STRENGTHENING OF CRACKED COMPRESSED MASONRY USING DIFFERENT TYPES OF REINFORCEMENT LOCATED IN THE BED JOINTS

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A b s t r a c t
In engineering practice, the repair and strengthening of the cracked masonry is carried out in several different ways. In general practice it is normal for individual cracked bricks to be removed and replaced, reinforce the masonry by using bowstrings or anchors, stitch with bars or bond the brick by means of chemical injection. As only limited information and recommendations are available for strengthening cracked masonry, the method selected for a particular application is usually based upon local experience and engineering instinct.
In this paper the investigations of strengthening vertically cracked compressed masonry wallettes with stitching bars of three different types are presented. The purpose of presented investigations was to check the effectiveness of strengthening in vertically cracked compressed masonry wallettes. The results of these investigations allow us to assess four ways of strengthening with respect of the obtained values of the compressive strengths and the modulus of elasticity of the masonry after repair.

S t r e s z c z e n i e
W praktyce inżynierskiej naprawy zarysowanych murów wykonuje się na kilka sposobów. Zazwyczaj stosuje się przemurowania zarysowanych obszarów, dozbrojenie za pomocą ściągów, zszycie rys przez układanie prętów w spoinach wspornych lub zespolenie muru przy pomocy iniekcji. Ze względu na ograniczoną ilość dostępnych informacji i zaleceń metoda wzmocnienia zarysowanych murów wybierana zwykle bywa na podstawie lokalnych doświadczeń wykonawczych i inżynierskiego wyczucia.
W artykule przedstawiono wyniki badań zarysowanych murów wzmocnionych przez zszycie zarysowań trzema typami prętów zbrojeniowych. Celem prezentowanych badań było określenie efektywności wzmocnienia zarysowanych murów. Uzyskane na podstawie badań wartości wytrzymałości na ściskanie i modułu sprężystości wzmocnionego muru pozwoliły ocenić efektywność czterech sposobów zbrojenia.

K e y w o r d s: **Masonry; Cracked masonry; Rrepair; Strengthening; Bed joint reinforcement.**

1. INTRODUCTION

Hairline cracks and significant cracks are the most common faults to be found in masonry construction. There are the results of different factors acting [1, 2, 3]. Especially dangerous and usually not accepted both from safety and utility condition point of view are cracks with width exceeding 0.3 mm. Of course, not all types of cracks are dangerous. Such damages connected with thermal influences or produced by bended supporting structural elements (like floor structures or spandrel beams of load-bearing frame constructions) didn't testify about problems with limit state conditions [4]. But always are not acceptable from serviceability limit state and should be repair. In case of masonry load-bearing internal or/and external walls as well as in non load-bearing partition walls, especially in situation of diagonal cracks appearance the repair process should be connected with their strengthening.

In engineering practice, the repair and strengthening of the cracked masonry is carried out in several different ways. In general practice it is normal for individual cracked bricks to be removed and replaced [1, 3]; reinforce the masonry by using bowstrings or anchors [3];

stitch with bars [2, 3, 5, 6, 7] or bond the brick by means of chemical injection [2, 4, 8]. As only limited information and recommendations are generally available for strengthening cracked masonry, the method selected for a particular application is usually based upon local experience and engineering instinct.

The purpose of presented investigations was to check the effectiveness of strengthening vertically cracked compressed masonry wallettes with stitching bars of three different types. The results of these investigations allow us to assess four ways of strengthening with respect to the obtained values of the compressive strengths and the modulus of elasticity of the masonry after repair.

2. DESCRIPTION OF INVESTIGATIONS

Presented investigations were carried out on elements illustrated in Fig. 1, which were made with the use of clay solid bricks and the most popular and wide used cement-lime mortar (in the ratio by volume of cement: lime: sand of 1 : 1 : 6). The strength class of the mortar was M5 (average normalised compressive strength f_m = 5 MPa) and of units was "15" (normalised compressive strength f_b = 15 MPa).

