The effect of cracks on the bearing capacity of masonry structures

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Summary. The research of the effect of different types of cracks in the elements on their bearing capacity according to the calculations by past and current codes – Building Regulations II-22-81 (SNiP II-22-81) and State Building Codes of Ukraine V.2.6-162:2010 (DBN V.2.6-162:2010) respectively, has been conducted. The effect of the three types of cracks in the masonry structures – through vertical (single, not the compressive overload ones), through horizontal and inclined ones along indents on the bearing capacity of masonry has been analyzed. The paper provides the numerical example in which the bearing capacity of the masonry pier in the initial state (before cracking) and after cracking has been analyzed according to the calculations by the above codes.

Key words: masonry structures, cracks, bearing capacity, central and eccentric compression, principal tensile stresses.

INTRODUCTION

Throughout Ukraine a large number of masonry buildings is erected and actively used. During the operation buildings receive different types of damages caused by numerous factors. The features of the negative effects on building structures and conditions of their non-destruction are specified in [1 – 3]. A more generalized research of the effects of typical defects and damages of masonry structures and buildings on their bearing capacity, conducted by the author, is described in [4].

In the publication [5] the author determined that one of the specific types of damages of masonry that affect the bearing capacity the most are cracks in the body and joints of structures. The research of the results of the inspection of a large number of buildings in Ukraine [6 – 10] has shown that a very substantial part of masonry buildings are subject to the occurrence of through vertical, inclined and horizontal cracks. The presence of these cracks in the structures undoubtedly negatively affects their bearing capacity and rigidity. This subject requires a research because it is necessary to assess the degree of reduction of the bearing capacity of the structure with cracks for a particular type of load. In the previous studies of this subject ([11 – 13]) the consideration of cracks when assessing the bearing capacity and seismic resistance of masonry structures is fragmented and (or) indirect (either too isolated or too general cases and indicators are considered) with the lack of clear systematization of their effects.

MATERIALS AND METHODS

The aim of the study the results of which are outlined in this paper is to determine, generalize and systematize the effects of cracks in the masonry structures on their bearing capacity.

The main method of the study is the analysis of the effect of cracking on the components of the formulas of the check of the masonry bearing capacity.

GENERAL PROVISIONS

The most crucial checks of the bearing capacity of masonry structures according to SNiP II-22-81 [14] are the checks of:

1) the eccentric compression;
2) the shear;
3) the principal tensile stresses.

As to the calculation by the current standards of Ukraine DBN V.2.6-162:2010 [15] adapted to Eurocode 6 [16] the essence of the eccentric compression and shear checks according to them remains. The main difference in the bearing capacity check between the past and current standards is that DBN V.2.6-162:2010 [15] has no analogues of the calculation of the principal tensile stresses for the unreinforced masonry. Instead DBN contains calculations for the bending check of the masonry.

Let us analyze the effect of the three types of cracks in the masonry structures – through vertical (single – not the compressive overload cracks), through horizontal and inclined ones along indents according to the above bearing capacity checks on the example of their formation in a pier.

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Single vertical through cracks (not the compressive overload ones). When a crack of this type appears, a solid section is divided into two separate parts. Therefore, when checking the bearing capacity of the element for the central and eccentric compression its separate sections are use instead of the solid one. The following formula is given for the calculation of the eccentrically compressed elements according to SNiP [14] (hereinafter all symbols are in accordance with [14]):

$$N \leq m_g \varphi_1 R A_c \omega. \qquad (1)$$

With the reduced cross-sectional area of the element the value of all the factors of the formula (1) will decrease, except for R (but it can also be reduced according to p. 3.11, *a* [14]). Thus, when the parts of the solid section are separated, the flexibility of the element λ and λ_c increases. This entails the reduction of values of the buckling factors φ and φ_c, and thus φ_1, which is the half of their sum.

The reduction of the compressed area A_c is evident at the reduced section.

The formula for determining the m_g factor contains the cross-sectional height h, which will be lower at the reduced thickness of the element, and the з factor, the value of which increases with the increase of the flexibility of the element λ.

However, the formula (1) contains a factor, the value of which increases with the decrease of the cross-sectional height h – ω factor, which takes into account the cage effect and is determined as $1+e_0/h$.

