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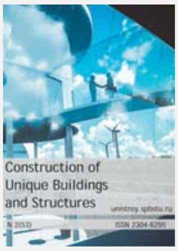

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Unconventional cases of the stone vaults

I.V. Skripchenko [1], V.V. Bespalov [2], S.Y. Lukichev [3], S.S. Zimin [4]

[1-4]*Peter the Great St. Petersburg Polytechnic University,29 Politechnicheskaya St., St. Petersburg, 195251, Russia*

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scientific article **doi: 10.18720/CUBS.53.7**	Received: 17.11.2016	Construction; vaulted structures; masonry; historical buildings; simulation; thrust line;

ABSTRACT

The evaluation of the technical condition of vaulted structures is the principal issue in the survey of historical buildings. It is also important to understand how any thrust system works, and what functions it performs. However, apart from visual inspection it is necessary to make apertures in vaulted ceilings and determine the methods of support. It is also very important to determine the strength characteristics of masonry. Unconventional cases should always be taken into account during the inspection of masonry vaulted structures. It needs to carefully conduct their inspection with the mandatory breaking opening and strength analysis based on numerical simulation before starting of all the reconstruction, restoration and repair. The use of modern program complexes in the simulation, such as Ansys, Abaqus, allows improving the quality of performed work.

Content

Contact information:

1 * +7(904)6419650, scripchenco-ilya@mail.ru (Ilya Skripchenko, Student)
2 +7(981)7850899, chanchullero@yandex.ru (Vladimir Bespalov, Student)
3 +7(929)1007311, serj_lu@mail.ru (Lukichev Sergey, Student)
4. +7(921)3477701, zimin_sergei@mail.ru (Sergej Zimin, Head Lecturer)

1. Introduction

It may encounter the issue of how to determine the condition of the stone vaults when examining historic buildings and assigning of further measures for repairing and strengthening of the structures. Due to unique designs, misunderstanding of the stone vaults specifics and insufficiently developed methods of calculation, the wrong conclusions about their condition are often made. This leads to, on the one hand, cost overruns in excessive reinforcement of predetermine efficient areas, and on the other hand, to abandonment of dangerous areas in vaults construction.

Currently, the most frequently used techniques to determine stresses in the vaults are using of finite element analysis software as Ansys, Abaqus and their analogues. Vault is simulated using the homogeneous model of masonry [1-3], and in some cases using the additional simulating of discrete model as a complex structure "brick plus mortar" [4-6]. To determine the stability of the vault, usually it is enough to draw the thrust line – and if it does not extend beyond the cross-section, the vault is considered stable.

Previous analysis of publications [7] shows that the criteria of masonry vaults strength has not been developed, and in Russia there are practically no researchers involved in the study of stone vaults. Also, there are quite a lot of researches devoted to masonry [8-13]. Foreign studies can be divided into two groups: the search for numerical simulation methods, which allows to represent the work of vaults of various configurations in the most accurate way [13-20], and the experimental study of brick arches and vaults failure mechanisms [20-25].

This article describes several structures used in one building that significantly affect the vaults, can be ambiguously interpreted and can be difficult to detect.

2. Goals and objectives

The goal of this work was to determine possible unconventional elements in the construction of vaults and their impact on the mechanics of such structures.

Objectives:

1) Show unconventional cases and how to detect them considering a real building as an illustrative example;

2) Carrying out finite element analysis taking into account the influence of such elements.

3. Materials and Methods

In the research the former building of the fortress at Kronshtadt was considered. It was used in the 80-ies as a medical post (Fig. 1). The building has a number of vaults of complex semi-conic shape with spandrels of different sizes and cross vaults.

Figure 1. The North-Western face of the subject building

This building is a good example, which contains several unconventional elements of vaulted structures, for example the brick arch, passing through the central part of the stone vaults. Each arch divides the vault into 2 parts and has a structure that is different from the rest of the masonry vault (Fig. 2).

Figure 2. Dividing arch with a different structure of masonry

As a result of masonry vault analysis, it has been suggested that it represents a truncated masonry of the former brick walls. In the analysis of the vaults structures this was taken into account, therefore, the structural model was adopted to split each vault into 2 parts that operate independently. In addition, for the vaults decreasing safety coefficients were adopted.

