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TIES IN UNREINFORCED MASONRY STRUCTURES: CASE STUDY IN KRK

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Abstract

This paper examines the use of ties in a 19th century stone masonry building in Krk, Croatia. To prevent the out-of-plane failure mechanisms buildings should have adequate structural integrity. The beneficial details in this case study include: i) timber ring beams inserted into the walls acting as horizontal ties; ii) connections between the timber floor beams and the masonry walls via anchoring iron ties; and iii) connections of the attic walls and the floor beams using diagonal iron ties. The mechanical properties of wrought iron ties have also been investigated.

Keywords: heritage buildings, unreinforced masonry, structural integrity, wrought iron ties, timber ring beams

1. Introduction

The recent earthquakes in Croatia in 2020 have reminded us again that heritage masonry buildings are highly vulnerable to seismic actions. In this paper we will focus on the prevention of out-of-plane failure mechanisms in masonry structures, which result from scarce wall-to-wall and wall-to-floor connections. Masonry buildings should have adequate structural integrity, i.e. they should behave like a box, in order to switch from the undesirable out-of-plane failure mechanisms to in-plane failure mechanisms. This includes: quoins - larger stone blocks at the corners of the building, appropriate bond pattern between the intersection walls, metal ties between the floor structure and the walls, etc. [1].

Detecting the elements that ensure the integrity of an existing building is very rarely possible since the skeleton of the building is covered by plaster, claddings and façade. The in-depth inspection of the skeleton of the building is only possible: (i) during a renovation or (ii) less favourable, in the event of a major earthquake, during a damage inspection. Although it is not desirable, a post-earthquake damage inspection can provide valuable information about the effectiveness of certain elements in historic buildings [1-4]. This is how construction details that ensured good performance in a previous earthquake was handed down to builders over generations [3].

The ties and quoins aim to enhance the box-like behaviour. Ties should be regularly spaced over the façade and appropriately connected to the walls and to the floor structure, in order to make the constraints effective [1]. The recent earthquakes in Central Italy proved that metal ties, when combined with a reasonably quality masonry, contributed to preventing collapse of the buildings [2]. When the quality of the masonry at the corners is enhanced by the presence of quoins, the vertical overturning of the façade will be prevented. However, the effectiveness of the quoins is limited when coupled with masonry with poor bond pattern or unconnected multi-leaf walls, as wall leafs tend to separate [1].

Lagomarsino [3] performed damage assessment on churches, being the most vulnerable among historical buildings, after the L'Aquila earthquake. He reports of horizontal wooden logs embedded into the masonry walls during construction and connected to the external walls by means of metal flats and anchor metal bars (Italian "capochiave con paletto") acting as ties. The anchor bars are often very small in size (about 60 cm long), since the anchoring is not limited only to the external wall but is diffused due to friction that develops over the entire length of the wooden log. However, the weak point was always found at the connection of the two nails between the metal anchor and the wooden log or in the

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insufficient overlapping. Günaydin et al. [4] showed that masonry buildings with horizontal timber bond beams in rural areas in Turkey behaved more stable than those in which timber bond beams were not used or partially used during the 2020 earthquake. They also report of poor splicing details of the beams, which contributed to their failure.

In this paper we will present a case study building explored as part of an ongoing research project on traditional stone masonry structures in the Kvarner Littoral. The building was recently reconstructed and adapted for a new purpose, and due to the replacement of the floor and roof structures an in-depth inspection of the building skeleton was possible. Structural connections between the walls, floors and the roof will be explained in detail. Also, the material and mechanical properties of several wrought iron ties extracted from the building were investigated.

2. Case study

The building is located in Krk, Croatia, incorporated into the old part of the city, which is listed as a cultural-historical urban complex in the Register of Cultural Properties. Over the years, the building has undergone various reconstructions. It consists of a central L-shaped part (consisting of two rectangular parts that were formerly two different buildings) and two smaller rectangular parts, added afterwards, making an E-shaped ground plan (Fig. 1b). The year of construction is not known, but the central L-shaped part of the building is displayed on the Second Habsburg cadastral survey from the 1819 [5].

It consists of a ground floor, two storeys and an attic, with approximate floor plan dimensions 20 x 12,5 m. The height of the roof cornice is around 10 m. It has an almost symmetrical arrangement of the openings on the front façade (Fig. 1a); the windows are rather large and extend over almost the entire floor (except on the attic).

