Strengthening of Stone Walls by Unilateral Applications of Reinforced Concrete

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SUMMARY:
The tests described below have been performed to determine the effects produced by various parameters of application of monolithic reinforced concrete, shotcrete or sprayed concrete on the load bearing capacity of stone masonry. These experimental researches have also allowed for developing the calculation methodology and practical recommendations for strengthening of stone masonry under seismic effects. These tests were conducted under static and dynamic loads on 54 ea. 1000x1000x250 mm samples of masonry strengthened with unilateral applications. Data obtained from experimental research has allowed for determination of the principles of behavior and the nature of deformation, to build the accurate model of work as well as to develop a method for determining the load bearing capacity of strengthened samples.

Keywords: seismic resistance, masonry, shotcrete, spray-concrete

1. INTRODUCTION

Nowadays seismicity index of stone masonry load bearing walls of large number of buildings located in seismic regions is below required. According to the performed surveys the stone structures of these buildings require additional strengthening. The best solutions for improving stone structures are those requiring no suspension of building usage, such as those performed on the external surface of walls. Currently a number of such methods is available while only few of them have undergone full scale researches and have found their application in the construction industry. The rest of them are currently being researched, or are in use for strengthening of structures without no theoretical basis and or recommendations for application available, resulting in exsessive consumption of materials or insuffiiency of strengthening. Application of monolithic reinforced concrete onto external surface of monolithic, shotcrete and sprayed concrete walls is among these strengthening methods. Although the method has been applied in earthquake-proof construction for quite long by now, neither specific numerical data nor methods of calculation of increased load bearing capacity are available.

2. TEST PROCEDURE

In the course of test planning and analysis of available data related to the research of stone masonry strengthening by unilateral application of monolithic concrete the following series of samples were defined for static load tests:
1 (KO) - reference samples of a brick masonry with no strengthening;
2 (M-6) – brick masonry strengthened by 60 mm thick application of monolithic concrete, no structural preparation performed on the side subject to strengthening, reinforced with Ø4 mm net, mesh size 100x100 mm;
3 (M-6-U/2) – brick masonry with 50% deepening of existing horizontal seams (every second seam) to the depth of 20 mm with subsequent filling with concrete in the course of concrete application (overall cross-section area of shear concrete in in seams is As= As=86520 mm^2)

4 (M-6-U) – samples similar to series 3 with the deepening of all of horizontal seams and their subsequent filling with concrete in the course of concrete application (overall cross-section area of shear concrete in seams As=160680 mm^2);
5 (M-6-Sh) – samples with application attached to brick masonry with 3 ea. extended concrete keys. Tuss size 103x89 mm (overall shearing cross-section area of continuous concrete keys, is As=275000 mm^2);
6 (M-6-A8) – applied reinforced concrete attached to brick masonry with nine anchors made of Ø8 A400 rebars, anchor spacing 400 mm, overall cross-section area A= 45300 mm^2, anchors installed into pre-drilled Ø20mm 150mm deep holes and filled with cement grout after installation;
7 (M-6-A10) - samples similar to series 6, with Ø10 mm anchors, overall cross-section area (A=707 mm^2);
8 (T-4-F) – brick masonry strengthened by 40 mm layer of applied fiber-shotcrete, (percentage of reinforcement μfv=1%);
9 (T-2-5) – brick masonry strengthened with 20 mm layer of shotcrete, reinforced with Ø4 mm net, mesh size 50x50 mm;
10 (T-4-10) – brick masonry strengthened with 40 mm layer of shotcrete, reinforced with Ø4 mm net, mesh size 100x100 mm;
11 (T-4-5) – brick masonry strengthened with 40 mm layer of shotcrete, reinforced with Ø4 mm net, mesh size 50x50 mm;
12 (T-6-5) – brick masonry strengthened with 60 mm layer of shotcrete, reinforced with Ø4 mm net, mesh size 50x50 mm;
13 (T-4-10P) – brick masonry strengthened with 40 mm layer of shotcrete, reinforced with Ø4 mm net, mesh size 100x100 mm, bars located parallel to the edges of sample;
14 (NSh-4-10) –brick masonry strengthened by application of 40 mm layer of spray-concrete reinforced with Ø4 mm net, mesh size 100x100 mm;
15 (NSh-4-10) – brick masonry strengthened by application of 4cm layer of spray-concrete with five Ø100 mm keys and 100 mm depth, reinforced with Ø4 mm net, mesh size 100x100 mm;

