Horizontal Stiffness of Confined Masonry Walls

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http://doi.org/10.29227/IM-2024-02-14

Submission date: *17.04.2024.* | Review date: *24.05.2024*

Abstract

This paper focuses on confined masonry walls. Confined walls are very popular in the seismic regions and are used as the prevention of excessive cracking, displacement and a loss of structural integrity. In terms of structural engineering, confined walls, similarly to walls in conventional buildings with conventional load-bearing wall structure, can function as the structure restraint, and not only the walls under mainly vertical load. This paper presents the original proposition of the algorithm that determines stiffness of a single area of the confined wall without openings and with openings, which is based on the S-T (strut-and-tie) method in accordance with European standards EN 1996-1-1:2010, draft Eurocode 6 (prEN 1996-1-1:2017), having regard to American standards FEMA 274 and FEMA 306.

Keywords: *Confined masonry, Shear walls, Stiffness, Shear, S-T Model*

1. Introduction

A positive effect of the combination of a masonry wall with concrete was observed for the first time in Europe, Asia, and the USA [1] after a series of earthquakes in the first half of the 20th century. Due to permanent connection between the masonry wall and reinforced concrete elements, deformation of the confined wall clearly differs from deformation of the infill wall in the framed structure, in which the frame interacts with the framed structure only in the corners [2]. Deformation of the wall and confining elements is the same in the masonry wall [3, 4, 5] in the initial phase of loading. After loosening of the masonry from reinforced concrete elements, horizontal forces are transmitted to the masonry through corners of reinforced concrete elements. Simultaneously vertical load from the floor is transmitted to the masonry. The interaction between the masonry and confining elements leads to a change in the mechanism of cracking and failure [3]. The behaviour of the confined wall is elastic until cracking, and stiffness of the structure is the highest. When the masonry infill wall or vertical joints between the masonry wall and confining reinforced concrete elements are cracked, stiffness starts to degrade. The maximum load causes the formation of cracks along the masonry diagonal and in the loaded corner of the wall. Also horizontal cracks along the reinforced concrete core in eccentric tension can be observed. A clear increase in displacement at decreasing load is found after reaching the maximum value. Previously developed diagonal cracks in the masonry divide the wall into two diaphragms. Stiffness of the confined wall at the time of failure is determined only by friction forces in the cracks and interlocking forces in the corner of girt and the core.

The confined wall has a lot in common with the unreinforced [6] and reinforced masonry wall and the infill wall in the framed structure [7, 8]. In the elastic phase, when the masonry is bonded to confining elements, deformations of the wall are similar to those in the unreinforced or reinforced wall. Interaction between the masonry wall and the surrounding reinforced concrete leads to the formation of compressed strut, as in the masonry infill wall in the framed structure. Common features for the behaviour of the confined wall and other types of masonry restraints cause that theoretical models refer to all other models used for unreinforced and reinforced walls, and the masonry infill wall in the framed structures.

This paper is a continuation of previous papers by the author [1, 2, 3], which focus on the load distribution on shear walls in buildings with load-bearing wall structures and framed structures. This paper describes an attempt to develop the procedure for determining stiffness of a single-storey confined wall.

2. Provisions of Standards EN 1996-1-1:2010 and prEN 1996-1-1:2017

The current provisions [9] and an updated version of the standard [10] have not proposed any guidelines for analyses of confined shear walls. Points 7.5.7 and 8.10 of the standard [10] are limited to general rules for verifying ULS for compression and shearing, without specifying the rules for determining stiffness and load distribution. Also other European standards, developed in the period preceding the standardization of design provisions, do not contain any guidelines how to distribute load with regard to characteristics of confined structures and masonry infill walls in framed structures.

3. Provisions of Standards FEMA 306 and FEMA 274

There are few methods for analysing shear walls in buildings with confined walls. Recommendations consider mainly load capacity models [11], and the distribution of load requires information on stiffness of stiffening elements. Hence, stiffness of the confined wall can be determined only in accordance with recommendations from the standards, in which load capacity is determined by the S-T model. This type of solution can be found in the standards FEMA 306 [12] and FEMA 274 [13], which specify the same method for analysing infill walls in the framed structure according to the diagram shown in Fig. 1. The diagonal strut coincided with the masonry diagonal was accepted for calculations performed to verify serviceability limit states and to determine stiffness. However, for eccentricities in columns and beams, two solutions, which are presented in Fig. 1, were analysed. It was clearly indicated that the masonry infill wall could be included in the calculations providing that the initial shear strength met the condition where $\tau 0 \geq 0.34$ N/mm2.

