The Nidaros Cathedral in Trondheim. The Norwegian National Symbol.
Stabilization of the Choir

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ABSTRACT: The Nidaros Dome had its great period in the Middle Age, when the cathedral stood in all its
glory as a gothic cathedral in English style. A fatal fire in 1531 destroyed the cathedral, and it was only rebuild
in a frugal way. But in 1869 the great restoration began, and the Norwegians could soon again be proud of
their national symbol. Unfortunately the choir was reconstructed too weak and cracks and deformations were the
results. An intervention was made in 1986, but the cracks apparently continued. In 1999 a panel in Trondheim was
arranged with the staff from NDR (Nidaros Domens Restaureringsarbejder) and 4 foreign structural engineers.
They should contribute to an assessment of the stability similar to what happened in Milan 600 years earlier.

1 HISTORY

King Olav Haraldsson was killed in 1030 in the Battle
of Sticklestad, which is situated c. 100 km north of
Trondheim.

His body was brought to Trondheim, where he was
buried. King Olav was canonised in 1031.

A wooden chapel was built above his grave, but
it was replaced by a large stone church in early
Romanesque style in the end of the 11th century,

From c. 1150 transepts were added to the north and
south sides, but in the period from 1180 to 1320
the Romanesque church was changed to a gothic
cathedral.

Several fires have ravaged the cathedral, but the
ultimate fire was in 1531, when the church and the
entire town did burn. The cathedral was in ruins.
The church was only restored in a poor way, the vault
in the chancel was replaced by a flat roof and the nave
was totally destroyed. The recovery to really greatness
belonged to the future.

The cathedral has an important meaning to the Nor­
wegians. According to the constitution the kings have
to be blessed here and the crown jewels are kept here.

The restoration of the cathedral took place in a
period of growing Norwegian nationalism and in that
way the church is not only a religious symbol but also
a symbol to the Norwegian state:

"When the Nidaros Dome lies in ruins, Norway is
hit by poverty, but if the cathedral stands in all its glory,
prosperity will apply to Norway".

Figure 1. The Nidaros Dome from the south west.

The cathedral is Europe's northernmost medieval
cathedral.

2 THE RESTORATION

The architects H. E. Schirmer (1869–1871) and later
Eilert C. B. Christie (1872–1906) did manage the
restoration works. Schirmer did work with the Chapter House, Christie with the Octagon, chancel, transepts and central tower.

It may have been difficult to rebuild a gothic cathedral c. 600 years after the end of the gothic period in Europe. Christie did a very careful restoration work, and he used the old traces in the walls from the medieval cathedral to reconstruct the vault.

But he had no traces to follow, when he constructed the buttressing system, Bjorlykke 2004.

The aisle walls, especially in the south side, were leaning 400 mm outwards, Ekroll & Storemyr (1998). The old heavy vaults had made their influence on the walls. Therefore an important step for Christie was to right the aisle walls to be plumb, which he did in a risky and successful intervention.

But though the new vaults were made much lighter than the old vaults, the buttressing system was constructed too weak to resist the forces from the vault.

The stability of the choir in Nidaros Cathedral therefore has been a matter of interest since the reconstruction.

Cracks in the vaults, the flying buttresses and the piers have been developed for several years. The aisle walls seemed again to lean outwards.

In 1935 a small marble column (without structural importance) did fall down, maybe due to the horizontal deformations of the walls, and it was close to hit some people.

The cracks in the Kings Porch on the south side of the choir were found to be worrying.

In 1951 a repair programme for the porch began, but the cracks apparently continued the subsequent years.

3 THE INTERVENTION IN 1986

For several years the cracks and the deformations were ascribed to bad foundations.

But in 1986 a Norwegian engineering firm, Reinertsen was hired to make investigations of the possibilities to improve the stability in relation to the horizontal forces from the vault.

They made several suggestions, among others to place steel trusses in the loft room above the vault, which became the preferred solution, see figure 3 (Reinertsen 1986).

It was important to avoid visible anchors through the choir.

The steel trusses were tensioned to about 20 kN. After the intervention the monitoring was nearly brought to an end, but it was obvious, that the cracks continued to grow.

