Seismic vulnerability assessment of the Aachen Cathedral based on measurements and numerical simulations

C. Butenweg & W. Kuhlmann
Institute of Structural Statics and Dynamics, Aachen University of Technology, Germany

M. López & S. Fernández
Universidad Técnica Federico Santa María, Valparaíso, Chile

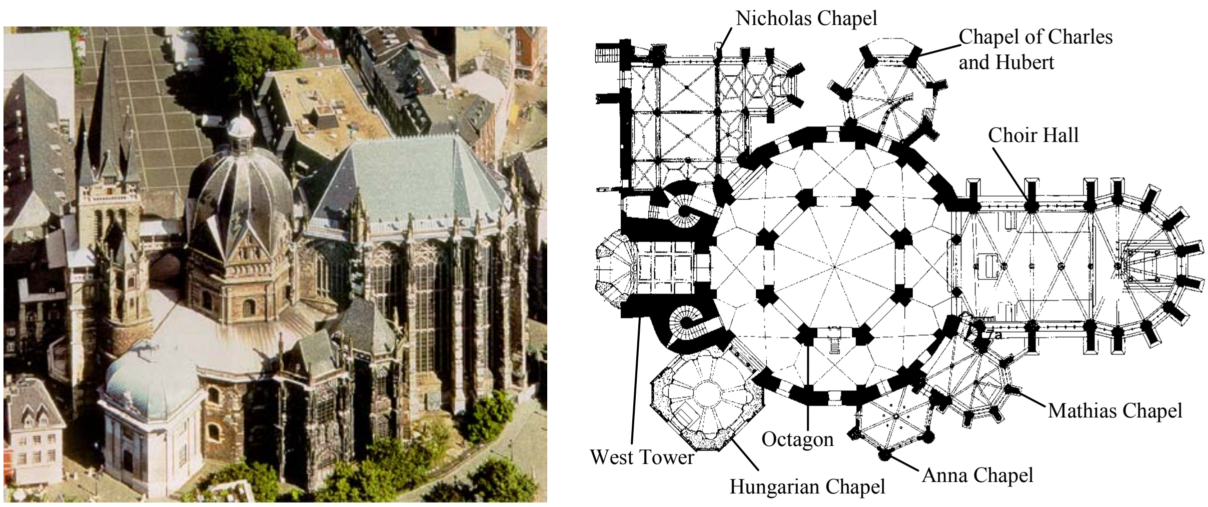
KEYWORDS: Aachen Cathedral, seismic vulnerability, historic buildings, measurements

ABSTRACT:

The Aachen Cathedral is the first German cultural monument that was included in the cultural world heritage list of the UNESCO in 1978. The cathedral was built around 800 AD and is a historical building of universal importance and one of the largest examples of religious architecture. After more than 1200 years of permanent use the static system of the cathedral shows considerable damage of the masonry, the medieval anchoring system, the roof construction, the vaults and the pillars. Therefore within the last century strengthening works were carried out to improve the cathedral's load bearing system. Due to the location of the cathedral in a seismic active region the assessment of the seismic vulnerability presented in this paper was necessary. The assessment is based on measurements of the eigenfrequencies and numerical simulations using a detailed finite element model of the cathedral.

1 INTRODUCTION

The Aachen Cathedral was built over a period of about 1100 years and consists today of the Octagon, the Choir Hall, the West Tower and five smaller chapels (Figure 1a, b). The core of the cathedral is the Palatine Chapel constructed around 800 AD under the Emperor Charlemagne. The chapel with its Octagonal basilica and cupola is surrounded by a 16-sided ambulatory. At the time of construction the Palatine Chapel with a height of 30.9 m was the largest domed building north of the alps. During the Gothic period the cathedral was extended by the Choir Hall and the smaller chapels to offer enough place for the pilgrims and guests of the coronations. The Choir Hall with the dimensions of 37 m in length, 21 m in width and 33 m in height is considerably taller than the chapels surrounding the Octagon and is called one of the masterpieces of Gothic architecture (Mainzer, 2003).



a) b)

Figure 1. Side view (a) and plan view (b) of the Aachen Cathedral.

