The Proposed Method for Determining Stiffness of Multi-Storey Masonry Shear Walls in Frame Buildings

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Abstract

The structure in frame buildings is stiffened with masonry infill walls. Such walls have a structural role and provide the stable geometry of the structure. It is characteristic for infill walls that they cannot take vertical loads from girts and slabs. The main objective of this paper is to develop the coherent procedure for determining stiffness in compliance with the current design standards. This paper presents the original bar method to determine internal forces in units in the multi-storey and multi-bay frame with masonry infill. The used relationships determined geometrical parameters of the compressed strut. The division into "slender" and "rigid" frames was introduced. The "slender" frames included frames with stiffness only at individual storeys, and the "rigid" frames included frames with masonry infill at each storey. It was proposed to extend the requirements for portal frames with additional requirements concerning the position of hinges in horizontal members of the frame. Stiffness determination and load distribution are the same as in the method used for walls in load-bearing structures and (one-storey) frame buildings. Elastic supports with stiffness determined from the solutions obtained for equivalent subsystems are introduced into horizontal planes of the storeys. The discussed method can determine internal forces in the walls in a safe manner.

Keywords: *Masonry Structures, Skeleton structures, Walls infilled frames, Stiffness of Wall*

1. Introduction

The most common method for determining stiffness of a framed structure with masonry infill walls is the wall replacement with a diagonal bar. In case of a wall with openings, one strut can be replaces with a few struts pin-connected to the frame. The bar method can safely determine cracking and maximum forces. This paper [1] describes the procedure for determining stiffness of a single-storey wall which infills the framed structure. Determination of stiffness in multi-storey frames is more troublesome. The main objective of this paper is to develop the coherent procedure for determining stiffness in compliance with Eurocode 6 and other current design standards. This paper is a continuation of previous papers by the author [1, 2, 3], which focus on the determination of stiffness and distribution of load on stiffening walls.

2. Standard requirements

The standard EN 1996-1-1 [4] and prEN 1996-1-1:2017 [5] have classified walls into load-bearing and non-load-bearing walls. As specified in point 1.5.10.1 [4] a stiffening wall should be considered as a load-bearing walls as it is designed to carry an imposed load in addition to its own weight. As specified in the standard [4], point 1.5.10.10, a stiffening wall is "a wall set perpendicular to another wall to give it support against lateral forces or to resist buckling and so to provide stability to the building". Walls which infill frames have a stiffening function as described in the standard [4] (point 6.2 and 6.7) are considered as shear walls. However, the interaction with the framed structure and the support against forces provided only by corners cause that such walls do not take any vertical loads from floors and girts in frames. The only observed load is an own weight of the wall and secondary items. The standards [4, 5] do not specify any recommendations for conducting a statistical analysis and dimensioning such a type of the structure.

The paper [1] described a relevant procedure for determining stiffness of a single-bay wall infilling the framed structure. This method was developed on the basis of the Canadian standard CSA S304.1-04 [6]. According to [6], the masonry infill can be replaces with the following width:

$$a = \frac{1}{2}\sqrt{a_h^2 + a_v^2}, \tag{1}$$

where:

$$a_v = 2{,}24\sqrt{\frac{E_{col} J_{col} h_n}{E_m t \sin 2\theta}}. \tag{2}$$

$$a_h = 4{,}44\sqrt{\frac{E_{bel} J_{bel} l_n}{E_m t \sin 2\theta}}. \tag{3}$$

or:

$$a_h = 2{,}24\sqrt{\frac{E_{bel} J_{bel} l_n}{E_m t \sin 2\theta}}. \tag{4}$$

The US standard ASCE/SEI 41-13 [7] considers the interaction between the framed structure and the masonry infill. No strut is introduced in this case, but the framed structure and the masonry wall are assumed to be tied. Stiffness of the connected framed

structure and the masonry wall is determined as in case of the bar with an I-shaped cross-section (columns are flanges, and the masonry wall is the web). Stiffness is calculated from the following equation:

$$K_{ini}^{solid} = \frac{1}{\frac{1}{K_{fl}} + \frac{1}{K_{shl}}}, \tag{5}$$

where:
K_{fl} – flexural stiffness of reinforced concrete columns of the frame,

$$K_{fl} = \frac{3E_c J_{ce}}{h_{cb}^3}, \tag{6}$$

K_{shl} – shear stiffness of the masonry wall.

$$K_{shl} = \frac{A_w G_m}{h_n}, \tag{7}$$

A_w – a cross-sectional area of masonry infill,
$G_m = 0{,}4E_m$ – modulus of masonry shear strain,
E_c – modulus of concrete elasticity,
J_{ce} – moment of inertia of cross-section of columns in the reinforced concrete frame,
b, h – width and height of cross-section of a column,
E_s – modulus of reinforcement elasticity,
A_{op} – an area of column reinforcement,
$h_{cb} = h_n$ – a column height equal to a height of the masonry infill.