Especially a big crack in the vault in the south eastern corner seemed to be serious, because the crack was quite through the vault and could be seen both from the choir and from the loft. It seemed to separate the corner. In addition the south eastern corner of the choir was leaning outwards in a diagonal direction.

In 1999 and 2000 the Norwegians arranged two seminars with participants from NDR and 4 foreign engineers, Jacques Heyman (England), Eberhard Stiwe (Germany), Krista Bergrren (Sweden) and Tonny Jespersen (Denmark). The stability of the choir was the main topic for the seminar.

The conclusion from the seminars was a recommendation to make new analyses of the stability of the choir, not only for the weight from the vault itself, but also from the forces from the wind.

Figure 2. The choir seen from west.

Figure 3. The steel trusses from 1986.
In addition the panel suggested an intervention to stabilize the eastern corners. The present writer was asked to perform the task. It was recommended too to continue the monitoring of the cracks and deformations.

4 MEDIEVAL RULES

Was the cathedral constructed in a way much different from other medieval cathedrals in Europe, since cracks and deformations apparently indicated a lack in the stability?

As mentioned in Heyman (1995) the medieval master builders used geometrical rules to design a cathedral. It could be interesting to use the rules “Ad quadratum” and “Ad triangulum” to The Nidaros Dome, see figure 5.

We can see that the top of the vault easily can be placed within a square with a base like the width of the choir, but the vault will rise above the top of the equilateral triangle with the same base.

According to these observations we can not conclude, that the Nidaros Dome is very different from many other medieval cathedrals.

It is of course impossible to conclude whether the choir is stable or not in the light of the geometric rules, but we can see, that questions and disagreements could arise, if the geometric rules were the only tools to analyse the stability.

5 THE MEASURING

Before the analysis could be done measuring of 4 cross sections in the choir and aisles were carried out.

This measuring gave important information’s about the geometry and the deformations of the arcade and aisle walls. From the measuring it appeared, that the pressure from the vault once more had caused horizontal deformations of the aisle walls, however in a smaller extent than before the restoration.

It is not known whether the displacements had increased after the intervention in 1986.

The top of the arcade walls however had only small displacement. The reason may be, that the roof structure supported the arcade walls in a horizontal direction, see below.

5.1 The roof

The roof construction consists of trusses made of steel. The pitch is about 58°, the roofing is copper.

The drawings from the restoration show, that the roof structure originally was planned and carried out to have a sliding support in the south side, probably with consideration for movements from changes in temperature.

But fortunately the sliding support has not worked in that way!

In the first place the roof structure would be unable to support the walls and prevent deformations from the pressure from the vault, if it had worked with a sliding support in one side, in the second place the horizontal forces from the wind on the roof could only be resisted in the side with a fixed support, i.e. the north side, and when this side was the shell side, all the load from wind and from the vault would work in the same direction.

There is no horizontal latticework in the loft room above the vault in the choir, so all the horizontal loads from wind from the south together with the pressure from the vault should in that way be resisted from the arcade walls and the aisle walls in the north side.
It is not probable, that the aisle walls would have been able to resist that load.

In the situation without sliding support, the greater part of the wind load will be transmitted to the windward side, which is much better for the traverse stability of the choir.

5.2 The vault

The vault is a pointed groined vault with a rectangular bay. The web consists of bricks with a thickness of 120 mm, plastered on both sides, the groins of a thickness of 350 mm. There are 6 bays in the choir; the length of the bays is c. 4.3 m. The width of the choir is varying from c. 10.4 m to 11.4 m. The reason to the lopsidedness is unknown.

The passive thrust line is used to determine the horizontal forces from the vault, which amounts to 68 kN per bay. The active force amounts to about 79 kN.

The corresponding vertical load from the vault is 153 kN.

5.3 The arcade wall

The arcade wall in the loft room is about 1300 mm thick and consists of bricks except for the facing wall, which are made of soapstone.

In the choir the arcade pillars consist of solid sandstone and the arcade wall consist of soapstone.

While the aisle walls are leaning outwards, the arcade pillars stay in a practically vertical line.

In the top of the arcade walls leaks from the parapet have caused severe frost damage in the brickwork, which just now is going to be repaired.

5.4 The flying buttresses

As mentioned above the buttressing system was constructed too weak.

The horizontal support from the flying buttresses is varying between 7 kN (the passive state of the thrust line) and 32 kN (the active state).

