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HERITAGE GROIN VAULT MODEL GENERATION FOR THE SAFE EXPLOITATION LIMITS DEFINITION

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Abstract. Groin vault construction first exploited by the Romans, was used in Romanesque architecture and reached its ultimate expression in the Gothic architecture of the Middle Ages. Time however shows itself as structural weakness or overloading, dynamic vibrations, settlement, as well in-plane and out-of-plane deformations which can cause failure of masonry structures. Safety criteria must be specified by determining deformation limits between interacting parts of groin vault, to prevent emergency situation in heritage buildings. Safe exploitation of the building after crack appearance is possible, however cracked groin vault parts interaction must be specified by friction as well. The foundation settlement affect is the reason of shell part disintegration and hinge forming in main supporting ribs in the heritage's vaulted structure.

Three-dimensional scanning of arch structure by means of 3D laser scanners has been done and was used for geometric modelling of masonry arch shell.

The structures thrust line changes position in cross section and internal forces relocate significantly after the abutment deformations and crack forming in groin vaults.

Hinge mechanism simulation between two rotating masonry parts has been performed and discussed at the present investigation. Crack propagation in arch cross section has been considered as the hinge rotation result. It defines the position of the thrust line and rotation point in cross section. Cyclic crack opening and contact between surfaces of masonry parts allow making assumption about the tensile stresses drop in interacting parts. Riga Dome Cathedral has a good example of groin vault in deformed condition which monitoring is esssential and which model has been created using improved rotation mechanism of masonry rib parts and cracks opening measurements. Deformed condition vault model and long term crack monitoring will be used for analysis of the abutments deformations influence.

Deformation criteria have been developed for safety exploitation of heritage masonry structures.

Keywords: structural masonry, masonry fracture, groined arch (vault), heritage building safety.

Introduction

In medieval times masonry unions were using time approved methods for masonry structures and cross sections, shell geometry, proportions and forms. The object of investigation is deformed structure of Riga Dome Cathedral in Latvia capital city. Gothic arches which were built in 13th century using clay solid bricks were ones of the first masonry groin vaults structures in Latvia. Cross arch and star arch were commonly used as types of heritage building shell for Gothic brick cathedrals. Building of Riga Dome Cathedral was long process with delays, breaks and design changes. Construction of Dome Cathedral in Riga initially was planned as a hall building with huge limestone blocks, finally was finished in bricks; the constructive system of Romanesque was replaced by Gothic, hence the proportions and composition of the whole construction were changed. The size of the building increased together with growing city demands. Tower and nearest roof parts were lost due to fire happened in 1547. The supporting piles and subsoil situation in Riga Dome cathedral are being investigated. Their condition today was found unsatisfied. Wooden piles were common subsoil improvement technology for aggressive subsoil conditions in medieval times. Wooden pile lifetime is almost unlimited at the under ground water level. However eight centuries of the building exploitation has changed the piles to the unsatisfied state.

There might be multiple reasons which can cause masonry structures failure such as structural weakness or overloading, dynamic vibrations, settlement, in-plane and out-of-plane deformations. The basement settlement and seasonal temperature changes are the most heavy load on masonry structures. To prevent the accidental situation in heritage buildings, safety criteria must be specified by determination of deformation limits between interacting parts of groin vault.

Numerical modeling of masonry structures using modern digital tools demands additional material parameters such as elasticity, stiffness, compression, tensile and shear resistance of stone material and lime mortar, friction angle and cracking energy. Interaction between the parts of the cracked masonry shell must be described allowing friction also, because safe exploitation of the building after crack forming is possible. Earlier calculation methods based on “middle third” rule predicted structural safety by force position in structural element cross section. After abutments deformations and crack forming in shell structures thrust line changes position at the arch cross section and internal forces of the construction relocate significantly. Therefore the main task of this research is safety exploitation criteria definition for deformed groin vault. Thrust line position in cross section depends on the shell curved surface geometry. Precise geometry model has been created using 3D laser scanner in the form of point cloud.