A width of the masonry strut can be determined from the relationship:

$$a = 0{,}175(\lambda_1 h_{col})^{-0{,}4} d \quad , \tag{1}$$

where:
d – a strut length (a diagonal of the masonry infill wall) calculated as:

$$d = \sqrt{h_n^2 + l_n^2} \quad . \tag{2}$$

A length of the contact area between the strut and the horizontal member in the column-to-column model is equal to:

$$l_{beff} = \frac{a}{\cos\theta_b} \quad , \tag{3}$$

and in the beam-to-beam model, this length is equal to:

$$l_{ceff} = \frac{a}{\cos\theta_c} \quad , \tag{4}$$

λ1 – coefficient determined form the following relationship:

$$\lambda_1 = \sqrt[4]{\frac{E_m t \sin 2\theta}{4 E_{col} J_{col} h_m}} \quad , \tag{5}$$

θb, θc – inclination of struts acc. to Fig. 1.

Based on the above mentioned standards, load capacity of the compressed strut should be determined from the following relationship:

$$\begin{aligned} R_s &= \frac{(\tau_0 + \mu\sigma_y) l t}{\cos\theta} \quad \text{– shearing,} \\ R_{dt} &= 2\sqrt{2} t h_n f_t^{'} \cos\theta \quad \text{– tension,} \\ R_{cc} &= a t f_{m90}^{'} \quad \text{– horizontal compression,} \end{aligned} \tag{6}$$

where:
τ0 – initial shear strength of the masonry,
μ – friction coefficient of mortar in bed joint,
$f_t^{'}$ – tensile strength of the masonry,
$f_{m90}^{'}$ – compressive strength in a direction parallel to the plane of bed joints,

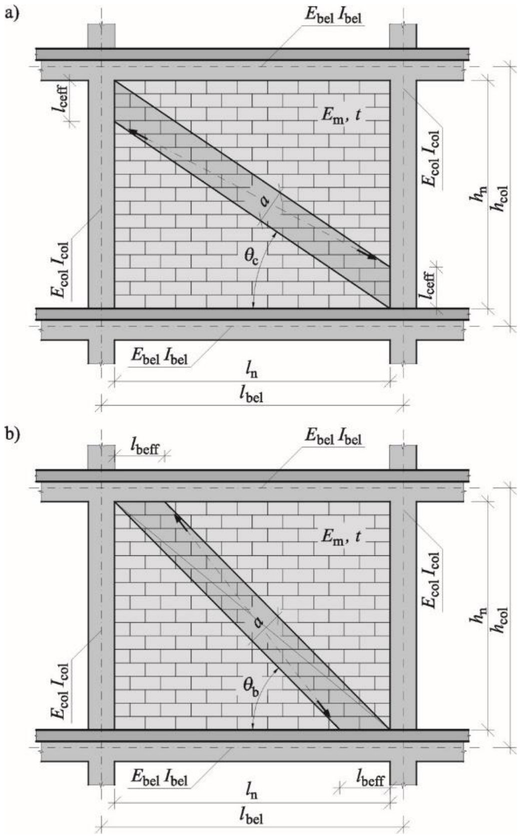

Fig. 1. Models of the frame with masonry infill according to FEMA 306 [12] and FEMA 274 [13] standards: a) model for determining eccentricities in beams (beam-to-beam), b) model for determining eccentricities in columns (column- to-column)

4. Algorithm for Determining Stiffness with the S-T Method

As in the masonry infill walls in the framed structures, confined walls [8] are analysed using rebar (strut-and-tie) models and diaphragm models. The majority of design standards specify ULS, but do not include stiffness issues of confined walls. In case of the strut-and-tie models, any provisions concerning stiffness can be found in the standards applicable in non-European countries. Generally, the diaphragm models have not been included in any provisions. A lack of unambiguous opinions on the interaction between the masonry and confined reinforced concrete elements is a possible reason. Further in this paper, there is described the original approach to the distribution of loads onto shear walls with the strut-and-tie method.

This method, which is used to verify ULS for the confined wall, and also the infill wall, can be also applied to determine stiffness and the distribution of loads. When the masonry and reinforced concrete (confining) elements act compositely, American standards FEMA 306 [12] and FEMA 274 [13] propose replacing the masonry with the compressed strut, whose width is calculated from the following equation:

$$a = 0{,}175d\left(h_{col}\sqrt[4]{\frac{E_m t \sin 2\theta}{4E_{col}I_{col}h_m}}\right)^{-0{,}4}, \tag{7}$$

where:

d – a length of the strut equal to a length of the masonry infill wall:

$$d = \sqrt{h_m^2 + l_m^2}. \tag{8}$$

Thus, a determined width of the strut is lower by at least 50% than a width of the strut determined in the masonry infill wall in the frame. This result is a consequence of an assumption that a dedicated strut in the confined masonry acts only with vertical confining elements.

A conventional strut-and-tie model replacing the frame is the second significant difference with reference to the masonry infill walls in the framed structure. Stiffness of a single-area confined wall (Fig. 2a.) is determined by replacing the structure composed of vertical cores and the masonry with vertical core (T bar) and diagonal strut (S bar) which are pin jointed – Fig. 2b, c.

