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MONITORING PROGRAMM CRITERIONS DEVELOPMENT FOR EVALUATION OF GROINED MASONRY ARCH STABILITY

MŪRA VELVJU STABILITĀTES NOVĒRTĒŠANAS MONITORINGA KRITĒRIJU IZSTRĀDE

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Introduction

Since past masonry structures were built by time-honored method of trial and error. The one of the first written rules and building code was "de Architectura" in ten volumes written by Marcus Vitruvius Pollio, roman architect approximately at 1st century. Medieval time masonry unions use time approved methods of masonry structure cross sections, shell geometry, proportions and forms. Masonry code in medieval Europe was distributed by Christianity influence as sacral building forms, proportions and architectural styles. An objective of investigation is deformed structure of Riga cathedral in Latvia capital city. 13th century built masonry Gothic arch shells which are built from solid clay bricks are one of the first masonry shell covered structures in Latvia. Cross arch and star arch shell where commonly used as type of heritage building shell. Long building process and changes in finale view of cathedral was usual by-effect in building process centuries ago. Riga Dome Cathedral had long erection process with stop breaks and design changes. Few steps of erection and enlargement by changing city demands took place also. Tower and nearest roof parts were lost due to fire happened in 1547. A cross and star type masonry arches were partly rebuilt after Swedish / Russian war in 16th century. Medieval European Hansa union cities were usually located near river deltas. The supporting piles and subsoil situation therefore in Riga Dome cathedral are survived today and found in the unsatisfied conditions. Weak subsoil under building foundations is common situation in the Old Riga city. For lot of buildings wooden piled foundations are used to transfer loads to dense sandy layer through loose sand located under footings. Wooden pile lifetime practically is not limited under ground water minimum level but the piles state after eight centuries of building exploitation has been evaluated as unsatisfied.

Structural weakness or overloading, dynamic vibrations, settlement, and in-plane and out-of-plane deformations can cause failure of masonry structures. To prevent the accidental situation in heritage buildings safety criteria must be specified by determining deformation limit between interacting parts of masonry arch shell.

Numerical modelling of masonry structures by modern computing tools demand additional material parameters such as elasticity, stiffness, compression, tensile and shear resistance of stone material and lime mortar, friction angle and cracking energy. Cracked masonry shell part interaction also must be specified by friction because safe exploitation of building after crack forming is possible. Thrust line in non-cracked arks show center of compression force in cross section and for medieval buildings almost is located on center of cross section predicted by geometric proportions carefully improved in mason unions. Later calculation methods based on "middle third" rule predicting structural safety by force position in structural element cross section. Uncracked masonry arch shells can be easily computed using modern GEM software's and plastic material approach. After support deformations and crack forming in shell structures thrust line change position in cross section and internal forces relocates significantly. Therefore the main task of present research is safety exploitation criteria definition for deformed masonry arch shell.

1. MASONRY COMPUTING EVOLUTION

The main problems in the structural analysis of historic buildings are following:

- Lack of data about geometric dimensions
- Material properties of the inner parts those are not visible exteriorly of the structural members that are huge in cross-sectional dimensions
- Difficulties in identifying the characteristics of construction materials
- Excessive cost of detailed laboratory analyses
- Variety of the data due to construction techniques and natural material utilization
- Altering material properties even along the same structural member due to long-lasting construction process
- Uncertainties in construction process and steps
- Indefiniteness of general stability and strength continuity due to the existing damage on the structure
- Inability in the application of modern construction materials, structural analysis and loading conditions.

Modern computing technique, mainly based on FEM software, gives possibility to detail analyze of heritage buildings. The historical review is necessary to understand the computing evolution and background of modern computing technologies.