Masonry shell geometry modeling

Structural modeling of masonry shell elements is reasonable in high precision only. Laser surface 3D scanner was used to avoid optical measuring and respective effects of low precision and immense amount of time spent for measurements. More than five arc rib geometric proportion types were found in previous geometry measurements. Regular geometric forms shown in Fig 1 are human interpretation of real geometry.

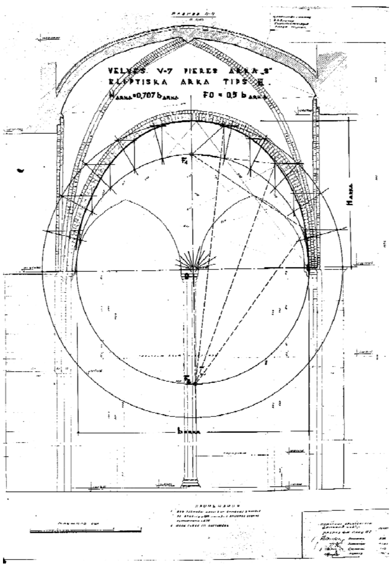

Fig 1. Optically measured main rib geometry by survey engineer Erdmanis in 1963.

Precision of the optical measurements and point net distribution is not satisfactory for the precise model used for the structural analysis.

3D laser scanner precision is 2-3cm measured point distance on surface and 2mm within 50m distance. Measurement mesh with 3cm step size provides necessary precision for structural modeling of curved surfaces. Whole cathedral interior 3D laser scanning was performed by Kalinka’s team during one week. Point cloud processing on the surface model proposed at the paper e.g. (Kalinka and Rutkovska 2007) is a guideline for surface model meshing. Point coordinate transfer to surface model by specialized tools is reverse engineering procedure. Point covering process with Geomagic Studio code is one of the ways to prepare the surface mesh model. Mesh model deviation from point cloud model is shown at the Fig 2.

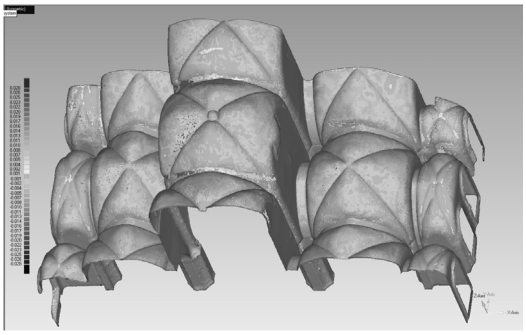

Fig 2. Mesh model deviations from point cloud model are within 2mm limits.

Modern computing codes are limited mostly to 100000 mesh elements. Therefore precise surface model consisting of 5,7 millions triangle elements is not useful for structural computation codes.

Ways to reduce the triangle elements mesh are:

– Reduction of the triangle elements amount at the flat surfaces gives ~90% reduction of plane triangle elements
– Reduction of the triangle elements amount at the curved surfaces gives ~50% reduction of the whole model triangle elements.
– Model size cutting in accordance with the structural analysis tasks, gives ~50% of the whole model triangles reduction.

Reducing of the triangle elements amount at the curved surface significantly increases triangle mesh deviation form point clouds. Mesh model deviation from point cloud generalized in Table 1 is the object of choice between model precision and triangle count in mesh.

Table 1. Mesh size influence on the model deviation in comparison with point cloud curved surface

Model size	Triangle side length	Mesh deviation
[triangle count]	[mm]	[mm]
5,7 million	34	0.015
4,0 million	51	0.700
2,3 million	73	0.810
1,7 million	103	1.346
1,2 million	126	1.622
0,8 million	166	1.670
0,6 million	189	3.585
0,4 million	212	4.259
0,2 million	266	6.497
0,1 million	414	9.788
0,05 million	685	12.971

Mesh model total deviation for 400 mm masonry shell is acceptable as 1/30 of shell thickness. Total geometry deviation during laser scanning must not exceed the limits of 13,4mm, to stay within allowed 5 % deviation limits of the axial force eccentricity for the structural calculations.

Model trimming by symmetry planes in most of the computing codes can be compensated by defining of computational problem symmetry.

Modeling of masonry shell elements using laser scanner data gives possibility of the cathedral modeling by FEM code. Therefore material properties must be defined.

