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Structural Analysis of the Church of Sint Lambertus in Maastricht

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ABSTRACT: The church of Sint Lambertus (Maastricht, The Netherlands) has been unoccupied since 1985 due to structural problems. Since its completion in 1916, the church has had a history of settlements and cracking. Measures have all turned out to be insufficient. To allow for a redesign of the building, a finite elements analysis has been made of the structural condition of the church. In a visualisation model the locations of the largest differential settlements were pointed out and explained. A step-by-step input of successive settlements and measures made it possible to assess the effect of each building phase on the total domed structure, and to create a reliable simulation of the current situation. Subsequently, this model was used to test different potential measures. On the basis of the results of these tests three recommendations were made to save the building for a new future use.

1 INTRODUCTION

The church of Sint Lambertus (Maastricht, The Netherlands) has been unoccupied since December 1985 because of structural problems, and is increasingly falling into decay ever since. Reuse of the building is only possible when an effective measure is found to solve these structural problems. To allow for a redesign of the building an analysis has been made of the structural condition of the church.

Figure 1 : Church of Sint Lambertus, Maastricht (Photo: KLM Aerocarta, 1924).

2 DESCRIPTION OF THE CHURCH

The church of Sint Lambertus was built between 1913 and 1916 on the former fortifications of the city of Maastricht, see Fig.1. Designed by J.H.H. van Groenendael in eclectic style, it is a rare and well-proportioned example of the neo-Romanesque-Byzantine style in The Netherlands, and it marks a turning point in the oeuvre of the architect. The ground plan of the church is a Latin cross with a large crossing, and the structure mainly consists of square domed spaces. On the crossing an octagonal ribbed vault, supported by four arches on piers, is constructed, see Fig. 2.

The exterior walls are made of Kunrader stone, a local limestone, whereas the interior walls mostly consist of marl. Due to the outbreak of the First World War during the erection, the used materials are of an inferior quality.

3 APPROACH

The analysis of the structural condition of the church consists of five parts:

1. Study of literature, analysis of the problems that have occurred and measures that have been taken in the period 1916-2004.
2. Dome mechanics and finite element modelling.
3. Analysis of the current condition of the building and description of its problematic nature.
4. Analysis of potential measures.
5. Recommendations.

3.1 Analysis of the problems and measures in the period 1916-2004

The church of Sint Lambertus has a history of settlements and cracking. Measures have all turned out to be insufficient.

Soon after its completion in 1916, crack development occurred in the vaults. Therefore, in 1931 an investigation was carried out: one of the four columns supporting the main dome was found out to be sagged. To strengthen the structure, in 1933 reinforced concrete arches were placed under the existing arches.

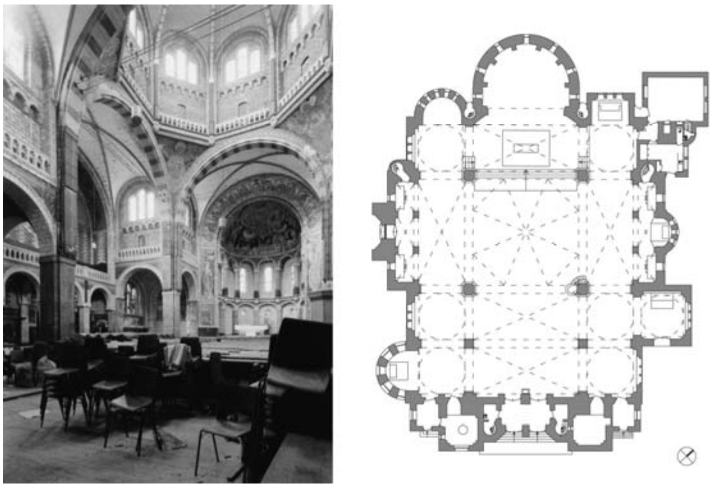

Figure 2 : Left: Interior of the church of Sint Lambertus (Photo: Aart de Bakker); Right: Ground plan of the church.