3. Stiffness of multi-bay frame

Stiffness of multi-bay frames with masonry infill [1] can be determined by the method of portal frames. The proposed modification consists in replacing infill walls with flexible horizontal supports and working under the following assumptions:

a) a multi-field system is divided into equivalent subsystems,
b) horizontal points of the division occur at places of zero bending moments,
c) zero bending moments in girts are observed at:
  i) the midspan of girts in case of fields in the frame without masonry infill,
  ii) 2/3 of the girt span in case of edge girts without infill,
  ii) 1/3 of the girt span in case of internal girts without infill,
d) columns are regarded as rigidly fixed,
e) masonry infill walls are replaced with flexible supports with stiffness k_s, which are introduced into separated bar systems,
f) stiffness of the equivalent subsystem is determined taking into account rotation of columns.

The procedure for developing an equivalent model of the multi-bay frame with masonry infill is presented in Fig. 1. At first, a width of compressed strut is determined from the relationship (1) and stiffness is determined from the following equation

$$k_s = \frac{EA}{d}\cos^2\theta. \tag{8}$$

Then, a frame with infill (Fig. 1a) is replaces with a bar model (Fig. 1b). The model is equipped with hinges in grits (Fig. 1c). In the final stage, separated bar subsystems composed of individual columns, girts and flexible supports representing masonry infill are loaded with a unit force P=1. The horizontal displacement of each subsystem Δ is searched to determine stiffness of the whole model.
It is necessary to determine stiffness of each subsystem, and then the overall stiffness of the system from the following equation:

$$K_w = \sum K_i, \tag{9}$$

where:
$K_i = 1/\Delta_i$ – stiffness of a bar subsystem,
Δ_i – horizontal displacement of a subsystem [1],
The overall horizontal displacement of the system is:

$$\Delta_c = \frac{P}{K_c}, \tag{10}$$

and internal forces acting on each of the subsystems are equal to:

$$P_{ci} = P\frac{K_i}{K_c}. \tag{11}$$

The above can be used to determine forces in individual compressed struts, which are equal to:

$$F_{mi} = \frac{EA_i}{d}\Delta_c\cos\theta. \tag{12}$$

This method can generate horizontal displacements greater by approx. 5% with reference to the detailed solution obtained from numerical or analytical methods. Therefore, stiffness of the whole model and internal forces in the frame bars can be carefully overestimated.

