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Strength evaluation of the Prussian vaults made from brick aggregate concrete

Оценка прочности кирпичебетонных Прусских сводов

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Ключевые слова: каменные конструкции; сжато изгибаемые элементы; поврежденные конструкции; обследование зданий; каменные своды; усиление конструкций; сводчатые конструкции

Abstract. The behavior of Prussian vaults of brick aggregate concrete differs both from the behavior of brick vaults and classical flat slabs. Such vaults are particularly susceptible to physical damage and deterioration. To determine the real bearing capacity of the vaults, the authors not only performed the in-situ determination on several sections with deflection control, but also numerical simulations of the multi-span system of Prussian vaults in the program complex Abaqus. Moreover, experimental comparisons between damaged and not damaged vaults were also performed in the historical building of the New Holland complex. Obtained results show that, the vaults adjacent to the loaded one exhibit opposite behavior and significant damages caused by the loaded one, both of which are useful outcomes for evaluation of this vaulting type.

Аннотация. Поведение прусских сводов из кирпичебетона отличается как от поведения кирпичных сводов, так и от поведения классических плоских перекрытий. Такие своды особенно чувствительны к повреждениям. Для определения реальной несущей способности сводов были проведены натурные эксперименты вырезанных полос сводов с контролем их деформаций. Представлена численная модель многопролетной системы прусских сводов, построенная в программном комплексе Abaqus. Также представлено экспериментальное сравнение поврежденных и не поврежденных сводов, проведенное в историческом здании комплекса Новой Голландии. Результаты показывают обратное направление работы сводов, смежных с нагружаемым сводом, а также значительное влияние повреждений на деформативность таких сводов, что может быть полезным при оценке прочности прусских сводов.

1. Introduction

Prussian vaults with embedded steel I-beams began to be used at the end of the 19th century, which was the most common solution in construction of slabs for houses till the 1930s. The masonry infill was either flat – as in case of Klein's ceiling (horizontal brickwork, supported on beams), or arched as in case of barrel vaults. In addition to masonry techniques, plain and reinforced slabs with ordinary and slag added concrete were also applied. We can often find slabs made from recycled brick aggregate mixed with lime and lime-cement blend, in historical buildings. The properties of these slabs in terms of good load-bearing capacity coupled with high fire and corrosion resistance, low cost and ease of assembly have increased their popularity both in housing and industrial buildings [1–5]. Additionally, they have been well appreciated from the recycling point of view, which is a famous notion for modern constructions [6]. Span of these floor structures can differ from 0.6 to 1.8 meters when designed with suitable thicknesses, where t is equal to h for regular slabs, while t can range between 14 to 20 cm when bow i.e. f/L is between 1/6 and 1/12 for barrel vaults (Figure 1). Besides these theoretical thicknesses, it is also a known fact that, most of the existing floors with this technique are in bad condition and require repairs or replacement.

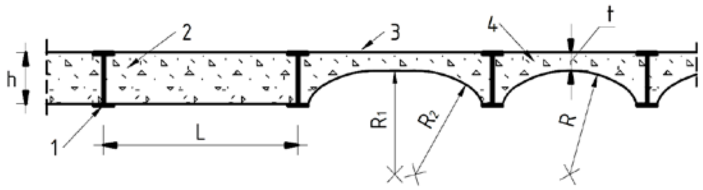

Figure 1. Prussian vaults from brick aggregate concrete 1 – steel beams, 2 – slab, 3 – barrel vault, 4 – cylindrical vault

Most common damages in joist floors with steel girders are [7–10]:

- Corrosion of bottom flanges for steel I beams are frequent especially for basement floors and unheated rooms when humidity level is high as well as external slabs exposed to moisture such as terraces, balconies and wet cores (Figure 2). Moreover, webs also frequently corrode in these conditions, which are only detectable by exposing the whole beam.
- Cracks on the plaster are also common along the beams caused by load or expansion caused by corrosion underneath (Figure 2a), as well as cracks (Figure 2b) and even loss of material from the floor surface (Figure 2 c, d).

Figure 2. Types of damages in Prussian vaults made from brick aggregate concrete: a – corrosion of steel beams, b – cracks, c, d – degradation of the material

The evaluation of current condition of historical Prussian vaults in buildings depends on experience and intuition of the surveyor especially for atypical structures, where incorrect estimation of bearing capacity can lead to expensive protective applications and strengthening techniques. Additionally, inadequate assessments can result in partial or complete removal and loss of building elements which is especially valid for the constructions dated to pre-war period since their designs may not meet modern requirements. Consequently, it is either necessary or useful to perform in-situ tests with preliminary loads [11]; since the results are more accurate than laboratory tests of cylindrical prism samples and can be used as base for evaluating the bearing capacity and serviceability of existing Prussian vaults [12–15].