Within the main investigations four series (three elements in each series), of strengthened samples and additionally, two series of un-strengthened elements, as reference members were examined. All tested specimens were loaded continuously until their complete destruction during one cycle. Readings of load level were made every 100 kN by means of a dynamometer, whereas the determination of the state of displacements of each wall was made with the use of set of inductive sensors located and fixed to the both surfaces of the tested wallette – as it was shown in Fig. 1. The accuracy of used sensors was 0,002 mm.

As a part of the research programme, material investigations included the measurement of the compressive strength and modulus of elasticity of the mortar using cylindrical samples according to Polish standard PN-71/B-04500 [9] as well as compressive and flexural strength using cuboids samples as recommended in European Standard EN 1015-11:1998 [10] were carried out. Also the compressive strength, stress-strain relationship and modulus of elasticity of the brick used in all samples according to European Standard EN 772-1:2000 [11] as well as on the two joint halves of bricks according to former (not now in use) Polish Standard PN-70/B-12016 [12] were determined.

Additionally, in accordance with European standard EN 1052-1:1998 [13] measurements of the compressive strength and modulus of elasticity of the masonry specimens shown in Fig. 2 were also carried out. All these types of masonry specimens were subjected to axially compression in one cycle and two orthogonal directions: parallel to the plane of the bed joints (series **AH** – 5 elements) and perpendicular to the bed joints (series **AV** – 5 elements).

All tested specimens were prepared by qualified bricklayers with specially attention to get the correct joint thickness (between 10 mm to 12 mm) and good mortar filling. Specimens were stored in the laboratory hall in normal conditions.

3. DESCRIPTION OF USED STRENGTHENING METHODS

The realised essential part of the research program of masonry wallettes is shown in Table 1. In the first

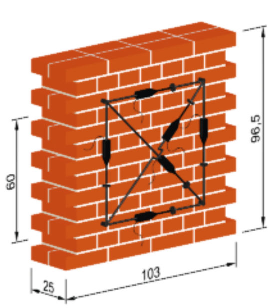


Figure 1.
Shape and overall dimensions of masonry specimen (dimensions are in centimetres)

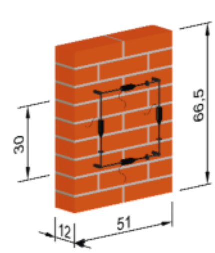


Figure 2.
View of the standard masonry specimen – according to EN 1052-1:2002 [13] (dimensions are in centimetres)

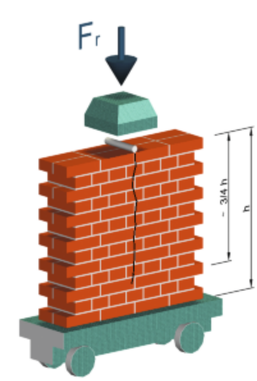


Figure 3.
Meaner of cracking the test specimens

Table 1.
The essential part of the research program of masonry wallettes

Series	No of specimens	Cracking	Strengthening method
B	5	Not	not-strengthened
C	3	Yes	not-strengthened
D	3	Yes	1 ϕ 6mm rod in bed joint (vertical spacing: fife and four brick layers – Fig. 4); slots filled with general purpose cement-lime mortar (1 : 1 : 3) – Fig. 6.
E	3	Yes	1 ϕ 6mm HB rod in bed joint (vertical spacing: fife and four brick layers – Fig. 4); slots filled with HB MM2 mortar – Fig. 6.
F	3	Yes	2 ϕ 6mm HB rod in bed joint (vertical spacing: fife and four brick layers – Fig. 4); slots filled with HB MM2 mortar – Fig. 6.
G	1	Yes	1 ϕ 6mm HB rod in bed joint (vertical spacing: fife and four brick layers – Fig. 4); slots filled with HB MM2 mortar – Fig. 6, and ϕ 6 mm ties arranged like shown in Fig. 8.

stage of the research work, the un-cracked and unstrengthened samples were examined. The series of these samples was marked with a symbol **B** and included 5 samples. The next stage of the investigation was cracking of the remaining built elements. Cracks were generated by means of a 16 mm diameter rod made of smooth carbon steel through which the force F_r was delivered from the head of the hydraulic press machine onto the tested element. The rod was placed in the centre (mid-span) of the length of the specimen. This way a single crack in the centre of the specimen was obtained. It was assumed that the crack should reach about 3/4 height of the element (from upper surface), along the centre line and with a visible width of about 1 mm (see Fig 3.).