Tests were performed under static load. According to approved test procedure load has been applied via distribution beam along one of the diagonals to masonry only (see fig. 1). For the purpose of testing samples were installed into the support with one of diagonals in upright position, while load was applied along this diagonal to masonry only. To ensure uniform transfer of load metal shoes were attached with cement and sand grout to the supporting areas of masonry. Static load was created with hydraulic pumping station and hydraulic jack. Load was increased gradually with increments of 10% of breaking load at preloading phase and 5% within the phase close to breaking. After each increment the load has been held for 2 minutes with subsequent recording of deformations. Deformations were measured longitudinally and laterally using dial gauges with 0.01 mm division value and 0.8 m basis installed along diagonals. Measuring instruments were installed both in the brick and applied concrete surfaces. Indicators were attached with pins screwed into pre-installed drive anchor.
For the purpose of dynamic tests three series of samples were defined as per type of reinforced concrete coupling with brick masonry as follows:
OK-1d - reference samples with no strengthening, used for determination of physical and mechanical properties of stone masonry.
OK-2ud - brick masonry strengthened with reinforced concrete with no structural preparation of surface used for concrete application (fig. 2.13)
OK-3Ud - brick masonry with 3 ea. 100x89 mm continuous horizontal tusses, 300 mm spacing where concrete filling after placement of concrete application acts as continuous key (fig. 2.14).

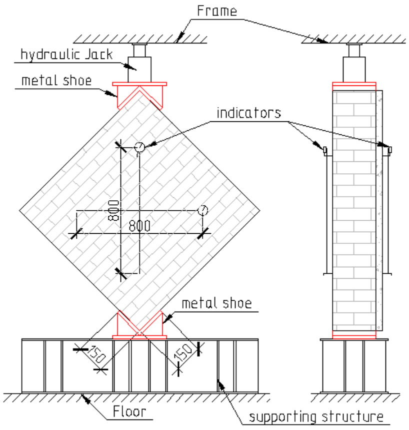

Figure 1. Test procedure

Dynamic tests were performed using weight testing unit with load applied to stone masonry along the diagonal of sample. Uniform transfer of load to dynamometers was achieved by application of metal joints. In order to increase the duration of impact load rubber damping liners were placed between the weight and dynamometer. Preliminary tests of said liners with due consideration given to specifications of weight testing unit and strength properties of samples have shown that impact duration might be increased to 25-28 ms instead of 10 ms in case of tough impact.
First phase of tests was performed to determine physical and mechanical properties of sample material: grade of bricks and compression strength of grout were determined in accordance with effective standards. Strength of monolithic concrete used for application has been determined from testing cubic samples prepared in the course of concrete works, while strength of shotcrete and sprayed concrete - from compression tests of cores drilled from the slabs prepared in the course of concrete application.
Subsequent phase comprised testing of masonry samples under the procedure detailed above. Table 1 shows test results.