It should be noted that the range of use of Prussian vaults is narrow in terms of geography and time period which made their investigation level insufficient even today. The closest option (in terms of geometry) is barrel brick vaults [16–19], which are commonly strengthened with composite reinforcement (fiber reinforced cementitious matrix or other types of surface polymer strengthening) similar to the Prussian ones [20–32]. At this point, selection of correct reinforcement type is dependent on the deformation compatibility between the body of the vault and the reinforcing material [33–35]; which is a hard task to determine, due to the lack of information about altered behavior of damaged Prussian vaults.

Consequently, the goal of this study was to determine this behavior and the evaluation of strength; which was ensured with numerical modeling and experimental comparison (samples from a historic building); and noted with deformation curves on diagrams.

2. Materials and Methods

Joist floors can be considered as vaults with span of L and bow of f, supported by steel beams; which spread forces (H in Figure 3) due to fixed condition of the supports. Additionally, similar computational schema can be used for vaults of the slab when the bow (f) is equal to $\mathrm{h}/3$; where obtained results have better correspondence with actual cases for lower $\mathrm{L/h}$ values. Lastly, calculations can be done for taking bending into consideration while disregarding tension since there is no reinforcement in the tension zone.

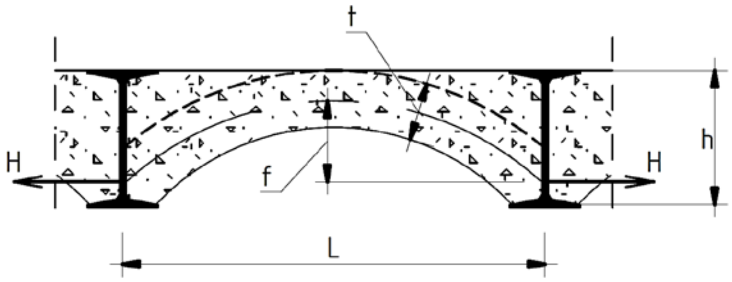

Figure 3. Simplified calculation schema for cylindrical vault

Bearing capacity of the vault q (kN/m^2) under distributed load can be calculated according to following equations, as shown in Figure 3:

- Compressive strength for thinnest cross-section (t) with regard to horizontal reaction (H). (in the key zone).

$$q_{c1} = \frac{8tR_b f}{L^2} \quad (1)$$

- Shear strength with regard to whole height (h) which is the same as the beam.

$$q_s = \frac{2hR_{bt}}{L-b} \quad (2)$$

- Compressive strength of the zones that support the bottom flanges of beams

$$q_{c2} = \frac{(b-s)R_b}{L-b}, \quad (3)$$

where R_b and R_{bt} – compressive and tensile strength of the material sampled from the vault;

b and s – respectively, width of the flange and web thickness of the beam.

These equations were collected to be used with the test results obtained from an historical building in St. Petersburg Russia. This is the building of the complex of New Holland, which is being restored at the moment. The building was built in 1779 and was used as a warehouse, and the last 100 years has not been exploited. The investigated vaults were installed in 1902 to replace the wooden ceilings. Strength of the material drilled in cores from these vaults showed that the critical bearing capacity is shear strength, as noted in Equation 2. Test results (from cores, Table 1) indicate that, compressive strength (R_b) is 12.2 MPa, which corresponds to B12.5 class (according to Russian State Standard GOST 10180-2012 [36]) and the corresponding tensile strength (R_{bt}) is 0.66 MPa (according to Russian regulations and rules SP 63.13330.2012 [37]).

Table 1. Core test results

No.	Dimensions, mm		h/d	η_1 (from GOST 28570)	Compressive test			
	d	h			load at failure P, kN	Core compressive strength R, MPa	Core compressive strength with η_1 R*η_1 MPa	Average compressive strength Rb, MPa
1	140.0	136.0	0.971	1.00	184.24	12.0	12.0	12.2
2	140.0	170.0	1.214	1.08	216.19	14.0	15.1	
3	140.0	180.0	1.286	1.10	123.71	8.0	8.8	
4	140.0	168.0	1.200	1.08	143.88	9.3	10.1	
5	140.0	173.0	1.236	1.08	78.30	5.1	5.5	
6	140.0	181.0	1.293	1.10	192.65	12.5	13.7	
7	140.0	142.0	1.014	1.00	199.37	12.9	12.9	
8	140.0	155.0	1.107	1.04	382.66	24.8	25.8	
9	140.0	142.0	1.014	1.00	71.58	4.6	4.6	
10	140.0	124.0	0.886	0.96	115.30	7.5	7.2	
11	140.0	135.0	0.964	1.00	261.59	17.0	17.0	
12	140.0	140.0	1.000	1.00	224.60	14.6	14.6	

