DETERMINATION OF OLD AND NEW DEFORMATIONS AT KÜCÜK AYA SOFYA (LITTLE HAGIA SOPHIA) MOSQUE IN ISTANBUL BY PHOTOGRAMMETRIC METHODS AND AN ATTEMPT OF THEIR INTERPRETATION

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ABSTRACT:

Scientists of Yildiz Technical University Istanbul and Darmstadt University of Technology have coorperated in order to collect and analyse different informations about the Kücük Aya Sofya Mosque (constructed between 527-536 A.D.) in Istanbul, one of the oldest and most important still existing buildings of byzantine era. The extraordinary beauty of the monument will be documented with a computer generated panoramic image of the indoors octagon. The great impact of the photographs to document how the building changed in time is shown by some examples. Furthermore the inclinations of the eight polygonal pillars in the central octagon and of the outer wall of the apse are determinated by photogrammetric methods. These inclinations are very large and generally very old, they might exist since the beginning of the building in the byzantine times of Justinian and his empress Theodora. But also present day deformations were found: there are a lot of cracks in the building. Some of them are controlled over a period of more than 20 years, especially the vertical cracks on the north-west and south-east corners of the dome. As a consequence the geometry of the whole dome was checked with photogrammetric methods, starting 1979 and ending 2002. The results of the deformation analysis are shown and discussed. In 2002 an in-and outdoor laser-scan of the complete building was performed. The results and further investigations are discussed. Additionally some of the damages resulting from the Izmit 1999 earthquake (magnitude 7,4) are documented.

KURZFASSUNG:

Wissenschaftler der Yildiz Technischen Universität Istanbul und der Technischen Universität Darmstadt haben bei der Untersuchung der Kleinen Hagia Sophia (gebaut 527-536 A.D.) in Istanbul, einem der ältesten und bedeutendsten noch existierenden Gebäude aus der frühbyzantinischen Zeit, zusammengearbeitet. Die außerordentliche Schönheit des Gebäudes wird zu Beginn durch die Wiedergabe einer gerechneten Panoramaaufnahme des inneren oktagonalen Zentralraumes aufgezeigt. Dann wird an einigen Beispielen die Bedeutung vorhandener Photos für die Dokumentation des sich verändernden Geschehens aufgezeigt. Die Schiefstellungen der Pfeiler und einer Apsisaußenwand werden nachgewiesen, wobei die These vertreten wird, dass diese Schiefstellungen älteren Ursprungs sind, d.h. eventuell noch aus den Zeiten von Justinian und Theodora stammen. Aber auch neuere Deformationen werden präsentiert: einige der vielen vorhandenen Risse des Baus konnten photogrammetrisch über den Zeitraum 1979-2002 beobachtet werden, gleiches gilt für die das zentrale Oktagon abschließende Kuppel. Die Ergebnisse werden diskutiert. Im Jahre 2002 wurde eine komplette Laserabtastung des Gebäudes durchgeführt, Ergebnisse und weitere notwendige Arbeiten werden besprochen. Zum Abschluß werden einige Schäden dokumentiert, welche durch das Izmit-Erdbeben (1999, Stärke 7,4 auf der Richterskala) neu entstanden sind.

1. INTRODUCTION

At Istanbul the church of Sergius-and-Bacchus (527-536 A.D.) or Little Hagia Sophia Mosque (**K**ücük **A**ya Sofya **M**osque = KAM) as it is called after the fall of Constantinople in the year 1453 and after changing the church into a mosque (1504) belongs to the oldest and most important still existing buildings of early byzantine era. The KAM was commissioned by the roman Emperor Justinian and his Empress Theodora as an annex to the existing Peter-and-Paul-Basilica inside the palace of Hormisdas, the KAM survived in most of its parts, the Peter-and-Paul-Basilica doesn't exist today any more. In spite of all its historical importance KAM is in a very poor condition today; we are convinced, that there is a real risk for the further existing of the building if nothing will be done for its restoration. Therefore the World Monuments Funds (www.wmf.org) has placed KAM into its list 2002 of the 100 most endangered sites all over the world. Specialists of the Yildiz Technical University / Istanbul have worked at KAM the last years to collect informations in different disciplines [2,3]. In this context a mixed group of scientists of Yildiz and the Technical University Darmstadt / Germany have performed extensive geodetic and photogrammetric observations including a complete laserscan of KAM. The photogrammetric and geodetic measurements have started in 1979 and have been repeated several times till 2002. Therefore the team was able to investigate different problems as for example the fundamental question of the quality and quantity of the deformations which may endanger the near future of the KAM. To understand some of the problems, let's have a first look at KAM: an octagonal

