Assessment of anomalies related to vertical deformations in heritage buildings with reinforced concrete structure and infill masonry walls

José Miranda Dias
Laboratório Nacional de Engenharia Civil, Lisboa, Portugal, mirandadias@lnec.pt

Abstract

Anomalies in heritage buildings with reinforced concrete structure, related to the cracking of infill masonry walls due to vertical deformations of their structural supporting elements, can have strong negative impact on these buildings, as they usually represent an important cultural and historical value to preserve. These deformations can affect the functionality, aesthetics and the safety of the referred heritage buildings, leading to significant costs associated to repair actions and decrease of their patrimonial value. Hence, a better knowledge of the vertical deformations in heritage buildings with reinforced concrete structure is needed.

In this paper, a general description of anomalies related to vertical deformations of the masonry walls and their reinforced concrete supporting elements (beam or slab support) is made. Relevant influencing factors of the wall-support basic behaviour are presented. An analysis of wall-support behaviour related to vertical deformations is carried out, based on the study of the stresses in the constituent elements of wall-support assembly (especially, masonry units, mortar joints and interface wall/support), and of their main types of deformation related with the rigidity of the reinforced concrete support of the wall, and also of the reinforced concrete element (beam or slab) confining at the top of the wall.

Serviceability requirements related to the limitation of damage in infill masonry walls, through the control of the deflections of reinforced concrete supports with due consideration of the respective building heritage relevance, are discussed. Finally, general strategies for repair and rehabilitation of building infill masonry walls with anomalies related to vertical deformations of their reinforced concrete supports, as well as for strengthening of these supports, are proposed.

Key-words: Concrete; Masonry; Buildings; Heritage; Rehabilitation

1 INTRODUCTION

Anomalies in heritage buildings with reinforced concrete structure, related to the cracking of infill masonry walls due to vertical deformations of their structural supporting elements, can have strong negative impact on these buildings, as they usually represent an important cultural and historical value to preserve. These deformations of the wall supports are, mainly, due to their excessive deformability, associated to high slenderness of the wall supports (large span and low height of the section) and/or weak link of the interface between masonry walls and their supports, and can affect the functionality, aesthetics and the safety of the referred heritage buildings, [1], [3], leading to significant costs associated to repair actions and decrease of their patrimonial value. The relation between excessive vertical deformations of the supporting element of masonry walls and the consequent anomalies, particularly related to the cracking of masonry walls, is not sufficiently known. Hence, a better knowledge of the vertical deformations in heritage buildings with reinforced concrete structure is needed.

In this paper, a general description of anomalies related to vertical deformations of the masonry walls and their reinforced concrete supporting elements (beam or slab support) is made. Relevant influencing factors of the wall-support basic behaviour are presented. An analysis of wall-support behaviour related to vertical deformations is carried out, based on the study of the stresses in the constituent elements of wall-support assembly (especially, masonry units, mortar joints and interface wall/support), and of their main types of deformation related with the rigidity of the reinforced concrete support of the wall, and also of the reinforced concrete element (beam or slab) confining at the top of the wall. Serviceability requirements related to the limitation of damage in infill masonry walls, through the control of the deflections of reinforced concrete supports with due consideration of the respective building heritage relevance, are discussed. Finally, general strategies for repair and rehabilitation of building infill masonry walls with anomalies related to vertical deformations of their reinforced concrete supports, as well as for strengthening of these supports, are proposed. The heritage buildings considered in the present analysis are those based on structural concrete elements associated to infill or resistant masonry walls, that are classified as cultural heritage, as well as buildings not included in this classification, but which present relevant cultural/historical value or public utility (these buildings are here referred as heritage buildings with the acronyms: “HBrc” buildings).

2 GENERAL DESCRIPTION OF ANOMALIES RELATED TO VERTICAL DEFORMATIONS OF MASONRY WALL SUPPORTING ELEMENT OF REINFORCED CONCRETE

Anomalies in masonry walls can result from a variety of sources, including external effects (shrinking and swelling of reactive clays with moisture variations, differential foundation movements [19], etc.), from dimensional changes in the masonry [12], and interactions of the masonry with other structural elements, particularly with their reinforced concrete supports [16]. In the specific case of excessive vertical deformations of reinforced concrete elements (see particular cases of excessive deformation of the supports in Figure 1, [1]), stresses can be induced in internal masonry walls and masonry walls of the external envelope of buildings, which can lead to negative consequences to these non-structural elements, due to their limited compression, tensile and shear tensile strength. The signs of anomalies in masonry walls and in their reinforced concrete supporting elements, due to excessive vertical deformations of these supporting elements, are, generally, both the deficiencies of aspect of these supports (sharp curvature of the beams and slabs) and, above all, the anomalies associated to the cracking of the masonry walls [3] and, more rarely, the slight cracking of the supporting elements. In the case of masonry walls cracking associated to the deformation of the supporting elements, the deflection at the mid span, corresponding to the onset of visible cracking in the wall (in certain cases a horizontal crack in base of the wall), is generally low, less than about 1/2000 of the span [1], [3], [8]. In case of anomalies related to excessive deformation of the supporting elements (beam or slab of reinforced concrete) of masonry walls, the position and configuration of the cracks that occur in the walls vary according to several factors, in particular: span/height ratio of the walls; mechanical characteristics of the constituent materials of the walls; presence or not of openings on the surface of the wall; possible interaction with concrete supporting element and other non-structural elements such as internal partitions [3].