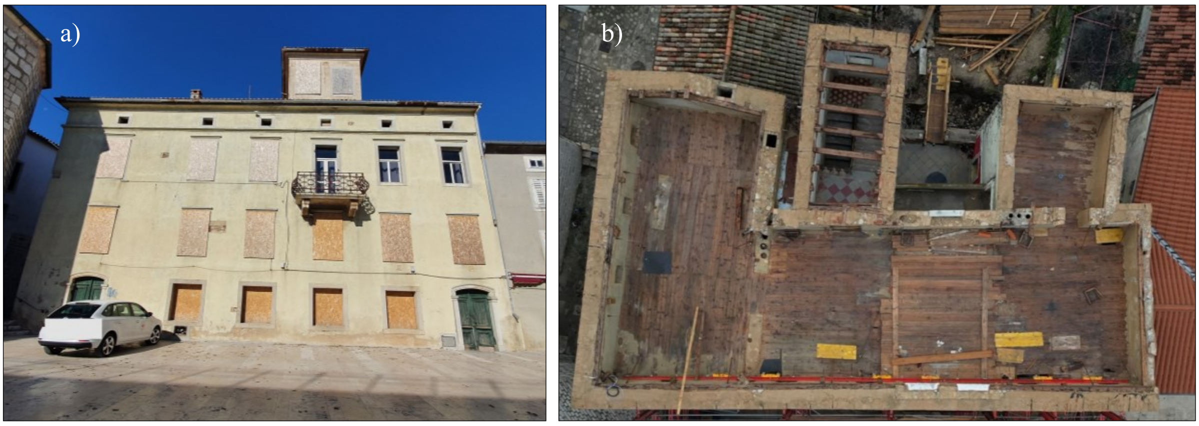

Figure 1. a) Front façade; b) Building plan at the roof level [6].

Figure 2. Masonry typology.

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The floor structures are made of timber beams and boards, as common in this region, while the roof structure is a king-post, covered with tiles. The walls may be categorized into rubble stone masonry (wall thickness 65 cm), though some later added walls are built of brick. The stone blocks are mostly of the same size, with considerably larger dimensions at the corners or at the openings (Fig. 2)

3. Ties

Since the floor is flexible in-plane additional elements have been provided to connect the walls and to ensure the global box-like behaviour. This includes horizontal timber ring beams embedded into the walls just below the floor level and floor-to-wall connections via both the horizontal and diagonal wrought iron ties.

3.1.Timber ring beams

The use of timber ring beams as ties is quite common in adobe masonry [7-9]. A traditional method to reinforce the adobe masonry includes the installation of beams at the corners or at the perimeter of the building, spaced at every 60 to100 cm over the wall height. The ring tie beams are usually made of timber, concrete, steel or straw bars and enable the building to behave as a box, increasing its resistance against the wind or the seismic loads [7].

Although the use of timber ring beams as ties is quite common in adobe masonry, it is not so common in stone masonry. D'Ayala and Paganoni [1] report of timber ties in residential buildings, inserted just below the floor level or above the openings, while Lagomarsino [3] reports of timber logs in churches, both in Aquila. Sorrentino et al. [2] indicate on the application of timber ties in Central Italy. Al Qablan et al. [10] report on timber string-courses embedded in ashlar buildings in Jordan, as an anti-seismic device.

Timber beams have been also used as ties in domes (it is well known that Brunelleschi used timber ring beams to absorb the horizontal thrusts in the dome of Florence [11]) and in arched structures (for example in churches in Albania [12].

Authors of this paper have not so far detected timber ring beams embedded into masonry in the Kvarner Littoral, so the discovery of the timber beams in Krk was the motive for presenting this unique case study. These beams have minimum dimensions 13 x 19 cm, and are made continuous like a ring around the perimeter walls (Fig. 3): at the joint of two beam ends wrought iron ties have been used. At the positions of the opening for chimney in the cross-section of the wall, timber beams have been omitted (since there isn't enough width, but also due to heating) and instead replaced with iron ties (denoted with a red arrow in Fig. 4). The ring beams have also been provided in the inner walls.

Figure 3. Timber ring beams at the roof level: a) Ground plan; b) Detail.

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Figure 4. Timber ring beams at the roof level.

The timber ring beams are provided at the floor levels and at the roof level (at the top of the attic walls). Note the connection of two beam ends using an iron tie (in order to ensure continuity), indicated with a red arrow in Fig. 5. No ring beams have been detected above the ground floor. This can be explained by the possibility that the ground floor had been probably built in an earlier period.