In order to be able to quantify exactly the effect of the methods of strengthening employed, three specimens were used from the **C** series which were cracked but unstrengthened, to provide a datum (reference members).

The following series included samples already strengthened. Stitching of the cracks in all samples was carried out on one side of the element only (Fig. 4 and Fig. 5). Bars were arranged in mechanically made slots at a depth of about 40 mm (see Fig. 6). For the **F** series (double bars), and to maintain the standard conditions of mortar cover (depends on the environmental exposition class), rods were embedded in the slots with a depth of

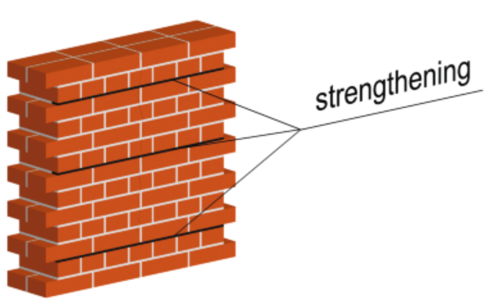


Figure 4.
Place of strengthening

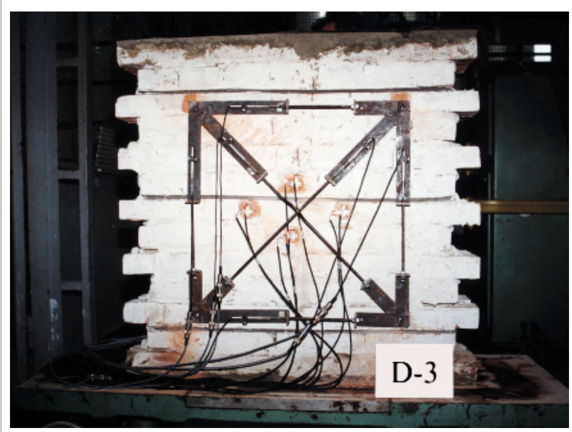


Figure 5.
View of strengthened model

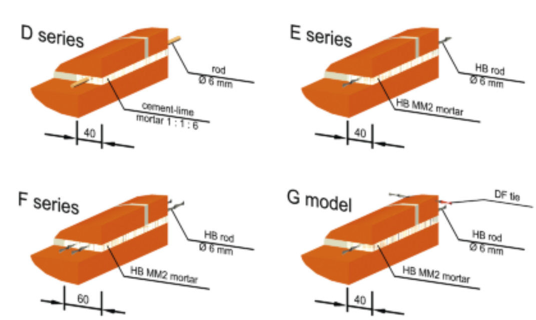


Figure 6.
Details of the strengthening

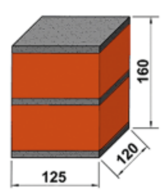
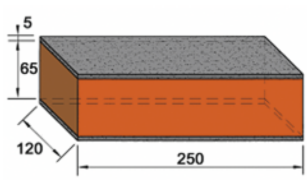
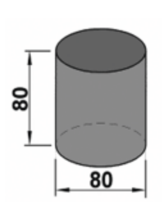
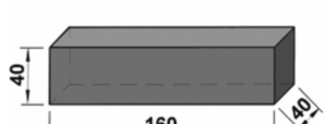
about 60 mm. Usually, the steel rods are placed in spacing not exceeding 400 mm in vertical direction. In presented investigations strengthening steel elements were located as shown in Fig. 4 and Fig. 5 (spacing ca. 380 mm and 310 mm).

The first method of strengthening was to stitch the cracks using a rod 6 mm in diameter embedded in general purpose cement-lime mortar (series of type **D** three elements) – see Fig. 6. This mortar had approximately the same characteristics and properties as the mortar used to make the test specimens. This is traditional type of strengthening and it is most popular and wide by used – not only in Poland (see [1, 2]).