3 RELEVANT INFLUENCING FACTORS OF THE WALL-BEAM/SLAB BEHAVIOR RELATED TO VERTICAL DEFORMATIONS

3.1 General

Infill masonry walls in buildings with reinforced concrete structure are considered non-structural elements and are, commonly, executed with different construction materials (clay bricks, calcium silicate blocks, aggregate concrete blocks, autoclaved aerated blocks, etc.) and workmanship. The infill masonry wall supported by the reinforced concrete element (slab/beam) is usually based on elastic brittle bricks/blocks, which are linked through mortar joints that act as planes of weakness, due to their low bond strength, particular in tension and shear. The resistance and deformability of the infill masonry depend on the individual mechanical characteristics of the constituent elements (bricks/blocks and mortar joints), as well as on the interaction between these elements. The deflections of the beams/slabs induce stresses and deformations in the infill masonry walls which they support, that can lead to their cracking, when a certain limit of stress in these masonry walls is reached. The bond between masonry units and mortar joint, in these masonry walls, is a weak link, which can either fail in tension (failure mode I) or shear (failure mode II) along the horizontal and vertical masonry joints. Vertical deflections of beams or slabs of reinforced concrete can, also, affect masonry walls that are located bellow them, in case they are directly connected to these structural elements, which can transmit significative loads to these masonry walls, forcing them to a loadbearing function that were not previewed for them, possibly leading to their cracking, due to their limited resistance to tension, compression and shear actions.

Previous research developed about the interaction of masonry walls and their confining structural elements, when subjected to vertical and lateral loads, comprising experimental or analytical studies, had shown the importance of the geometry and mechanical characteristics of the infill masonry wall and of the confining structural elements, as well as the mechanical characteristics of the interface between the infill wall and the concrete frame, such as the examples of works of Burhouse (Building Research Station) [2], Stafford Smith [5], and Page [7]. So, in the following, relevant aspects of the mechanical characteristics of the masonry units, mortar joints and mortar-brick/block interface, as well as the mechanical behaviour of the interface between the masonry wall and the structural supporting element of reinforced concrete, are discussed.

3.2 Relevant behaviour characteristics of the assembly wall-beam/slab

3.2.1 General

The infill masonry wall-slab/beam assembly behaviour, related to vertical deformations, is influenced by the interaction of the masonry wall with its supporting element (slab/beam); at low levels of loading, the assembly performs in monolithic way, but, as loading increases, the masonry walls tend to partially separate from supporting elements [1]. Important parameters which could affect that behaviour, namely the onset of cracking and the long term/creep effects, could be related, particularly to mechanical properties of the masonry wall constituents and of the supporting element, as well as the mechanical characteristics of the masonry wall-slab/beam interface [13], [18]. Relevant parameters could be the length to height ratio of the masonry wall; the relative rigidity of the supporting element; the presence of openings, and the mechanical resistance of the masonry wall.

3.2.2 General analysis of a masonry wall-slab/beam model

In order to have qualitative indications about masonry wall-slab/beam behaviour related to vertical deformations, it can be useful a simplified analysis of an idealized model of a masonry wall-beam assembly, simply supported, subjected to a uniformly distributed vertical load at the top of the wall. In this model, both vertical stresses (eventually leading to arching action) and shear stresses at the wall-beam interface are concentrated towards the supports [9], with symmetrical distribution (Figure 2). These vertical and shear stresses can have a maximum value at each end part of beam and gradually decrease their value, approximately, to zero, at a distance to the half span that will depend, in great part, on the flexibility of the beam. In the mode described before, there is a trend for the supporting element to deflect downwards away from the masonry wall, with the potential development of a crack in the interface between the top of the beam/slab and the bottom of the wall. The shear force tends to counteract the downward deflection of the beam. The concentration of vertical stresses towards the supports is gradually more intense, as the walls have a ratio of height to span (h/L) greater than about 0.6, which correspond to a situation more favourable to avoid excessive deflections that can generate cracks in masonry. Below this ratio of 0.6, the supporting element should be assumed as an effective flexural member, and the induced shear stress, at the wall-beam interface, increases significantly.

