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SCANNING AS BASIS FOR STRUCTURAL ANALYSIS

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Abstract

The paper describes the experience with scanning of the King's entrance of the Nidaros Cathedral, as basis for 3-dimensional modelling and FEM-meshing. The study has shown that scanning of even the most complex geometric shapes is efficient and an accurate basis for structural analysis. Existing procedures for FEM-meshing based on closed bodies performed satisfactory. Besides studying the potential of scanning, the work aimed at finding adequate explanations for the observed cracking in the entrance-wall by structural analysis. Two scenarios, horizontal loading from choir-vaults and differential settlements were investigated. The analyses indicate that settlements could be a plausible explanation for cracking, however the belonging deformations seemed too small to justify the crack-widths of the observed main crack.

Key Words

Laser scanning, structural analysis.

1 Introduction

Laser scanning has become a versatile technique for a number of applications. In the construction world, lasers has been used for surveying purposes for many years. Scanning of structures, however, has just recently been introduced to the civil engineering community, and the perspectives are most promising. Laser scanning provides a new means for making digital models of existing structures. Digital models can henceforth be converted to true geometrical models applicable for FEM-meshing. In order to investigate the potential of structural analysis based on scanned geometry, The Nidaros Cathedral was chosen as a case study (Høiseth et al 2002). The Cathedral has complex geometrical shapes with respect to the structural components, such as arches and vaults. In addition, the vast number of sculptures and ornaments connected to loadcarrying members makes the geometry of structural members somewhat vague. Therefore, the cathedral was considered a challenging case for scanning, and excellent in order to evaluate possible limitations with respect to subsequent structural modelling.

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For natural reasons, the study did not involve the whole cathedral, but was restricted to the area known as the King's entrance. This was done because the entrance is representative with respect to geometric shapes and because NDR[4] considered the entrance to be of particular interest due to severe cracking, which has developed during the last decades. Besides studying the potential of scanning, the intention was therefore also to find adequate explanations for the deformations by means of structural analysis.

