CRITERIA FOR EVALUATION OF MASONRY-STRUCTURE BEHAVIOUR IN MINING AREAS

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Abstract

Adequate defining of forecast effects caused by the mining area curvature requires processing the standards of the masonry resistance to shear deformations obtained on laboratory models to criteria of the strain-resistance, applicable to the real, mining deformed wall-structure. That problem is analyzed in chapters 2 and 3, where the elastic-plastic-damage model (Barcelona Model) is used as a basic numerical model.

We can see the masonry strain-resistance as a value measured by the modulus *G* – strongly dependent on introduced boundary conditions, where functions of *G*-decreasing are numerically obtainable in an easy way. For analyzed system building-mining deformed subsoil, a proposition of the mining subsoil modulus C^{MCC} was given, where value of a real cooperation zone for building and subsoil is estimated on the basis of the Modified Cam-clay model. Inelastic analyses of the wall object lead to statement – areas where the stress state, produced by the increasing mining deformations, satisfy the equations of the initial plastic surface (that in turn generate masonry degradation) arise and develop according to areas of the critical value of principal strains ε_I, obtained in elastic model. For large strains however, the elastic analysis will overstate resistance category of the subject structure.

Streszczenie

Wiarygodne określenie efektów oddziaływania krzywizny terenu na rzeczywisty obiekt budowlany wymaga określenia odpowiednich kryteriów odporności odkształceniowej rzeczywistej konstrukcji ścianowej (rozdziały 2 i 3 pracy). Autor analizował kolejno: 1) skuteczność stosowania niesprężystego modelu konstytutywnego w odtwarzaniu badań laboratoryjnych ścinania, 2) wyznaczył numerycznie funkcje degradacji sztywności muru w procesie ścinania realizowanego w badaniach laboratoryjnych oraz w procesie czystego ścinania, 3) przedstawił model obliczeniowy układu konstrukcja-podłoże górnicze, wprowadzając propozycję modelu podłoża górniczego wyrażonego wielkością modułu C^{MCC}, wykorzystującego określoną wcześniej wielkość obszaru współpracy konstrukcji z wyginającym się podłożem górniczym. Analizy niesprężyste wydzielonej z obiektu ściany prowadzą m.in. do stwierdzeń: obszary, w których naprężenia spełniają równania początkowej powierzchni plastyczności i wywołują przy dalszych deformacjach degradację materiału powstają w miejscach krytycznych wartości odkształceń ε_I, zgodnych, do określonego poziomu odkształceń z obszarami wyznaczanymi w modelu sprężystym. Przy znacznych natomiast odkształceniach postaciowych analiza sprężysta będzie nieprawidłowo zawyżać ocenę kategorii odporności badanego obiektu budowlanego.

Keywords: **Mining areas; Mining subsoil; Mining activity effects; Masonry structure behaviour; Plastic-damage material model; Masonry-resistance to shear deformations; Category of objects-resistance.**

1. INTRODUCTION

According to the nowadays standards it needs to be stated, that for the right evaluation of a masonry-structure behaviour the numerical analyses with advanced constitutive models are required. In opposite to that statement, even if building is running a risk of damages because of irregular vertical ground displacements (e.g. mining generated), the non-linear analyses are not in a common use in the engineering practice.

Effects that appear in the mining-deformed building structure are usually evaluated in two different ways. Classical way (1) uses calculation systems based on structure mechanics methods [1, 2]. Numerical way (2), basing on the MES-models, uses linear-elasticity equations, both for a structure and for subsoil.

Generally, the following mining activity effects should be analysed separately – in accordance with [3, 4]:

– out of plumb deflection of the building objects (T_b), caused by the mining area deflection,
– non-dilatational strain angle for structure (θ_b), that corresponds to its local shear – deformation, caused by the mining area curvature, and
– width of the cracks (a_w) – taken into account for the existing buildings, mining deformed.

Therefore, as a measure of the wall structure effort resulting from mining flexure, one should consider ([3]) its local shear deformations – Fig. 1.