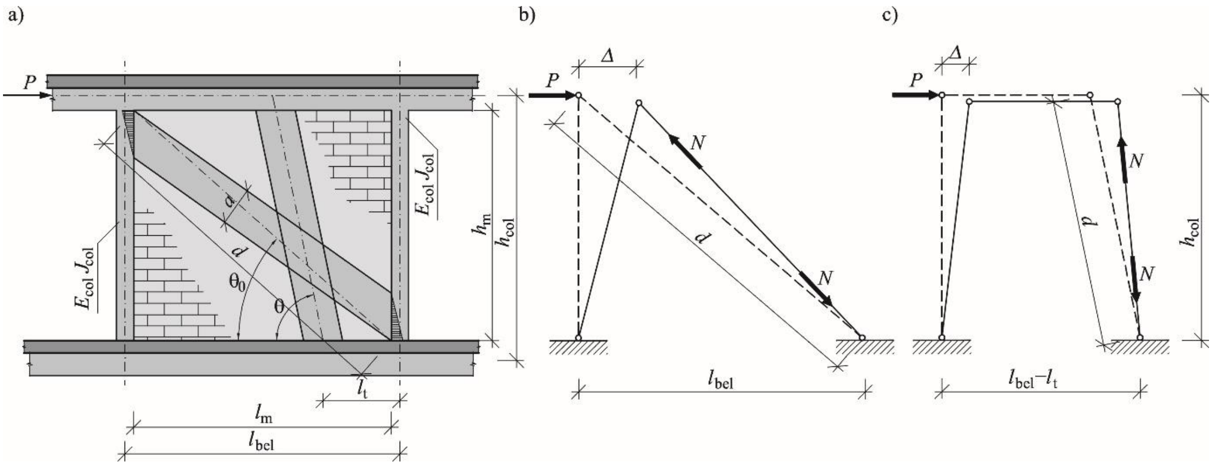

Fig. 2. A truss model of a single area of confined wall: a) geometry and markings, b) S-T model of a slender wall hcol/lbel>1.0, c) ST model of a squat wall hcol/lbel≤1.0

The standard [13] does not specify how to include dimension ratio of the wall and the contribution of load on the floor. Following the paper [14], under the combined horizontal and vertical (from the floor) load inclination of the strut can be determined from the following relationships:

$$\theta = \begin{cases} 81{,}47\theta_0^{-(5{,}87\mu + 0{,}42)} \rightarrow h_{col}/l_{bel} \le 1, \mu < 2 \\ 1{,}118\theta_0\mu^{(0{,}455\theta_0 - 0{,}547)} \rightarrow h_{col}/l_{bel} > 1, \mu \ge 2 \end{cases}, \tag{9}$$

where:

θ0 – an angle of inclination of the wall diagonal, expressed in radians,

μ – the ratio between horizontal shear load P and the total vertical load on the wall G+Q.

The displacement lt of the bottom strut against the wall corner is determined from the following relationship:

$$l_t = \begin{cases} -(7{,}74\mu + 1{,}48)(h_{col}/l_{bel}) + 2{,}59\mu + 2{,}81 \rightarrow h_{col}/l_{bel} \le 1 \\ (3{,}70\mu + 1{,}20)(h_{col}/l_{bel}) - 9{,}61\mu + 2{,}56 \rightarrow h_{col}/l_{bel} > 1 \end{cases}. \tag{10}$$

Under load distribution on shear walls, it is not necessary to modify the inclination and position of the bottom node in the compressed strut as only horizontal load is taken into account. The truss shape can be additionally corrected while verifying ULS.

Horizontal displacement of the frame with any inclination of the strut can be determined from the following expression:

$$\Delta = \frac{P h_{col} tg^2\theta}{E_{col}A_{col}} + \frac{P h_{col}}{E_m A_d \sin\theta \cos^2\theta}, \tag{11}$$

where:

Ad = atm – cross-sectional area of the compressed strut,

P = 1 kN.

Stiffness of the truss model shown in Fig. 2b, c is equal to:

$$K=\frac{(E_{col}A_{col})(E_m A_d)\sin\theta\cos^2\theta}{h_{col}(E_m A_d)\sin^3\theta+h_{col}(E_{col}A_{col})}. \tag{12}$$

A force in the compressed strut should be determined from the following relationship:

$$N=\frac{E_m A_d}{d^2}l_{bel}\Delta. \tag{13}$$

Options concerning confined walls with window and door openings can be divided into two groups:

a) group I – confined walls with unconfined openings,
b) group II – confined walls with confined openings.

In walls from Group I, the area of an opening is smaller than the maximum value of 1.5 m2 as specified in the standard [9]. For the above cases the procedure specified in the standard ASCE/SEI 41-13 [15] is sufficient for including the presence of openings and is based on reducing stiffness of the wall without openings in accordance with the following relationship:

$$K_{ini}^{opening}=\left(1-2\frac{A_{op}}{A_w}\right)K_{ini}^{solid}, \tag{14}$$

where:
Aop – an area of openings,
Aw – a cross-sectional area of infill wall,
K_{ini}^{solid} – stiffness of the truss model without openings calculated from the equation (12).
If Aop ≥ 0.5Aw, then the compressed strut can be neglected in the analysed area of the wall.