The following formula is given for the calculation of masonry for shear in the horizontal untied joints and the tied joints for the rubble masonry according to SNiP [14]:

$$Q \leq (R_{sq} + 0{,}8 n \mu \sigma_0) A. \qquad (2)$$

Similarly to previous check the design cross-sectional area A and its compressed part A_c (with decreasing of the cross-sectional height) will reduce (however the proportion of the shear force on the isolated area will reduce as well), but the value of the average stress from the compressive force σ_0 will slightly increase. A significant reduction in the total bearing capacity of the general pier from two separate parts is not expected.

The following formula is provided for the calculation of the elements for the principal tensile stresses according to SNiP [14]:

$$Q \leq \frac{R_{tq} A_c}{\nu} \qquad (3)$$

The formula of determining R_{tq} contains the multiplier σ_0 – the average stress of the compressive force, the influence of which is similar to the shear verification of the masonry, so at the decrease of the design cross-sectional area A_c we obtain a slight increase in the value of the design resistance R_{tq}, that is offset by an expected decrease in the size of the value of A_c itself (with decreasing of the cross-sectional height).

Horizontal through cracks. With the presence of this type of cracks when verifying the masonry of the eccentric compression there are certain features for the determination of the ω factor, which takes into account the cage effect. In this case the part of the section A_c in the limit state works with the same stresses equal to the local compression (crushing) strength limit R_c [17, 18]. For the masonry of small stones outside the ratio between the breaking points of the crushing and the compression is:

$$\frac{R_c}{R} = \sqrt[3]{\frac{A}{A_c}} \qquad (4)$$

It follows from the above and further transformations that in this case the ω ratio can be determined by the formula:

$$\omega = \sqrt[3]{\frac{A}{A_c}} \qquad (5)$$

When checking the masonry for shear according to the formula (2) the value of its respective design resistance R_{sq} in the section with a horizontal crack will be equal to zero due to the lack of adhesion between the parts that are shifted relative to each other. Only the second member of the formula (2) which is responsible for the friction forces will be involved in the check.

When checking the masonry for the principal tensile stresses its cleavage along the inclined indent is analyzed. When the cleavage of the masonry with a horizontal crack occurs, in the place with a crack along which the cleavage indent passes there is no contact between chipping parts. Therefore, when this check of the masonry is performed, it is advisable to exclude the area with the width of a brick size on which the cleavage indent coincides with the crack from the design area A_c. The maximum value of the width of the excluded area corresponds to the maximum size of a brick of 250 mm.

Cracks along inclined indents. In the case when the masonry with this type of crack is subject to the eccentric compression on the area of the design section of the masonry where a part (step) of the indent passes, there is no adhesion and normal contact between the parts of the element separated by a crack. Therefore, when calculating the masonry for the eccentric compression it is necessary to use the weakened cross-sectional area A_c with the reduction of the design resistance by 25% in the area with the width of a brick size where the crack indent passes along the design section (up to 250 mm).

The determination of the ω factor in the situation of the inclined crack does not change and is conducted according to the provisions of [14].

When the masonry element with an inclined crack is subject to the shear there is a similar effect as for the eccentric compression. In this case the design area A_c should be weakened by excluding the area of the design section of a brick size (of the width up to 250 mm) in which there is no contact between the parts of the element.

When the principal tensile stresses act in the masonry with an inclined crack its cleavage resistance R_{tq} is equal to zero since the resistance in the indent of both components R_{tw} (tensile and shear at tension) is equal to zero:

$$R_{tq} = \sqrt{R_{tw}(R_{tw} + \sigma_0)} = 0 \text{ при } R_{tw} = 0. \quad (6)$$

However, if a vertical compressive stress is detected in the respective area along the indent (for example, when calculating in the software), the shear resistance will not be equal to zero at the action of friction forces and it can be estimated by the formula (2).

THE EFFECTS OF CRACKS ON THE BEARING CAPACITY OF MASONRY STRUCTURES ACCORDING TO THE CALCULATIONS BY DBN V.2.6-162:2010

Concerning the checks of the bearing capacity according to DBN V.2.6-162:2010 [15], the calculations and the effects of cracks are quite similar to those performed according to SNiP II-22-81 [14], except for the absence of the consideration of the principal tensile stresses and the existence of the bending check. The absence of the first check in the current standards is a disadvantage because under certain specific effects (including seismic ones) the destruction often takes place at the principal tensile stresses (cross inclined cracks). However, the conventional analogue in DBN is the bending check of the masonry (p. 11.3.1 [15]). Let's estimate the effect on the results according to the calculation by DBN V.2.6-162:2010 of the presence of 3 types of cracks considered above.