Another problem is the way of supporting vaults. In the simulation of the vaults using the finite element method, a structural model has a great influence on the result which depends on the type of bearing. Usually masonry vaults moves to the vertical direction with the future resting on a foundation or rests on the front wall layer. In this case, an unconventional way of supporting the wall and its backfill was discovered (Fig. 3, 4).

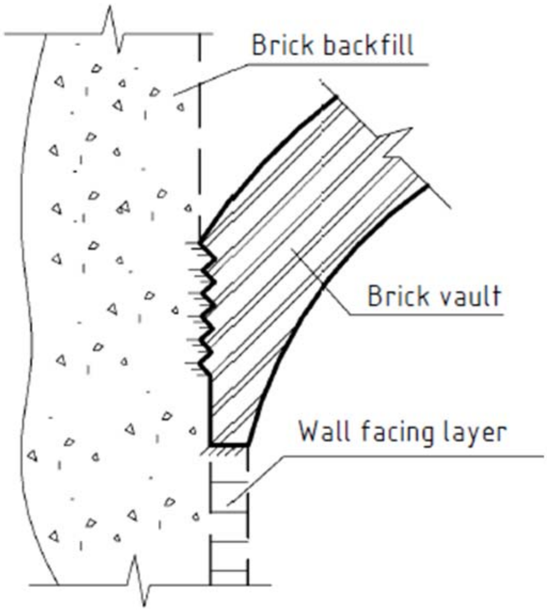

Figure 3. The result of the breaking opening of support area of the vault

Figure 4. Schematic illustration of vault structural support

In the key side of each stone vault an aperture of complex shape was discovered (Fig. 5). All the apertures came out directly on the roof of the building and were one of the reasons of moisture penetration to the interior of the structure. To determine the extent of the effect of such apertures at the stress state of a vault, it was necessary to take them into account in the analytical models of the vaults.

Figure 5. The aperture in the key area of the vault

In addition, the end walls of the building represent a complex issue from the perspective of mechanical behavior. They bear the thrust from the massive vaulted structures (Fig. 6) and must be calculated on the perception of this load; it is possible impact on the outer layers and the overall stability of the wall.

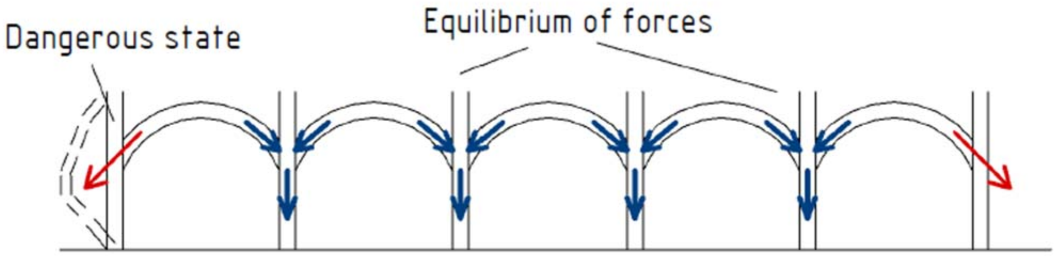

Figure 6. A simplified scheme of the thrust loads on the building

4. Results and discussion

The most of the building vaults have a maximum span of 6 meters and a constant thickness of cross-section 0.8 meters. With the previously adopted multistage supporting masonry for the backing and facing layers, a structural scheme of the vaults was accepted as being flat resting on one brick (0.25 m) at the bottom face and vertically to the wall (Fig. 7). The load that was taken is only its dead load, and also the concrete backfill of the vault was taken into account. To obtain a complete picture of the stresses that are perpendicular to the horizontal joints of masonry, cylindrical coordinate system was adopted with the axis which follow the arc of the vault. The results of the simulation (Fig. 8) show that in the vaults tensile stresses acting perpendicular to the mortar joints do not exist. With the absence of cracks on the inner side of the vaults, we can conclude the correctness of the chosen structural scheme with the multistage resting on the backing.