For the next three methods of strengthening a repair technique was used, which was developed in Great Britain and is widely used for strengthening masonry construction including vaults, arches and brick-bridges [14, 15]. Strengthening cracked elements of **E**, **F** and **G** series was carried out by crack stitching with special HB spiral bars (see Fig. 7) of about 6 mm diameter. The bars were made of austenitic stainless steel and embedded in cementitious, thixotropic, injectable, non-shrink HB MM2 grout. Strengthening of the **E** samples (3 specimens – see Table 1) was

Figure 7.
View of the HB spiral bar

Table 2.
The average values of mechanical properties for masonry units and cement-lime mortar

Testing method	Determined value					
	Compressive strength		Bending strength		Modulus of elasticity	
	$f_{c,i}$ [MPa]	v_{fc} [%]	f_{xi} [MPa]	v_{fx} [%]	E_i [MPa]	v_E [%]
Clay brick masonry units						
PN-70/B-12016 [12] 	9.2	14.7	-	-	-	-
EN 772-1:2000 [11] 	19.2	7.8	-	-	4620	15.1
General purpose cement-lime mortar (1 : 1 : 6)						
PN-71/B-04500 [9] 	5.7	9.6	-	-	5480	8.9
EN 1015-11:1998 [10] 	4.3	9.5	1.5	10.2	-	-

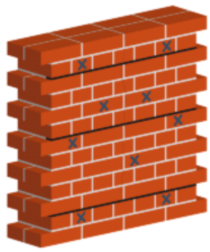


Figure 8.
Place of location of DF ties in model G

wall strengthening. In presented investigation the strengthening steel bars were located only in the one side of the wall. As a result the growth of the stiffness of this wall part with the co-relation to the other one is observed. Therefore, it the assumption was made, that ties perpendicular to the wall surface should prevent the axially compressed specimens from internal longitudinal cracks, which could appear as the result of the stiffness difference of the both external parts of tested wallette.

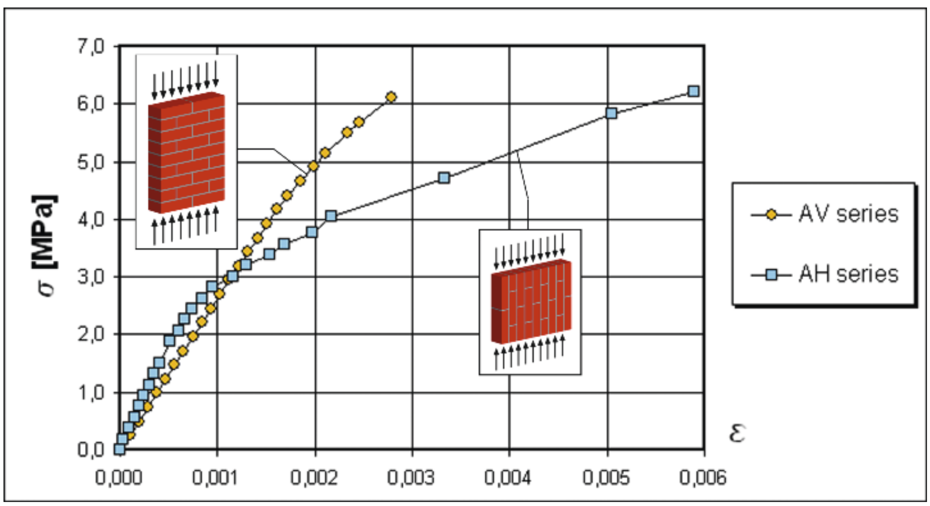


Figure 9.
The average σ-ε relationships determined for AV and AH series

achieved using three HB bars embedded in the mortar HB MM2 as shown in Fig. 6.

The methods of strengthening the samples in the **F** series, which include three elements, were close to the method used in the **E** series tests. The difference was that only two rods in a single bed joint were used. Additionally, double bars to maintain the standard conditions of mortar cover were embedded in the slots at the depth of about 60 mm.