In 1976, walls and vaults appeared again to be seriously cracked. According to investigations, the following defects were diagnosed: the masonry on top of the concrete ring was cracked, which caused the partial nullification of the vault mechanism and the arches being overloaded;

the vaults had an unfavourable geometry, by which the centre of pressures was pushed in the direction of the transverse arches; the filling up with masonry was insufficient or of a poor quality which caused tension in the top of the arches. To consolidate the structure, tension rods were placed between the arches under the main dome, and five vaults were taken down and replaced by a lighter structure. After two years of restoration the church was reopened for the public in 1978.

However, in December 1985 the condition of the building deteriorated so seriously that the church had to be closed immediately, see Fig. 3. A new investigation was started, this time also including measuring; in 1988, 1990 and 2001 the level of the bed joints, differential settlements and dilatancies were measured.

To investigate the cause of the problems more precisely, in this research project a visualisation was made in which the measured settlements were projected enlarged onto the underground, see Fig. 4. This projection shows that the whole building has been subject to settlements but that the most considerable differences in settlement appear at the location of the transept. If this image is subsequently compared with a plan of the former fortifications, it becomes evident that it is precisely this transept that is built on top of a dry moat between two ramparts, see Figs. 5, 6. It can be presumed that the dry moat has probably been filled while levelling the site but that the ground had not been settled sufficiently at the time of erection.

Figure 3 : Crack pattern in one of the cupolas.

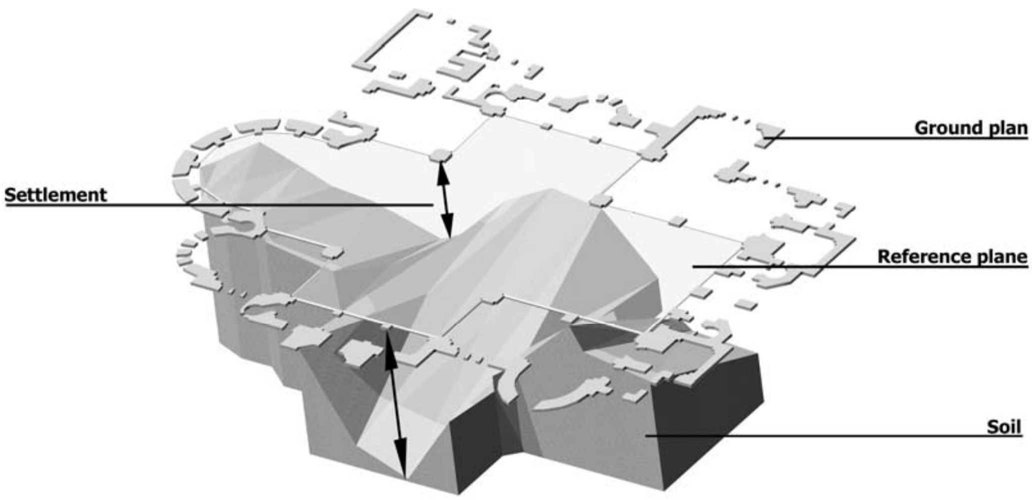

Figure 4 : Settlements visualised as subsidence of the soil under the building.