The hall with a glassed surface of more than 1000 m^2 was consecrated in 1414 after a building period of sixty years. The five smaller chapels Mathias, Anna, Hungarian, Nicholas and Charles & Hubert were added during the 15th century. The West Tower with its final height of 74 m was reconstructed in 1884. The Aachen Cathedral, an important example of Carolingian style with a huge number of visitors per year, was the first German cultural monument to be admitted in the cultural world heritage list of the UNESCO in 1978. In the last century a lot of strengthening works were carried out to ensure the structural safety of the cathedral under usual loads like wind, snow and dead load.

Although the location of the cathedral belongs to seismic zone three according to the German code (E DIN 4149, 2003) the dynamic behaviour of the cathedral under earthquake load has not yet been investigated due to the complex geometry and the uncertainties of the material and cross-section data as well as the sophisticated strengthening works during the last century. To investigate the structural safety under earthquake load the cathedral was analyzed by the Institute of Structural Statics and Dynamics of the University of Technology Aachen on behalf of the construction management of the cathedral. The investigations are based on the development of a detailed finite element model under consideration of all relevant material data, cross section data and strengthening works during the last century. The composition of the required data was friendly supported by the engineering company Kempen in Aachen which has a long experience concerning reconstruction works of the cathedral. Because of the complex stiffness and mass distribution of the system measurements of the eigenfrequencies were used for the calibration of the numerical model. Afterwards the calibrated model was adopted for both a multi modal and a time history analysis to calculate the relevant stresses in the load bearing system. Based on the results the seismic vulnerability of the cathedral was evaluated.

2 STATIC SYSTEM OF THE CATHEDRAL

Nowadays the Aachen Cathedral consists essentially of the West Tower, the Octagon and the Choir Hall. The most important aspect of the static system in terms of a horizontal earthquake excitation is the common lateral load carrying system of the Choir Hall and the Octagon. Due to the slim columns and the glassed surfaces the Choir Hall is not able to carry the horizontal loads like wind or earthquake forces to the foundation. Therefore several anchor systems have been installed over the last centuries to connect the Choir Hall to the compact Octagon to ensure the structural stability under horizontal loads. In the following the functionality of the different anchor systems is presented.

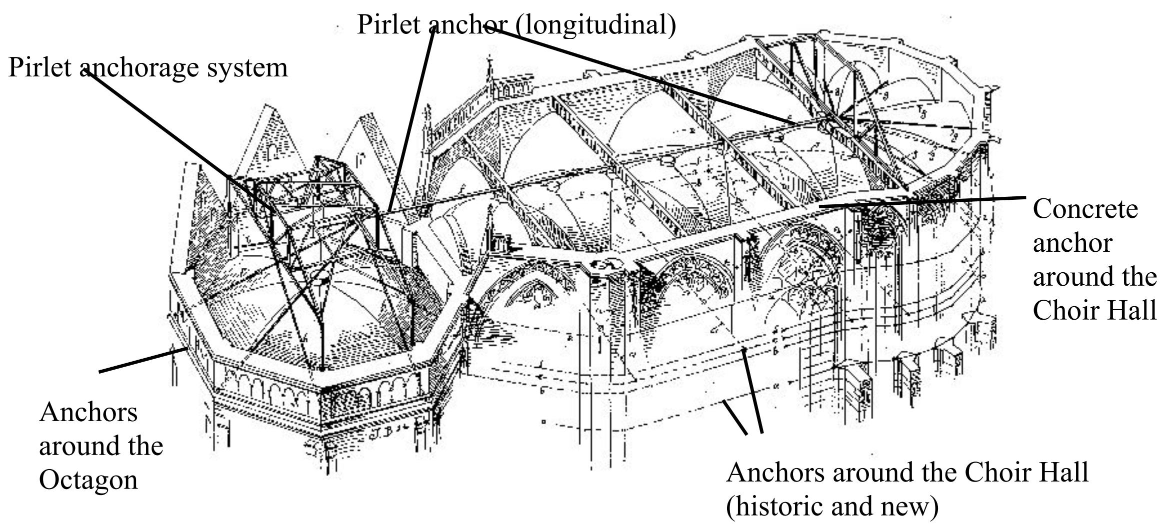


Figure 2. Sketch of the anchor system.

