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# Analysis on the mechanical properties of historical brick masonry after machinery demolition

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## HIGHLIGHTS

- Bricks and mortar pieces collected from the demolition plot, were classified separately.
- Masonry wall sections obtained from demolition debris were tested under compressive and shear loads.
- Wall sections had higher compressive strength and initial shear strength than specified values for new buildings.
- The cracks after triplet shear test indicated interface failures.
- Optimal condition for reuse of wall pieces was identified.

## GRAPHICAL ABSTRACT

The process of the study: Investigation into the properties of debris, Laboratory tests.

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## ABSTRACT

The demolition process of a historical brick masonry building in St. Petersburg, Russia was observed as a case study and research was conducted on the possibility of reusing the resultant debris, which was composed of high quality brick masonry, as new building material. Therefore, samples from the demolition debris, i.e. brick, mortar and wall pieces were collected and tested for their mechanical properties, according to Russian standards, when available, and according to International Standards for the rest. The results for the compression test of brick and mortar separately as well as wall prisms indicated that their strength was still higher than standard limits, therefore, these wall pieces could be reused under appropriate conditions. Additionally, the bed mortar was tested under shear loads in order to understand if the jointing was still reliable or not. Eurococe 6 (Eurocode 6: Design of masonry structures – Part 1–1: General Rules for Reinforced and Unreinforced Masonry Structures, (2005)) defines a reference table for comparison, which showed that the shear resistance obtained from the wall prisms was also reliable.



## 1. Introduction to the reclaiming project

This paper is based on information gathered from a case study regarding a demolition project and tests conducted on the physical properties of the demolition debris collected from the site (Fig. 1). The focus of the study was on the end-of-life scenarios of masonry

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buildings and hence the possible disposal and reuse options for masonry wall components. Details regarding the case building and its demolition process, as well as the laboratory tests conducted on small quantities of debris samples are presented in the following sections.

### 1.1. End-of-life for masonry construction

Owing to their durability and prevalence throughout the ages, there exists a vast stock of masonry buildings in the world, yet, some of them are being demolished and disposed of. Apart from their deterioration and age, the reasons behind the demolition of such buildings appear to be: changes in building bye-laws or redundancies of buildings; which sometimes are carried out to clear the plots for new and mostly taller buildings [8]. On the other hand, buildings struck by disasters especially earthquakes have to be demolished also as they are no longer safe for habitation.

A study on the deconstruction of Earthquake-damaged buildings in Turkey illustrates that, although slightly damaged buildings can be strengthened for safe occupancy some are severely damaged and cannot be rehabilitated. Such buildings underwent partial deconstruction, whenever it was possible to reclaim building materials or components from them. The researcher attracts attention to the impact of deconstruction method on the recovery rates and the quality of the construction materials and recommends top-down technique i.e. deconstructing the building story by story, starting from its roof. On the other hand, when demolition is selected as the method of disposal it results in further damage on the recoverable material and the resultant debris mix is almost impossible to sort out [9].

Another option is partial demolition of old masonry buildings and refurbishment of the remaining parts. For instance, "façade retention" is a common approach to conserving the historical characteristics of an area by keeping the old façade intact and demolishing the spaces behind. The new building is then constructed behind the original façade[1] [1].

Whichever approach is selected for the end-of-life scenario, huge amounts of masonry makes up the demolition waste. On the other end, since these buildings are not always demolished due to wear and tear, the condition of masonry walls after partial or complete demolition may still be of a good quality that may be conducive to their use elsewhere.

One method for the reuse of masonry components is the salvage of good quality bricks (Fig. 2). This method is mostly favored owing to the vintage look of the bricks that can be integrated into the modern architectural designs. Regardless of the design intention, this is indeed a useful way to prevent valuable material from being dumped as waste and thus contribute to environmental and economic sustainability.

In addition to the reclaimed single bricks, using wall pieces as recovered masonry wall sections is a possible scenario as illustrated in the Cubo House project. This project was an addition and alteration intervention in an existing dwelling where some parts of the building were demolished and many components were reused. Within this context, one old masonry wall of the building was cut carefully into rectangular pieces and the sections were reused on the new elevation (Fig. 3). This approach not only helped to salvage the old materials but also carried the historical style of the building to its current design with a new understanding [17].

In view of these examples of different recovery scales, from brick units to wall sections, masonry wall debris can be re-assessed as a secondary source of construction material that offers alternative design solutions depending on the inherent potential of the waste material.

### 1.2. The case study building

To assess the condition of the rubble and the potential of reusing the masonry material, the demolition process of a historical brick masonry building was observed and a few samples were obtained to conduct the further tests. Although the demolition process itself, which uses considerable force, was the main parameter effecting the final state of the material, the condition and characteristics of the building throughout its service life were also a very important parameter. Information on the location, history, change in functions, material of the building as well as its construction have been presented in the following section.

#### 1.2.1. The building and its location

The building was located on Pirogovskaya Quay 11, on the banks of Neva River in Vyborg District near Lenin Square, which is close to the central business district of St. Petersburg, in Russia. It is surrounded by small scale production plants as well as offices and housing blocks. Construction on this plot was started in 1853 and buildings were added over time; however the exact date of construction of the case study building is not known. During its lifetime, it was used for many different purposes; from storage to production to a photography studio [7]. After its demolition, the structure will be replaced by a modern hotel building.