The above referred idealized model of a masonry wall-beam assembly allows to estimate the vertical and shear stress distribution at the wall-beam interface [9]. Based on numerical simulation by finite element method [9], it was shown that, for wall-beam assembly, the distribution of stresses at the interface of the wall with the beam (vertical pressure exerted by the wall on the beam) could be considered approximately linear, parabolic or cubic type, respectively for values of a stiffness parameter K_d greater than 7, between 7 and 5, and lesser than 5, being K_d defined by:

$$K_d = \left[\frac{E_w . t . h^3}{E_v . \mathrm{I}}\right]^{\frac{1}{4}} \tag{1}$$

E_w - elastic modulus of the masonry wall;
E_v - elastic modulus of the beam;
t, h - width and height of the masonry wall;
I - moment of inertia of the section and elastic modulus of the beam

The maximum vertical stress (compression) in the masonry wall (f_m - vd. Figure 2) is given by:

$$f_m = \left[\frac{W_w \,. C_1}{\mathrm{L\,.\,t}}\right] = p_w \,. C_1 \qquad (2)$$

L - span of the beam;
W_w - total vertical load in the beam/wall assembly; p_w - mean pressure vertical load in the wall;

The maximum shear stress along the interface wall/beam is given by:

$$\tau_m = \left[\frac{W_w . C_1 . C_2}{L\,.\,\mathrm{t}}\right] \qquad (3)$$

Considering the results of numerical simulation by finite element method, these values of vertical and shear stresses are defined in relation to the parameters C_1 and C_2, being C_1 the value vertical stress concentration in the wall above referred [9]. These parameters are related to K_d and to the constants α, ß, e γ (see definition of these constants in Figure 3).

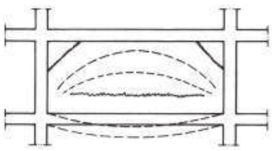
$$C_1 = 1 + \beta . K_d \qquad (4)$$

$$C_2 = \alpha + \Upsilon . K_a \qquad (5)$$

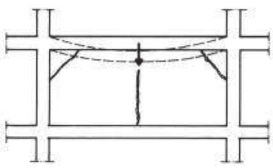
Where K_a is defined as follows:

$$K_a = \left[\frac{E_w . t . h}{E_v . A_v}\right] \qquad (6)$$

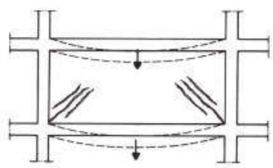
A_v – Area of the beam cross-section



a) Case of lower slab more deformable (presence of the compression arc marked in dot line)



b) Case of upper slab more deformable



c) Case of upper and lower slabs with identical deformations

Figure 1. Cracking in masonry walls related to excessive vertical deformations of concrete supporting elements (slabs) [1]

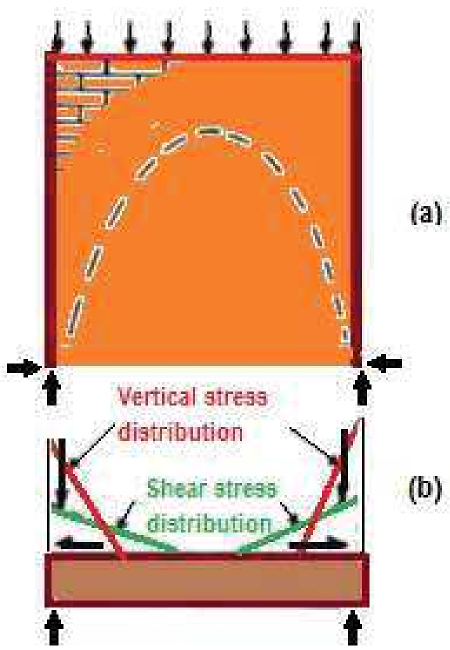


Figure 2. Model of wall-beam assembly: (a) arching forces in wall; (b) vertical and shear forces in beam [9]

4 ANALYSIS OF WALL/BEAM BEHAVIOR RELATED TO VERTICAL DEFORMATIONS

4.1 General

Relevant aspects of the behaviour of wall/support assembly, in case of excessive vertical deformations, can be accessed through the analysis of the evolution of stress distribution in wall and in the support, and particularly in the interface zone between wall and the support. With the increasing of vertical deformations, the stresses in the masonry wall constituents (bricks/blocks and/or mortar joints), and on that interface zone, can overcame certain limits, which lead eventually to onset of wall cracking. These limits of stress are essentially related to the strength resistance of these constituents of the wall. The estimation of stresses based of masonry wall/beam-slab model described in 3.2.2, can be useful to indicate the approximate pattern of stresses of wall/supporting assembly in a building. An approximate estimation of vertical stress distribution along the contact surface wall/beam-slab, can be made assuming it dependent on the stiffness parameter K_d defined for the referred masonry wall/beam-slab model, as defined in 3.2.2. Considering the usual brittle and fragile characteristics of masonry walls, compared, in terms of strength, with its supports (beam/slab), these walls are more susceptible to cracking, especially in case of the presence of openings (see in Figure 4 the variation of bending moment in the beam with different openings).