Historic anchors: Originally, five iron anchors were installed for the connection of the Choir Hall to the Octagon. At the Octagon the anchors were placed in the masonry walls and at the Choir Hall the anchors were built in between the slim columns as shown in Figure 2. These anchors are now supposed to be not carrying any load due to corrosion and inappropriate repair works during the last centuries.

Pirlet-anchor: In investigations lead by Prof. Pirlet in 1917 it was demonstrated that a new anchor system was necessary for two reasons: Firstly, to avoid lateral displacements (expansion) of the columns of the Choir Hall due to the gravity action on the arcs and the roof. Secondly, to connect the Choir Hall to the Octagon and transfer horizontal loads (wind and earthquake) from the Choir Hall to the Octagons load bearing system.

The result of these considerations was the so-called Pirlet-anchor (Buchkremer 1928, Karlsverein 1967) that was installed in the 1920's. It is the Pirlet-anchor that nowadays ensures the stability of the Choir Hall with its four 27 m high windows. The main anchor in longitudinal direction is composed of four prestressed steel L-profiles. At the East end of the Choir Hall this main anchor is connected to several circularly aligned steel anchors which carry the anchor force to the outer columns. At the Octagon the situation was more difficult due to the impossibility of creating a vertical support above the vault of the Octagon. For this reason the sophisticated structure of Figure 3a (view from NW) was constructed.

Further concrete and steel anchors: In addition to the Pirlet-anchor a concrete anchor that surrounds the Choir Hall has been built in. Furthermore, new steel anchors have been added in recent years to the outside of the Choir Hall at approximately the height of the historic anchors as shown in Figure 3b. Around the Octagon a new steel anchor is being installed right now.

Figure 3. Anchorage truss at the Octagon (a) and Anchors around the Choir Hall (b).

3 NUMERICAL MODEL

A CAD model of the cathedral was built up by using the finite element pre- and postprocessor FEMAP (FEMAP, 2003). The geometric information was taken from construction plans and photo material as far as possible. In case of missing or contradictory information additional measurements on site were made. In the next step the CAD model was transferred into a finite element model. This requires the meshing of the geometric objects (lines and surfaces) with structural elements. As structural elements beams and trusses were applied for the lines and shell elements for the surfaces. To achieve a realistic simulation of the structural behaviour the element size for the automatic mesh generation was chosen to approximately one meter. Using this element size the complete finite element model of the cathedral consists of a total of 20061 elements. While Table 1 gives a description of the size of the model and the number of the different elements used, the model itself is shown in Figure 4. All material and cross section data of the CAD model were automatically assigned during the generation to the finite elements. The boundary conditions of the model were modeled rigidly clamped and do not include any soil structure interaction effects. In the last step the structural model was exported to ANSYS (ANSYS, 2003) to execute the static, multi modal and time history analyses.

Table 1. Description of the finite element model.

Nodes	19284
No. of cross sections	76
No. of material properties	11
Total no. of DOF's	85311
Comp. size of the model	337 MB

Total no. of elements	20061
Shell elements	17843
Beam elements	1799
Truss elements	45
Mass elements	374

Figure 4. Finite element model of the Aachen Cathedral.

4 MEASUREMENTS

4.1 Measurement of the Cathedral eigenfrequencies

The measurements were carried out at two different points: at the top of the Choir Hall and above the belfry in the Tower. Due to its compactness no useful eigenfrequencies can be measured at the Octagon. Figure 5a was taken during the measurements at the top of the Choir Hall. Considering the structure of the whole cathedral the first eigenfrequency is expected to be a mode where the end of the Choir Hall swings perpendicular to the longitudinal axis of the cathedral. Higher modes are supposed to be vibrations in the longitudinal axis and vibrations of the Tower. The measured eigenfrequencies can be used for the calibration of the numerical model, because both the exact stiffness and the mass distribution of the cathedral are unknown.

a) b)

Figure 5. Measuring the frequencies at the Choir Hall (a) and in the West Tower (b).