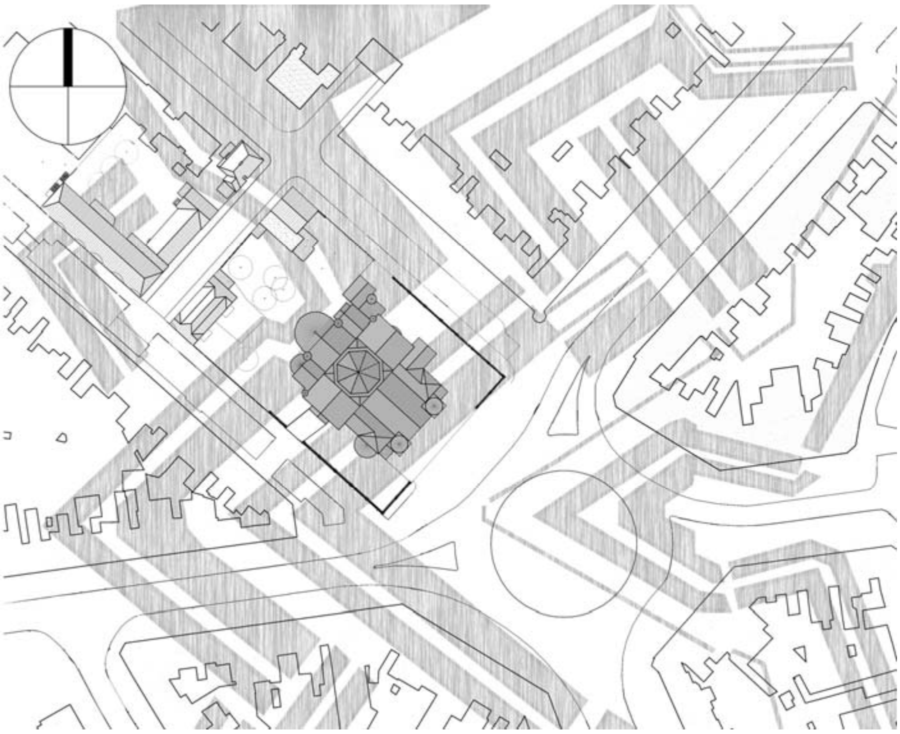

Figure 5 : Site plan with the former fortifications in grey.

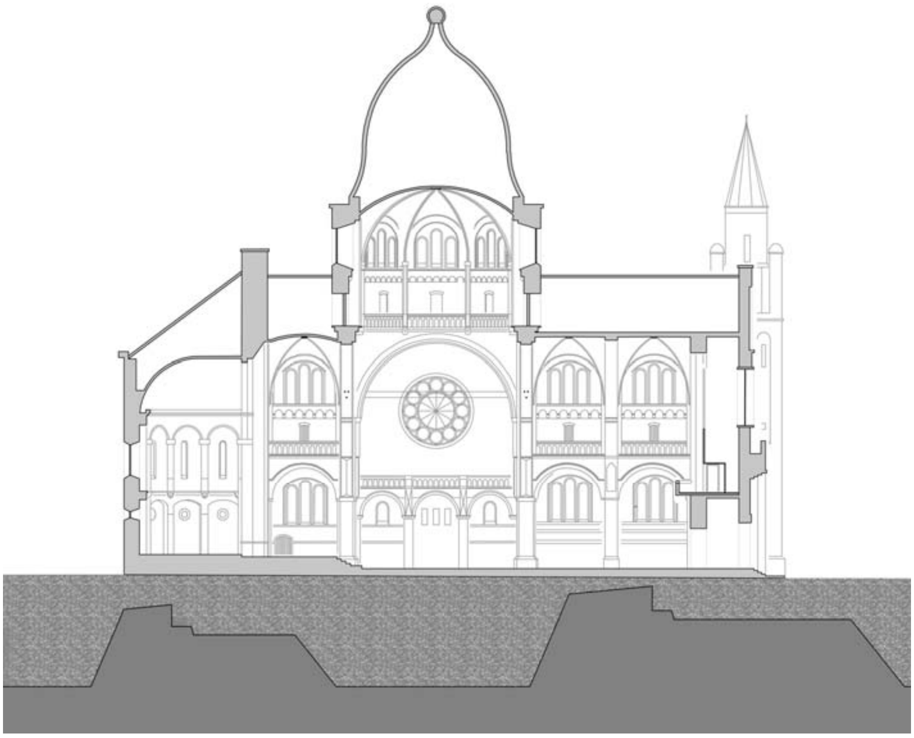

Figure 6 : Cross section of the church with former fortifications in the subsoil.

3.2 Dome mechanics and finite element modelling

The structure of the church of Sint Lambertus mostly consists of masonry cupolas. These brick domes are usually thick but often not reinforced and have little bending and tensile strength. In the pressure zone they act as a membrane due to their pressure and shear resistance. However, in the tensile zone masonry domes tend to widen, causing the lower part of the dome to crack and the upper part to sag. The radial cracks divide the cupola into parallel segments, having a load bearing capacity that is similar to that of arches.