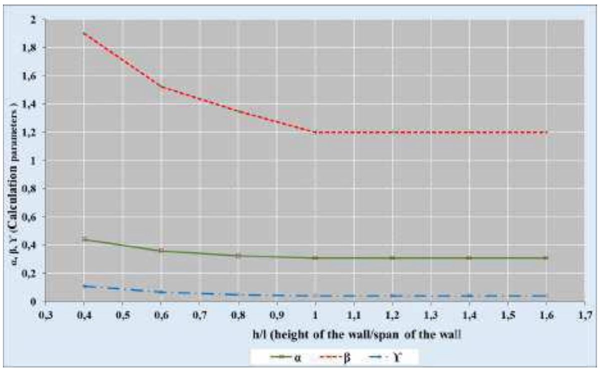


Figure 3. Definition of the constants α, ß, e γ [9]

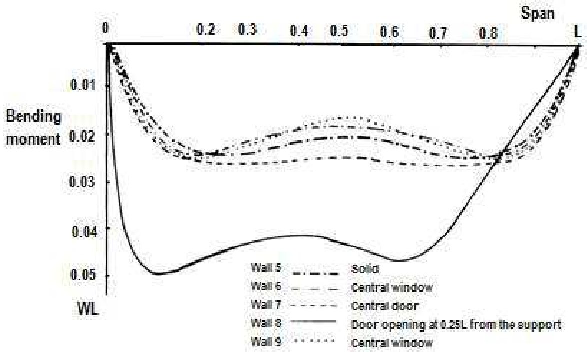


Figure 4. Beam moments in wall-beam with openings [9]

4.2 Stresses in the constituent elements of masonry wall-beam/slab assembly and related strength characteristics

The assessment of masonry wall-beam/slab assembly behaviour subjected to excessive vertical deformations, particularly the approximate location of corresponding cracking, can be based on the analysis of the stresses installed on that assembly and the strength characteristics of their constituents. Masonry elements composed by masonry units and mortars (bricks, concrete blocks, etc.), compared with the reinforced concrete supports, present a lower ductile behaviour and a lower tensile strength, which could lead to cracking in the wall, for large imposed vertical deformations. Considering the masonry element, cracking may occur if the tensile, compressive or shear stresses in the masonry wall are larger than the strength of the masonry. The same considerations apply to the masonry wall-beam/slab interface. At the level of masonry constituents, it is particularly important to study the behaviour of the mortar joints, as planes of weakness, regarding its evolution from the onset of cracking, till it reaches the failure caused by certain imposed stress state associated to excessive wall/support deformations due to vertical loads.

Combinations of tension, shear, and compression failure modes can be adequately considered through a failure envelope curve for a masonry element [6], where the tensile failures of the bed joints and cracking of the bricks are included. Detailed modes of failure in a masonry element could be [10]: cracking of the masonry units in shear; splitting of masonry units in tension; and diagonal tension cracking of masonry units; cracking in the joint; sliding along a bed joint. Properties of mortar and masonry units can influence the shear bond strength of the mortar joints to a lesser extent than the level of precompression and, depending on that level, failure can occur in the joints alone or as a combined block/brick or mortar joint failure [16]. Hence, the influence of mortar joint strength must be considered in the failure of masonry; other properties, particularly, related to crack propagation, dilatancy and softening, can also influence the behaviour of masonry elements.

In some cases of excessive vertical deformation, a near vertical crack can occur at the mid span of masonry wall. In this case, as deformation increases, a tensile failure of brick/block-mortar interface can occur, especially, in zones with high concentration of stress, and where mortar joints have low tensile bond strength. In the vertical load of wall/support assembly, the formation of an arc of compression can generate high compressive stress in the wall, near the ends of the support, and a formation of cracks that grow parallel to the direction of the compressive stress. In this case, also compression/shear stress can develop in the upper zone of the wall (Figure 1b), as well as in the lower zone of the wall near both ends of the support (Figure 1c). In case of vertical loads, the behaviour of the interface between concrete supporting elements and masonry wall, which is relevant for overall wall/support assembly behaviour, depend on the strength characteristics (tensile and shear bond strength) and ductility of the interface joint between masonry units and the concrete support, in particular of that joint material [16]. A tensile failure (near horizontal crack) is possible at the base of the masonry panel subjected to excessive deformations due to vertical loads [1], by lack of tensile bond strength of the link between the mortar and the masonry unit (example of Figure 1a) or of the link between the mortar and the support (in case of horizontal crack in the interface wall/support).

