Stress and strain in beam-wall interface in transition floor on support columns of structural masonry buildings

Désir J. Marie[1], Santos G. D. Cortivo[1]

[1]*Dept. of Civil Engineering, Federal University of Rio Grande do Sul*
Av. Osvaldo Aranha 99, 90035-190, Rio Grande do Sul, Brasil
jean.marie@ufrgs.br, guilherme.dallcortivo@gmail.com

Abstract. This article aims to understand, through numerical modeling, the influencing parameters in the arch effect, a phenomenon that arises in the interaction of structural masonry walls on reinforced concrete beams in transition floor on column supports. Among the consequences of the arc effect is the migration of the acting loads to the region close to the columns, causing stress peaks in the wall and reducing the bending moment acting in the support beam. The finite element modeling and the properties of the materials adopted are presented. The increase in stiffness due to the presence of the wall caused deflections in the beam of order up to 8 times smaller than expected from the elastic line equation. In the wall, even in the most favorable situations, such as beams supported by columns, we noticed an increase in acting stresses of up to 2.2 times. This points out that, by not considering the arc effect, the support beam may be oversized, exposing the wall to stresses greater than those calculated.

Keywords: Structural Masonry, Numerical Analysis, Arc Effect, Beam-Wall Interaction, Structural Safety.

1 Introduction

In Brazil, structural masonry was associated, in the 1990s, with Housing Projects of Social Interest. However, factors such as the improvement in the quality of blocks (Santiago and Beck [1]), the updating of design standards such as NBR 15812[2] and NBR 15961[3] and more recently the unification of design standards in NBR 16868[4] created conditions for its use in taller and higher standard buildings. However, comfort indicators associated with high standard developments such as large ground floor, playgrounds and parking lot are items that are not compatible with the essence of structural masonry and are more suitable in reinforced concrete structures. It is a well known disadvantage of masonry when compared to concrete. To combine the best of both, conventional reinforced concrete structures is used over support columns as a transition from these first floors to the highest ones.

In buildings with "transition floors" the walls of the first floor type transfer the loads received through a beam. Reinforced concrete and structural masonry are different materials, and therefore behave differently. The deformation of the beam results in a change in the distribution of stresses in the masonry, a phenomenon called the arc effect. This work investigates the parameters that most influence it, as well as the recommendations of current standards for its consideration. Among the analyzed parameters are: the beam span, its inertia, the wall resistance, the beam wall contact, and the type of supports. The best modeling strategy is discussed considering the material parameters and the contact coefficient, as well as the allowable strain limits.

2 The arc effect

2.1 Definition and Review

The arc effect is understood as a redistribution of stresses due to the deformation of the reinforced concrete beam used as transition element between the wall and the support columns. The beam deformation induces normal tensile stresses at the interface between the materials. These stresses are absorbed by the bedding mortar of the blocks and cause, when they exceed the stress limit of the material, debonding or split between the wall and the beam in the central part of the span. As a result, the load migrates from the center to the region of the supports, causing two important simultaneous effects: stress peaks in the masonry in the regions close to the supports and reduction of the bending moment in the middle of the span. The diagram in Fig. 1 illustrates the situation:

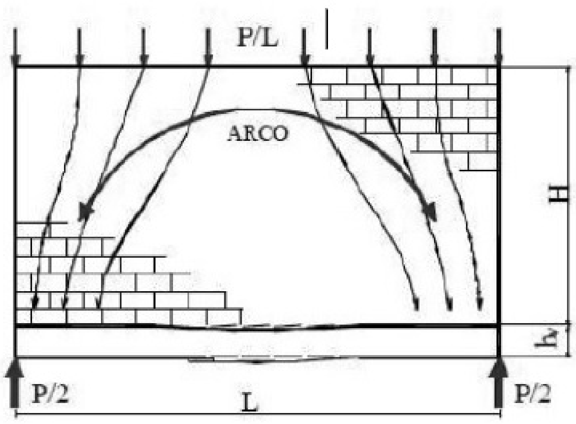


Figure 1. Redistribution of stresses in case of debonding in the center part of the span (Barbosa [5])

Wood [6] points out that the maximum moment $PL/8$ expected for the scheme in Fig. 1 can drop to a value between $PL/20$ and $PL/274$, that is, a reduction of 60 to 97 % in the expected value. Other authors: Rosenhaupt [7], Burhouse [8] and Navaratnarajahm [9] emphasize that the arch effect is more likely to occur over a height equivalent to 70% of the span.