Compressive and tensile strengths obtained from core samples can be used in the equations 1-3 for the calculation of overall strength for vaults in question. On the other hand, values calculated in this manner do not reflect real boundary conditions of the vaults especially for the zones close to supports, since there are probable damages occurred during long operation time, cracks, material degradation, etc. Therefore, the authors of this study performed in situ tests on 5 slabs with 50 cm width (b) cut out from the vaults between beams; including well preserved and damaged sections, as explained in Figures 5 and 6.

Figure 4. The structure of the brick aggregate concrete vaults and core samples in the compressive test

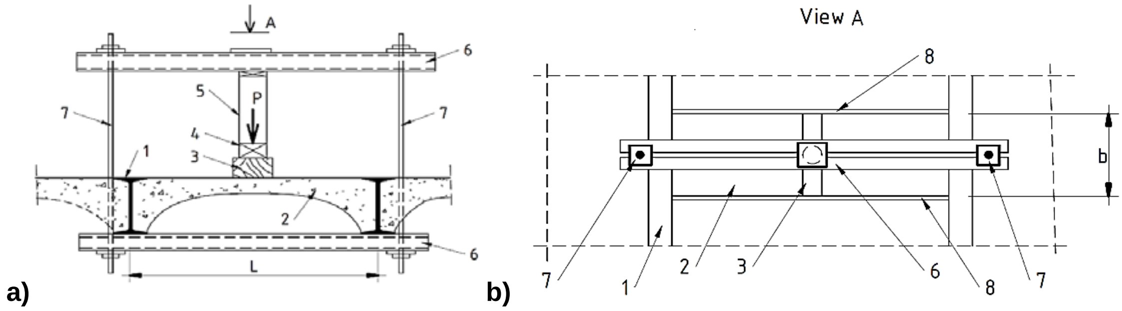

Figure 6. Test bench: 1 – steel beams, 2 – Prussian vault with brick aggregate concrete, 3 – spacer, 4 – dynamometer, 5 – hydraulic actuator, 6 – cross-arm, 7 – steel cables, 8 – cutting joint

Load was applied by hydraulic actuator as shown in Figures 6 and 7, the deflections of the sections were measured in the mid-span (L/2) and the widths of existing as well as new cracks were also noted.

Figure 7. Test setup during the process

3. Results and Discussion

It must be mentioned that in accordance with Figure 3 the equation 1 is not accurate because it does not include the bending moments which are crucial especially for concentrated loads such as partition walls between the beams in the upper story. Therefore, FEM (Finite Element Method) can be preferred for accurate determination of stress state, which was used with barrel vaults between 40 cm deep steel I-beams located at 155 cm interval, for the scope of this study. Additionally, minimum height (near the key) was assumed to be 14 cm, where the calculations were performed with 20 kN/m^3 own weight (q) and 10 kN/m distributed load (P, 12 cm thick 3.5 m. high, plastered masonry partition wall) in the center line of the vault parallel to the beams (i.e. concentrated load in this flat model), as shown in Figure 8.

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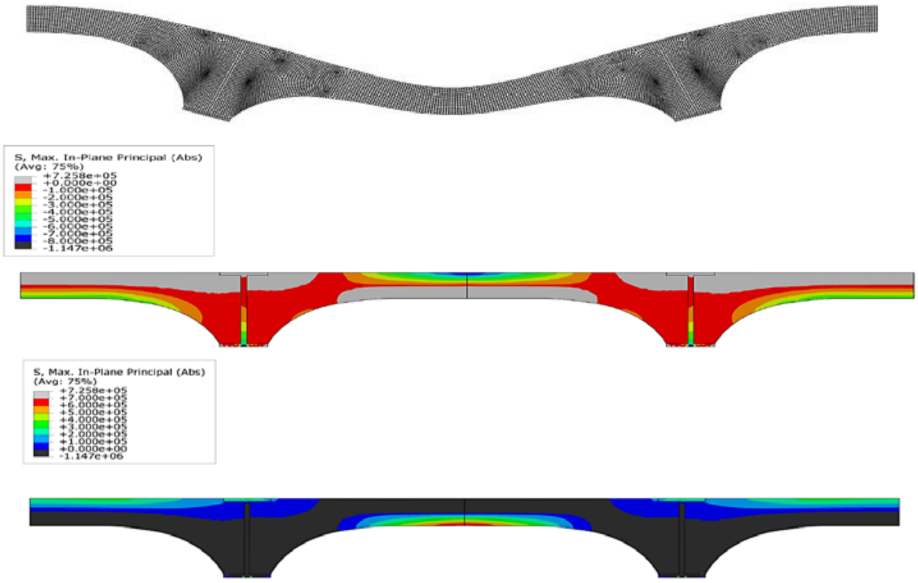