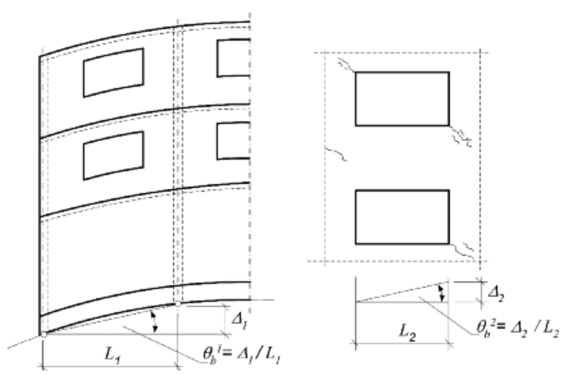


Figure 1.
Fragment of mining deformed wall

According to [5], the evaluation process of the cracks or damage-hazard for the wall-structure requires (equation (1)) that a specified allowable value (θ_b) will not be exceeded.

$$\theta_b^{\text{calculated}} \leq \theta_b^{\text{allowable}}, \tag{1}$$

where: $\theta_b^{\text{allowable}}$ – given out in [5].

Author of the item [6] rewrote condition (1) to form (2)

$$\theta_{Sd} \leq \theta_{adm}, \tag{2}$$

where: θ_{Sd} corresponds to $\theta_b^{\text{calculated}}$ from (1) – identified for the laboratory masonry-models (or numerical ones) as a local-obtained value of the non-dilatational strain ε_{12}, θ_{adm} – e.g. laboratory-determined, corresponds to $\theta_b^{\text{allowable}}$ from (1).

The study [6] gives out functions τ_i- θ_i (shear stress – non-dilatational strain values) for different masonry models subjected to the "constrained" shearing in direction perpendicular to bed joints. The $\theta_{cr,i}$ values (according to values $\tau_{cr,i}$) recorded during the first cracks formation allowed the evaluation of the θ_{adm} values (Fig. 3. chapter 2).

The above functions τ_i- θ_i can be called "masonry model strain-functions" specifying the masonry resistance to shear deformations being forced in a specific way.

Now we want to determine effects caused by the mining area curvature in the real wall-structure object in relation to assumptions provided in [5] and laboratory tests results [6].

Adequate defining of the above effects requires, in author's opinion, processing the standards of the masonry-resistance to shear deformations obtained on laboratory models to criteria of the strain-resistance, applicable to the real mining deformed wall-structure.

That problem is analyzed in following chapters, where the elastic-plastic-damage model, (Barcelona Model) is used as a basic numerical model [7, 8, 9].

2. MASONRY MODELS INVESTIGATIONS DESCRIBING THE NON-DILATATIONAL STRAIN-RESISTANCE

It is acknowledged that the reliability of evaluation of the Serviceability Limit State for building structure subjected to subsoil deformations (e.g. the repeated mining generated ones) is strongly connected with the appropriate strain state assessment.

The non-dilatational strain angle θ_b values – recommended in mining areas as the admissible ones for particular operation state PSGU [10, 11, 12] – result from the:

– In situ observations which have been carried out for buildings existing in mining deformed areas, and
– Laboratory investigations for masonry models subjected to some selected states – initial stresses σ_v and boundary vertical displacements, in accordance with vertical displacements of the mining deformed wall [6].

Attempts trying to correlate the above and outcomes of the numerical simulations have not been satisfying so far, and the reasons are as follows:

- Description of the material constitutive relations, and
- Non-adequate formulation of the structure-subsoil interaction problem.

So far the developed heterogeneous masonry models have not been used for engineering analyses, mainly because of the lack of reliable parameters required for them.

Obviously, description of the masonry by means of an isotropic model – e.g. by the elastic-plastic-damage model used here called further e-p-d model – carries many simplifications introduced to its real behaviour.

In author's opinion, carried out investigations regarding application of the e-p-d model for analyses of masonry structures can be used to justify that some simplifications are acceptable – e.g. [13÷19].

Procedure for numerical reproducing in e-p-d model of the shear-tests carried out on masonry laboratory-models [6] was presented in details in items [17, 18, 20].

