The medieval castle Spøttrup. Stabilization of the south wing

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ABSTRACT: The Spøttrup Castle was built in the early 1500 years as a rampart. The south wing was changed in a radical way in 1579, where a row of columns in the middle of the banqueting hall were removed. But the alteration caused increasing horizontal forces from the vault on the walls, which probably resulted in cracks in the vault and deformations of the walls. The Danish Government took possession of the castle in 1937 and a badly needed restoration could be started. One of the purposes with the restoration was to remove interior walls in the banqueting hall and then re-create the great hall. But now the problems with the forces from the vault started again.

1 INTRODUCTION

The medieval castle Spøttrup is situated in the northern part of Denmark, in a little peninsula, Salling, near to the inlet Limfjorden in Jutland (fig. 1).

The castle is built in the beginning of the 1500 years by one of the bishops from Viborg.

It is one of the most impressive, strongly fortified medieval castles in Denmark.

The group of buildings consist of 3 wings, the south, east and north wing; towards the west the complex was closed by a tower and the west wall.

Round the castle there are 2 moats separated by a big rampart. The castle and ramparts were constructed as a fortification in the turbulent times in Denmark with civil war and with religious disagreements culminating with the reformation in 1536.

The south wing was the oldest part of the buildings.

The castle was in the close of the 1800 years in a state of serious decay and the moats were filled up with earth (fig. 2).

In that time the buildings were privately owned, and the owner was unable to finance a restoration.

In the beginning of the 1900 years the public opinion called for an intervention from the Government to take over the castle, which was done in 1937, and the restoration of the unique edifice could begin.

The main idea for the restoration was to re-create the great, banqueting hall in the second floor in the south wing as it was in 1579 by removing added interior walls, which divided the hall into several small rooms, and to re-establish the rampart around the castle.

The work was carried out in the years 1937–1941.

Architect Mogens Clemmensen was in charge of the restoration.
Some years after the restoration, it was obvious, that something was wrong in the south wing, illustrated by the following examples.

2 THE SYMPTOMS

In the loft we could in 1984 note, that the chimney pot from 1970 had got a settlement of about 20 mm, see figure 3. The chimney was standing right on the vault above the banqueting hall. The chimney increased the local load on the vault considerably.

In the floor above the banqueting hall we could register, that the skirting board on the south wall had moved outwards from the skirting board on the adjacent wall, see figure 4.

In the tile floor in the banqueting hall we could find cracks in the longitudinal direction near the south wall, see figure 5.

It was evident, that the south wall was moving outwards, and we could register a lot of cracks in the crown of the vault and between the south wall and the vault webs above the windows, see figures 6 and 7.

As a consequence of the last-mentioned cracks the earth filling between the vault and the wooden floor did fall through the cracks.

Figure 3. The settlement in the chimney in the loft room.

Figure 4. The skirting board in the floor above the banqueting hall is moving outwards. The south wall is to the left.

Figure 5. Cracks in the tile floor in the banqueting hall. The south wall is to the left.

Figure 6. Cracks in the web vault above a window in the south wall.

Figure 7. Longitudinal cracks in the underneath of the vault.
Every year in April when the season should begin again, it was necessary to remove a lot of earth from the tile floor in the banqueting hall.

As the south wall was in the process of leaning outwards the roof tiles near the top of the wall were lifted, which was easy to see from the gables of the south wing.

3 HISTORIC RETROSPECT

Henrik Below, a German nobleman, became in 1579 the owner of the castle.

From the beginning the banqueting hall was build with columns in the middle. But Henrik Below wanted an imposing great hall, and he therefore made a radical alteration of the south wing by removing the columns from the middle of the banqueting hall.

But he made the new vault too flat, see figure 8, so that the horizontal forces increased very much.

We don’t know what happened in the years after the alteration in the south wing, but a lot of symptoms may have arisen, symptoms like the above mentioned.

Henrik Below may perhaps have installed interior longitudinal walls as a replacement for the missing columns?