Figure 8. Calculations for the own weight (q) and concentrated load (P): deflection in the scale 1000:1 (a), stress distribution, compression (b) and tension (c)

Defined loading condition results in tensile stress below the structure for the loaded vault while opposite case appears for the adjacent ones i.e. tension occurs on top; since horizontal reaction (H, Figure 3) converts model into a multi-span system, as shown in Figure 8.

Maximum tensile stress (σ) calculated from model in Figure 8c is 0.7 MPa which is quite close to the strength value from core samples (R_{bt}) i.e. 0.66 MPa. On the other hand, material resists up to 12.2 MPa compression while only 0.8 MPa stress occurred under this loading, which states that 10 kN/m for this system is much lower than the one for failure state.

Figure 9 shows the measured correlation between load and deflection "P-μ" for chosen vault sections. It was experienced that cracked vaults resulted in lower stiffness than non-damaged ones as expected (approximately twice lower according to the diagram). Additionally, applying and releasing 40 kN concentrated load made system exhibit elastic behavior, while it became brittle after this limit and cracks appeared.

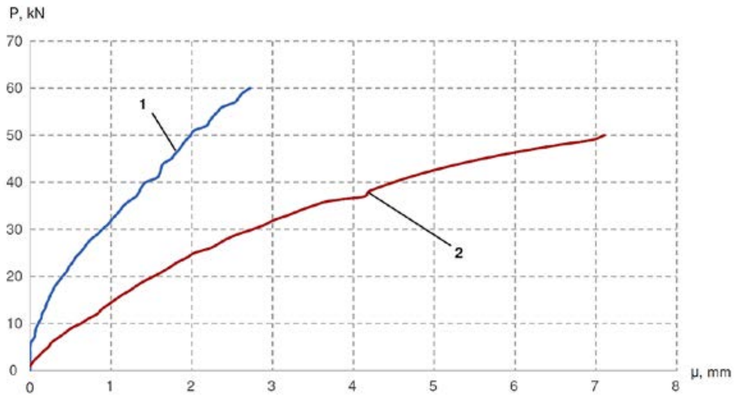

Figure 9. Experimental tests curves „load-deflection": 1 – four non-damaged vault results (Figure 6a), 2 – one damaged vault (Figure 6b)

After applying 10 and 40 kN loads discussed above, 60kN was also experienced on these actions which did not also cause destruction. Consequently, although the structure exhibited a significant bearing capacity; the repairing alternatives can still be required as follows [9, 10]:

The durability of the vaults should be provided considering the operating conditions of the cellar. The load-bearing capacity should be improved. The vaults should be well isolated from high humidity levels and temperature changes especially in basement floors. Corrosion of supports in vaults should be prevented or at least the continuity should be limited as much as possible. Preparing an easy access for future repairs. Often the access is limited due to existing sanitary, running water and electric wiring systems.

Depending on the type and extent of damages of the vault there are several repair solutions.

Implementation of strain relief reinforced concrete slab supported directly on the upper flanges of steal I-beams and vault sections; reinforcement of the vault soffit with steel grids covered with cement-lime mortar with throwelled finish; reinforcement of the vaults soffit with Fiber Reinforced Cementitious Matrix (FRCM) materials. The solution requires putting non-organic mortar on a previously prepared surface with simultaneous embedding of the composite mesh. Later the finishing layer of mortar is placed [38–40].

4. Conclusions

The Prussian vaults made from recycled brick aggregate are prevalent in historical buildings, though the current condition of the vaults raise doubts about their structural reliability. On the other hand, determination of bearing capacity and probability of cracks is not very complex when numerical methods are used with mechanical properties obtained from samples. Additionally, in situ determination gives more accurate results for damaged vaults since they can exhibit unexpectable unique behaviors. Based on the findings of this study; the following conclusions can be drawn:

1. Prussian vaults operate as continuous beam, where loaded one exhibits compression on top and tension at bottom, while adjacent ones demonstrate the opposite behavior i.e. tension on top and compression at bottom. The success of this behavior is highly dependent on the adhesion of concrete vault and metal beams; which needs further investigations because at the moment, this dependence is not investigated, and it is not included in the regulations;
2. Experimental results presented that the vaults demonstrate non-linear deformation characteristics starting from first loading seconds. It can be caused by the particularities of the structure of brick aggregate concrete and possible minor damage of all vaults;
3. Although the load-carrying capacity were almost the same for damaged and undamaged vaults; damaged wall exhibited greater deformability.