Results of the parametrical tests have confirmed the e-p-d model as being able to assess the effort and degradation state for masonry wall-structures on vertically deformed subsoil.

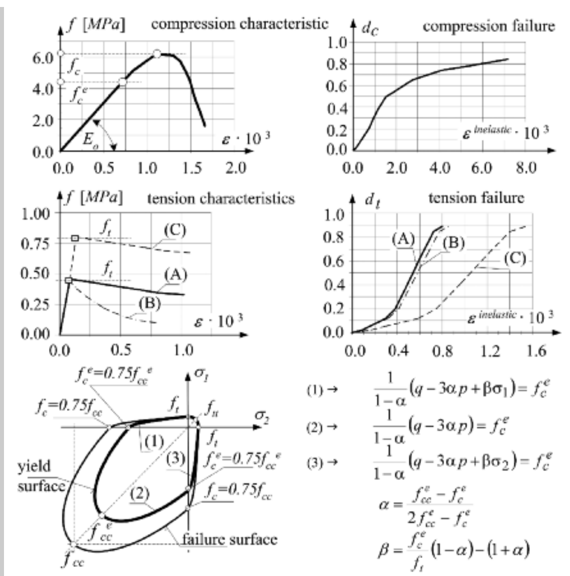


Figure 2.
Brief description of elastic plastic-damage model (e-p-d)

To make tracing of the following analyses possible Fig. 2 presents general description of the e-p-d model for masonry as:

- compression and tension characteristics,
- degradation curves for compression and tension, and
- an initial yield surface with strain hardening character of the twofold-mechanism.

Let's now compare possibility of recording phenomena related to the process of models shearing of masonry fragments:

1) for laboratory investigations – Fig. 3a (in accordance with [6]), and
2) for numerical tests, reproducing the laboratory ones – Fig. 3b.

For (1) changes are recorded – non-dilatational strain angle θ_i as a function of the increasing shear stress τ_i (for different vertical compression-stresses $\sigma_{c,i}$). A range of the measured critical values ($\theta_{cr,i}$, $\tau_{cr,i}$) that corresponded to cracks widths of 0.1÷0.3 mm was marked symbolically in Fig. 3a.

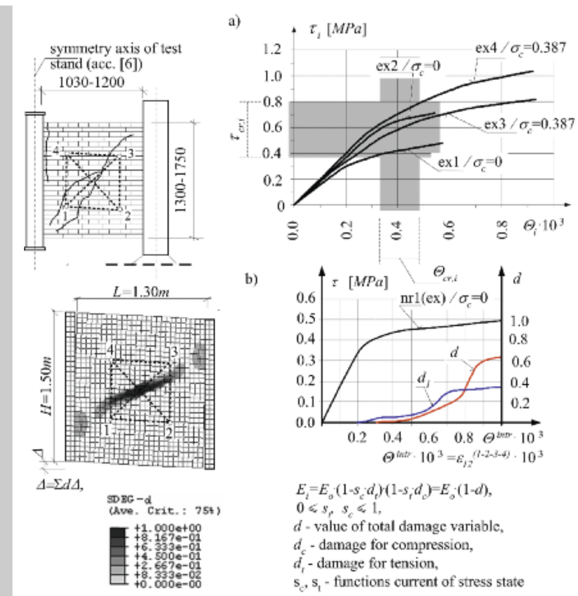


Figure 3.
a) Sheared masonry-model and τ_i- θ_i functions (according to [6]), b) numerically reproduced shearing masonry test

For (2) functions τ_i- $\theta_{intr,i}$ (as the numerical reproduction τ_i- θ_i from Fig. 3a) are accompanied by areas of the arising material degradation. Figure 3b shows as an example numerically obtained function $nr1(\mathrm{ex}1)/\sigma_c=0$ (in accordance with $\mathrm{ex}1/\sigma_c=0$ in Fig. 3a). Process of the material degradation that arises with incrementally forced shear deformations of a model (realized by $d\Delta$-value increase) is illustrated twice: by function of degradation d – related to the zone of measurements (1-2-3-4), and by function $d1$ that presents the average degradation for the all degraded zones of a model.