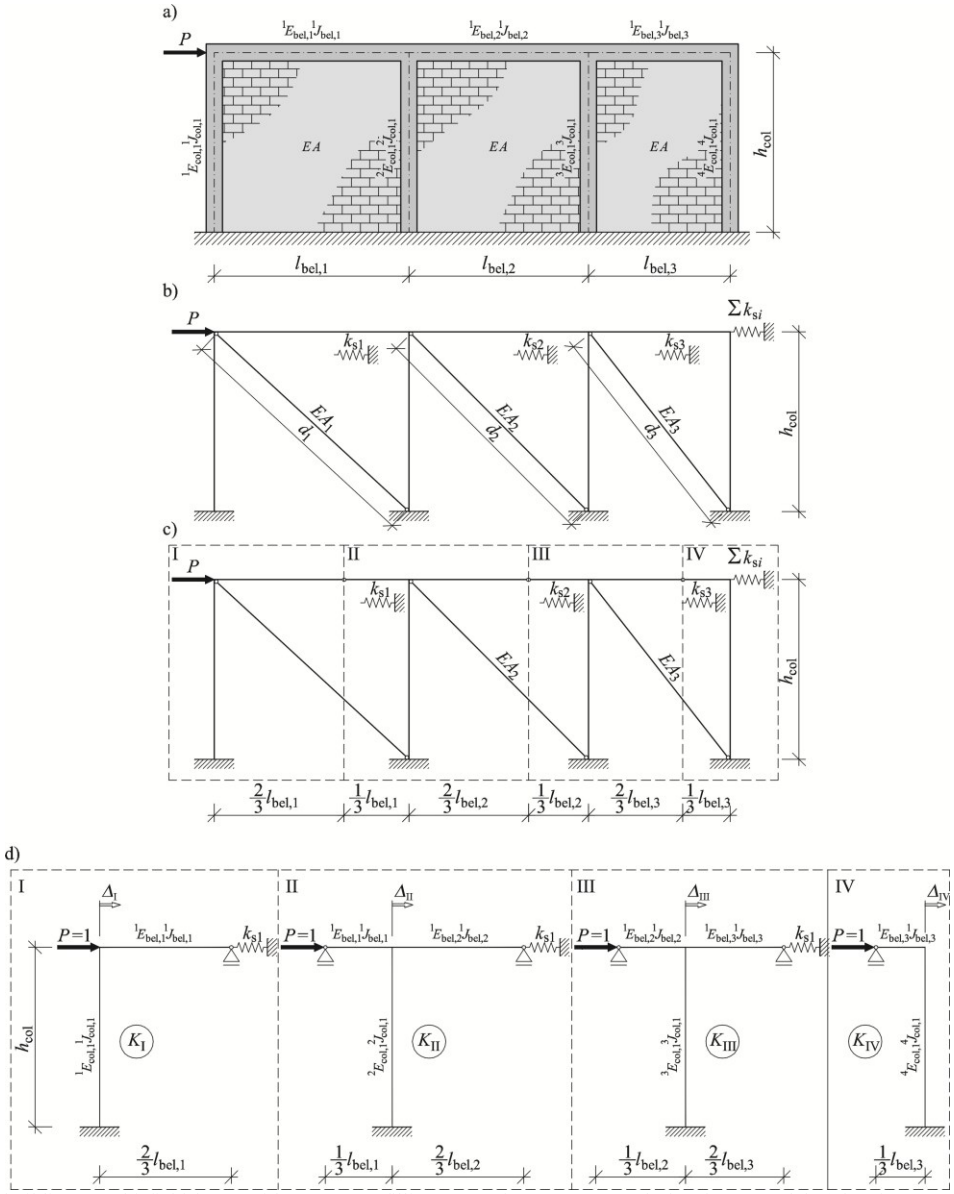

Fig 1. Stages of building a multi-field frame with a masonry filling [1]: a) frame geometry, b) bar frame model, c) bar frame model divided into equivalent subsystems, d) static diagrams of equivalent subsystems

4. Proposed method for calculating stiffening of a multi-storey frame

For multi-field multi-storey frames, the procedure for developing bar subsystems is similar to that for a single-storey model. However, the frames should be categorized into "slender" or "rigid" ones. The "slender" frames – Fig. 2 – should include frames with stiffness only at individual storeys, whereas the "rigid" frames – Fig. 4 – have masonry infill at each storey.

All fields of "slender" frames with masonry infill require hinges in girts. In the girt with a strut replacing the masonry, a hinge is within a distance of 2/3 of the girt span. A hinge in the adjacent girt should be at a distance of 1/3 of the girt span.

Stiffness is determined by at first distinguishing storeys with masonry infill, and then their division into individual equivalent subsystems – Fig. 2c. The result obtained for each subsystem is used to determine horizontal stiffness and a moment the column restraint. The overall horizontal displacement of each subsystem should also include the displacement caused by a column rotation, which is determined by stiffness of elements on a lower storey. This procedure provides horizontal stiffness of each equivalent subsystem and stiffness of each storey. Fig. 2a presents a four-bay and four-storey "slender" frame whose fields at the highest storey are filled with masonry. Fig. 2b illustrates a bar model with diagonal struts replacing infill walls, and Fig. 2c presents the separate storey with a division into equivalent subsystems:

Fig. 3 shows static schemes of equivalent subsystems at the highest storey. As in case of the single-storey system, each subsystem was loaded with unit forces P=1, and flexible horizontal supports were added to each place with diagonal struts.

At the highest storey (Fig. 3) horizontal displacements of individual subsets are calculated from the following relationships:
a) edge subsystem with a flexible horizontal support:

$$\Delta_I = \frac{-P\left(3^1E_{bel,i}\,{}^1J_{bel,i}h_{col} + 4^iE_{col,1}\,{}^iJ_{col,1}\left(\frac{2}{3}l_{bel,i}\right)\right)h_{col}^3}{\left(-6^iE_{col,1}\,{}^iJ_{col,1}\right)^2\left(\frac{2}{3}l_{bel,i}\right) - \left(12^iE_{col,1}\,{}^iJ_{col,1} + k_{si}h_{col}^3\right)\left(3^1E_{bel,i}\,{}^1J_{bel,i}h_{col} + 4^iE_{col,1}\,{}^iJ_{col,1}\left(\frac{2}{3}l_{bel,i}\right)\right)} + \phi_I h \quad (13)$$

,

b) edge subsystem without a horizontal support:

$$\Delta_I = \frac{-P\left(4^{i}E_{col,1}{}^{i}J_{col,1}\left(\frac{2}{3}l_{bel,i}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\right)h_{col}^3}{\left(-6^{i}E_{col,1}{}^{i}J_{col,1}\right)^2\left(\frac{2}{3}l_{bel,i}\right)-\left(12^{i}E_{col,1}{}^{i}J_{col,1}\left(4^{i}E_{col,1}{}^{i}J_{col,1}\left(\frac{2}{3}l_{bel,i}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\right)\right.} + \phi_I h \tag{14}$$