1.1. Geometrical approach

Time honored geometry of arch structures was approved by geometric methods till 17th century. Arch and cross arch is a statically indeterminate structure and therefore the first calculation methods were developed to simplify design methodology. In 17th century ca. 1670 Hook's proposed hanging flexible line thrust line definition method, that was brilliant idea for very first arch geometry approach. Adequately weight distributed hanged line give ideal tension line which in inverse form gives ideal compression line or trench line as brilliant solution of statically indeterminate structure. That type of solution is useful for vertically loaded arch structure but doesn't include horizontal loading. In Riga Dome cathedral three arch horizontal interacting forms the horizontal loading eliminate this methodology usage for that type of buildings. Developed by Moseley (1833) “new Theorem in Statics” where the Principle of Least Pressure was proposed describes structures widely. Later Moseley (1843) specialised this approach to arches. Methodology, proposed by Villarceau (1853) for reducing the statically indeterminate level of arch by inserting the three hinges to statically determinate system, was mostly applied analytic method till development of elastic analysis method. Towards the end of the 17th century, the studies of Galileo on strength analysis brought the medieval structural theory to the end. In those times, the scientific deal was mainly in the analysis of string-resembling the arch form under vertical forces. In 1826, Navier put forward idea that the buildings should be designed by means of calculations of the stresses on its structural members rather than the application of some geometric rules.

2.2. Elastic analysis

In the 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 performed. 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 cause some cracking of the arch and Winkler was well aware this affect, notably at the position of the line of thrust, which could be very differ from the calculated. Winlker proposed some ways for controlling the position of the thrust line by inserting internal hinges in the arch constructions. Castigliano (1879) applied his theory of elastic systems also for masonry bridges. Elasticity theory gives admissible results in the range of 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 the masonry shell systems is giving uncertain results and therefore computing approach development is necessary. The historical development review of first computational methods was done by Heyman [1,2].

2.3. Kinematic approach and arch collapse mechanism

Hinge forming by loading, thermal variations or geometric changes is most often of arch collapse reasons. Material plasticity in hinges in self-weight loaded masonry shell system is main reason of safety limit exceeding initiated by support deformation. Support deformation creates the hinges in arch masonry structure as interaction contact by sliding surface. Safe exploitation criteria therefore must be defined. The kinematic or 'mechanism' method was introduced by Heyman [3] for the first time. Heyman assumptions for arch safety analyze method were infinite compressive strength and friction resistance and zero tensile strength. He pointed out that plastic limit analysis can apply well to the case of masonry gravity structures, such as piers and arch bridges. In his book, for the single span arch, Heyman assumed the arch will collapse when four hinges are formed. Furthermore, he assumed that the arch has infinite compressive strength and sliding failures cannot occur. The hinges can alternately develop at the intrados or extrados of the arch, and in failure conditions, the thrust line must pass through the hinges. Therefore, it is possible to determine the magnitude of the applied load which will cause the arch to collapse. By Heyman, [4,5] the kinematic approach takes into account a collapse mechanism activated by an adequate number of plastic hinges. As main criteria of safe exploitation definition was Heyman proposed methodology. When the thrust line in a cross section is adjacent to the ring of the arch, a hinge is opened in that point. According to the upper bound theorem from the theory of plasticity, the maximum load corresponding to some collapse mechanism is greater or equal to the maximum load corresponding to the real collapse mechanism. This theorem implies that when the thrust line is adjacent to the ring of the arch in four points then the arch is not safe. Friction is high enough between stones and sliding failure cannot occur. The masonry has an infinite compressive strength practically. More complicate collapse mechanism has been considered for twin-span models by Hughes [6]. The pioneer in using modern computational methods to determine the collapse load of block structures was Livesley [7], who attempted to find solution by a linear programming problem using the lower bound formulation. In his paper Livesley showed that the adoption of associative friction leads to an incorrect collapse mechanism. It may also give an overestimate of the true collapse load as results. When using linear programming to solve limit analysis problems, flow will always occur normal to the specified surface (i.e. according to the so-called 'normality rule').

3. Masonry material approach

In present research are proposed two step computational approaches. A complete and detailed review of micro and macro material approach may be found in Lourenco [8] for mechanical aspects at both scales. The first stage of presented computational methodology is deformed structure modeling by elastic macro modeling approach to understand building state in common and decrease computing amount. In second stage of analysis deformed structure state must be investigated interaction between cracked masonry parts. Therefore micro modeling material approach is most convenient.

