RIGA TECHNICAL UNIVERSITY

Kaspars BONDARS

DURABILITY PROGNOSES OF MASONRY STRUCTURES

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Construction
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DOCTORAL THESIS
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CONFIRMATION

I hereby confirm that I have developed this Doctoral Thesis, which has been submitted for consideration to Riga Technical University for obtaining the Degree of Doctor of Engineering. The Doctoral Thesis has not been handed in to some other university with the purpose of obtaining an academic degree.

Kaspars Bondars ....

Date ....

The Doctoral Thesis is written in Latvian language, contains the Introduction, Literature Review (1 part), Research Section (1 part), Conclusions and Bibliography. The content of the thesis is covered on 141 pages. This work contains 70 pictures, 6 tables and the bibliography listing 153 literature sources.

GENERAL WORK DESCRIPTION

Urgency of the subject:

For many thousand years masonry has been the dominating building technology reaching its peak development during the period of medieval sacral construction. Until the XIX century stone floor and ceiling coverings dominated in long-span construction. Between the IX and the XIX centuries in the Baltic Sea region masonry technology was the prevailing method in sacral construction.

The condition of historical building structures is negatively affected by external factors and the working load. Degradation of foundation structures of the stone buildings and irregular deformation of the bearing supports lead to formation of cracks and fissures in the historic masonry structures and – as a result – worsened conditions of use. Uneven load on the building foundation and irregular deformation of the bearing supports result in the changes of the stone massive stress-state causing local disintegration. Decreased operating safety of masonry vaulting is the result of deformations in the stone massive. Excessive deformation of the bearing supports threatens with the loss of stability of masonry vaulting and subsequent progressive breakdown.

There are 263 churches in the records of the Register of Latvian State Inspection for Protection of Cultural Monuments, the majority of which have been built as massive masonry structures. In addition to churches and cathedrals the other objects that fall within the scope of the analysis are convents and monasteries, town halls, fortification walls, castles and other buildings with masonry vaulting.

The vaulting of The Dome Cathedral, the Church of San Giorgio, St Jacob's Church, and St Peter’s Church – the churches located in the historic centre of Riga – are examples of masonry work. Besides, in other places in Latvia monumental churches built in Gothic style v can be found, such as, St Simon’s Church in Cesis and Ikskile church. Similarly with Riga historic centre, the historic centres of the cities like Ventspils, Kiel, Hamburg, Luebeck, Szczecin, Gdańsk, Rostock, Rotterdam and Amsterdam are also built on the base silted up from riverbed aggradations. The methodology developed in this work can be used for analysing the condition of such historic buildings. The UNESCO list of the World Cultural Heritage includes 55 churches, seven of which are wooden structures whereas 48 are stone masonry churches built in Romanesque and Gothic style. The UNESCO list of the World cultural Heritage includes historic centres of such cities as Tallinn in Estonia, Riga in Latvia, the old towns of Quedlinburg and Regensburg in Germany, the historic centre of Korfu in Greece, and the old towns of Avila, Caceres, Segovia and Santiago de Compostela in Spain.

For assessment of the existing masonry vaulting it is necessary to develop the method of computerised masonry vaulting measurement and analysis as well as develop the methodology for performing ancient masonry vaulting safety analysis.

Goals and tasks of the presented work:

a) Develop the methodology for measuring the masonry vaulting and computer analysis of the measurement results:

   a. approbate the laser scanning method for performing automated measurement of the masonry vaulting;

   b. evaluate data processing algorithms for effective transformation of the building surface scan data and capture of the digital surface model;

   c. approbate application of the obtained methods for surface transformation by structural analysis and design software;

   d. select the masonry material testing method for determining the specific properties of the material;

   e. define specific properties of the masonry material for the structural analysis and design software.

b) Develop the methodology for analysing the degree of safety of historic masonry vaulting:

   a. perform computer-aided analysis of the existing buildings' masonry floors/ceilings by modelling their ultimate load bearing capacity;

   b. evaluate how deformation of the masonry bearing supports affects stability of the vaults, their serviceability and safety;

   c. perform validation of the proposed computation model against Riga Dome Cathedral crack/fissure monitoring data by analysing the behaviour of the masonry material and service load;

   d. analyse the current deformed condition of the masonry vaults by comparing to deformation monitoring data;

   e. perform modelling of load bearing capacity and stability of the heritage masonry vault structures with the help of structural analysis and design software.

The following topics are advanced for defence:

a) Application of reverse engineering method for analysis of the existing masonry vault structures;

b) Method of forecasting the limits of safe serviceability by analysing vault crack/fissure monitoring data.

Scientific novelty of the doctoral research paper:

The newly-developed methodology presented in this paper provides for the opportunity to perform analysis of masonry structures and develop reconstruction plans, which purpose is to preserve the existing heritage buildings. The given method allows evaluation of the existing masonry vault service conditions and modelling the masonry vault floor/ceiling safety. The given methodology has been approbated in Riga Dome Cathedral and opens up the possibilities for performing analysis of other heritage buildings. This methodology can be used for analysing the condition of dozens of heritage masonry building structures on Riga scale, hundreds - on Latvia's scale and thousands on the European scale.

Within the framework of the doctoral paper the vault structures were analysed for the first time with the help of a spatial model by applying high resolution surface geometry. The work makes use of the building science achievements and the structural design and analysis software that is widely applied in Latvia and which makes possible evaluation of the masonry service conditions and modelling the behaviour of existing building structures. Impact of external factors, wear and masonry materials long-term effects worsen the condition of the building structures and lower service safety.

Although research and modelling of the heritage masonry buildings have been receiving great attention both in Latvia and in the world, nonetheless, to ensure full-scale analysis and planned reconstruction works a comprehensive solution is required, which is offered in this paper.

In this doctoral thesis the three-dimension laser scanning technology has been used for creating a masonry vault computer model obtained from a digitalised surface point cloud. Reverse engineering is widely practised in the world; however it is not applied in the masonry structural analysis. Creation of geometrical models based on laser scan data is used in machine building industry, dentistry and for surface digitalisation of various manufactured articles. The precision of surface measurements ensured by laser scanning offers an opportunity to perform surface measurements of arched buildings and structures with the precision that is ten times higher compared to optical measuring of arched surfaces. In Latvia, heritage masonry buildings, bridges and arches are scanned to obtain digitalised surface models for the purpose of reconstruction or capturing their condition.

As for deformed condition of masonry vaulting, while being modelled at the elastic material stage, it is difficult to estimate the effect of uneven support deformation, therefore non-linear calculation methods for determining specific material behaviour have been developed.

Around the world, modelling of peculiar properties of a material is a well-studied approach, thus it opens up the possibility for describing the masonry material properties both with the help of discretisation [see Section 3.1.4] and material homogenisation [see Section 3.1.5] method. Literature provides many detailed descriptions of masonry defects and their effect on the physical properties of masonry materials. Masonry structures are being modelled with the help of material homogenisation method by assessing the long-term load effect on plasticity. In addition, the method offers an opportunity to analyse and evaluate the effect on the stress-strain state of the heritage masonry massive and vaulting produced at various construction and reconstruction stages over the period of service.

Within the framework of the doctoral paper, construction of Riga Dome Cathedral at its various historic stages was studied with the purpose of performing a more detailed analysis of the masonry parts behaviour in their existing deformed condition.

To ensure measurement of cracks displacement in Riga Dome Cathedral an automated cracks monitoring programme has been developed, which allows for assessing the deformation tendency in the real-time mode and focuses on the zones with the highest deformation dynamics. The new method allows enhancing the accuracy of the existing monitoring programme measurements through the analysis of the obtained results as well as substantiates the necessity of further research.

Practical application of the work:

The methodology opens up the opportunities of measuring, modelling and planning for damage monitoring, reconstruction and service safety assessment of the existing buildings and structures.

Application of laser scanning for geometrical model definition allows improving the model accuracy and saves human resources as well as rules out the mistakes connected to data interpretation and processing. Recent practice of creating geometrical vault models has been confined to interpretation of geometrical proportions by way of optical measurements on a coordinate plane grid.

The new method gives an opportunity to prepare the object geometrical data for reconstruction, to analyse the existing structure stress-state, simulate reconstruction effects and evaluate the reconstruction efficiency.

Analysis of Riga Dome Cathedral vaults and deformed state of vertical structures has been conducted by applying the actually stated service conditions and the service load. Analysis of the structures embraces uneven deformations of the foundation, temperature changes, their distribution by the structure transverse sections and the impact of humidity changes on the masonry materials.

Further development of the method:

a) analysis of results by defining more accurately the monitoring programme and further necessity of additional research of the masonry materials;
b) computer modelling of reconstruction process and evaluation of the obtained reinforcement effect; giving recommendations for development of the reconstruction project;
c) simulation of changes under service conditions with the help of computer-aided analysis with the aim to evaluate the emergency load impact and other changes in service conditions.

Work approbation and publications

For validation of the computer model the Riga Dome Cathedral cracks monitoring programme data were used. The cracks monitoring system installed in Riga Dome Cathedral performs consecutive cracks measurement at 22 points. For assessment of cracks dynamics measurement of crack openings is performed automatically at two-hour intervals. By analysing the load on Riga Dome Cathedral masonry vaults and cracks displacements further service safety of the building is forecasted. The computer model has been approbated and the load has been analysed on the basis of the accumulated monitoring data. For the purpose of computer model calculations specific properties of the materials were obtained from the conducted material tests. In the course of computer simulation the load on masonry vaults and resulting effects were evaluated.

The following were used as the feed data:

a) historic research of the course of construction based on the archive data provided by Latvian State Inspection for Protection of Cultural Monuments,
b) historic research of the structural components building technology [1];
c) evaluation of the structural changes introduced during reconstructions;
d) research of the technical condition of the structural components [2];
e) laboratory research of the structure building materials [2];
f) chemical analysis of the mortar [3];
g) monitoring data of microclimate of the building [4];
h) laser scanning of structural components geometry [5; 6];
i) fixing and measuring of structural defects [7; 8];
j) research of the foundation supports condition, examination of the foundation [8; 9; 10];
k) engineering and geological research [9; 10];
l) groundwater level fluctuations monitoring data [11];
m) groundwater microbiological research [12];
n) structural load research;
o) radar probing data of the structure [8];
p) subsidence monitoring data [13];
q) cracks opening monitoring data [14].