Table 1. Static test data for strengthened samples

Ref. No. of series	Presented breaking load	Shearing force	Shearing force increment		Energy, $\frac{kN \cdot m}{m}$
	P_p, kN	Q, kN	Q, kN	%	
Series 1 (KO)	108,41	75,92	reference	reference	0,0218
Series 2 (M-6)	156,42	109,53	33,61	44	0,42
Series 3 (M-6-U/2)	185,56	129,94	54,02	71	0,68
Series 4 (M-6-U)	211,31	147,97	72,05	95	1,00
Series 5 (M-6-Sh)	293,56	205,58	129,66	171	1,51
Series 6 (M-6-A8)	291,59	204,19	128,27	169	1,50
Series 7 (M-6-A10)	330,01	231,10	155,18	204	1,47
Series 8 (T-4-F)	250,90	175,70	99,78	131	3,447
Series 9 (T-2-5)	172,15	120,55	44,63	59	2,964
Series 10 (T-4-10)	237,61	166,39	90,47	119	3,865
Series 11 (T-4-5)	306,61	214,71	138,79	183	4,641
Series 12 (T-6-5)	253,43	177,47	101,55	134	4,062
Series 13 (T-4-10P)	222,75	155,99	80,07	105	3,571
Series 14 (N-4-10)	227,51	159,32	83,40	110	2,944
Series 15 (NSh-4-10)	215,39	150,83	74,91	99	3,105

Due to almost complete impossibility of achieving similar strength properties for all samples of brick mortar in the course of their preparation, for KO-1 sample breaking load was presented as tensile resistance of masonry along the non-bonded seam.
The tests performed on reference samples series 1 (KO) have confirmed the brittle nature of breaking - once max. load is reached brittle (virtually instant) fracture of sample occurs through a single crack along the vertical diagonal with sample breaking into 2 fragments. Whereas the moment of diagonal crack occurrence virtually coincided with the moment of sample breakage. Relative tensile deformations at the moment of masonry collapse measured to about $\varepsilon=22x10^{-5}$.
Load bearing capacity of masonry with no strengthening applied (reference samples) may be calculated against main tension forces from the equation:

$$Q \le \frac{R_{tq} hL}{\nu}, \quad (1)$$

where Q: - design lateral force, h - wall thickness, L - length of wall section to be strengthened, ν - irregularity ratio of tangential stresses in the cross-section. For rectangular cross-sections ν may be assumed as 1.5; R_{tq} - design resistance to shearing of masonry pressurized under design force N, determined with overload index of 0.9 from the equation:

$$R_{tq} = \sqrt{R_{tw}(R_{tw} + \sigma_0)}, \quad (2)$$

where R_{tw} - design resistance to main tension forces, σ0 - stress of pressurization with force = N, equal to

$$\sigma_0 = \frac{0{,}9N}{Lh}. \quad (3)$$

Analytical result of calculation of reference samples load bearing capacity against main tension stresses is 5.1% different from experimental data (experimental value = 75,92 kN, analytical value = 79,99 kN).
Load bearing capacity of samples strengthened with concrete application is determined from the equation:

$$Q_f = Q + Q_{ad}. \quad (4)$$

where Q - load bearing capacity of masonry with no strengthening, Q_{ad} - load bearing capacity of masonry and applied concrete junction (determined depending on specific structural features of junction).
Breakage pattern of M-6 series samples: shear along applied concrete-masonry contact surface (shear along the non-bonded seam). No damage to applied reinforced concrete found. Tests of masonry samples strengthened with applied reinforced concrete with no structural preparation of base surface showed 45% increase of breaking load, relative compression and tension deformations corresponding to the commencement of collapse; deformations 30 and 50% larger than those of KO series samples.

Bearing capacity of M-6 series samples increases due to firm adhesion of masonry and applied concrete along the non-bonded seam Q_{ad}. The sample breaks once this adhesion has collapsed. Considering the existing pressurization factor (load was applied to the body of masonry) increase of load bearing capacity Qad may be found from the equation:

$$Q_{ad} = R'_{sq} 0{,}2 A_{ya} \quad (5)$$

where R_{sq}' – design masonry resistance to shear along the non-bonded seam;
A - area within which main tension stresses are in effect.
Convergence of M-6 series samples load bearing capacity calculated from the equation (4) and obtained experimentally measures to 5.2%.
Breakage pattern of M-6-U/2 and M-6-U series samples: shearing of brick along applied concrete—masonry contact plane with separation (break off and displacement) of flat fragments of bricks from the main body of masonry along the microkeys lateral surface—brick contact area) shear along the bonded seam). Whereas no shearing of concrete microkeys formed in the course of concrete application was observed.
Microkeys ensuring adhesion of masonry and applied concrete increase load bearing capacity of M-6-U/2 series samples by 72%, and that of M-6-U series – by 94% as compared to KO series samples.