3.1. Macro modelling approach

Homogenizations of material included in most of building codes give simplify rules for material property description and usage in calculations. In previously done research other heritage brick building was investigated to find masonry material elasticity properties and work out material definitions according Latvian building code. Elasticity modulus has been obtained from the test results of 1912 year built groined arch masonry material. The homogenization of material means generalization of stone and mortar properties for elastic material property definition adopted for computational usage in elastic stage. Long lasting linear elastic material approach was used for analytic calculations in Hooke's law defined in 1676.

To understand the heritage masonry there are 3 point brick bending tests done. Bending test results are shown in figure 1 highlighting main problem of heritage masonry material definition – load bearing resistance result dispersion obtained due to hand made manufacturing process. 3 point bending tests show different tensile resistance by crash force. Tests show equal elasticity modulus and brittleness of material for all specimens.

Structural analysis in elastic stage using FEM linear masonry approach is generally used. At the same time elastic theory can not be applied for case when internal forces in masonry is close to limit of compression resistance. The plasticity theory must be used in that case. Not only quality of manufactured bricks significantly affect to whole masonry material properties, but also usage of the various stone materials, block size and form variations, mortar component variations and joint thickness variations.

Aim of this investigation is to give possibility to understand and analyze masonry arch, in fact, any combination of them, i.e., a masonry building. Behind plaster layers forming the regular forms and levels wall surface a most irregular internal structure of masonry is found. Homogeneity, isotropy, uniformity of the mechanical properties, etc., all the common assumptions of modern conventional structural analysis cannot be applied in this case without violence to the most basic common sense. Mechanical properties of masonry have been obtained from the results of the tests performed in Riga Technical University. By using these results in computational analysis the obtained sress-strain state can be used for evaluation of deformed state structural understanding.

Masonry has been modelled by FEM computer code STAAD Pro using following material properties: 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), thermal linear expansion coefficient (α_t = 0.000005 1/degree), density (ρ = 18 kN/m3), 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).

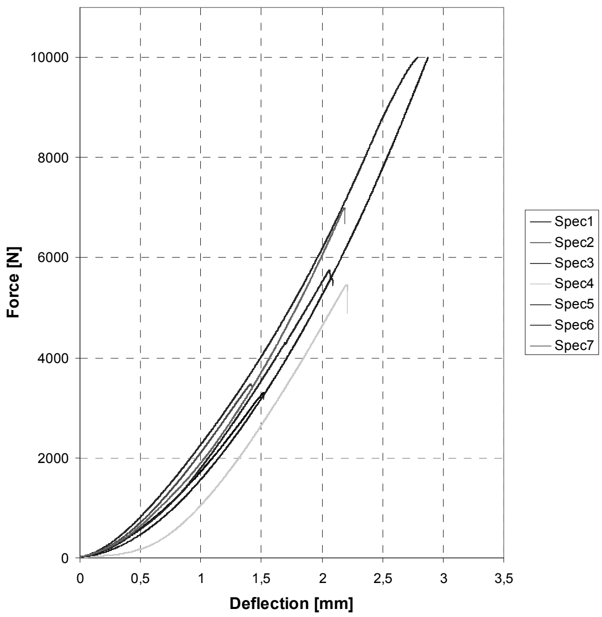

Fig. 1. Three point brick bending test results

Equation 1 defines tangential critical stress for starting of crack forming

$$\tau_{red} \leq R_{sq} + 0.8 * \mu * \sigma_0 \quad (1)$$

where μ = 0.7 friction coefficient of mortar; σ_0 – average value of compression stresses issued by dead loading with reduction coefficient 0.9.

Macro modelling approach is simplifying material description and may normally be used in analytic FEM structural computing [9]. The macro modeling of masonry as a composite is the latest developed material approach by Rots [10]. Lourenço and Rots [11] macro-modelling technique, specifically formulated for the analysis of masonry constructions, is based on considering all inelastic phenomena simultaneously in the masonry joints by means of a composite interface model. This model, stemming from plasticity, comprehends three different failure mechanisms, namely, a straight tension cut-off for mode I failure, the Coulomb friction model for mode II failure as well as an elliptical cap for compression and combined shear-compression failure. As in the previous case, Lourenço and Rots model requires the values of the initial axial and shear stiffness K_N and K_T as input data.