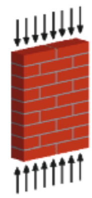
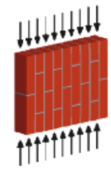
The last method of crack repair (only one model marked as **G** was tested) was also similar to the method used in the samples of the **E** series. However, in addition to the stitching rods 9 special DF ties were used fixed perpendicular to the surface of the masonry (see Fig. 8). Normally, the number of steel ties in case of masonry cavity or veneer walls should be not less than determined in computation (according to wind lateral loads) and not less than 5 in 1m^2 of the wall surface. There are not any detailed requirements for number of ties in case of cracked masonry solid

4. RESULTS OF INVESTIGATIONS

4.1. Material properties

Experimental average (calculated based on the results of 5 tested samples) values of material properties (compressive and flexural strength and modulus of elasticity if they were determined) obtained from investigations of clay solid bricks and general purpose cement-lime mortar (1 : 1 : 6) are presented in Table 2. The significant differences between values obtained from tests according to Polish national standards and European standards are visible, especially in case of compressive strength of masonry units. Former Polish national standards for determination of this strength were connected with the type of masonry units. Simply, for each type of masonry unit there was a separate standard. Moreover, the shape and overall dimension, as well as testing procedure were also different. Hence, the lack of the results compatibility was observed.

Table 3.
Compressive strength and modulus of elasticity of masonry – from tests according to EN 1052-1:1998 [13] regulations

Determined value	AV series	AH series	$\frac{\text{value}_{AH}}{\text{value}_{AV}}$
			
Compressive strength $\mathbf{f_c}$ [MPa]	6.2	6.1	0.98
Coefficient of variation v_f [%]	6.3	7.3	-
Modulus of elasticity $\mathbf{E_m}$ [MPa]	2620	3130	1.19
Coefficient of variation v_E [%]	14.7	9.1	-

Graphs of average values of σ-ε relationships for **AV** and **AH** series are shown in Fig. 9. The average values of compressive strengths obtained for both **AV** and **AH** series are very similar but deformation of the samples loaded in parallel to the plane of the bed joints is almost double. It was connected with first (sometimes not visible) vertical cracks appearance in case of specimens' compressed compatible with bed joints direction. But the ultimate value of the compressive stresses at failure was almost the same (the orthogonal ratio is 0.98) for both types of investigation – see Table 3 below, where the average values of compressive strengths and modulus of elasticity from the tests on the samples of type **AV** and **AH** are shown. Interesting is the fact, that modulus of elasticity of masonry wallettes compressed parallel to bed joint was ca.20% greater than determined for **AV** specimens.

4.2. Main investigations

All the tested samples in the **B** series cracked and deteriorated in a similar way. When 40÷50% of the maximum compressive stress was reached the first cracks in the samples started to appear. The cracks developed and combined under the influence of the increasing load until the sample got separated by vertical cracks into three or four individual posts.

Table 4 shows the average values of compressive strength and of the modulus of elasticity obtained from the investigations of the samples in the **B** and strengthened elements, while in Fig. 10 there is a comparison of σ-ε relationships for un-strengthened and un-cracked samples of the **AV** (standards specimens) and **B** (wallette specimens) series.

The stress-strain relationships for the samples of the series **B** and **AV** test specimens are almost identical. Greater carrying capacity of the samples of the **B** series can be explained due to the reduced influence of the slenderness ratio of these elements.

The mode of failure of the samples in the **C** series range (cracked but un-strengthened) was similar to the uncracked samples in the **B** series. Table 4 presents the values of compressive strength and of the modulus of elasticity which were obtained from investigations of the specimens in the analysed **C** series. Graphs of σ-ε relationships for the series of

Table 4.
Compressive strength and modulus of elasticity of models B, C, D, E, F series and G

Series	**Reinforcement**	**Cracked**	**Compressive strength f [MPa]**	**Modulus of elasticity E [MPa]**
B	Not	Not	6.8	2710
C	Not	Yes	3.5	1520
D	Yes	Yes	5.7	1940
E	Yes	Yes	5.7	2320
F	Yes	Yes	6.9	2180
Model G	Yes 1)	Yes	7.6	2250

