Research on Crack Formation in Gypsum Partitions with Doorway by Means of FEM and Fracture Mechanics

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Abstract. Cracking damage in non-loadbearing internal partition walls is a serious problem that frequently occurs in new buildings within the short term after putting them into service or even before completion of construction. Damage in partition walls is sometimes so great that they cannot be accepted by their occupiers. This problem was illustrated by the example of damage in a gypsum partition wall with doorway attributed to deflection of the slabs beneath and above it. In searching for the deflection which causes damage in masonry walls, fracture mechanics applied to the Finite Element Method (FEM) have been used. For a description of gypsum behaviour, the smeared cracking material model has been selected, where stresses are transferred across the narrowly opened crack until its width reaches the ultimate value. Cracks in the Finite Element models overlapped the real damage observed in the buildings. In order to avoid cracks under the deflection of large floor slabs, the model of a wall with reinforcement in the doorstep zone and a 40 mm thick elastic junction between the partition and ceiling has been analysed.

1. Introduction

Cracking of partition walls in newly commissioned buildings is a frequent phenomenon. It is difficult, and probably impossible to eliminate it completely because we are not able to anticipate accurately enough the spatial behaviour of building structures. Using overdimensioned sections of structural elements in order to eliminate small cracks would be an action unjustified economically, however, designers should know and apply solutions reducing the probability of cracking of partition walls based on the floor slab. Sometimes, one may have an impression that the only criterion they follow is to achieve the safety of the structure at the lowest costs of execution, paying no attention to usability requirements. Fissures that occasionally appear or small span cracking of partition walls are not causes for concern generally, however, often the scale of damage is unacceptable for the buyers – the more so that under Polish technical conditions [1] any cracks are regarded as prohibited. In clause 7.1 of Eurocode 6, it is stated, that structures shall be designed and constructed so as not to exceed serviceability limit state (SLS), therefore it is relevant to prevent partition walls cracking [2].

The effect of ill-considered solutions is the necessity of performing accelerated repair work, often even before commissioning of the building. One example of this includes the analysed damage to walls in buildings of mixed wall and pillar reinforced concrete structure.
2. Resistance of partition walls to distortion

The design of a reinforced concrete element bent in the serviceability limit state comes down to checking whether its bending falls within the range of permissible values. According to the principles of calculations for floor slabs, their limit deflections usually should not exceed 1/250 of the span. It was stated in Eurocode 2 that in the case in which deflections that occur after completion of the structure may cause damage to adjacent elements (e.g. non-bearing partitions), they should be limited to the value of 1/500 [3]. According to the Polish masonry wall standard [4], the wall will not get cracked with span width above 0.3 mm, if the maximum angle of its distortion θsd does not exceed the permissible value of θadm. This requirement concerns stiffening walls, however it can be also applied to other types of vertical partitions (including internal non-bearing ones). The value of the permissible angle of wall distortion θadm depends on the type of mortar and wall elements used, and it is from 0.2 mm/m for walls made of cellular concrete on cement mortar to 0.5 mm/m for walls made of elements from group 1 on cement and lime mortar [4, 5, 6]. Values of limit deflections of floor slabs determined according to the presented above, permitted distortion angles of walls vary from leff/4000 to leff/10000, and in practice cannot be achieved. According to experimental research described in the literature, initiation of cracking in masonry walls takes place at floor slab deflection in the range of 1/1000 to 1/10000. According to Beeby and Narayanan [7] and Derkacz [8], initiation of cracking in masonry walls without door opening often takes place at floor slab deflection value below 1/1000. According to the experimental research of Brameshuber and others [9], initiation of cracking of solid, silicate and aerated concrete partitions occurs at floor slab deflection above 1/5000.

3. Test materials and methods

The analyses were carried out using the finite element method. Numerical analyses have been conducted with use of the program Abaqus/Standard. For a description of material properties, the constitutive smeared cracking material model developed by Hillerborg and others [10] was used. Its basis is the assumption that cracking mechanics properly simulate behaviour of fragile materials in a state of tensile stress, and plasticity is appropriate for their modelling in the compaction state. While stretching, the material behaves in a way linear to the limit stress $f_t$, at which initiation of cracking takes place. After opening of the crack, transfer of stresses does not disappear suddenly but decreases in line with the growth of its span [10]. For the purpose of the completed analyses, linear dependency of stresses on deformations of materials in the state of stretching during bending until the moment when cracking is initiated (achievement of limit strength $f_t$ and displacement $u_{th}$) and stresses on displacements after cracking was assumed, the mathematical model of which is presented in figure 1.