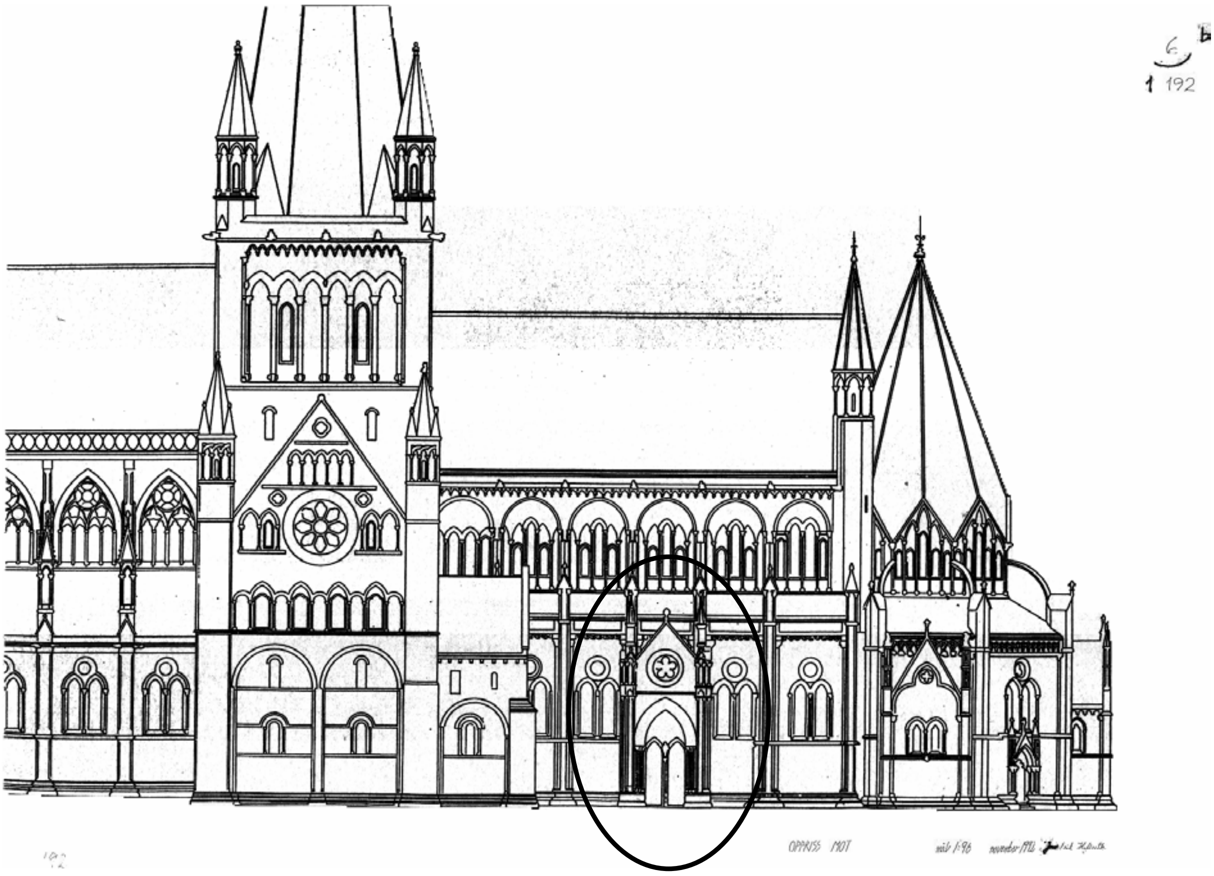

Figure 1 Nidaros Cathedral with the King's entrance encircled

2 Scanning the King's entrance

2.1 The Cyrax system

Cyrax is a portable, 3D laser scanning system for capturing, visualisation and modelling of complex structures and sites.

The scanner unit operates in a 40° vertical by 40° horizontal sector in space, for each scan. When the scanning starts, a laser beam is emitted, pointing towards the left, uppermost corner of the chosen spacious segment. The distance from the scanner to the target is measured by the laser-lights "time of flight". Next, the same action is repeated, however the direction of the emitted laser beam is rotated downwards by a set angle. This procedure continuous until the left, lowermost corner of the chosen segment is reached, and a complete column of points have been measured. Subsequently, a new column of points, with a set horizontal angle to the right, is

[4] Nidaros Cathedral Restoration Works

measured. The scan is completed when the lowermost, right angle of the chosen segment is reached. The result is a regular cloud of points on the surface of the scanned object, with known relative co-ordinates.

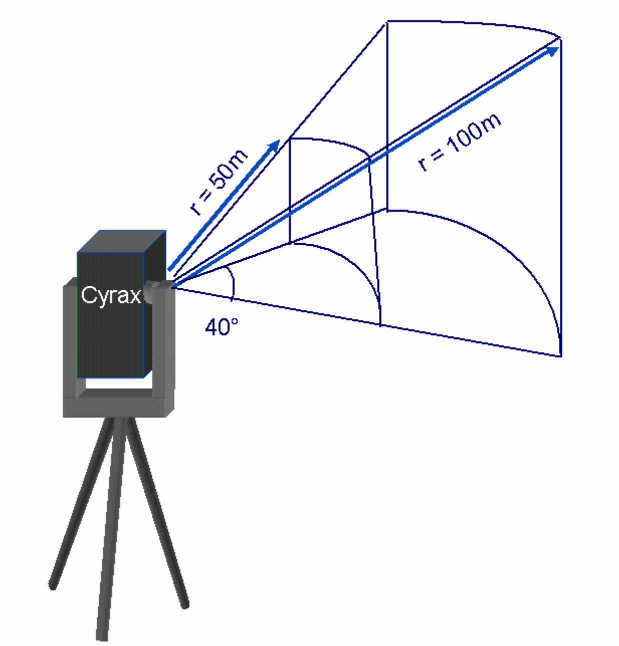

Figure 2 Cyrax scanner

The scanner also records the intensity of the reflected pulse, from all the measured points. This enables the associated software, Cyclone (Cyra Tech Inc 2001), to visualise the object through various graphical techniques. By combining separate scans, complete 3-dimensional models of structures, including exterior as well as interior surfaces are readily available. The software supports the .dxf file format, which implies that the models can be imported to popular CAD-programs like AutoCad and Microstation. From there, the necessary geometric entities can be transferred to mesh-generators like Femgen (TNO 2001), which was used in the current study. This way, a geometric model with true, in-situ measures, for FEM-purposes should be achieved.