3.2. Micro modeling approach

Micro modelling of masonry material gives possibility precisely describing an interaction between stone materials but significantly increase computing time. In early stage of micro modeling dry joint approach was used. In the latest developments a block and a mortar in the joints are represented by continuum models, whilst the interface unit-mortar is represented by discontinuous elements. The Young model, the Poisson coefficient and the inelastic properties of the units and the mortar are taken into account. Micro modeling is widely investigated and described by Lourenco and Rots [12] and allows calculate plasticity of mortar material and stone material, load bearing tensile and compression resistances depending from joint position, friction angle etc. Micro modelling material approach must be used in second step of computational investigation to analyze support settlement in case of deformed structure. For those purposes additional masonry material properties must by involved.

4. Monitoring data collection

After World War Two Riga Dome cathedral was closed as church and reorganized to concert hall. Soviet government put serious amount of funding to uplift and repair the structure of this one, installed new ventilation, heating and fire safety systems. Latest funding in those systems renovation, crack monitoring and geological survey gave a possibility to install long term monitoring system and make the present research.

4.1. Cracked arch photo fixation

Since 1959 cracks has been surveyed in the Riga cathedral. Photo fixation made by heritage building protection institutions shows lack of cracks in masonry shells. This information is useful for understanding the new cracks development and prolongation of existing one during a long term monitoring.

4.2. Arch masonry building sequence and layer orientation fixation

Collected in State Cultural Monument Archive materials keep information about structure investigations and reconstruction processes of Dome cathedral. From 1960 to 1961 each arch has been sketched and described by J. Stukmanis. Each brick and block sizes, form, orientation and position in masonry structure have been described very carefully. Arch orientation, rib positions, brick sizes and forms were fixed in his work (fig. 2), as well as, description of damages and cracks for each arch.

Fixation of damages after World War Two is very useful information in nowadays to understand changes during the time, since plastering of arch surface was accomplished and cracks have been hided after it fixation. Existing cracks prolongation and widening, as well as new cracks fixation of masonry structure therefore can be done by present crack monitoring.

4.3. Cathedral scanning by 3D Leica laser scanners

3D detailed scanning of the Dome cathedral performed in 2006 by Leica laser scanner give precise geometric surface of building and can be used for computational analyze of structure. Precision of 20mm on internal surfaces and less detailed for outside surfaces usually used for scanning the structures.

Figure 3 shows plan of building section, obtained from 3D scanned model. This plan highlights geometrical uniformity of structure in comparing with measurements made by hand tools by Slavietis, Seglins and Drugis in 1959. Scanned Gothic arch geometry is preferable in comparing with Erdmanis 1963 proportionality findings also (fig. 4). Proportion findings are simplifying method of geometric approach using for the hand calculations of thrust line. Geometrical inequalities lead to serious difference between existing and real state in cross section.

By means of modern computational FEM software there is a possibility to analyze the whole building. The laser scanning can be evaluated as very fast geometric modelling of construction.