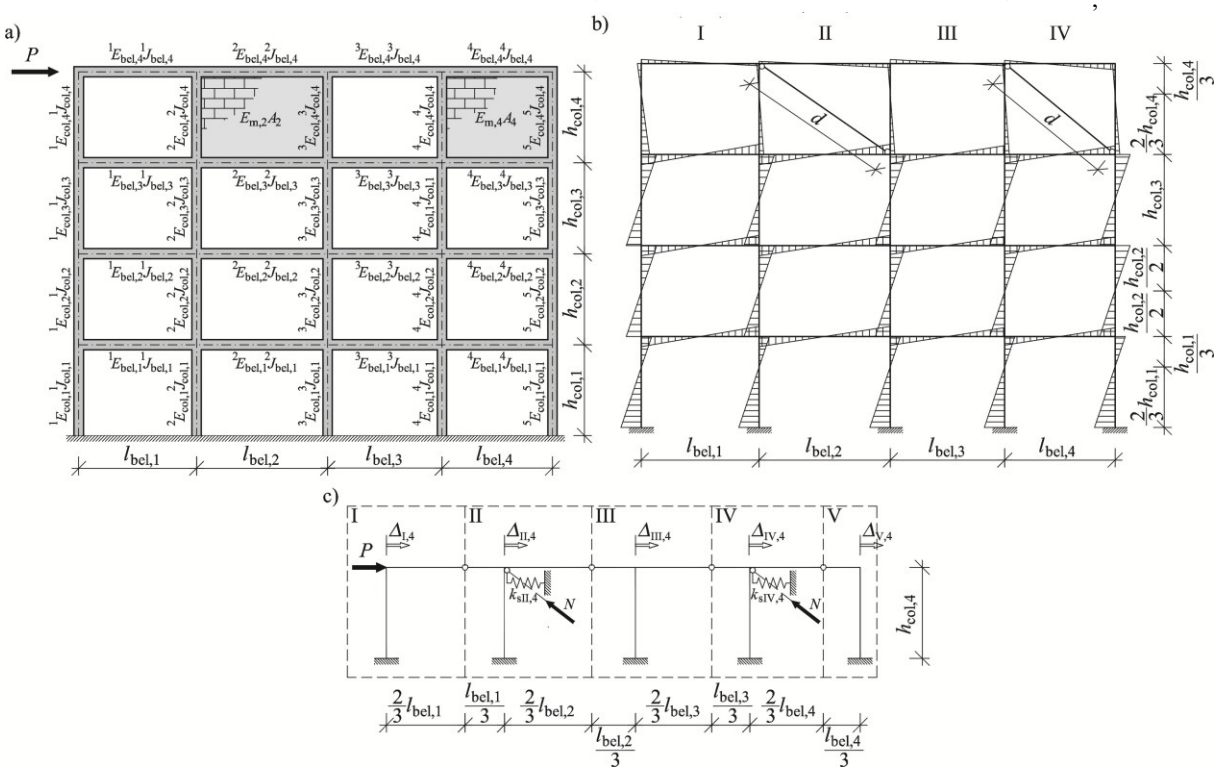

Fig. 2 Multi-storey „slender" frame with masonry filling: a) frame geometry, b) bar frame model, c) bar frame model divided into equivalent subsystems of the highest storey

c) inner subsystem with a flexible horizontal support:

$$\Delta_{II} = \frac{-P\left(4^{i+1}E_{col,1}{}^{i+1}J_{col,1}\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\left(\frac{1}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i+1}{}^{1}J_{bel,i+1}\left(\frac{2}{3}l_{bel,i}\right)\right)h_{col}^3}{\left(-6^{i+1}E_{col,1}{}^{i+1}J_{col,1}\right)^2\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)-\left(12^{i+1}E_{col,1}{}^{i+1}J_{col,1}+k_{si+1}h_{col}^3\left(4^{i+1}E_{col,1}{}^{i+1}J_{col,1}\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\left(\frac{1}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i+1}{}^{1}J_{bel,i+1}\left(\frac{2}{3}l_{bel,i}\right)\right)\right)} + \phi_{II} h, \tag{15}$$

d) inner subsystem without a horizontal support:

$$\Delta_{II} = \frac{-P\left(4^{i+1}E_{col,1}{}^{i+1}J_{col,1}\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\left(\frac{1}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i+1}{}^{1}J_{bel,i+1}\left(\frac{2}{3}l_{bel,i}\right)\right)h_{col}^3}{\left(-6^{i+1}E_{col,1}{}^{i+1}J_{col,1}\right)^2\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)-\left(12^{i+1}E_{col,1}{}^{i+1}J_{col,1}\left(4^{i+1}E_{col,1}{}^{i+1}J_{col,1}\left(\frac{1}{3}l_{bel,i}\right)\left(\frac{2}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i}{}^{1}J_{bel,i}\left(\frac{1}{3}l_{bel,i+1}\right)+3^{1}E_{bel,i+1}{}^{1}J_{bel,i+1}\left(\frac{2}{3}l_{bel,i}\right)\right)\right)} + \phi_{II} h, \tag{16}$$

where:

$$\phi_I = \frac{M_I}{k_{MI}}, \tag{17}$$

$$k_{MI} = \frac{4E_{col}J_{col}}{h_{col}} + \frac{4E_{bel}J_{bel}}{l_{bel}}, \tag{18}$$