Thus the load bearing capacity of these domes is based upon a combination of membrane behaviour and arch behaviour. By using computer programs based on the finite elements method the behaviour of complex domed structures can be simulated under various loadings.

In order to be able to analyse the current condition of the church of Sint Lambertus, a simplified 3D-model of the structure has been created in de finite elements program DIANA, see Fig. 7. The model embodies the most important building phases, as listed in paragraph 3.1, to make an accurate simulation of the current situation of the church.

Because of the direct relation between the complexity of the model and the time needed for calculating, the structure is simplified to a three dimensional wire model of a representative part of the church building: the main dome with its adjacent bays. The analyses are all based on linear elastic calculations.

All model phases are loaded with gravity. The dead weight of the structure is calculated by the program and based on the input of geometry and material properties. The differential settlements are translated into displacements of the supports, the column bases.

3.3 Analysis of the current condition and description of its problematic nature

The step-by-step input of successive settlements and measures made it possible to study in each phase the effect on the total structure. For instance, the reinforced concrete arches dating from 1933 do in fact strengthen the structure, although the reinforcement is not connected to the original arches, and indeed reduce thrusts on the supporting piers.

The installation of the tension rods and the replacement of the vaults had a positive effect on the structure as a whole as well.

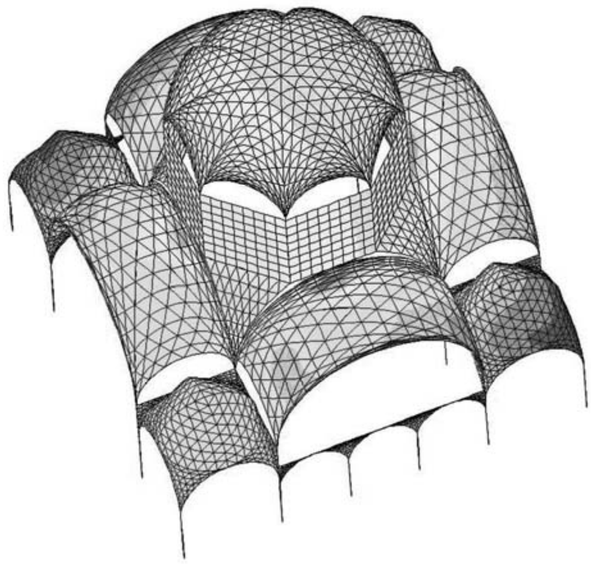

Figure 7 : Model of the structure in DIANA.

When analysing the resulting displacements of the church of Sint Lambertus in the current situation, it becomes evident that the largest settlements take place in the north-eastern part of the building. However, the most considerable differences in settlement are located in the south-western part. These very differences in settlement will cause crack development. The small cupolas are loaded by the thrust of the main dome in such a way that they are pushed outwards and deform slightly. At the bottom of these cupolas tensile stresses appear on either side of the outwards pointing forces. This will lead to crack development perpendicular to these tensile stresses, see Fig. 8. The direction of this crack development in the model appears to correspond with the actual cracking in the church building, see Fig. 9. Also the differences between the north-eastern and the south-western part in the model, as shown in the resulting displacements, correspond with the differences in crack development between the various cupolas in the building.

Concerning the current condition of the building it can be concluded that the combination of huge thrusts and differential settlements has caused the crack development. Especially the southernmost cupola shows large cracks. Furthermore, the model analysis gives evidence that earlier measures had a positive effect, but are not sufficient.

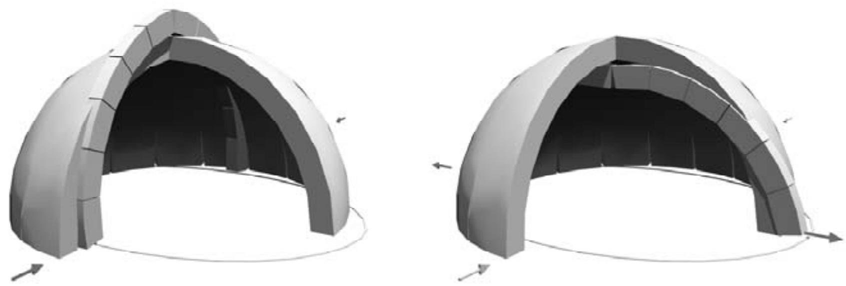

Figure 8 : Crack development in domes due to imposed deformations.