2.2 Scanning and model assembly

Scanning was done from 11 different positions, 7 locations outside the entrance and 3 positions inside the gateway of the entrance. Due to time-limitations, merely the west-part inside the gateway was covered. This was however covered completely, from the north-south symmetry-line of the floor, all the way up to the uppermost part of the ceiling. In order to cover the complete entrance, from outside to inside, a scan was also taken from inside the choir of the church.

For many scanner positions, more than one scan was taken. Five fixed-points, for instance, which were surveyed also by total-station, were scanned with very high resolution. Also the main crack in the west part of the entrance was subjected to a separate scan with high resolution, see Figure 5.

All scans were taken during one day, including 3 scans of an outside sculpture located on top of one of the cathedral's alcoves. Hence, for each position, the necessary scans were taken in one hour, in average.

Having assembled the scans from all positions, the complete 3-dimensional scan-model consisted of more than 4.5 million points in total. Experience showed that it was important to combine scans in the field, because the representation of combination-targets could be insufficient, and additional scanning necessary.

Point-cloud meshing, minor adjustments, and the production of illustrations was done after the scanning was completed, during two working days.

2.3 Scanning accuracy

According to the specifications, the Cyrax scanner is accurate within +-2mm with respect to surfaces, while the absolute error is less than 6mm, independent of the distance between scanner and target. This should, for civil engineering purposes be well within the limits, also when it concerns structural analysis.

When combining scans, however, the errors may become somewhat larger, depending on :

- the number of common targets in pairs of scans subjected to combination
- the relative position of common targets. Targets should not be positioned along a line or too close, in relation to the scanned area
- in which order the combination is performed

In order to quantify the precision of the assembled model, the model was compared with the results of ordinary surveying. This was done by mounting 5 fixed-points within the scanned area, which were also surveyed with Theodolite. The positions of the fixed-points, as obtained by surveying, were imported to the scan-model, and combined with the corresponding scanned points. The deviation in relative position between the scanned and surveyed results was between 2 and 8 mm, with an average of 4.8 mm.

3 Transforming scan-model into FEM-mesh

3.1 From scan-model to FEM-preprocessor

Structural modelling in preprocessors for FEM-packages are often done by the following procedure: define vertices/points, draw lines/curves between vertices, connect lines to make surfaces, connect surfaces to create volumes. In principle, this is similar to how modelling is done in CAD-programs, however the representation of objects, the file formats, are not identical. Due to a growing demand for efficient FEM-modelling of CAD drawings, some preprocessors, like Femgen, allows import of popular CAD-formats like DXF[5]. Likewise, because full benefit of scan-models requires that they can be handled also by CAD-programs, Cyclone offers export in, amongst others, DXF-format. Hence, by communication via the DXF format, transformation of scan-models can be handled as illustrated in Figure 2, either directly from the scan-manipulation program to the preprocessor, or through a CAD-program.
In essence, transferring a scan-model to a FEM-preprocessor directly, or through a CAD-program, can be done in three different ways:

- From point-cloud to vertices, lines and curves. Cyclone includes drawing capabilities, such that lines and curves can be drawn between scanned points. In the case of a rectangular scanned surface, f instance, four edge-points would be selected and connected by drawn lines.
- From point-cloud to two- and three dimensional objects. Geometric objects like surfaces, cylinders, spheres etc are recognized and Cyclone provides algorithms for representing them by best-fit objects.
- From point-cloud to contour lines. For plane and volumetric objects, contour lines may be a suitable basis for modelling in FEM-preprocessors

[5] DXF – Drawing Interchange Format, first introduced by AutoDesk AutoCAD.