The ring beams at one corner of the attic walls have been additionally connected by a cross iron tie at the top to prevent their separation (Fig. 6).

Figure 5. Timber ring beams at the floor levels.

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Figure 6. Connection of timber ring beams at a corner via iron ties.

3.2. Horizontal wall-to-floor connections

Wall-to-floor connections play a crucial role in the global stability of masonry buildings under seismic actions [13]. In this case study, connections between the timber floor beams and the masonry walls are placed at every fourth beam in the floor (Fig. 7). Wrought iron ties are anchored to the external walls by means of anchor iron bars (red arrow on Fig. 7). Three nails are used to connect the iron flat and the timber beam.

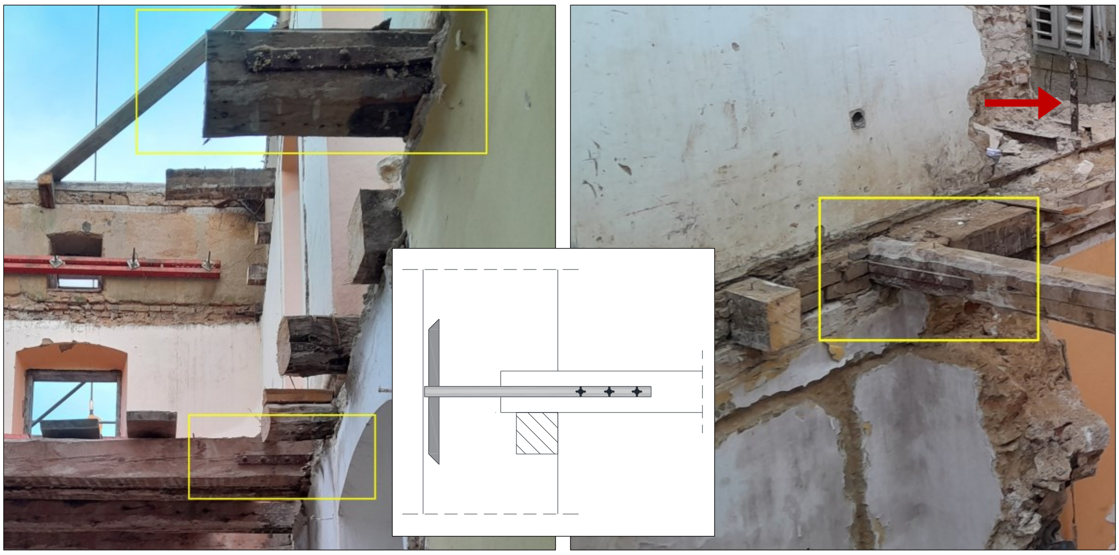

Figure 7. Horizontal wall-to-floor ties.

3.3. Diagonal wall-to-floor ties

Diagonal iron ties are used to connect the attic walls and the floor beams, placed at every fourth or fifth floor beam (Fig. 4, Fig. 8). These ties have a "hockey stick" shape so that they can be attached to the floor beam by two nails, while the upper part of the tie is twisted by 90° and then bent into an L shape, so that it encompasses the timber ring beam (Fig. 8). The ties have a uniform rectangular cross-section measuring 45 mm in width, while the thickness varied from 8,5 to 12,5 mm, depending on the element.

4. Material properties of wrought iron ties

Material and mechanical properties of iron ties were inspected on seven diagonal wall-to-floor ties extracted from the attic. From each diagonal tie one testing specimen was prepared. One sample was used to obtain chemical composition (Fig. 9) - the GDS analysis provided an insight into the concentrations of the secondary elements [14].

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Figure 8. a) Diagonal wall-to-floor iron ties.

4.1. Chemical properties of wrought iron ties

Table 1 shows the mean values of the measured weight percentage *w* of individual elements and their standard deviation *SD* obtained using glow-discharge spectrometer (GDS)[14]. The cross-section was prepared by polishing. According to the very low carbon content, a soft but very ductile material can be expected, what will be confirmed by tensile testing.

Figure 9. a) Cross section of a diagonal tie; b) Detail of forged connection confirming it is wrought iron.