Relative compression deformations corresponding to commencement of breaking increased by 33% (ε=2 10^{-3}) as for M-6-U/2 series samples and by 67% (ε=2.5 10^{-3}) for M-6-U series.
Relative tension deformations remained virtually unchanged (ε=1.1 10^{-3}) as for M-6-U/2 series and increased by 67% (ε=2 10^{-3}) for OK-4-U series.
Load bearing capacity increases due to strength of adhesion between masonry and applied concrete along the non-bonded seam Qad as well as to strength of masonry and applied concrete joint along the bonded seam and may be calculated from the equation:

$$Q_{sq} = R_{sq} A_{ck} \qquad (6)$$

where R_{sq}' – design masonry resistance to shear along the bonded seam;
A_{ck}=0,2 A_{ck0} - contact area of lateral surface of microkeys to brick within the zone of significant values of main tension stresses of the samples.
Overall load bearing capacity of M-6-U/2 and M-6-U series samples Qf is defined by the sum of load bearing capacities of masonry with no strengthening Q, adhesion of masonry and applied concrete along the non-bonded seam Qad and that of strengthened sample joint along the bonded seam Qad.
Convergence of load bearing capacities of M-6-U/2 and M-6-U series samples calculated from the equation (7) and obtained experimentally measures to 0.77%.
Load bearing capacity of M-6-Sh series samples increases due to availability of key joint between masonry and applied concrete (Qs). As seen from the experiment, breakage of samples occurs due to collapse of masonry along the contact area of lateral key surface. Due to high load bearing capacity of key joint a part of overall load bearing capacity, produced by the strength of joint along bonded and non-bonded seams is not realized. Increase of load bearing capacity is calculated from the equation:

$$Q_s = R_s A_{ck} \qquad (7)$$

where Rs - design compression resistance of masonry, Ashs - key lateral surface—bricks contact area within the zone of significant values of main tension stresses of samples.
Convergence of M-6-Sh series samples load bearing capacity calculated from the equation (8) and obtained experimentally measures to 2.7%.
Breakage pattern of M-6-A/8 and M-6-A-10 series samples: shear along the applied concrete—masonry contact surface with collapse of connection joint between rebars and masonry.
In M-6-A8 series samples indicative deformation of anchor bars located in close proximity to loaded diagonal is observed, occurring in case of tensile deformations measuring to 3-5 mm.
Similar deformation of anchor bars in keyless vertical joints of reinforced concrete walls was noted by many researchers having allowed for evaluation of load bearing capacity of masonry and applied concrete joint using the proven technique for calculation of keyless vertical seams load bearing capacity.
In M-6-A8 and M-6-A10 series samples Increased load bearing capacity is ensured through load bearing capacity Qsw of joint between masonry and concrete applied on anchor rebars. Due to high load bearing capacity of anchoring between masonry and applied concrete a part of overall load bearing capacity, produced by the strength of joint along bonded and non-bonded seams is not realized. Increase of load bearing capacity is calculated from the equation:

$$Q_{sw} = R_{sw} A_{sw} \qquad (8)$$

where Rsw - design resistance of crosswise reinforcement for group I limit conditions;
Asw - cross-section area of anchor bars.
Convergence of load bearing capacities of M-6-A8 and M-6-A10 series samples calculated from the equation (10) and obtained experimentally measures to 0.9 and 18.3%. respectively
Nature of collapse of samples strengthened with shotcrete (series 8, 10-13) was found to be substantially different from that of reference samples and seres 2-7. Upon achieving 75 to 90% of max. load 2 symmetrical (as related to vertical diagonal) cracks opened (see fig. 2).
Whereas samples were still taking load cracks continued opening as pressure imposed by jack increased. Deformations stopped increasing once loading was discontinued. Samples were taking maximum load when deformations measured to about ε=200x10-5. As loads were further increased, cracks continued slow opening with 5 to 10% decrease of load, after that deformations stopped increasing and load stabilized. While attempting to further increase the load, in some cases load has