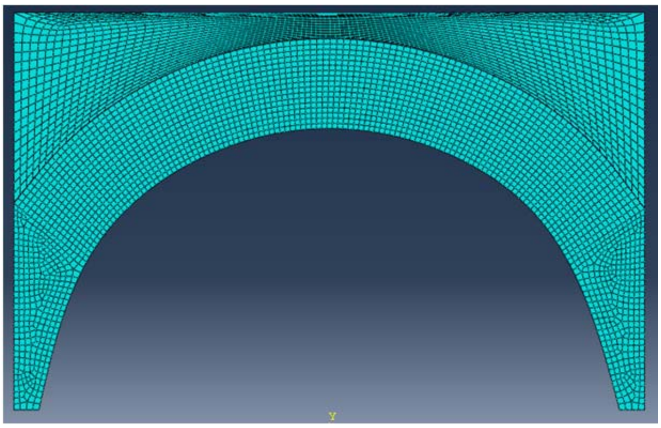

Figure 7. Analytical model of the vault

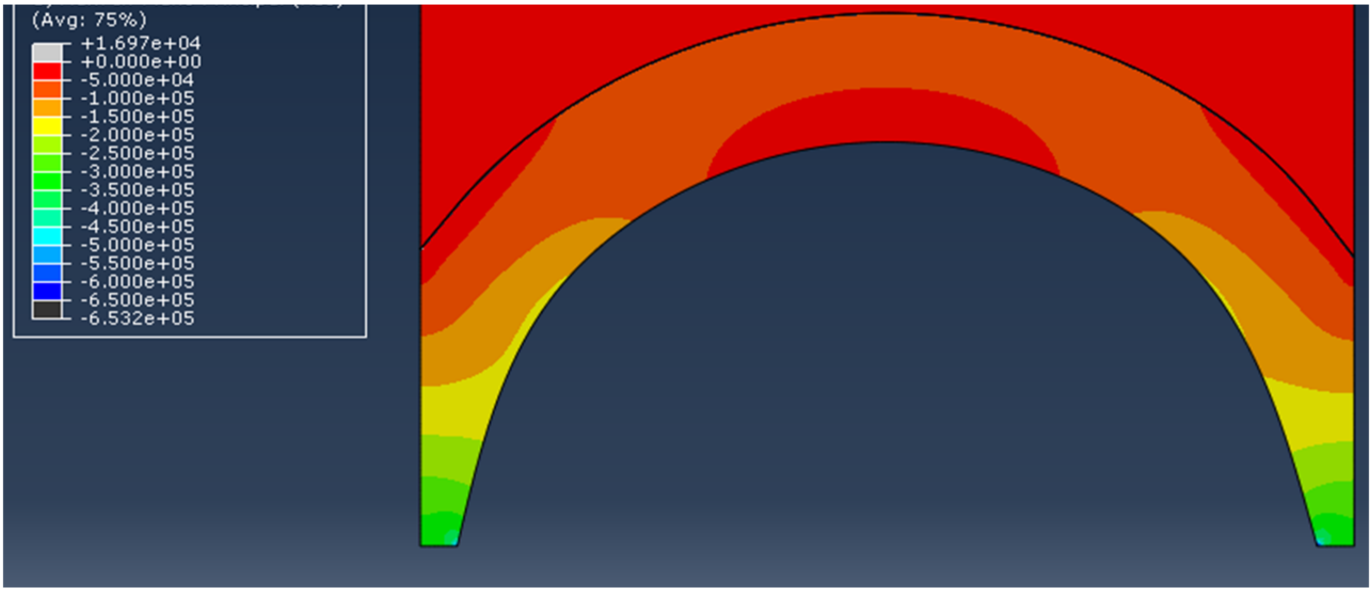

Figure 8. Stress distribution of normal stress (Pa) acting perpendicular to the mortar joints of masonry

For the analysis of inclined aperture in the vault a three-dimensional computational model was made. Based on the calculation results (Fig. 9) the greatest tensile stresses occur in the area of the upper third section of the vault, where the thrust line passes. Tensile stresses occur only on the side walls of the aperture, perpendicular to the lines of action of the main compressive stresses, which is consistent with the results obtained earlier for analogous structures [21].

