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Bojan Milošević¹, Žarko Petrović², Marina Mijalković³, Andrija Zorić⁴

UTICAJ ZIDANE ISPUNE NA NOSIVOST RAMOVSKIH KONSTRUKCIJA

Rezime:

Kod objekata visokogradnje, velika je primena ramovskih konstrukcija, kod kojih je prostor između stubova i greda u potpunosti ili delimično ispunjen nearmiranim zidovima. U procesu modeliranja i projektovanja ramovskih konstrukcija uticaj zidova ispune, kao i njihova krutost su se uglavnom ignorisali tokom analize konstrukcije. Cilj ovog rada je da se prikažu neke od metoda modeliranja koje su danas dostupne za opisivanje odziva ramovskih konstrukcija ispunjenih zidovima, kao i njihova interakcija sa elementima ramovske konstrukcije kada su podvrgnute opterećenju u svojoj ravni.

Ključne reči: ramovski nosači, zidana ispuna, zamenjujući dijagonalni štap

EFFECT OF WALL INFILL ON THE CAPACITY OF THE FRAME STRUCTURES

Summary:

In building construction, frame structures are widely used, in which the space between columns and beams is completely or partially filled with unreinforced walls. In the process of modelling and design of frame structures, the impact of the walls, as well as their rigidity, were largely ignored during the structural analysis. The aim of this paper is to present some of the modelling methods available today to describe the response of frame structures filled with walls and their interactions with frame structures when subjected to load in their plane.

Key words: frame structures, wall infill, equivalent diagonal strut

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1. INTRODUCTION

The use of frame structures that are filled with walls made of masonry elements in the building structure, industrial and commercial buildings, is wide. The role of the wall infill between the structural elements of the reinforced concrete frame is related to the architectural demands such as protection of the interior of the building from the environment and to separate the interior spaces.

During the process of designing new structures and assessing the load-bearing capacity of the existing ones, the wall infill located between the elements of the frame structure is usually considered as a non-structural element. In general, the role of masonry infill in the analysis of frame structures is neglected and it is assumed that it will not participate in the transmission of any load both axial and lateral, and its influence on the frame structure is ignored due to ignorance of their composite behaviour [1, 2]. The filling walls not only increase the mass of the building but on the one hand increase the stiffness while on the other hand reduce the ductility of the structure, which leads to a change in the period of oscillation of the frame structure [3, 4]. The wall infill can significantly increase the load-bearing capacity of the frame structure and thus serves as an important reserve of strength in case of unpredictable extreme events (local impact, explosion or earthquake).

If the building meets the conditions of regularity both in the base and in the height of the building, i.e., if the wall infill is properly distributed in the design phase, it usually has a positive impact on the static and dynamic characteristics of the structure. On the other hand, the negative effects caused by improper positioning of the infill walls can lead to the formation of short elements, the appearance of a flexible floor or the appearance of torsion of the building [2]. These phenomena cannot be avoided, but they can be significantly prevented by proper design. Therefore, it is necessary for civil engineers in the design phase of structures to consider all the necessary factors, including the infill walls, which play an important role in the load-bearing capacity of the structure and its deformation characteristics [5].

The reason for neglecting the walls of the infill in the design process is partly the result of incomplete knowledge of the behaviour of quasi-brittle materials from which the infill is made and the lack of conclusions of experimental and analytical results that support the reliability of procedures for adequate and safe design of these structures [3]. The lack of realistic and simple analytical models for filling modelling as well as the ignorance of the interaction between the infill walls and the frame structure is another obstacle for its consideration in the analysis and constructive modelling of structures [6].

The aim of this paper is to consider the proposed analytical macromodels for the analysis of a frame structure filled with a wall whose width is not related to the stiffness of the material from which the wall is made, as well as to point out special challenges imposed by the presence and complex action of filling. The paper presents simplified analytical expressions for modelling a wall infill using the macro method, namely simplified simple single models and their application through concrete examples.

2. MODELLING OF FRAMES FILLED WITH MASONRY WALLS

In the phase of analysis and design of frame structures that are filled with walls, due to the large number of different parameters, the behavior of the frame structure is difficult to determine, especially due to the large number of possible forms of failure that must be considered [7]. Analytical modeling of a frame structure filled with a wall contains various parameters that define the elements for masonry, mortar, as well as the connection between the frame and the wall infill. As the wall infill is made of masonry elements of different strengths and stiffnesses in the modeling phase of the frame structure filled with walls, special attention should be paid to the adequate modeling of the wall infill. The mechanical characteristics of the masonry infill depend on both the masonry elements and the applied mortar.