For the confined walls from Group II, when the openings are surrounded with confining reinforced concrete elements, the arrangement of bars depends on the dimension ratio of the wall components – wall strips, lintels, opening areas, and structures of floors. None provisions have contained reliable guidelines; thus, reliable recommendations described in the literature can be applied. The paper [16] formulated neutral recommendations for creating the S-T model of the wall with different types of openings.

In case of the wall with a single door opening, where the dimension ratio of the end panel is h/l≤2, and the floor is elastic, a diagonal strut can be modelled in such a panel (Fig. 3a). For the wall with the rigid floor, panel 1 should be modelled as the diagonal strut when the dimension ratio is h/l≤2.5 (Fig. 4a).

If the floor is flexible, it is recommended to model the lintel as the diagonal strut running from the opening corner to the opposite bottom corner of the panel regardless of the dimension ratio and loading rate providing that hn/ln > 0.3. Otherwise the strut in the lintel is recommended (Fig. 3a).

If the floor is rigid, the diagonal strut is recommended in the lintel regardless of the dimension ratio and the rate of lateral loading (Fig. 4). For the wall with the flexible floor, it is permissible to model the end strip of the wall as the diagonal strut. When the ratio of dimensions of the lintel is hn/ln > 0.3, the end strip can be neglected (Fig. 3b). It is also recommended to neglect the presence of the end strip of the wall for the wall with the rigid floor (Fig. 4). When a window opening is in the wall, besides two end wall strips, there is also a lintel and a spandrel area. In case of the flexible floor (Fig. 5), the end strip of the wall does not have the strut if the dimension ratio is h/l > 2.5 (Fig. 5a). The end strip of the wall can be replaced with the diagonal strut when the ratio is h/l ≤ 2.5, and the ratio for the lintel strip is hd/ln > 0.3 (Fig. 5). If the dimension ratio for the end strip of the wall is not greater than 2.5, and the ratio between the height and the length of the spandrel area is greater than 0.3, the strut in the end strip does not run along the wall diagonal, but is approaching the bottom corner of the opening (Fig. 5). The end strip of the wall and the spandrel area can be replaced with the struts if the dimension ratio is greater than 0.3 (Fig. 5). If the lintel is not modelled with the diagonal strut, then the spandrel area can be represented by the diagonal strut. Otherwise the strut is not needed in the spandrel area, except for the situation when the dimension ratio of the lintel and spandrel area is greater than 0.3 (Fig. 5).