The building was a three story high block with solid brick envelope and a gable steel roof (Fig. 4). Although the external walls were almost identical for the entire building, the construction techniques of the slabs, beams and columns differed from story to story. Use of different materials and techniques together in a single building was a common practice in many historical buildings in Russia especially in ones damaged buildings during the war, as well as the newly built ones belonging to the post-revolution and post-war era of economic crisis. Besides documentation of its architectural aspects, demolition process of the building was also observed and is presented in the following section.

#### 1.2.2. Demolition process

The waste management regulations in Russia obligate the detection of material types and expected amounts in rubble prior to starting the demolition work. While the disposal methods are followed according to type of material, as per the State laws [18]. Hence the demolishing firm has to submit information on types, approximate amounts of materials and planned disposal methods to the authorities. The company that had undertaken the demolition job of the case study area, designed the process as selective demolition. This method included the separation and sale of metals to recycling factory, temporary use of rubble as ground cover for leveling and draining the site during construction work; and lastly, removing the rotten wood in order to protect other materials from decay also.

The fenestration and metal roof were dismantled and then the structure was demolished with hydraulic pulverizer and a bucket type excavator was used to carry the broken pieces and dump them in sorted piles. Consequently, large wall sections, small crushed wall fragments and timber pieces were accumulated on the plot; whereas metal waste was frequently transported to the recycling factory. The rubble was to be used as hard core for repairs of worn-out roads, according to the regulations Russian Federation [18] while the larger pieces of masonry wall sections seemed appropriate for reuse (Fig. 4). For this reason, such samples were collected and their mechanical properties were tested.

[1] Heritage and value is beyond the context of this study.

**Fig. 1.** The process of the study: investigation into the properties of debris, laboratory tests.

**Fig. 2.** Reclaimed brick being sold at a demolition contractors yard in Ankara, Turkey.

### *1.3. Investigation into properties of debris*

A visual inspection of the demolition waste, which was composed of slightly deteriorated single bricks, mortar pieces and still intact masonry wall sections, was satisfactory with regard to its reusability (Fig. 5).

It was felt that reclaimed bricks can be re-used instead of new bricks, if they can comply with the current building codes.

Additionally, the broken wall pieces can be cut into smaller sections similar to ashlar masonry blocks (Fig. 6). These wall sections can be reused as secondary masonry units if old mortar can ensure the required integrity between the old bricks.

On the other hand, the old mortar pieces were tested to determine their physical properties only; their reuse has not been dwelt upon. Hence, commercially available mortar will have to be used for making the new walls with the reclaimed bricks or masonry wall sections. The mortar may be strengthened by adding fiber reinforcement also.

The size of the wall pieces may depend on the properties/strength of the recovered wall prisms; however prisms that were tested for their strength in this research were cut to 20 $\times$ 20 $\times$ 20 and 20 $\times$ 20 $\times$ 10 cm pieces. These sizes were appropriate for retaining their integrity and reducing waste from crumbling. The weight of the reclaimed wall sections could be a critical parameter in terms of workmanship during the bonding of the new wall as well as its total weight in the main structure. The 20 $\times$ 20 $\times$ 20 cm wall piece weighed about 15 kg each, while the weight of the 20 $\times$ 20 $\times$ 10 cm pieces was approximately 7.5 kg.

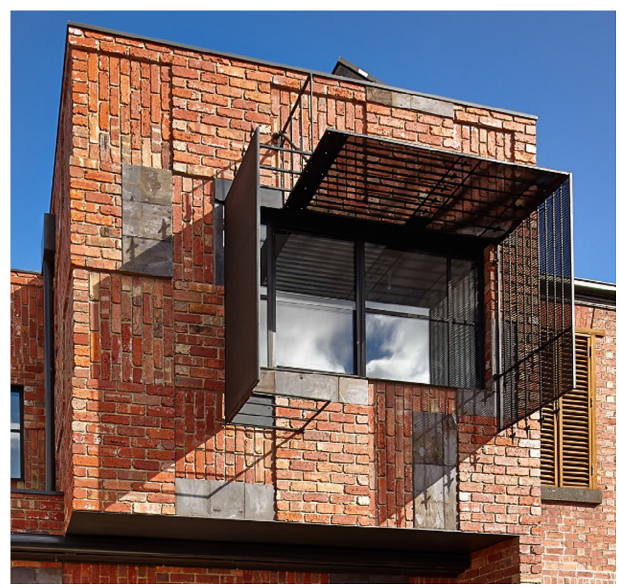

**Fig. 3.** Reclaimed masonry wall sections [17].

In order to analyze the inherent strength of the debris, three types of material, i.e. whole bricks, mortar fragments and wall sections (Fig. 5) were collected from the plot and brought to the Testing Laboratory of the Civil Engineering Institute of Peter the Great Saint-Petersburg Polytechnic University, in Russia. This laboratory has several testing facilities for the analysis of historical structures, including masonry walls.

Since the main parts of the building had been demolished at the time of material collection, the exact prior locations of the


**Fig. 4.** Construction techniques and material of the building. (a) Citywalls, 2009 (the upper image only, the yellow building is from [7]).

samples on the building were not clear. Therefore, they were randomly chosen from the bulk of construction waste, which was waiting to be delivered to the disposal area. Twenty-four intact bricks that had detached from the walls due to the impacts of the demolition machinery were collected, and they were in good condition.