nave is the centre of an irregular square, a rectangular narthex is on the west, a half hexagonal apse on the east. Figure 1 presents KAM; the photogrammetric image was taken from a a lifting truck.
One of the major problems can be seen directly: the main railway on the European side of Istanbul which was built between 1870-1890 runs directly along the south side of the building in a very short distance of only a few meters. The traffic on this railway is very heavy today: trains are passing in 10-minutes intervals the building.

Figure 1. Gereral view of KAM and railway

On the one hand the railways vibrations act directly at the structure of KAM; on the other hand there is a compression of the soil beneath the rails. Such a compression may disturbs the situation of the groundwater especially the drain off. In that context some further explanations shall be given: the height of KAM over sea level is only a few meters because the building was erected in a distance of about twenty meters to the old town wall which was built next to the seaside. Today there is a big street on a filled ground between old town wall and coastline. At the other (northern) side of KAM the terrain rises up to the place where the hippodrome was found in historic times. That situation and the compression of the soil are reasonable for problems concerning the groundwater.
Beside the manyfold importance of the KAM an extraordinary but not well known beauty of the monument exists, which can be seen only inside the central octagon. To give a small illustration of that inherent beauty a panoramic image was computed by merging nine photographs which is shown in figure 2.

2. IMAGES AS A RECORD OF CHANGES

The existent fund of photogrammetric and other images is a document of different things which happened at KAM. For example the development or the condition of the building can be seen. Three concrete examples are presented in the following:
The first example gives an impression of the integration of the KAM into a general architectonical situation. After changing the byzantine church into a mosque some typical islamic architectonic elements were appended in- and outdoor, outdoor the elements minaret, tomb and a square with medrese and fountain for the washing, cf. figure 3.

Figure 2. Panoramic image of the central octagon

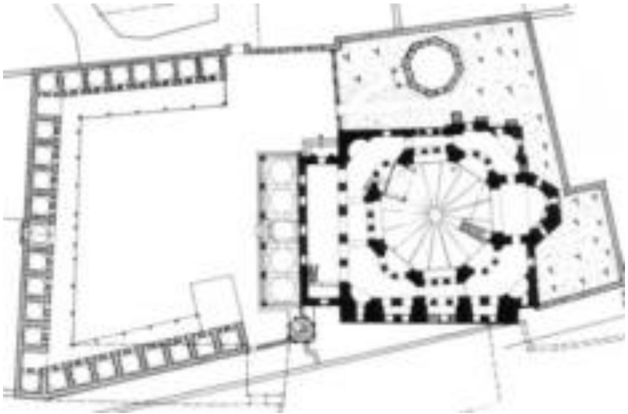

Figure 3. Architectonical ensemble of KAM in the last century, [1]

In the year 1979 the visitor could see the square (figure 4), but in the nineties he couldn't (figure 5). The utilization of the medrese had changed; some parts were rebuilt or reorganized. Today the medrese houses some tourist-shops. Due to these developments, a few new jobs were created on the one hand but on the other hand the architectonic situation (the aesthetics of the ensemble) was disturbed completely.
In the second example we see an orthophoto of the north wall of KAM generated by some photogrammetric images. This orthophoto shows 1500 years of changing, repairing of problems and damages: recording with the help of visualization. Such an orthophoto can be a hot spot of information and a very great help for the work of experts dealing with such old monuments. Let us have a detailed look at the situation of the central north side. There we will find some evident hints to conclude that the building entrances have changed.