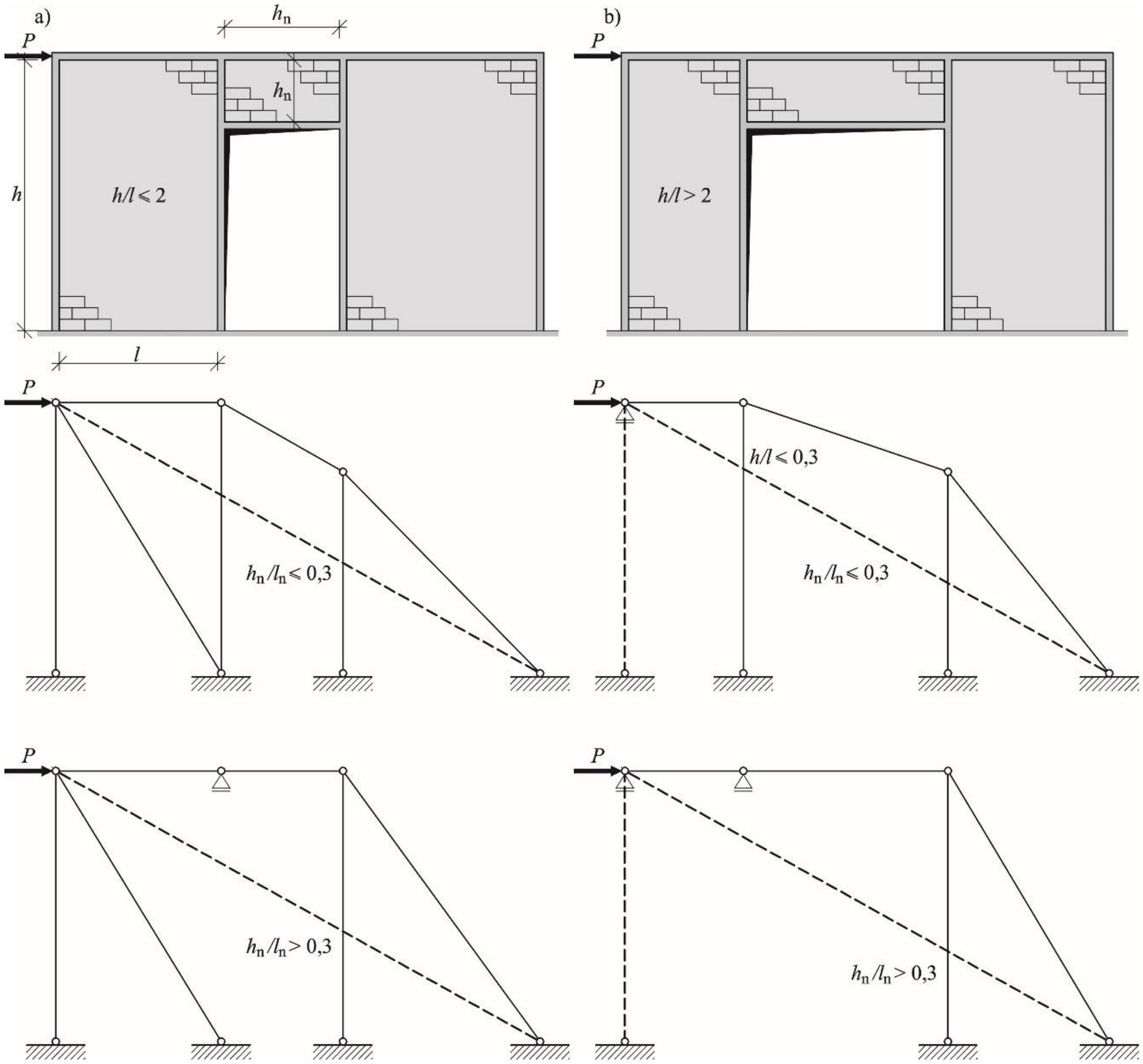

Fig. 3. S-T model of a wall loaded horizontally with a door opening and a flexible floor (description in the text)

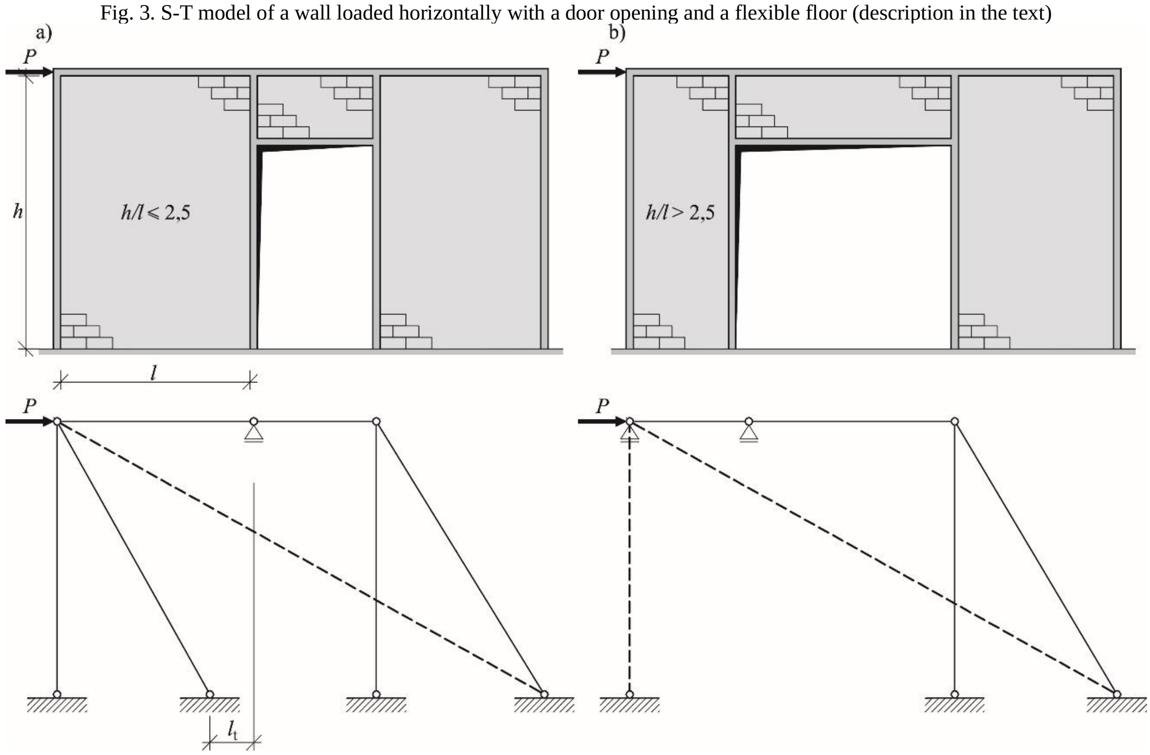

Fig. 4. S-T model of a wall loaded horizontally with a door opening and a rigid floor (description in the text)