Almost all bricks varied in tones of orange-brown while only two of them were light yellowish in color. The bricks were categorized into 9 different types according to their production sources, which could be identified from the seals, except for one group where the seal could not be deciphered. The label on the surface of the brick gave the name of the factory and order number as illustrated in Fig. 3. The average dimensions obtained from these 24 bricks were $25.4 \times 12.4 \times 7.1$ cm ($l \times$ w $\times$ h) while the mean weight was 4.5 kg[2] and the range was between 3.1 and 5.2 kg. In addition to bricks, mortar pieces that had detached and fallen with the impacts of machinery, or separated manually with simple hand tools were collected for the study. It was seen that the bond between the brick and mortar was very strong therefore it was not easy to separate the mortar from the bricks. A visual inspection of the mortar indicated that it was cement based with apparent traces of lime. Beside bricks and mortar pieces, three wall sections with average

[2] The weight was measured when bricks stayed outside during the last week of August 2015 without prior drying or preparation. According to 56 total measurements (at 3 h interval during day and night), the range of temperature varied from 13.2 °C to 24.9 °C and humidity level from 30.55% to 92.67% [16]. Therefore, the values here also reflect the moisture content in the pores of the bricks.

**Fig. 5.** Recovered brick, mortar samples and wall pieces.

dimensions of $113 \times 63 \times 58$ cm ($l \times w \times h$) and 667 kg[3] were obtained from the site (Fig. 5). The 60 cm thick wall sections had traces of permanent plaster on the external surfaces while the internal surfaces were either plastered or their plaster had been stripped off later, during conversion of the space for other uses. The walls consisted of inner and outer layers of 12 cm thick brick with about 36 cm brick infill. The exposed walls had been constructed with English Bond[4] and although the outer and inner surfaces of the walls shared the same bonding pattern, one to one locational correspondence did not exist, i.e. the mortar line on one surface was not necessarily aligned with the other. Additionally, the infill was also of the same quality solid bricks as the ones used for the surfaces.

## 2. Methodology

In this section, the material that were used for the study as well as the manner in which they were prepared for the tests, are described in detail. Further, the methods used for testing the samples are also presented here.

Special codes or standards for the assessment and labeling of reclaimed construction material are not available. However, they are expected to confirm the requirements for new building material. Therefore, current building codes and standards are valid for the evaluation of both old and new material. Lastly, the samples were prepared according to Russian standards; while International standards were used if related Russian standards were not available.

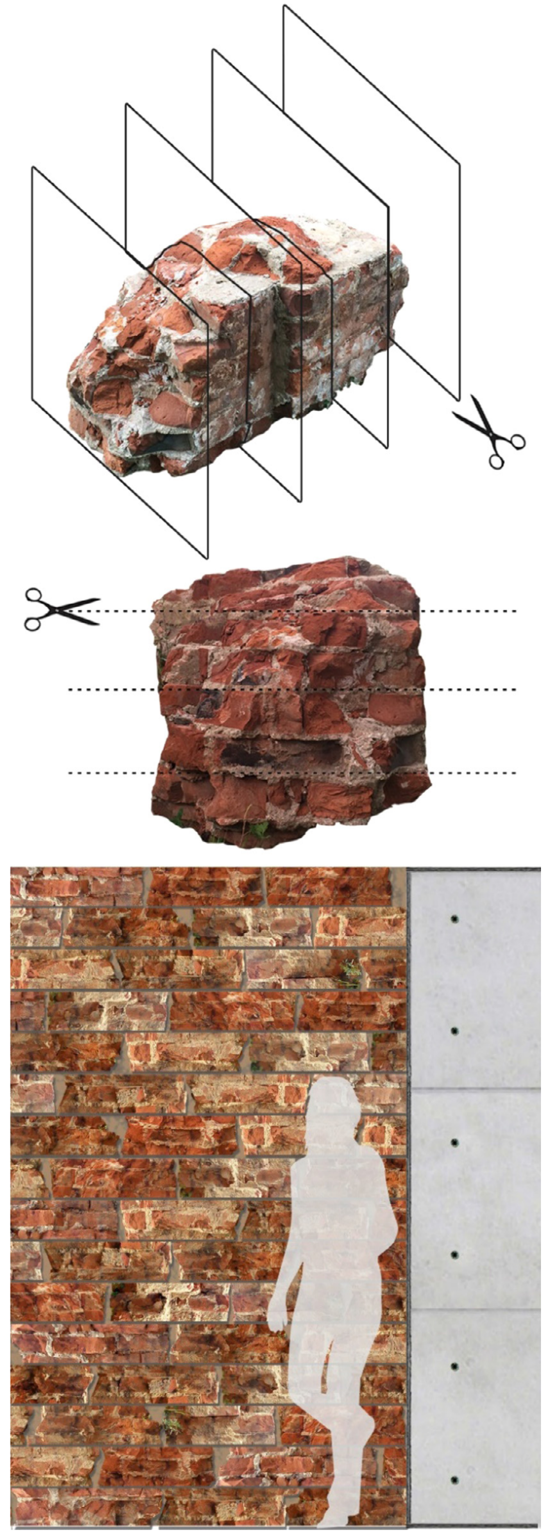

**Fig. 6.** Proposal for reusing the masonry wall sections.

### 2.1. Material

Among 24 bricks collected from the plot, 9 were allocated for the compression test, 9 for flexural test and 6 were cleaned for the exhibition in the brick history archives. Three bricks were kept

[3] The weight was approximately calculated according to volumetric assumptions of 80% brick and 20% mortar within the wall. The densities were obtained from direct measurements of brick and mortar separately.

