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To cite this article: Adam Piekarczyk 2019 IOP Conf. Ser.: Mater. Sci. Eng. 471 052018

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Cracking and Failure Mechanism of Masonry Walls Loaded Vertically and Supported by Deflecting Structural Member

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Abstract. The paper describes some results of tests on solid walls and walls with openings in full scale, which were built on the steel structure subjected to vertical deflection. The walls had the length of 4550 mm, the height of 2450 mm and the thickness of 180 mm and were made of silicate blocks of group 1 per PN-EN 1996-1-1 standard with mean compressive strength of 17.7 N/mm². The specimens had thin bed joints and unfilled head joints. Solid walls (A type), walls with one door opening located unsymmetrically in relation to the vertical axis (B type), specimens with two door openings located symmetrically (C type) and walls with one door and one window opening (D type). The tests were carried out in the specially designed steel stand that allowed to test masonry full scale walls subjected to simultaneous increasing of vertical compression load and deflection of the structure which they are supported on. The vertical load of the top walls edge was realized with the use of two hydraulic jacks with range up to 500 kN. The vertical deflections of steel structure supporting the masonry wall were realized in two ways, by means of loading the top edge of wall and with use of the elements of deflection enforcement system. Apart from vertical loading and support displacements, the displacements of the masonry along the eleven sections on each surface in two fields were also measured. The measurement of changes of the measuring sections length was used for calculating the mean deformation angles of the specimen in both fields. The walls without openings were rigid enough to separate from the support even at the deflection not exceeding 1.5 mm. The walls with one door opening located unsymmetrically also crack at early stage of tests. In this case, the separation from the support of a part of the wall without opening occur and cracks appear at the end of lintels caused by rotation of parts of wall separated by door opening (at early stage of tests treated as rotations of rigid bodies). In the case of walls with two symmetrically located door openings, the first crack appeared at the ends of the lintels as a result of rotations of pillars caused by small, smaller than 3 mm support deflection. The first cracking of walls with the window and door openings took place under the window opening and in the area, where lintel was supported by external pillar adjacent to the window opening.

1. Introduction
A very common cause of masonry walls cracking is the deflection of the floors on which these vertical building partitions were erected. Even a few millimetres deflection of the floor can lead to cracking of the walls. Such cracks result from vertical displacements that occur after masonry wall construction and are a consequence of loading the upper edge of the load-bearing walls, the self-weight of floor layers and floor finishing materials (installation elements, suspended ceiling, plaster etc.), live load and increment of floor deflection as the effect of delayed deformations including those connected with shrinkage and creep of concrete. Due to low early strength of masonry (fresh not hardened mortar) and rheological properties of the masonry, when determining the deflection of the floor after wall erection,
self-weight of the wall without plaster layers need not to be considered, provided that the walls have been raised on not propped floor. Prevention of damages to such walls consist primarily in limiting the deflection of the floors at the design and construction stage. While designing the structure, attention should be paid to appropriate static assumptions, including the use of floors supported on all edges on supports with stiffness as high as possible, shortening of outer spans of multi-span structures, construction of supports with possibly similar stiffness on all storeys, etc. During the construction stage this should be borne in mind to build walls on floors after removing its props, preferably completely. The masonry walls should be made using cement-lime mortars with the normal-thickness joints. It is desirable to finish such walls so that wall and ceiling plasterings are separated from each other. The attention also requires appropriate connection of the vertical edges of the walls with other walls, which will allow to minimize vertical cracking at the junction of these members. The use of reinforcement placed in the horizontal bed joints of masonry can also lead to a reduction of the cracks width, but usually does not prevent to their occurrence, especially in the case of walls with openings. There are also such executive errors that consist bricklaying of partition walls on deformable layers of floors, as well as screeds and levelling layers made of cement mortars of much greater thickness than assumed in the project. More information on the ways of limiting deflection of floors occurring after erection of masonry walls, calculation of these displacements and the permissible values can be found in [1], [2], [3] and in standards [4], [5], [6], [7], [8].

2. Materials, specimens and tests program

2.1. Materials

The specimens were made of calcium silicate blocks group 1 according to PN-EN 1996-1-1 standard [9], 250 mm long, 180 mm wide and 220 mm high and medium compressive strength \( f_{cb} \) equal to 17.7 N/mm\(^2\) and normalised strength \( f_{b} = 21.8 \) N/mm\(^2\). The thin layer mortar had a mean compressive strength \( f_{m} = 12.5 \) N/mm\(^2\).