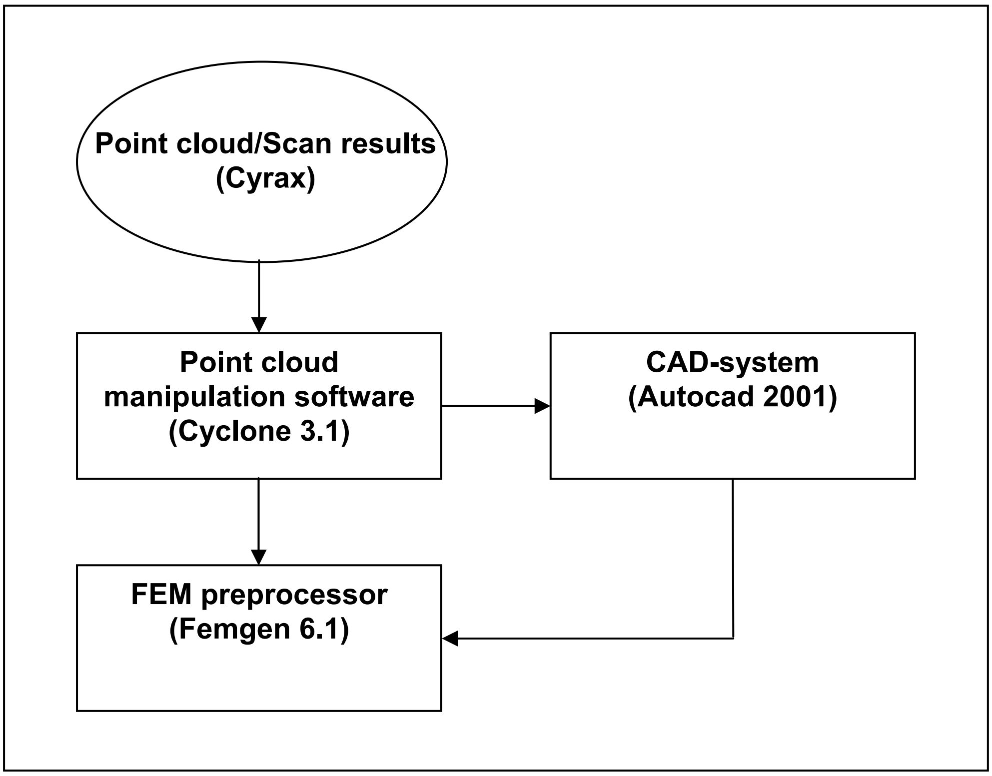

Figure 3 Strategies for FEM-modelling

3.2 FEM-preprocessing by simple geometric objects

In transferring the scan model of the King's entrance to Femgen, all of the three procedures as described in the previous section were considered. Due to the irregular and complex geometry of the entrance, the pragmatic solution: *From point-cloud to vertices, lines and curves* procedure was used. The vertices, lines and curves were drawn in Cyclone, and transferred to Femgen. Because of symmetry, merely the west-part of the entrance was modelled.

A line-model of the western part of the entrance was hence exported to Femgen. In Femgen, the lines were successively connected in such a way that they described the edges of closed volumetric shapes.

Having established a volumetric model, the FEM-meshing was performed automatically, with the Delaunay meshing algorithm in Femgen. The applied FEM-model is shown in Figure 4. The left-hand side of the figure shows the element mesh, the right-hand side illustrates the model in a "hidden fill" style. The mesh consisted of 24032 tetrahedrons connected to 6367 nodes. Even if the FEM-model must be considered quite large, a linear elastic analysis required merely 104 CPU-seconds on a 1.1 GHz portable PC.