Table 1. Chemical composition obtained via glow-discharge spectrometer [14]

Element	C	Mn	Si	P	S	Mo	Ni	Cr	Cu	Al	Sn	As
w (%)	0,0199	0,32	0,0553	0,0589	0,0186	0,0016	0,0197	0,0038	0,0801	0,0065	0,0312	0,0021
SD (%)	18,42	3,65	-	33,66	36,37	48,8	-	37,33	-	-	38,3	-

4.2. Mechanical properties of wrought iron ties

Testing specimens were prepared by waterjet cutting, using a high-pressure jet of a mixture of water and an abrasive substance (Fig. 10). This cutting method was selected because it does not heat the metal,

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which is preferable since exposure to high temperatures can change its characteristics. According to [15] it is possible to test specimens as-manufactured (without the cross-section reduction), but there is a possibility that the fracture may then occur outside the extensometer length. The surface of the specimens was additionally sanded with an 80 grit flap disc to remove the rust and old paint.

The dimensions of the specimens have been selected to match the so-called proportional specimens [15], in which the gauge length L_o is in direct relationship with the cross-sectional area by the equation $L_o = 5{,}65 \cdot (a_o \cdot b_o)^{1/2}$. However, since the thickness of the specimens after sanding a_o varied from 8,1 to 12,1 mm (i.e. the gauge length would be different for each specimen), due to the ease of testing it was decided to adopt the extensometer gauge length L_e equal to 100 mm (corresponding to the specimen with the largest thickness) for all specimens. A transition radius R of 25 mm was selected between the gripped ends and the parallel (reduced) length (Fig. 11). The following symbols are used: L_t – specimen length (L_t = 500 mm), L_c – length of the parallel reduced section (L_c = 130 mm), b – specimen width, b_o and a_o – width and thickness of the parallel length (reduced section) respectively.

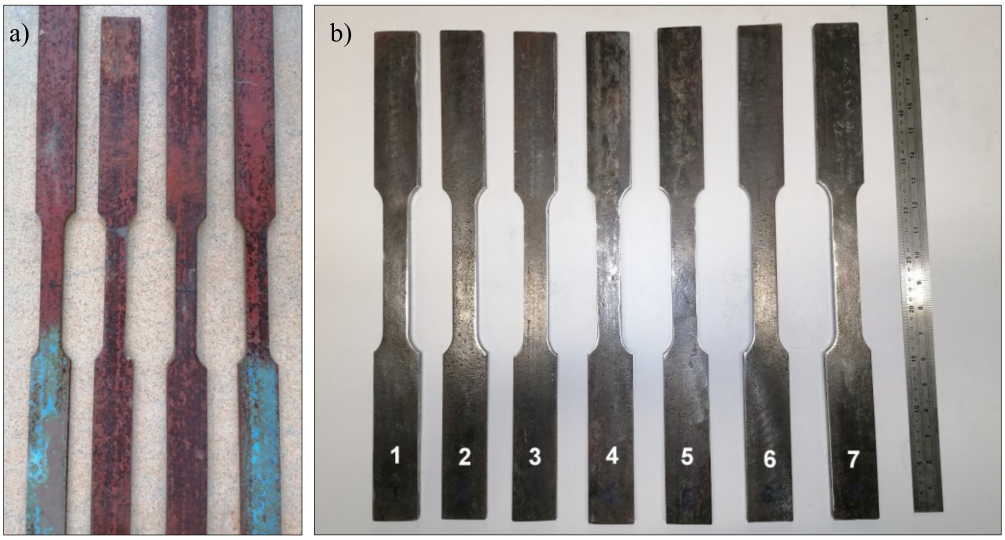

Figure 10. Preparation of specimens: a) after waterjet cutting; b) after sanding.

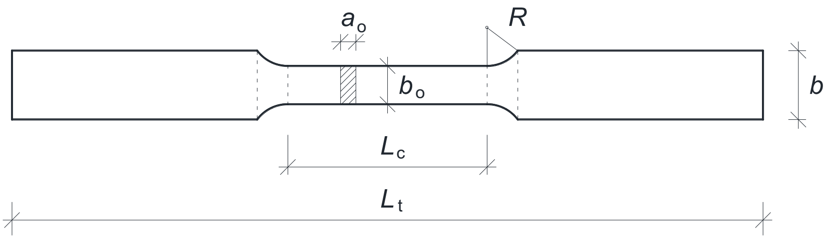

Figure 11. Specimen details.

