

Construction and materials of Visby medieval city wall – risk of damage

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ABSTRACT:

The City Wall in Visby was built in two periods in 13th and 14th century. The first wall was made as a lower three-leaf wall with two shells built of lime stone and fat lime mortar and a soft and porous rubble core of lime stone and clay mortar. The second wall was built higher on top of the old one. It was mostly built as a solid wall in lime stone and lime mortar. Due to its construction and form, a major part of the force is carried by the outer shell of the wall. As restorations have been made during 20th century the joints of lime mortar has been partly repointed with strong cement mortar, followed by leached lime inside from the mortar in the wall. In February 2012 a part of the wall collapsed and fell down as the outer shell of the masonry collapsed. This paper presents an analysis of the wall structure and its materials as well as the increased risk of damage due to the restorations of the 20th century.

Keywords: city wall, lime mortar, clay mortar, three-leaf wall, rubble core, masonry structure, deterioration

1 INTRODUCTION

In February 2012 a part of the medieval city wall of Visby collapsed and fell down. It is a protected ruin and it is one of the best preserved city walls in northern Europe. Many people are living very close and some houses are even integrated with the city wall. Especially in summer time many tourists enjoy sunset with their back to the wall. The wall has to be safe to be close by. Collapses like this must be avoided if possible. As tragic as the collapse was, it opened a new opportunity for understanding the construction and the materials of the wall. The first part of the research project, as presented in this paper, will try to answer the questions about how the city wall was built and what could cause the collapse.

Visby is known for being a well preserved Hansa town along with its city wall, and became a UNESCO World Heritage Site in 1995. The city wall was originally approx. 3.6 km long and 3.44 km is still standing. The construction material is local limestone. Originally it had 29 large towers and 22 small wall towers riding on top of the wall. Out of them 27 large towers and 9 of the small towers remain [1]. It was constructed in several periods. From the 12th century the oldest parts are still standing represented by some houses and a defence tower. The part of the wall following the sea line, called “the sea wall” was built before the rest, called “the land wall”. The knowledge about the years of construction is relatively vague. The land wall was constructed in two major periods. The first period took place somewhere between 1250 and 1288 when the first known battle took place [2]. The wall was then approx. 6 meters high with crenellations on the higher part facing the outside and an included rampart walk on the inside of the wall built on arches (see figure 1). During the second

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building period the land wall was built higher, with 2-3 meters and the wall towers were added. This period took place sometime between 1289 and 1361. As the Danish king Valdemar Atterdag conquered Visby in 1361 it was complete. In this battle a part of the wall was torn down and later reconstructed. Since then smaller parts of the wall have collapsed and been reconstructed many times. The years of collapses are only exceptionally documented such as 1361, 1525, 1679, 19th century, 1961 [3] and 2012, but the collapses are in many cases easily recognized in the masonry. Several collapses was probably triggered by the wall towers as their construction had a load distribution concentrated to the one wall leaf facing the outside.



Figure 1. Visby City Wall seen from outside and inside. The smaller wall towers are riding on top of the wall. In many places one can see old collapses as well as different kinds of reinforcing structures.

Until 18th century it was considered being a functioning defence wall but in 1805 the city wall and the medieval church ruins of Visby was protected as ancient monuments. Several restorations have taken place since then but there is a serial of lacking finances following the modern history of the wall. The restorations of the 19th century sought to reinforce the wall. Iron rods were placed to reinforce two wall towers, the top of the wall was partly covered with concrete and retaining walls were built on several places to support the wall. The restorations of the 20th century mainly focused on repointing the wall. It was mainly done with cement mortar in the 1930-1970's, according to the philosophy and technique of the time [4, 5]. Also some reinforcement with concrete [3] and iron ties were made as some parts of the wall was found close to collapse.

The collapse of 2012 has meant a unique possibility for researchers to document the two building phases of the land wall, to study the performance of the structure and its materials, as well as the effect of modern restorations. This paper describes the materials and the construction of the wall along with an analysis of the complex situation that finally led to the collapse. The building phases have been documented and analysed by building archaeologists and will be presented in a separate paper. As the National Heritage Board decided to rebuild the wall it had to be dismantled in order to be reconstructed. The dismantling of the medieval masonry gave a unique opportunity to study the construction of the masonry and the performance of its material.