4.2 Measurements during the peal of the bells

During the peal of the bells the eigenfrequencies and accelerations were measured (Figure 5b). First evaluations showed that no danger of resonance effects exists because the eigenfrequencies of the bells and the West Tower do not correspond. In a future part of this project the obtained results of the accelerations will be used to compute the stresses and displacements of the West Tower by using the detailed finite element model. Then it will be possible to quantitatively compare the stresses and displacements due to a strong earthquake and the ringing of the bells.

4.3 Results

As the main result, Figure 6 shows the spectra at the end of the Choir Hall in the two horizontal directions that were obtained from the measurements. The left diagram corresponds to the transverse direction (x), the right diagram to the longitudinal direction (y) of the cathedral. The first eigenfrequency in x-direction occurs at 1,13 Hz, in y-direction at 2,13 Hz.

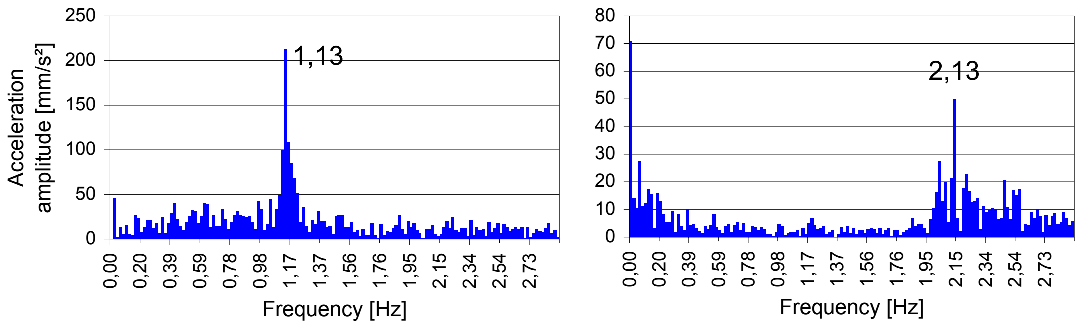


Figure 6. Results of the measurements at the end of the Choir Hall.

The spectra of the Tower are presented in Figure 7. In x-direction the eigenfrequency is 2,36 Hz. The eigenfrequency in y-direction is 2,05 Hz and almost coincides with the eigenfrequency in y-direction measured at the Choir Hall. The Tower's eigenfrequency in x-direction is higher which is easily explained by the increased stiffness due to the Nicholas and the Hungarian chapel.

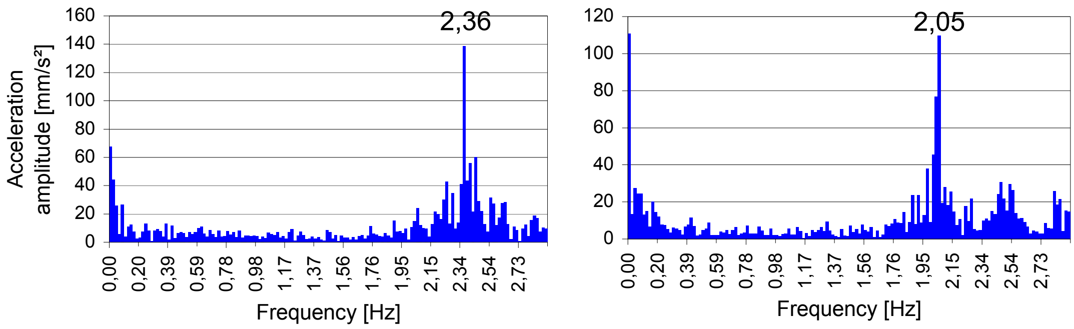


Figure 7. Results of the measurements in the West Tower.