Since the first attempt to model the response of a frame structure filled with walls as a composite, several methods have been developed, which are grouped into two main categories: micro-models, i.e., detailed models, based on the finite element method and macro-models or simplified models, based on the diagonal bar equivalent method [8].

Micro-modeling is a complex method that can be used to simulate the behavior of a structure in detail, using appropriate constitutive models, and is based on the division of the wall infill and the frame structure into an appropriate number of finite elements. The main advantage of micro modeling is reflected in the fact that it takes into account local effects related to stress distribution, cracking, crushing and interaction of masonry infill and frame structure [1]. Although micro modeling can provide an accurate computational representation of material and geometric aspects, it is rarely used because the calculation itself is computer-intensive and too time-consuming to be used in the practical analysis of large structures [9].

Wall modeling using macro elements can be defined as the use of different types of diagonal bars. It is generally accepted that under horizontal loading, the infill wall acts as an equivalent diagonal bar that can be modeled as an element connecting the nodes between the beams and columns, and is applicable only when the wall infill is without openings [7]. Since the first attempts to model the behavior of frame structures filled with walls, indicated that a diagonal bar with appropriate geometric and mechanical characteristics can solve the problem, the single diagonal bar model is the most commonly used macro model. The geometric property of the diagonal rod required in the analysis is the cross-sectional area of the rod, which is defined as the product of the wall thickness of the infill and the width of the equivalent diagonal bar - w . The length of the diagonal bar, d , is determined by the length of the diagonal of the wall infill (Figure 1).

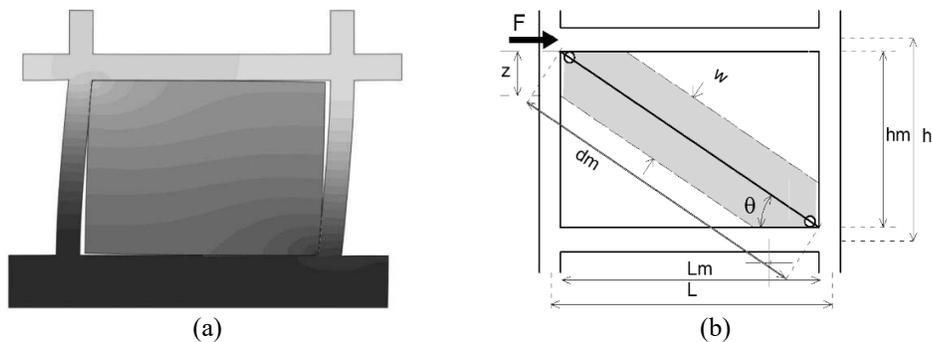


Figure 1 – Models of the masonry infill walls in RC frames: a) micro-model b) macro-model

In recent decades, a large number of experimental and numerical studies have been conducted to define an acceptable model for structural analysis that would take into account the interaction between the wall infill and the frame structure [6]. In the modeling of masonry infill using a diagonally pressed bar, a large number of methods have been presented in the literature that have been defined by various researchers or presented in regulations for the calculation of structures. Each method defines a simplified analytical model for reproducing the main aspects of the interaction mechanism, which defines the width of the diagonal rod w depending on the length of the pressed diagonal. Some of the macro models take into account the relative stiffness between the infill and the frame structure when defining the equivalent width of the diagonal bar, while other models determine the width of the diagonal bar indirectly based on the length of the diagonal relative to the wall geometry.

In the early 1960s, Polyakov was the first to notice that an infill wall could be represented by a diagonal element [11]. Based on Polyakov's research, Holmes conducted experimental research on steel frames filled with brick walls and concrete masonry elements [12]. He developed a semi-empirical method for designing frames that are exposed to lateral loads. Holmes states that the width of the diagonal bar should be one third of the length of the diagonal of the wall infill.

Based on experimental data obtained by examining steel frames filled with walls, Stafford Smith [13], defines that the w/d ratio is in the range of 0,10 to 0,25.

Syrmakezis and Vratsanou [14] model the pressed diagonal of a wall infill using five bars, proposing an empirical equation for determining the total width of the pressed diagonal:

$$\frac{w}{h} = 0,64 \frac{l}{h} + 3 \left(\frac{d_c}{l} - 0,1 \right),$$

where h and l are the length of the column and the beam respectively and d_c is the thickness of the column

Priestley and Cavali [15] respectively pointed out that the large width of the diagonal rod results in a stiffer structure and thus a potentially larger seismic response. They proposed that the w/d ratio is 0,25 when the frame structure is filled with a wall and exposed to seismic forces.