2.2. Specimens and tests program

The tests concerned the full-scale walls with a length of 4550 mm and a height of 2450 mm with thin bed joints and unfilled head joints. Walls without openings and with door and window openings were tested. Type A walls did not have openings (figure 1). The type B specimens contained one door opening located asymmetrically in relation to the vertical axis of the wall (figure 1b). The type C walls had two symmetrically placed door openings (figure 1c). The walls type D contained one door opening and one window (figure 1d). Above the door openings of type B and C specimens there were precast single-span reinforced concrete lintels with a cross-sectional width of 180 mm and a height of 220 mm. Above the door and window openings in the type D walls there was two-span continuous precast lintel the same cross-section as the lintels in type B and C walls. The lintel length was selected in such a way that the bearing length was not less than 125 mm. On the upper surface of the walls there was a reinforced concrete rim beam with a cross-section of 180×200 mm. Two walls of type B, C and D were tested. In case of walls type A tree walls were tested including one wall without RC rim beam In total 9 masonry walls were investigated.

3. Test stand and testing procedure

The tests were carried out in a specially designed test stand shown in figure 2. The walls were built directly in the stand on a slender steel beam supported for the time of wall erection (item 8 in figure 2). After the wall was built, the reinforced concrete precast rim beam was placed using mortar on the upper wall surface (item 5 in figure 2). The vertical load as \( F \) forces was induced by hydraulic jacks with the range of up to 500 kN (item 3 in figure 2). Forces \( F \) were measured using force gauge, also with the range of up to 500 kN (item 2 in figure 2). The forces \( F \) were transferred to the tested wall by means of I-section steel crossbeams (item 4 in figure 2).
Figure 1. Tested full-scale walls: a) type A without openings, b) type B with one asymmetrically placed door opening, c) type C with two door openings, d) type D with door and window opening.

Figure 2. Test stand: 1 – steel frame, 2 – force gauge with range with the range to 500 kN, 3 – hydraulic jack with the range to 500 kN, 4 – steel crossbeam, 5 – reinforced concrete rim, 6 – tested wall, 7 – members of the system for measuring the vertical displacements, 8 – flexible wall support (steel beam), 9 – external support of the beam, 10 – elements of the system enforcing vertical displacements, 11 – hydraulic jack with range to 150 kN, 12 – force gauge with the range to 100 kN, 13 – force gauge with the range to 50 kN, 14 – screws for fixing the deflections.
Vertical displacements of the beam supporting the masonry wall in the test stand reflected deflections of real elements of reinforced concrete floors, lintel beams or foundations. The flexural stiffness of the steel beam was intentionally small to make possible to enforce additional displacements except those resulting from the vertical load with $F$ forces. Additional deflections of the structure supporting the masonry wall results from the loads acting directly on this structure (self-weight of floor, imposed floor loads) and as a result of delayed deformation of concrete (creep and shrinkage), which can be greater than elastic deformations even more than three times. Therefore, the vertical displacement $\delta_{vi}$ of the steel beam supporting the masonry wall was carried out in two ways. First, the deflection was induced by vertical load – $F$ forces, and then it was optionally increased to the previously planned for a given phase of the test using a set of elements for this purpose and equipped with hydraulic jacks with range of up to 150 kN and force gauges with the range of 50 kN and 100 kN (items 10, 11, 12 and 13 in figure 2). Deflection of the beam supporting the wall was measured by means of displacement transducers with a measuring range of $\pm 50$ mm mounted to steel angles, which were connected to the outer supports of the test stand regardless of the deflected wall support (item 7 in figure 2). Vertical displacements were measured on both sides of the wall in 1/6 and 5/6 span of the support beam (deflections $\delta_{v1}$), in 1/3 and 2/3 of the span (deflections $\delta_{v2}$) and in the middle of the beam span (deflections $\delta_{v3}$). In addition, vertical displacements were measured at the support of the beam. The deflection planned in a given test phase was fixed by means of M30 screws (item 14 in figure 2).