2 METHODS

In order to describe and analyse the construction of the wall a combination of archive studies and visual inspection on site of the wall in general and specifically at the location of the collapse where parts of the wall have been deconstructed in order to make it possible to reconstruct it.

The part of the wall closest to the collapse was documented with laser scanning which is a powerful tool to examine and describe the 3D geometry of the wall and the collapsed parts [6]. The laser scan was used to extract sections through the wall, to develop the geometry of supporting structures with exact fit as well as providing a 3D model of the collapsed part of the wall.

Thin section specimens were prepared from the historic mortars. An UV-fluorescent epoxy was used in vacuum impregnation of the samples before they were polished down to a thickness of ca 3

µm and studied with an Olympus BH-2 Polarization Microscope. The magnification of the pictures shown here is 20 times.

The mortars of the wall were also studied in situ together with masons in order describe their performance in adhesion to the limestone.

3 MATERIAL AND CONSTRUCTION

3.1. Construction

The land wall is about 8 to 10 meters high, about 2 meters wide at the base and about 0.7 meters wide at the coping. Basically it is a three-leaf wall with a rubble core but since it was built in at least two different stages it has a more complicated structure.

Although no current investigation of its foundation has been carried out, different sources points toward there being varying foundations [2, 3]. On many places it probably stands directly on bedrock but in some places it stands on soil and old sea bed. Earlier investigations have also shown that some parts have a 20 cm thick layer of soil mixed with limestone chips [3]. At the location of the collapse the foundation of the wall seem to change from standing directly on bedrock to soil. A complementary geotechnical investigation needs to be carried out to verify the condition of the foundation. Another prerequisite at the site of the collapse is that there is about two meters higher ground level on the inside of the wall.

The original land wall was about 6 meters high and had parapet with crenellation, a rampart walk on top of an arcade on the inside. The contour of that wall can still be seen within the stonework of the current wall [7]. The wall has a thin outer leaf of bonded masonry, about 25-50 cm thick, and the arcade of pointed masonry arches, approximately 70 cm thick, on the inside and in between a loose rubble core of stones varying in size and clay mortar. There does not seem to be any through stones and stones that bind the outer leaf into the core seem to be limited. The outer leaf and the arcade were built with lime mortar. The parapet wall was built as a homogeneous wall about 75 cm thick. Since the thickness of the parapet wall is wider than the outer leaf of the lower part of the wall it has to partly stand on the core and partly on the outer leaf masonry.

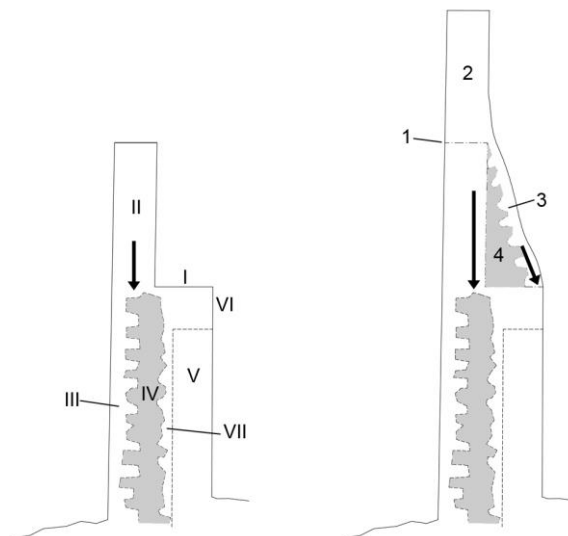


Figure 2. Simplified sections of the land wall. The section to the left show the land wall before it was heightened and the section to the right shows it after the heightening and how it is today. The arrows show the eccentric loading of the outer leaf and the thrusting force from the bottle neck shape. 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 bottle neck shaped masonry. 4) Upper core inside former parapet wall.

When the wall was raised with 2-3 meters, the parapet wall was used as an outer leaf and on the rampart walk a bottle neck shaped addition was built with an inner leaf and an upwards narrowing core of smaller stones and lime mortar pressed against the parapet wall. Since the parapet wall was reused as an outer leaf, no binding stones or through stones exists between the two leaves in this area. The upper part above the former parapet wall was built homogeneous solid wall.



Figure 3. Two photos showing the same part of the wall at two different stages during 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 middle part of the wall. 4) Upper core inside parapet wall. 5) Top with solid masonry.