In the Romanian regulations [16] for the design of structures in seismically active areas, the width of the diagonal bar with which the infill wall can be replaced is one tenth of the diagonal bar length ($w=0,10d$)

Hamburger and Chakradeo studied steel-frame buildings with masonry infill, and gave special attention to the beam-column joint [17]. They proposed the use of equivalent diagonal struts placed next to the openings (i.e., one infill wall with one opening, thus two struts are used). The struts should be tangent to the corner of the window opening. Looking at the results of the numerical model they recommended that the width of each equivalent strut should not exceed twice the infill thickness.

3. NUMERICAL ANALYSIS

In order to analyze the influence of the wall infill on the behavior of the RC frame structure exposed to horizontal force, a numerical analysis was performed. The frame is made of C25/30 concrete, filled with Porotherm 38 N+F clay masonry elements, connected with M 10 mortar. The geometry of the examined masonry-infilled RC frame is shown in Figure 2.

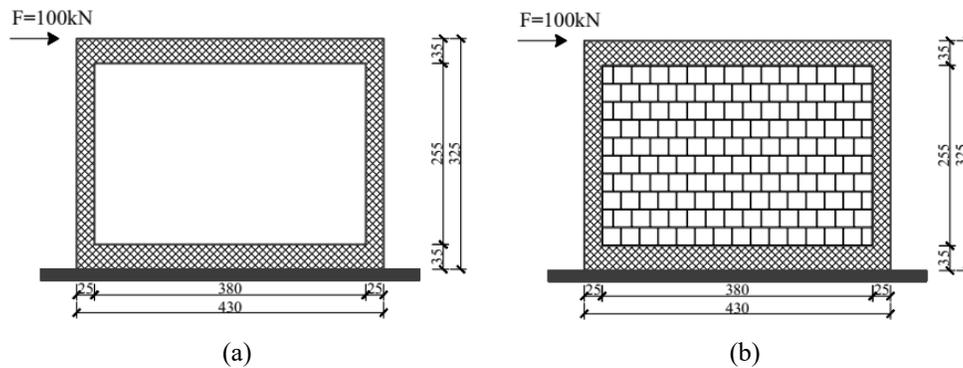


Figure 2 – The geometry of examined structure: a) bare frame b) infilled frame

Table 1 – Mechanical characteristics of the masonry according to EC6 [18]

Compressive strength of masonry mortar	f_m [MPa]	10,00
Normalized mean compressive strength of a masonry unit	f_b [MPa]	8,53
Characteristic compressive strength of masonry	f_k [MPa]	4,03
Modulus of elasticity of masonry	E [MPa]	4027,68

Based on the dimensions of the framed structure (Figure 2), as well as on the mechanical characteristics of the masonry infill (Table 1) numerical models were developed in the Tower and Abaqus software packages. The analysis was performed using bare frame model and infilled frame macro-models. Macro-models with beam and shell elements were examined. Standard bar and shell elements built-in in Tower software package were used, and in case of Abaqus software package the beam elements B32 and shell quadrilateral elements S8R with quadratic shape functions were used. The translational degrees of freedom were constrained at the adjacent nodes of beam and shell elements in the case of macro-models with shell elements for infill wall. Therefore, the connection between RC frame and infill wall was modelled as ideal without slipping. The values of the width of the diagonal strut in model with beam element was determined based on the recommendations in the literature [11-17] (Table 2).

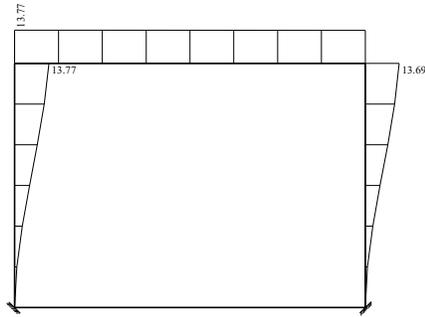
Table 2 – Diagonal strut width

	Holms	Smiths	Paulay and Priestley	Symakezis	Hamburger
w [cm]	156,00	46,90	117,25	225,90	50,00

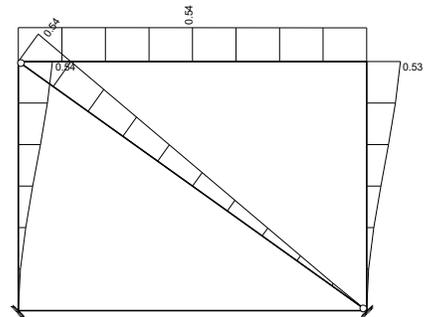
3.1 RESULTS AND DISSCUSION

A comparative analysis of the obtained displacements of the top of the frame structure under the action of a horizontal test load is performed.