![Figure 1 Assumed model of stress – material displacement dependence in the uniaxial loading in tension](image)

Limit displacement $u_{th}$ can be calculated from the dependency (1):
The parameters of gypsum walls were assumed based on the results of experimental tests [11]. The properties of partition walls taken into consideration in the analysis are shown in table 1.

| Strength-related parameters of partition walls |
|-----------------------------------------------|
| Compression strength | Tensile strength | Young modulus | Poisson’s ratio | Ratio of compression strength in double-axis state to strength of single-axis state | Limit displacement during stretching | Bulk density |
| fc [Mpa] | ft [Mpa] | E [Mpa] | v [-] | fo/fc | uo [mm] | ρ [kg/m³] |
| Gypsum walls | 6.88 | 2.87 | 4866 | 0.220 | 1.16 | 0.035 | 900 |

Steel and settlement spacer made of agglomerated cork 5 mm thick used along the edge of the wall were modelled as ideally elastic. The assumed material properties are presented in table 2.

| Mechanical properties of steel and elastic spacer made of agglomerated cork |
|-----------------------------------------------|
| Steel | Elastic spacer |
| Young modulus E [MPa] | 210000 | 2.55 |
| Poisson’s ratio v [-] | 0.3 | 0 |

Before undertaking the analysis of walls subject to floor slab bending, the material model was checked by conducting trial numerical analyses and confirming their compliance with the results of analytical tests.

3.1 Adapting the material model and verifying the results of laboratory tests

The calculations checking tensile strength during bending of the assumed material model were carried out for gypsum beams, dimensions 40 x 40 x 160 mm, subject to three-point bending. The numerical analysis was conducted in the flat state of stress. In discretization of the model, quadrangular elements CPS4 were used. Four meshes were used in which the number of finite elements (FE) was from 1946 to 7189. Division of the meshes (apart from the thinnest one) was made with FE densification within the zone of expected cracking of the material.

A summary of the maximum values of deformations and tensile stresses for all meshes used in the calculations is presented in table 3.
Table 3. Summary of maximum values of bending for dividing meshes used and comparison of flexural strength with results of laboratory tests

| Number of elements | Maximum vertical deformations [mm] | Maximum tensile stresses [MPa] | Tensile strength during bending – laboratory tests [MPa] |
|--------------------|------------------------------------|--------------------------------|-------------------------------------------------------|
| 1946               | 0.0529                             | 2.940                          |                                                       |
| 2584               | 0.0527                             | 2.903                          |                                                       |
| 3921               | 0.0525                             | 2.887                          |                                                       |
| 7189               | 0.0529                             | 2.877                          | 2.87                                                  |

Figure 2 presents the map of normal stresses $S_{11}$ for dividing mesh 7189 FE under the influence of break force $P = 1320$ N.

![Figure 2](image)

**Figure 2** Map of normal stresses $S_{11}$ for the sample bent at the moment of cracking [MPa]. Dividing mesh 7189 ES

Figure 3 illustrates the map of elements fulfilling the condition of cracking under the influence of force $P = 1320$ N.

![Figure 3](image)

**Figure 3** Elements fulfilling the criterion of cracking under the influence of force $P = 1320$ N

In order to verify deformability, a beam bent according to the static scheme presented in figure 4 was modelled.

![Figure 4](image)

**Figure 4** Static scheme of gypsum beam 60 x 100 x 500 mm in the bending test

The comparison of results obtained from numerical analyses and laboratory tests is presented in tab.4.
Table 4. Comparison of values regarding deflection of beams 60x100x500 mm subject to bending obtained in experimental and numerical tests

| Value of force P [N] | Tensile stresses for extreme fibres [MPa] | Vertical deformations [mm] |
|---------------------|------------------------------------------|---------------------------|
| 1820                | 1.40                                     | 0.145                     |
| 2208                | 2.87                                     | 0.225                     |

The values of stresses and deformations of test elements obtained in the numerical analyses showed satisfactory compliance with the experimental tests conducted. For the bended gypsum beams of similar strength Klin [12] obtained similar stress – strain dependencies.

3.2 FEM Analyses for walls subject to floor slab deflections

The study presents the results of FEM calculations for partition walls with a doorway in the middle of the span subject to distortions. Static schemes of actual non-bearing walls in which cracking occurred were mapped. They were based on cross-reinforced floor slabs 25 cm thick. Walls made of gypsum blocks connected using tongue and groove joints with the doorway in the middle of the span were analysed. Various values of deflection for the support on which the wall is based were assumed and stresses appearing in it and cracking progress were analysed.

Forcing of deformations was performed by functional relocation in the vertical direction of the steel beams modelling the slab under the wall and the slab above the wall. For the purpose of the completed analyses, the function of deformation for the reinforced concrete floor slab, span 7.2 m, was developed for the maximum deflection at the value of l/250, as presented in the equation (3):

\[
y = -1.133x^4 \cdot 10^{-13} + 1.6312027x^3 \cdot 10^{-9} - 5.1384402298x^2 \cdot 10^{-6} \\
- 5.2840043160831x \cdot 10^{-3} - 1.05526993661442 \cdot 10^{-2}
\]

where: \( y \) – displacement on vertical axis [mm], \( x \) – distance on horizontal axis [mm].

In the first step of the analysis, bending of the lower steel beam was performed up to the maximum value of l/250 and in the next step deflection of the beam above the wall was forced. The join of the steel beam and the bottom edge of the wall was modelled as unrestricted and in the zone of contact it was described using coefficient of friction \( \mu = 0.2 \) [9]. The calculations were conducted in the plane state of stress.