Vertical through cracks. This effect is taken into account in a similar way as according to SNiP [14]. The following formulas are provided for the calculation of elements under the vertical, shear and bending loads respectively according to DBN [15] (hereinafter all symbols are in accordance with [15]):

$$N_{Ed} \leq \Phi\, t\, f_d. \quad (7)$$

$$V_{Rd} \leq f_{vd}\, t\, l_c. \quad (8)$$

$$M_{Ed} \leq f_{xd}\, Z. \quad (9)$$

Similarly to SNiP [14] if there is a vertical crack, the calculation of the separate sections is performed as well, and in the result the values of the respective factors in the formulas (7), (8) and (9), such as the flexibility and eccentricity factor Φ, the length of the compressed part of the wall l_c and the resistance moment Z experience significant losses.

Horizontal through cracks. When performing the calculations according to DBN [15] the horizontal crack is taken into account in the checks for central, eccentric compression and shear in the similar way as for SNiP [14]. In the bending check by the formula (9) the bending strength of the masonry f_{xd1} will be equal to zero since there are no connections between the separated parts, therefore only the component of the bending resistance from the compressive stresses remains and this formula will have the following form:

$$M_{Rd} = \sigma_d Z. \quad (10)$$

Cracks along inclined indents. An inclined crack is taken into account in the central and eccentric compression checks in the similar way as for SNiP [14]. If the element experiences the shear load, then the resistance to the horizontal force on the area of a brick size along which the crack indent passes must be equal to zero. However, if there are compressive stresses on the horizontal areas of the indent, the residual strength of the horizontal force is present because of the friction forces in these areas. In the case of a bending load the bending resistance in the horizontal section will not reduce significantly.

The assessment of the effect of cracking in the material of structures on the reduction of the power consumption and plasticity of a structural system with a possible corresponding increase of the damage tolerance factor k_1 according to DBN [19] requires a separate consideration and research.

AN EXAMPLE OF DETERMINING THE EFFECT OF CRACKS ON THE BEARING CAPACITY OF THE MASONRY PIER

To understand the effect of cracks on the bearing capacity of the element we analyze the bearing capacity of a brick pier with the sizes of 0,51×0,77×2,8 m before and after the formation of cracks of the foregoing types. The pier is built of bricks with the sizes of 0,25×0,12×0,065 m. The calculation for the effect of vertical and horizontal forces was performed according to the past codes SNiP II-22-81 [14] and the current ones DBN V.2.6-162:2010 [15]. The cases of the central (e = 0) and eccentric (e = 0,17h = 0,131 m – the eccentricity is on the border of the cross-sectional core) application of the vertical compressive force are considered. Vertical, horizontal and inclined cracks were taken into account according to the foregoing principles. The dimensions of the separated sections for the calculation with consideration of vertical cracks are taken as 0,51×0,46 m and 0,51×0,31 m.

The results of the calculation are presented in Tabs. 1, 2 and graphically in Figs. 1, 2. The following designations are used in this tables: N_u, N_{Rd} – the initial bearing capacity of the pier for the vertical force; N_{u1}, N_{Rd1} – the bearing capacity for the pier with a crack of the vertical force; Q_u, V_{Rd} – the initial bearing capacity of the pier for the horizontal force; Q_{u1}, V_{Rd1} – the bearing capacity of the pier with a crack for the horizontal force; $k_N = N_{u1}/N_u$ (N_{Rd1}/N_{Rd}) – the reduction factor of the bearing capacity for the vertical force; $k_V = Q_{u1}/Q_u$ (V_{Rd1}/V_{Rd}) – the reduction factor of the bearing capacity for the horizontal force.

It be seen from the results of the calculation that the greatest loss of the bearing

Table 1. The bearing capacity of the masonry pier before and after the crack formation (according to SNiP II-22-81 [14])

The crack type	N_u, kN	N_{u1}, kN	k_N	Q_u, kN	Q_{u1}, kN	k_V
The cenrtal compression						
Vertical	571,5	440,42	0,771	108,44	96,37	0,889
Horizontal		571,5	1		76,85	0,709
Inclined		525,11	0,919		0	0
The eccentric compression						
Vertical	441,22	157,1	0,356	76,94	32,3	0,42
Horizontal		433,13	0,982		46,52	0,605
Inclined		405,41	0,919		0	0

Table 2. The bearing capacity of the masonry pier before and after the crack formation (according to DBN V.2.6-162:2010 [15])