5 CALIBRATION OF THE NUMERICAL MODEL

For a complex model like the Aachen Cathedral which includes a lot of uncertainties a calibration with measured eigenfrequencies is necessary. The material properties of the cathedral were determined from reliable experimental results (IBAC, 1990). The geometry was obtained with a good accuracy from the construction plans. Therefore the calibration of the model was carried out only by variation of the mass distribution. During calibration nodal masses were added to the system to represent non-structural masses which were not taken into account before. The calibration was repeated until a good agreement of calculated and measured eigenfrequencies was achieved. Table 2 includes the results of the first three calculated and measured eigenfrequencies. The good agreement of the frequencies demonstrates that the model was successfully calibrated. Figure 8 shows the first two eigenfrequencies of the cathedral. The first eigenmode is a translation mode of the Choir Hall in x-direction while the Tower and the Octagon are hardly affected. In the second eigenmode which is also translation mode, but in the longitudinal direction of the cathedral (y), the whole cathedral is part of the movements.

Table 2. Comparison of measured and computed eigenfrequencies.

Eigenfrequency	Measurement [Hz]	Numerical Simulation [Hz]
1	1,13	1,13
2	2,13	2,14
3	2,36	2,32

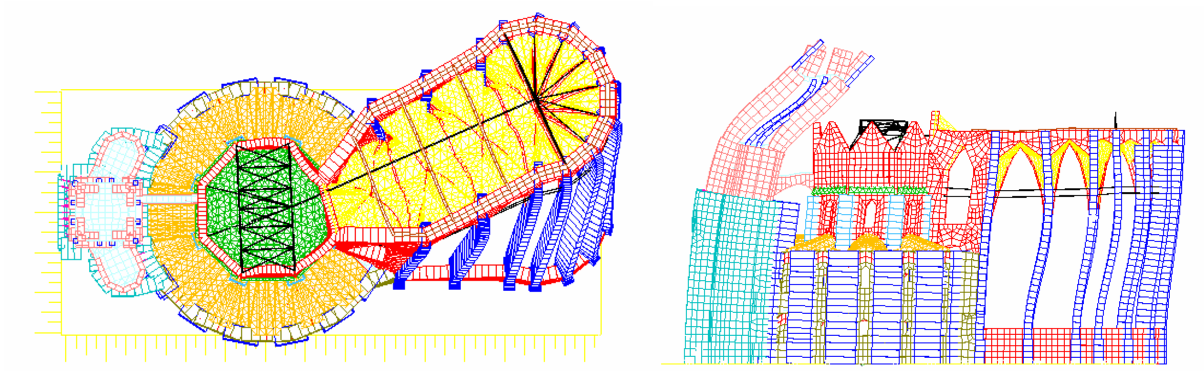


Figure 8. First and second eigenmode of the Aachen Cathedral.

6 NUMERICAL SIMULATIONS

The seismic vulnerability of the cathedral was evaluated by using response spectrum and time history analyses. The seismic loads were defined according to the E DIN 4149 which content is equivalent to EC 8 (EC 8, 2003). As an essential indicator for the seismic vulnerability the calculated forces in the anchor system are used.

6.1 Spectrum analysis

For definition of the horizontal elastic response spectrum according to E DIN 4149 the following parameters are used: Seismic zone: 3, underground class: A, building ground: 3, damping: 5%. The behaviour factor for consideration of the structure ductility was chosen conservatively to q = 1.5. Figure 9 shows the resulting design response spectrum. The response spectrum analysis was carried out separately for longitudinal and transverse direction of the cathedral. The results are superposed with the self-weight as given in Table 3.

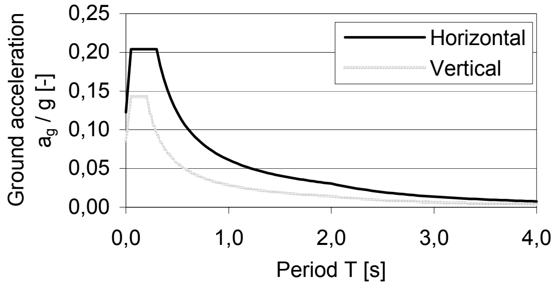


Figure 9. Spectrum according to E DIN 4149 for elastic analysis.

