collapse, posing a risk both to human health and to losing the authenticity of the medieval heritage. There is a great need for a more profound understanding of the deterioration process and the weaknesses of the structure. There is also a need for constant maintenance in order to remove plants and trees and diminish the conditions for plants to grow and, at the same time, prevent the bedding mortar from losing its binding effect, starting with the exchange of cement pointing mortar. As long as the cement joints are left in the wall, the deterioration will increase and continue.

ACKNOWLEDGEMENTS

We wish to thank the National Heritage Board for financing the research project and for providing the laser scanning. We also like to thank the masons at Byggnadshyttan in Gotland for their sterling effort to dismantle the wall. Our thanks also go to St. Gobain for preparing the thin sections for analysis.

REFERENCES

[1] W. Falck, *Visby stadsmur: en kulturhistorisk vandring,* Riksantikvarieämbetet, Stockholm, 1995.

[2] O. Janse, *Visby stadsmur.* 2. Omarb. Uppl., Wahlström & Widstrand, Stockholm, 1949.

[3] K. Balksten & U. Mebus, (red.), *Bruk av ruiner,* Fornsalens förlag, Visby, 2013.

[4] N. Cnattingius, (red.), *Rädda Visby ringmur! Rapport från en kampanj 1989-1995,* Cementa, Danderyd, 1996.

[5] G. Hammarlund, *Utredningar och projekteringshandlingar,* Gotlands museums arkiv, Visby, 1961.

[6] U. Mebus, *Mötesanteckningar Visby Ringmur, Antikvariska principer för återuppbyggnad (Dnr 3.3.1-830-2012),* Riksantikvarieämbetet, Visby, 2014.

[7] C. Thelin, F. Höst & C. Rosenberg, *Analysis of historic masonry structures supported by 3D laser scanning.* J. Jasiénko, (ed) Proceeding of the 8th International Conference on Structural Analysis of Historic Construction, SAHC-2012, 15-17 October 2012, Poland, 2012.

[8] E. Eckhoff & O. Janse, *Visby stadsmur. D. 2, Planscher,* Wahlström & Widstrand, Stockholm, 1922.

[9] Rothstein, E. E. von, Handledning i allmänna byggnadsläran med hufvudsakligt afseende på husbyggnadskonsten samt kostnadsförslagers uppgörande, 2. öfversedda, tillökta och delvis omarb. uppl., Beijer, Stockholm, 1875

[10] J. Heyman, *The Stone Skeleton: Structural Engineering of Masonry,* Cambridge University Press, Cambridge, 1995.

[11] P. Beckmann & R. Bowles, *Structural Aspects of Building Conservation,* Second edition, Elsevier Ltd, Oxford, 2004.

[12] Forster, A., Binder loss in traditional mass masonry: a cause for concern? Structural Survey. Vol 25 Iss: 2, pp 148-170, 2007

[13] Balksten, K., Traditional lime mortar and plaster: reconstruction with emphasis on durability, Chalmers University of Technology, Diss. Göteborg: Chalmers tekniska högskola, 2007

[14] Nilsson, L-O et al, Material och transportprocesser. Göteborg: CTH. Inst. för byggnadsmaterial: Kurskompendium, 2000

[15] Burström, P.G., Byggnadsmaterial: uppbyggnad, tillverkning och egenskaper, Studentlitteratur, Lund, 2001

[16] R. F. Craig, *Soil Mechanics,* 6th edition, E &FN Spon, London, 1997.

[17] Cintec Worldwide , [online], Available: http://www.cintec.com/cintec/anchoring-reinforcement-home.php, [2014, April 10].

[18] J. Gustafsson & J. Silvemark, *From magnificent fortification to withering heritage: A comparative study of construction techniques for joining cavity walls,* Degree project, KTH Royal Institute of Technology, Stockholm, 2013.