Lastly, further researches can be conducted on strength determination of Prussian vaults with various damages caused by moisture, settlement, defrosting, etc. as well as the relation of strength and deformability with alternative recycled brick-cement mixture ratios.

References

1. Bargmann, H. Historische Bautabellen. Normen und Konstruktioshinweise von 1870 bis 1960 [Norms and constructional references from 1870 to 1960]. Werner Verlag, Dusseldorf, 2001, 598 p. (ger.)
2. Ahnert, R., Krause, K.H. Typische Baukonstruktionen von 1860 bis 1960. Zur Beurteilung der vorhandenen Bausubstanz [Typical building constructions from 1860 to 1960. For the assessment of the existing building fabric]. Band 1,2. Berlin, 2009. 341 p. (ger)
3. Berngard, V.R. Arki i svody. Rukovodstvo k ustroystvu i raschetu arochnykh i svodchatykh perekrytiy [Arches and vaults. Guide to the design and calculation of arched and vaulted floors]. Saint-Petersburg, 1901. 128 p. (rus)
4. Grozdov, V.T. Kirpichnyye svody perekrytiy starykh zhilykh i obshchestvennykh zdaniy [Brick vaults of floors of old residential and public buildings]. Saint-Petersburg, 1999. 25 p. (rus)
5. Lakhtin, N.K. Raschet arok i svodov [The calculation of arches and vaults]. Saint-Petersburg, 1911. 493 p. (rus)
6. Ucer, D., Ulybin, A., Zubkov, S., Elias–Ozkan, S.T. Analysis on the mechanical properties of historical brick masonry after machinery demolition. Construction and Building Materials. 2018. No. 161. Pp. 186–195.
7. Hankammer, G. Schaden an Gebauden. Erkennen und Beurteilen [Identification and assessment]. Berlin. 2016, 106 p. (ger)
8. Ulybin, A.V., Laptev, Ye.A. Osobennosti obsledovaniya perekrytiy po stalnym balkam s nakatom v vide svodikov [Features of inspection of overlappings on steel beams with a rolling in the form of vaults]. Obsledovaniye zdaniy i sooruzheniy: problemy i puti ikh resheniya: materialy VI mezhdunarodnoy nauchno–prakticheskoy konferentsii. Saint–Petersburg. 2015. Pp. 95–105. (rus)
9. Fizdel, I.A. Defekty v konstruktsiyakh, sooruzheniya i metody ikh ustraneniya [Defects in structures, structures

Литература

1. Bargmann H. Historische Bautabellen. Normen und Konstruktioshinweise von 1870 bis 1960. Werner Verlag, Dusseldorf, 2001. 598 p.
2. Ahnert R., Krause K.H. Typische Baukonstruktionen von 1860 bis 1960. Zur Beurteilung der vorhandenen Bausubstanz. Band 1,2. Berlin, 2009. 341 p.
3. Бернгард В.Р. Арки и своды. Руководство к устройству и расчету арочных и сводчатых перекрытий. Санкт-Петербург, 1901. 128 С.
4. Гроздов В.Т. Кирпичные своды перекрытий старых жилых и общественных зданий, Санкт-Петербург, 1999. 25 с.
5. Лахтин Н.К. Расчет арок и сводов. Руководство к аналитическому и графическому расчету арочных и сводчатых перекрытий. Санкт-Петербург, 1911. 493 с.
6. Ucer D., Ulybin A., Zubkov S., Elias-Ozkan S.T. Analysis on the mechanical properties of historical brick masonry after machinery demolition // Construction and Building Materials. 2018. № 161. Pp. 186–195.
7. Hankammer G. Schaden an Gebauden. Erkennen und Beurteilen. Berlin. 2016, 106 p.
8. Улыбин А. В., Лаптев Е. А. Особенности обследования перекрытий по стальным балкам с накатом в виде сводиков // Обследование зданий и сооружений: проблемы и пути их решения: материалы VI международной научно-практической конференции. СПБ.: Изд-во Политехнического университета, 2015. С. 95–105.
9. Физдель И.А. Дефекты в конструкциях, сооружения и методы их устранения. Москва. 1987. 176 с.
10. Методические рекомендации. Исследования деформаций. Расчет несущей способности и конструктивное укрепление древних распорных систем. Москва: Росреставрация, 1989. 182 с.