Masonry computational methods

Masonry consisting of stone and mortar is inhomogeneous material in micro scale modeling approach. For modeling of large building parts of whole building macro modeling and homogenization of material must be used.

Since 17th century engineers use material homogenizations for masonry material approach. Hooke's law defined in 1676 for approach of long lasting linear elastic material was used for analytical calculations. Modulus of elasticity was defined as main parameter for elastic material approach.

In end of 19th century elastic analysis was developed. In fact, until ca. 1880, engineers divided arches into "elastic", made of wood or wrought iron, and "rigid", made of masonry. Poncelet (1852) was conscious of the problem and in his historical review of arch theory suggested to apply the elastic theory to masonry arches in order to obtain a unique solution. Already in the 1860's some elastic analysis of masonry arches were made. Winlker (1879) make a discussion of elastic material approach to masonry structure. However, he added a discussion on the "Störungen" that can affect the position of the line of thrust. Their main origins were: the deformation of the centering during construction, the yield of the buttresses under the thrust and the effect of changes of temperature. All these perturbations would produce some cracking of the arch and Winkler was noticed this affect notably the position of the line of thrust, which could be very different from the calculated. Winlker suggested that some means of controlling the position of the line of thrust by inserting internal hinges during construction. Castigliano (1879) applied his theory of elastic systems also for masonry bridges. Elasticity theory gives admissible results till elasticity limit of material. In heritage building supporting structures compressive stress level is not high and elastic material behavior is applicable. In early stage of elastic analysis develop for masonry structures engineers showed a certain resistance because of material anisotropic and irregularity. Elastic material approach in masonry shell systems gives uncertain results therefore computing approach development seams necessary. The historical development review of first computational methods was done by (Heyman 1999).

For masonry computing with triangular finite elements material homogenization is only way of masonry material definition. Latest developments of GEM code taking into account material strength limiting values and unlinearity of elastic properties.

Material homogenization for FEM involves some assumptions:

– Triangle orientation of model is not fixed globally, therefore material properties must by defined as isotropic.
– Compressive and tensile limits must de defined for weakest orientation

Masonry material compressive and tensile resistance depends on bed joint orientation as described in (Page 1983 – Fig 3) and (Dhanasekar *et al.* 1985) publications.

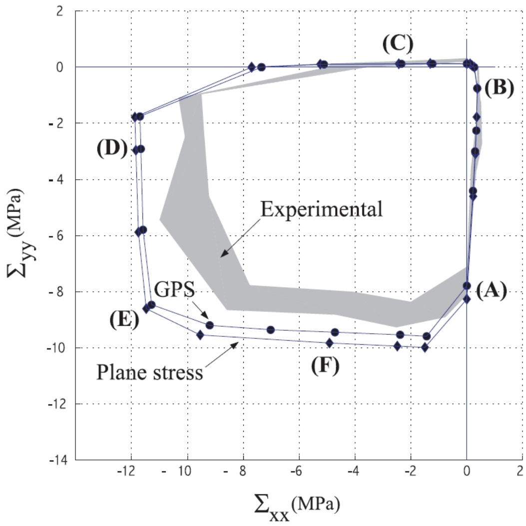

Fig 3. Masonry resistance in biaxial loading according to bed joint orientation (Page 1983).

Homogenization method and triangular model meshing eliminates masonry orientation effect by unknown internal force orientation.

Homogenizations of material included in most of building codes give simplify rules for material property description and usage in calculations. In previously done research bricks were investigated to find masonry material elasticity properties, e. g. (Bondars and Korjakins 2007a) and work out material definitions according Latvian building code. The homogenization of material means generalization of stone and mortar properties for elastic material property definition adopted for computational usage in elastic stage. Elasticity dependence from brick and masonry class defined from cube resistances of brick and mortar material shown given by previous papers, e.g. (Bondars and Korjakins 2007b).