The crack type	N_{Rd}, kN	N_{Rd1}, kN	k_N	V_{Rd}, kN	V_{Rd1}, kN	k_V
The cenrtal compression						
Vertical	528,56	452,58	0,856	168,54	153,35	0,91
Horizontal		528,56	1		79,28	0,47
Inclined		485,66	0,919		139,56	0,828
The eccentric compression						
Vertical	379,25	169,46	0,447	89,78	34,73	0,387
Horizontal		379,25	1		36,99	0,412
Inclined		348,47	0,919		72,64	0,809

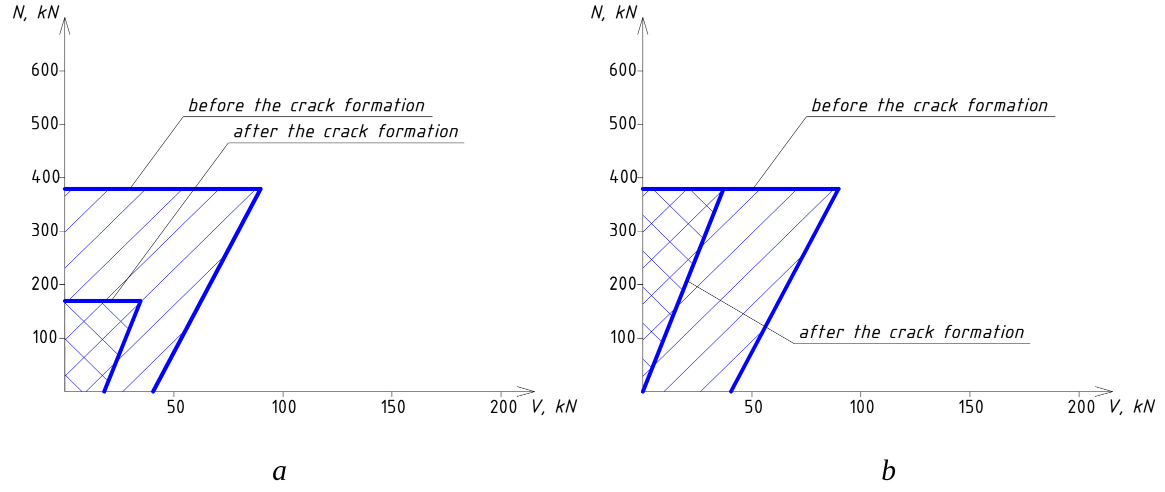

Fig. 2. The graphs of limits of the bearing capacity of the masonry pier before and after the crack formation at the eccentric compression (according to DBN V.2.6-162:2010 [15]): *a* – of a vertical crack, *b* – of a horizontal crack

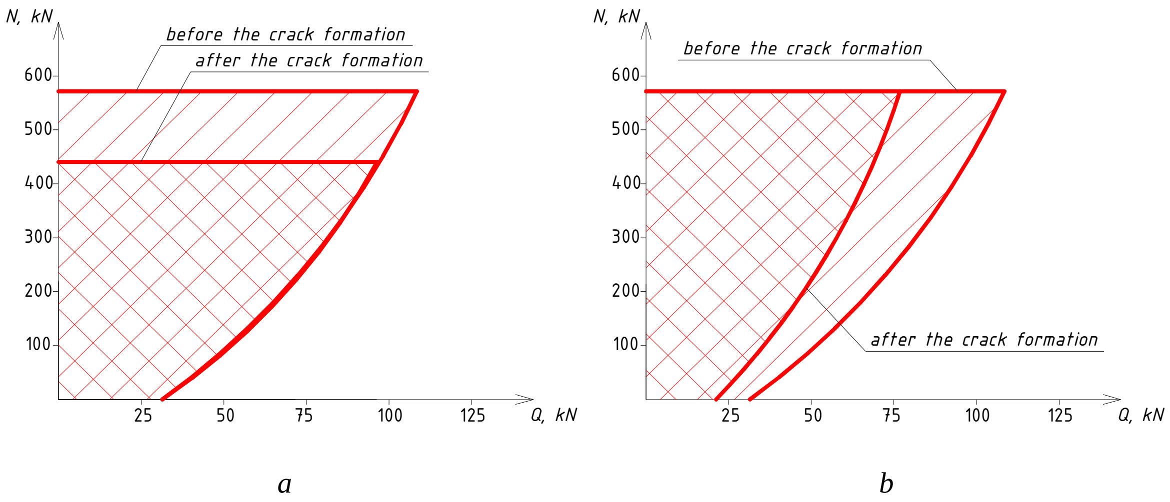

Fig. 1. The graphs of limits of the bearing capacity of the masonry pier before and after the crack formation at the central compression (according to SNiP II-22-81 [14]): *a* – of a vertical crack, *b* – of a horizontal crack