increased by about 1-5%, with further growth of cracks width. Where load was maintained it decreased by 5 to 20%, deformations stabilized as well.
This pattern has been observed till certain moment after which attempts of increasing jack pressure caused no increase of load in the sample with increasing deformations. Though, when increasing of pressure discontinued deformations stopped increasing, load transferred to the sample showed no decrease. In all cases upon decreasing the load has stabilized before it has reached values corresponding to the bearing capacity of masonry with no strengthening applied.
It should be noted that in the course of testing of all samples strengthened with shotcrete and sprayed concrete upon occurrence and opening of cracks bending of samples was observed along the axis aligned with vertical diagonal. Bending of sample reached 30 to 60 mm.
Said behavior observed till relative deformations of about $\varepsilon=2000\ x10^{-5}$ were reached. Further loading of sample discontinued due to changing work pattern caused by loss of sample stability within the plane,
Analysis of elements of samples collapsed in the course of experiments allowed for determining of their breakage pattern: series 2 and 4-9 samples collapse with outermost brick plate break away from the body of masonry, i.e. once masonry reaches the design shear resistance along the bonded cross-section. Note that no damage to shotcrete was discovered in shotcrete—masonry contact area.
Nature of breakage of series 9 (T-2-5) samples strengthened with 20 mm layer of shotcrete was different form breakage pattern of samples strengthened with 40 and 60 mm layers of shotcrete. Collapse pattern of series 9 samples was very similar to that of reference samples: occurrence of a single crack was observed along the compressed diagonal with its further opening i.e. once masonry has reached critical values of main tensile stresses.

Collapse of series 2 sample

Collapse of series 8 sample

Figure 2. Cracks observed in the course of strengthened samples tests

Collapse pattern of series 14 samples (N-4-10) strengthened with application of sprayed concrete was similar to that of samples strengthened with shotcrete - 2 cracks occurred through the masonry along the vertical diagonal. However, once critical value has been reached, load rapidly decreased to 40% with subsequent stabilization. Further behavior of sample was similar to that of sample strengthened with shotcrete.
Series 15 samples (NSh-4-10) unlike series 14 showed no rapid decrease of load once critical values has been reached. However, keys produced no expected increase of load bearing capacity. It may have been caused by particular features of keys structure since cement grout was running out from the holes in the course of work, hence keys were filled manually and upon collapse key holes turned out to have not been filled completely.
Collapse pattern of series 7 and 10-15 samples strengthened with 4 and 6 cm layers of shotcrete and sprayed concrete, featuring occurrence of 2 opening cracks is well correlated with numerical

experiment data using the elastic approach for modeling loaded behavior of masonry sample with reinforced concrete strengthening element. In the center of models created in SCAD computing complexes using various types of end components (enclosures, bars) vertical zone of minimum shear tension is observed (for bar type end elements) corresponding to masonry shear behavior along the bonded seam. As distance from central diagonal increases, models feature stresses (forces) increasing to significant values comparable with masonry strength along the bonded seam. Area of said significant shear stress (force) zones is 10-12% of calculated model area.

Having compared the nature of samples deformation one may conclude that in the context of energy samples strengthened with applied concrete feature several times higher energy capacity as compared to reference samples Said effect significantly reduces seismic reaction of strengthened buildings preventing brittle collapse of stone masonry structural elements.

As described above, performed tests have allowed for determination of collapse pattern of strengthened samples which were found to be similar for all series other than series 9. Collapse occurs once design value of shear resistance along bonded seam is reached.

Basing on the determined collapse pattern load bearing capacity of strengthened samples is defined by load bearing capacity of masonry against main tensile stresses and applied concrete adhesion with sample, engaging the external layer of masonry till design shear resistance value is reached.