[4] Bonding types [6]: Alternative rows of header and stretcher bonds.

aside in case re-tests were required. 9 bricks were clean enough so no further cleaning was done before the flexural test. GOST 8462[5] recommends the application of flexural test prior to compression test, and therefore bricks were prepared accordingly. According to this standard, bricks that have been tested for their flexural strength are then cut into regular prisms that can be bonded together for further compression strength tests. Thus, the 3 bricks that had clean breaks and 3 non-tested bricks were cut into halves and the pieces were joined together with the help of conventional gypsum mortar (Fig. 7).

GOST 5802[6] defines the preparation method, dimensional requirements and capping conditions for mortar samples. Accordingly, the samples were cut and shaped as 20–30 mm prisms with 20–40 mm height and capped with gypsum mortar.

One wall section among the three illustrated in Fig. 5 was randomly selected for the preparation of a wall prism while the other two were allocated for further research. Strength test setups for wall prisms were not available in Russian standards. Therefore, the prisms were cut, shaped, capped and prepared according to ASTM C1532[7]. Professional judgement is used for choosing the less damaged part if the aim is to find the maximum strength; or the most damaged part if the aim is to find the minimum strength. Hence, from the point of view of possible reuse, it was more meaningful to select the pieces with the most damage. Therefore, samples close to the edges of the wall pieces were more suitable because of the greater damage due to the harsh impacts of demolition. Six samples were prepared as illustrated in Fig. 8. ASTM C1314[8] was used for cutting and dimensioning the samples; this standard is valid for both the recently built wall sections as well as extracted historical samples.

Two ASTM standards used here; i.e. C1314 and C1532, fall into the destructive testing method classification. On the other hand, ASTM also offers non-destructive or partially-destructive testing methods for the assessment of masonry wall strengths i.e. compressive and shear strengths with the help of flat jack method in situ[9] (C1196 and C1531).

The researchers opted for destructive sampling and testing for this case study since the masonry walls were already broken into pieces during the demolition of the building. Additionally, their reuse was not planned in a new project. Hence, special care was not needed for the leftovers while creating the prismatic samples from the broken walls.

Nevertheless, if the demolition is pre-planned and the reuse of salvage is possible, then non-destructive methods for the strength determination would be advantageous in terms of obtaining larger numbers of less damaged units and diminishing the waste.

Three samples measuring $20 \times 20 \times 20$ cm were prepared as wall prisms for compression test. Additionally, EN 1052-3[10] was used for the preparation of three samples with $20 \times 10 \times 20$ cm ($l \times w \times h$) edges for shear test as illustrated in Fig. 8.

The wall prisms for compression test were capped with gypsum mortar while the samples for shear test were not capped since the surfaces were suitable for the test setup (Fig. 9).