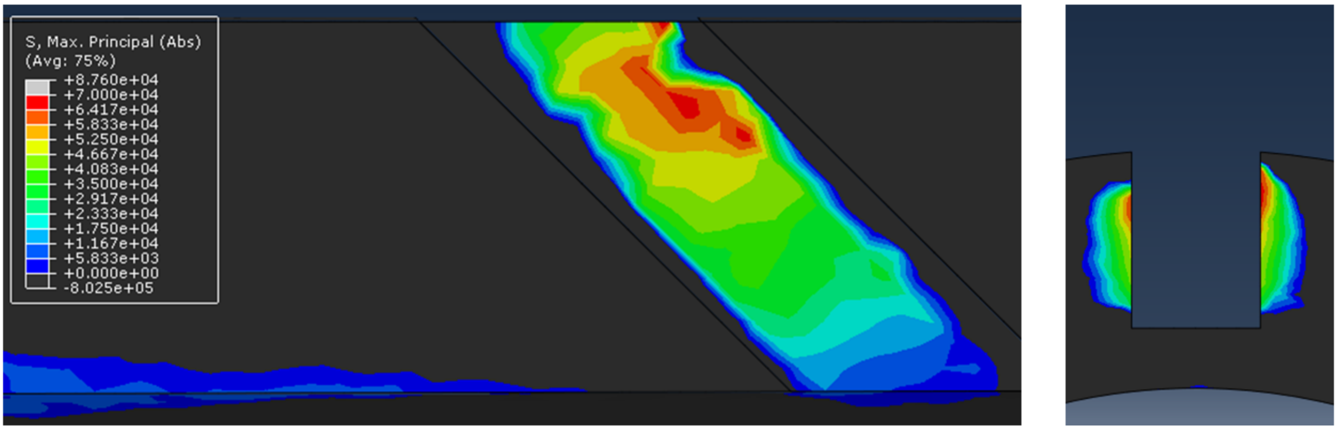

Figure 9. Longitudinal and cross-section of the aperture. Stress distribution of principal tensile stresses

In the of opening of the walls there is a concentration of tensile stresses reaching 0.05...0.07 MPa, which is in the most cases higher than resistance (tensile strength at the direction of bound masonry). In addition to these areas, the brick and the mortar joints are not protected and could be exposed to strong hydration. Thus, the actual tensile strength may be much lower than estimated. From this we can conclude that such apertures should be carefully examined. Their side walls in the location of the pressure line need to be specially reinforced with a preliminary strength calculation of the vault.

To check the load accommodation of the brick backfill of the building end walls it was calculated on a unilateral load of a vaulted ceiling. In addition to the dead load of masonry facing layers and backfill of the walls, it was accompanied by boundary conditions taken from the calculation results of vault with a span of 6 m (Fig. 8). For the simulation of bounding of facing layers with brick backfill conjunction was taken as a rigid. The volume weight of the backfill was taken as equal to the volumetric weight of masonry and the modulus of elasticity and was assumed to be one quarter of masonry elasticity modulus, which reflects a partial ligation. The calculated finite-element scheme walls, maximum principal stresses distribution and their paths are shown in Fig. 10.