In samples strengthened with 40 and 60 mm layers of of shotcrete and sprayed concrete load bearing resistance increases due to strength of adherence between masonry and applied concrete (Qsq). According to the determined collapse pattern increment of load bearing capacity may be calculated from the equation:

$$Q_{sq} = R_{sq} \cdot A_{re}, \qquad (9)$$

where R_{sq} – design masonry resistance to shear along the bonded cross-section;

Are – area of contact between masonry and applied concrete where horizontal shear forces reach significant values.

From the results of SCAD modeling shear force values were obtained at masonry—applied concrete contact area. For the purpose of analysis zone of significant values was assumed as 10% of overall sample surface.

Basing on the performed analysis overall load bearing capacity (Q_f) of strengthened samples may be defined as load bearing capacity of non-strengthened masonry sample Q plus load bearing capacity of adhesion between masonry alnd applied concrete Qsq and calculated from the equation:

$$Q_f = Q + Q_{sq}. \qquad (10)$$

Convergence of 10, 13-15 series samples load bearing capacity calculated from the equation (3, 17) and obtained experimentally measures to 22%. Other series feature parameters of applied concrete beyond the limit conditions of suggested equation.

Comparison of obtained results has shown that suggested equation (12, 13) allows for determining load bearing capacity of samples strengthened with 40-60 mm of applied concrete layer with sufficient accuracy. Whereas samples used in the course of experinent demonstrated certain strength margin which may possibly be explained by effects caused by reinforcement, requiring additional researches.

Increment of load bearing capacity for sampes strengthened with 20 mm layer of shotcrete is substantially lower if compared to design value due to collapse pattern being mainly determined by tensile stresses.

Basing on static tests data generalized diagrams of masonry deformations were built in relative values (fig. 3), describing the increase of strengthened samples load bearing capacities against applied concrete parameters. Relative deformations were calculated dividing absolute values by the value of measurement basis length.

In the course of dynamic tests strength of masonry with reinforced concrete applied was found to have increased by 22% due to adhesion force. Structural measures ensuring adhesion between masonry and concrete also contributed to increase of rigidity: deepening of seams - by 20%, concrete keys - by 55%, rebar anchors - by 58%. External (unilateral) application of reinforced concrete also contribute to increasing of masonry load bearing capacity. For OK-2Ud series samples equivalent static load was found to have increased by 26% as compared to reference sample, for OK-3Ud series the increment measured to 77%. Due to engagement of applied reinforced concrete previous damage to masonry does not result in brittle collapse. Strengthened samples take dynamic load pro rata with the rigidity of masonry and applied concrete.