3.2. Limestone

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

3.3. Mortar

The historic mortar present in the city wall is mainly of three different characters and they are correlating 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 fat pure air lime mortar (a). It is a white, very lime rich and rather homogeneous mortar that was used for adhesion between the limestones. It is found up until the top of the former parapet. In the core under the pathway of the older part of the wall, a clay soil (b) was used as bedding mortar. It can be described as a brown clay soil with a natural content of sand particles; once and then a small lime lump can be found. The clay mortar is, as expected, powdering when dry and stabile 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 lime mortar (c) was used in the core as well as in the two leaves. It was not as rich on lime as the mortar from the first building phase. This mortar has the

colour of sand rather than of the white lime, it was slightly less homogeneous than mortar (a). Both lime mortars had very good adhesion to the limestone, but the mortar (c) from 14th century showed slightly more stickiness than the mortar (a) from the 13th century, despite the lower lime content.



Figure 4. The fat lime mortar (a) is white and rather homogeneous. Lots of smaller lime lumps exist. It has a good adhesion to the limestone. The clay mortar (b) of the wall core is in good condition, powdering when dry and stable when wet. It has filled up the stone core very well. The type of mortar used in the second building phase (c) has a very good adhesion to the lime stone and is in general extremely well preserved despite its exposed position.

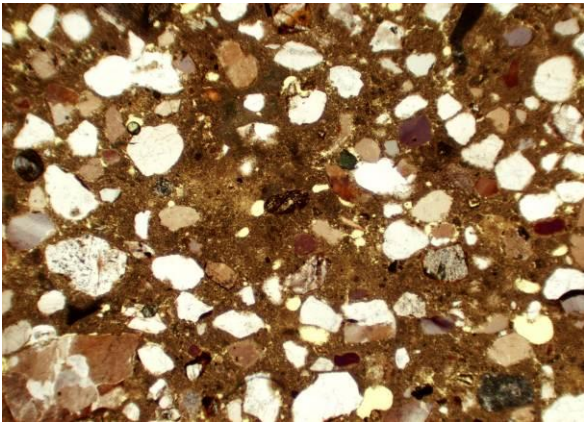


Figure 5. The first picture is showing the concrete cover on top of the wall, and directly beneath it is the type (c) mortar. Here this mortar was more deteriorated and more wet in approx. half a meter from the concrete layer than it was in general – not surprising for a 700 year old lime mortar situated on top of a wall. The second picture is showing the cement mortar covering the old lime mortar, showing the area of lime mortar just behind the cement as deteriorated in a thickness of approx. 5 cm.

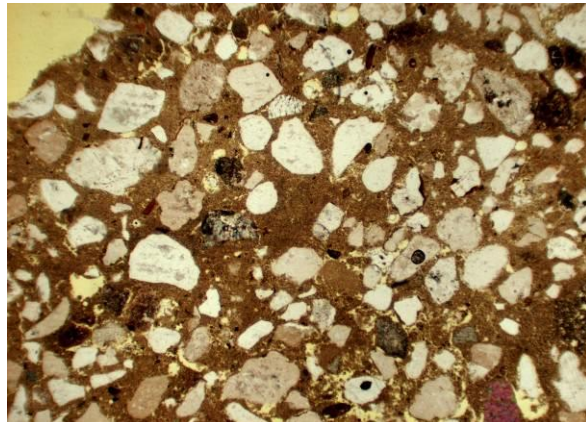
All three kinds of mortar have been used in thick layers, filling up the void between the irregular stones, giving large quantities of mortar. The lime mortar is well hardened in the whole structure, even though they don't contain any hydraulic components.

During 20th century restorations a large amount of the joints was repointed with a strong cement mortar to a depth up to 10 cm at the most. Also the top of the wall was covered with a cement layer of

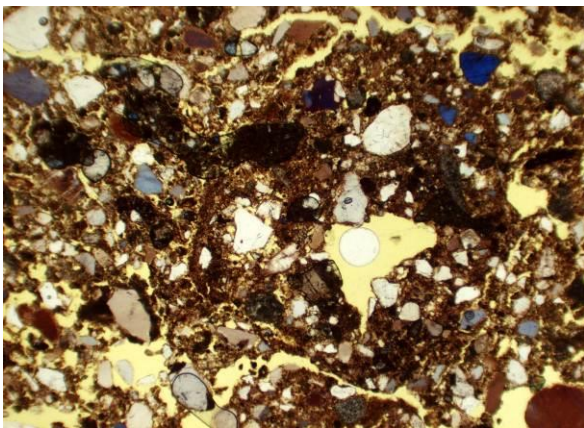
approx. 10 cm to protect water from intruding the wall. The deterioration of lime mortar can mainly be seen just beneath the top layer of the wall or lower down behind joints of cement.