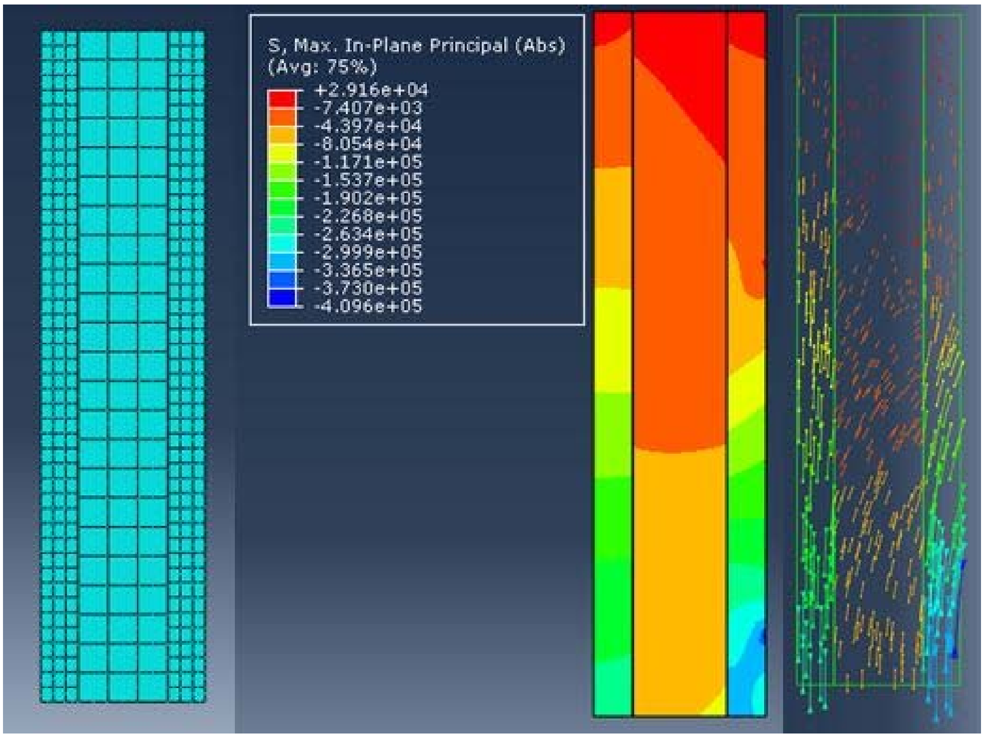

Figure 10. Stress distribution of maximum principal stresses (Pa) and lines of its action

The analysis of the trajectories of the maximum principal stresses shows that the brick backfill completely absorbs the horizontal thrust from the vault and does not transmit it on the outer face layer, which works only on its own weight. In addition, the backfill takes over a part of the vertical load, unloading inner facial layer: in the area of heel vault voltage was 0.2-0.4 MPa, in contrast to the obtained in the heel of the vault of 0.25-0.5 MPa. However, in case of damage to the part of the inner face, backing layers can be incorporated into the work to a greater degree and cause buckling of the outer facing layers, which ultimately may lead to collapse of the entire structure. Therefore, such end walls should always be checked on the adequacy of the backfill width and the integrity of the facial layers, and should be subjected to strength calculations in the relevant software systems.

5. Conclusions

The results of this study show the following:

- It needs to pay attention to the structure of masonry vaults, the degree of damage and the location of the bed joints (in this case, a demolition of a stone wall was discovered). Similarly, it can be detected by observables of other elements, which previously worked together with vault – columns, spandrels, apertures, etc. All of them can have a significant impact on the structural scheme of the vaults and must be considered when analysing them;
- To produce the right structural scheme it also needs to find out the exact way of the vault support from the wall or foundation and breaking open is highly recommended;
- In the case of apertures in vaults the effects of connectivity areas under and over the vault should be taken into account. The side walls of the opening should be strengthened in case of a sufficiently wide area on the pressure line in the upper third of the vault. All apertures should be taken into consideration in the simulation model;
- Terminal vaults of the vault chain always bear against exterior walls of buildings or other constructions, where structural reduction of thrust loads is necessary. The element that reduces thrust is one of the most critical elements in buildings with vaulted structures. In case of bearing capacity loss, they can cause the progressive collapse of the entire chain of vaulted structures. Therefore, they should be inspected as detailed as possible and calculated with appropriate importance coefficients.

Such unconventional cases should always be taken into account during the inspection of masonry vaulted structures. It needs to carefully conduct their inspection with the mandatory breaking opening and strength analysis based on numerical simulation before starting of all the reconstruction, restoration and repair.

In the vaulted structures in addition to considered in this paper, there are many other unconventional cases. A study of their impact on the mechanics of vaults is planned by the authors for the future work.

References

[1] Zucchini A., Lourenco P.B. A coupled homogenisation-damage model for masonry cracking. Computers and Structures. 2004. No. 82. Pp. 917–929.

[2] Zhang Y., Macorini L., Izzuddin B.A. Mesoscale partitioned analysis of brick-masonry arches. Engineering Structures. 2016. Vol. 124. Pp. 142-166.