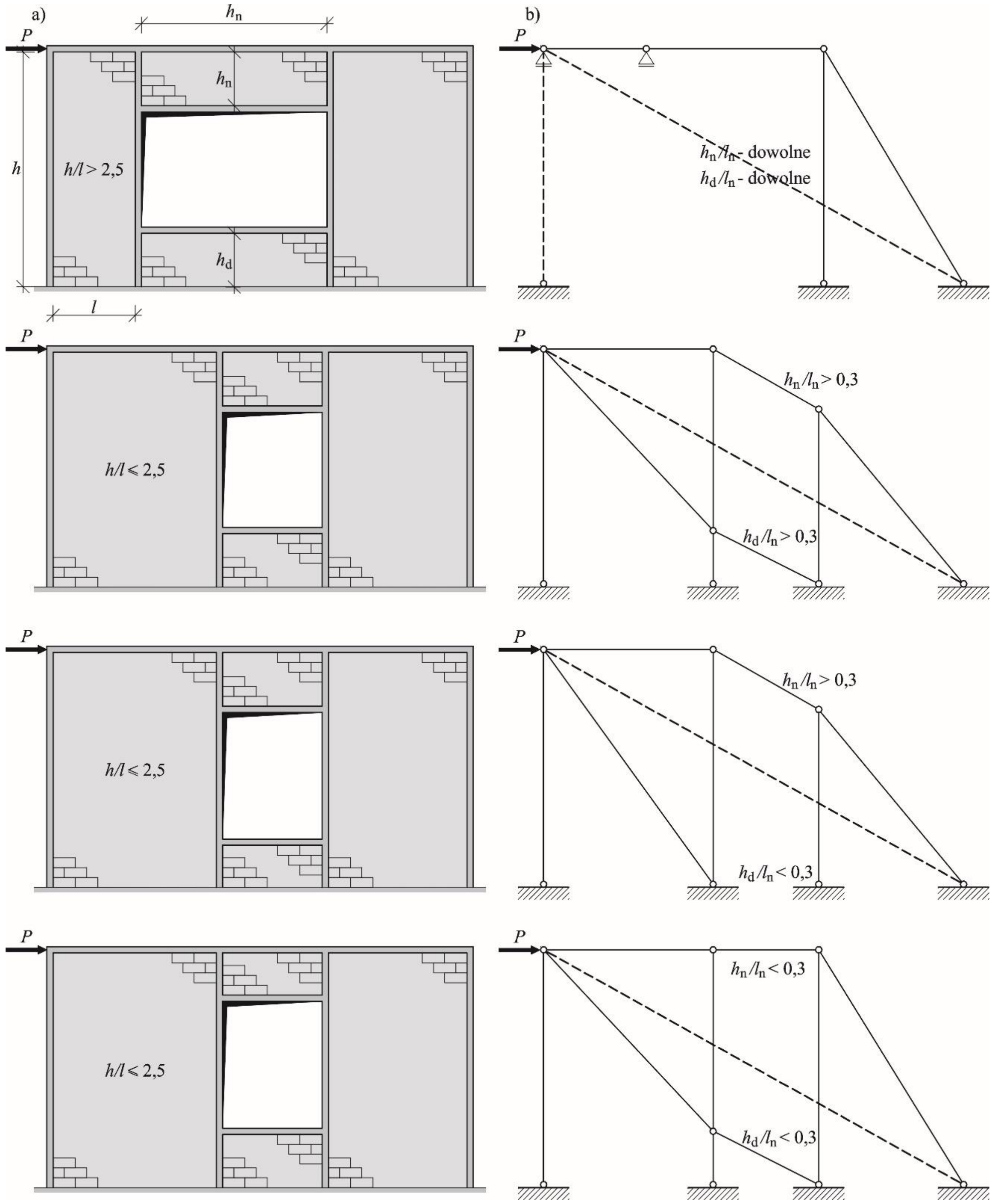

Fig. 5. S-T model of a wall loaded horizontally with a window opening and a flexible floor (description in the text)

In case of the flexible floor (Fig. 6), the strut is formed in the end strip of the wall if its shape factor (h/l) is greater than 2.5 (Fig. 6a). The end panel can be modelled with the diagonal strut if its shape factor is not greater than 2.5, and the dimension ratio of the spandrel area is lower than 0.3. If the shape factor for the wall strip is not greater than 2.5, and that for the spandrel area is greater than 0.3, the strut does not run along the wall diagonal, but is approaching the bottom corner of the opening in the end strip. The spandrel area should be modelled with the strut when the shape factor is greater than 0.3, otherwise it can be neglected. The lintel should be neglected regardless of its ratios, and panel 3 should be always modelled with the diagonal strut.