2.2 Concept of relative stiffness of the wall-beam system

Stafford and Riddington [10] and also Davies and Ahmed [11] realized that several parameters influence the way the stresses are distributed in the beam-wall system, highlighting among them: the inertia (I_v) and the span (L) of the beam, the height of the wall (H), the wall thickness (t_p) and the moduli of elasticity of the materials (E_p and E_v). These factors are correlated in the concept of relative stiffness, calculated with eq.(eq. (1)) and (eq. (2)) according to studies by these authors, respectively.

$$K = \sqrt[4]{\frac{E_p\, t_p\, L^3}{E_v\, I_v}} \tag{1}$$

$$R = \sqrt[4]{\frac{E_p\, t_p\, H^3}{E_v\, I_v}} \tag{2}$$

Although they do not provide equal values, the equations of Stafford and Riddington [10] and Davies and Ahmed [11] make the same evaluation. Low relative stiffness values indicate a rigid beam relative to the wall and little arch effect. Higher relative stiffness values correspond to more flexible beams. These beams have larger splits between the beam and the wall, causing more significant changes in the stresses distribution.

3 Modeling strategy

The arc effect analysis can be conducted as a stress plane state problem and the masonry can be analyzed as a homogeneous material, that is, without discretizing blocks and mortar separately, which greatly simplifies the modeling process. In fact, this means that it is possible to apply some homogenization technique to the masonry to define its elastic characteristics, as Buhan and Felice [12], Kuczma and Wybranowska [13], Lourenço and Zucchini [14] and Désir [15] point it out in their papers.

However, in the case of the analysis of arc effect, it is necessary to analyze the contact between wall and beam and the program used presented a more satisfactory performance when the interface is treated as a contact surface. Thus, it was considered more appropriate to model the wall-beam set with hexagonal solid finite elements of 8 and 20 nodes, respectively, available in the Mecway© software and very suitable for modeling this type of problem. The problem was treated with a non-linear scheme, since the arc effect is necessarily associated with split and slip at the beam-wall interface, deformations treated as irreversible. The constitutive laws of the materials are considered through their characteristic parameters which are summarized in table 1.

Table 1. Materials Properties

	Characteristic strength (MPa)	Elastic modulus (GPa)	Poisson Coefficient
Reinforced concrete (beam)	30	28,16	.3
Concrete blocks	20	16,00	.2

The behavior of the beam-wall interface is described with a set of independent springs that limit the splitting and slipping movement. The parameters used are the normal and tangential stiffnesses and the friction coefficient. The definition of these values, fundamental for the analysis of adherence between two surfaces, involves many complex parameters such as adhesion, roughness and intermeshing. Ghassan and Armin [16] estimated, through tests, values of the order of 203,58 GPa/m for normal stiffness and 257,87 GPa/m for tangential stiffness. The friction coefficient is taken equal to 0,6 according to the English standard BS 5628[17].

Equations (1) and (2) deal with relative stiffness, a fundamental factor in the appearance of the arc effect and show the weight of parameters such as beam inertia, span length and wall height. Three different spans will be analyzed and they are of 3, 4,6 and 6 meters, considered as representative of the usual spans in residential buildings. The arc effect depends on the dimensions of the wall and beam. Generally, beams are designed to limit the deflection according to the requirements of NBR 6118[18]. Equation (3), where ℓ is the span length, E the concrete modulus of elasticity, I the beam inertia and q the applied load in all cases, must be verified in the case of a simply supported beam.

$$\frac{5\,q\,\ell^4}{384\,E\,I} \leq \frac{\ell}{250} \tag{3}$$

In this work, the situation of a residential building with 12 stories is considered for the calculation of q. The final load value used was 350,89 kN/m. The resulting cross sections for the three spans, according to eq. (3) are summarized in Table 2

Table 2. Theoretical displacement for the chosen cross sections

Span	Cross section (cm)	Theoretical debonding (cm)	Allowable debonding (cm)
3,0 m	19 x 45	0,91	1,20
4,6 m	19 x 65	1,67	1,84
6,0 m	19 x 85	2,16	2,40

In Table 2 each span is associated to an ideal required cross section, according to NBR 6118 [18]. Using these cross sections for a different span leads to undersized or oversized models. Table 3 shows a set of nine cases which is used for a parametric analysis of the arc effect. Case 1, case 5 and case 9 are required sections according to NBR-6118 [18] requirements. Case 2, case 3 and case 6 are cases of oversized sections where the deflections are less than allowed in the code. Case 4, case 7 and case 8 are cases of undersized sections where the deflections are greater than allowed in the code.