Functions τ_i-θ_i with their initial angle α_i, as well the characteristic obtained values $\theta_{cr,i}$ – for laboratory tests and degradation d – for numerical tests, are strongly boundary conditions-dependent (so they are dependent on constrained-shearing conception).

That statement is significant, if we want to assume that the above relations determine masonry-resistance to shear deformations.

The following comparisons have been carried out on a little geometrically simplified model – Fig. 4a. To make numerical results a measure-base independent, the θ_{intr}-recording have been replaced by the forced increments $d(\Delta/L)$-recording; where Δ/L meet a value θ_b [3, 5].

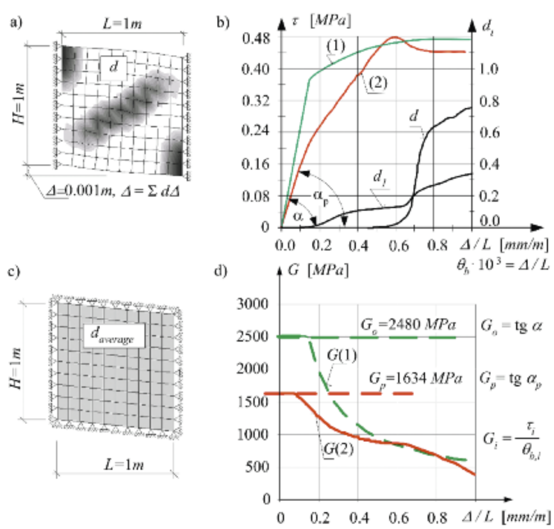


Figure 4.
a) Numerical model for constrained shearing, b) functions τ_i-Δ/L for pure and constrained shearing, c) model for pure shearing, d) modulus G degradation

Fig. 4b presents two functions τ-Δ/L: pure shearing – (1), and constrained shearing – (2). For constrained shearing (2) the increasing degradation process was traced by function: d – related to four central elements of the model, and $d1$ – that presents an average degradation for the all degraded areas. We can see that the initial masonry strain resistance for (2), measured by the modulus G_p, is dependent on introduced boundary conditions and its value is lower than the value of the pure shear modulus G. Effect of the incrementally forced shearing can be seen as the arising material rigidity degradation and modulus G degreasing. Numerically obtained functions of the G-degradation are presented in Fig. 4d in succession: (1) – function for the pure shearing (in accordance with model in Fig. 4c), (2) – function for the constrained shearing (in accordance with model in Fig. 4a).

3. MASONRY-WALL STRAIN RESISTANCE AND RESISTANCE OF THE MASONRY MODELS. CONCLUSIONS

The type of the building object induces an equivalent reaction of the mining-deformed subsoil on that object.

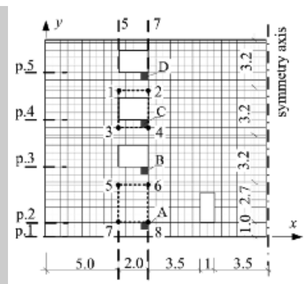
Therefore it is possible for a given object, according to the forecast effects of mining, to consider the reaction D [10, 11] as a constituent of the deformation state arising in the beside-surface rock-mass layer (here defined as a mining subsoil).

Resistance of building structure to the reaction D impact means such value of D_o of this impact whose exceeding will result in exceeding of specified limit state. In some cases the above may apply to Ultimate Limit State, providing the building safety, or to Serviceability Limit State, providing that buildings are serviceable [10, 11].

Introducing the Transit Serviceability Limit State (PSGU) for buildings in mining areas allows mitigation of the usability criteria of the Serviceability Limit State.

Therefore in accordance with [5] it is advisable to carry out individual analysis – to determine acceptable deformation values for a building structure; those are θ_b or a_w values.

Considerations on shearing of the masonry models, presented in the previous chapter, led to definition – masonry shear-resistance, or masonry strain-resistance for the constrained shearing.