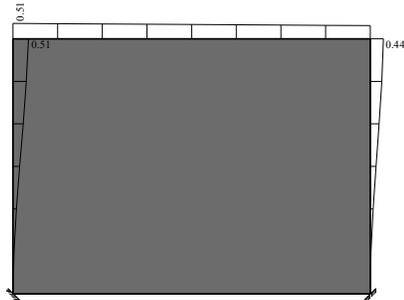
Figures 3 a-f show the displacements obtained using the Tower software [19], while Figures 4 a-f show the displacements obtained using the Abaqus software [20].



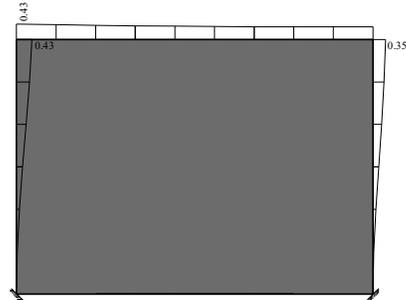
Uticaji u gredi: max $X_p = 13.77$ / min $X_p = 0.00$ m / 1000
(a)



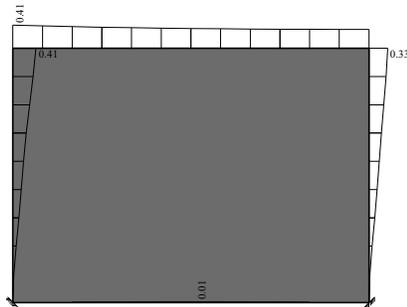
Uticaji u gredi: max $X_p = 0.54$ / min $X_p = 0.00$ m / 1000
(b)



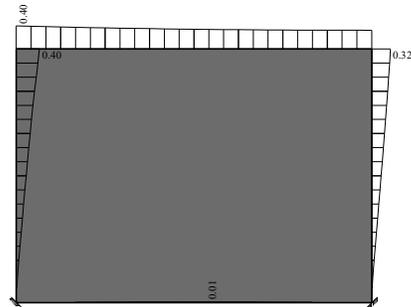
Uticaji u gredi: max $X_p = 0.51$ / min $X_p = 0.00$ m / 1000
(c)



Uticaji u gredi: max $X_p = 0.43$ / min $X_p = 0.00$ m / 1000
(d)



Uticaji u gredi: max $X_p = 0.41$ / min $X_p = 0.00$ m / 1000
(e)



Uticaji u gredi: max $X_p = 0.40$ / min $X_p = 0.00$ m / 1000
(f)

Figure 3 – Displacements for the examined masonry frame RC structure modelled in Tower: a) bare frame model, b) model with diagonal strut, c) model with 1 shell element, d) model with 6 shell elements, e) model with 12 shell elements, f) model with 48 shell elements