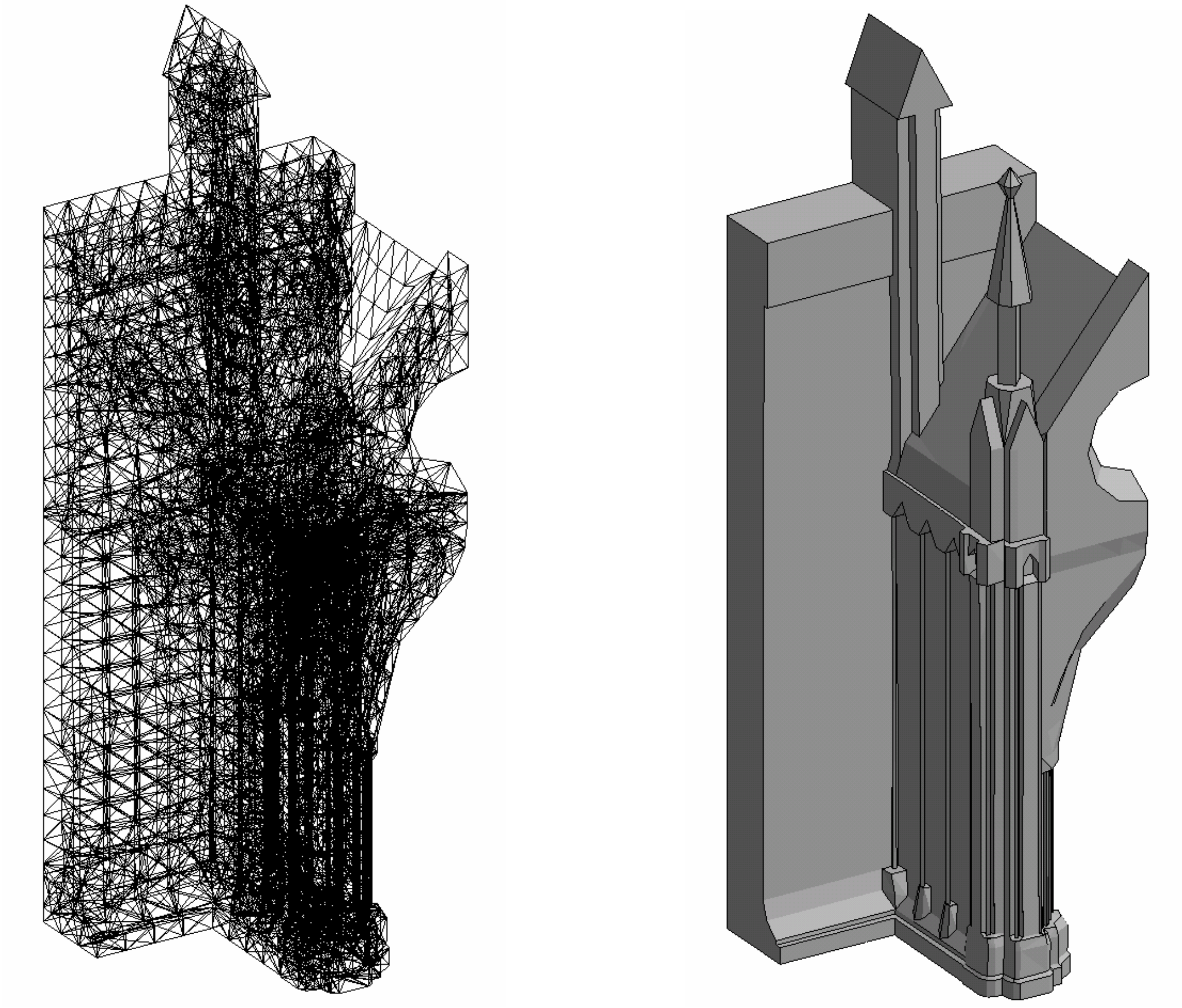

Figure 4 FEM-mesh of the western part of the entrance, line-representation and hidden/fill-representation

4 Linear elastic analyses

4.1 Objectives and analyses performed

Severe cracking in the west-wall of the King's entrance was a matter of concern, as shown in Figure 5. The cracking of the entrance-wall could be due to:

- external loading by load-transfer from the choir-vaults, through the butresses
- differential settlements

or a combination of both. Therefore, two analyses were carried out in order to study the likelihood of both alternatives. The boundary conditions and the applied force/deformation for the two cases, are illustrated in Figure 6. In the first case, the base of the entrance was fixed, while a realistic horizontal force from the Choir-wall of the cathedral was applied. In the second case, differential settlements as recorded over several years, was prescribed. Material parameters were taken from experimental tests of typical stone/block-material representative for the entrance: Young's modulus equal to 25.22 Mpa and an anticipated Poison's ratio of 0.2.