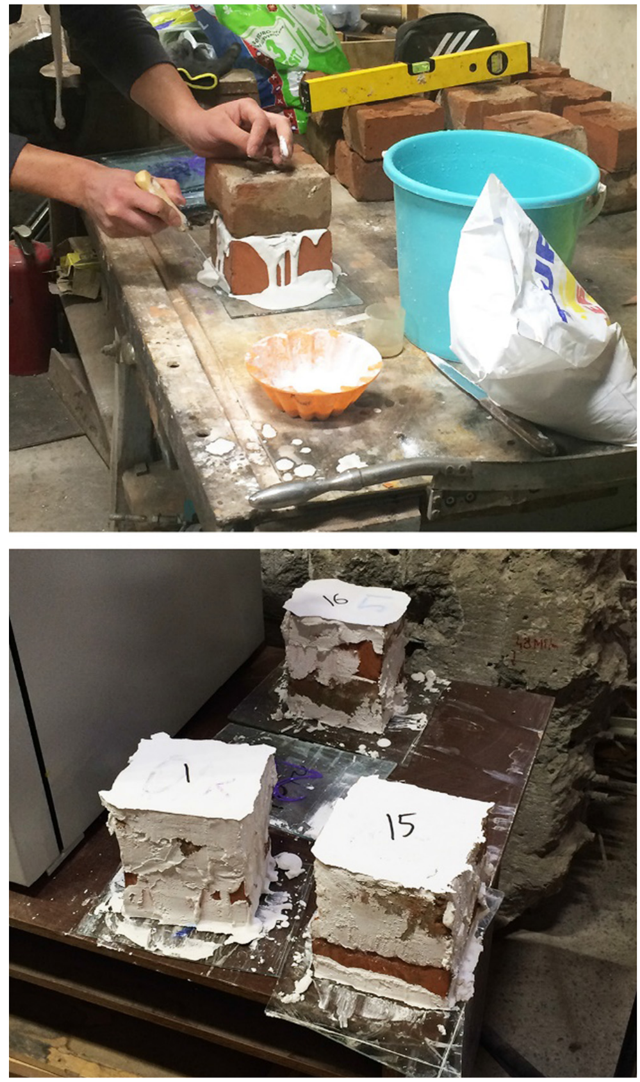


**Fig. 7.** Preparation of samples for physical property test and ready samples.

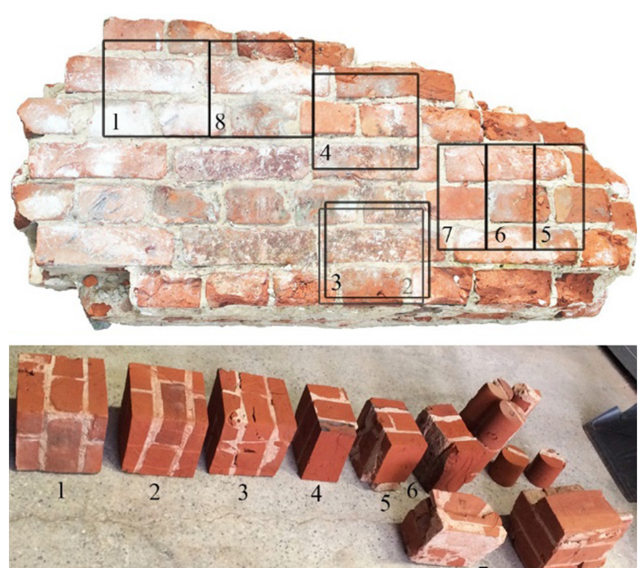


**Fig. 8.** Wall prism samples prepared for compression and shear tests (Sample #7 and #8 were broken during the cutting process, sample #2 is behind sample #3).

[5] GOST 8462: Wall materials, methods for determination of ultimate compressive and flexural strength, (1985) [14].

[6] GOST 5802: Mortars, test methods, (1986).

[7] ASTM C1532: Standard Practice for Selection, Removal, and Shipment of Manufactured Masonry Units and Masonry Specimens from Existing Construction, (2012) [5].

[8] ASTM C1314: Standard Test Method for Compressive Strength of Masonry Prisms, (2014) [3].

[9] ASTM C1196: Standard Test Method for In Situ Compressive Stress Within Solid Unit Masonry Estimated Using Flat jack Measurements, (2014) [2]. ASTM C1531: Standard Test Methods for In Situ Measurement of Masonry Mortar Joint Shear Strength Index, (2016) [4].

[10] EN 1052-3: Methods of Test for Masonry, Part 3: Determination of Initial Shear Strength, (2007) [10].

### 2.2. Method

GOST 530[11] defines the methodology for classifying the masonry units according to many aspects, such as: density, compressive strength and dimensions. Similarly, GOST 28013[12] defines methods for the categorization of mortars with respect to different parameters. Lastly, SNIP[13] defines a method to derive the ultimate compressive strength as well as allowable strength limits of masonry walls with respect to the strength of bricks and mortar, separately.

These standards were used to determine the strengths of bricks and mortar fragments obtained from the demolition plot separately, and then to derive the combined wall strength accordingly. Additionally, the wall prisms obtained from the broken wall sections were tested for their strength and the results were compared with the derived values for the walls. This comparison was done to see if the actual strength of the wall sections was equivalent to the calculated values or not, in order to decide if the wall sections could be reused for new constructions. The component classifications, ultimate stress calculations and tests on samples are detailed in the following section.

#### 2.2.1. Strength determination of brick and mortar separately

GOST 530[11] and GOST 8462[5] were used for the classification of bricks, even though the building in question, and thus the bricks obtained from it were much older than the publication of these standards, they were still used as the guide to assess the samples in terms of modern brick nomination. Additionally, GOST 5802[6] was used for the analyses on mortar since it defines the assessment of parameters related to wet and dry mixtures such as: viscosity, water retention capacity, tensile strength, elasticity and plasticity shrinkage.

*2.2.1.1. Classification of bricks.* According to the classifications in the related standards, the samples of solid bricks obtained from the plot fell into the unprotected masonry group, i.e. open to atmospheric conditions and penetration of water on site. Since the damage to the bricks was not significant, they were considered to be intact; i.e. whole bricks. They did not comply with the standard classification of 1 NF [Normal Format 250 × 120 × 65 mm, $l \times$ w × h] or 1.4 NF [250 × 120 × 88 mm] but fell in between the two. Lastly, with the mean density of 2,010.02 kg/m$^3$, they belong to class 2.4 having a range of 2010–2400 kg/m$^3$. Hence, the only prescriptive relationship between the possible area of use and brick type in the standards was based on density. While this class of brick can be used in protected spaces without plastering; they need protection when exposed to weathering.

The aforementioned standards were used to test the flexural strength of bricks until they failed and then the broken halves were used for further compression assessment, if the break was a clean one. Accordingly, the flexural test was applied first to the 9 bricks by loading the mid spans in evenly distributed manner across their widths. The results that were calculated using Eq. (1) are presented in Table 1.

$$S = 3Wl/2bh^2 \tag{1}$$

where $S$ is the modulus of rupture of the specimen at the plane of failure, $W$ is the maximum load indicated by the testing machine, $l$ is the distance between the supports i.e. 20 cm, $b$ is the net width of the specimen at the plane of failure, $h$ is the depth to bed surface (GOST 8462[5]: 4). Pieces of the bricks with a clean break, which were 3 in number only, as well as the three non-tested brick halves were

**Fig. 9.** Cracks during compression and shear tests.

stacked in twos and bound with gypsum mortar. These units were placed in the testing setup and loads were applied to them until they failed. These values were then used in Eq. (2) to find the compressive strength of the brick pieces as given in Table 2.

$$C = W/A \tag{2}$$

where $C$ is the compressive strength of the specimen, $W$ is the maximum load indicated by the testing machine, and $A$ is the average of the gross areas of the upper and lower bearing surfaces. (GOST 8462[5]: 3).