Compared with some other gothic cathedrals it seems to be very little, for instance the cathedral in Lichfield, where the corresponding support amounts to 30–1000 kN, with reference to Heyman (1995).

5.5 The pier and the aisle wall

The new measuring showed, that the aisle wall did lean more outwards than the arcade wall, which was surprising, in the light of the weakness of the flying buttress.

Monitoring during a period indicated that the distance from the arcade wall to the aisle wall in the triforium seemed to increase. Since the flying buttresses were unable to support the arcade wall in an acceptable way, it could be expected, that the arcade wall would move more outwards than the aisle wall with the result, that the distance between the arcade wall and the aisle wall instead would decrease forming cracks in the top of the vault above the aisle.

But the observation was different. The cracks in the vault above the aisles were on the underneath of the vault.

However cracks were found in the tiles in the triforium. But the reason for these cracks was the increasing distance between the aisle wall and the arcade wall, see figure 7.
5.6 The roof above the aisle

The statically calculations of the load from the vault demonstrated, that the choir was standing in a strained equilibrium, and that it was a good idea to erect the steel trusses in 1986.

But even with the help from the steel trusses tensioned to 20 kN, it was difficult to construct a thrust line with a proper way from the top of the walls to the bottom.

In addition the clerestorium passage caused splitting forces in the arcade wall.

Further investigations however revealed, very surprising, that the roof above the aisle vault was carried by steel rafters well bolted to the clerestorium wall and to the aisle wall, and it seemed to be probable, that the rafters took part in the structural system and relieved the flying buttresses, see figure 8.

The steel rafters were able to resist both pressure and tension, and they have done great usefulness in connection with both pressures from the vault and perhaps especially the forces from the wind.

Could Architect Christie have had this aspect in view?

6 THE THRUST LINE

With the help from both the steel trusses in the loft and the steel rafters in the roof above the aisle the thrust line now could be constructed in a statically acceptable way.

The analysis demonstrated, that it would be optimal to tension the trusses in the loft room from 20 kN to 50 kN.

This operation was planned to be made in two steps with 30–35 kN as the first target, which was done in 2002, and on that occasion measuring nuts were mounted on the steel trusses, so its now easy to follow the actual forces in the trusses.

The second step has not yet been realised, because the Norwegians wanted to evaluate the results from the first tensioning.

The last step can be accomplished if necessary.

7 STABILIZATION OF THE EAST CORNERS

The corners were fixed with a new transverse steel truss near the eastern gable, which should prevent movements of the corner in the north–south direction,
and two longitudinal anchors to prevent movements in the eastern direction.

The new eastern steel truss is designed for 35 kN, while the longitudinal anchors are designed for 16 kN.

The temperature in the loft room can change from $-10^\circ$C in the winter to $+20^\circ$C in the summer. This results of course in considerable movements of the anchors. With a length of 26 m from the east to the west gables, the change in dilatation and contraction will amount to 4.7 mm related to the mean temperature 5°C.

If the anchor is rigidly connected to the two gables, the strain in the anchor will change as follows:

$$\varepsilon = \alpha \times \Delta T$$  \hspace{1cm} (1)

$$\varepsilon = 12 \times 10^{-6} \times 15 = 1.8 \times 10^{-4}$$  \hspace{1cm} (2)

$$\sigma = E \times \varepsilon = 2 \times 10^5 \times 1.8 \times 10^{-4} = 36 \text{ N/mm}^2$$  \hspace{1cm} (3)

The anchor is Ø20 mm, which means, that the force will change:

$$\Delta P = \pi / 4 \times 20^2 \times 36 = 11.3 \text{ kN}.$$  \hspace{1cm} (4)

The force in the anchor will consequently vary from the designed force 16 kN to 27.3 kN in the winter and to 4.7 kN in the summer.

A change in the force of this size is an undesirable situation; we therefore build in a spring in the anchor. The spring was placed in a cylindrical box, see figure 10.

The spring box contained a spring with a spring coefficient $R_1 = 500 \text{ N/mm}$.