4.3 Analysis of basic behaviour of masonry wall-beam/slab assembly in case of excessive vertical deformations

4.3.1 General

To characterize the behaviour of masonry wall-beam/slab assembly in case of excessive vertical deformations, among other influential factors, height/span ratio of the wall (h/L) and the stiffness parameter, K_d, should be considered. To simplify the analysis of the behaviour of wall-slab/beam assembly subjected to vertical deformations, it can be assumed that vertical displacements applied on the top of the masonry wall are, approximately, correspondent to a uniform distributed load applied by upper supporting element to the wall. Therefore, taking into account the model exposed in 3.2.2 (wall/support), the distribution of stresses in the wall/support assembly in a building, in case of excessive vertical deformations, should be in part dependent on the rigidity of the lower supporting element. That dependence, in simplified terms, could be expressed, for a determined value of height/span ratio (h/L) of the wall, in three main conventional situations, which the behaviour of wall/support assembly can be included: a low rigidity (high flexibility); a medium rigidity (medium flexibility); and a high rigidity (low flexibility). In the following, relevant interesting combinations of height/span ratio of the wall (h/L) and the stiffness parameter K_d (4.3.2, 4.3.3 and 4.3.4) are analysed, relatively to the behaviour of masonry wall-beam/slab assembly in case of excessive vertical deformations.

4.3.2 Type of behaviour related to high span/height ratio of the wall and low rigidity of the support

In one type of behaviour referred by ISO 4356 [4], the height/span ratio (h/L) of the wall is lower than 0,29 (i.e. L/h > 3.5), and the supporting element (beam or slab) forces the supported wall to deform in its own plane, following the deformations of that supporting element, and possibly absorbing some load from the upper confining beam (or slab), with likely cracking of the wall; when a certain deformation limit of the supporting element is reached, a vertical cracking can generally manifest in its maximum deformation zone (half span), at the bottom of the wall, as well as oblique shear cracking in the upper corners of the wall, and a separation cracking in the interface between the wall and the upper beam (or slab).

Considering the wall/beam model described in 3.2.2, and assuming the ratio h/L lower than 0,29, for K_d lesser or equal than 5, the beam/slab can be considered to have high flexibility (with similarity with the case described above of the supporting element forcing the supported wall to deform in its own plane); the distribution of vertical contact stress approximates to a third-degree parabola and is prolonged to the centre of the beam/slab, being less concentrated on the supports. The concentration of vertical stresses, f_m, is following estimated, for K_d lesser or equal than 5 (for the value of h/L = 0.29, according to Figure 3, $\beta \approx 2.1$; p_w is the mean pressure vertical load in the wall).

$$\frac{\mathrm{h}}{\mathrm{L}} = 0.29 \ \rightarrow \beta \approx 2.1 \rightarrow \ f_m = p_w \, . \, C_1 = p_w \, . \, [1 + 2.1 \text{ x } \ K_d]; \ K_d \leq 5 \rightarrow \ f_m \leq 10.5 \text{ x } \ p_w \qquad (7)$$

In this model, as the deformation of the support increases, relevant stress concentration in the supports can occur and compressive stress in the wall increases. In case of a high flexible supporting element, as the deformation increases, the compressive stress in wall near the ends of the supporting element also increases; maximum vertical pressure, f_m, near the end of the wall/beam could be near ten times the mean vertical pressure – see equation 7. If the stresses installed on the walls are higher than the compressive and shear strength of the bricks/block and of mortar joints, a situation of local masonry wall crushing may occur. Also shear stress can increase in the interface wall/support near the supports. Tensile stresses distributed throughout the central part of the wall can be significative and, if the horizontal principal tensile stress in that zone of the wall reaches the tensile strength of the wall, an approximate vertical crack can occur at mid span of the wall, with similarity to the situation of possible occurrence of a vertical crack in the type of behaviour above described (ISO 4356 [4]).

4.3.3 Type of behaviour related to medium span/height ratio of the wall and medium rigidity of the support

In other type of behaviour referred in ISO 4356 [4], where the height/span ratio (h/L) of the wall is approximately in the range 0.29-0.67 (i.e., 1.5 < L/h <3.5), the compressive strength and deformation limit of the partition walls are high; possibly, contiguous internal partitions are present; and the openings are small in size. In addition, the supporting element (beam or slab) deforms more than the partition wall due, for example, to the absence of a partition wall on the inferior level floor and in the same plane of a reinforced concrete beam/slab. In such cases, a separation gap can be formed between the wall and the supporting slab/beam, as well as an oblique shear cracking in the upper corners of the wall. If the upper support element deforms more than the wall, and if it does not have a layer of compressible material placed on its top, there will be a tendency of wall to absorb some load from the upper support, and it is possible the occurrence of oblique shear cracking in the respective upper corners.