Based on the analysis of the aggregated test and research data, the condition of the building deformed vaults has been modelled and their service safety has been evaluated. Research and monitoring data analysis has been compared to the existing vault defects and their dynamics. The interim research results were presented at the following scientific conferences with the contribution articles published in the following issues of publications:

a) Bondars K., Korjakins A., Improved deformation mechanism of masonry vault // Mechanics of masonry structures strengthened with composite materials Università IUAV di Venezia. 22-24 April, 2009. Italy, Venice. Issue of the conference publications, pages 23-23.
b) Korjakins A., Bondars K., Definition of the safe exploitation limits of Dome Cathedral by monitoring of support deformation and existing cracks // "Science

and innovations in construction SIB 2008", 10-15 November 2008, Russia, Voronezh. – Issue of conference publications, pages 177-182.

c) Bondars K., Korjakins A., Developing evaluation criteria for masonry vault stability monitoring // 49. RTU Scientific conference, 2008, Latvia, Riga. - RTU scientific research publications. 2nd series, Construction science. – 9th Volume. (2008), pages 25-36.

d) Bondars K., Korjakins A., Safety criteria development on groined masonry arch stability initiated by structure support deformations // 4th International Specialty Conference on the Conceptual Approach to Structural Design. Dept of Architecture & Construction, Università IUAV di Venezia. 27-29 June 2007. Italy, Venice. - Issue of the conference publications on a CD, page 12.

e) Bondars K., Korjakins A., Influence of deformation at a heritage building support on stability of groined masonry arch // "Computational Civil Engineering 2007", 5th International Symposium, 25 May 2007, Romania, Iaşi. – Issue of the conference publications, pages 39-54.

f) Bondars K., Korjakins A. Modelling of structural masonry groined arch // International Construction Conference "Construction'05". 26 May 2005, Latvia, Jelgava, - Issue of the conference publications, pages 21-26.

The results of the doctoral research paper were presented at the following international scientific conferences:

a) Korjakins A., Bondars K., Definition the safe exploitation limits of groin vault in heritage masonry structures // International conference on civil engineering design and construction "Eurocodes - science and practice", 9-11 September 2010. Bulgaria, Varna. - Issue of conference publications, pages 327-332.

b) Bondars K., Korjakins A., Elaborating the model of heritage groined masonry arch for definition of the safe exploitation limits // X International conference, "Modern building materials, structures and techniques", 19-21 May 2010. Lithuania, Vilnius. - Issue of conference publications, pages 868-873.

SUMMARY OF THE DEVELOPED METHODOLOGY

The work methodology includes a set of methods for evaluating the safety of masonry buildings, including examination of specific properties of the materials and methods of their manufacture in order to define the physical properties of historic masonry materials for the computer model.

Within the framework of the doctoral research application the laser scanning for creation of the geometrical model of masonry vaults and further data transformation with the help of a number of widely-applied building structure analysis programmes. By using the crack displacement data provided by the crack monitoring programme, analysis of the vault abutments deformation has been performed.

By studying the evolution of cracks under the impact of abutments deformation the ultimate vault tensile strength was modelled and the criterion of the vault safe service was defined. The terms of safe service were forecasted by way of calibrating the vault abutments deformation, effects produced by the temperature load, operation load and materials degradation with the crack monitoring data.

Description of the methodology:

The proposed and approbated in this doctoral research methodology for inspection, measuring, analysis and forecasting the safe service terms of the heritage masonry buildings consists of the following elements:

a) visual examination of the defects of inspected building for establishing the scope and character of defects;

b) development of defect monitoring scheme to control defect evolution,

c) laser scanning of the structure surface thus obtaining the point clusters descriptive of the masonry surface;

d) modelling the spatial surface thus obtaining a digitalised model of the building structural surfaces and purifying the scanned data from the data that have no relevance to the structural surface data;

e) processing, modification and transformation of the scanned data into the surface of spatial model by retaining as much as possible the geometric precision of the surfaces and setting up a computer model of the quality most appropriate for the purpose of structural analysis;

f) selection of the most effective and efficient method for defining the properties of the masonry material by observing specific goal requirements set for the structural analysis;

g) choosing the scope of the masonry material testing in order to obtain the necessary masonry parameters for further material properties definition to be used in the computer analysis;

h) obtaining possible information about any reconstruction of the building or changes in the construction process for further adjustments of the computer calculation model;

i) aggregate information on the service conditions to define the impact for inclusion in the computer calculation model;

j) modelling spatial operation of the building by assessing the masonry material long-term deformation effects;

k) adaptation of the service conditions to the analysis with the purpose to achieve the computer model behaviour corresponding to the monitoring data;

l) analysis of the results by adjusting the monitoring programme and defining more accurately the need for additional examination of the masonry materials;

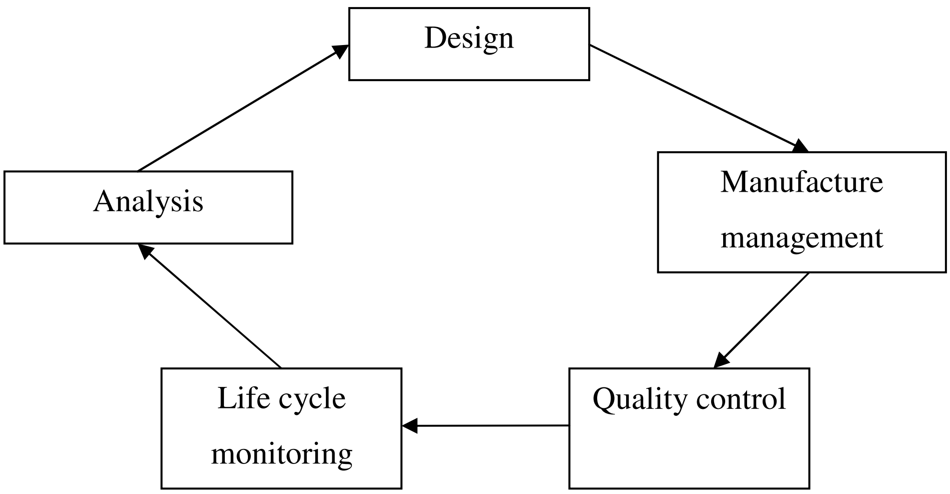
m) evaluation of the reconstruction computer model and assessment of the obtained results and giving recommendations in respect of the reconstruction project development;

n) simulation of the changes in service conditions with the help of the computer analysis with the purpose to evaluate the effect produced by the changes in the service load.

The methodology proposed by this doctoral research allows reducing the labour intensity required for the vault analysis, evaluating the construction stages and reconstruction effects, performing in-depth examination of the building service conditions and assisting in reconstruction planning.

SECTION 2 – APPLICATION OF REVERSE ENGINEERING IN ANALYSIS OF THE BUILDING STRUCTURE

Within the framework of the doctoral research application of reverse engineering for analysis of the status of existing building structures was approbated. Reverse engineering is widely applied in manufacturing; it ensures the full cycle of component development and improvement, provides feedback on the changes in service based on life cycle monitoring, see Picture 1. For development of components the computer software CAD/CAE/CAM/PLM is widely used, which includes component design – CAD *(Computer Aided Design)*, computer calculations – CAE (C*omputer Aided Engineering)*, computerised component manufacturing management – CAM (C*omputer Aided Manufacturing)* and component post-manufacturing and long-term control of property changes with the aim to improve the product – PLM *(Product Lifecycle Management)*.



Picture 1. Reverse engineering of machine-building components ensures feedback analysis.

Approbation of reverse engineering for the analysis of the building structures is ensured by a number of successive stages:

a) digitalisation of the building structure surface – 3D laser scanning;
b) processing, purification and adjustment of the scanned data;
c) Creation of the mesh model;
d) Transformation of the model with the help of computer-aided construction engineering software;
e) Defining the material by testing the masonry materials;
f) Structural analysis;

g) Analysis of the deformed condition and distribution of defects as shown in a computer model and that of a real-life structure;
h) Forecasting the defects evolution of a structure by analysing the defects evolution monitoring data;
i) reconstruction analysis and obtained improvements analysis;
j) supervision and analysis of post-reconstruction structural changes.

The final stages of reverse engineering of the building structures differ from those in the machine building sphere, the core distinction being the possibility to re-manufacture the machine-building component with improved properties whereas the properties of the existing building structures can be only improved through reconstruction.

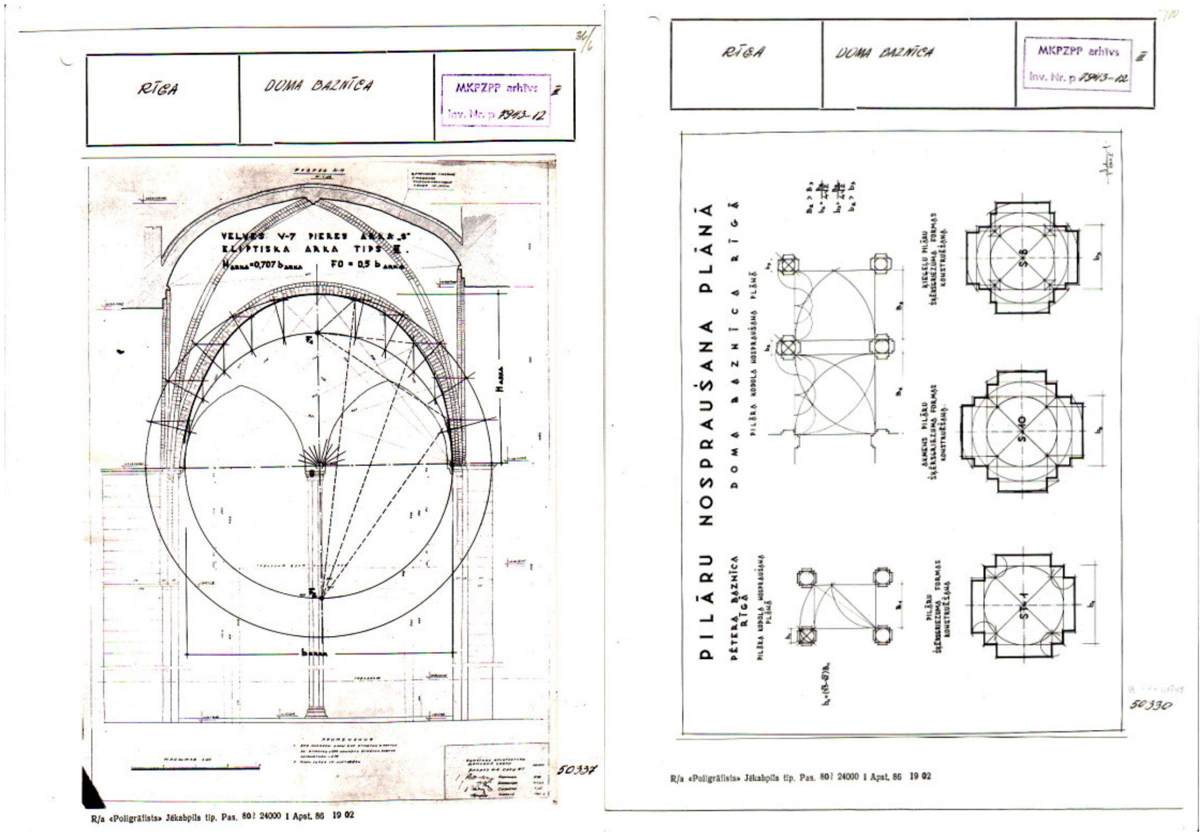
The doctoral research, having evaluated the specific characteristics of reverse engineering, sets out the distinctive features of the heritage masonry structure analysis:

a) matching of big data volumes from various scanning stations;
b) plane duplication from the neighbouring point clusters;
c) shortage of the measurement data due to formation of the planes hidden from the scanner direct visibility;
d) location of the scanning station on the floor level;
e) the necessity of manual adjustments of the model by deleting the finishing layers and elements of the interior;
f) manual adjustment of the model by modelling the hidden planes;
g) discrepancy of the import formats of the structural analysis programme data;
h) the size of the model created by computer software for structural analysis has its constraints that does not allow for the full-scale model analysis;
i) lower scan mesh quotient and lower precision requirements;
j) opportunity to perform automatic analysis of repeated geometric inspection of the deformed form;
k) material specific properties and their changes during the time of service are not known;
l) lack of material homogeneity and variance of properties;
m) internal defects of the structure materials.