Besides of the values of forces $F$ and vertical displacements $\delta_{vi}$, the wall deformations along 11 measuring bases on both wall surfaces were also measured in two areas conventionally marked as left “L” and right “R” (figure 3). The lengths of horizontal measurement bases were 1950 mm, the vertical bases had the length of 1900 mm, while the diagonal bases were 2723 mm long. Changes in the length of measurement bases caused by changes in the vertical load $F$ and vertical deflections of the beam supporting the wall $\delta_{vi}$ were measured by means of displacement transducers with a measuring range of $\pm 5$ mm and $\pm 10$ mm. On the basis of registered changes in the length of measuring bases denoted in figure 4 by the letters $a$ to $k$, the values of the deformation angles $\theta_i$ were calculated. It was assumed that the mean value of deformation angle in the area “L” is the arithmetic mean of the values of angles form $\theta_1$ to $\theta_4$ (a total of 8 angles determined on both wall surfaces). For example, angle $\theta_4$ (see figure 4) was calculated from the formula

\[
\theta_4 = \arcsin\left(\frac{d^2 - e^2 - c^2}{2ec}\right).
\]
Figure 4. Scheme of determination of deformation angles on the basis of changes in the length of measuring bases

4. Discussion of the walls cracking and failure mechanism

Table 1 summarizes the selected values that accompanied the appearance of the first cracks of the tested walls. Table 2 contains test results referring to failure of the masonry walls, i.e. the moment when it was not possible to obtain higher $F$ force. The tables contain load values of the upper edge of the wall at the cracking appearance $p_{cr}$ and ultimate load $p_{u}$ in kN/m$^2$ (column 3), obtained from the formula

$$ p_i = \frac{2F_i}{L^2 t} \quad (2) $$

where: $F$ – force transferred to the wall form a single hydraulic jack, kN,
$L_1$ – wall length, m ($L_1 = 4.551$ m),
t – wall thickness, m ($t = 0.18$ m).

Column 6 presents the values of the deflection occurring in the middle of the span of the supporting beam $\delta_{1/2,cr}$ and $\delta_{1/2,u}$ accompanied by appropriate load $p_i$. Column 5 of tables 1 and 2 contain values of the deflection in the middle of the beam span to beam length ($L = 4500$ mm) ratio $\delta_{1/2,L}$. In column 6 there are mean values of deformation angles $\theta_{mv,cr}$ and $\theta_{mv,u}$ in the conventional left area “L” and right area “R” of individual walls. Next is a description of the cracking and drawings showing cracking pattern (columns 7 and 8).

Table 1. Selected tests results obtained at the moment of first cracking appearance

| Wall | Area | load $p_{cr}$, kN/m$^2$ | deflection $\delta_{1/2,cr}$, mm | ratio $\delta_{1/2,cr}/L$ | mean angle $\theta_{mv,cr}$, mm/m | cracks description | cracking pattern |
|------|------|------------------------|-------------------------------|---------------------|-----------------------------|-------------------|-----------------|
| 1.   | „L”  | 0                      | 1.20                          | 1/3750              | 0.005                       | detachment from supporting beam | ![Cracking Pattern](image1) |
| A-1  | „R”  | 0                      | 1.40                          | 1/3214              | 0.006                       | detachment from supporting beam | ![Cracking Pattern](image2) |
| A-2  | „L”  | 0                      | 1.40                          | 1/3214              | 0.013                       | detachment from supporting beam | ![Cracking Pattern](image3) |
| „R”  | 0                      | 1.40                          | 1/3214              | 0.008                       | ![Cracking Pattern](image4) |
### Table 2. Continued

| Wall | Area | load $p_{cr}$, kN/m² | deflection $\delta_{1/2, cr}$, mm | ratio $\delta_{1/2, cr}/L$ | mean angle $\theta_{m, cr}$, mm/m | cracks description | cracking pattern |
|------|------|-----------------------|-----------------------------------|--------------------------|---------------------------------|-------------------|-----------------|
| A- bwn | „L” | 0 1.62 1/2778 | 0.025 | detachment from supporting beam | | |
| | „R” | 0 0.019 | | cracks at the end of the lintel on the side of wider pillar | | |
| B-1 | „L” | 0 1.39 1/3237 | 0.179 | detachment from supporting beam | | |
| | „R” | 0 0.011 | | cracks at both ends of the lintel | | |
| B-2 | „L” | 87 1.49 1/3020 | 0.089 | detachment from supporting beam | | |
| | „R” | 87 0.016 | | cracks at both ends of the lintel | | |
| C-1 | „L” | 74 2.69 1/1673 | 0.211 | horizontal and vertical cracks at the end of the lintel on the side of external pillar | | |
| | „R” | 74 0.134 | | | | |
| C-2 | „L” | 88 1.71 1/2632 | 0.069 | horizontal and vertical cracks at the end of the lintel on the side of internal pillar | | |
| | „R” | 88 0.089 | | | | |
| | „L” | 0 0.080 | no cracks | | | |
| D-1 | „L” | 78 1.29 1/3488 | 0.080 | detachment from supporting beam; oblique “stepped” cracking under the window | | |
| | „R” | 78 0.676 | | | | |
| | „L” | 78 0.216 | no cracks | | | |
| D-2 | „R” | 0 2.00 1/2250 | 3.52 | detachment from supporting beam; oblique “stepped” cracks under the window; horizontal and vertical cracks at the end of the lintel on the side of external pillar | | |