[3] Clementi F., Gazzani V., Poiani M., Lenci S. Assessment of seismic behaviour of heritage masonry buildings using numerical modelling. Journal of Building Engineering. 2016. Vol. 8. Pp. 29-47.

[4] Zimin S.S., Bespalov V.V., Kazimirova A.S. The computational model stone arch. Proceeding of the DonNACEA. 2015. No. 3(113). Pp. 33–37. (rus)

[5] Drougkas A., Roca P., Molins C. Analytical micro-modeling of masonry periodic unit cells – Elastic properties. International Journal of Solids and Structures. 2015. Vol. 69–70, Pp. 169-188.

[6] Ramaglia G., Lignola G.P., Prota A. Collapse analysis of slender masonry barrel vaults. Engineering Structures. 2016. Vol. 117. Pp. 86-100.

[7] Zimin S.S., Kokotkova O.D., Bespalov V.V. Vault structures of historical buildings. Construction of unique buildings and structures. 2015. No. 2(29). Pp. 57-72. (rus)

[8] Derkach V.N., Orlovich R.B. Empiricheskiye kriterii prochnosti kamennoy kladki v usloviyakh slozhnogo napryazhennogo sostoyaniya [Empirical strength criteria masonry under complex stress state]. Stroitelstvo i rekonstruktsiya. 2010. No. 6(32). Pp. 8-12. (rus)

[9] Derkach V.N., Orlovich R.B. Estimation of masonry mortars strength during stone buildings investigation. Magazine of Civil Engineering. 2011. No. 7. Pp. 3-10. (rus)

[10] Ulybin A.V., Zubkov S.V. Control methods for strength of ceramic bricks in the inspection of buildings. Magazine of Civil Engineering. 2012. No. 3. Pp. 29-34. (rus)

[11] Ulybin A.V., Zubkov S.V., Sudar O. U., Laptev E. A. Standard and alternative methods of determination of the strength of brick at inspection of buildings and structures. Construction of unique buildings and structures. 2014. No. 3(18). Pp. 9-24. (rus)

[12] Zubkov S.V., Ulybin A.V., Fedotov S.D. Assesment of the mechanical properties of brick masonry by a flat-jack method. Magazine of Civil Engineering. 2015. No. 8. Pp. 20-29. (rus)

[13] Betti M., Drosopoulos G.A., Stavroulakis G.E. Two non-linear finite element models developed for assessment of failure of masonry arches. Comptes Rendus Mecanique. 2008. No. 336. Pp. 42–53.

[14] Riveiro B., Solla M., Arteaga I., Arias P., Morer P. A novel approach to evaluate masonry arch stability on the basis of limit analysis theory and non-destructive geometric characterization. Automation in Construction. 2013. No. 31. Pp. 140-148.

[15] Block P., Lachauer L. Three-dimensional funicular analysis of masonry vaults. Mechanics Research Communications. 2014. No. 56. Pp. 53-60.

[16] Harvey W. J. Application of the mechanism analysis to masonry arches. The Structural Engineer. 1988. No. 66(5). Pp. 77–84.

[17] Milani G., Rossi M., Calderini C., Lagomarsino S. Tilting plane tests on a small-scale masonry cross vault: Experimental results and numerical simulations through a heterogeneous approach. Engineering Structures. No. 123. Pp. 300-312.

[18] Milani G. Upper bound sequential linear programming mesh adaptation scheme for collapse analysis of masonry vaults. Advances in Engineering Software. No. 79. Pp. 91-110.

[19] Huerta S. Mechanics of masonry vaults: The equilibrium approach. International Seminar on Structural Analysis of Historical Constructions. 2001. No. 3. Pp. 47–69.

[20] Carini A., Genna F. Stability and strength of old masonry vaults under compressive longitudinal loads: Engineering analyses of a case study. Engineering Structures. 2012. No. 40. Pp. 218-229.

[21] Bovo M., Mazzotti C., Savoia M. Structural behaviour of historical stone arches and vaults: Experimental tests and numerical analyses. Engineering Materials. 2014. No. 628. Pp. 43-48.