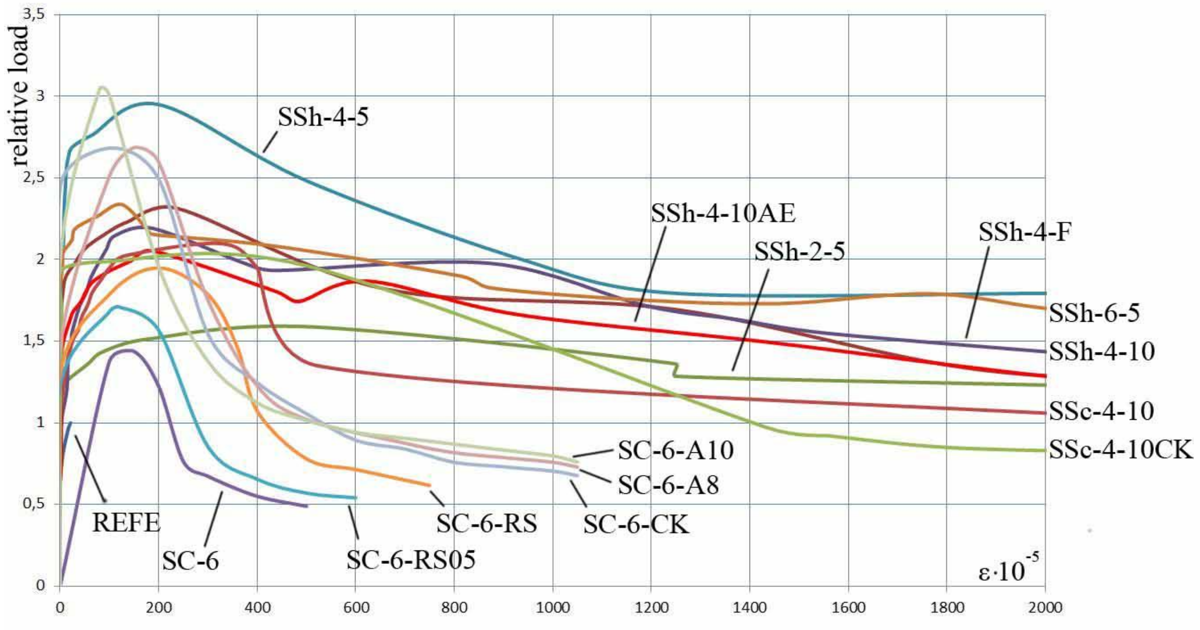

Figure 3. Diagrams of masonry deformation (tension)

In accordance with the developed procedure dynamic tests of masonry samples were performed with the following results obtained.