3-point bending tests performed by Riga Technical university building material test laboratory show wide range of material compressive and tensile resistances for clay bricks of Riga Dome cathedral. In according with test results homogenous material properties are defined as: prime modulus of elasticity (E_0 = 3600 MPa), average modulus of elasticity (E_{mean} = 818 MPa), Yong's modulus (G = 1200 MPa), Poisson's ratio (0.2), linear thermal expansion coefficient (α_t = 0.000005 1/degree), density (ρ = 18 kN/m^3), brick compression resistance (R_1 = 4.5 MPa), mortar compression resistance (R_2 = 2.5 MPa), masonry compression resistance (R = 1.1 MPa), masonry centric tensile resistance (R_t = 0.05 MPa), masonry shear resistance for head joint (R_{sq} = 0.11 MPa), masonry tensile resistance in bending for head joint (R_{tb}=0.08 MPa), resistance to main tensile stresses (R_{tw} = 0.08 MPa), coefficient of creep effect (v = 2.2).

Defined in equation 1 by Latvian building code methodology limiting tangential stresses is based on Moore stress theory:

$$\tau_{red} \le R_{sq} + 0.8 * \mu * \sigma_0, \qquad (1)$$

where μ = 0.7 friction coefficient by joint mortar; σ_0 – compression stresses average value from lightest loading with reduction coefficient 0.9. Tangential limiting value is defined as crack forming value for shear forces in macro modeling material approach.

To compare numerical investigation by FEM code with real movements crack monitoring is providing since year 2002. As the investigation complex for Riga Dome cathedral automated crack monitoring system was proposed by Riga Technical university staff.

Crack monitoring system

Two years of crack monitoring by optical tensometer system collect the tendencies of widening of the cracks.

Surveillance des Ouvrages par Fibres (SOFO) optical fiber sensors monitoring system received from Smartec are mounted in year 2007 to change mechanical tensometer crack monitoring to a long term monitoring system. Optical sensors measure the cracks for controlling movement of masonry parts in five years for ensuring safe exploitation. According with mechanical tensometer monitoring reports presented from 2005 crack oscillation varies 1–2 mm every year depending on season. The main reason of optical tensometer usage is computational control of measurement data, long lasting life period and minimized side factor's influence on measurement's quality. Principal scheme of Smartec Bee unit and tensometer connection is given in Fig 4.

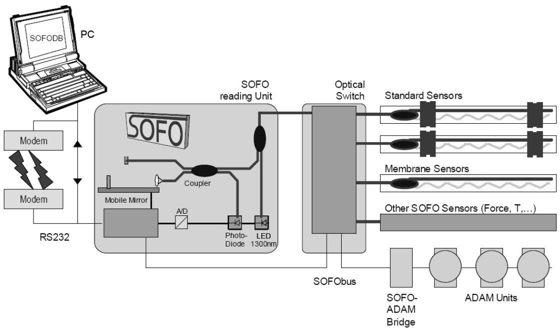

Fig 4. SOFO principles of optic tensometer

The SOFO measuring system gives precision of 0.02mm therefore defining high level of monitoring. Used as reading unit Smartec Bee allows control of 24 optical sensor units and communicates with registration PC trough telephone line. Additional thermo sensors for external and internal temperature control are included in measured program. Data storage in reading unit internal memory gives data downloading possibility by reasonable schedule. Battery support of reading unit gives possibility of non-stop monitoring. Crack widening caused by support deformation is the criteria of safe criteria exploitation definition workout.

Cathedral cross section and tensometer montage scheme on masonry shell ribs shown in Fig 5.

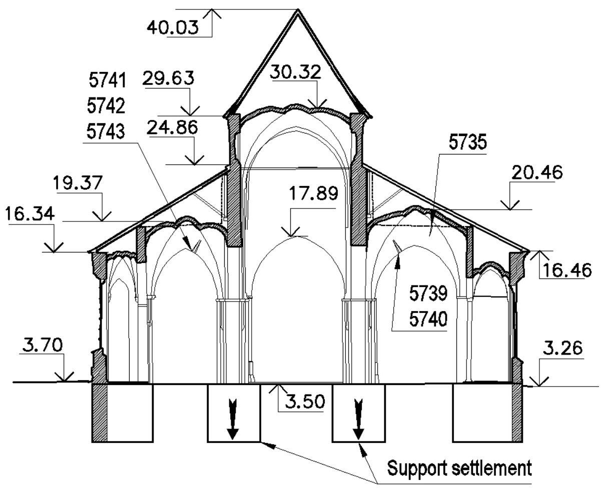

Fig 5. Optical tensometer montage scheme on masonry shell ribs

SOFO readings in Figs 6 and 7 show seasonal crack oscillations by tensometer 5735 and 5740 in two year period.