Linear-elastic model, $R_t = 6km$:

	$\Delta_v(5\text{-}7)[m]$	$\theta_b \cdot 10^3$	$\varepsilon_{12} \cdot 10^3$ (A-D)
p.5	0.00080	0.40	0.14
p.4	0.00087	0.44	0.17
p.3	0.00083	0.42	0.13
p.2	0.00062	0.31	0.12
p.1	0.00063	0.31	—

Figure 5.
Meshed wall-model and some selected strain-result θ_b and ε_{12} for elastic solution

Let's extend the above experiments determining the mining-effect values for a wall-structure. The wall analyzed beneath (Fig. 5÷8) was isolated from a building structure protected against mining-effects for the III category of mining deformations.

For that wall adequate strain-analysis for reaction $D=R_t=6\,km$ will be carried out, where value $R_t=6\,km$ corresponds to extreme radius-value of mining area curvature for the III category of mining deformations.

The following was used for the building-mining subsoil system (B)-(P_g):

- For subsystem (B) – masonry wall model enabling intermediate consideration of transverse walls and floors impact, where $E=E_0=6200\ MPa$ (obtained in accordance with PN-B-03002:1999 for $f_b=20\,MPa$, $f_m=10\,MPa$, $\alpha_c=1000$) for masonry wall, for concrete (continuous footing, lintels and wreaths) $E=30500\,MPa$.
- For subsystem (P_g) – subsoil parametrical model with corrected modulus of subgrade reaction $\mathbf{C}^{MCC}$, basically based on classical engineering procedure [2] but simultaneously taking advantage of the critical state model (Modified Cam-clay model) allowing for the real co-operation range – h_g, building-mining subsoil [21, 22]; $C^{MCC}=E/(3\,(1\text{-}\nu)\cdot h_g)=31\,kN/m^3$. The real co-operation range $h_g=1{,}5\cdot h_1$ (which results from the foundation framework geometry – continuous footings spacing $L_H>6\,m$ as well as continuous footing width under considered longitudinal wall $h_1=0{,}6\,m<1\,m$, with spacing of perpendicular continuous footings $L_B=10\,m$).

Figure 5 presents the analyzed, FEM-meshed, wall model (with symmetry axis) where the following are marked:

1) horizontal sections (p.1÷p.5) and vertical (5, 7) – used for location of the analyzed non-dilatational strain angles $\theta_b=\Delta_v/L$, provided on the right hand-side of the Fig. 5;

   where: in accordance with [23, 24] $\theta_b^{\text{allowable}}=0.0004$, and in accordance with [3] $\theta_b^{\text{PSGU}}\leq 0.001$,
2) elements (A, B, C, D) – in which numerical values of the non-dilatational strain ε_{12} are read out (right hand-side of the Fig. 5),
3) areas (1-2-3-4) and (5-6-7-8) of the mining deformed wall, analyzed in Fig. 7.

Conclusion 1. In linear-elastic solution (for $R_t=6\,km$) we have received "signals" that masonry strain-resistance in some local zones of the wall was used up – $\theta_b\approx\theta_b^{\text{allowable}}$ – Fig. 5 (chart on the right hand-side); whereas values of the non-dilatational strain 12 are not useful for searching or prediction of the masonry damage or cracks zones.

Figure 6 presents continuation of the linear-elastic analyses – chart of the principal tensile strains 1, for values bounded by inequality given in figure.

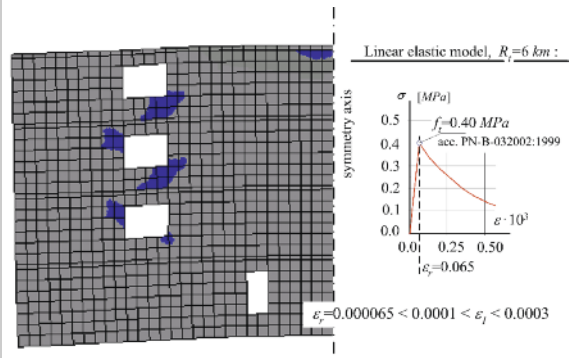


Figure 6.
Chart of the principal tensile strains ε_1 for values bounded by given inequality

Conclusion 2. Zones of principal tensile strains ε_1 determined in the elastic analysis as the ones which meet a condition of $\varepsilon_1\geq\varepsilon_r$ (where r is the standard value of deformation related to masonry wall tensile strength) turn out to be a good indicator of possible cracking zones – see material degradation zones in Fig. 8.