1) – reinforced in bed joints and additionally introduced 9 perpendicular ties

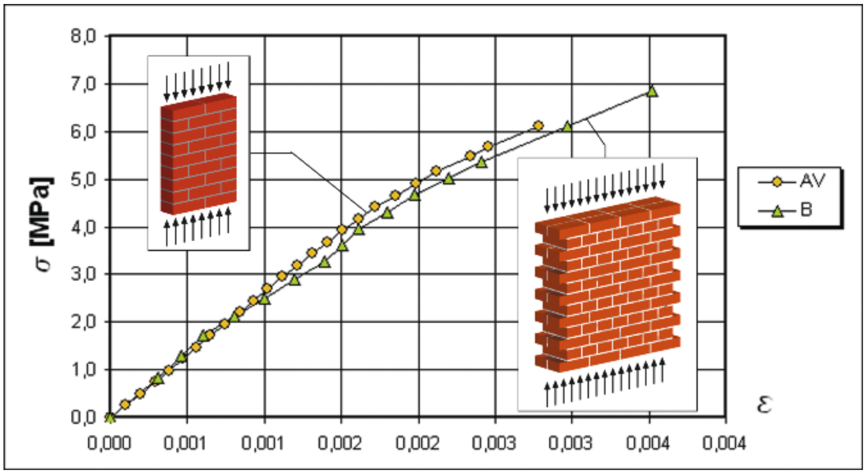


Figure 10.
Comparison of σ-ε relationships for un-strengthened and un-cracked samples

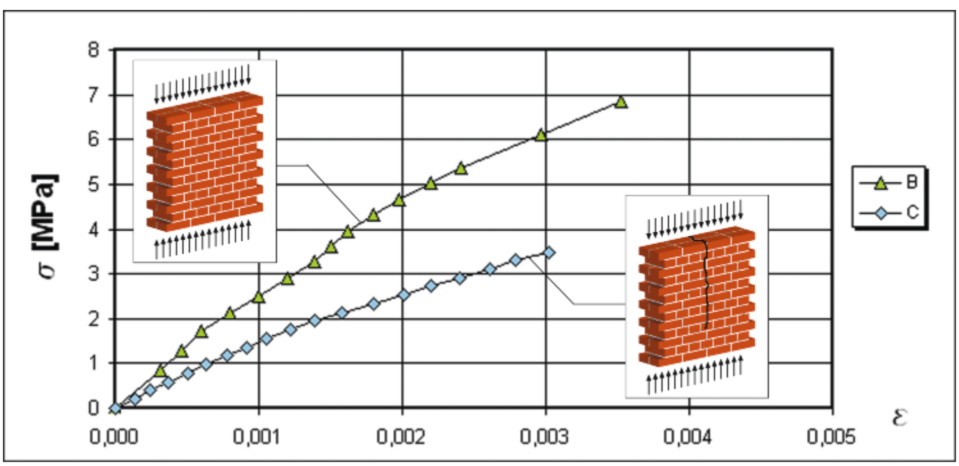


Figure 11.
The σ-ε relationships for the B and C series

Table 5.
Comparison of compressive strength and modulus of elasticity for all tested masonry wallettes

Series number / Parameter	Not strengthened elements		Strengthened elements			
	B	C	D	E	F	G
f_i / f_B	1	0.51	0.83	0.83	1.08	1.11
f_i / f_C	1.96	1	1.63	1.63	2.00	2.18
E_i / E_B	1	0.56	0.71	0.86	0.80	0.83
E_i / E_C	1.79	1	1.28	1.53	1.43	1.48