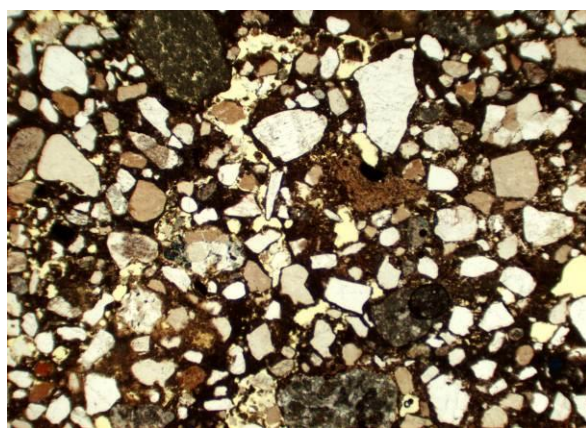
a1: Lime mortar from beneath the crenellations.



a2: Lime mortar from outside masonry leaf, in level with pathway.



b: Clay mortar from the lower wall core.



c: Lime mortar from the upper compact wall, above crenellations.

Figure 6. The samples a1 and a2 represent the type of fat lime mortars 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. It is a very fat lime mortar where the amount of lime is higher than the amount of sand, approx. 1.5:1 in volume [10, 11]. The sample (b) represents the clay mortar used in the wall core beneath the rampart walk. It is a clay soil containing sand giving a rather fat clay mortar. The sample c represent the type of lime mortar used in the second building phase, the mixing ratio is approx. 1:1.5 of lime and fine grained sand. The yellow colour shows the pore system, the brown colour shows the binder and the other particles show minerals from the sand. The width of each thin section is equivalent to 4.5 mm of the sample.

4 RESULTS AND DISCUSSION

4.1. Structural behaviour

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 into the core. The arcade on the inside initially carries its own load and the load of the rampart walk, and it provides an inner support for the core. The former parapet wall (now outer leaf of the upper middle part of the wall) is thicker than the lower leaf and is therefore standing both on the core and the outer leaf. Since the lower core is weak deform 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.

With the heightening of the wall 2-4 meters masonry was put on the former parapet and an inner leaning leaf wall was added on top of the former rampart wall. Since the parapet wall was used as an outer leaf in the raising of the wall there are no binding stones at all in this part. The raising of the wall led to more load needed to be carried by the thin outer leaf of the lower older part of the wall.

The repointing of the wall in parts with a stiff modern cement mortar might have affected the loading situation further by providing a stiffer loading path at the outer part of the wall that might concentrate 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 levels of stress in many places of the wall. Even though it has in many parts been standing at least 750 years its condition implies that the margin for further loading is limited.

4.2. Deterioration due to moisture

With moisture present in a masonry several deterioration processes can occur; frost damage, leaching 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. [4].

The water itself can lead to frost damages as the ice crystals grow inside a porous material [10, 12, 13]. Due to the pore system in the mortar the water can be transported inside the wall in various ranges. If the mortar consists of a collapsed pore system [12] the frost damages can be of a severe nature giving material loss as the ice crystals expand. If the mortar consists of a few numbers of air pores and thin capillary pores the mortar can resist frost much better giving air captured inside as a buffer zone for the ice crystals to grow [10, 12, 13]. The lime mortars of Visby city wall originally were made very fat with a high content of lime compared to sand (2:1 to 1:1 in volume (lime: sand)) [4]. They are made extremely compact giving a very good frost resistance and a low capillary transport. Due to their 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 on the parts that were never repointed.

The lime binder can be described as a soluble salt with a very low solubility; 0,014 g/l at a critical RH of ~100 % [14]. It means that if lime mortar is saturated with moisture for a very long time the lime will slowly be solved [15] followed by a lost binding effect in the mortar. If there are also a presence of some salts giving a lower pH the solubility increases as acid-base reactions solve the lime. This is a common phenomenon in old masonry constructions and can be recognized as stalactites and flow stone as precipitations on the stone masonry. As the cement mortars used for repointing during the 20th century have lower vapour permeability than the original lime mortar [10], the moisture can stay longer inside the joints now than before [16]. On the city wall of Visby the phenomenon with lime precipitations can be seen only where the joints has been repointed with cement mortar.