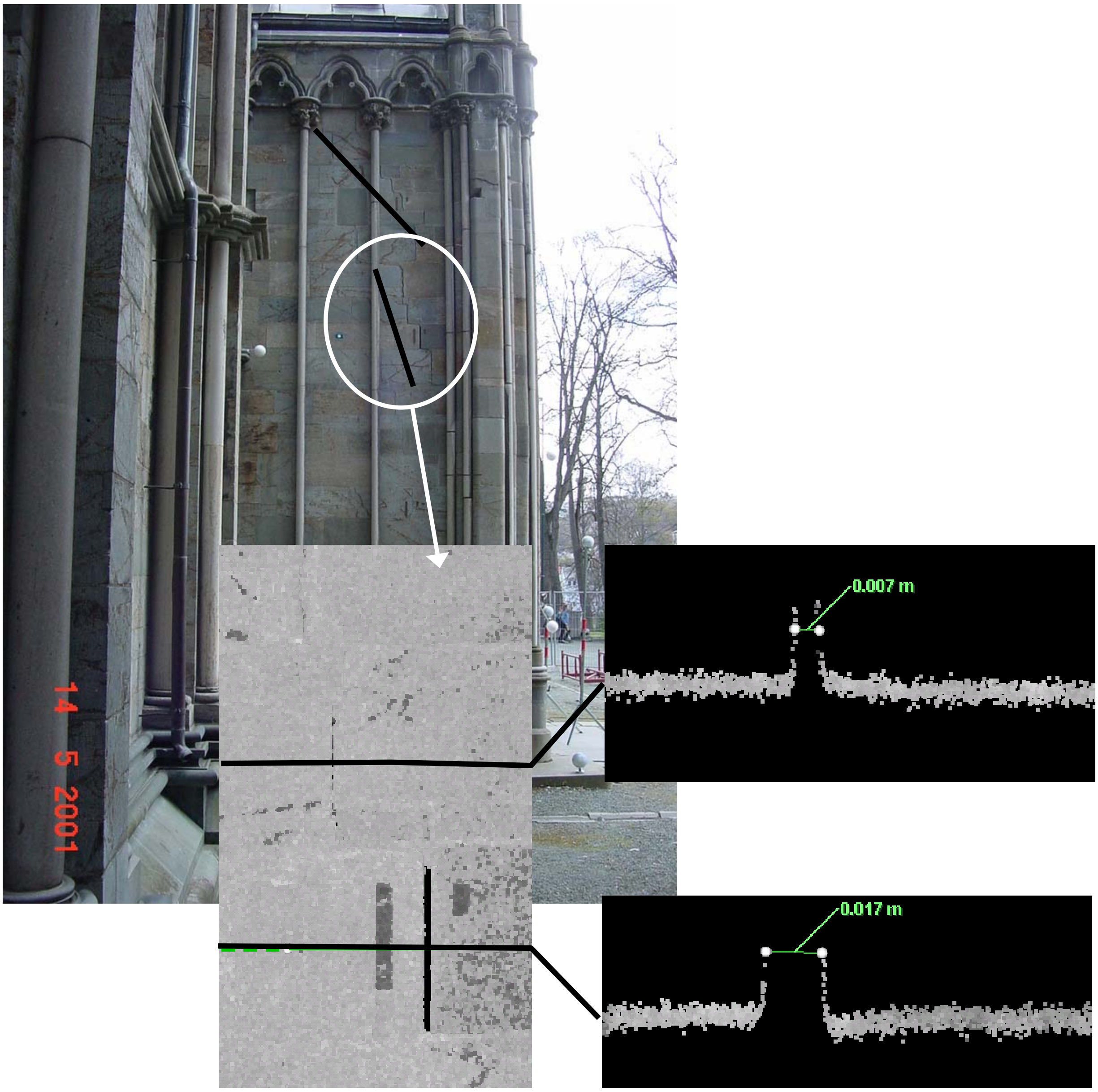

Figure 5 Cracks in the entrance west-wall, picture and scans showing the crack-widths

4.2 Evaluation of results

In both cases, the direction of the largest principal stress (tension), was in agreement with a normal to the average direction of the existing main crack in the west-wall of the entrance. This suggests that if the main crack in the entrance-wall should be due to structural loading or settlements, the direction would be approximately like what is actually the case.