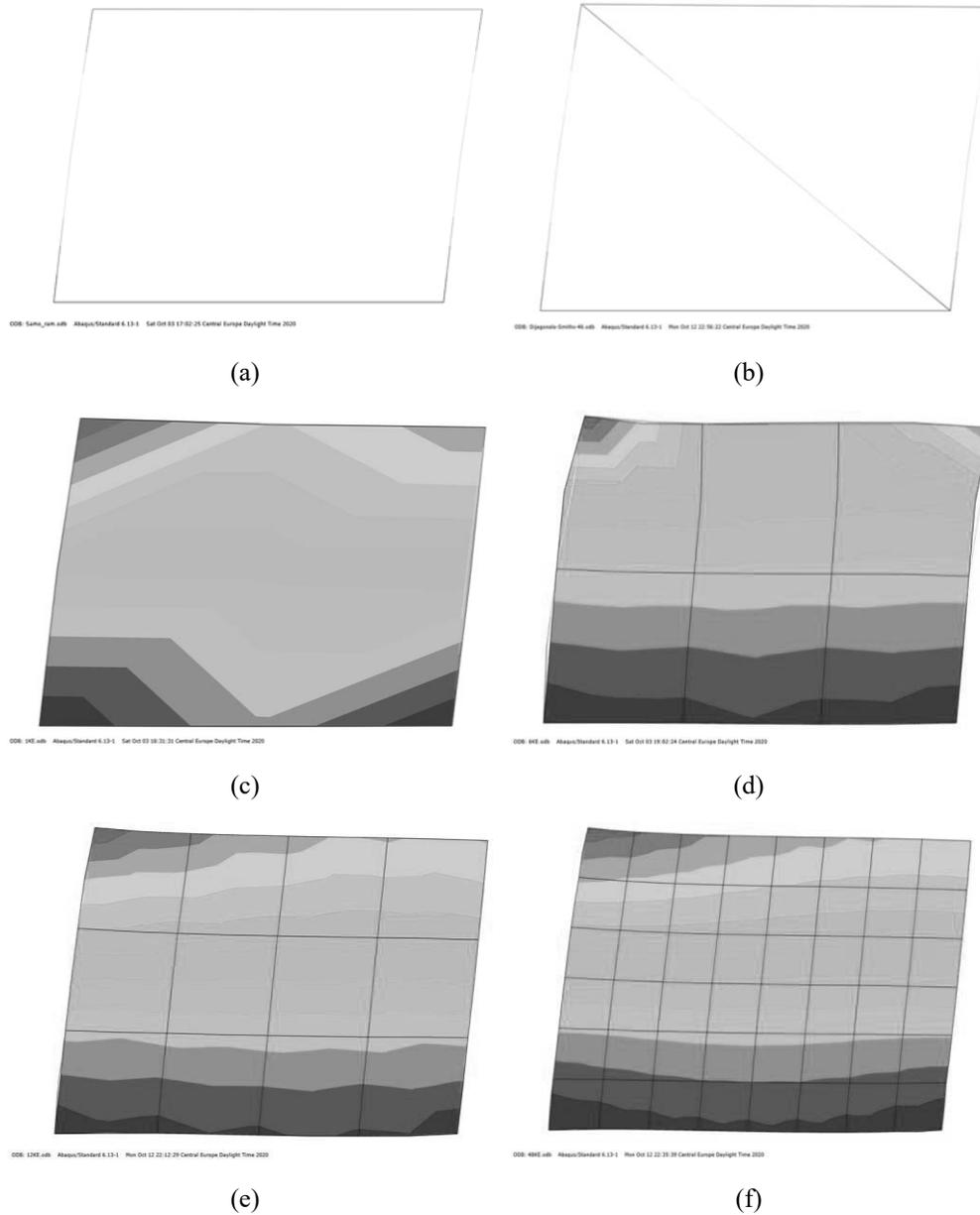


Figure 4 – Displacements for the examined masonry frame RC structure modelled in Abaqus: a) bare frame model, b) model with diagonal strut, c) model with 1 shell element, d) model with 6 shell elements, e) model with 12 shell elements, f) model with 48 shell elements

Comparative representation of the obtained displacements of the top of the examined frame is shown in Table 3.

Table 3 – Presentation of obtained results

		w [cm]	Displacement of the top of the frame structure [mm]	
			Tower	Abaqus
	Bare frame structure	/	13,77	13,77
Models with diagonal strut	Holms	156,00	0,54	0,54
	Smiths, Rumunski propis	46,90	1,49	1,50
	Smiths, Paulay i Pristley	117,25	0,68	0,68
	Symakezis	225,90	0,39	0,39
	Hamburger	50,00	1,41	1,42
Models with shell elements	1 finite element	/	0,51	0,37
	6 finite elements	/	0,43	0,39
	12 finite elements	/	0,41	0,29
	48 finite elements	/	0,40	0,27

The results show good agreement between models developed in the commercial software package Tower and highly sophisticated software package Abaqus. There is slight deviation of the results in the cases of the models with shell elements, which arises from the different finite element formulations in two software packages. There are significant differences in the displacement of the top of the frame in cases of the models with diagonal strut protracted due to different width of the diagonal strut.

4. CONCLUSION

The paper presents the modelling of reinforced concrete frame girders with infill walls. The existing literature points out the importance of the analysis of such girders with regard to their frequent use in building structures. One of the basic methods for analysing the impact of infill walls: the macro method has its advantages and disadvantages which are reflected in the accuracy but also the practicality of their application.

The results obtained by numerical analysis of the frame girder examined in the paper can be seen the influence of the infill walls on the behaviour of reinforced concrete frame girders. The parameter that was analysed is the displacement of the top of the object as one of the basic parameters in the seismic analysis of structures. The difference between the displacement of the top of the frame girder with and without the infill is large, considering the significantly stiffer structure of the frame with the infill. The application of the diagonal rod is very simple from the aspect of numerical analysis, but the results depend directly on the adopted width of the rod, which varies significantly from author to author. Based on the analysis of the obtained results of displacement of the top of the frame structure without masonry infill, as well as the frame

structure when it is filled with wall, it is concluded that the use of replacement diagonal bar is limited.

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