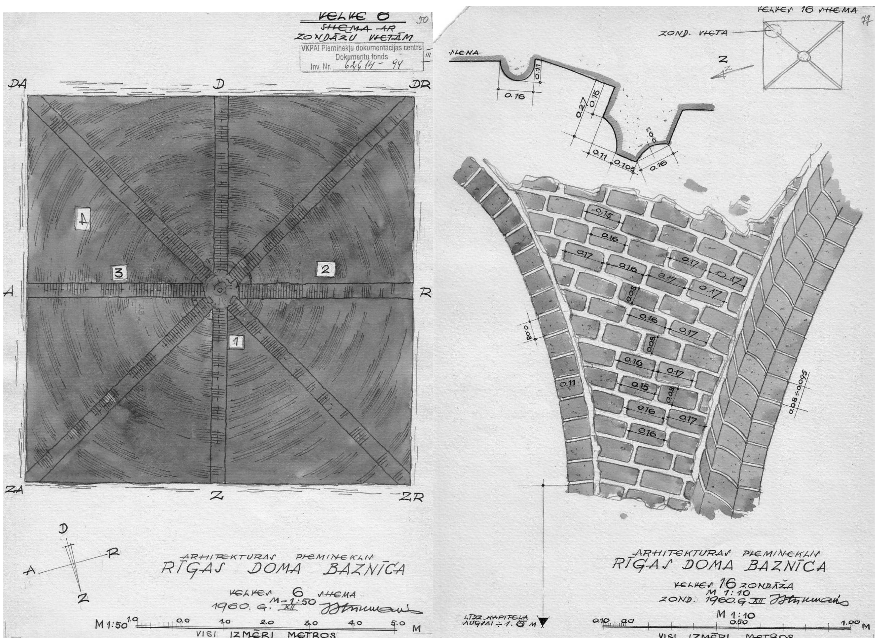

Fig. 2. Careful fixation of all cross arch shells was done by J. Stukmanis

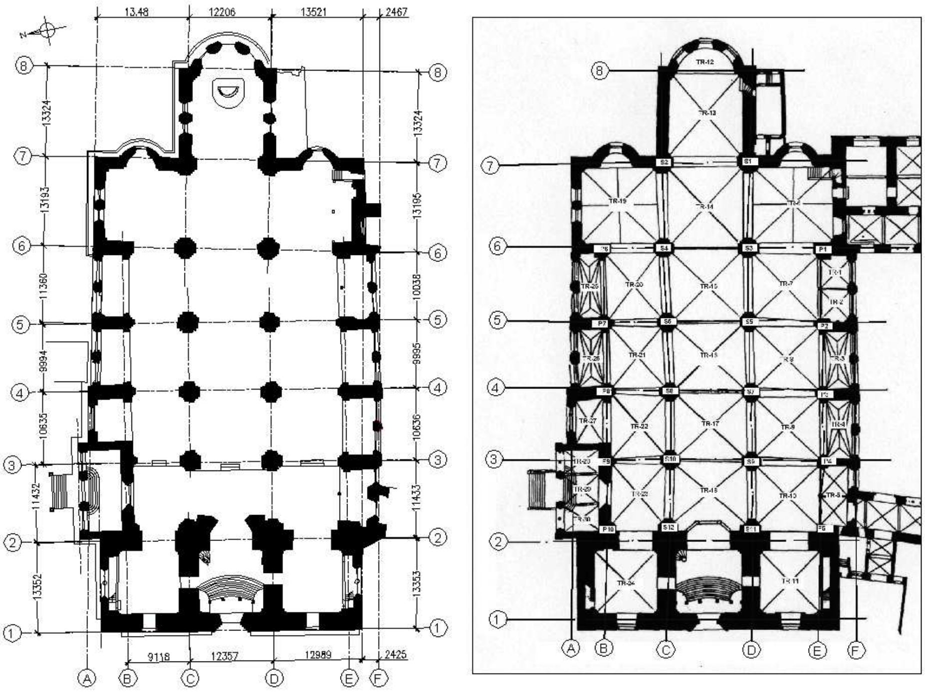

Fig. 3. Full 3D model of Dome cathedral made by walls and arches marking

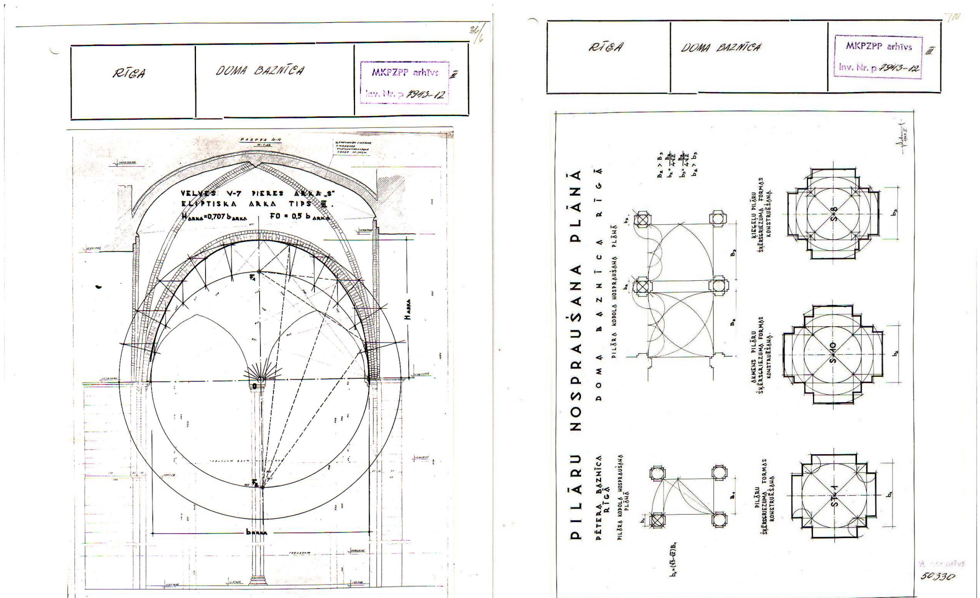

Fig. 4. Proportionality findings by Erdmanis in 1963

4.4. Microclimate monitoring

The microclimate monitoring for internal temperature and humidity was performed from January 2002 to June 2004 by Dome cathedral staff. Temperature oscillation significantly influences on masonry deformations and crack movement. External and internal temperature measurements are included in monitoring program of installed in 2006 year SOFO type equipment.

Temperature initiated deformations simulated by computer modeling show significant influence on crack forming, prolongation and movements. Cyclic temperature loading in eight hundred years of cathedral life time affect not only internal comfort but also stress situation in cross arch system seriously changing thrust line position. Solar radiation effect on cathedral external surface can be defined as load on FEM elements also.

4.5. Support condition survey

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. Cross section of piled supported column footing is shown in figure 5. Marked as 7'''D low density sand layer around the wooden pile footing is main reason of unequal deformation of Dome cathedral part.

State of wooden piling was evaluated as an unsuited also. Support deformations during the time counted as main reason of crack forming in masonry arch. One of the aims of the present research is definition the safe exploitation limits. Extreme support deformations of masonry shell system change force lines and part interacting stresses in the shell sections. Obtained information about thrust line position changing in cross section of construction due to cracking of masonry can be used for definition safe criteria of building expluatation. Further deformations of supports can cause a crack prolongation, plastic hinge forming and unequal support deformation possibility.

To understanding ground water flow and level changes in the Old Town the Riga city Department ordered ground water control monitoring from Balt-Ost-Geo Company. The ground water table monitoring during 2006 showed wooden pile coverage approximately on 0.4m and less. In the case of wooden pile tops are not covered by ground water table wood structure is possible degradation of these one.