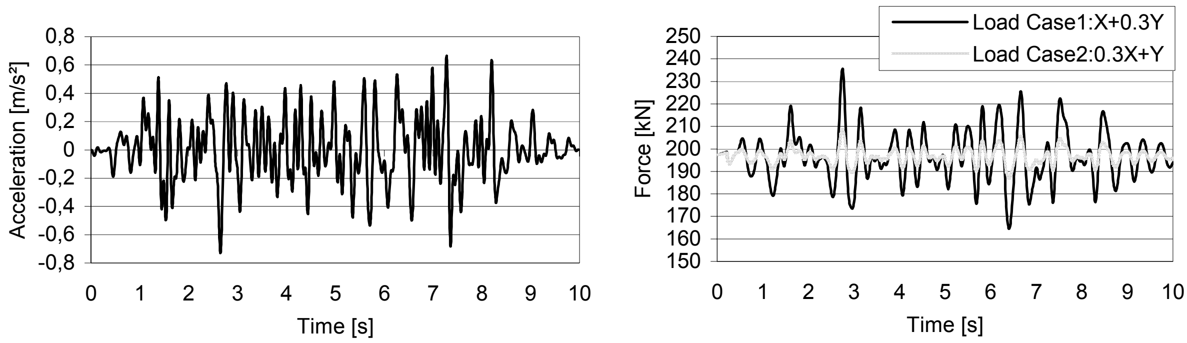
Table 3. Superposition scheme.

Load Case	Combination	Description	Main anchor stress [MPa]
SW	-	Self-weight	14,2
EX	-	Spectrum X-direction	-
EY	-	Spectrum Y-direction	-
EXY	1,0 EX + 0,3 EY	1,0 Spectrum X + 0,3 Spectrum Y	-
EYX	0,3 EX + 1,0 EY	0,3 Spectrum X + 1,0 Spectrum Y	-
EXYMax	+ EXY + SW	Max (1,0 Spectrum X + 0,3 Spectrum Y)	21,0
EXYMin	- EXY + SW	Min (1,0 Spectrum X + 0,3 Spectrum Y)	7,4
EYXMax	+ EYX + SW	Max (0,3 Spectrum X + 1,0 Spectrum Y)	16,4
EYXMin	- EYX + SW	Min (0,3 Spectrum X + 1,0 Spectrum Y)	12,0

By using the first twenty eigenfrequencies more than 90% of the total effective mass for each degree of freedom was considered, as required in the code. The result for the maximum stress in the main anchor was 21 MPa, the minimum stress 7,4 MPa. This means that the anchor is in all cases still under tension and the maximum tensile stresses are far below the steel's yield stress.

6.2 Time history analysis

For the time history analysis an accelerogram with a duration of 10 s as shown in Figure 10a was generated (Meskouris, 2000, 2003) compatible to the design spectrum in Figure 9. The resulting force in the main anchor over the time is shown in Figure 10b. From the maximum and minimum forces of 235,6 and 164,6 kN and the cross section area of 139,2 cm² the maximum and minimum stresses are calculated to 16,9 and 11,8 MPa. As expected the stresses due to the seismic load obtained by the time history analysis are smaller than those from the spectrum analysis.



(a) (b)

Figure 10. Synthetic accelerogram (a) and main anchor force over the time (b).

7 SUMMARY

The behaviour of the Aachen Cathedral under earthquake load was numerically simulated. For this reason a detailed finite element model was developed which shows very good consistency with the eigenfrequencies that were measured in the cathedral.

It was found that in both the spectrum and the time history analysis the anchor system of the cathedral is able to withstand the strongest earthquakes that are likely to occur in the region. For further verification of this result it is recommended to take into account the soil-structure interaction as well as the stiffness of the five chapels that surround the cathedral and to carry out the numerical simulations based on probabilistic assumptions of the material properties.

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