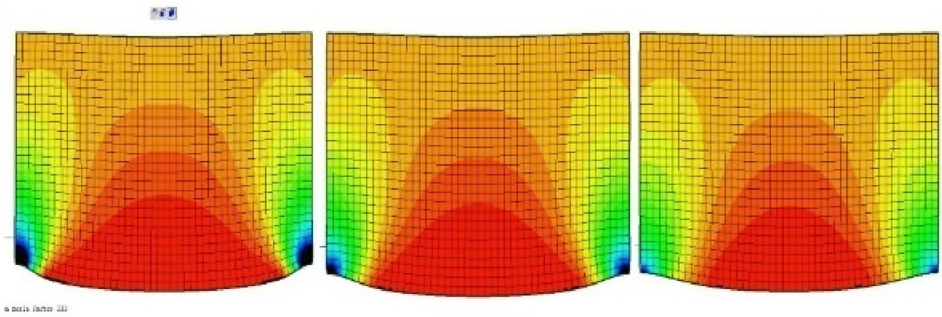
Table 3. Nine Basic cases for a parametric analysis

Cross section	Span of 3,0 m	Span of 4,6 m	Span of 6,0 m
19 x 45	Case 1	Case 4	Case 7
19 x 65	Case 2	Case 5	Case 8
19 x 85	Case 3	Case 6	Case 9

4 Results of the basic models

The simulations allow to analyze, for each length, several aspects depending on the dimensions of a given cross section that influence the relative stiffness, the bending moment, the compression length in the support region, the deflection of the beam-wall system, the stress distribution on the wall. The average stress on the compression length allows to calculate the required characteristic strength for the blocks. Santos [19] presents a detailed analysis of the simulations for all the cases. This article presents a summary of this analysis, showing a comparison between the different cases. The arc effect causes a reduction in the contact length between the wall and the beam, increasing the tension in the masonry in the support region. Therefore, the compression length is a relevant parameter for the analysis of the arc effect phenomenon. The results of the 4,6 m beam cases are briefly presented and then the main results of the set of simulations are summarized in some tables.

For the 4.6 m set, the maximum deflection according to NBR 6118[18] would be 18.4 mm. The beam that best meets this value is the V19x65, which, when considered isolated, has a deflection of 17.85 mm with an associated elastic moment of 928.10 kN.m. Figure 2 shows the vertical stresses in a wall supported on beams of section V19x45, V19x65 and V19x85, respectively. The arc effect unloads the central third of the span where tensile stresses around zero are observed, meanwhile, compressive stresses as high as 10 MPa ocurred near the beam ends. As moving away from the beam up the wall, the compression stresses gradually decrease. Above 70% of the wall height, the average value is of the order of 2MPa.



(a) V19x45 (b) V19x65 (c) V19x85

Figure 2. Stress distribution in the Wall for the cases involving the 4,6m beam

It can be seen that the arc effect decreases as the beam becomes more rigid, as shown by the relative stiffness values Table 4 calculated with eq. (1) and (2). Bending moment, deflection and beam-wall split follow the same trend.

Table 4. Relative stiffness values for the cases involving the 4,6m beam

Relative Stiffness	V19x45	V19x65	V19x85
Stafford and Riddington [10]	9,24	7,01	5,73
Davies and Ahmed [11]	6,37	4,83	3,95

The splits in the contact elements allow to determine in each case the value of the compression length as registered in Table 5. Applying the design expression of the NBR 16868 [4] with the values of average bearing stresses defines the prism/block strength necessary for an efficiency of 0.65, for example, in the compression length region.

Table 5. Compression length and average stresses in the region of the supports

Span of 4,6 m	Compression length (m)	Average stress on supports (MPa)	Design fpk / fbk (MPa)
19 x 45	0,90	9,44	39,7 / 61,15
19 x 65	1,45	5,86	24,67 /37,96
19 x 85	2,05	4,14	17,43 / 26,82

5 Influence of other parameters

Some additional parameters such as the characteristics of the beam-wall contact surface, the characteristic strength of the blocks and the support conditions also influence, more or less significantly, the phenomenon of arc effect. A 50% variation in the normal and tangential stiffness of the interface did not show significant changes in the compressive length values. When changing the resistance of the block, the bending moment follows a tendency inversely proportional to the resistance of the blocks because it changes the relative stiffness beam-wall. Smaller values lead to higher values of compressive length and average stress on the bearing region.