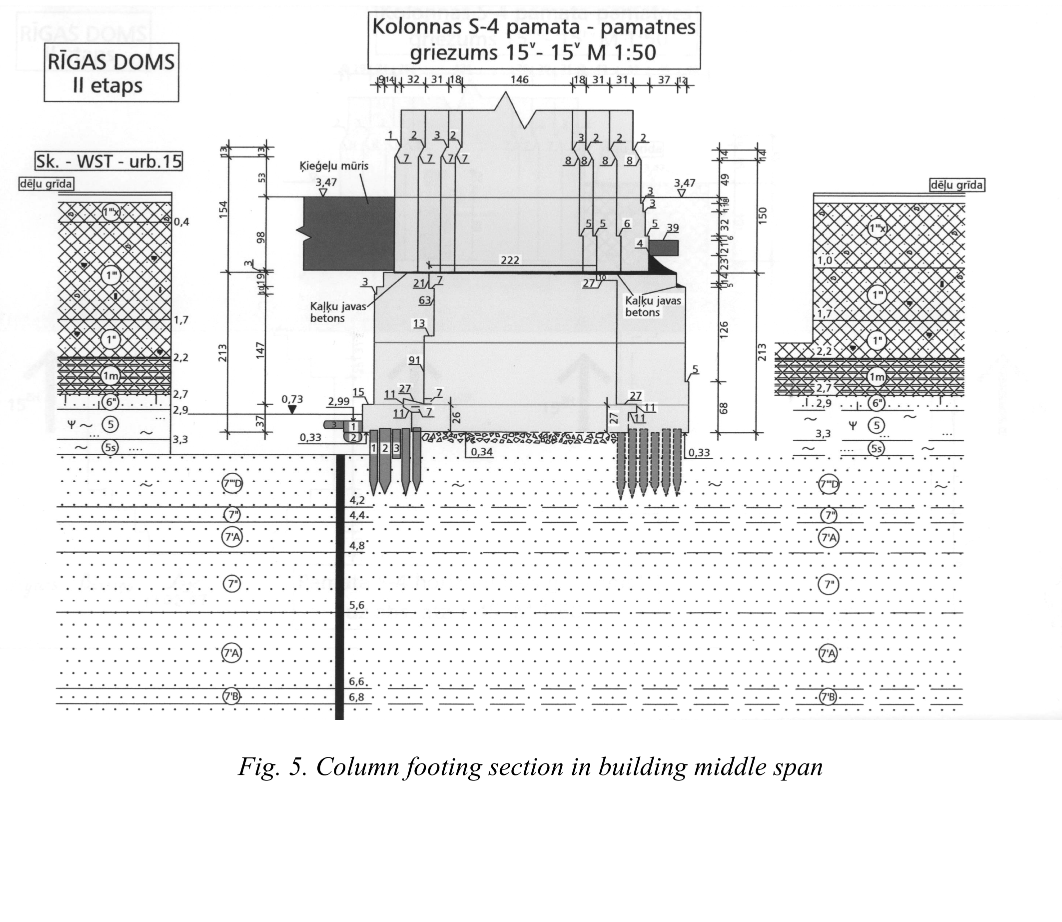

Fig. 5. Column footing section in building middle span

4.6. SOFO deformation monitoring system development

Surveillance des Ouvrages par Fibres (SOFO) optical fiber sensors monitoring system made in Switzerland company Smartec has been installed and envisaged to perform crack monitoring to a long term for building self exploitation. According with mechanical tensometer monitoring reports presented from 2005 crack oscillations are in range 1-2mm every year depending on season. The main reason of optical tensometer usage is computational control of measurement data, long lasting life period and minimized casual factor's influence on measurement's quality.

The SOFO measuring system has precision of 0.02mm. Used equipment 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 measurement program. Internal memory of reading unit gives possibility of data downloading by reasonable schedule. Battery support of reading unit gives possibility of non-stop monitoring. Supports deformation can be evaluated from changing of cracks opening and as result defined criteria of safe exploitation building.

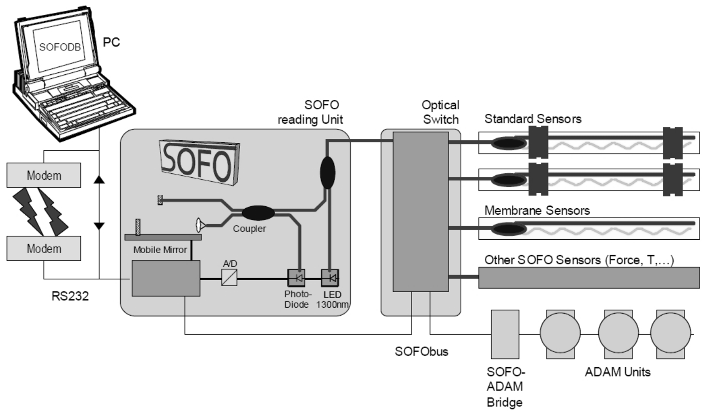

Fig. 6. SOFO principles of optic tensometer

Conclusions

The present research is a part of huge monitoring and investigation amount done in the Riga Dome cathedral. All previously collected investigations data and calculations improve the cathedral structure detailed understanding. The presented overlook of masonry material computing technologies and possible material assumptions received from available papers is used for prepare FEM model and making a choice of computational strategy. Laser scanning based surface geometric data has been transferred to FEM computational software and significantly reduced modelling time.

Detailed investigations of existing material properties, exploitation conditions and deformed situation should be done for structural analysis of heritage building. There no developed methodologies describing masonry material behaviour taking in account side effects of building process. It is necessary to take in account the casual effects of building process, such as significant dispersion of material properties, geometric and material variations, state of deformed shell structure and interactions between materials. Wind, solar radiation and temperature loading have not a bid affect on computational results but can be important. Two steps computational method should be developed for evaluating an affect of masonry arch deformed shape on thrust line position in cross section of arch shell.