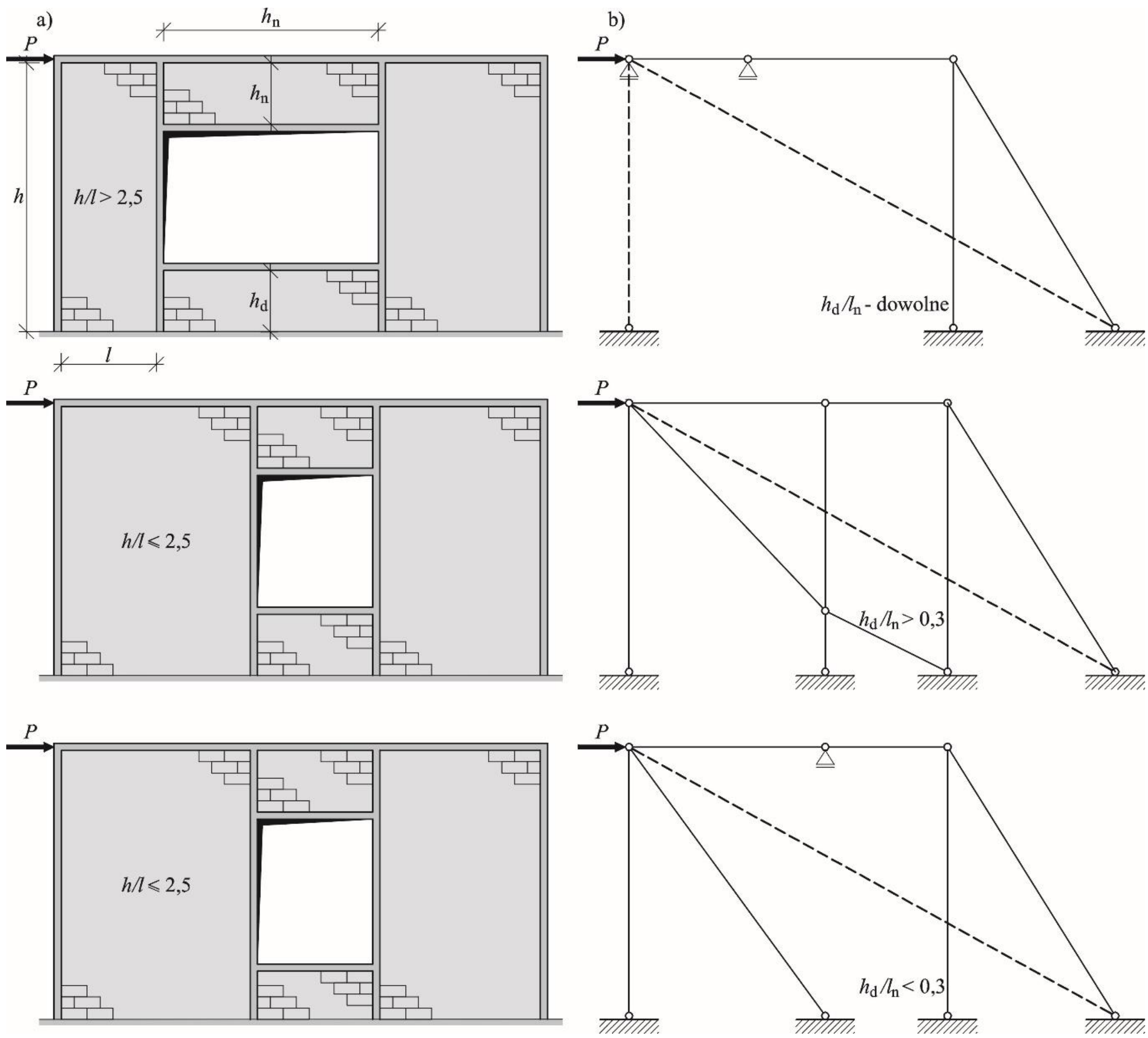

Fig. 6. S-T model of a wall loaded horizontally with a door opening and a flexible floor (description in the text)

To determine stiffness Kcal of any confined wall, horizontal displacements of the developed S-T models should be determined at first. For statistically determinable trusses, displacement and then stiffness can be calculated analytically. In other cases it is reasonable to create a numerical FEM model. The wall with an opening with a complex arrangement of bars can be replaced with an equivalent strut with the identical stiffness and the area equal to:

$$A_d = \frac{K_{cal} E_{col} A_{col} h_{col}}{E_{col} E_m A_{col} \sin\theta \cos^2\theta - K_{cal} E_m h_{col} \sin^3\theta} \quad (15)$$

This procedure allows the combination of a few confined walls (trusses) even with the complex arrangement of openings. In case of a group of confined walls arranged in series, first the S-T model should be developed for each individual wall, and then they should be pinned – Fig. 7.