Regarding the type of supports the analysis deserves a more in-depth look. All models presented so far consider that the beam is supported, at its ends, on nodes located at the height of the centroid of its cross section. This approach aims to respect the support conditions presupposed in the pre-sizing that considers an elastic beam. Thus, it is easier to compare models with monolithic beam-wall system with the theoretical calculation of an isolated beam receiving the same load. However, it is known that in a real situation the beam is supported by columns. This configuration tends to reduce the arc effect, since the column allows a larger support area and the deformations will be smaller due to the axis of inertia being at the bottom of the beam.

Figure 3 illustrates the stress distributions observed in the walls supported on 4,6 m beams when those lay over a length of 40 cm, which corresponds to one of the dimensions of the columns. There is a clear decrease in the arc effect when compared to the models supported by nodes (Fig. 2).

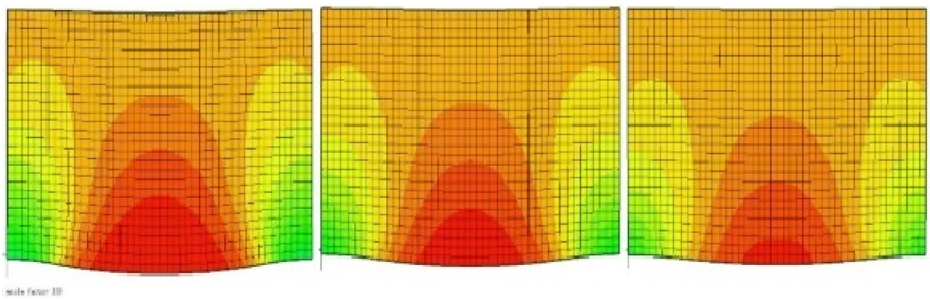


Figure 3. Stress distribution considering the column cross section as support

Table 6 summarizes the deflection values, split values, compression length and average stress on the bearing area for all models where the area of the column cross section is discretized.

Compared with the cases supported by nodes, it is noticed that all deflections are reduced to 70% of the expected values. There was split only in undersized models. The compression lengths increased from 55% to 85% reducing the value of the average stresses acting in the support region by about 60%. The table 7 completes the analysis of the overloading in the region of the supports with the necessary values of prism and block strength.

Table 6. Summary of simulations for beams supported on 19X40cm columns

	Cross Sections	Deflection (mm)	Split (mm)	Compression length (m)	Average stress (MPa)
Span of 3 m	19 x 45	0,259	0,000	2,20	2,52
	19 x 65	0,222	0,000	3,00	1,85
	19 x 85	0,204	0,000	3,00	1,85
Span of 4,6 m	19 x 45	0,6	0,008	2,50	3,40
	19 x 65	0,554	0,000	2,90	2,93
	19 x 85	0,483	0,000	3,42	2,46
Span of 6 m	19 x 45	1,068	0,035	2,70	4,10
	19 x 65	0,940	0,001	3,25	3,41
	19 x 85	0,852	0,000	3,75	2,95

Table 7. Comparison of strength estimates for the two approaches

	Cross	Beams supported on nodes		Beams supported on columns	
	Sections	fpk (MPa)	fbk (MPa)	fpk (MPa)	fbk (MPa)
Span of 3 m	19 x 45	23,32	35,88	10,61	16,32
	19 x 65	15,16	23,32	7,78	11,98
	19 x 85	12,04	18,52	7,78	11,89
Span of 4,6 m	19 x 45	39,70	61,15	14,31	**22,02**
	19 x 65	24,67	37,96	12,33	19,00
	19 x 85	17,43	26,82	10,35	15,96
Span of 6 m	19 x 45	50,10	77,08	17,26	**26,55**
	19 x 65	32,18	49,50	14,35	**22,08**
	19 x 85	22,78	35,04	12,42	19,10

It is observed that the lower occurrence of arch effect in the cases of beams on columns reduces greatly the number of cases that would show crushing of the wall. Only the undersized beam situations generate stress averages above the 20 MPa characteristic strength of the concrete blocks, which would lead to local crushing of the wall. However, it is important to remember that these stress values can increase, since this value are averages, and the blocks at the ends of the beams may have even higher stresses, and also because in this work only the gravitational forces are considered, neglecting the forces resulting from the lateral loads, mainly the forces due to the wind.