The anchor itself is a spring too, but a rigid one:

$$R_2 = E \times F / L = 2 \times 10^5 \times 314 / 26000$$  \hspace{1cm} (5)

where $E =$ the elasticity coefficient, $F =$ the area of the anchor and $L =$ the length of the anchor.

$$R_2 = 2415 \text{ N/mm}$$  \hspace{1cm} (6)

The combined spring coefficient is then:

$$1/R = 1/R_1 + 1/R_2$$  \hspace{1cm} (7)

$$1/R = 1 / 500 + 1 / 2415$$  \hspace{1cm} (8)

$$R = 414 \text{ N/mm}$$  \hspace{1cm} (9)

With the spring box build in, the forces in the anchor will vary only:

$$\Delta P = 4.7 \times 414 \times 10^{-3} = 1.9 \text{ kN}.$$  \hspace{1cm} (10)

See figure 11.

This value has temporarily been confirmed by measuring of the variation of the forces during one year.

The spring acts as a compression spring, which means, that the spring can be tightened if necessary.

In addition a spring in compression is safer than a spring in tension.

Actually the forces of course will change too in the transverse steel trusses substantiated to the temperature. It would have been optimal with a spring build in here too.

From a theoretical point of view the change in forces will be independent of the distance, see equations (1)–(4).

The transverse distance in the loft room is about 11.4 m, the dilatation and contraction will therefore amount to $\pm 2.1 \text{ mm}$, but a truss will always have initial deformations owing to the slips in the connections contrary to a straight anchor.

The variation of the forces for the transverse trusses have been measured to be less than $\pm 4 \text{ kN}$ during a year from the mean force of about 30–35 kN, which may be assessed as acceptable.
8 WIND ON THE CHOIR

8.1 A comparison between the choir and the nave
As mentioned in 4.6, there is no horizontal latticework in the loft room above the choir contrary to the nave.

From the Middle Age the masonry in the nave has been more powerful than in the choir, and Christie restored it in that way.

But also the roof structure was made stronger, especially with regard to the transverse stability, as the roof structure here was provided with a horizontal latticework.

The difference in structure between the choir and the nave is thought-provoking, since the load from the wind practically is the same.

The nave was restored about 40 years later than the choir. Why was the nave constructed much stronger?

There is no actual answer for that question.

8.2 The load from the wind
The choir is situated in the traditional direction east-west. The most serious influence from the wind is consequently wind from south-north.

NMI (Norwegian Meteorological Institute) has made anemometry for some years. The wind speed from the south is the most dangerous.

NMI has assessed the wind speed to 39.6 m/s in a level of 30 m above the ground corresponding to the level for the top of the roof.

The total horizontal characteristic load from the south wind on the roof is 0.98 kN/m², which is 11.5 kN/m or 49 kN per bay.

The roof in the choir has no connection to the adjacent gables, so it is impossible to imagine, that some of the load from the roof could be directly transmitted to the gables by the roof structure. The horizontal load therefore has to be resisted by the walls alone.

8.3 The reinforcement of the transverse stability
The calculations demonstrated that the choir was unable to resist the above mentioned forces with a satisfactory safety, and the author of this paper therefore suggested building in a horizontal latticework in the loft room above the vault, as in the nave.

The new horizontal latticework has been designed and will soon be realized.

The horizontal latticework is not designed to resist all the wind from the south, but it has to relieve the arcade wall, the aisle wall and the steel rafters in the roof above the aisle and in that way transmit some of the wind load to the gables in the choir.

Many cracks in the cathedral come of the pressure from the vault.

But some of them might be a result of the forces from the wind.

The new horizontal latticework will reduce the number of that kind of cracks in the future.

9 THE RESTORATION IN THE FUTURE
The Norwegians have been working with the cathedral practically since the restoration in 1869.

For the moment many soapstone in the top of the arcade wall will be replaced owing to decay from the weather.

But the Norwegians, and especially the people from Trondheim ought to be happy, that a lot of restoration work still have to be done, because the legend say: "The actual day when the restoration of the Nidaros Dome is finished, the church and the whole town will disappear in the inlet".

REFERENCES
Figure 3 is from Consulting Engineers Reinertsen in Trondheim.
Figure 6 is from (Gerhard Fischer 1942-43).
Figure 1 and 2 are from the NDR publication: "Nidaros Cathedral and the Archbishops Palace" 1995 (Editors: Øystein Ekroll. Jill Krokstad, Tove Søreide).