[11] GOST 530: General Specifications for Brick, Stone and Ceramic Units, (2012) [12].
[12] GOST 28013: Mortars, General Specifications, (1998) [15].
[13] SNIP [II-22-81]: Standard for Design of Stone and Reinforced Masonry Structures, (1987) [19].

*2.2.1.2. Classification of mortar.* The aforementioned standard was used for the compressive strength characterization of 21 pieces of mortar, and the results obtained from Eq. (3) are given in Table 2.

$$f_m = P/A \tag{3}$$

where: $f_m$ is the compressive strength, $P$ is the total maximum load and $A$ is the area of loaded surface. (GOST 5802[6]: 12).

*2.2.2. Derived strength of wall prisms*

Before testing the wall pieces for their strength, expected compressive wall strengths were derived with respect to the strength of their components; i.e. brick and mortar, according to SNIP[14]; which defines a method to calculate the ultimate and allowable strengths with Eq. (4).

$$f'_m = AC[1 - (a/(b + f_m/2C))]\gamma \tag{4}$$

where $f'_m$ is the specified compressive strength of masonry, $C$ is the strength of the unit under compression, $f_m$ is the strength of mortar (cube strength), $A$ is the coefficient that characterizes the maximum possible strength; thus $A = (100 + R1)/(100\,m + nR1)$. Coefficients $a$, $b$, $m$ and $n$ are defined according to the shape and dimensions of the masonry units, while $\gamma$ is the coefficient for the strength level of mortar, which is 1 in this case (*SNIP*[20]: 7). Although the slenderness ratio and support conditions alter the strength of a wall significantly, this document does not define any dimensional limitation for this formula. Therefore, the results obtained should be regarded as prescriptive and broad approximations. On the other hand, the walls are generally quite thick in Russia, about 50–100 cm, owing to the harsh climate there; while the approximate clear heights are about 3 m. Therefore, the formula might reflect the condition for comparatively thicker walls.

*2.2.3. Strength tests on wall prisms*

ASTM C1314[8] was used for the compression test of masonry prisms in accordance with their original load bearing direction as illustrated in Fig. 9. Eq. (5) was used for the calculation of actual strength and the results are given in Table 3.

$$f_{mt} = \textit{Max. compressive load/Cross sectional area} \tag{5}$$

where $f_{mt}$ is the prism's maximum compressive load sustained by the net cross sectional area of that prism (ASTM C1314: 5).

EN 1052-3[15] was used in order to detect the initial shear strength of the bed mortar joint without pre-loading and the results obtained according to Eq. (6) are presented in Table 4.

$$f_{v0i} = F_{imax}/(A_1 + A_2) \tag{6}$$

where $f_{v0i}$ is the initial shear strength, $F$ is the maximum force applied, $A_1$ is the area of the upper joint, and $A_2$ is the area of the lower joint (EN 1052-3: 12).

## 3. Results

The results obtained from the tests as well as derivations obtained from the equations are presented in the following sections.

### 3.1. Strength of bricks

Flexural and compressive strength test results for the bricks are given in Table 1; where the first and second column gives the width ($b$) and height ($h$) of the units respectively, while the third and fourth columns give the maximum load ($W$) and flexural strength of the unit ($S$). Additionally, the length of the prepared samples ($l$, half-length of the bricks), width ($b$), surface area of the units ($A$), maximum load ($W$) and the actual compressive strength ($C$) are presented in this table.

The mean compressive strength was calculated to be 10.75 MPa while the range was 4.85–18.38 MPa. Additionally, the flexural strength ranged from 2.03 to 8.79 MPa whereas the mean was calculated to be 5.28 MPa.

These bricks were determined as "average" i.e. Type M250 for flexural strength and Class M75 for compressive strength. Since the lower class governs for safety's sake, these bricks can be classified as having Class M75[16] (GOST 530).

### 3.2. Mortar strength

The compressive strength values obtained for the 21 mortar samples are listed in Table 2; The first, second and third column in this table give the lenght ($l$), width ($b$) and surface area ($A$) of the samples respectively; the fourth column gives the maximum load ($P$); the fifth column gives actual compresive strength of the samples ($f_{m\ sample}$) and the last two columns indicate the correction ($K$) [17] of sample's strength into cube strength value ($f_{m\ cube}$).

This mortar falls into class M100[18] having a range of 7.14–22.62 MPa and a mean of 14.13 MPa (GOST 28013[12]).

### 3.3. Strength calculation of wall with respect to its components

The compressive strengths of bricks and mortar from Tables 1 and 2 were used in Eq. (4) to derive the ultimate wall strength and its specific safety limit. These values were calculated to be 3.53 MPa and 1.97 MPa respectively. Consequently, this type of brick and mortar combination is appropriate for walls under 1.97 MPa compressive loads. Additionally, wall prisms were tested under direct compression for comparison and the results are presented in the following section.