In further work the methodology of safety criteria definition of heritage exploitation will be developed. This methodology will use the laser scanned of curved arch and walls surface, as well as information obtained from the crack monitoring. The crack monitoring by installation long term optical tensometer tool allows perform more detailed structure investigation and control safety state of Riga Dome Cathedral.

In the future investigations the scanned masonry arch surfaces will be transformed as geometrical model for analysis by FEM software.

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Bondars K., Korjakins A. Mūra velvju stabilitātes novērtēšanas monitoringa kritēriju izstrāde.
Lai analizētu un noteiktu drošas ekspluatācijas kritērijus tikusi izstrādāta plaisu kutību monitoringa sistēma Rīgas Doma baznīcas arku pārsegumam. Pamatu sēšanās izraisītu iekšējo spēku palielinājums un pārdalīšanās ir novedusi pie plaisu veidošanos mūra velvju konstrukcijās. Darbā tiek definēts vēsturisku mūra ēku pamatu deformāciju drošas ekspluatācijas kritērijs. Iepriekšējos gados veiktās izpētes un apsekošanas tiek izmantotas par bāzi pamatu sēšanās monitoringa programmas izstrādei. Trīsdimensiju mūra velvju lāzera skanēšana pielietojot Leica 3D skaneri ir par pamatu lai aprakstītu deformētu arku ģeometrisko datormodeli un analizētu balstu sēšanos. Rīgas Doma baznīcas pamatu sēšanās monitorings un datormodelēšana tika pielietota, lai salīdzinātu esošo, defomēto stāvokli, ar datorsimulāciju. Divdesmit viens optiskās šķiedras sensors SOFO tiek lietots, lai mērītu plaisu deformācijas sienās un velvēs un lai noteiktu drošas ekspluatācijas robežas. Izstrādāts vēsturisku ēku drošas ekspluatācijas kritēriju modelēšanas algoritms balstoties uz mūra velvju vairākpakāpju datoranalīzi.

Bondars K., Korjakins A. Monitoring programm criterions development for evaluation of groined masonry arch stability.
The program for monitoring of cracked arch shell structure of Riga Dome cathedral has been developed for definition of masonry arch stability criteria. Settlement of supports induced strains in masonry arch shells, leads

to stress redistribution and crack forming in masonry shell structures. Deformation criteria are developed for safety exploitation of heritage masonry structures. 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. Previously accomplished monitoring data were used for developing monitoring program to define unequal settlement of the supports. Monitoring of Riga Dome cathedral support settlements has been done to define settlement inequality and obtained results have been used for computer modelling of deformed structure shape tasking in account existing cracks in the masonry structure. Monitoring of existing cracks vy mean twenty one free of temperature effects optical fibre sensors of SOFO type are performing now for deformations measurement with aim of definition the safe exploitation limits. Algorithm of modelling the safe exploitation criteria for heritage has been developed using multilevel analysis of masonry shell.

Бондарс К., Корякин А. Разработка критериев программы мониторинга для оценки стабильности кирпичных сводов.

Для определения критериев стабильности арки кирпичной кладки была разработана программа контроля деформаций структуры сводов Рижского Домского собора. Осадки опор вызвают перераспределение напряжения в сводах киричной кладки, которые ведут к формированию трещин. Критерии деформации разработаны для безопасной эксплуатации конструкции кирпичной кладки исторических зданий. Данные предварительных изысканий использовались для разработки контрольной программы по определению неравномерных осадок опор. Проведён мониторинг осадок опор Рижского Домского собора и трехмерное сканирование несущих конструкций для создания компьюторной модели здания и оценки его деформации. Проводится мониторинг существующих трещин стен и свода собора свободными от температурных эффектов оптическими датчиками типа SOFO чтобы измерить деформации и установить безопасные пределы эксплуатации. Разработан алгоритм для моделирования критериев безопасной эксплуатации исторических зданий на основе многоуровневого анализа сводов из кирпичной кладки.