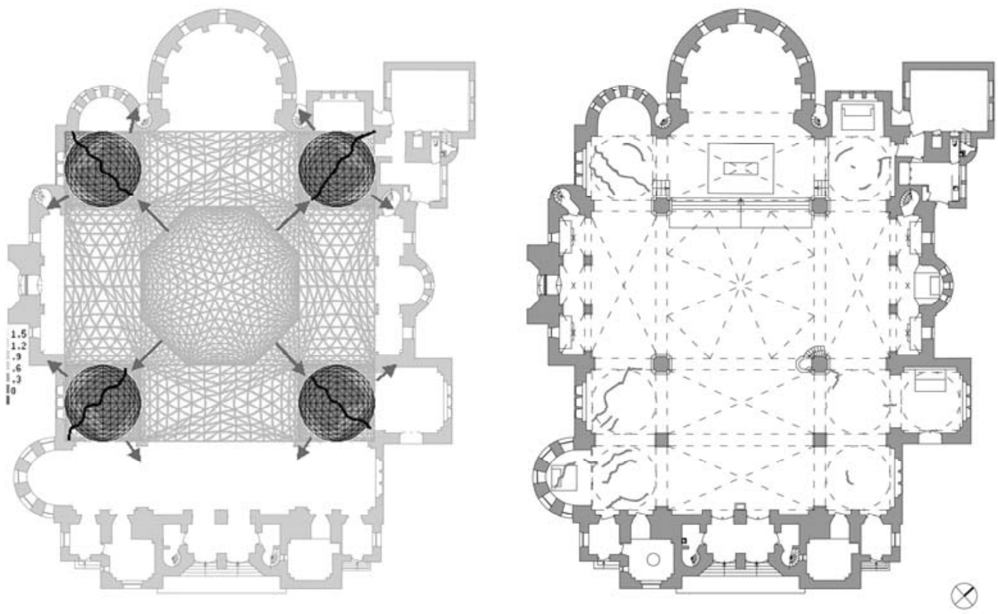

Figure 9 : Left: Tensile stresses; Right: the interrelated crack development.

3.4 *Analysis of potential measures*

Based upon the results of the model analysis, it was assumed that tensile stresses in the cupolas should be reduced by 50 % in order to put the building back in use. The compressive stresses and resulting displacement may not increase due to new measures.

To attain this result, a number of potential measures were simulated and calculated in the DIANA-model.

3.4.1 Reduction of thrusts

The tension rods between the arches under the main dome are not placed in the most constructively effective position. By replacing them to the springing of the arches, the calculations give evidence of decreasing thrusts entailing tensile stresses in the cupolas to decrease.

3.4.2 Neutralization of settlement and fixation of the situation with jacks

The present settlements could be neutralized by jacking up the columns. According to calculation it appears that the local neutralization of the settlement causes the problems only to shift.

3.4.3 Stabilisation of cupolas by increasing the loading

By increasing the loading on a cupola, the outwards directed forces could be bended downwards. However, from calculations it appears that the concentrations of tensile stresses hardly diminish.

3.4.4 Strengthening of cupolas by thickening the cross section

The cupolas can be strengthened by thickening their cross sections by adding a concrete layer at their tops . In this way the area over which the imposed loading is spread will increase, causing the stresses to decrease. According to calculations it appears that this gives the most optimal effect when the thickness is increased from 200 mm to 400 mm. Both the tensile and the compressive stresses are considerably reduced. When the cupolas are thickened even more, the increase in dead load almost nullifies the positive effect.