### 3.4. Strength of wall prisms

Three prisms cut out from the broken wall pieces were tested for compression and the results are given in Table 3; where the first and second columns present the surface area, maximum load, compressive strengths obtained from the samples ($f_{mt\ sample}$), respectively; as well as the conversion ($K$)[19] into corrected compressive strengths ($f_{mt\ corrected}$).

The mean compression value obtained from three wall prisms is 8.70 MPa where the range is between 7.43 and 10.55 MPa as shown in Table 3.

Additionally, the results from the shear tests on the three prisms are given in Table 4; where the first column indicates the interface surface area ($A_1 + A_2$); the second gives the maximum

[14] SNIP [II-22-81]: Design of Stone and Reinforced Masonry Structures, (1987).

[15] EN 1052-3: Methods of Test for Masonry Part 3: Determination of Initial Shear Strength, (2007) [10].

[16] M 250 (Mark 250) requires five samples' average compressive strength to be 25 MPa while each solid brick cannot be less than 20 MPa, besides, five samples' average flexure strength to be 3.9 MPa while each solid brick cannot be less than 2.0 MPa. M75 requires five samples' average compressive strength to be 7.5 MPa while each brick cannot be less than 5 MPa, besides, no numeric value was noted for the flexural strength. Therefore, the bricks fall under M75 type in final verdict (GOST 530, 2012).

[17] K is the correction factor to convert the obtained result into standard cube strength to use during the derivation of wall strength [13].

[18] M100 mortar: The average compressive strength for the five samples must be at least 10 MPa while the smallest value of each individual sample could at least be 7.5 MPa (GOST 530, 2012).

[19] ASTM C1314 (2014) defines correction factors (K) according to ratio of prism height to lateral dimension. Although there is not a correction factor for 1:1 i.e. the ratio for the samples of this study, the closest ratio is 1:1.3 where the corresponding K is 0.75. Therefore 0.75 was assumed as an appropriate correction value.

**Table 1**
Results of brick tests.

| Brick | Flexural strength | | | | Compressive strength | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $b$ [mm] | $h$ [mm] | $W$ [kN] | $S$ [MPa] | $l$ [mm] | $b$ [mm] | $A$ [cm$^2$] | $W$ [kN] | $C$ [MPa] |
| 1 | – | – | – | – | 130 | 130 | 169 | 108.5 | 6.42 |
| 2 | – | – | – | – | 130 | 130 | 169 | 125 | 7.40 |
| 3 | – | – | – | – | 120 | 120 | 144 | 264.6 | 18.38 |
| 4 | – | – | – | – | 130 | 130 | 169 | 114.3 | 6.76 |
| 5 | – | – | – | – | 100 | 135 | 135 | 208.5 | 15.44 |
| 6 | – | – | – | – | 130 | 130 | 169 | 198.1 | 11.72 |
| 7 | 120 | 70 | 8.63 | 4.40 | 120 | 135 | 162 | 78.5 | 4.85 |
| 8 | 130 | 70 | 16.04 | 7.55 | 130 | 130 | 169 | 132.5 | 7.84 |
| 9 | 130 | 75 | 17.11 | 7.02 | 130 | 130 | 169 | 303.4 | 17.95 |
| 10 | 140 | 75 | 9.62 | 3.66 | – | – | – | – | – |
| 11 | 120 | 70 | 12.09 | 6.17 | – | – | – | – | – |
| 12 | 125 | 75 | 9.92 | 4.23 | – | – | – | – | – |
| 13 | 130 | 80 | 5.62 | 2.03 | – | – | – | – | – |
| 14 | 125 | 65 | 6.37 | 3.62 | – | – | – | – | – |
| 15 | 120 | 75 | 19.78 | 8.79 | – | – | – | – | – |
| | | | Mean | 5.28 | | | | Mean | 10.75 |
| | | | sd | 2.09 | | | | sd | 4.97 |
| | | | COV | 0.40 | | | | COV | 0.46 |

**Table 2**
Compresion test results of mortar.

| Mortar | Compression test | | | | | | |
|---|---|---|---|---|---|---|---|
| | $l$ [mm] | $b$ [mm] | $A$ [cm$^2$] | $P$ [kN] | $f_{m\ sample}$ [MPa] | $K$ | $f_{m\ cube}$ [MPa] |
| 1 | 20 | 20 | 4 | 8.2 | 20.50 | 0.56 | 11.48 |
| 2 | 20 | 20 | 4 | 8.2 | 20.50 | 0.56 | 11.48 |
| 3 | 20 | 20 | 4 | 5.1 | 12.75 | 0.56 | 7.14 |
| 4 | 20 | 20 | 4 | 6.1 | 15.25 | 0.56 | 8.54 |
| 5 | 21 | 22 | 4.62 | 12.2 | 26.41 | 0.62 | 16.37 |
| 6 | 21 | 21 | 4.41 | 7.4 | 16.78 | 0.62 | 10.40 |
| 7 | 32 | 32 | 10.24 | 18.8 | 18.36 | 0.74 | 13.59 |
| 8 | 32 | 31 | 9.92 | 17.2 | 17.34 | 0.74 | 12.83 |
| 9 | 32 | 32 | 10.24 | 20.3 | 19.82 | 0.74 | 14.67 |
| 10 | 32 | 32 | 10.24 | 12.4 | 12.11 | 0.74 | 8.96 |
| 11 | 32 | 33 | 10.56 | 30.7 | 29.07 | 0.74 | 21.51 |
| 12 | 32 | 32 | 10.24 | 25 | 24.41 | 0.74 | 18.07 |
| 13 | 31 | 31 | 9.61 | 21.2 | 22.06 | 0.74 | 16.32 |
| 14 | 32 | 33 | 10.56 | 17.3 | 16.38 | 0.74 | 12.12 |
| 15 | 32 | 32 | 10.24 | 19.1 | 18.65 | 0.74 | 13.80 |
| 16 | 30 | 31 | 9.3 | 15 | 16.13 | 0.74 | 11.94 |
| 17 | 31 | 32 | 9.92 | 16.4 | 16.53 | 0.74 | 12.23 |
| 18 | 32 | 32 | 10.24 | 31.3 | 30.57 | 0.74 | 22.62 |
| 19 | 33 | 33 | 10.89 | 30.6 | 28.10 | 0.74 | 20.79 |
| 20 | 32 | 32 | 10.24 | 21.1 | 20.61 | 0.74 | 15.25 |
| 21 | 31 | 31 | 9.61 | 21.6 | 22.48 | 0.74 | 16.63 |
| | | | | | | Mean | 14.13 |
| | | | | | | sd | 4.10 |
| | | | | | | COV | 0.29 |