Porous materials such as limestone, cement mortars and lime mortars all have different properties when it comes to swelling and shrinkage due to temperature and moisture [17]. The thermal expansion coefficient of cement mortar can be two to three times higher than for limestone, and two times higher than for lime mortar [17, 18], at normal temperatures. The effect often seen at old masonry repointed with cement mortars is stiff cement mortars with cracks between the stone and mortar, giving no or low adhesion. As those cracks are thin they lead water inside by capillary transport. Having a moist environment and a soluble lime the life condition is excellent for the small crustacean “woodlouse” as well as for several plants. The woodlouse need the moisture as they breathe through gills, they need the lime to build their shells and they feed on decaying plants and leaves [19], producing humus. They live well in symbiosis with several plants and a small seed can easily grow in the moist environment behind the cement mortar. As the roots grow bigger they can cause damage far inside the wall and are almost impossible to remove, see figure 7. On the parts of the city wall where the joints still consists of original lime mortar no plants growing from inside the wall can be found [4].



Figure 7. a) A small plant with a large root system reaching far inside the city wall. It has been able to grow first after the joints were repointed with cement mortar. b) Woodlice found in the moist environment behind cement mortar.

All together the cement mortars placed outside the joint of the city wall can lead to an increased deterioration and the longer time they remain the more it will increase, since each one of those described phenomenon increases the risk of the other.

4.3. A theory of collapse

The collapse in 2012 resulted in the falling down of approximately 90 m² of the outer masonry leaf, see figure 6. The upper part of the wall consisting of solid masonry did not fall down and remained as an arch above the damaged part.

The cause of damage is complicated and consists of several components:

- The construction of the wall in different stages and without through stones and in parts few or no binding stones at all.
- The levels of stress in the outer masonry leaf as described in structural analysis given above.
- The foundation changes from being direct on the bedrock to being on soil.
- Different ground levels at the location of the collapse. The ground level is approximately 2 meters higher on the inside of the wall.
- The weakening of the lime mortar in the masonry within the wall due to repointing with low permeable cement mortar since a higher content of moisture is leading to deterioration.
- High levels of moisture within the wall due to the ground level and drainage from the inside (made in 2011) leading local leakage of 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 contained water. The load situation gave high stress in the outer leaf. In combination with a structure lacking through stones and insufficient binding stones and a weak adhesion in the bedding lime mortar in the lower part of the wall, it lead to a domino effect causing the extent of the collapse.



Figure 8. Visby City Wall in 26th of February 2012, a couple of days after the collapse.



Figure 9. The area where the collapse probably started is a part of the wall where the masonry leaf was no thicker than a foot length, see the marked area. No binding stones were used in this part.

5 CONCLUSIONS

The construction and the materials used in the wall have been analysed providing an understanding for the load situation and the deterioration process. The analyse of the wall has shown a complex situation with a combination of risks causing the collapse; the load situation coming from two building phases, the lacking of through stones, the deterioration of bedding mortars combined with strong and low permeable pointing mortar and the frost risk due to an increased moisture exposure from leaching water. With the load situation as in the city wall of Visby, with the load carried in the outer part of the outer leaf, the security margins probably are low in many places. If the stress situations change, a collapse can be expected. If the bedding mortar loses some of its binding effect it increases the risk of shear failure, and as the outer masonry leaf is very thin there is a risk of buckling of the leaf. The

restoration of the 20th century with low permeable and strong pointing mortar can have a negative effect as the moisture content increases behind in the same time as the surface of the masonry leaf becomes stiffer. Even though this deterioration process is slow it needs to end before a new collapse take place.

For the rest of the wall there is a great need for further understanding the deterioration process and the weakness in structure. There is also a need for constant maintenance in order to remove plants and threes and diminish the conditions for plants to grow and in 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 joint are left on the wall the increase of deterioration will be a fact.

6 ACKNOWLEDGEMENT

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 på Gotland for a well performed job deconstruction the wall. Thanks to Tyréns for performing geo radar and to St Gobain for performing thin sections for analysis.

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