E_{col} – modulus of elasticity of the column at the analysed storey,
J_{col} – moment of inertia of the column at the analysed storey,
h_{col} – height of the column at the analysed storey,
E_{bel} – modulus of elasticity of the girt at the analysed storey,
J_{bel} – moment of inertia of the girt at the analysed storey,
l_{bel} – span of the girt at the analysed storey,
M_{I} – moment of restraint calculated from the following relationship:

$$M_I = -\frac{2E_{col,i}J_{col,i}}{h_{col}}Z_1 + \frac{6E_{col,i}J_{col,i}}{h_{col}}\Delta_I, \tag{19}$$

i) edge subsystem with a flexible horizontal support:

$$Z_1 = \frac{6^i E_{col,1}\,{}^i J_{col,1} P h_{col}^2 \left(\frac{2}{3} l_{bel,i}\right)}{\left(-6^i E_{col,1}\,{}^i J_{col,1}\right)^2 \left(\frac{2}{3} l_{bel,i}\right) - \left(12^i E_{col,1}\,{}^i J_{col,1} + k_{si} h_{col}^3\right)\left(3^1 E_{bel,i}\,{}^1 J_{bel,i} h_{col} + 4^i E_{col,1}\,{}^i J_{col,1}\left(\frac{2}{3} l_{bel,i}\right)\right)}, \quad (20)$$

ii) edge subsystem without a flexible support:

$$Z_1 = \frac{6^i E_{col,1}\,{}^i J_{col,1} P h_{col}^2 \left(\frac{2}{3} l_{bel,i}\right)}{\left(-6^i E_{col,1}\,{}^i J_{col,1}\right)^2 \left(\frac{2}{3} l_{bel,i}\right) - \left(12^i E_{col,1}\,{}^i J_{col,1}\right)\left(3^1 E_{bel,i}\,{}^1 J_{bel,i} h_{col} + 4^i E_{col,1}\,{}^i J_{col,1}\left(\frac{2}{3} l_{bel,i}\right)\right)}, \quad (21)$$

$$\phi_{II} = \frac{M_{II}}{k_{MII}}, \quad (22)$$

$$k_{MII} = \frac{4E_{col} J_{col}}{h_{col}} + \frac{4^L E_{bel}\,{}^L J_{bel}}{{}^L l_{bel}} + \frac{4^P E_{bel}\,{}^P J_{bel}}{{}^P l_{bel}}, \quad (23)$$

E_{col} – modulus of elasticity of the column at a lower storey,
J_{col} – moment of inertia of the column at this storey,
h_{col} – height of the column at the analysed storey,
${}^{\mathrm{L}}E_{\mathrm{bel}}$ – modulus of the girt elasticity at the analysed storey (from the left side),
${}^{\mathrm{L}}J_{\mathrm{bel}}$ – moment of inertia of the girt at the analysed storey (from the left side),
${}^{\mathrm{L}}l_{\mathrm{bel}}$ – span of the girt at the analysed storey (from the left side),
${}^{\mathrm{P}}E_{\mathrm{bel}}$ – modulus of the girt elasticity at the analysed storey (from the right side),
${}^{\mathrm{P}}J_{\mathrm{bel}}$ – moment of inertia of the girt at the analysed storey (from the right side),
${}^{\mathrm{P}}l_{\mathrm{bel}}$ – span of the girt at the analysed storey (from the right side).

M_{II} – moment of restraint calculated from the following relationship:

$$M_{II} = -\frac{2E_{col,i} J_{col,i}}{h_{col}} Z_1 + \frac{6E_{col,i} J_{col,i}}{h_{col}} \Delta_{II}, \quad (24)$$

i) inner subsystem with a flexible horizontal support:

$$Z_1 = \frac{6^i E_{col,1}\,{}^i J_{col,1} P h_{col}^2 \left(\frac{2}{3} l_{bel,i}\right)\left(\frac{1}{3} l_{bel,i+1}\right)}{\left(-6^{i+1} E_{col,1}\,{}^{i+1} J_{col,1}\right)^2 \left(\frac{1}{3} l_{bel,i}\right)\left(\frac{2}{3} l_{bel,i+1}\right) - \left(12^{i+1} E_{col,1}\,{}^{i+1} J_{col,1} + k_{si+1} h_{col}^3\right)\left(4^{i+1} E_{col,1}\,{}^{i+1} J_{col,1}\left(\frac{1}{3} l_{bel,i}\right)\left(\frac{2}{3} l_{bel,i+1}\right) + 3^1 E_{bel,i}\,{}^1 J_{bel,i}\left(\frac{1}{3} l_{bel,i+1}\right) + 3^1 E_{bel,i+1}\,{}^1 J_{bel,i+1}\left(\frac{2}{3} l_{bel,i}\right)\right)}, \quad (25)$$

ii) inner subsystem without a flexible support:

$$Z_1 = \frac{6^i E_{col,1}\,{}^i J_{col,1} P h_{col}^2 \left(\frac{2}{3} l_{bel,i}\right)\left(\frac{1}{3} l_{bel,i+1}\right)}{\left(-6^{i+1} E_{col,1}\,{}^{i+1} J_{col,1}\right)^2 \left(\frac{1}{3} l_{bel,i}\right)\left(\frac{2}{3} l_{bel,i+1}\right) - \left(12^{i+1} E_{col,1}\,{}^{i+1} J_{col,1}\right)\left(4^{i+1} E_{col,1}\,{}^{i+1} J_{col,1}\left(\frac{1}{3} l_{bel,i}\right)\left(\frac{2}{3} l_{bel,i+1}\right) + 3^1 E_{bel,i}\,{}^1 J_{bel,i}\left(\frac{1}{3} l_{bel,i+1}\right) + 3^1 E_{bel,i+1}\,{}^1 J_{bel,i+1}\left(\frac{2}{3} l_{bel,i}\right)\right)}, \quad (26)$$

Determined displacements can be used to determine stiffness of each subsystem, and the overall stiffness of the storey is calculated from the following relationship (9).

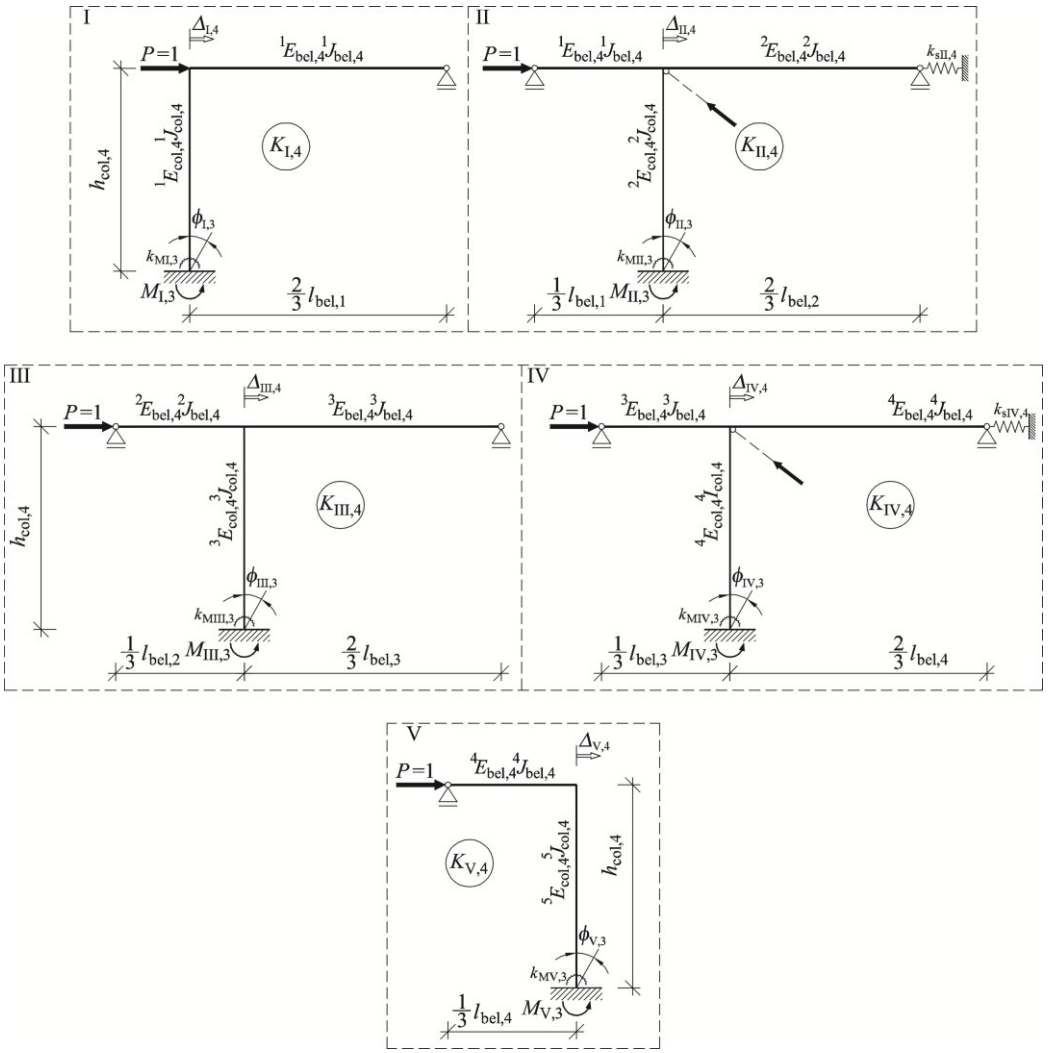

Fig. 3. Static diagrams of replacement subsystems of the highest storey of a multi-field "slender" frame with masonry filling

The main difference in the procedure for "rigid" frames in a significant reduction of bending moments in columns and girts. To determine stiffness of a storey, the masonry infill is replaced with diagonal struts, and girts are entered in a half length of each girt. As in case of the "slender" frame, stiffness is determined by at first distinguishing the storey with masonry infill, and then its division into individual equivalent subsystems – Fig. 4c. The result obtained for each subsystem is used to determine vertical stiffness, and then stiffness of each storey. Fig. 4.16a presents a four-bay and four-storey "rigid" frame whose fields at each storey are filled with masonry. Fig. 4b illustrates a bar model with diagonal struts replacing infill walls, and Fig. 4c presents the separate storey with a division into equivalent subsystems.