Until recently, the technique for obtaining the geometry of building structures for subsequent analysis was a time- and labour-consuming measuring process with the help of optical tools.

Geometric surface modelling

Vault measuring in Riga Dome Cathedral (see Picture 2) that was performed in 1959 for analytical calculation purposes demonstrated a wide range of applied proportions, singling out eight peaked arch proportion types and four vault proportion types. Search for the proportions lead into a deadlock due to the great variety of geometrical proportions and vault geometry conjunction at different levels. For application of this data in analytical design or for the final construction of geometric elements model the unified proportion system should have been adopted, which would indicate the geometric model error. Impact of the geometric error on the results of analytical computation would fully exclude the conformity of the structural analysis to the actual building behaviour model.



Picture 2. Search for geometric form of vault proportions.

High-precision geometric measuring and modelling is connected to the analysis of a great number of vault types and evaluation of their interaction.

Within the framework of the doctoral research the laser scan data were used for generating the surface with the aim to create the digital model that would be as close as possible to the actual object. Transformation of the laser scans into the structural design model is an innovative solution for structural analysis. For creation of a digital model the measurement data from Kalinka research [5] were used by transforming the documented surface data into a computer-aided structural design model.

The spatial building model obtained as result of laser scanning can be used both for presentation and structural analysis purposes as well as for the purpose of reconstruction planning and creation of spatial documents referring to the heritage elements [6].

Kalinka [15] marked the advantages of laser scanning by comparing it to optical measuring technique:

a) considerable reduction of the time required for performing the same amount of measurements (by 70 - 80%);
b) high precision with adjustment possibilities (~2mm per 50m distance);
c) setting the adjustable angular measurement mesh structure on the scanned surface thus getting the required measurement mesh size (20x20mm);
d) exclusion of human error in interpreting the measurement data;
e) obtaining the spatial geometrical model by converting the data between computer programmes.

A surface model is created by processing these points and prepared for further structural analysis as a surface mesh model. Research shows that the process of formation of hidden planes and removal of interior elements and finishing layers require the largest share of time and effort.

Model transformation for structural analysis software packages

Within the framework of the doctoral research the geometric model was created by using the three-dimensional laser scan data with subsequent data cloud processing thus combining the graphic design and structural analysis software.

In order to generalise the applicability of the method developed in this doctoral research, certain criteria were introduced, which observation would allow for the widest possible application of the method without binding it to any specific laser equipment manufacturer and data processing software.

Within the framework of the doctoral research the following data processing criteria were suggested:

a) to ensure application of a wide range of three-dimensional laser scanners the output data transformation format should contain point coordinates data without additional information on the surface colour, texture, etc. All laser scanner manufacturers support the *.xyz format;

b) for point cluster processing a specialised programme is required, which would allow to:
   a. delete the points located outside the scanned planes;
   b. collate the points on the common planes thus decreasing point divergence against the plane;
   c. delete the points that refer to the interior and finishing layers;
   d. replace the covering/bordering and the interior detail planes with the structural surface planes;
   e. unite separate planes within a unified surface element;
   f. trim the planes against the design model boundaries or symmetry planes;
   g. transform the surface on a mesh model;
   h. reduce the number of surface-describing plane elements without reducing the surface accuracy;
   i. process graphic files of large size;
   j. ensure compatibility with structural design and analysis software by supporting the core data transformation file formats.

c) the transformed data format and the data content should be compatible with the data import opportunities offered by most frequently used structural design and analysis software;

d) the structural model should ensure the possibility for analysis with the help of each particular structural design and analysis software without exceeding the amount of elements and by adjusting to the finite element types and ensuring the analysis pattern (within the linear elasticity boundaries, elastic-plastic boundaries or breakdown theory boundaries);

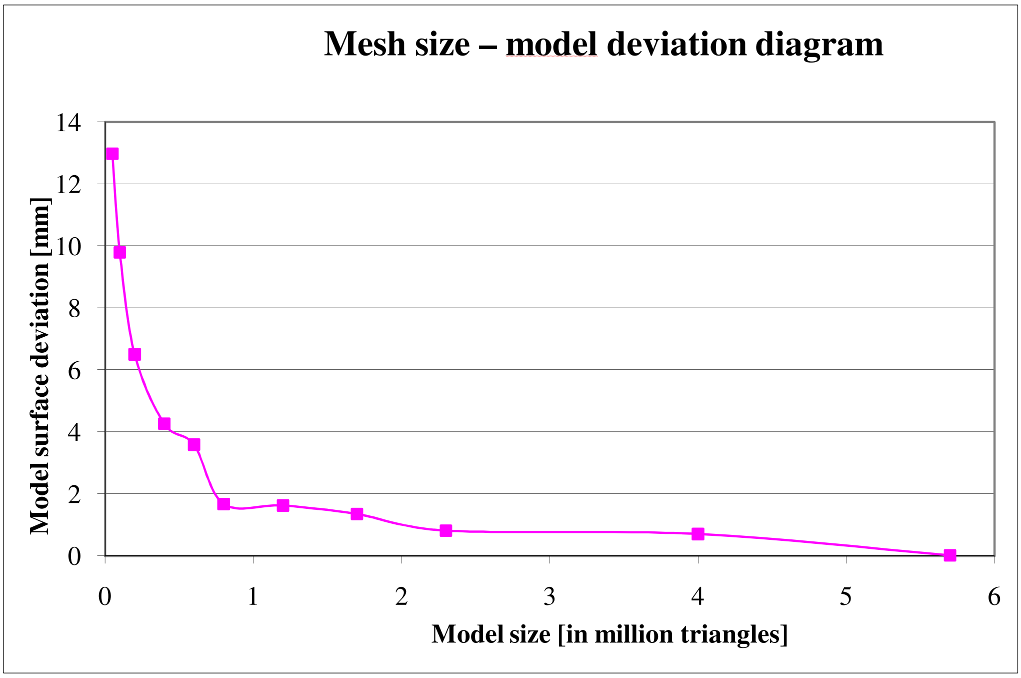
e) in the course of structural analysis each analysis pattern should be provided with the opportunity to define the required characteristic values of the material;

f) computer simulation should ensure fulfilment of the set task, for example: internal strength testing, deformation testing, collapse safety testing and the like.

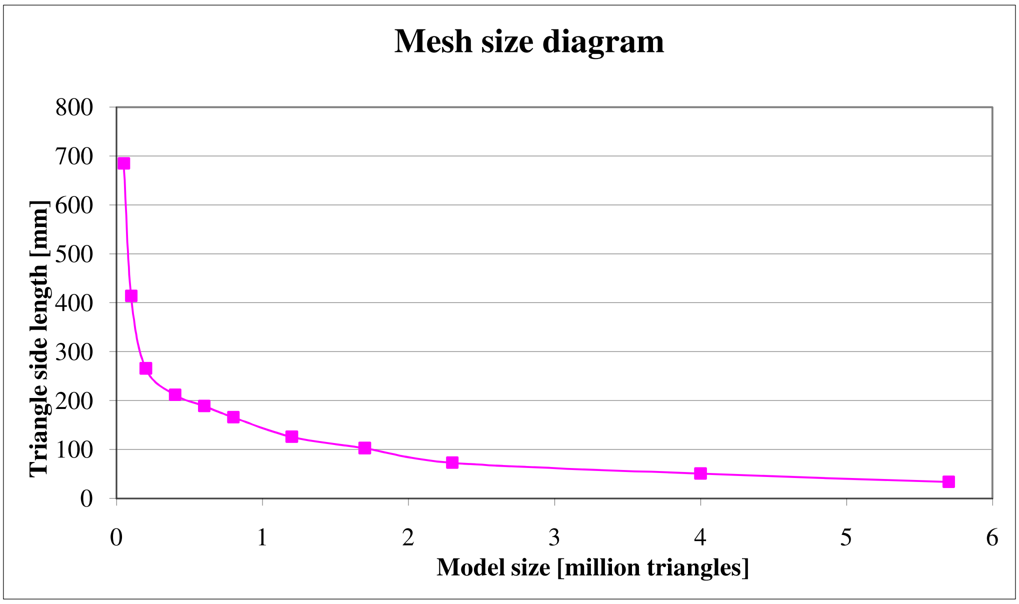
The FEM structural element design software packages include a more or less convenient pre-processor, which ensures creation of a design model and graphic data processing, and which supports import of the model geometry or parametric model import.

In the doctoral research paper data transformation programmes were compared by demonstrating the process of transformation, data volume and the time consumed. Data transformation pattern with the minimum time consumption and mutual compatibility of computer programmes was developed.

By way of calibrating the surface deviations and the number of elements the model of the part of the Dome Cathedral building was generated, which provided for an opportunity to perform analysis of irregular deformations of the corner vault abutments. The model was created with the surface accuracy below 13.4 mm and the mesh model size consisting of 97000 triangular elements. Augmentation of the geometric mesh quotient size determines decrease in the model curved plane accuracy. Correlation between the geometric accuracy of the cross vault shell surface model and the model fidelity is shown in Picture 3.



Picture 3. Mesh model size calibration by changing the mesh element.



Picture 4. Mesh model size and accuracy calibration by changing the mesh element.

By calibrating the mesh model element dimensions analysis of their impact on the model dimensions was performed (see Picture 4). The optimal mesh element side dimensions were determined, which in the case of Riga Dome Cathedral vaults are 150 – 200mm.

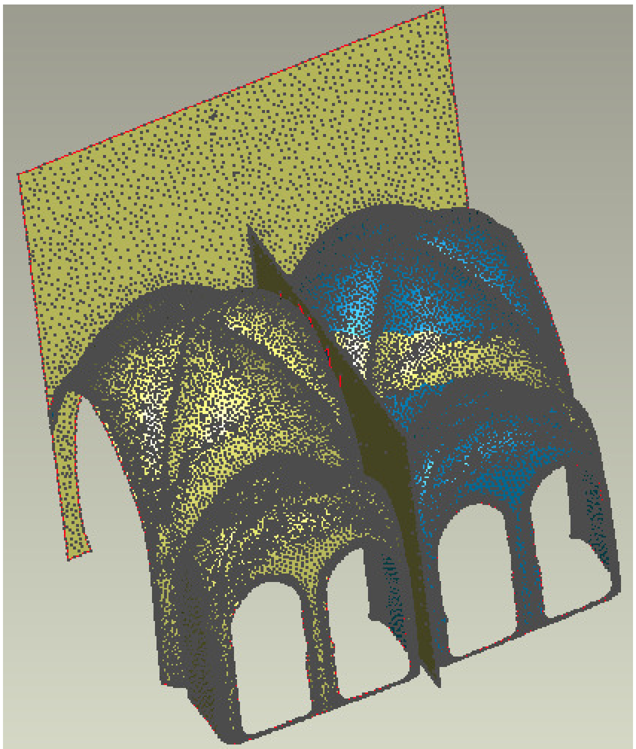
By performing mesh calibration, the abutments irregular deformation design model element dimensions and the mesh model dimensions were obtained. During the doctoral research the reverse engineering method was approbated for structural analysis and design software that is widely used in Latvia, such as Staad Pro V8i and Sap 2000 v14.2. Commercial structural analysis and design software are not suitable for large-scale model processing, the limits being:

a) 225000 plate elements for Staad Pro V8i,

b) 100000 plate elements for Sap 2000 v14.2.