3.4.5 Cutting out the affected spot to safeguard the church building

The southernmost cupola is the most critical part of the structure. It has been cracked severely and is about to collapse. Furthermore the crack development is still increasing. By demolishing this cupola, it is possible to cut out the affected spot out of the structure, by which the rest of the building will be safeguarded. The calculations give evidence that this intervention hardly has any negative consequence for the total structure, which is remarkable. From the composition of the building, one could assume that the small cupolas by means of their weight contribute to the neutralisation of the thrusts of the main dome. The demolition of one of these cupolas would, in that case, have had a negative effect on the structure as a whole. Apparently these cupolas are not heavy enough to play a substantial role in the neutralisation or reduction of the thrusts.

3.5 Recommendations

On the basis of the possible solutions analysed the following measures would be recommended:

- The reduction of the thrusts of the main dome, by replacing the existing tension rods to the springing of the arches.
- The demolition of the most critical cupola.
- The strengthening of the cupolas by thickening their sections from 200 mm to 400 mm.

The argument for these measures is the preservation of the building as a whole, with its interior spatial effect as the most valuable aspect. Both the replacement of the tension rods and the thickening of the cupolas should not have any impact on the monumental interior.

Nevertheless, the demolition of the fourth cupola would have a strong impact on the interior, and would in this way affect the historical and cultural value of the building. Therefore, this would be the least desirable of the three options.

4 ACCURACY

The information on the settlements dating before 1988 is not very precise and is probably unreliable. For the data that are missing or are incomplete reasoned assumption was made. These inaccuracies in input data have been corrected in the final simulation of the phases from 1988 till now, because from this period of time data from precision measurements are available.

The most substantial inaccuracies in input consist of simplifications of geometry. This is mostly the case for the connections between the different geometric parts which correspond less with the actual situation in a wire model than would have been the case with a volumetric model.

Also the linear-elastic calculations do correspond less with the reality than nonlinear-elastic calculations would have done. On the other hand, the extensive periods of time implied by effecting a nonlinear calculation would only have been useful if the input data had been sufficiently accurate.

The input of this model was primarily based on measurements of settlements. Neither the composition of the subsoil, nor the quality of the foundations was fed into the model directly. Therefore it is not possible to make any prediction on proceeding settlements.

5 CONCLUSIONS

For this research several reports and results of measurements that had taken place in the past were used. Within the setting of this project it was not possible to carry out new measurements in situ, neither was there much time available to do the calculations. When no data were available, as was the case for the properties of the building materials used in the structure, a reasoned assumption was always made.

The model of the current situation, as developed in this research project, is a simplified reproduction of the structure. The numerical output in itself is therefore of little relevance. It, however, gives the opportunity to compare the different phases and potential solutions. The model does give insight into the behaviour of the structure. For instance, the results enable us to deduce the effect of the settlement of one of the piers on the remaining parts of the building. From the location of the maximum tensile stresses it can be concluded where the crack development will take place and what direction the crack will have.

Based on this principle model it is very well possible to investigate different potential measures to improve the condition of the structure. To retain more precise data on the recommended measurements a further, more specific research and a more precise model shall be necessary.

Certainly it is possible to carry out a closer research on the church of Sint Lambertus. Using a volumetric model for the finite elements analysis will lead to more precise results. Material research could give more accurate data on the properties of the materials used. With those input data it would be appropriate to effect non-linear elastic calculations. In any case it is strongly recommended to proceed with the periodical precision measurements to monitor the ongoing process of settlement.

REFERENCES

Bouwens, R.H.H.L. 1991. *St. Lambertuskerk; Maastrichts silhouet 33*. Maastricht: Stichting Historische Reeks Maastricht.

Heinle, E. and Schlaich, J. 1996. *Kuppeln aller Zeiten – aller Kulturen*. Stuttgart: Deutsche Verlags-Anstalt.

Heyman, J. 1996. *Arches, vaults and buttresses; masonry structures and their engineering*. Aldershot: Variorum.

Thunnissen, H.J.W. 1950. *Gewelven; hun constructie en toepassing in de historische en hedendaagse bouwkunst*. Amsterdam: Ahrend.

Wassenaar, Ingenieursbureau. 1991. *Rapport 1622 herziene versie*. Wassenaar: Ingenieursbureau Wassenaar.