Considering the wall/beam model described in 3.2.2, and assuming K_d has values between 5 and 7, the beam/slab can be considered to have medium rigidity, with a parabolic (quadratic) distribution of vertical stresses. The concentration of vertical stresses, f_m, is following estimated, for K_d between 5 and 7 (for the value of h/L = 0.60, according to Figure 3, $\beta \approx 1.55$; for h/L = 0.67, $\beta \approx 1.45$).

$$\frac{\mathrm{h}}{\mathrm{L}} = 0.67 \ \rightarrow \beta \approx 1.45 \rightarrow \ f_m = p_w \,.\, C_1 = p_w \,.\, [1 + 1.45 \text{ x } K_d]; \ 5 \leq K_d \leq 7 \rightarrow \ f_m \leq 11.2.\, p_w \qquad (8)$$

Compression stresses are higher next to the supports (vertical stresses near 11.2 x p_w), with the exception of the areas located in the middle span of the base of the wall, where, due to the deformation of the medium rigid support, a separation gap can be formed between the wall and the supporting slab/beam, similar as in the type of behaviour above described (ISO 4356 [4]). The occurrence of higher deformations in the upper support element (beam or slab), which is confining at the top of the masonry wall, compared to those of its lower support element, may lead to the transmission of some load to the confining wall (the magnitude of that load could depend, in part, on the stiffness of the wall and of the upper support (beam/slab), as well as the stiffness of the wall lower support (beam/slab), which can induce high stresses, and lead to cracking in the walls, namely possible shear cracks in the upper corners of the wall (Figure 1b). That shear cracks have similarity to the situation of possible occurrence of the oblique shear cracking in the upper corners of the wall, in the type of behaviour above described (ISO 4356 [4]). There may be situations where the upper and lower support elements with medium rigidity have almost identical deformations, in which case possible cracks in the masonry wall can occur, usually, running diagonally from the corners of the base of the wall (Figure 1c).

4.3.4 Type of behaviour related to low span/height ratio of the wall and high rigidity of the support

The third relevant type of behaviour, referred in ISO 4356 [4], is related to the cases where h/L ratio of the wall is greater than 0.67 (i.e., the span/height (L/h) ratio of the wall is less than 1.5), and due to possible deformation of the upper slab/beam, the wall may absorb some load of this element, and transmit a substantial part of that load, through the effect of an arc of compression to the lower slab/beam, at the end of the span. In this case, a vertical cracking may appear in the lower part of the wall, as well as oblique shear cracking may occur in the upper corners of the wall. According to the model of 3.2.2, if K_d is greater or equal 7, the support can be considered to have high rigidity, with the distribution of vertical stresses along the contact surface approximately linear (triangular) [9], with high concentration of vertical stresses on the supports. The concentration of vertical stresses,

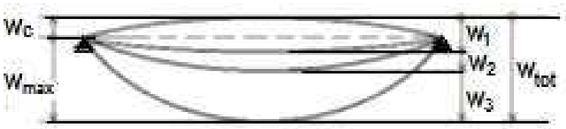
f_m, is following estimated (for values of h/L in the range 0.60-1.0, according to Figure 3, β varies, approximately, between 1.55 and 1.2; for values of h/L greater or equal to 1.0, β has a constant value of 1.2).

$$\frac{h}{L} \geq 1 \ \rightarrow \beta \approx 1.2 \rightarrow \ f_m = p_w \,.\, C_1 = p_w \,.\, [1 + 1.2 \text{ x } K_d] \ ; \ K_d \geq 7 \rightarrow \ f_m \geq 9.4 \text{ x } p_w \qquad (9)$$

It is relevant to refer, that, in the case of masonry walls with a high height/length ratio of the wall, there is a strong interaction between the wall and their supporting elements, and composite action between the two elements (wall and support) is considered progressively effective for increasing values of h/L ratio, greater than 0,67. Due to the restriction of the supports, an arc of compression on the wall is materialized, which allows the transfer of loads to the ends of the support element, inducing significant shear stresses in the area of the wall-beam connection, next to the referred ends of the supports (see Figure 2). The distribution of vertical loads along the supporting element depends on the relative stiffness of the beam/slab and the masonry wall and, in case of a high rigid supporting element, significative concentration of compression stress in the wall can be generated near the ends of the support, reaching levels of stresses eventually larger than the compressive strength of the masonry, which can be possible, mainly, due to the confinement effect caused by biaxial compression states, which could raise, locally, the effective compressive strength of the wall, [16]. This arc of compression can be associated with the possible appearance of vertical cracks in the middle area, accompanied or not by oblique shear cracks in the upper part of the wall; and also associated to the horizontal tension stresses located in the central zone of the wall (bottom part of the wall), which can possibly correspond to a vertical crack, with similarity to the situation of possible occurrence of the vertical crack in the type of behaviour above described (ISO 4356 [4]).