Thick plate elements were used in the process of modelling with the help of Mindlin - Reissner equation. Description of the plate elements and their applicability are provided in Section 3.6 of the doctoral thesis.

For support deformation analysis the surface model of the part of the building was developed (see Picture 5).



Picture 5. Vault support deformation analysis model, fragment of Riga Dome Cathedral lateral area.

The doctoral thesis provides analysis of the most efficient ways of data processing; information about data transformation and labour-intensity, data and file formats as well as processing tools are summarised in Table 2.2 of the doctoral thesis.

Application of reverse engineering principles in the analysis of existing masonry structures is characterised by the scarcity of information about the specific material properties and their degradation in the course of service.

Defining specific properties of the masonry materials

Masonry material homogenisation approach is widely used in masonry material analysis, which determines the impact of creep and contraction on the material elasticity indicators. Although such material assumption and elasticity calculation method is used by a vast majority of structural designers, the method fails to provide analysis of masonry plasticity at various stress levels. For the purpose of masonry structure design analysis Latvian building code allows to perform linear elastic analysis of masonry structures since the masonry load carrying capacity is applied within the 50% limits, up to which masonry may be regarded as a linear elastic material.

For determination of the tensile strength indicators a variety of methods are used, most popular among them being partial destruction test method such as Schmidt's surface hardness test [16; 17], probe penetration testing [18], drilling [19], anchor rotation test [20] and others, found in many research works. Such test calibration should be performed repeatedly for each heritage masonry type.

For evaluation of the structure homogeneity initially developed technologies like ultra scan, X-ray and radiology were used. Evolvement of modern scanners for masonry structures is mainly based on radio wave radar scanning technologies. For detection of hidden masonry defects the methods that make use of geo radar for structural scanning have been developed [21; 22; 23; 24]. Radar scanning of Riga Dome Cathedral pillars showed presence of mass concrete inside the pillars and a small-sized cavern [8] inside the pillar in "L" zone [see Picture 2.24].

During analysis [25; 26] of the masonry material behaviour under a uniaxial compression the homogeneous material model was introduced in the computer analysis, which combined the masonry stones and mortar interaction effects. By using this method for defining the material properties, laboratory records and the masonry material elasticity indicator adjustment ratios specified in the Latvian building code [27] homogenised masonry material properties were defined.

For evaluation of nonlinearity of the masonry material the method [28] applied for assessment of the impact of cracks on the changes in elastic properties was used. Macro modelling technique [29] is acknowledged in masonry analysis research, and in its essence incorporates masonry nonlinear effects with the composite interface model. This model examines three masonry plane or structure breakdown mechanisms. Those are pure tensile breakdown along the masonry mortar, friction force breakdown along the joint resulting from tangential stresses and elliptic normal stress, as well as integrated tangential stress state breakdown model.

Examination of the properties of Riga Dome Cathedral masonry materials [2] and laboratory research records published in scientific papers provided an idea of the properties of masonry material. In the course of testing masonry samples from a part of Riga Dome Cathedral cornice the following figures for compression resistance were derived: R_{min} = 4.2 MPa, R_{vid} = 5.82MPa and R_{max} = 9.2MPa. During testing of the seven bricks for tensile resistance in bending at three points [30] minimal tensile resistance was determined [31]. In the course of processing laboratory research data the following masonry parameters were adopted, which were used in computer simulation by defining the masonry as being at a linear elastic stage.

Homogenised masonry material properties indicators

Table 1

Prime modulus of elasticity	E_0 = 3,6 GPa
Average modulus of elasticity	E_{mean} = 818 MPa
Yong's modulus	G = 1,2 GPa
Poisson's ratio	0,2
Thermal linear expansion coefficient	α_t = 0.000005 1/degree
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	ν = 2.2
Material density	ρ=1600 kg/m^3

Parameters of the masonry homogenised material model derived on the basis of the methods set by Latvian building code and in the course of laboratory tests are summarised in Table 1.

In modelling the impact of temperature, snow load and wind impact with the help of Staad Pro structural design software the hybrid elements equation with 3-node plate elements. This formulation of the model elements allows evaluating the plane bending moment and internal strength components generated by transversal force.

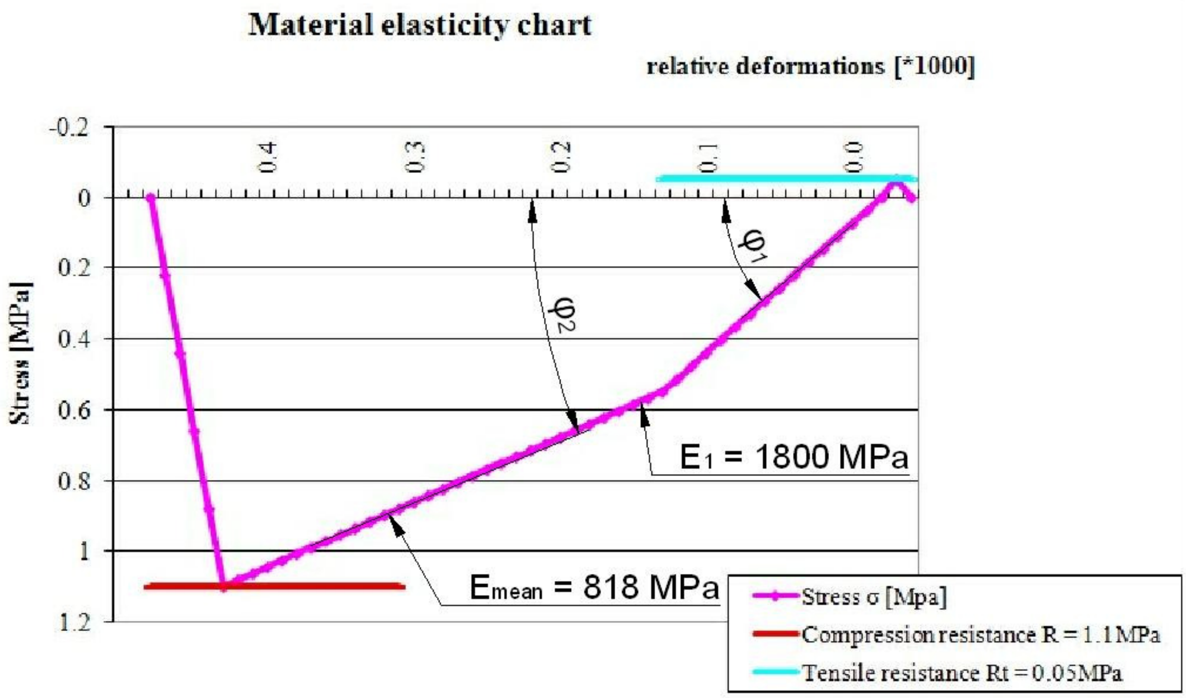
Plasticity evaluation and breakdown theories in masonry structural analysis

Breakdown caused by compression forces is characterised by development of scattered micro-cracks with subsequent merging accompanied by progressive damage localisation and propagation of macro cracks. Prior to breakdown borderline state the sample demonstrated development of cracks caused by transversal force [18], which results in breakdown. Masonry structure breakdown processes [19] were evaluated with the help of a breakdown model. Compression force created a vertical crack in the sample that went along the axis line forming the sample parts separation plane.

Nowadays, numerous masonry structural analysis techniques have been developed, such as finite element method with interface elements, discrete element method and mesh models. For symmetric structures with the ordinary stress values or for previously tested structures where cracks dislocation and development are known beforehand, interface elements are placed along the crack development route. Based on the [29] fissure zone analysis, in the masonry computer model the number of elements in the fissure zone have been increased.

After Cundall [32] developed the discrete element method, it began to be widely used and caused interest among the researchers [33] due to the possibilities it offered in describing the masonry structure with the help of discrete elements.

In the course of analysis of the information provided by literature it was stated that masonry creep depends mainly on internal stress level, temperature, humidity and cyclic load impact. For stress level until the 50% of the load carrying capacity the creep effect is classified as a deformation component.



Picture 6. Masonry elasticity chart showing ultimate load carrying capacity under tensile and compression stress.

For modelling the masonry vault break-up effects the theory of thick plates was applied and Mindlin-Reissner equation was used. The structural design software SAP 2000 was used for modelling by applying isoparametric plane elements and non-linear properties of homogenised masonry material (see Picture 6).

With the help of the masonry material homogenisation method in non-linear masonry analysis masonry properties were defined as depending on the stress state in transverse section (see Picture 6). Upon defining the non-linear character of the material elastic properties, the parameter of ultimate carrying capacity under tensile and compression stress was introduced in the model.

The ultimate carrying capacity of vertical leaf-wall masonry structures and principles of heritage buildings destruction were studied by Binda [34], who proved that crippling of external layers increases with the load increase. Excess loan on leaf-wall masonry pilasters, uneven prongs deformation, weak bonding between masonry layers and varying operation impact on the layer materials resulted in significant damage caused to heritage buildings even leading to ultimate decay [35]. Varying wall packing properties may be considered the key reasons for leaf-masonry destruction given the packing failure to operate in unison with the masonry wall behaviour, pitting of the masonry joint shell and mutual vertical disintegration of layers. In the course of development of the methodology for existing masonry structural analysis presented in the doctoral research it was concluded that in case of leaf-wall masonry the material should be defined as layered structure.

SECTION 3 – STRUCTURAL ANALYSIS AT DEFORMED STAGE

Structural load

The load on heritage masonry structures is comprised of foundation settlement, temperature impact, snow load, wind impact, dynamic impact by external factors and service load. This doctoral research puts forward an assumption that temperature impact is the second most significant factor in masonry structural load after foundation deformations.

Roof structure supports of Gothic sacral buildings are built exactly on vertical structures therefore snow load does not have any serious impact on the vault load. Snow load effect is seen in stress accumulation within vertical structures. The research paper analyses the impact of snow load on the stress changes inside the structures. Under the full snow load, internal stress in the columns of Riga Dome Cathedral central zone constitutes 1.5% of the total vertical load, which results in increase of stress in the column cross section by 0.012 MPa. The snow load effect is a vertically directed compression force inside the column causing an increase in vertical column stability.