The distribution of the principal stress and strain showed a maximum level somewhat displaced towards the lower north corner of the entrance-wall, compared to the real location of the main crack. This could be due to the rigorous boundary conditions in both analyses, the idealization of the loadings, as well as the applied element-types and the mesh-resolution.

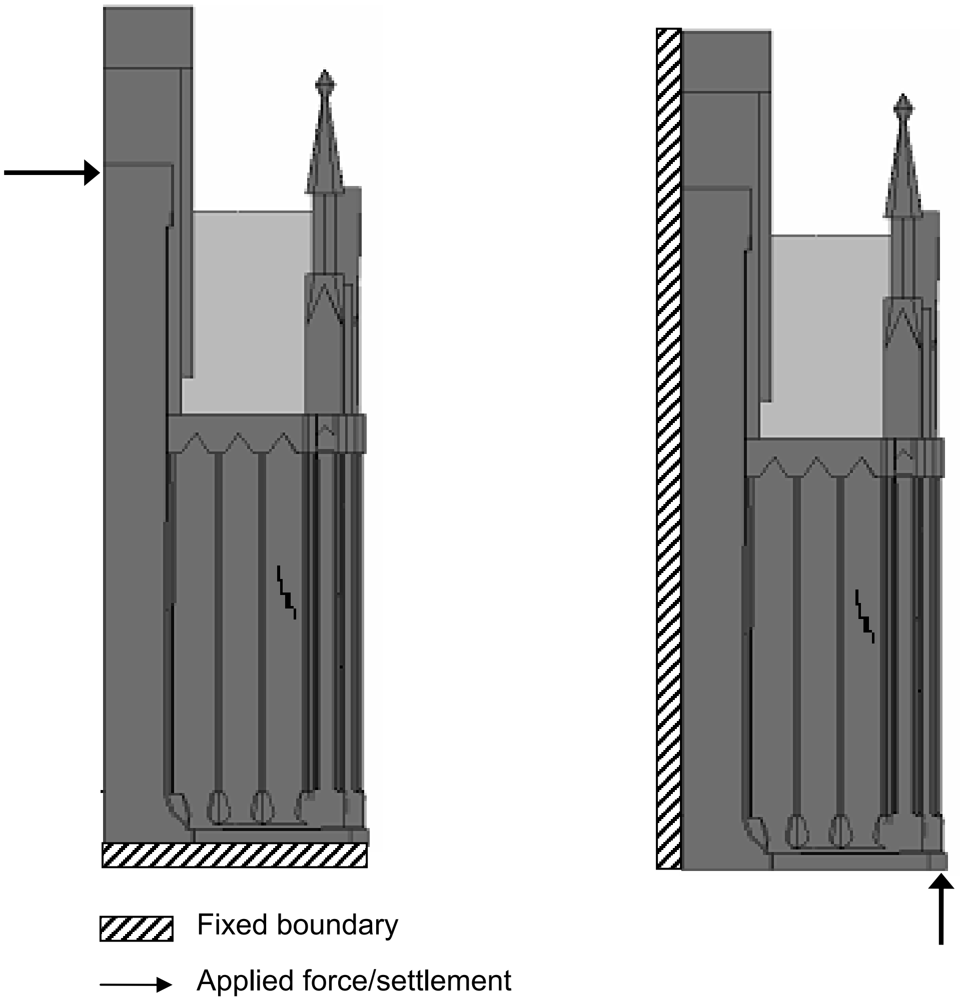

Figure 6 Boundary conditions and applied force/deformation in linear-elastic analyses

The results of horizontal loading showed however very small levels of deformation stress and strains. With respect to the largest principal stress, the maximum value in the entrance-wall, which was 0.12 MPa, must be less than the tensile strength of the blocks. Taking into account that visible cracks are present, not only in the joints of the brickwork, but also really through block units, *it is unlikely that the cracking in the entrance-wall is due to horizontal forces*. This assumption is also justified by the calculated deformations, which were far too small, as compared to the 7 mm crack-width of the existing main crack.