1) – wall without the RC rim beam
Table 3. Selected test results at the walls failure

| Wall | Area | load $p_c$, kN/m² | deflection $\delta_{1/2,cr}$, mm | ratio $\delta_{1/2,cr}/L$ | mean angle $\theta_{mv,cr}$, mm/m | cracks description | cracking pattern |
|------|------|------------------|-----------------|-----------------|----------------|-----------------|-----------------|
| 1.   |      | 286              | 6.05            | 1/744           | 0.086          | vertical crack in the middle of the wall length; detachment from supporting beam |
|      |      |                  |                 |                 | 0.130          | oblique cracks running from the lower corners; detachment from supporting beam; crushing the masonry in the lower corners |
|      |      | 609              | 25.6            | 1,176           | 2.61           | oblique cracks running from the lower corners; detachment from supporting beam; crushing the masonry in the lower corners |
|      |      |                  |                 |                 | 4.64           | oblique cracks running from the lower corners; detachment from supporting beam |
|      |      | 521              | 19.7            | 1/228           | 3.23           | oblique cracks running from the lower corners; detachment from supporting beam |
|      |      |                  |                 |                 | 3.47           | oblique cracks running from the lower corners; detachment from supporting beam |
|      |      | 391              | 11.2            | 1/402           | 12.2           | horizontal and vertical cracks at both ends of the lintel; diagonal cracking of pillar; detachment of a part of the pillar separated by the crack; crushing the masonry under the lintel on the side of the narrow pillar; detachment from the supporting beam |
|      |      |                  |                 |                 | 1.15           | horizontal and vertical cracks at the end of the lintel on the side of the wider pillar; detachment from the supporting beam |

As expected, in the walls with openings a different cracking and failure mechanism was observed than in case of walls without openings. A common feature for all walls was detachment from the supporting beam, which in the case of walls without openings and with window and door opening always occurred at the beginning of the test with a slight deflection not exceeding 2.0 mm and without loading the upper edge of the wall or with low load.

In the case of walls without openings, a twofold mechanism of failure was observed. One of the walls failed with a relatively small load and deflection in a manner typical for bending members, i.e. the vertical crack running through the entire height of the wall. Two walls without openings failed due to
shear with oblique multi cracks (including the wall without RC rim beam, where the ultimate load and accompanying deflection was lower).

Table 4. Continued

| Wall | Area | load \( p_{cr} \), kN/m² | deflection \( \delta_{1/2,cr} \), mm | ratio \( \delta_{1/2,cr}/L \) | mean angle \( \theta_{mv,cr} \), mm/m | cracks description | cracking pattern |
|------|------|--------------------------|-------------------------------|-----------------------------|---------------------------|------------------|-----------------|
| 1.   | 2.   | 3.                       | 4.                           | 5.                          | 6.                        | 7.               | 8.              |
| „L”  | B-2  | 354                      | 6.59                         | 1/683                       |                           | cracks at the ends of the lintel; detachment of the end of the rim; detachment from the supporting beam; crack under the lintel on the side of the wider pillar; opening of vertical joints over the lintel; diagonal cracking of external pillar |               |
| „R”  |      |                          |                              |                             |                           | horizontal cracks at the end of the rim; detachment from the supporting beam; horizontal and vertical cracks at the ends of the lintel; cracks under the lintel on the side of the internal pillar; “stepped” cracking of the external pillar; detachment from the supporting beam |               |
| „L”  |      |                          |                              |                             |                           | horizontal and vertical cracks at the ends of the lintel; cracks under the lintel on the side of the internal pillar; “stepped” cracking of the external pillar; detachment from the supporting beam |               |
| „R”  | C-1  | 620                      | 23.4                         | 1/192                       |                           | horizontal and vertical cracks at the ends of the lintel; cracks under the lintel on the side of the internal pillar; detachment from the supporting beam |               |

The first cracks in walls type B with one door opening appeared in the areas at the end of the lintel and walls were detached from supporting beam. Failure followed by oblique cracking of narrow pillar.

In the case of walls type C with two door openings, the first cracks at the deflection no of more than 3 mm and the load not exceeding 90 kN/m² were observed at the ends of the lintels. Failure of walls type C manifested by the development of cracks at the ends of the lintel and the formation of the oblique cracks in one of the external pillars.