The sensors highlight hinge rotation mechanism of shell rib. Support deforming leads to crack opening under tensometer 5740. Deformation indicated by tensometer 5735 is mainly from seasonal temperature and humidity changes. Deformation progress highlighted from tensometer 5740 readings 0.18mm/year. 21 optical tensometers register crack oscillations every two hours. Structure deformations as an exploitation condition and loading effects are recorded for future numerical model validation.

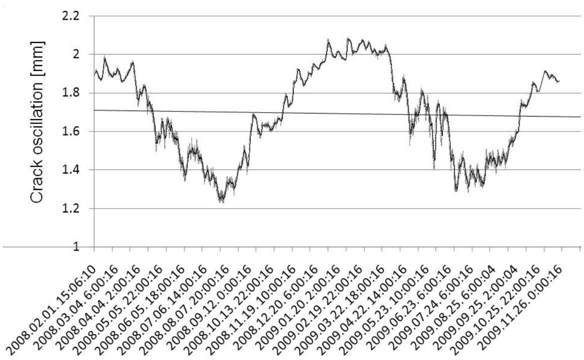

Fig 6. Tensometer 5735 data from 01.02.2009 to 26.11.2009

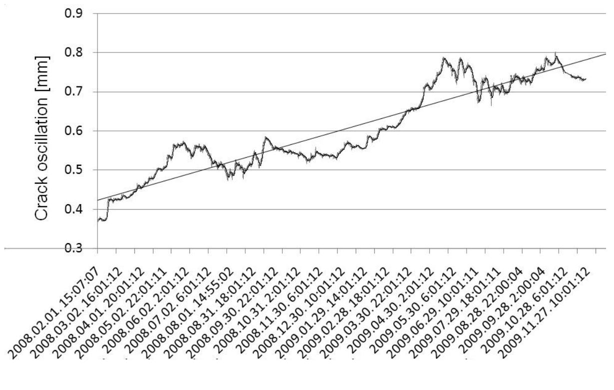

Fig 7. Tensometer 5740 data from 01.02.2009 to 26.11.2009

Developing masonry shell exploitation safety limits numerical simulation using natural loading and load combinations is required.

Masonry shell loading

Self weight loaded cathedrals shells in exploitation time are affected by humidity, temperature changes and support deformations. Humidity affects the masonry mortar by increasing plasticity. Masonry plasticity under high level internal forces is a reason for changes of shell geometry and decrease safety exploitation limit. Also mortar degradation is the effect of lime bounding component exposure to moisture.

Temperature measurements provided by crack monitoring system show good correlation between crack movements and temperature changes. Crack opening Temperature loading is considered as second significant loading on masonry structure.

Internal and outside temperature is measured in the same cycle as crack oscillation. As additional control surface temperature on wall surface from interior and exterior were measured manually. Temperature of masonry wall surface diverges in winter from air temperature by -2 ºC from inside and +2 ºC from outside. In the hottest summer day the situation was similar for internal surfaces but extremely differs from outside surfaces exposed to sun radiation. Surface temperature divergence was +16 ºC due to sun radiation effect.

Long term support settlement is main loading on rigid building structure. Masonry shell overloading by unequal support deformations is a reason of crack forming in shell ribs. Low tensile resistance of masonry materials and seasonally cyclic temperature oscillation leads to existing crack prolongation.

Support condition and subsoil situation survey in last two years made by CM GIB Geotechnical Company presented by Celmins and Markvarts show weak soil layer presence under footings. Started in 2005 geotechnical survey is more detailed than in former Soviet period ever done. Geological investigations highlight deteriorate of pile and subsoil conditions. Wooden piles and surrounding low density sand reduce subsoil stiffness and bearing capacity.