Maximum wind-caused horizontal displacement value for Riga Dome Cathedral in shell cross-direction constitutes 14-17 mm in the middle area at the central point of the ceiling. Wind-caused increase of compression on the column external fibre reaches 0.017 MPa while compression in the external fibre of the wall buttresses equals 0.002 MPa. Wind load causes a noticeable increase of stress in the vault ceilings; however detailed analysis of this issue is possible only with the help of a real geometric model.

Every seasonal temperature change causes new displacements since the deformed displacement between the blocks has a tendency to retain some part of displacement that resulted from temperature changes in previous periods. Since 2006 automatic temperature measurements both on the inside and on the external surface of the load bearing walls have been performed with the help of the automatic monitoring system. Upon performing analysis of the monitoring data the difference in temperature inside the building was obtained, which constitutes Δt = +7.4 ºC up to +20.4 ºC , while outside the building it is Δt = -8.7 up to +30.1. Based on the measurements provided by the monitoring system and manual masonry surface temperature measurements, climatologic impact [36] and building code methods [37] the temperature load on the masonry structure was determined. Such temperature fluctuations lead to extension of internal surface within the temperature block boundaries by 0.3mm in summer season and to extension of the external wall surface by 2.3mm against the deformations during the coldest season. Total seasonal masonry thermal displacement of the building in vertical direction constitutes ~15mm. Maximum stress changes inside the external fibre of the vault shell are: $\Delta\sigma t^{\circ} = 0.012$MPa.

Service load does not have any impact on the vault ceilings. Dynamic effect produced by the Cathedral bell chiming [38] creates significant load on the slender bell-tower structures. In the analysis of the vault ceiling structures performed in this research paper, the live load is not included in the analysis of vault ceiling strength and stress resistance.

Prolonged masonry construction works determine gradual accumulation of deadweight and redistribution of stress already in the course of construction. The largest stress in the masonry structures is caused by the masonry structure deadweight itself. Deadweight-caused stress in the vertical masonry structures equals 0.78 MPa thus constituting 70% of the masonry load carrying capacity and is located in the area lacking significant plasticity effects of the lime mortar.

Over the period of many years the administration staff of Riga Dome Cathedral by own efforts performed internal microclimate measurements. Masonry material properties use to change with time therefore in monitoring of heritage building structures great attention should be paid to masonry degradation caused by humidity. In the homogenised material model for definition of the long-term material stress effect adjustment factors [39] were applied with account of the lime mortar creep.

Crack monitoring

Over the recent years thanks to support and funding on the part of Riga Dome administration a large volume of information was collected in respect of Riga Dome Cathedral service and operation environment and technical condition of the building structures. By making the information on the results of each examination stage public via mass media, it became possible to attract serious attention of the community to the condition of the building.

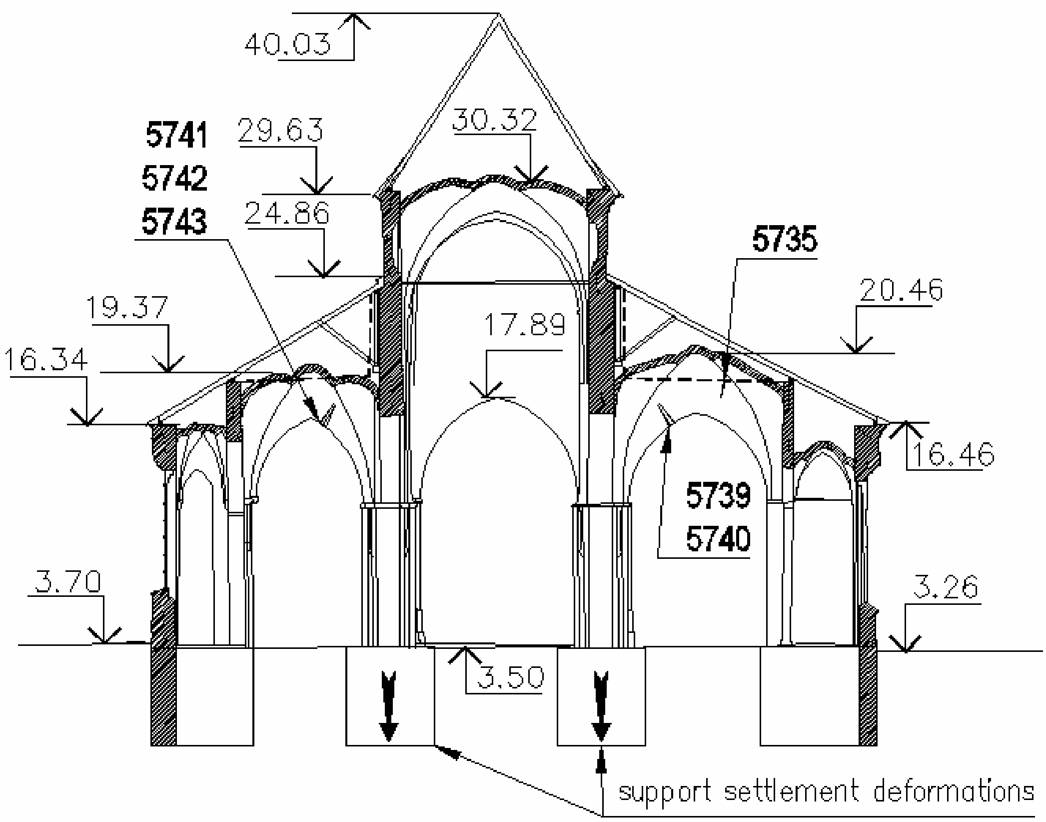
The bedding and foundation research indicates the geodynamics of the foundation strata, the reports [9] provides information on reduction of the bedding elasticity values and degradation of the structure wooden piles. The bedding experiences various deformations under the influence of the foundations enduring various levels of load the main reason for that being damaged wooden piles and poorly compacted loamy soil, which prove to be the main cause of bearing supports deformation. The task of crack monitoring is to provide information about the changes in crack openings in the course of time, which also point at the foundation deformations.

The methodology developed in the doctoral research offers a high quality efficient crack monitoring system that would replace the traditionally applied noniuses and mechanic deformation meters.

In 2005 an agreement was concluded between Riga Technical University and administration of Riga Dome on the basis of which visible defects of the masonry vaults were investigated and a monitoring programme was developed. Durability of sensors, fire security and protection from the impact of external environment were pronounced as the key requirements for selection of the monitoring system tensometer type. Special attention was paid to high accuracy of measurements and computerised data input and control possibilities. For the above stated reasons the optic fibre Surveillance des Ouvrages par Fibres (SOFO) tensometers were selected.

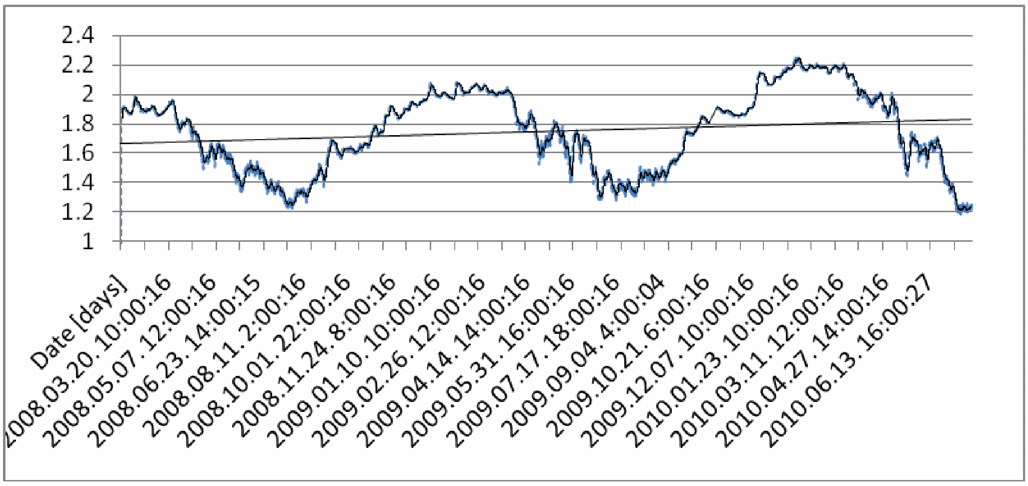
Monitoring system is programmed to perform measurements at 120-min intervals to record crack displacement at various periods during the day and night. Such scanning frequency ensures accumulation of the monitoring data over the 70-day period in the device memory.

SOFO optic tensometers are installed at the bottom and top sides of Riga Dome Cathedral vaults. Such location of sensors ensures measurement of displacements within the +/-2.5mm boundaries, measuring both crack contraction and expansion. There are 22 optic tensometers and three temperature sensors installed on the Cathedral vaults and the main arches. Picture 7 shows the location of the sensors meant for monitoring of arch crack opening thus forming a hinge along both sides of the fissure zone.

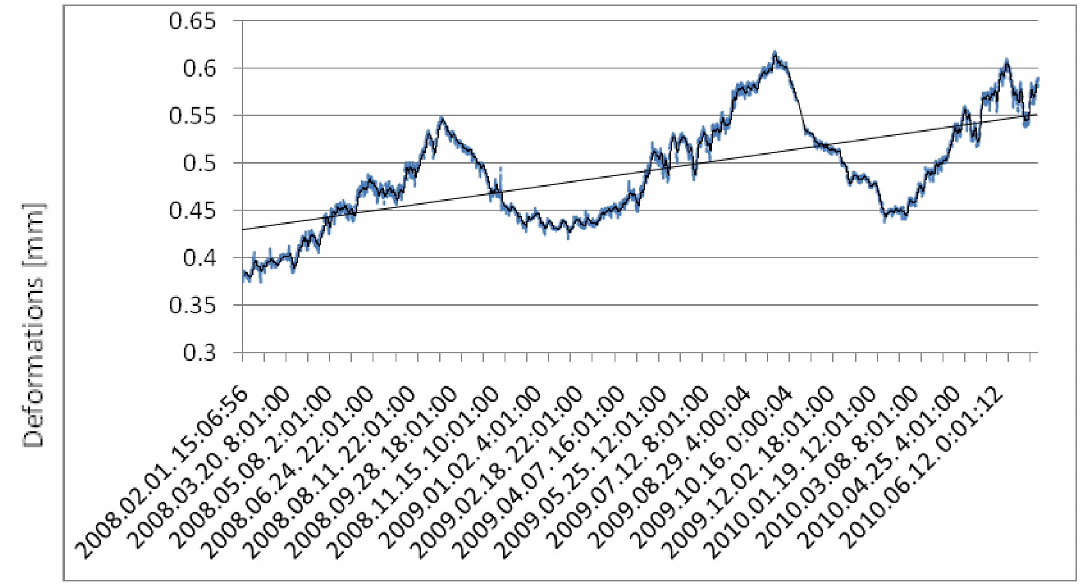


Picture 7. Tensometer location scheme view in section.