Specimens were tested on Zwick Röll Z600E (Fig. 12) according to method A1 [15] with strain rate control, based on the feedback obtained from the extensometer in the range up to yielding (recommended strain rate 0,00025 s^{-1} was applied). In the yielding range, the strain rate control over the parallel length (L_c =130 mm) achieved by controlling the crosshead separation rate was used (strain rate equal to 0,00025 s^{-1} was applied), while after the yielding phase the strain rate was increased to 0,0067 s^{-1} (crosshead separation rate). Grip to grip length was 334 mm.

The results of the tensile tests are presented in Table 2, while the stress-strain relationships are given in Fig. 13. The following symbols are used: R_{eH} – upper yield strength, R_m – tensile strength (stress corresponding to maximum load), A_{gt} – deformation at maximum load, A_t – deformation at

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fracture and m_E – slope of the elastic part of the graph corresponding to the tangent of the angle of inclination of the line of linear regression in the stress-strain diagram between 10% and 40% of R_{eH}.

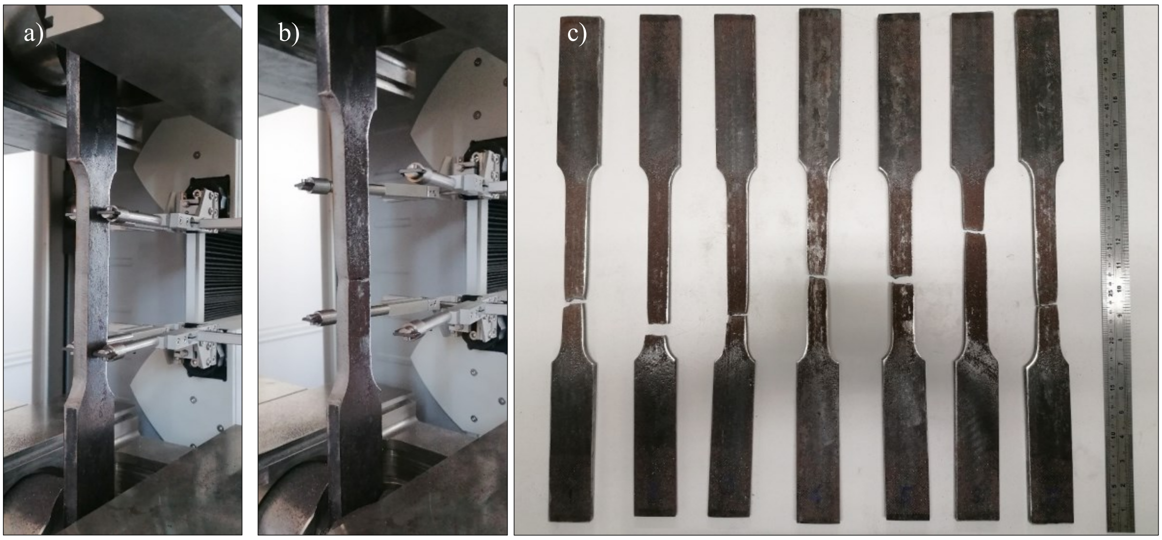

Figure 12. a) Testing setup; b) Specimen 7 just after fracture; c) Specimens after testing.

Table 2. Tensile testing of ties

Specimen	b (mm)	b_0 * (mm)	a_0 * (mm)	R_{eH} (MPa)	R_m (MPa)	A_{gt} (%)	A_t (%)	m_E (GPa)
1	45,8	24,78	9,70	278,7	359,2	18,6	27,5	198,8
2	44,8	24,63	8,07	239,1	318,9	16,4	16,9	187,1
3	44,8	24,75	8,10	243,3	325,5	18,5	26,7	160,1
4	45,8	24,83	12,00	230,6	339,4	20,4	35,4	194,6
5	45,6	24,87	12,13	233,8	346,7	17,1	20,2	174,2
6	45,2	24,55	8,03	241,8	327,8	18,2	26,7	182,9
7	45,3	24,65	8,13	239,1	330,3	20,0	34,4	154,8
mean				243,8	335,4	18,5	26,8	178,9
SD				16,0	13,9	1,4	6,7	16,7