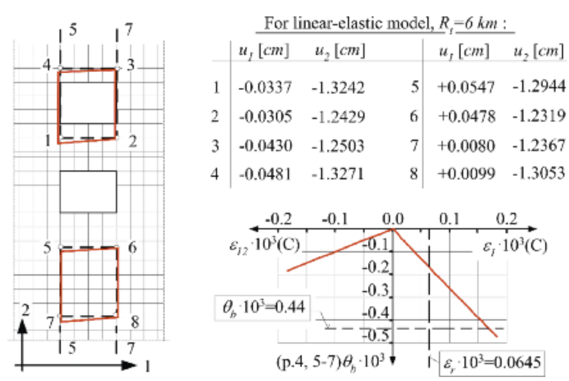
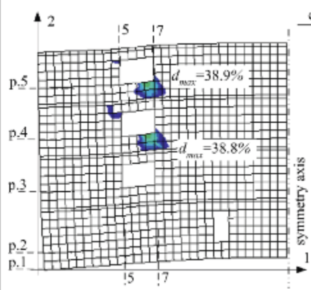


Figure 7.
Deformations of two selected zones (from Fig. 5) and chart of strains in selected point C

Fig. 7 presents the deformed zones (1-2-3-4) and (5-6-7-8) distinguished in Fig. 5. Their shear-like forms meet the forced deformations for models investigated in chapter 2. Chart presented on the right hand-side of the Fig. 7 shows (for element C from Fig. 5) values ε_1 and ε_{12}, increasing together the with increase of the non-dilatational strain angle θ_b (localized: p. 4, 5÷7).



elastic plastic-damage model, R_t =10 *km*:

	Δ_y(5-7)[*m*]	$\theta_b \cdot 10^3$	$\varepsilon_{12} \cdot 10^3$ (A-D)
p.5	0.00071	0.36	0.33
p.4	0.00075	0.37	0.44
p.3	0.00062	0.31	0.18
p.2	0.00043	0.21	0.08
p.1	0.00043	0.21	—

$d \cong d_t = 38.9\%$

Figure 8.
Degradation zones accompanied with tension in masonry wall for R_t=10 *km*.

These above analyses have been extended to the developed analysis carried out on the elastic-plastic-damage model e-p-d (see chapter 2). Fig. 8 presents zones of the masonry degradation produced by tensile stresses.

Conclusion 3. The wall zones in which stress states satisfy (at appropriate wall deformation) equation of the initial plastic surface, resulting on the other hand in material degradation, occur and develop according to zones of critical value ε_r (see Fig. 4 for elastic model).

In model e-p-d both values θ_b as well as ε_{12} (in the analysed range 5-7) "signalize" too large non-dilatational strains leading to material degradation. Direct value of ε_1 decides about material degradation in the middle of the wall (in the last floor).

Figure 8 presents solution e-p-d (for incrementally realized wall deformation process) which approximately corresponds to elastic wall local behaviour for R_t=6 *km*.

That behaviour – θ_b {calculated} ≈ θ_b {allowable} – has been received for R_t=10 *km*, for material parameters from tests in chapter 2.

Fig. 8 shows the degradation-zones that arose in masonry wall. The maximal degradation-values are $d \approx d_t \approx$ 38%, where d_t – tension degradation.

The extreme values for R_t=6 *km* (that increased suitably to denotations marked in Fig. 8) are: $\theta_b \cdot 10^3 \approx 0.596$, $\varepsilon_{12} \cdot 10^3 \approx 0.71$, $d \approx d_t \approx 63\%$.

Conclusion 4. The inelastic strain-analysis for the wall of an object protected against mining-effects for the III category of mining deformations classifies the analyzed wall to the (2) category of objects resistance, distinguished from the elastic analysis, which allows classifying that wall to the (3) category of objects resistance [11].

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