and methods for their elimination]. Moscow. 1987. 176 p. (rus)
10. Guidelines. Deformation studies. Calculation of bearing capacity and constructive strengthening of ancient spacer systems. Moscow: Rosrestavratsiya, 1989. 182 p. (rus)
11. Lewicki, B. Obciążenia próbne konstrukcji istniejących budynków. Metodyka postępowania i kryteria oceny [Trial loads on the construction of existing buildings. Methodology of conduct and evaluation criteria]. Warszawa, 1997. 294 p. (pl)
12. Steffens, K., Burkert, T. Eksperimentelle Bestimmung der Tragfahigkeit von Mauerwerk – Belastungsversuche an Mauerwerksbauten in situ [Experimental determination of the load–bearing capacity of masonry – Load tests on masonry structures in situ]. Berlin, 2009. 122 p. (ger)
13. ASTM Standard C 1197–91: In situ measurment of masonry deformability properties using the flatjack method. 1991. 12 p.
14. Orłowicz, R., Rzeszotarski, A. Okreslenie niśnosci wybranych stropów w przedwojennych budynkach [Determination of the bearing capacity of selected ceilings in pre-war buildings]. XI Konferencja Naukowo–Techniczna Rzeczoznawstwa Budowlanego. Warszawa, 2010. Pp. 293–303. (pl)
15. Zanaz, A. Approche probabiliste d'aide au diagnostic des voûtes en maçonnerie [Probabilistic approach to help with the diagnosis of masonry vaults]. Ph.D. Thesis. Université de Limoges. 2016. 208 p. (fr)
16. D'Ayala, D.F., Tomasoni, E. Three-Dimensional Analysis of Masonry Vaults Using Limit State Analysis with Finite Friction. International journal of architectural heritage. 2011. No. 5(2). Pp. 140–171.
17. Pintucchi, B., Zani, N. A simple model for performing nonlinear static and dynamic analyses of unreinforced and FRP–strengthened masonry arches. European Journal of Mechanics – A/Solids. 2016. No. 59. Pp. 210–231.
18. Hamdy, G., Kamal, O., Al-Hariri, O., El-Salakawy, T. Plane and vaulted masonry elements strengthened by different techniques: testing, numerical modeling and nonlinear analysis. Journal of Building Engineering. 2018. No. 15. Pp. 203–217.
19. Zakrevskaya, L.V., Lubin, P.A., Avdeev, S.N., Gandelsman, I.A., Filippov, S.V. Dome houses made of soil–concrete based on local raw materials. Magazine of Civil Engineering. 2017. 75(7). Pp. 123–128.
20. Alekseenko, V.N., Zhilenko, O.B. Seismic stability of the restored architectural monument. Magazine of Civil Engineering. 2016. 67(7). Pp. 31–38.
21. Malena, M., de Felice, G. Debonding of composites on a curved masonry substrate: experimental results and analytical formulation. Composite Structures. 2014. No. 112. Pp. 194–206.
22. Castori, G., Borri, A., Corradi, M. Behavior of thin masonry arches repaired using composite materials. Composites Part B: Engineering. 2016. No. 87. Pp. 311–321.
23. Garmendia, L., Larrinaga, P., San-Mateos, R., San-Jose, J.T. Strengthening masonry vaults with organic and inorganic composites: an experimental approach. Materials and Design. 2015. No. 85. Pp. 102–114.
24. Taranu, N., Oprisan, G., Budescu, M., Taranu, G., Bejan, L. Improving structural response of masonry vaults strengthened with polymeric textile composite strips. Latest Trends on Engineering Mechanics, Structures, Engineering Geology. 2010. Pp. 186–191.
25. Dizhur, D., Griffith, M., Ingham, J. Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips. Engineering Structures. 2014. No. 59. Pp. 330–343.
26. Hojdys, L., Krajewski, P. Glass fiber grids embedded in a cement–based matrix as strengthening of masonry structures. Structural Analysis of Historical Constructions. 2016. Pp. 372–376.