[22] Sarhosis V., Oliveira D.V., Lemos J.V., Lourenco P.B. The effect of skew angle on the mechanical behaviour of masonry arches. Mechanics Research Communications. 2014. No. 61. Pp. 53-59.

[23] López-Almansa F., Sarrablo V., Lourenço P.B., Barros J.A.O., Roca P., Porto F., Modena C. Reinforced brick masonry light vaults: Semi-prefabrication, construction, testing and numerical modeling. Construction and Building Materials. 2010. Vol. 24(10) Pp. 1799-1814.

[24] Carini A., Genna F. Stability and strength of old masonry vaults under compressive longitudinal loads: Engineering analyses of a case study. Engineering Structures. 2012. Vol. 4. Pp. 218-229.

[25] Bespalov V., Orlovich R., Zimin S. Stress-Strain State of Brick Masonry Vault with an Aperture. MATEC Web of Conferences. 2016. No. 53. 001009.

Нетипичные случаи каменных сводов

И.В. Скрипченко[1], В.В. Беспалов[2], С.Ю. Лукичев[3], С.С. Зимин[4]

[1-4]Санкт-Петербургский политехнический университет Петра Великого, 195251, Россия, г. Санкт-Петербург, Политехническая ул., 29.

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КЛЮЧЕВЫЕ СЛОВА

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исторические здания,
расчет,
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АННОТАЦИЯ

Оценка технического состояния сводчатых конструкций – одна из наиболее сложных проблем при обследовании исторических зданий. Также важно понимание работы распорных систем, и их функциональных особенностей. Кроме того, помимо визуального обследования, необходимо определять способы опирания сводчатых конструкций, в том числе с проведением вскрытия кладки. Нестандартные случаи всегда следует принимать во внимание при обследовании каменных сводчатых конструкций. Такое обследование необходимо тщательно проводить перед работами по ремонту, реставрации и реконструкции, с обязательным проведением прочностного анализа, основанного на численном моделировании. Использование современных конечно-элементных программных комплексов, таких как Ansys, Abaqus, позволяет улучшить качество выполняемой работы.

Контакты авторов:

1 * +7(904)6419650, scripchenco-ilya@mail.ru (Скрипченко Илья Валентинович, студент)
2 +7(981)7850899, chanchullero@yandex.ru (Беспалов Владимир Владимирович, студент)
3 +7(929)1007311, serj_lu@mail.ru (Лукичев Сергей Юрьевич, студент)
4 +7(921)3477701, zimin_sergei@mail.ru (Зимин Сергей Сергеевич, старший преподаватель)

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Литература

[1] Zucchini A., Lourenco P.B. A coupled homogenisation-damage model for masonry cracking. Computers and Structures. 2004. No. 82. Pp. 917–929.

[2] Zhang Y., Macorini L., Izzuddin B.A. Mesoscale partitioned analysis of brick-masonry arches. Engineering Structures. 2016. Vol. 124. Pp. 142-166.

[3] Clementi F., Gazzani V., Poiani M., Lenci S. Assessment of seismic behaviour of heritage masonry buildings using numerical modelling. Journal of Building Engineering. 2016. Vol. 8. Pp. 29-47.

[4] Зимин С. С., Беспалов В. В., Казимирова А. С. Расчетная модель каменной арочной конструкции // Вестник ДонНАСА. 2015. №3(113). С. 33-37.

[5] Drougkas A., Roca P., Molins C. Analytical micro-modeling of masonry periodic unit cells – Elastic properties. International Journal of Solids and Structures. 2015. Vol. 69–70, Pp. 169-188.

[6] Ramaglia G., Lignola G.P., Prota A. Collapse analysis of slender masonry barrel vaults. Engineering Structures. 2016. Vol. 117. Pp. 86-100.

[7] Зимин С. С., Беспалов В. В., Кокоткова О. Д. Сводчатые конструкции исторических зданий // Строительство уникальных зданий и сооружений. 2015. № 2(29). С. 57-72.

[8] Деркач В. Н., Орлович Р. Б. Эмпирические критерии прочности каменной кладки в условиях сложного напряженного состояния // Строительство и реконструкция. 2010. № 6 (32). С. 8-12.