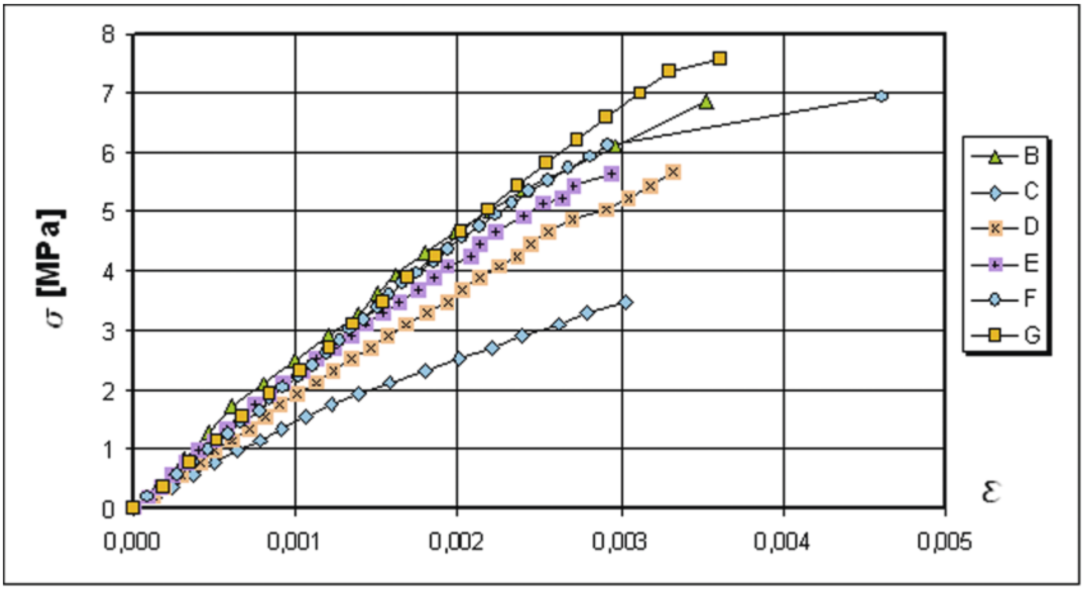


Figure 12.
The σ-ε relationships for models of all tested series

samples not cracked in series **B**, and cracked but unstrengthened in series **C** are shown in Fig. 11. Both average relationships have a curvilinear form. The stiffness of the cracked wallettes (**C** series) was about 40% lower than in of case non-cracked elements. Also the maximal deformation at failure (ε_u) was ca. 15% lower than obtained in compression tests of non-cracked masonry elements. As the effect of these situation a considerable difference was noted between the compressive strength and modulus of elasticity for samples cracked and uncracked. The values for the cracked samples were about half the uncracked samples.

The pattern of fine cracks in the reinforced samples of the **D**, **E** and **F** series was similar but completely different from the pattern of cracking in the unreinforced specimens of the **B** and **C** series. In the strengthened samples the failure always occurred in the internal joint across the brick headers (longitudinal internal crack). All the samples split into two separate panels (shields). Small perpendicular cracks occurred on the surface, which did not contain reinforcement while on the strengthened face there was no sign of cracking. That means that mode of failure was strongly dependent on the value of horizontal tensile stresses acting in perpendicular direction to the plane of the wallette. Applied reinforcement carried the horizontal tensile stresses that appeared according to Hilsdorfs' theory in plane of the specimens, but stresses acted in perpendicular directions are also high and much greater than tensile strength of the masonry in that same direction. As the effect, the failure caused by these stresses must demonstrate by dividing of the masonry wallette into two separate shields.

In order to eliminate the adverse crack down the internal joint across the headers, it was decided to include 9 transverse ties in the last sample (model marked as **G**). In this single sample, the failure also occurred along the internal joint in spite of including the ties. However incorporation of the ties made it possible to obtain the greatest compressive strength of all the test samples, e.g. over 30% greater than in case of specimens in E series, which were reinforced also with one ϕ6 mm HB bar in bed joints (see Fig. 6) but without ties. It was also noticed that the surfaces contained a greater number of hairline cracks than elsewhere.

5. RESULTS ANALYSIS

The average graphs of the σ-ε relationships for models of all series are shown in Fig. 12. From the comparison presented in this figure it can be seen, that the stress-strain relationship obtained for samples in the **D** series, strengthened with copper rods places oneself exactly among similar relationship to that obtained from the measurement of the un-cracked samples in the **B** series and the cracked samples in the **C** series. Use of this type of strengthening gives the positive effect from ultimate compressive stresses (compressive strength) point of view but is also con-