First cracks in type D walls after the wall detachment from supporting beam were formed at the deflection of no more than 2 mm under the window opening and had the nature of oblique “stepped”
cracks. Failure of walls this type consisted of crushing the masonry unit under the longer span of the lintel or the oblique cracking of the external pillar adjoining the door opening.

Table 5. Continued

| Wall | Area | load p_kN/m² | deflection δ_{1/2,cr}, mm | ratio δ_{1/2,cr}/L | mean angle θ_{mv,cr}, mm/m | cracks description                                                                 | cracking pattern |
|------|------|--------------|-----------------------------|-------------------|---------------------------|----------------------------------------------------------------------------------|-----------------|
| 1.   | 2.   | 3.           | 4.                          | 5.                | 6.                        | 7.                                                                                | 8.              |
| „L“ |      |              |                             |                   |                           |                                                                                   |                 |
|      |      |              |                             |                   |                           |                                                                                   |                 |
| C-2  | 538  | 22.0         | 1/205                       |                   |                           |                                                                                   |                 |
| „R“  |      |              |                             |                   |                           |                                                                                   |                 |
|      |      |              |                             |                   |                           |                                                                                   |                 |
| „L“  |      |              |                             |                   |                           |                                                                                   |                 |
|      |      |              |                             |                   |                           |                                                                                   |                 |
| D-1  | 458  | 15.0         | 1/300                       |                   |                           |                                                                                   |                 |
| „R“  |      |              |                             |                   |                           |                                                                                   |                 |
|      |      |              |                             |                   |                           |                                                                                   |                 |
| „L“  |      |              |                             |                   |                           |                                                                                   |                 |
|      |      |              |                             |                   |                           |                                                                                   |                 |
| D-2  | 519  | 20.0         | 1/225                       |                   |                           |                                                                                   |                 |
| „R“  |      |              |                             |                   |                           |                                                                                   |                 |

horizontal cracks at the end of the lintel on the side of external pillar;
vertical and diagonal cracks at the end of the lintel on the side of internal pillar;
vertical and diagonal cracking of external pillar;
detachment from the supporting beam

vertical and diagonal cracks at the end of the lintel on the side of internal pillar;
vertical and diagonal cracks at the end of the lintel on the side of external pillar;
vertical and diagonal cracks at the end of the lintel on the side of external pillar;
detachment from the supporting beam

diagonal „stepped” cracking

vertical and horizontal cracks at the end of the lintel on the side of the external pillar; oblique “stepped” cracks under the window; detachment from the supporting beam
vertical and horizontal cracks at the end of the lintel on the side of the external pillar; diagonal crack in the bottom corner; horizontal cracks of the internal pillar; detachment from the supporting beam
vertical and horizontal cracks at the end of the lintel on the side of the external pillar; opening of vertical joints over the lintel; oblique “stepped” cracks under the window; detachment from the supporting beam; crushing of masonry unit under the lintel on the side of the external pillar
5. Conclusions

On the basis of tests of full-scale masonry walls subjected to compression and additionally vertical deflection of the supporting beam carried out in the described range it can be concluded that the first cracks occur at a small, not exceeding 2.7 mm deflection, which is less than 1/1700 of the supporting beam span and zero or low loading of the upper edge of the walls. This can be confirmed by the conclusions drawn from the papers [10] and [11], where to minimize the possibility of small cracks in load-bearing walls it was proposed to limit the deflection of structural elements supporting load-bearing walls up to 1/2000 or even 1/3330. In the case of walls without openings, the wall is detached from the supporting beam first. In walls with openings the first cracks usually appear at the ends of the lintels and additionally for walls with window opening, part of wall under the window is separated.

Failure of the tested masonry walls most often consisted of oblique cracks, including diagonal cracking of external pillars in the walls with openings or crushing of the masonry units under the lintel and in the area of the lower corners.

Failure of the wall containing one door opening and one wall without opening occurred at the deflection of less than 1/500 of length of the supporting beam. In most cases, deflection at the moment of wall failure was more than 1/300 of the span length.

In the case of walls with unsymmetrical geometry, the effect of this asymmetry on the deformation angles $\theta_i$ was visible. In walls type B, the part without opening acted almost like a rigid body compared to the other part of the wall, which of course had an effect on the mechanism of cracking and failure. Slightly smaller, but equally clear were the disproportions of deformations in the case of walls with door and window opening. The part of the wall containing the window opening experienced at least four times larger deformations, the measure of which was the deformation angle $\theta_i$.

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