5 LIMITATION OF DAMAGE IN EXISTING “HBrc” BUILDINGS THROUGH PREVENTIVE CONTROL OF THE DEFORMATIONS OF THE WALL CONCRETE SUPPORTS

After building construction, their masonry walls often can have problems related to serviceability, generally due to their brittle behaviour and low tensile strength [7], which can lead to cracking phenomena that, usually, do not comprise structural risks, but can have aesthetic negative impact in buildings, particularly in “HBrc” buildings, with inevitable need of repair. Therefore, it is important the survey of the problems related to building serviceability, especially through the careful monitoring of the signs of excessive deformations of masonry walls supports, that can particularly lead to the onset of masonry cracking and their progression along the time. Besides the cases where deformations of a reinforced concrete support should not exceed certain limiting value that adversely affects its proper functioning or appearance, these deformations should not exceed those that can be accommodated by other connected elements such as partitions, glazing, cladding, services or finishes. According to EC6 (EC6 - EN 1996-1-1:2005 - Section 7, Serviceability Limit State, 7.1 General, [15]), the serviceability of masonry members should not be impaired by the behaviour of other structural elements, such as deformations of floors or walls. Generally, the serviceability limit states in buildings should take into account, for example, stiffness criteria expressed in terms of limits for vertical deflections. Vertical deformations, in accordance with EC2 (EC2 - EN 1992-1-1:2004 [14]), are represented schematically in Figure 5 (Figure 5 is based on EN 1992-1-1:2004 - A1.4.3). Deflections and limiting values may be obtained from ISO 4356 [4].



w_c - Precamber in the unloaded structural member
w_1 - Initial part of the deflection under permanent loads of the relevant combination of actions
w_2 - Long-term part of the deflection under permanent loads
w_3 - Additional part of the deflection due to the variable actions of the relevant combination of actions
w_{tot} Total deflection as sum of w_1, w_2, w_3
w_{max} Remaining total deflection taking into account the precamber

Figure 5. Definition of of vertical deflections (EN 1992-1-1:2004 - A1.4.3 - Figure A1.1)

The appearance and functionality of the structure could be reduced when the sag of the support (beam/slab) subjected to quasi-permanent loads exceeds span/250 (EC2 - EN 1992-1-1:2004 [14]), which can be a limit to consider in the survey of potential situations of excessive vertical deformations in an existing building. For the deflection after construction, span/500 is possibly a suitable limit, for quasi-permanent loads, to avoid deflections that could damage adjacent parts of the structure, and this limit should be checked in the referred survey. For heritage buildings, where there is a particular concern about sensible elements (especially decorative elements), other limits more severe may be considered. The limit state of deformation may be checked in the survey by comparing observed deflections with the limiting values of the span/depth ratio (L/d), according to EC2 (EN 1992-1-1:2004, 7.4.2). For beams/slabs (with spans exceeding 7 m) or flat slabs (with the greater span exceeding 8,5 m), which support partitions liable to be damaged by excessive deflections, the values of L/d, above referred, should be adequately increased (EN 1992-1-1:2004, 5.3.2.2 (1)), namely in case of “HBrc” buildings.

Although the values of the deformations of the infill wall supports (beams or slabs) could be lesser than the deformation limits specified on structural code EC2, these deformations can, in some cases, lead to masonry cracking, which could be inacceptable in case of “HBrc” buildings, which is very important to preserve aesthetic aspect; in worst cases, even deformation values near span/1000 can lead to cracking, and that can be, particularly, possible in the case of presence of openings, of local deficient quality of the wall or if long term effects (creep) of the supports are significative. So, the evaluation of the deformation of the supporting elements that lead to cracking of masonry walls should be based, for each specific case, on the consideration of the deformation characteristics of the walls and supports and its interaction, as well as taking in due account the results of the observation experience of buildings subjected to vertical deformations.

6 STRATEGIES FOR PREVENTION, REPAIR AND REHABILITATION OF WALLS AND REINFORCED CONCRETE SUPPORTS

Strategies for repair and rehabilitation of walls, in order to avoid or minimize the occurrence of damage due to excessive vertical deformations, should be based on a careful and detailed analysis of the anomalies, particularly related with masonry cracking. Cracking repair depends on a correct diagnosis of the source of the movements producing the cracks, and if this movement is stabilized or not [17]. In the situations where the occurrence of masonry cracking is clearly due to the excessive vertical deformations of the supports, the need to limit the progression of that cracking, which is particularly relevant in the case of a heritage building, enforces the corresponding repair actions. The main objective of the repair actions should be to enhance the capacity of the masonry to accommodate the deformations of their concrete supports, and to minimize or even avoid cracking by assuring that the induced tensile stresses in the walls are controlled; and to increase, if possible, wall tensile strength (bond strength). For this objective, it is recommended, particularly, the following: avoiding the rigid link between the masonry and the supports, through the use of joints, at the top/bottom of the infill walls, filled with a deformable mortar or other similar material, in order to allow the deformation of the support structure, without endangering the stability of those infill walls; in certain cases, the solution is strengthening the supports to minimize their vertical deformations, for example with addition of steel elements or of Fibre Reinforced Polymer (FRP).