Figure 4. West side of KAM 1979

Figure 5. West side of KAM 1998

Figure 6. North side of KAM

To find an answer to the open question of the original location of the Peter-and-Paul-Basilica to which KAM was connected an important hint could be the deformations of the four big pillars on the southern part of the octagonal centre. Their upper parts show a great deviation from the vertical in radial direction while the four pillars on the northern part stand straight This leads to the conclusion that in times of construction a static stabilizing mass of any sort of building had adjoined to the northern wall of KAM.

At least the orthophoto directs our attention to the fact that KAM – we think most parts inclusive the octagonal centre and the dome – had survived in the last 1500 years a lot of desastrous earthquakes (average: one earthquake every 30 years), the last big one was the Izmit-earthquake august 1999 with a magnitude of 7,4 which will be discussed at the end of the article.

The third example gives a first impression of the various cracks in the building especially in the octagonal centre. The dome of the KAM – later discussed in detail but now have a first look at figure 13 – consists of sixteen different segments, eight segments curved only in one direction with a window in it for the light and for static reasons and eight stronger segments curved in both directions in an alternate order. At the sides of the windows next to the border between the different segments there are theoretically weak points in the construction of the dome, in reality there are a lot of cracks. In the following we concentrate at two cracks of the described type: the first and most prominent crack (A) in the north east of the building starts in the dome in a height above the windows and passes through the whole building inside and outside. Crack (B) in the south west of the building is the symmetrical pendant and in some way the static answer of (A). The third crack (C) is a little bit untypical before it runs through the middle of a double curved segment above one of the big pillars. Figure 7 shows the context of the three discussed cracks.

Figure 7. Location of the discussed cracks

In figures 8-10 we show zoomed details of images taken at different times and we see the changings of the three cracks from the point of view of quality: two of the cracks can be seen today but they didn't exist or they were hidden at former times, one crack could be seen years ago but today it is plastered. To have a look at the changing of two of the cracks (A und C) from the point of view of quantity some photogrammetric studies were performed: measurements were performed on images taken in the years 1979 and 2002 with the help of an analytical photogrammetric system (WILD AC3), some photogrammetric blocks were adjusted by the bundle-method. At this way the changings of the two cracks in the last 20 years were determined: crack (A) and (C) opened more than 1 cm.

Figure 8. Crack (A): left: before 1908
right: in the year 2002

Figure 9. Crack (B): left: in the year 1968
right: in the year 2000

Figure 10. Crack (C): left: before 1908
right: in the year 2002

3. OLD DEFORMATIONS

Different photogrammetric studies suggested that the whole apse of KAM is declined due to the vertical. Therefore some images were measured and a bundle adjustment was calculated. The result can be seen very good at the front wall of the apse in the east of the building: the height of the front wall is about 10,5 m, the deviation from the vertical at the top of the wall is about 45 cm, cf. figure 11. It seems that the whole apse is not in a vertical equilibrium.

The problems of the vertical balances of the eight big pillars of the central octagon are also very interesting and important for static reasons. Therefore the direction of each pillar was photogrammetricaly checked using vertical plumb lines. Some images of each pillar were measured. The results of the bundle adjustment are shown in figure 11. The four pillars at the north side are in balance, the four at the south side are inclined due to the vertical with a deviation in radial direction of 30-40 cm, the height of the pillars is about 9,5 m. These deformations of the pillars result from the horizontal strength of the dome. It may be the static equilibrium from the beginning of the building. The question of asymmetry of that equilibrium stays unanswered.

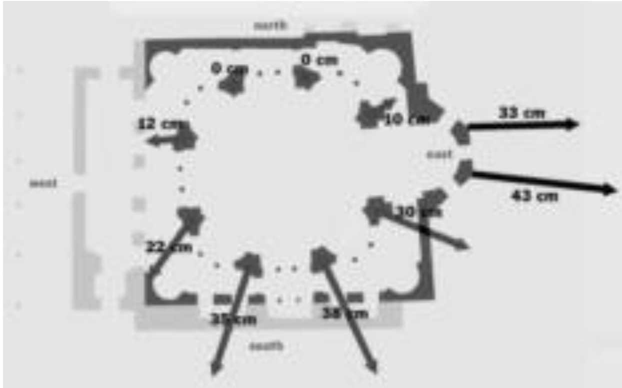

Figure 11. Deformations at the top of the pillars
and the front wall of the apse

4. NEW DEFORMATIONS

The growing of the cracks gave reasons for trying now to analyse the deformation of the whole dome of the KAM with existing photogrammetric images. To illustrate the cleverness of the construction we see in figure 12 a photogrammetric image of the roof of the dome taken from the minaret and in figure 13 the inside surface in form of visualized laser measurements.