The analysis accounting for differential settlements showed a maximum (tension) principal stress of 3.02 MPa. Usually, the tensile strength of rock-like materials are between 5% and 10% of the compressive strength. The compressive strength for lime-stone is typically about 50 MPa. *Therefore, the obtained stress-level due to differential settlements may well generate cracking even through block units*. The associated deformations were however small also in this case, when compared to the 7 mm crack-width. Integrating the largest principal strain along a line approximately corresponding to the direction of the principal strain, gave a linear-elastic deformation of about 0.5 mm. In case all the elastic energy should be released in one single crack, the crack-width would therefore at least be in the order of 0.5 mm. Stress-redistribution could in this case imply a larger crack-width, more in agreement with the existing main crack.

This could be investigated by a nonlinear analysis, accounting for cracking, but such an approach was outside the scope of the current study.
After the scanning and the analyses were completed, large vertical gaps between the top of the marble columns and the solid stone column of the entrance were discovered. This can not be justified by the analyses results. One explanation could be interior expansion of block-units, which has been recognized previously. If this should be the case, such a structural behaviour would most likely also have influence on the crack-widths in the entrance-wall.

5 Conclusions

The study has shown that scanning of structures with even the most complex geometric shapes is efficient and a precise basis for three-dimensional modelling. Scanning the King's entrance, combining scans and producing a scan model was carried out in about three-working days by two operators. 5 fixed points were scanned and surveyed by traditional means. The difference in measured location was between 2 and 8 mm, with an average of 4.8 mm. Since the scanning was performed, additional software has been developed, which allows multiple scans to be combined without the use of predefined targets. This will improve the scanning efficiency considerably, and may be also have an influence on the already adequate accuracy.
Converting the scan point-clouds to geometric objects, which is necessary for FEM-meshing, was in this study to a large extent done manually. The study demonstrated that this practice was possible, however time-consuming and tedious for composite geometries. Most likely, there will be a growing demand for simpler and more robust export of geometric models to formats recognized by CAD-software. This will be beneficial also with respect to FEM-meshing. In fact, the meshing techniques used for visualization of the point-clouds, captures in most cases the surface of the scanned object. It is a tempting idea, that these algorithms should be a splendid basis for development of a FEM-meshing method.
The automatic algorithms for FEM-meshing performed well. It should be noticed that, for most parts, a three-dimensional pyramid element was used. For automatic meshing this is known to be perhaps the most versatile FEM-element for general bodies. In many cases, like in the entrance-wall, brick-elements would have been favourable. It is a well-known fact, however, that three-dimensional automatic modelling techniques are not always reliable for such elements in combination with difficult geometry.
The King's entrance of the Nidaros Cathedral was chosen as subject for the study for two reasons: the entrance is representative for the cathedral with respect to geometric shapes and because NDR considered the entrance to be of particular interest, due to severe cracking. In the entrance-wall, a main crack, with a crack-width of about 7 mm has developed during the last decades. With the produced FEM-model, the response to horizontal loading from the choir-vaults and the influence of differential settlements were investigated by linear-elastic analysis. The results of the analyses indicate that the horizontal forces from the choir-vaults produce minor deformations in the entrance wall, and is probably not significant with respect to the observed cracks.
The measured differential settlements may be the reason for crack-initiation, but the belonging deformations seems insufficient compared to the measured crack-widths. The history of the settlements is however incomplete, and the differential settlements may have been larger than what was anticipated in the analysis. Differential settlements should therefore be considered as a possible explanation for the cracking, at least partly.
A third possibility, or contribution to the cracking, may be interior expansion of block-units, which has been recognized previously.

6 Acknowledgements

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Scanning of structures, as a means for structural analysis, is a new technique. Willem van Spanje and Erwin Beerninck at Delfttech bv did their utmost to produce the necessary 3-dimensional scan-models during some hectic days.
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