capacity occurs at the eccentrically applied compressive force when there is a vertical through crack (k_N = 0,356, k_V = 0,42 according to SNiP II-22-81 [14], k_N = 0,447, k_V = 0,387 according to DBN V.2.6-162:2010 [15]). This is due to the rapid reduction of the compressed area in both separated parts and a great flexibility in a smaller separated part (with the cross-sectional sizes of 0,51×0,31 m).

A significant loss of the bearing capacity for the shear force also occurs when there is a horizontal crack at the calculation by DBN [15] (k_V = 0,47 at the central compression, k_V = 0,412 at the eccentric one) since in this situation the shear bearing capacity does not include the adhesion force between the separated parts and the friction force is reduced due to the reduction of the maximum compressive stress, which occurs at the decrease of the compression bearing capacity.

Since based on the analyzed provisions regarding the presence of an inclined crack in a masonry element and formula (6) we obtain that when calculating the strength for the principal tensile stresses according to SNiP II-22-81 [14] the cleavage resistance R_{tq} of the masonry is equal to zero, we have that according to these standards the strength for the shear force is equal to zero (Q_{u1} = 0) when there is an inclined crack in the section.

A through horizontal crack does not affect the bearing capacity for the central compression (according to SNiP [14]) and the central and eccentric compression (according to DBN [15]). The slight reduction of the bearing capacity for the eccentric compression according to SNiP [14] occurs due to the effect of the clarified ω factor, which takes into account the cage effect.

Thus, the cracks in the masonry structures and buildings can be taken into account directly and comprehensively when checking their bearing capacity by means of the above approaches.

CONCLUSIONS

In the results of the studies outlined in the paper we can make the following conclusins:

1. The main differences in the chekcs of the bearing capacity between the past and current standards are that DBN V.2.6-162:2010 [15] has no any analogues of the calculation of the principal tensile stresses for the unreinforced masonry.

2. The vertical, through horizontal and inclined cracks in the masonry structures and buildings can be taken into account directly and comprehensively when checking their bearing capacity with the help of the approaches outlined in the paper. The considered methods of taking into account cracks should be further verified by performing the appropriate physical experiments.

3. The greatest loss of bearing capacity 3.The greatest loss of bearing capacity occurs at the eccentrically applied compressive force with the existence of a vertical through crack (k_N = 0,356, k_V = 0,42 according to SNiP II-22-81 [14], k_N = 0,447, k_V = 0,387 according to DBN V.2.6-162:2010 [15]). This is due to a sharp decrease in the area of compressed zones in the two separate parts and a great flexibility in a smaller separated part

4. A significant loss of the bearing capacity of the element of the transverse force is traced at the existence of a horizontal crack according to the calculation by DBN [15] (k_V = 0,47 at the central compression, k_V = 0,412 at the eccentric one) as in the bearing capacity of the shear in this situation the adhesion strength between the separated parts is completely absent and the friction force is reduced due to the reduction of the maximum compressive stress, which occurs at the decreasing of the bearing capacity of the compression.

5. With the existence of an inclined crack there is no strength of the transverse force in the section of the element (Q_{u1} = 0) as when calculating the principal tensile stresses strength according to SNiP II-22-81 [14] the cleavage resistance of the masonry R_{tq} is equal to zero.

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ВЛИЯНИЕ ТРЕЩИН НА НЕСУЩУЮ СПОСОБНОСТЬ КАМЕННЫХ КОНСТРУКЦИЙ

Аннотация. Исследовано влияние различных видов трещин в элементах на их несущую способность, согласно расчетам по прошлым (СНиП II-22-81) и действующим нормам (ДБН В.2.6-162: 2010). Проанализировано влияние трех вариантов трещин в каменных конструкциях – вертикальных сквозных (одинарных, не от перегрузки на сжатие), горизонтальных сквозных и наклонных по штрабе – на несущую способность каменной кладки. Приведен численный анализ несущей способности каменного простенка в начальном состоянии (до образования трещин) и после образования трещин, согласно расчетам по вышеуказанным нормативным документам.

Ключевые слова: каменные конструкции, трещины, несущая способность, центральное и внецентренное сжатие, главные растягивающие напряжения.