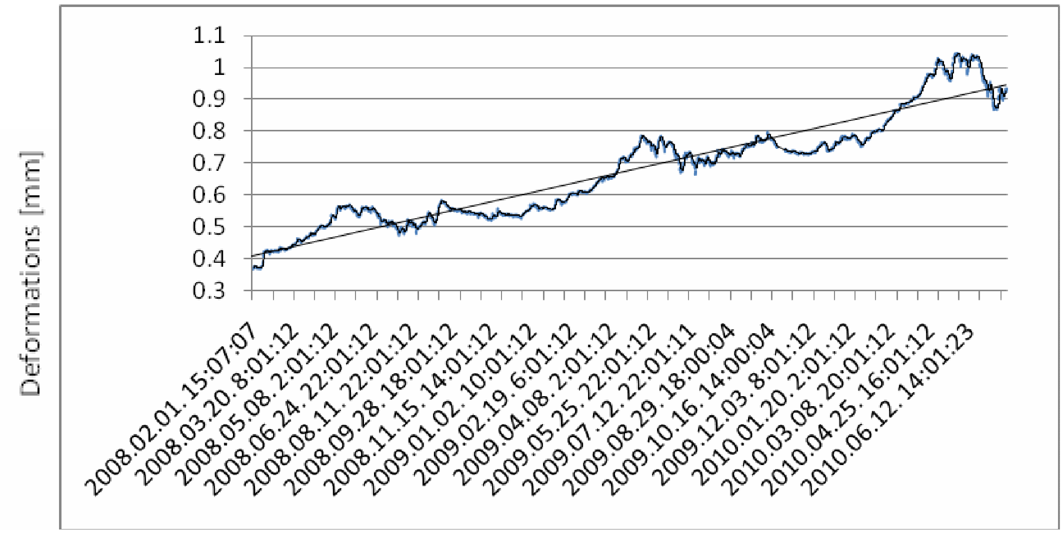
Sensor readings over the last three year period show joint crack evolution (see Pictures 8, 9 and 10). Optic tensometer measurements taken from the upper side of the vault rib (sensor 5735) and two optic tensometers (sensors 5739 and 5740) at the vault bottom control displacement of the hinge mechanism of the arched masonry part.



Picture 8. Sensor 5735 is located on the arch rib along axis “2”, between axes “C” and “D”. The sensor is placed on the top side of the arch rib and shows irregular displacement of external support in the tower southern area against the tower masonry part. The extesometer shows displacements of the upper hinge external part of the four hinged mechanism.

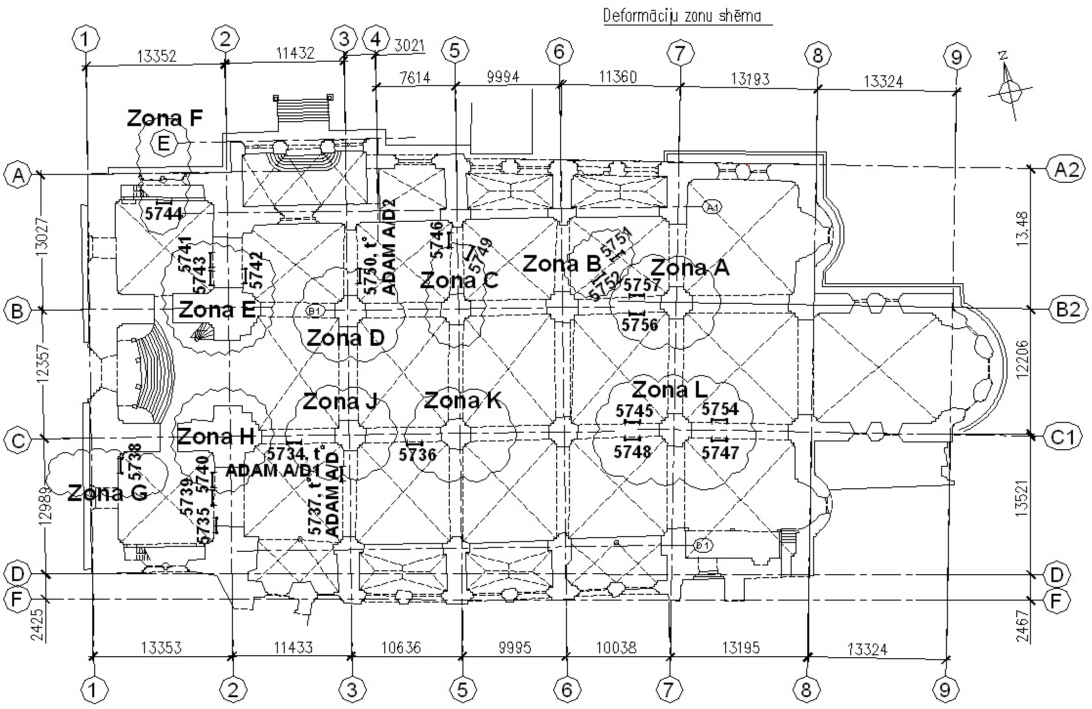


Picture 9. Sensor 5739 is placed on the arch rib along axis “2”, between axes “C” and “D” on the hall side, at the bottom of the arch rib. The crack does not show direct displacement of the arch rib external hinge, however together with sensor 5740 shows separation of the wedge-shaped brick clading made during the earlier reconstruction of the original arch rib. The wedge closing makes the arch rib more flat however the crack does not ensure joint action of the original arch and the sealing.



Picture 10. Sensor 5740 is placed on the arch rib along axis “2”, between axes “C” and “D” on the hall side, at the bottom of the arch rib. The crack does not show direct displacement of the arch rib external hinge, however together with sensor 5739 shows separation of the wedge-shaped brick clading made during the earlier reconstruction of the original arch rib. The wedge closing makes the arch rib more flat however the crack does not ensure joint action of the original arch and the sealing.

Crack monitoring proved existence of eleven irregular deformation zones in Riga Dome Cathedral (see Picture 11).



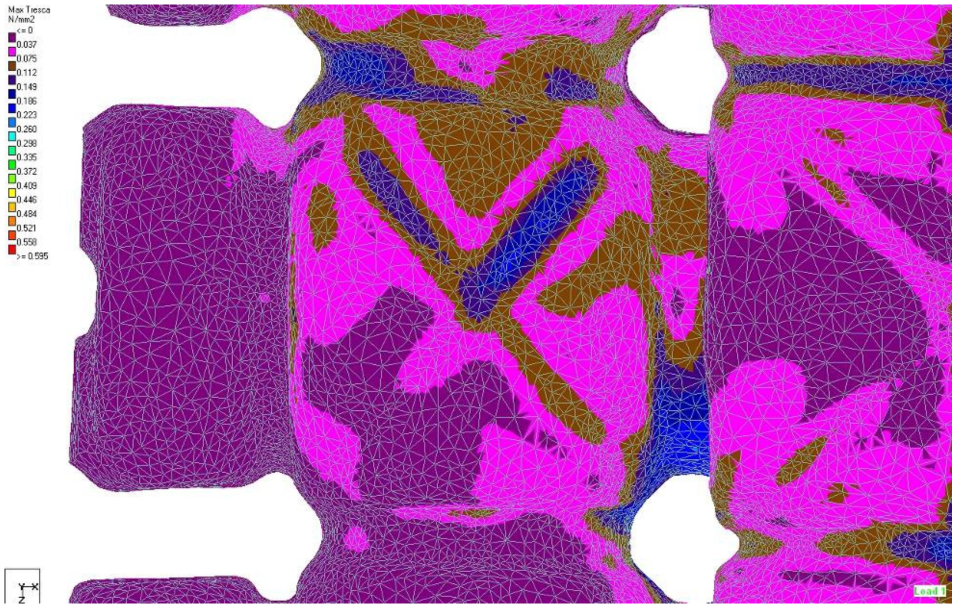
Picture 11. Riga Dome Cathedral foundation deformation zones and location of crack monitoring sensors.

The installed monitoring system ensures control over displacement of eleven hinge mechanisms and allows analysing the displacement of masonry parts.

Modelling local destruction of vault structures

Tensile stresses weaken the lateral area, which in case of a discrete analysis model are described as hinges between masonry parts. Formation of more than three hinges in a masonry vault transverse section creates the hinge mechanism, which threatens with vault destruction. Vault safe operation criterion has direct relation to reciprocal displacements of the vault parts. Unequal settlement of the foundation is reflected in the changes of the vault crack openings since each crack forms a hinge on the vault rib thus concentrating the displacement. Formation of hinges and mutual contact between the masonry parts [40] lead to the changes in the vault geometry that are disproportionate with the rotation mechanism geometry.

The system of initial geometric proportions in the course of vault construction provides for location of the compression force axis in the core transverse section zone. While modelling deformation of the bearing columns and imitating their unequal settlement (see Picture 12) it can be seen that tensile stress is developed in the masonry vault shell and the pylon ribs. In the course of analysis the yield point was determined at which masonry deformation is going to start if the tensile stress exceeds the masonry tensile load carrying capacity.

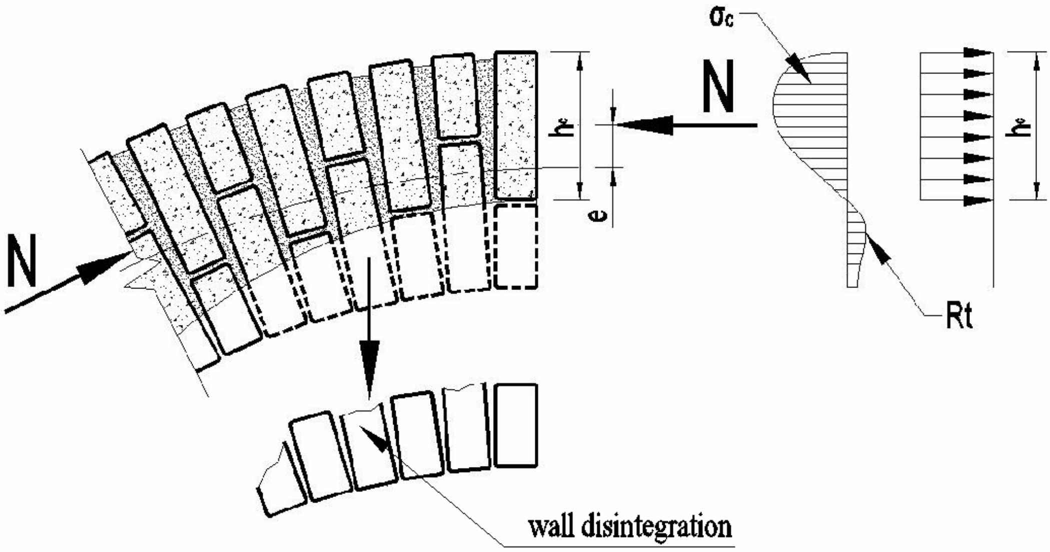


Picture 12. Significant increase of tensile stress registered in the masonry vault and the pylon rib.