11. Lewicki B. Obciążenia próbne konstrukcji istniejących budynków. Metodyka postępowania i kryteria oceny. Warszawa, 1997. 294 p.
12. Steffens K., Burkert T. Eksperimentelle Bestimmung der Tragfahigkeit von Mauerwerk – Belastungsversuche an Mauerwerksbauten in situ. Berlin, 2009. 122 p.
13. ASTM Standard C 1197-91: In situ measurment of masonry deformability properties using the flatjack method. 1991. 12 p.
14. Orłowicz R., Rzeszotarski A. Okreslenie niśnosci wybranych stropów w przedwojennych budynkach // XI Konferencja Naukowo-Techniczna Rzeczoznawstwa Budowlanego. Warszawa, 2010. Pp. 293–303.
15. Zanaz A. Approche probabiliste d'aide au diagnostic des voûtes en maçonnerie. Ph.D. Thesis. Université de Limoges. 2016. 208 p.
16. D'Ayala D.F., Tomasoni E. Three-Dimensional Analysis of Masonry Vaults Using Limit State Analysis with Finite Friction // International journal of architectural heritage. 2011. № 5(2). Pp. 140–171.
17. Pintucchi B., Zani N. A simple model for performing nonlinear static and dynamic analyses of unreinforced and FRP-strengthened masonry arches // European Journal of Mechanics - A/Solids. 2016. № 59. Pp. 210–231.
18. Hamdy G., Kamal O., Al-Hariri O., El-Salakawy T. Plane and vaulted masonry elements strengthened by different techniques: testing, numerical modeling and nonlinear analysis // Journal of Building Engineering. 2018. № 15. Pp. 203–217.
19. Закревская Л.В., Любин П.А., Авдеев С.Н., Гандельсман И.А., Филиппов С.В. Купольные дома из грунтобетона на основе местного сырья // Инженерно-строительный журнал. 2017. № 7(75). С. 123–128.
20. Алексеенко В.Н., Жиленко О.Б. Сейсмостойкость отрестраврированного памятника архитектуры // Инженерно-строительный журнал. 2016. № 7(67). С. 31–38.
21. Malena M., de Felice G. Debonding of composites on a curved masonry substrate: experimental results and analytical formulation // Composite Structures. 2014. № 112. Pp. 194–206.
22. Castori G., Borri A., Corradi M. Behavior of thin masonry arches repaired using composite materials // Composites Part B: Engineering. 2016. № 87. Pp. 311–321.
23. Garmendia L., Larrinaga P., San-Mateos R., San-Jose J.T. Strengthening masonry vaults with organic and inorganic composites: an experimental approach // Materials and Design. 2015. № 85. Pp. 102–114.
24. Taranu N., Oprisan G., Budescu M., Taranu G., Bejan L. Improving structural response of masonry vaults strengthened with polymeric textile composite strips // Latest Trends on Engineering Mechanics, Structures, Engineering Geology. 2010. Pp. 186–191.
25. Dizhur D., Griffith M., Ingham J. Out-of-plane strengthening of unreinforced masonry walls using near surface mounted fibre reinforced polymer strips // Engineering Structures. 2014. № 59. Pp. 330–343.
26. Hojdys L., Krajewski P. Glass fiber grids embedded in a cement–based matrix as strengthening of masonry structures // Structural Analysis of Historical Constructions. 2016. Pp. 372–376.
27. Carozzi F.G., Poggi C., Bertolesi E., Milani G. Ancient masonry arches and vaults strengthened with TRM, SRG and FRP composites: experimental evaluation // Composite Structures. 2018. № 187. Pp. 466–480.
28. Skvortsova A.N., Lycheva K.A., Voznyakovskii A.A., Koltsova T.S., Larionova T.V. Strengthening mechanisms and properties of composite materials with carbon nanofibers // Materials Physics and Mechanics. 2016. № 25(1). Pp. 30–36.