**Table 3**
Compression test results on masonry prisms.

| Prism | *Area* [cm$^2$] | *Load* [kgf] | $f_{mt\ sample}$ [kgf/cm$^2$] | $K$ | $f_{mt\ corrected}$ [MPa] |
|---|---|---|---|---|---|
| 1 | 408.59 | 57500 | 140.73 | 0.75 | 10.55 |
| 2 | 401.77 | 43500 | 108.27 | | 8.12 |
| 3 | 436.77 | 43250 | 99.02 | | 7.43 |
| | | | | Mean | 8.70 |
| | | | | sd | 1.34 |
| | | | | COV | 0.15 |

load ($F_{imax}$) and the third presents the inital shear strength values ($f_{v0i}$).

Accordingly, the mean initial shear strength value obtained from these three wall prisms was calculated to be 0.16 MPa while the range was 0.11–0.24 MPa.

## 4. Discussion

Test results are compared and discussed under two sections related to the compression and shear strengths of the wall pieces.

**Table 4**
Results of triplet shear test on masonry prisms.

| Prism | $A_1 + A_2$ [cm$^2$] | $F$ [kgf] | $f_{v0i}$ [MPa] |
|---|---|---|---|
| 4 | 484.77 | 1166 | 0.24 |
| 5 | 472.33 | 533 | 0.11 |
| 6 | 428.33 | 600 | 0.14 |
| | | Mean | 0.16 |
| | | sd | 0.05 |
| | | COV | 0.33 |

### *4.1. Compressive strength comparison*

Two ultimate compressive strength values were obtained: one was derived from the combined strengths of the bricks and mortars, while the other was obtained from the compression test on wall prisms. The derived ultimate strength was calculated to be 3.53 MPa; which was double the allowable limit of 1.97 MPa. Hence, it can be stated that the wall pieces can be re-used safely in place of new building material. Besides determining the strength of the prisms, ASTM C1314[8] also recommends analyzing and classifying crack types, since they reveal the joint characteristics of the wall. Although different failure types occurred during the tests, the most critical type of crack formation, i.e. interface failure, was observed only once during the compression tests. This type of crack is critical since it reveals weak adhesion between the brick and the mortar. This shows that the bonding between the bricks and mortar continues to hold its integrity, which is good in terms of reusability.

### *4.2. Shear strength comparison*

Eurocode 6[20] states that, when a masonry unit is solid clay brick and the mortar is general-purpose mortar, the expected initial shear strength should be larger than 0.1 MPa.

The mean value of the shear tests was 0.16 MPa while the range was from 0.11 to 0.24 MPa. This value was also high compared to the allowable limit, which means that such wall pieces can safely be reused as new building material. Besides the strength comparisons, crack formations give clues about bonding properties of the mortar, two crack types i.e. interface failure and mortar failure were observed in the samples. Although cracks at interfaces indicate comparatively weak bonding, the shear strength of the prisms were seen to be higher than specified limits. Therefore, the wall sections can be labeled as reliable under limit shear loads.

## 5. Conclusion

The main approach throughout the study was to investigate the possible reuse options in two ways. First was to check if the condition of the single bricks were compatible with the new ones in the market, while the second one was to see if the recovered masonry wall sections could stay intact until specified strength limits.

Consistent to the initial visual inspections on the site, the single bricks and wall pieces obtained from the demolition debris exhibited a high potential for reuse according to the laboratory tests. Since all of the samples tested were able to pass the allowable limits for strength; therefore, their re-use for new construction can be recommended. Not only were the wall pieces and the bricks stronger than allowable limits, the samples also did not exhibit any brittle behavior during the tests; i.e. they did not disintegrate under the loads. Hence, these masonry wall components can be used under appropriate conditions with suitable design configurations.

All in all, the reuse of this material does not only decrease the amount of demolition waste, but also diminishes the need for new brick production, which are two important parameters in terms of ecological and economic sustainability. Additionally, reusing the material can be assessed as a way of translating the cultural and historical value of the buildings into current design solutions.

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