4 THE MEASURING IN THE SOUTH WING

The measuring included measurements of the geometry of the walls and the vault.

Besides registration of the deformations of the south wall. The preliminary studies included the foundation and the roof structure too.

4.1 The south wall

The south wall was 1.65 m thick. It was constructed with two outer skins of bricks, 150 mm thick, and rubble, field stones and mortar fill between the skins.

The exterior of the top of the south wall was leaning about 200–300 mm outwards in proportion to the position on the ground, while the inner skin had a reduced deformation, because the roof structure did support this part of the wall. As a logical consequence of this we could find a very big longitudinal crack in the top of the wall.

The big wall was going to split.

The north wall was only about 1 m thick and had fewer deformations. But the total free length for the north wall was only 16 m as the wall here was supported by the other wings and the staircase building, while the free length for the south wall was about 29 m, see figure 9.

In figure 2 we can see 3 pilasters, or so-called secrets. They have no structural meaning; their function was to be toilets.

4.2 The vault

The vault was a barrel vault with likeness to the cross vault, as minor vaults were placed above the windows. The vault consisted of bricks plastered on the underneath and it was 300 mm thick.

The height of the vault was 1.50 m and the span was about 7 m. The length of the bay was approximately 4.5 m.

The wooden floor was in a level of 0.30 m above the top of the vault. The space between the vault and the wooden floor was filled with earth.

4.3 The roof structure

The roof structure seemed to be practically without damage, except for a little rot in some rafters. But the roof did apparently not exert any pressure on the wall; if anything it supported the inner skin, see 4.1.

4.4 The foundations

The foundation was made by granite boulder into a depth of 2.5 m below the water in the moat, where the ground was sound.

None of the cracks in the castle indicated, that anything should be wrong with the foundations.
The south wing

Figure 9. The south wing with the anchors and beams.

5 THE ANALYSIS

The development in the cracks in the vault and the walls was followed during more than a year.

The crack width did vary during the year for mostly of the cracks due to temperature and humidity condition.

After a year it could be seen, that many of the cracks after all were increased 0.1–0.2 mm.

This alone was not disturbing, but the knowledge that the wall in the top was splitting, was more worrying. We did not know the extent of the cracks in vertical direction.

The geometric measurement made it possible to calculate the loads from the vault, the fill and from the chimney, and subsequently make thrust lines to determine the forces on the walls.

5.1 The results

Even with the background that the wall was intact, the calculations demonstrated that the south wing was in a dangerous situation due to the load from the chimney.

The bays without chimney were exposed for a horizontal load of 164 kN including the load from the vault, the fill, the floor and the walls in the upper storey.

The vertical load from the chimney could be distributed on two bays.

The maximum horizontal load for a bay became then 249 kN acting about 4.5 m above the base of the wall. (The loads in characteristic values).

This was too much for the wall.

It was impossible to construct a thrust line from the top of the wall to the base within the cross section in a satisfactory way.

We therefore suggested providing the south wing with transverse anchors.

Why didn't the south wing collapse, when it was impossible to find a safe thrust line within the cross section?

First at all the structure is sound if it is possible to find a safe equilibrium for that structure. But the opposite argument isn't necessarily correct.

Next the plastic theory for masonry makes no use of the tensile strength.

There is no doubt, that the deformation of the bays with the chimney will produce horizontal tension and bending in the south wall and in that way involve the adjacent bays in the equilibrium.

We don't want to use the material property tension, when we examine the load capacity for a masonry structure, but it can be the answer, that an apparently unstable structure doesn't collapse.

The structure with the splitting of the wall was to compare with a zipper, which was in the process of being ripped open.

5.2 The intervention

It was very important, that the anchors were invisible from the banqueting hall; therefore they were placed in the cavity between the wooden floor and the vault.

As the wooden floor should be dismounted, the heavy fill could be removed in the same opportunity.

Fortunately there was enough space between the vault and the floor to place the anchors in the cavity.

The optimal place for an anchor is to be placed in the same level as the base for the thrust line, which isn't necessarily at the base for the vault, but as usual a little higher.