[9] Деркач В. Н., Орлович Р. Б. Оценка прочности кладочных растворов при обследовании каменных зданий // Инженерно-строительный журнал. 2011. № 7. С. 3-10.

[10] Улыбин А. В., Зубков С. В. О методах контроля прочности керамического кирпича при обследовании зданий и сооружений // Инженерно-строительный журнал. 2012. № 3. С. 29-34.

[11] Улыбин А. В., Зубков С. В., Сударь О. Ю., Лаптев Е.А. Стандартная и альтернативная методики определения прочности кирпича при обследовании зданий и сооружений // Строительство уникальных зданий и сооружений. 2014. № 3 (18). С. 9-24.

[12] Зубков С. В., Улыбин А. В., Федотов С. Д. Исследование механических свойств кирпичной кладки методом плоских домкратов // Инженерно-строительный журнал. 2015. № 8. С. 20-29.

[13] Betti M., Drosopoulos G.A., Stavroulakis G.E. Two non-linear finite element models developed for assessment of failure of masonry arches. Comptes Rendus Mecanique. 2008. No. 336. Pp. 42–53.

[14] Riveiro B., Solla M., Arteaga I., Arias P., Morer P. A novel approach to evaluate masonry arch stability on the basis of limit analysis theory and non-destructive geometric characterization. Automation in Construction. 2013. No. 31. Pp. 140-148.

[15] Block P., Lachauer L. Three-dimensional funicular analysis of masonry vaults. Mechanics Research Communications. 2014. No. 56. Pp. 53-60.

[16] Harvey W. J. Application of the mechanism analysis to masonry arches. The Structural Engineer. 1988. No. 66(5). Pp. 77–84.

[17] Milani G., Rossi M., Calderini C., Lagomarsino S. Tilting plane tests on a small-scale masonry cross vault: Experimental results and numerical simulations through a heterogeneous approach. Engineering Structures. No. 123. Pp. 300-312.

[18] Milani G. Upper bound sequential linear programming mesh adaptation scheme for collapse analysis of masonry vaults. Advances in Engineering Software. No. 79. Pp. 91-110.

[19] Huerta S. Mechanics of masonry vaults: The equilibrium approach. International Seminar on Structural Analysis of Historical Constructions. 2001. No. 3. Pp. 47–69.

[20] Carini A., Genna F. Stability and strength of old masonry vaults under compressive longitudinal loads: Engineering analyses of a case study. Engineering Structures. 2012. No. 40. Pp. 218-229.

[21] Bovo M., Mazzotti C., Savoia M. Structural behaviour of historical stone arches and vaults: Experimental tests and numerical analyses. Engineering Materials. 2014. No. 628. Pp. 43-48.

[22] Sarhosis V., Oliveira D.V., Lemos J.V., Lourenco P.B. The effect of skew angle on the mechanical behaviour of masonry arches. Mechanics Research Communications. 2014. No. 61. Pp. 53-59.

[23] López-Almansa F., Sarrablo V., Lourenço P.B., Barros J.A.O., Roca P., Porto F., Modena C. Reinforced brick masonry light vaults: Semi-prefabrication, construction, testing and numerical modeling. Construction and Building Materials. 2010. Vol. 24(10) Pp. 1799-1814.

[24] Carini A., Genna F. Stability and strength of old masonry vaults under compressive longitudinal loads: Engineering analyses of a case study. Engineering Structures. 2012. Vol. 4. Pp. 218-229.

[25] Bespalov V., Orlovich R., Zimin S. Stress-Strain State of Brick Masonry Vault with an Aperture. MATEC Web of Conferences. 2016. No. 53. 001009.

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Скрипченко И.В., Беспалов В.В., Лукичев С.Ю., Зимин С.С. Нетипичные случаи каменных сводов, Строительство уникальных зданий и сооружений, 2017, №2 (53). С. 87-95.

Skripchenko I.V., Bespalov V.V., Lukichev S.Y., Zimin S.S. Unconventional cases of the stone vaults / Скрипченко И.В., Беспалов В.В., Лукичев С.Ю., Зимин С.С. Нетипичные случаи каменных сводов ©