27. Carozzi, F.G., Poggi, C., Bertolesi, E., Milani, G. Ancient masonry arches and vaults strengthened with TRM, SRG and FRP composites: experimental evaluation. Composite Structures. 2018. No. 187. Pp. 466–480.
28. Skvortsova, A.N., Lycheva, K.A., Voznyakovskii, A.A., Koltsova, T.S., Larionova, T.V. Strengthening mechanisms and properties of composite materials with carbon nanofibres. Materials Physics and Mechanics. 2016. No. 25(1). Pp. 30–36.
29. Quadflieg, T., Stolyarov, O., Gries, T. Carbon fibres as sensor for buildings [Carbonfaserbewehrung als Sensor für Bauwerke]. Beton und Stahlbetonbau. 2017. No. 112(8). Pp. 541–544.
30. Stolyarov, O., Quadflieg, T., Gries, T. Characterization of shear behavior of warp–knitted fabrics applied to composite reinforcement. Journal of the Textile Institute. 2017. No. 108(1). Pp. 89–94.
31. Gizdatullin, G.A., Khusainov, R.R., Khozin, V.G., Krasinikova, N.M. Strength and deformability of concrete structures reinforced with fibre-reinforced polymer bars. Magazine of Civil Engineering. 2016. No. 62(2). Pp. 32–41.
32. Plevkov, V., Belov, V., Baldin, I., Nevskiy, A., Veselov, A., Serov, E. Diagram of non-linear straining of carbon-fiber reinforced concrete at static effect. Solid State Phenomena. 2016. No. 871. Pp. 173–181.
33. Bespalov, V.V., Ucer, D., Salmanov, I.D., Kurbanov, I.N., Kupavykh, S.V. Deformation compatibility of masonry and composite materials. Magazine of Civil Engineering. 2018. No. 2. Pp. 136–150.
34. Klyuev, S.V., Klyuev, A.V., Abakarov, A.D., Shorstova, E.S., Gafarova, N.G. The effect of particulate reinforcement on strength and deformation characteristics of fine–grained concrete. Magazine of Civil Engineering. 2017. No. 75(7). Pp. 66–75.
35. Medvedev, V.N., Semeniuk, S.D. Durability and deformability of braced bending elements with external sheet reinforcement. Magazine of Civil Engineering. 2016. No. 63(3). Pp. 3–15.
36. Russian state standard 10180–2012. Concretes. Methods for strength determination using reference specimens. Moscow, 2012. 34 p.
37. Russian regulations and rules 63.13330.2012 Concrete and won concrete construction. Design requirements. Moscow, 2012. 152 p.
38. Papanikolaou, C., Triantafillou, T., Fabregat, P.R. Increase of load-carrying capacity of masonry with textile reinforced rendering. Mauerwerk. 2015. No. 19. Pp. 40–51.
39. Biolzi, L., Ghittoni, C., Fedele, R., Rosati, G. Experimental and theoretical issues in FRP-concrete bonding. Construction and Building Materials. 2013. No. 41. Pp. 182–190.
40. Aiello, M.A., Sciolti, S.M. Bond analysis of masonry structures strengthened with CFRP sheets. Construction and Building Materials. 2006. No. 20. Pp. 90–100.

29. Quadflieg T., Stolyarov O., Gries T. Carbon fibres as sensor for buildings // Beton und Stahlbetonbau. 2017. № 112(8). Pp. 541–544.
30. Stolyarov O., Quadflieg T., Gries T. Characterization of shear behavior of warp-knitted fabrics applied to composite reinforcement // Journal of the Textile Institute. 2017. № 108(1). Pp. 89–94.
31. Гиздатуллин А.Р., Хусаинов Р.Р., Хозин В.Г., Красиникова Н.М. Прочность и деформативность бетонных конструкций, армированных полимеркомпозитными стержнями // Инженерно–строительный журнал. 2016. № 2(62). С. 32–41.
32. Plevkov V., Belov V., Baldin I., Nevskiy A., Veselov A., Serov E. Diagram of non–linear straining of carbon–fiber reinforced concrete at static effect. Solid State Phenomena. 2016. № 871. Pp. 173–181.
33. Беспалов В.В., Ючер Д., Салманов И.Д., Курбанов И.Н., Купавых С.В. Деформационная совместимость каменной кладки с композитными материалами // Инженерно-строительный журнал. 2018. № 2(78). С. 136–150.
34. Клюев С.В., Клюев А.В., Абакаров А.Д., Шорстова Е.С., Гафарова Н.Е. Влияние дисперсного армирования на прочностные и деформативые характеристики мелкозернистого бетона // Инженерно–строительный журнал. 2017. № 7(75). С. 66–75.
35. Медведев В.Н., Семенюк С.Д. Прочность и деформативность балочных изгибаемых элементов с внешним листовым армированием // Инженерно–строительный журнал. 2016. № 3(63). С. 3–15.
36. ГОСТ 10180–2012. Бетоны. Методы определения прочности по контрольным образцам. Москва, 2012. 34 с.
37. СП 63.13330.2012 Бетонные и железобетонные конструкции. Основные положения. Москва, 2012. 152 с.
38. Papanikolaou C., Triantafillou T., Fabregat P.R. Increase of load–carrying capacity of masonry with textile reinforced rendering // Mauerwerk. 2015. № 19. Pp. 40–51.
39. Biolzi L., Ghittoni C., Fedele R., Rosati G. Experimental and theoretical issues in FRP–concrete bonding // Construction and Building Materials. 2013. № 41. Pp. 182–190.
40. Aiello M.A., Sciolti S.M. Bond analysis of masonry structures strengthened with CFRP sheets. Construction and Building Materials. 2006. № 20. Pp. 90–100.

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