6 Conclusions

In this work, the load transmission of the set of standard floors in the transitional floor was studied through the analysis of the stress redistribution at the beam-wall interface, comparing the basic design approach via the elastic line of the beam with a more realistic evaluation considering the support area on the columns. The simulations presented in this work confirm the influence of the beam and wall dimensions, through the concept of relative stiffness. The compression length, when expressed as % of the span length, decreases for larger span values while increasing for higher beam cross sections. The approach of pre-sizing by limit deflection proved to be very conservative, accusing crushing in all situations as it always tends to define a compression length in the order of 1/3 of the span. The explicit consideration of the support area on the columns showed that the arch effect occurs, but in lesser intensity, as both the beam-wall split and the average stress on the compression length decrease. In this case, only situations considered to be undersized would show crushing. This study only addressed the situation of a simply supported beam with gravitational loads. It would also be important to evaluate the influence of some other aspects such as: the consideration of lateral actions that can introduce an overload on the wall, the presence of openings in the wall, the case of continuous beams and also the consideration of shear forces in the bearing structures.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] W. C. Santiago and A. T. Beck. A method for doing good. *International Journal for Blab La Blab*, vol. XI, n. 4, pp. 662–672, 2018.
[2] NBR-15812. *Alvenaria Estrutural - Blocos Cerâmicos*. ABNT, 2010.
[3] NBR-15961. *Alvenaria Estrutural - Blocos de Concreto*. ABNT, 2010.
[4] NBR-16868. *Alvenaria Estrutural*. ABNT, 2020.
[5] P. C. Barbosa. *Interação entre paredes de alvenaria estrutural e vigas e concreto armado*. São Carlos, 2000.
[6] R. H. Wood. The composite action of brick panel walls supported on reinforced. *National Building Studies/HMSO*, vol. 1, n. 13, 1952.
[7] S. Rosenhaupt. Experimental study of masonry walls on beams. *Journal Of The Structural Division*, vol. 88, n. 1, pp. 137–166, 1962.
[8] P. Burhouse. Composite action between brick penal wall and their supporting beams. *Proceedings of the institution of Civil Engineers*, vol. 43, n. 1, pp. 175–194, 1969.
[9] V. Navaratnarajahm. Composite action of brick walls supported on beams. *International Seminar/Workshop on planning, design, construction of load-bearing brick buildings for developing countries*, vol. 1, n. 1, pp. 204–225, 1981.
[10] S. B. Stafford and J. R. Riddington. The composite behaviour of elastic wall-beam systems. *Proceedings of the Institutio of Civil Engineers*, vol. I, n. 1, pp. 377–391, 1977.
[11] S. R. Davies and A. E. Ahmed. An approximate method for analysing composite walls/beams. *International Symposium On Load-Bearing Brickwork*, vol. I, n. 1, pp. 305–320, 1977.
[12] P. D. Buhan and G. D. Felice. A homogenization approach to the ultimate strenght of brick masonry. *Journal of the Mechanics and Physics of Solids*, vol. 45, n. 7, pp. 1085–1104, 1997.
[13] M. Kuczma and K. Wybranowska. Numerical homogenization of elastic brick masonry. *Civil and Environmental Engineering Reports*, vol. 1, n. 1, pp. 135–152, 3005.
[14] P. B. Lourenço and A. Zucchini. Homogenisation approaches for structural analysis of masonry buildings. *Us Army Corps od Engineers - Engineer Research and Development Center*, vol. 1, n. 1, 2008.
[15] J. M. Désir. Analysis of the contribuition of masonry infill in the overall stiffness of concrete frames. *15th International Brick and Block Masonry Conference*, vol. 1, n. 1, 2012.
[16] K. Ghassan and M. Armin. Constitutive models for nonlinear finite element analysis of masonry prisms and infill walls. *Structural Analysis of Historical Constructions*, vol. 1, n. 1, pp. 59–76, 2006.
[17] BS-5628. *Code of practice for use of masonry*. BSI, 2005.
[18] NBR-6118. *Projeto de Estruturas de Concreto - Procedimento*. ABNT, 2014.
[19] G. D. C. D. Santos. *Interação entre paredes de alvenaria estrutural e vigas e concreto armado*. Universidade Federal do Rio Grande do Sul, Porto Alegre, 2019.