It is possible to use an anchor in a level above the base of the thrust line, if there are enough vertical loads
from the roof and especially from the wall above the anchor.

In Spottrup this was not a problem.

In the ultimate collapse situation, the upper part of the wall will be lifted. Consequently a heavy upper part can prevent collapse, see the model in figure 11.

As a matter of fact the anchors were converted to beams in the two bays with the chimney, see figure 9 and 10.

The beams were able to distribute the concentrated load to act more uniform on the vault.

The anchors were fixed primarily of a steel plate placed just behind the outer skin.

5.3 How to determine the force in the anchors?

The structure with the south and north walls connected with the roof structure and the anchor is 2 times statically indeterminate, which means that it’s possible to choose two parameters in the statically analysis.

The two chosen parameters could be the horizontal forces in the steel anchor and in the roof support.

But a more convenient way is to choose two points, which the thrust line has to pass through, for instance point B and C in the north wall, see figure 11.

Then it is possible to use the equilibrium equations for the 3 parts I, II and III, after which the forces in the anchor and the horizontal support from the roof easily can be found.

If the first calculations are not satisfactory, new chooses has to be made until a safe thrust line can be found.

As the north wall is thinner than the south wall, the calculations are made primarily for that wall. Subsequent the south wall can be investigated.

5.4 How to determine the vertical stabilizing load?

If a collapse is starting, some parts of the walls above the horizontal forces will be lifted as mentioned above.

It is difficult to determine the extension of the area, which can be included in the stabilizing load.

For want of a better method at that time (1988) we used the area, which was defined from 2 lines with an inclination of 30 degrees above the vault spring.

This method was presumably very safe, but it was nevertheless possible to find satisfactory thrust lines in the walls for all the bays by using that stabilizing area.

5.5 Investigation of the state of stress behind the anchor plate

The state of stress behind the anchor plate is a complicated spatial state of stress.

First we have to investigate if punching could be risky.

Though the fill in the walls was irregular, the mortar ensured a good cohesion between the rubble and the anchor.
field stones, so it was obvious that punching could not appear in walls with these thicknesses and with such a big vertical load.

The state of stress behind the anchor plate can be investigated as a state of hydrostatic pressure, which is illustrated in figure 12, where the spatial state of stress is simplified as a plane state of stress in point B.

The following conditions are necessary for the state of hydrostatic pressure:

\[ k = \frac{m \cdot \sin(v)}{\sin(u + v)} \]  
\[ l = \frac{m \cdot \sin(u)}{\sin(u + v)} \]  

Where \( m \) is the height of the anchor plate, \( k \) and \( l \) the extension of the pressure zones and \( u \) and \( v \) the angles between a horizontal line and the direction for the pressures.

The extension of the pressure zones can subsequent be calculated:

\[ m = \frac{S}{\sigma d} \]  

Where \( \sigma \) is the compressive strength for the new bricks in the conical hole and \( d \) is the depth of the anchor plate. \( S \) is the force from the anchor.

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**Figure 11.** A theoretical failure pattern to the left and practical thrust lines to the right.

**Figure 12.** Hydrostatic pressure in point B.

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6 AFTER THE INTERVENTION

The originally plan was to built in anchors or beams in all 6 bays of the south wing.

But as a start only 4 bays were reinforced.
The measuring of the cracks continued a time after the intervention.
The result was satisfying, as none of the cracks seemed to be active any longer.
In figure 13 we can see, that a visible anchor in the banqueting hall would have destroyed the room seriously.

7 CONCLUSION

As mentioned above a main idea for the restoration was to remove the interior walls in the great, banqueting hall, so the south wing could rise again, as it was in 1579.

But exactly that noble action was the main reason that the vault now could continue to press the walls outwards, which led to new cracks and settlements of the vault.
To re-create an earlier design can be to re-create an unstable structure.

REFERENCE

Figure 8 is made by architect Erik Einar Holm M.A.A 1983.