Presented method for safe exploitation limit prediction is settlement prognosis analyzing monitoring data. Unequal settlement for central columns and perimeter wall foundations is the reason of crack prolongation in masonry shells.

Settlement numerical modeling

3D laser scanner data transferred to numerical model is high precision guaranty from geometry point of view. Masonry material investigations make possible usage of homogenization method for material approach. Influence of central column settlement on internal stress level is shown in Fig 8.

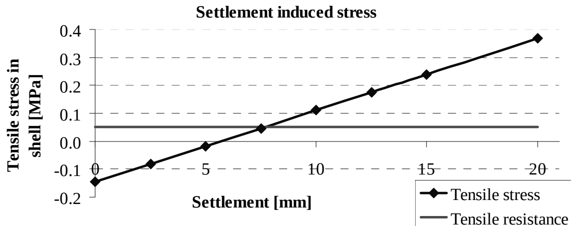

Fig 8. Stress development in masonry shell induced by central column settlement

Limiting value of tensile stress for homogenous material defines the masonry centric tensile resistance (Rt = 0.05 MPa). Previous researches eg. (Anzani *et al.* 2000); (Anzani *et al.* 2001) show masonry creep effect starting from 50 % of compressive resistance. In mentioned paper e.g. (Anzani *et al.* 2001) are shown cyclic loading effect on masonry deformation properties and compressive resistance limit, shown in Fig 9.

High compressive stresses and creep effect in masonry shell hinge forming zone leads to geometric nonlinearity.

Progressive collapse investigation e.g. (Macchi 1992) highlights loading when wind, foundation deformations and earthquake combinations leads to load bearing limits. Such load combinations induce serious structural damage or even building part collapse. Degradation of masonry material, cyclic loading and load combination effect are presented in investigation e.g. (Binda 1997). As pointed out in the historic masonry tower collapse investigation e.g. (Binda 1997) no significant material degradation found before accident.

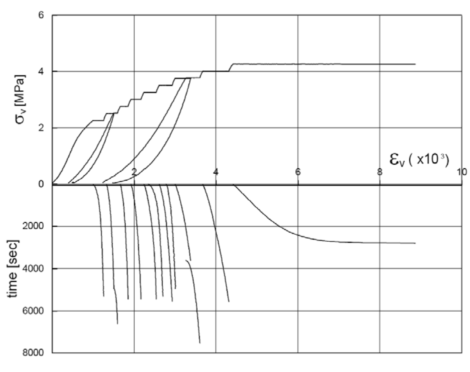

Fig 9. Masonry creep in cyclic compressive loading tests (Anzani *et al.* 2001)

Numerical simulation and model examination on possible load combinations is the proper method for safe exploitation limit definition. Central column basement progressive settlement has been found in Riga Dome cathedral. Assumption of the crack linear growth by 0.18 mm in one year period is taken as average progress for hinged mechanism movements. Deformation transfer is the key to monitoring data analysis. Hinged masonry structure deforms and the pressure under foundations changes in long term.

Conclusion

The present research is a small part of huge monitoring and investigations amount done in Riga cathedral.

Several conclusions can be formulated from the performed work. Detailed investigations of the material properties, exploitation conditions and deformed situation must be taken into account for generation of numerical model.

Laser scanning based surface geometric data transferred to FEM computational software significantly reduces modeling time. Improved laser scanned precision and computational model limits will give the powerful tool for structural analyze of heritage buildings in the future.

Analysis of each hinged mechanism separately and mechanisms complex for the whole cathedral most dangerous parts highlighted to pay extra attention. Safe exploitation time taking into account linear unequal settlement progress 0.18mm/year is defined for 30 years.

Data collected from SOFO reading unit approves assumption about seasonal temperature changes effect on masonry structures. Measured temperature oscillation from -1.1 ºC to 24.1 ºC gives stress changes in massonry shell by 0.012 MPa.

It is necessary to point out the side effect of building process and exploitation: significant dispersion of material properties; geometric and material variations; deformed conditions and various material interactions.

Proposed methodology is the only way for the safe exploitation limits definition of heritage masonry shell structures. Numeric simulations highlight deformed shape influence on thrust line position in arch shell and leads to safe exploitation criteria definition for the whole building.

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