In the course of modelling the irregular settlement deformation of the columns in the middle area in relation to deformation of the side wall foundations the deformation linear boundary value was obtained: 40 mm. The tensile stress reaches the ultimate stress resistance value and the vault surface develops a crack. Further irregular deformations of the foundation cause evolution of the crack zone leading to disintegration of the masonry wall. Further deformation of the supports is compensated with rotation of the masonry parts hinge mechanism.

In the doctoral research paper the vault analysis in its linear elastic stage, by applying the structural design and analysis software Staad Pro, was suggested as the one of the first approximation computation methods. During computational analysis with the help of thick plate isoparametric triangular elements that involves hybrid element formulation [see Section 3.5 of the Doctoral thesis] it becomes possible to cover a much larger part of the building or even the whole of the building. Such approach allows selecting critical zones for the second-stage analysis that examines disintegration of the masonry structure. For modelling the crack zone the structural design & analysis software SAP 2000 was applied that provided description of the homogenised masonry material non-linear properties and introduced the material ultimate strength limit (see Picture 12).

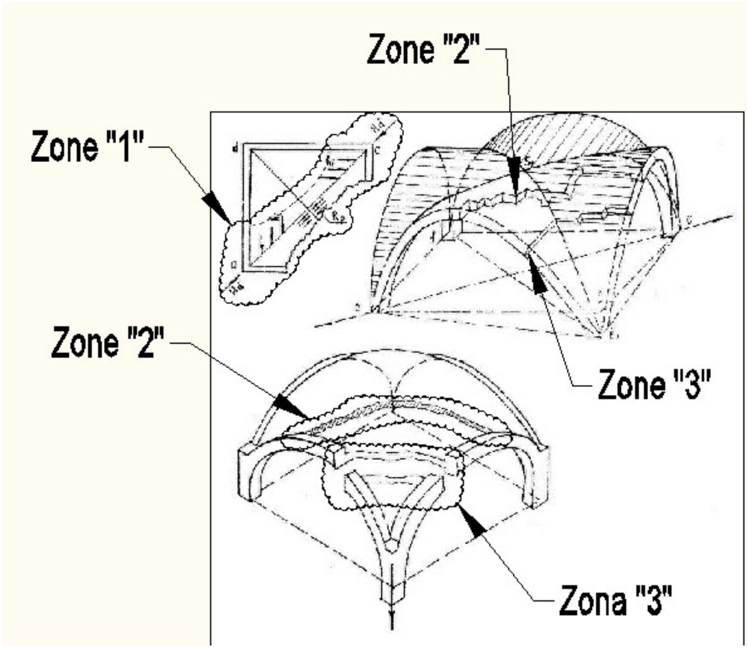
For the purpose of locating the compression force axis in transverse section a Microsoft Excel work table was created, which included verification values according to the existing building code [27]. The developed table ensures fissure testing for internal strength, admissible eccentricities and compression force axis location in the fissure. The bending moment created by supports deformation increases the tensile stress and leads to disintegration of the local cross-section (see Picture 13). Under the impact of cyclic load such fissure triggers pitting of joints, which may result in vault disintegration.



Picture 13. Lateral disintegration under the influence of cyclic eccentric load causing vault joint pitting and lateral disintegration

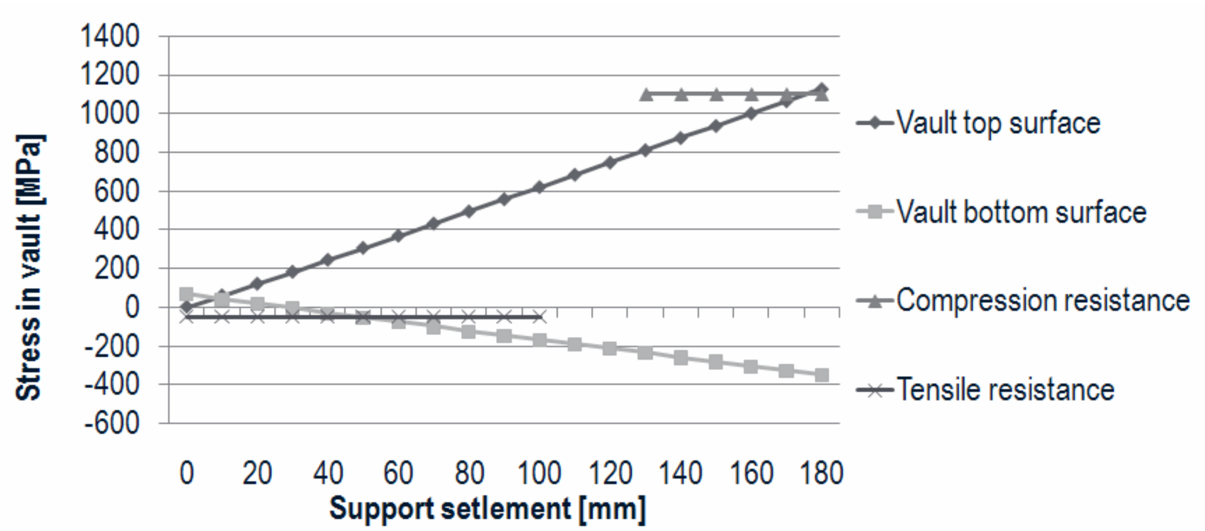
In the course of analysis of the deformation-caused fissures three zones have been singled out (see Picture 14):

a) Zone "1" – deformation of the vault corner support node causes decrease of the axial force on the adjacent diagonal and increase of stress on the perpendicular vault diagonal,
b) Zone "2" – deformation of the vault corner support node causes formation of the rotation hinge in the upper part of the vault shell,
c) Zone "3" – deformation of the vault corner support node causes formation of the rotation hinge at the bottom part of the vault shell.

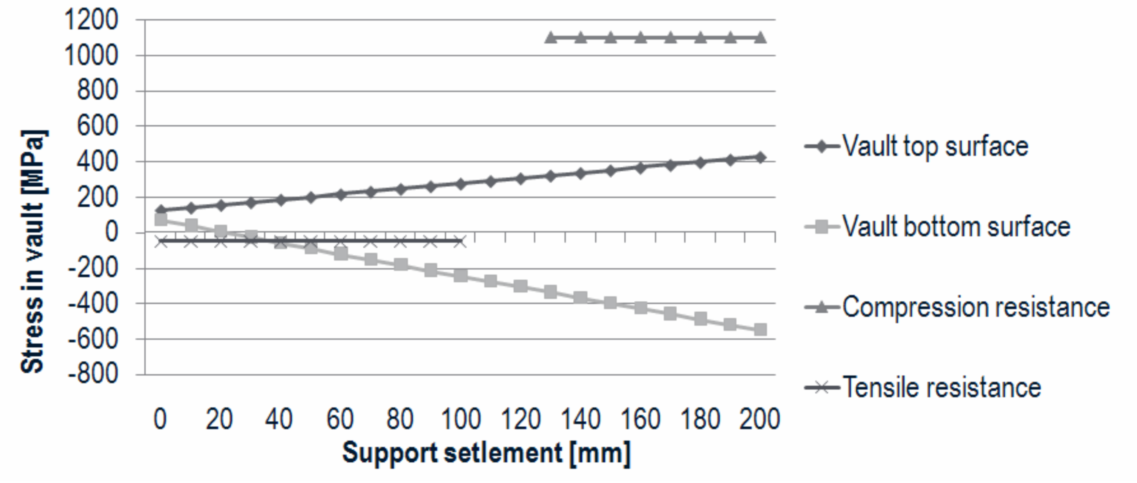


Picture 14. Formation of the hinge zones under the impact of support deformation causes deformation in zones “2” and “3” and redistribution and increase of stress in the rib zone “1”.

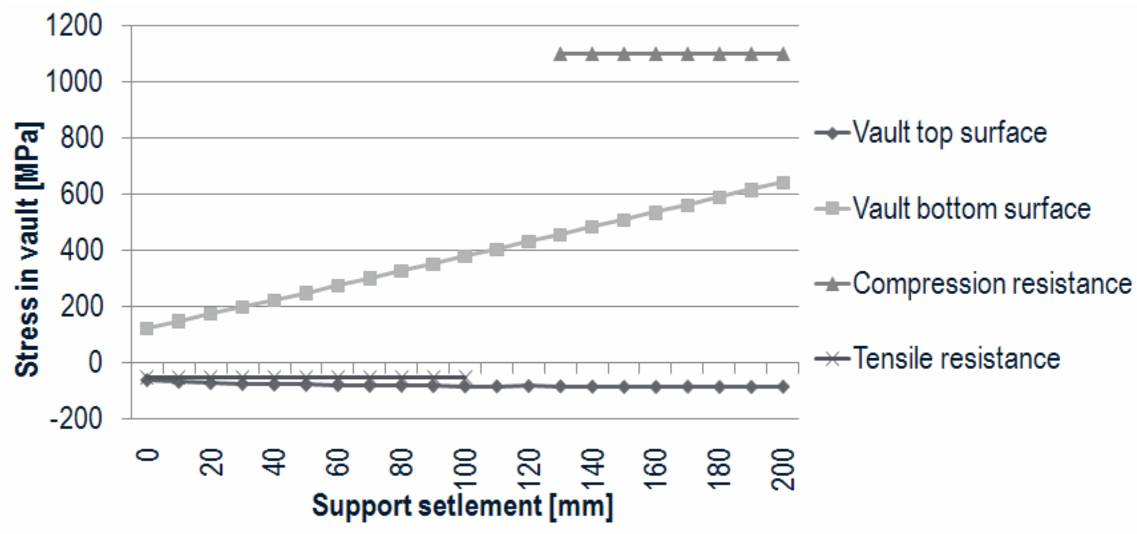
In the course of modelling supports deformation the linear relationship was derived reaching the ultimate tensile strength value in the vault shell (see Pictures 15, 16 and 17). During support deformation in zones “2” and “3” tensile stress is developed thus creating the areas where the masonry elements can lose stress resistance (see Picture 3.10).



Picture 15. Stress change in zone “2” influenced by vault support deformation.



Picture 16. Stress change in zone “3”, influenced by vault support deformation.



Picture 17. Stress change in zone “1”, influenced by vault support deformation.

When the load in fissure zones “2” and “3” is relieved the axial force in the vault shell structure is reoriented towards zone “1”.

During formation of the masonry block by the deformed support – in zone “3” its stability is ensured by the balance of forces. The stability of the console part is provided by resistance of section. The moment equilibrium in section is described by the equation 1. [41].

$$R_t * h_p * z \geq Q * a \quad (1)$$

where: h_p – height of the extended zone;

z – combined power of the extended and compressed zones, lever of the couple of forces;

Q – deadweight force of the rotating masonry part;

a – lever of the rotating masonry part with relation to the inspected fissure.

Formation of hinges and mutual contact of masonry parts [42] lead to changes in the vault geometry that are disproportionate to the rotation mechanism geometry. At the place of contact of the masonry parts a caving is formed under the impact of compression stress, which is manifested through masonry mortar plasticity.