4 Results of numerical analysis

In the numerical tests conducted, vertical partitions made of synthetic gypsum, height and length of 7.2 m, with a doorway 1 m wide and 2 m high in the middle of their span were modelled. In order to avoid the effect of excessive accumulation of stresses, the top corners of the doorways were rounded with an arc of radius \( r = 5 \) mm. Given the symmetry of geometry, edge conditions and deformations, one half of the wall was assumed as the analytical model, by dividing it along the vertical axis in the middle of the doorway span.

4.1 Plain wall with circumferential settlement joint made of agglomerated cork 5 mm thick

The join of the wall with the load bearing structure along its horizontal edges was made using a spacer made of agglomerated cork 5 mm thick. One half of the wall, divided along the vertical axis in the middle of its span (figure 5) was assumed as the static scheme.
Figure 5. Static scheme of the model of gypsum wall subject to deformations

The commencement of cracking of the partition model occurred in the second step of the analysis (deformations of the spacer made of agglomerated cork above the wall), at the deflection value $a = 1.1$ mm. Figure 6 presents the map of normal stresses $\sigma_x$ with marked points of maximum values at the moment of cracking.

Figure 6. Map of normal stresses $\sigma_x$ [MPa] of gypsum wall under the influence of deflection of the upper slab with deflection value of $a = 1.1$ mm

The analysis was finished at deflection of the slab above the wall at the value of $a = 2.5$ mm. Figure 7 presents the map of normal stresses $\sigma_x$ in the area of the doorway corner and the map of finite elements fulfilling the cracking criterion, at maximum deflection ending the numerical analysis.
Figure 7. a) Map of normal stresses $\sigma_x$ [MPa]; b) map of elements cracked under the influence of deflection of the top floor slab with deflection value of $a = 2.5$ mm

It must be mentioned that the map of cracked elements shows only the point and the direction of damage. The width of the fissures depends on the densification of the mesh of finite elements.

4.2 Reinforced wall in the doorstep zone of the doorway with 40 mm settlement joint of the top edge

In order to reduce the influence of floor slab deflection on cracking of the gypsum wall, reinforcement in the doorstep zone of the doorway, a settlement joint of the top horizontal edge 40 mm thick and a settlement joint of the bottom edge of the wall 5 mm thick were used. The reinforcement was made using a galvanized steel flat bar, cross section 2 x 40 mm. The join of the reinforcement with gypsum was modelled as stiff. The settlement joint of the top edge of the wall was made using flexible polyurethane foam of density 25 kg/m$^3$. The model of dependency of stresses on foam deformations in the state of uniaxial compression assumed in the analyses is presented in figure 8.

Figure 8. Dependence stress – strain of polyurethane foam used as settlement joint of the top edge of gypsum wall

The static scheme for the model of the reinforced gypsum wall with settlement joint of the top horizontal edge at the height of 40 mm is presented in figure 9.
Figure 9. Static scheme of reinforced gypsum wall subject to deformations

The completed test did not show cracking of the gypsum wall constructed in this way. The analysis was finished at the value of bottom and top floor slabs deflection of $a = 28.5$ mm. Figure 10 presents the map of normal stresses $\sigma_x$ of the gypsum wall in the step ending the numerical analysis.

Figure 10. Map of normal stresses $\sigma_x$ [MPa] of gypsum wall under the influence of floor slab deflection of $a = 28.5$ mm

Application of reinforcement changed the layout of stresses in the wall. Maximum tensile stresses in the axis of steel symmetry (in the middle of the partition span) were $74$ MPa. Maximum tensile stresses of the gypsum wall in the zone in contact with the reinforcing steel reached the value of $0.8$ MPa. Maximum tensile stresses in the zone above the doorway were $0.15$ MPa and normal limit compressive stresses reached the value of $-0.35$ MPa.

5. Conclusions

The completed test proved that walls of gypsum blocks of density $900$ kg/m$^3$ with a plain doorway in the middle of the span crack as result of deformations of the slab above the wall with deflection value of $a \approx 1/6700$ (after deformation of the slab under the wall). The progress of cracks induced follows the cracks observed in actual structures the examples of which are presented in figure 11.
The obtained values of ceiling slab deflections causing cracks are compliant with the values of the permissible angle of distortion given in the Polish standard PN-B 03002: 2007 [4] and with values of deflections obtained in experimental tests of masonry walls described in the literature [2,3].

In order to reduce cracking of partition walls made of gypsum blocks, they should be protected from damage which may appear as a result of exceeding the permissible angle of distortion using reinforcement in the doorstep zone of doorways or by reinforcing corners of walls by means of galvanized bars laid at the angle of 45° to the edge of doorway (grove can be cut using a diamond cutting disc). Reinforcement in the doorstep zone using galvanized steel hoop should be made when the first layer of gypsum blocks is built. The join with the ceiling slab should be made in a flexible way, using a material with low modulus of elasticity, with thickness allowing compensation of stresses from the ceiling slab deflecting above the wall. In addition, it is recommended that a flexible connection be made with the floor slab under the partition wall, for example using polyethylene foam 3-5 mm thick.

References

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