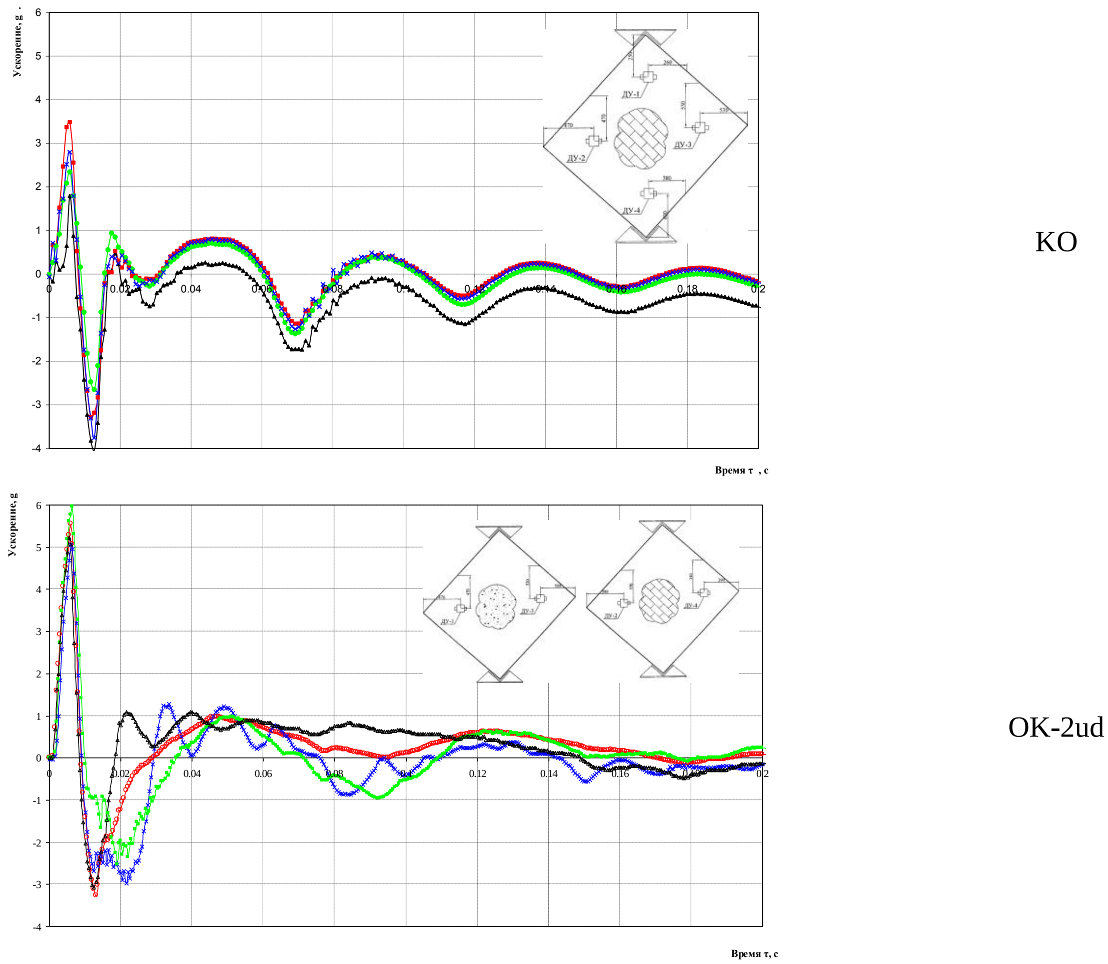

Figure 4. The acceleration KO and OK-2ud

For OK-2Ud series samples equivalent static load was found to have increased by 26% as compared to reference sample, for OK-3Ud series the increment measured to 77%.

CONCLUSIONS

Basing on the performed experimental researches of masonry stress-strain state strengthened with unilateral application of monolithic concrete, shotcrete and sprayed concrete under combined action of horizontal and vertical loads the following conclusions can be made:

1. External (unilateral) application of reinforced concrete has been found to increase the load bearing capacity of structural elements made of bricks by up to 45% when no additional fastening is used. Where applied reinforced concrete is fixed with concrete microkeys using existing horizontal seams between the bricks load bearing capacity increment may measure up to 90%. Where applied concrete is additionally fixed to masonry with extended concrete keys formed in the course of concreting in pre-arranged horizontal tusses increment may reach 170% and 200% where applied reinforced concrete is fixed with rebar anchors. Unilateral application of shotcrete and sprayed concrete, when reinforced with nets, results in 2 to 2.8 times increases bearing capacity of masonry. In this case the possibility of masonry brittle collapse is completely eliminated while flexible properties exert to full extent, substantially increasing seismic resistance of stone structures and eliminating the possibility of their collapse. Energy capacity of strengthened samples more than 200 times exceed that of regular masonry.
2. Collapse pattern has been determined for masonry samples strengthened with external (unilateral) reinforced concrete applications under various options of concrete application to masonry. Collapse pattern of M-6 series samples: shear along "applied concrete—masonry" contact plane (along non-bonded seam); M-6-U/2 and M-6-U series: shear of brick along "applied concrete—masonry" contact plane with separation (break away and displacement) of brick flat fragments from the masonry main body along the microkey lateral surface—concrete contact area (shear along bonded seam); M-6-Sh series - collapse of masonry along lateral surface of concrete keys contact area, series M-6-A8 and M-6-A10 - shear along "applied concrete—masonry" contact plane with collapse of anchor rebars to masonry connection joint. Collapse pattern determined for samples strengthened with 4-6 cm of shotcrete and sprayed concrete: sample collapses once stone masonry shear resistance along bonded section reaches its design value.
3. Elastoplastic nature of strengthened elements deformation was determined, observed till breakage of connections between external (unilateral) applied concrete and masonry. Obtained results indicate that joint behavior of masonry and external (unilateral) concrete application allows for increasing of seismic resistance of stone buildings and structures and prevention of instant collapse of structural elements as well as development of progressive failure.
4. Advisable thickness of layer for the purpose of practical shotcrete and sprayed concrete application in seismic strengthening of existing buildings is 40-60 mm.
5. Unilaterally applied shotcrete and sprayed concrete are effectively engaged into dynamic behavior of samples due to high adhesion requiring no additional design measures.
- direction of rebars in reinforcement net does not affect load bearing capacity of samples.
6. Method of concrete application by shotcreting and spraying does not affect load bearing capacity of strengthened sample, though energy capacity of shotcrete is substantially higher, affecting the behavior of structure within the plastic phase.
7. Application of keys when strengthening with sprayed concrete produced no effect on load bearing capacity but substantially affected the deformation pattern. Such strengthening features higher energy capacity and safer operation as compared to keyless sprayed concrete.

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