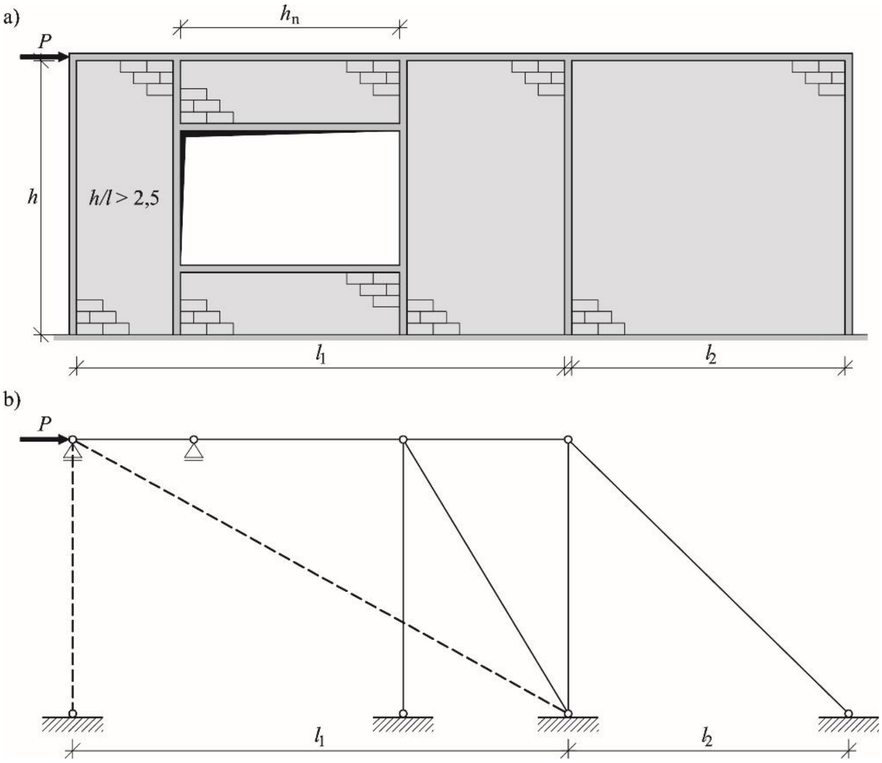

Fig. 7. S-T model of a group of two confined walls (description in the text)

A similar procedure can be applied to multi-storey confined walls. Regardless of stiffness of the floor, the multi-storey confined wall with or without openings can be divided into groups of one-storey walls – Fig. 8.

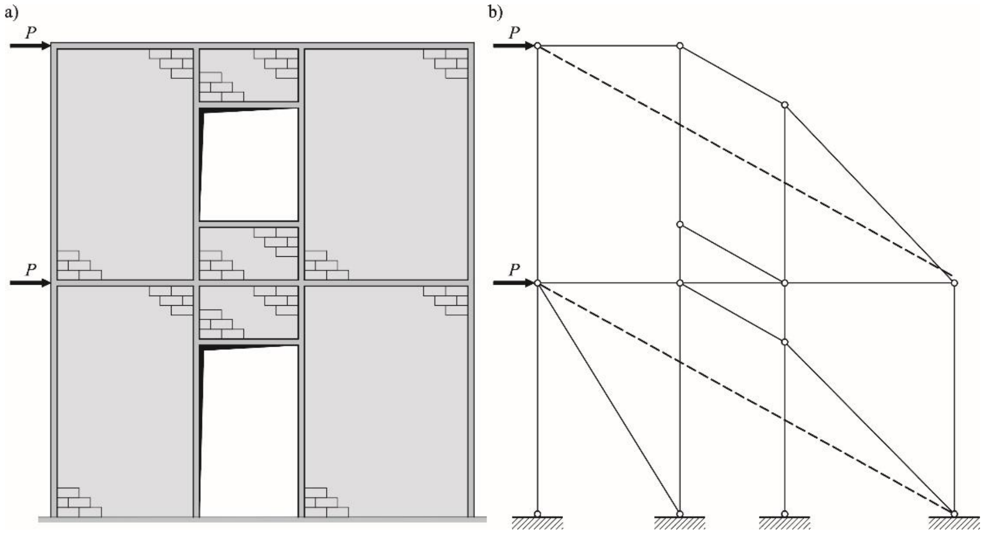

Fig. 8. S-T model of a two-storey confined wall (description in the text)

After determining stiffness of individual stiffening groups, stiffness of the whole wall can be determined assuming that individual trusses are arranged in series. Stiffness of the whole shear wall $K_w = \sum K_i$ is a sum of stiffness values of components of the trusses Ki [8]. If the trusses are placed storey by storey, then stiffness is determined as in case of the wall with an opening.

5. Conclusion

If horizontal displacements of the shear wall are known, then horizontal loads can be distributed. This paper proposes the strut-and-tie method, in which the confined masonry wall can be replaced with the truss. Based on the calculation procedures specified in the standards [12, 13] the relationships were developed to determine stiffness of a single area of the confined wall. The created theoretical models were adjusted to European standards [9, 10]. It was proposed to adapt the original methods, described in the paper [14, 16] to walls with openings and multi-storey walls. Stiffness of individual stiffening groups allows the distribution of loads as in the buildings with load bearing wall structure [6] and framed structure [8] and consists in replacing the walls with elastic supports.

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