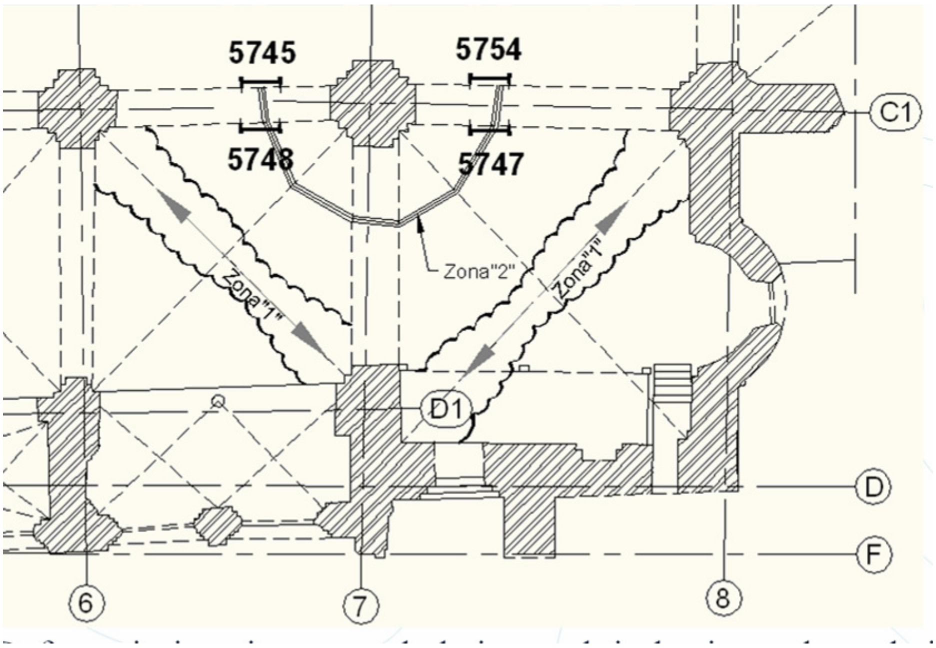
Modelling global stability and evaluation of progressive collapse

After tower collapse of St Peter's Church in 1666 a decision was made to reinforce the Riga Dome Cathedral tower. The forged reinforcements made in those times have survived till today. Each church reconstruction changes the internal force distribution within structures thus making the overall masonry structure analysis more complicated. In the world practice there were certain cases [43] when displacement of supports caused progressive collapse of the vaults.

Propagation of plasticity in the contact areas of the hinge cross-sections is the main reason of collapse of the aches under the deadweight load resulting from excessive displacement of supports. Kinematic method or method of rotation mechanism of masonry rib parts was developed in the work of Heyman [44] that was introduced in the masonry arch computations. Heyman's [45; 46] kinematic collapse method analyses the arch collapse mechanism, that is, formation of the four hinges in the arch structure. From the plasticity theorem it follows that when the compression axis line is located nearer to the arch surface at the four points, the safety criterion is surpassed.

Material property test data and assessment of their disintegration speed have noticeable effect on building collapse forecasting. Effect of accumulated creep deformations can be seen in the geometry of the vault curvatures, decrease of the structural rise leads to non-linear increase of internal stress, which only adds to the creep effects. Heyman [46] considered that plasticity limit state analyse method can be successfully applied for gravity structures under deadweight load, such as masonry bridges, arches and vaults.

Crack monitoring data of the Dome Cathedral deformation zone "L" point to the cyclic full relief of supports during winter/summer season.



Picture 18. Transfer of the vault support horizontal reaction to neighbouring structures.

Abutment deformation in zone “L” causes vault support shear transfer to the neighbouring columns and part of the wall on the axis “7” (see Picture 18).

Sensors 5745; 5747; 5748 and 5754 – installed by the belted column, in the point of intersection of axis “C” and “7”. Sensors are installed in middle area and on the attic side and provide a full crack evolution picture. With the help of the data provided by these sensors column vertical deformations were calculated in relation to the dimensions of the neighbouring walls. Relative column seasonal displacement in relation to other wall dimensions constitutes 0.57mm.

In the course of analysis of the derived data automatic link was established between the structural design & analysis software and MS Excel work tables, thus ensuring lateral testing against permissible strains, resulting force eccentricity, development of cracks, and the value of the axial and transversal force. On the basis of the processed results a report on distribution of cracks within the elements was prepared. For better formulation of the task to be analysed by the structural design & analysis software SAP 2000 these areas were recorded with a higher finite elements resolution, thus ensuring analysis of crack distribution based on the material non-linear properties.

Development of masonry shell vault safe service criteria

It was established by the doctoral research that a twofold collapse threat is inherent in the vertical support deformation:

a) Vault transverse disintegration resulting from cyclic, eccentric stress developed in parallel to the vault shell surface, close to the neutral axis,
b) Loss of resistance by certain areas of the vault masonry as a result of masonry element rotation.

Masonry transversal displacement is connected to pitting of the joint material; this effect was not analysed in the doctoral research paper. Vault lime pitting threats are assessed with the help of traditional masonry research methods. This kind of disintegration is characteristic of the Riga Dome Cathedral deformation zone "B". Development of disintegration should be analysed with the help of local masonry joint and brick resistance monitoring. This kind of disintegration does not threaten with large-scale progressive collapse of the Cathedral structures.

Safety analysis of the second kind of collapse was performed with the help of the method approbated in the doctoral research paper. Formation of the hinge in vault section and increase of compressive stress in the masonry material leads to creep and to the situation when the material properties and deformations reach the linearity limits. Further increase of the hinge fissure opening and cyclic fluctuations create excessive geometric displacement of the vault parts [47].

Safe service of the vaults depends on the extent of deformation [29] by subdividing into support deformations in variously directions. Safe service limits of the vault masonry parts impacted by rotation were established with the help of computer analysis. In the course of modelling the safe service limits for Riga Dome Cathedral deformed abutments were defined by comparative analysis of the correlation between crack displacements and vault geometry and deformation of supports.

Disintegration of the masonry abutments and loss of the bond between the blocks were modelled with the help of the computer software. Crack development scenario caused by support deformation was modelled with the help of the GEM software SAP 2000 non-linear modulus. Internal strains produced by support deformation and fissure zones were compared to the Riga Dome Cathedral crack monitoring data.

Safe service limit for the vault zone "H" was defined as follows: vault rib stability loss at the 1/24 of abutment deformations from span length. Assumption based on the support deformation and crack monitoring results. Geometric location of the vault rib rotation points determines displacements inside the vault shell. If the support deformation linear trend persists, which is 0.18mm/year, loss of stability in the vault shell zones “2” and “3” is forecasted after 95 years.

For development of the methodology suggested by the doctoral research paper is should be necessary to include methods for evaluation of the impact of the following factors:

a) Influence of humidity migration on deterioration of the material properties;
b) Degradation of the mortar binding agents during subsequent period of service;
c) Carbonisation of clay bricks during the period of service;
d) Masonry shrinkage during subsequent period of service;
e) Influence of masonry techniques on distribution of internal strains;
f) Redistribution of internal strains caused by reconstruction

and other effects of minor significance.

CONCLUSIONS

The goals and tasks set by the doctoral research paper have been achieved. The research provides a finalised methodology for technical analysis, preservation and service safety evaluation of the historic heritage architectural structures.

Within the framework of the research paper the methodology for structural analysis of the historic masonry vaults was developed by applying reverse engineering principles and approbating the technique for analysis of the building structure.

1. It was established that in comparison with the traditional masonry measuring techniques laser scanning of the masonry vaults surface is much less labour-intensive and saves up to 50-80% of the time required for analysis of geometric complexity of the surface planes.
2. It was established that in contrast to industrial reverse engineering modelling the masonry surface planes cannot be fully automated and data processing has to be done manually, which comprises 70% of the total required labour-intensity.
3. Suggested data transformation format: *.dxf (Drawing Interchange Format) for data exchange between modelling and analysis software thus ranking the methodology together with a wide range of structural design and analysis tools and decreasing the transformable information volume.
4. Along with minimisation of the result calculation error the permissible model deviation from the actual structure surface geometry was obtained with simultaneous analysis of geometrical dimensions of the model elements and influence of the model elements numerical size. In case of Riga Dome Cathedral masonry vaults the optimal model surface deviation thus defined represents the value below 14.3mm.
5. The existing masonry material is characterised by a wide dispersion of load-carrying capacity values. For investigation of masonry material properties the non-destructive or minimally destructive testing methods were selected thus observing the requirements for protection of historic architectural monument.
6. For defining the masonry mortar tensile strength it was suggested to use PNT-G drill penetration power test, which provides especially accurate results for low-strength masonry mortars.
7. It is proposed to use the double-flat jack test for direct measurement high accuracy method for determining the characteristic elasticity values of the homogenised masonry.

8. It was suggested to describe the homogenised masonry material deformation – stress chart with the help of linear areas by including collapse criteria for tension and compression.
9. It was suggested that for the purpose of homogenised material model the characteristic values for material resistance should be defined as minimal in the stress state planar diagram so that it would be possible to evaluate masonry strata orientation in relation to elements orientation in the mesh model.
10. It is recommended to use radio radar for scanning masonry massive to determine homogeneity and possibility to apply material homogenised property characteristics in structural analysis.

The methodology was developed that provides for the opportunity to perform analysis of the safety of existing masonry building ceiling/floor structures by applying a series of consecutive methods. By analysing the crack monitoring data the safe service limits for the most active deformation zones in a really existing structure were forecasted.

11. Masonry structures loaded with the deadweight have been modelled by taking into account the building geometric principle thus ensuring dislocation of the compression force in the cross section central zone. It was established that if irregular deformations of Riga Dome Cathedral vault foundations exceed 40mm the vault shell tensile strength limit will be exceeded.
12. In the course of analysing increased threat of global collapse by excluding the vault support node from the joint action, the internal force relocation mechanism – transfer of the load to the neighbouring supports – was defined.
13. It was established that wind load creates stress in the outer fibres of the building perimeter walls, which constitutes 1.5% of the stresses present in the masonry massive. These stresses cannot be fully referred to the vault shell structure and the wind load effect is assumed to be of lower significance and is not included in the vault safety analysis.
14. As a result of analysis it was established that temperature seasonal impact in the vault transverse section causes strain increase and decrease within the range ±1.5% of the stress caused by the deadweight. Displacement within the temperature block boundaries is reflected in the changes of crack openings, in the vault ribs, with the masonry massive rotating in the contact hinge.

15. It was established that irregular support settlement deformations together with crack displacement caused by temperature impact lead to seasonal changes of the vault condition and are determinative for assessing the vault operation safety limits.
16. Deformation zones recorded fluctuations of crack openings, which, as real geometric model analysis showed, are transferred to irregular support deformations. It was stated that displacements of the hinge mechanism in the vault ribs determine transformed crack displacements in the vault shell, which are dependent upon the real vault geometry.
17. Masonry vault shell safe service limit was demonstrated that is dependent on the shell support displacements arising as a part of the vault geometric dimensions. By analysing dynamic deformation within Riga Dome Cathedral zone “H” the safe service limit of 95 years was obtained.

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