Figure 12. Dome of KAM, image taken from the minaret

These laser measurements are taken from a campaign in early summer of 2002 where a complete laser-scan of KAM was performed. Some additional architectonic data: the dome built from brick masonry has an inside diameter of 16,5 m, the double curved segments have to pass the strength into the big pillars to get the static equilibrium, but only with the help of the deformations of the pillars. To get the searched information of the deformation of the dome we have measured and calculated 20 images of a bundle block taken in 1979 (camera TMK from

CARL ZEISS, ck = 60 mm, format 9 cm · 12 cm) and 35 images of a bundle block taken in 2002 (camera PENTAX67, ck = 105 mm, format 6 cm · 7 cm).

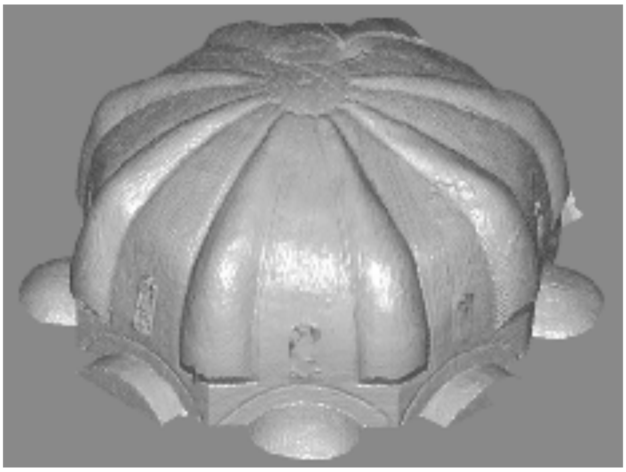

Figure 13: Surface of the dome inside, visualization of laser measurements

A lot of natural points in the painted ornamental decoration of the dome could be defined and measured in both data sets, normally each point was identified and measured in more than 5 images of each dataset. The measurements of the image coordinates were performed with the analytical photogrammetric stereo system WILD AC3. In the year 1979 some points in the ornament were connected with a three dimensional geodetic network with an overall precision of ±3mm.

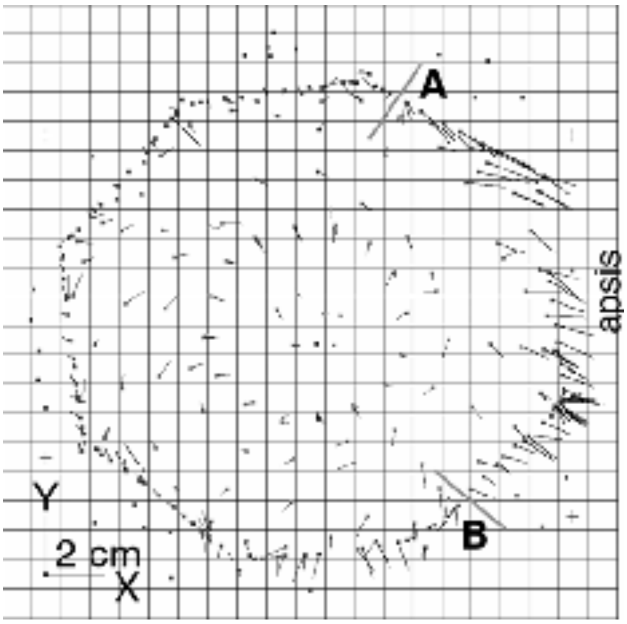

Figure 14. Deformation vectors of the dome, xy-plane, grid: 1 m, Cracks (A) and (B) signed

The 1979-bundle block with a precision of ±2 mm was in the free adjustment settled with s-transformation to the geodetic points. The precision of the 2002-bundle block was the same: ±2mm.