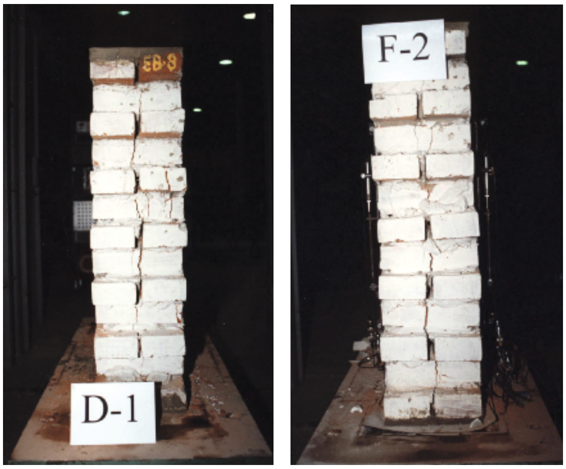


Figure 13.
Failure of D-1 and F-2 models

nected with the negative effect: change of the mode of failure from typical (set of vertical cracks) to not safe by division of the strengthened element by means of internal longitudinal crack into two separate parts.

Specimens strengthened with the use of the British technique produced evidence of similar properties to samples that were un-cracked. The stress-strain relationships obtained from the investigations of **E**, **F** and **G** models approximate to the graph for the samples in the **B** series (unreinforced and not-strengthened elements). Especially, the behaviour of masonry wallettes in F series (strengthened by means of 2 ϕ 6 mm HB rods in bed joints – see Fig. 6) was quite the same than in case of unreinforced and not-cracked specimens **B** series. As it was expected, the best results (the maximal strengthening effectiveness) was achieved for **G** model, which was additionally strengthened with 9 ties in perpendicular direction to the plane of the wall.

The comparison of compressive strength and the modulus of elasticity determined for all masonry wallettes in the entire programme is shown in Table 5. The most effective method of strengthening proved to be the use of stitching bars together with the transverse ties. The value of the measured compressive strength was about 10% greater than the compressive strength of the uncracked elements and more than twice the compressive strength of unreinforced, cracked masonry.

The results of the investigations of the **F** series samples do not look as good as the results of the **G** series sample. A 100% increase of compressive strength was obtained in relation to the cracked masonry, which compares to the compressive strength of the un-cracked masonry.

The average values of performance of the specimens of the D and E series are identical. Strengthening with the use of single rods gave a 60% increase of compressive strength in comparison to cracked masonry, which compares to 80% of the compressive strength of un-cracked masonry. In spite of the identical values of compressive strength under compression, the method of strengthening used in the models of the **E** series appears to be better providing a modulus of elasticity closer to the value of uncracked masonry.

Unfortunately, all strengthening methods using HB rods (including **G** model) also gave negative effect, as it was observed in case of **D** series models (reinforced by means of ϕ 6 mm rods), namely changing of the mode of failure from typical (set of vertical cracks) to dividing of the masonry wallette by means of internal longitudinal crack into two separate parts (Fig. 13). From safety point of view it is dangerous situation, because appearance of the internal longitudinal crack is not visible on the wall surfaces.

6. CONCLUSIONS

The problem of strengthening methods of cracked masonry walls is very important and still not well explained. In engineering practice there are some classical methods, as well as some new methods based on the modern material and technological solutions. Unfortunately, there are not detailed and precise requirements and regulations how effective such strengthening methods are, especially method based on the use of reinforcement placing in mechanically made slots in bed joints of existing, damaged (cracked) masonry wall.

Due to the limited scope of the preformed and presented tests, the investigations of the effectiveness of different methods of cracked masonry strengthening can only be indicative. To get the reliable results from the quantitative point of view the subsequent both experimental and theoretical works should be carried out.

However, on the basis of the test it can be stated that:

- Repair of cracks by means of stitching bars is an effective solution and, as presented, the investigations showed an increase of 60 to 100% of carrying capacity compared to the cracked masonry.
- The biggest increase of carrying capacity was obtained for specimens strengthened with HB

stitching bars in the bed joints and with DF transverse ties across the bricks.

- The average values of the elasticity modulus for reinforced masonry were 15% to 30% less then the values of modulus determined for un-cracked masonry.
- Additionally the use of stitching bars reduces crack formation in the masonry and is connected with significant increasing of ultimate strength.
- For masonry of thickness equal length of the one brick, all strengthening methods by means of stitches on one side gave only the negative effect, namely changing the mode of failure from typical (set of vertical cracks) to dividing the masonry wallette by means of internal longitudinal crack into two separate parts at failure.

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