Fig. 5 shows static schemes of equivalent subsystems at the highest storey. As in case of the single-storey system, each subsystem was loaded with unit forces P=1, and flexible horizontal supports were added to each place with diagonal struts. Horizontal displacements of each subsystem are determined from the following relationships (13) – (18) neglecting horizontal displacements of columns. Determined displacements can be used to determined stiffness of each subsystem, and the overall stiffness of the storey is calculated from the following relationship (9).

The proposed method can be successfully applied to infill walls without openings. In the walls with openings, the significance of diagonal struts considerably declines. Therefore, analysing each equivalent subsystem with openings, the stiffness can be reduced from the relationship specified in the standard ASCE/SEI 41-13 [7]:

$$K_{ini}^{opening} = \left(1 - 2\frac{A_{op}}{A_w}\right) K_{ini}^{solid} \tag{27}$$

,

where:

A_{op} – an area of openings,

A_w – a cross-sectional area of infill wall,

K_{ini}^{solid} – determined stiffness of the equivalent subsystem without openings.

If $A_{op} \geq 0.52A_w$, then the compressed strut can be neglected in the analysed area of the wall.

Using the proposed method, axial forces in equivalent struts can be determined, which is the base to verify ULS. Therefore, this method is not adequate to determine internal forces in structural parts the infill wall. The most appropriate method is the method of overall stiffness proposed in this paper.

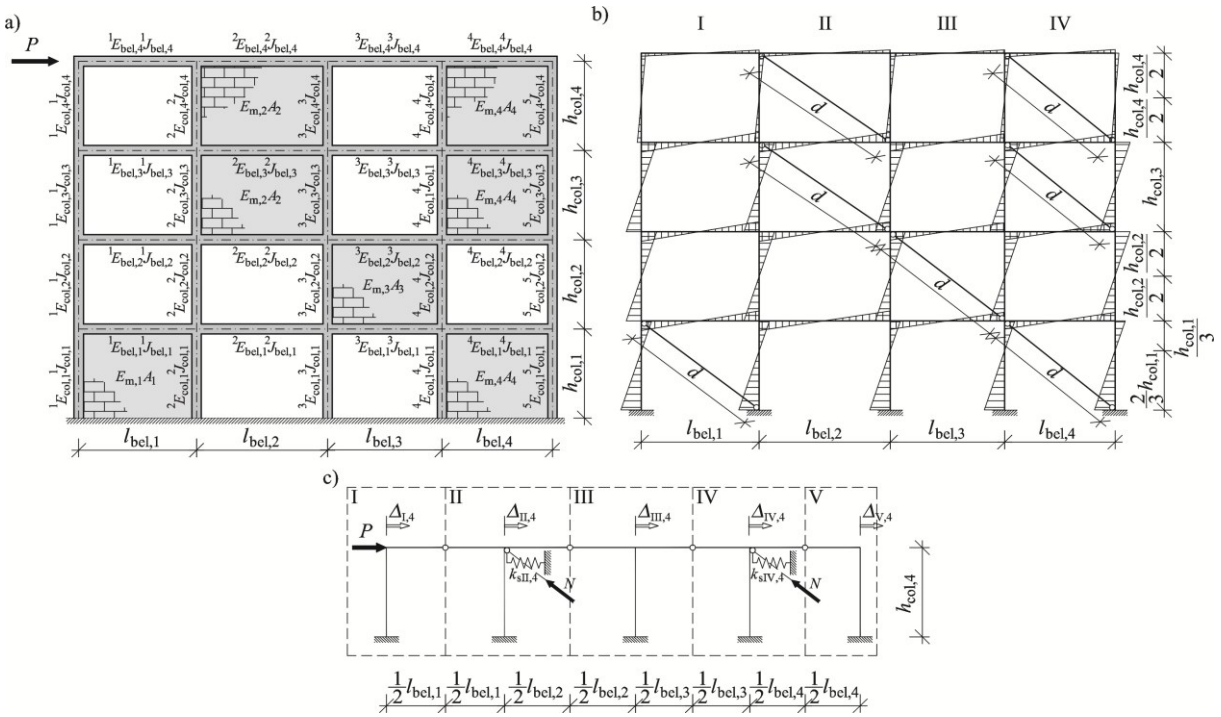

Fig. 4. Multi-storey „rigid" frame with masonry filling: a) frame geometry, b) bar frame model, c) bar frame model divided into equivalent subsystems of the highest storey