* average value of 3 measurements within the parallel length

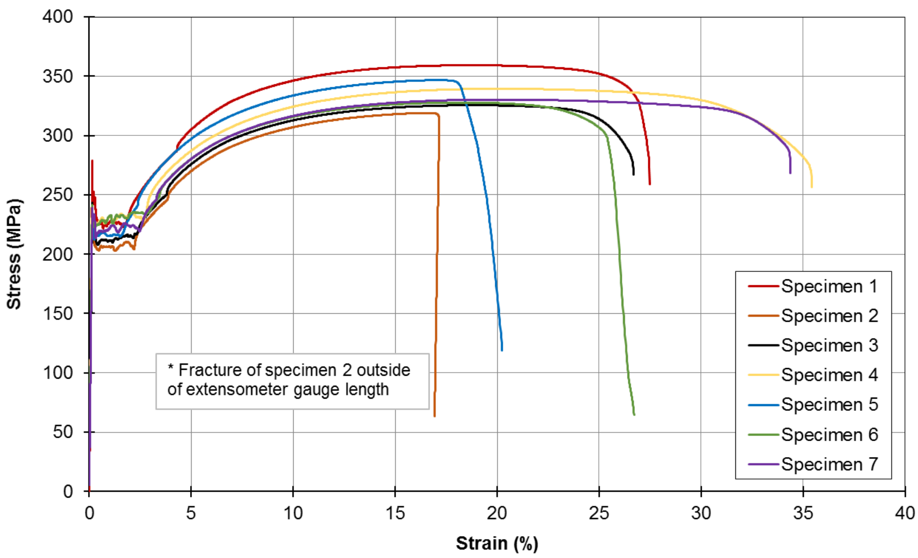

Figure 13. Stress-strain diagram of iron ties.

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The following values were obtained: mean yield strength 244 MPa, mean tensile strength 335 MPa and mean elongation at fracture 26,8 %. When compared with the results of tensile test of ties from Czech Republic [16] or Italy [17], differences may be noticed, what can be attributed to the different composition of wrought iron and different periods of production, so special care should be taken when assuming mechanical properties from different periods and different countries.

Fig. 14 presents the fracture surfaces of two specimens, where the foliar fractures may be noted. Specimen 2 had a smaller tensile strength and significantly smaller deformation A_t, what can be attributed to the defect in the cross section visible as a white spot in Fig. 14a.

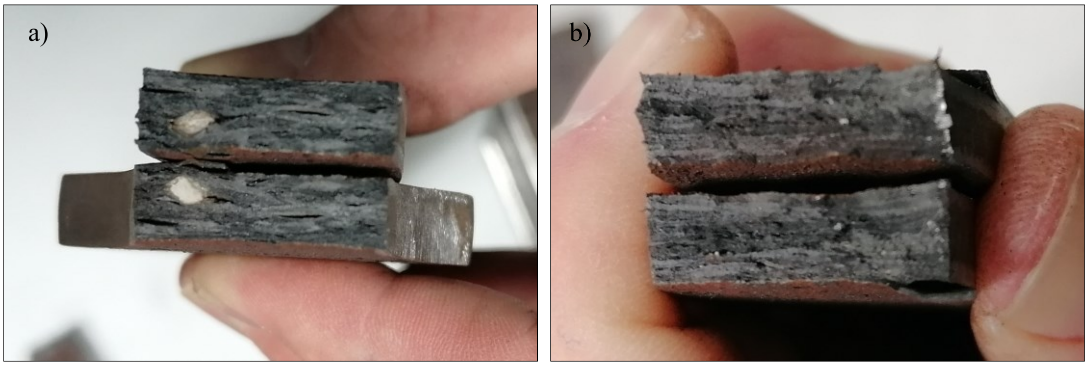

Figure 14. Fracture surfaces: a) Specimen 2; b) Specimen 3.

5. Conclusions

In this paper we presented the application of ties in a stone masonry building located in Krk, Croatia, placed in order to insure an adequate structural integrity, a property that masonry structures often lack. Detecting the elements that ensure the integrity of the building is very rarely possible; this kind of inspection of the skeleton of the building is possible during a renovation or unfortunately in the event of a major earthquake, during a damage inspection.

The in-depth inspection of the case study building and related tensile testing showed the following:

- Horizontal timber ring beams have been embedded into the masonry at the floor and at the roof level. The timber beams were connected by metal flats at their ends to ensure their continuity. Authors of this paper have not so far detected timber ring beams embedded into masonry in the Kvarner Littoral. There may be more such cases in our country, but they still have not been documented.
- Horizontal wall-to-floor connections were obtained by wrought iron flats anchored into the external walls.
- Diagonal wall-to-floor connections via iron ties were used at the roof level. Exceptional level of craftsmanship was noted.
- Tensile testing of diagonal iron ties gave the following results: mean yield strength 244 MPa, mean tensile strength 335 MPa, mean elongation at fracture 26,8 %.

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