7 CONCLUSIONS

In this paper, a general description of anomalies related to vertical deformations of the masonry walls and their reinforced concrete supporting elements was made. Relevant influencing factors of the wall-support assembly basic behaviour were presented. An analysis of wall-support behaviour related to vertical deformations is carried out, based on the study of the stresses in the constituent elements of wall-support assembly, and of their main types of deformation related with the rigidity of the reinforced concrete support of the wall, and also of the reinforced concrete element confining at the top of the wall. Serviceability requirements related to the limitation of damage in infill masonry walls, through the control of the deflections of reinforced concrete supports with due consideration of the respective building heritage relevance, are discussed. Finally, general strategies for repair and rehabilitation of building infill masonry walls with anomalies related to vertical deformations of their reinforced concrete supports, as well as for strengthening of these supports, are proposed.

ACKNOWLEDGEMENTS

LNEC Planned Research Programme (P2I Project “COREAP” – Service life, conservation and rehabilitation of walls of buildings with relevant patrimonial value) has funded the present study.

REFERENCES

[1] Centre Scientifique et Technique de la Construction, CSTC (1963). La fissuration des maçonneries. Bruxelles, CSTC, Mars, 1967. Note d´information technique 65.

[2] Burhouse, P. (1969). Composite action between brick panel walls and their supporting beams. Building Research Station. BRS CP2/70, Watford, Herts.

[3] Pfefferman, O. (1975). Fissuration des cloisons en maçonnerie due à une déformation excessive du support. Étude experimentale. CSTC - Revue, Bruxelles, 4.

[4] ISO 4356 (1977). Bases du calcul des constructions – Déformations des bâtiments à l´état limite d´utilisation. Genève : ISO.

[5] Stafford Smith, B.; Pradolin, L. (1978). A contribution towards the design of heavily loaded masonry walls on reinforced concrete beams. Proc. of North American, 1, Boulder, Colorado.

[6] Mann W.; Müller H. (1982). Failure of shear-stressed masonry - An enlarged theory, tests and application to shear walls. Proceedings of the British Ceramic Society, pp. 223-35.

[7] Page, A. W.; Kleeman, P. W.; Bryant, L. (1993). Development of serviceability criteria for masonry structures. Proc. of North American, 1, Boulder, Colorado, pp. 185-198.

[8] Miranda Dias, J. L. (1994). Cracking of masonry walls due to the movement of their supporting elements (in Portuguese). 2.º Encontro sobre Conservação e Reabilitação de Edifícios. Lisboa, LNEC, pp. 785-796. http://repositorio.lnec.pt:8080/jspui/handle/123456789/1010442.

[9] Hendry, A. W. (1998). Masonry Walls in Composite Action. Structural Masonry, pp. 226-253.

[10] Van der Pluijm, R.; Rutten, H.; Ceelen, M. (2000). Shear behaviour of bed joints. 12th international

brick/block masonry conference; 2000. doi: 10.1111/j.1743-6109.2012.02948.x.

[11] Page, A. W. (2001). The serviceability design of low-rise masonry structures. Prog. Struct. Eng Mater, Vol.3, Issue 3, pp. 257-267.

[12] Miranda Dias, J. L. (2002). Movements in masonry walls caused by temperature and moisture changes. Proceedings of 6th International masonry conference, 2002, pp. 86-94. Google Scholar

[13] Miranda Dias, J. L. (2003). Cracking around the interface joint between masonry panels and their supporting reinforced concrete beams in buildings. Proceedings of 2nd international structural engineering and construction conference, vol. I, University of Rome, Italy, pp. 745-52. Google Scholar

[14] EN 1992-1-1 (2004). Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings. Brussels: CEN.

[15] EN 1996-1-1 (2005). Eurocode 6: Design of masonry structures - Part 1-1: General rules for reinforced and unreinforced masonry structures. Brussels: CEN.

[16] Miranda Dias, J. L. (2007). Cracking due to shear in masonry mortar joints and around the interface between masonry walls and reinforced concrete beams. J. Constr. Build. Mater., 2007; 21: pp. 446-57. https://doi.org/10.1016/j.conbuildmat.2005.07.016.

[17] CIB (2015). Defects in Masonry Walls. Guidance on Cracking: Identification, Prevention and Repair - Prevention of Cracking in Masonry Walls. W023, Wall Structures. CIB Publication 403/ ISBN 978-90-6363-090-4.

[18] Sousa, R.; Sousa, H. (2015). Analysis of the susceptibility of infilling masonry walls to crack due to vertical deformation of concrete structures. 6th International Conference on Mechanics and Materials in Design. Ponta Delgada/Azores, 2, pp. 26-30.

[19] Miranda Dias, J. L. (2018). Preventive and curative measures in heritage buildings due to settlements risk with consequent degradation of their masonry walls. Congresso Betão Estrutural 2018 (BE2018), LNEC. http://scholar.google.pt/scholar?oi=bibs&cluster=4685596917337781184&btnI=1&nossl=1&hl=pt-PT