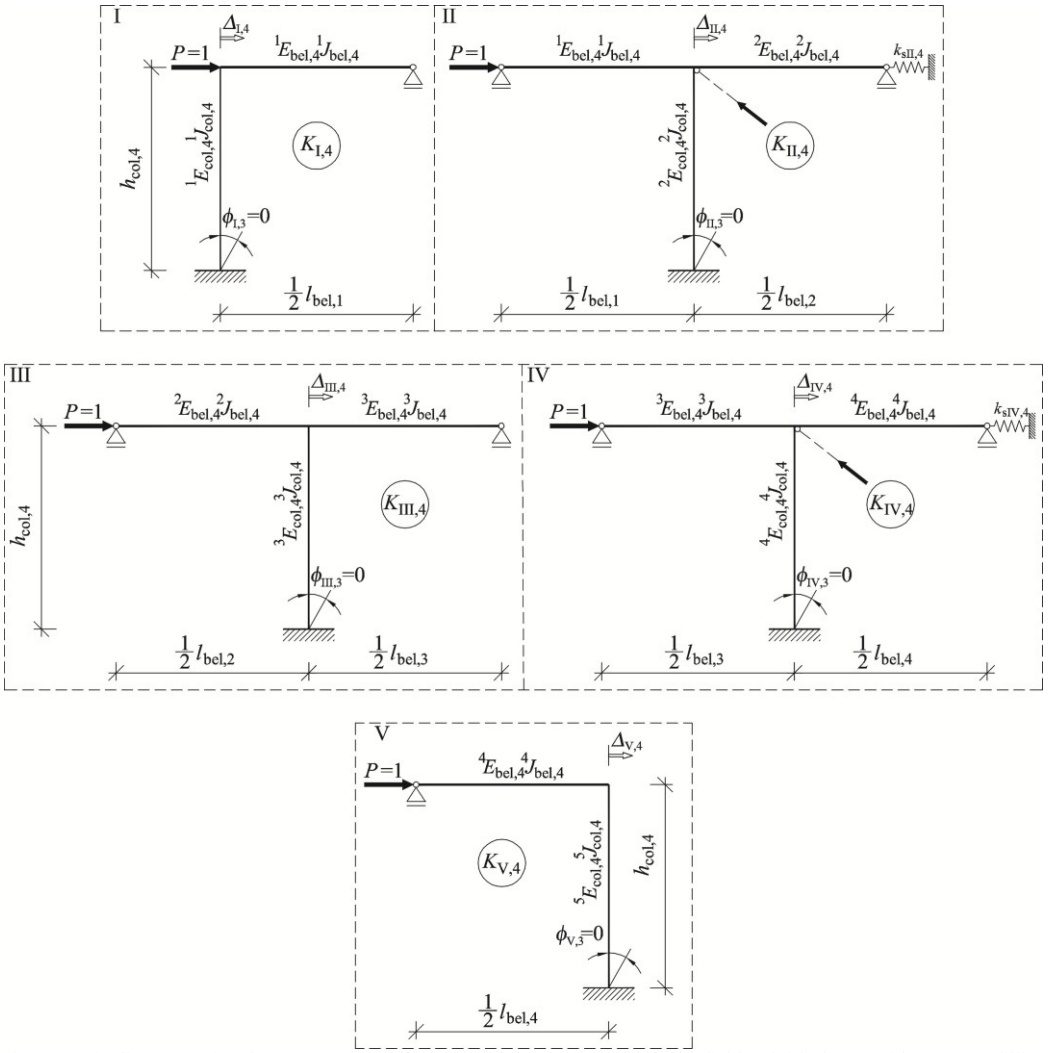

Fig. 5. Static diagrams of replacement subsystems of the highest storey of a multi-field „ rigid" frame with masonry filling

5. Conclusion

The load distribution into individual parts of the frame infill depends on stiffness of the masonry-wall system [1]. This paper presents the original bar method to determine internal forces in units in the multi-storey and multi-bay frame with masonry infill. The used relationships determined geometrical parameters of the compressed strut in accordance with standards [6, 7]. The proposed procedure was similar to the procedure for single-storey frames widely described in the paper [1]. It was necessary to divide the frame into bar subsystems and to determine equivalent stiffness values. The main difference with reference to single-storey frames was the frame division into "slender" and "rigid" frames. The "slender" frames included frames with stiffness only at individual storeys, and the "rigid" frames included frames with masonry infill at each storey. It was proposed to extend the requirements for portal frames with additional requirements concerning the position of hinges in horizontal members of the frame. All fields in the "slender" frames, which had masonry infill required hinges in the girts – within a distance of 2/3 of the girt span (in the field filled with masonry). A hinge in the adjacent girt should be at a distance of 1/3 of the girt span. And the "rigid" frames were characterized by a significant reduction in bending moments in columns and girts. To determine stiffness of a storey, the masonry infill is replaced with diagonal struts, and girts are entered in a half length of each girt.

Stiffness determination and load distribution are the same as in the method used for walls in load-bearing structures [2] and (one-storey) frame buildings [1]. Elastic supports with stiffness determined from the solutions obtained for equivalent subsystems are introduced into horizontal planes of the storeys.

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