After extensive common analysis of the two blocks and looking at the real situation of the cracks some points west of the cracks in the lower and physically less disturbed regions of the dome were chosen for the connection of the two blocks with the help of the s-transformation in the free adjustment. Three dimensional deformation vectors were projected to the xy-plane, see figure 14, and to the xz-plane, see figure 15. It is not surprising that the part of the dome in the east between the two discussed cracks (A) and (B) had completely moved about 1 cm in direction of the apse before the whole apse seems to be out of balance. The height of the dome had sagged about 2 cm maybe as a consequence of the horizontal moving of a part of the dome but the definite analysis will just be possible with some more information to be find in the future. From static point of view the cracks – especially (A) and (B) – are very important elements for a definite analysis. The question of the time linearity of the moving is unanswered , next time we will look for a third bundle-block of the year 1998, one year before the big Izmit – earthquake.

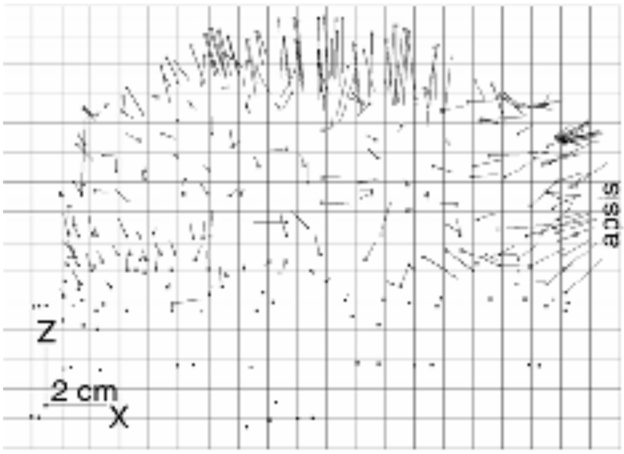

Figure 15. Deformation vectors of the dome, xz-plane, grid: 1 m

5. DOCUMENTATION OF THE EARTHQUAKE DAMAGES

The shocks of the last big so called Izmit-earthquake in Turkey (in august 1999, magnitude 7,4) gave reason for some additional damages in the KAM which can be documented with photographs and photogrammetric images, look at the examples in figure 16. Some of the damages are really new but most of them are hidden before or placed at the weak points of the building well known to the experts, in figure 17 we see an example of that theory: with the help of digital image processing it could be shown, that the defect of the piece broken in 1999 was known some years before, the piece was once more renovated in former times.

Figure 16. Damages of the earthquake in august, 1999

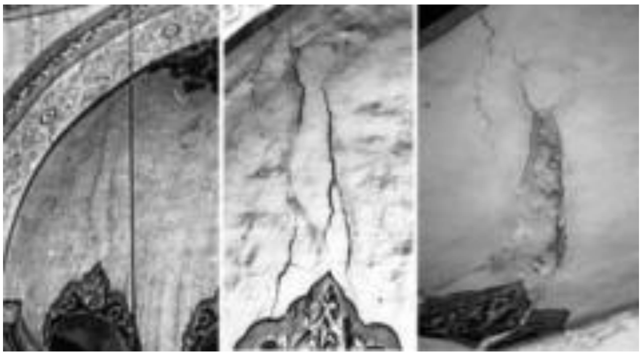

Figure 17. Damage of the earthquake 1999 (right), same situation 1979 (middle) and earlier than 1908 (left)

6. CONCLUSIONS

An edifice of such quality and importance like the KAM needs all efforts to save and guarantee its function and existence. On the one hand risk for the building or at least for same parts of the dome are existing at present day. The necessary restoration works are in stagnation, it may be caused by the necessary and also missing money but more by being afraid of the consequences of possibly unprofessional or risky decisions. On the other hand we must realize that the edifice especially the octagonal centre with the dome, exists for 1500 years because of the very high robustness of the structure. But now the disregarding of the existing dynamic effects in some parts of the dome may be the wrong decision of dealing with. One of the scientific answers must be to collect and distribute all existing information of KAM, the old idea of a complete and usable building information system must be recalled.

7. References

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