ARCH EFFECT – A LITERATURE REVIEW

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SUMMARY

In order to present some comments, criticisms and suggestion, the paper conceptualizes the arching effect and analyzes the design methodologies for the composite action of the wall-beam, the arching effect, in structural masonry, proposed by Riddington and Stafford Smith and by Davies and Ahmed.

INTRODUCTION

With the resurgence of structural masonry in the 1950s and the return to the construction of buildings using this technique, the problem of a wall supported by beams, which was very common in buildings on columns, became important. Studies on this subject were initiated by R. H. Wood in 1952, when he proposed rules for the determination of bending moments in the design of wall-beam structures, based on empirical determination from the results of laboratory tests. In 1969 Wood and Simms published another study on the theme where the previous proposal was revised and refined.

The studies of these researchers showed that the structural masonry walls supported by beams act together, when the beam, on being loaded by the wall, deforms, causing a displacement of the wall in the deformed region. This means that the action of the wall on the beam, initially a uniformly distributed load, becomes concentrated close to the supports, thus causing a substantial reduction in the bending moments in the beam in relation to those obtained with the uniformly distributed load.

Wood and Simms proposed a simple method (Figure 1) for the calculation of the beam-wall combination, adopting a rectangular block with vertical compression stresses close to the supports, extending to a distance x from the supports. The arching effect presupposes the displacement of the wall and beam in the central region, due to flexural deformations of the beam, and thus, the length x of the stress block must be seen as the length of contact, close to the supports, between the wall and the beam.

Following the initial study by Wood and Simms, the problem of the composite wall/beam action has been studied by many researchers including: Burhouse, Rosenhaupt, Davies and Ahmed, Riddinghton and Stafford Smith, and Hendry and Ahmed. The quantification of the effects of this composite action, besides being necessary for understanding it, aims at the rational sizing of the wall and of the beam, in order to resist the actions resulting from the behavior of the arching in a more economical way, that is, to allow a reduction in the material costs while maintaining the structural integrity.

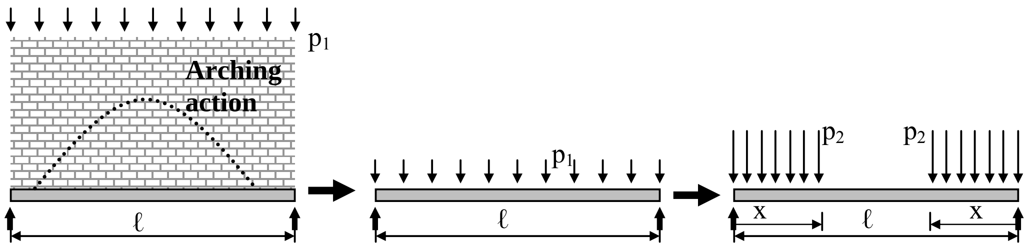

Figure 1. Schematic representation of the proposal of Wood and Simms (1969)

These studies, aimed at understanding the phenomenon and describing it through equations, were based on both numerical and experimental analysis. For the structural scheme, although there is a predominance of walls supported by simply supported beams, many studies have considered walls over continuous beams and, both for the masonry and for the beam, many materials have been tested. For the wall clay bricks and ceramic and concrete blocks have been used, and for the beam reinforced concrete, metal profiles and mixed section beams (metal profiles embedded in concrete).

Hendry published two books in 1981: *An Introduction to Load-Bearing Brickwork*, with the co-authors B. P. Sinha and S. R. Davies, and *Structural Brickwork*. In them (one chapter each), he condenses the results of research on the arching effect. Drysdale, together with Ahmed and Baker, in 1994, published the book *Masonry Structures: Behavior and Design,* where they also dedicated a chapter to addressing this subject, however, expanding a little on the theme, indicating the lack of evolution of research on the subject. Both authors adopt the results of the research carried out by Riddington and Stafford Smith and by Davies and Ahmed, which are adopted by consensus as a parameter for the study of the arching effect until today.

More recently, some studies on the arching effect have been published. Hardy (2000), through a finite elements analysis, studied the action of the arching effect on masonry walls supported by steel beams In his research, he analyzed the area of contact and the compression and flexural stresses in the steel beam and in the masonry. Jagadish and Ramachandra (2000) proposed a rational design method for the composite wall-beam systems, for which they carried out a comparative study between the English and Indian standards.

In the past decade, in Brazil, master's and doctoral theses have been produced, including *Composite Wall-Beam Action in Masonry Structures* (Tomazela, 1995), *Influence of Settling on Structural Masonry of Buildings* (Holanda, 2002) and *The Contribution of shear walls to the Action of the Arching Effect in Masonry Structures* (Carvalho, 2007), addressing, directly or indirectly, the arching effect.

THE ARCHING EFFECT

The studies of Wood (1952) and Wood and Simms (1969), had proposed a method for the calculation of very simple beam-wall composites (Figure 1), which was improved in later studies. However, they had already observed the need for a sufficiently strong link between the wall and the beam, in order to allow the development of the shearing forces required for the full development of the composite action between the wall and its support beam and related it to the wall height/span ratio, establishing that for values of this ratio lower than 0.6, the shearing becomes greater than that supportable at the wall-beam interface.

Burhouse (1969) carried out a study to investigate the effects of a variation in the wall height/span ratio, where he proposed, as a way to avoid the occurrence of slippage between the wall and the beam, that no changes should be made to Wood's recommendation: H/L ≥ 0.6.

> The composite action between the wall and the beam will not occur without the transfer of shear load by the interface between the two components, nor without the transfer of shear load by the mortar joints between the rows of masonry. (BURHOUSE, 1969).
>
> The composite action cannot be achieved unless there is a link between the wall and beam sufficient to allow the development of the required shear load. The great compression stresses near the supports result in great friction forces along the interface, and show that if the wall height/span ratio is > 0.6 then the friction forces developed are sufficient to promote the required shear capacity. HENDRY et al. (1981)

Although there is a consensus among researchers for the ratio of H/L ≥ 0.6 for the occurrence of the arching effect, Hendry (1981) observes that the composite action is still possible, for values lower than 0.6, however, treating the element as one purely of flexure. In a recent study, JAGADISH and RAMACHANDRA (2000) adopted the value of 0.5 for the H/L ratio and they observe:

> With the ratio decreasing below 0.5 the arch becomes more flattened, resulting in a greater horizontal thrust close to the supports and consequently a greater shear load in the horizontal joints of the masonry and along the wall/beam interface. Consequently, it is advisable, in order to obtain the advantages of the composite action of the wall/beam systems, that the H/L ratio is greater than 0.5.

In order to simulate the composite wall/beam action, the model of a tied arch where the arch is formed by the wall and beam acting as a tie is used (Davies and Ahmed, 1978; Hendry, 1981; and Burhouse 1969). Burhouse also suggests that all of the reinforcement should be placed on supports and the length of their anchorage be determined with some clearance.

The beam, on being loaded by the wall, deforms, and due to its flexing the arching action occurs in the wall. The degree of arching is dependent on the relative wall/beam stiffness, and the flexural and axial stiffness must also be considered. Although the shear force tends to act against the deformation of the beam, this tends to incline downward, moving away from the wall, with the possible development of cracks between the top of the beam and base of the wall. The shear force also induces an axial stress in the beam, with a magnitude which varies along the span. In the wall, an arching action is developed and the vertical stresses concentrate close to the supports.

- The more rigid the beam, the less its deformation and the larger the area of contact with the wall will be. The distribution of shear and vertical stresses, in these areas, may be represented in an approximate way by a parabolic diagram (2º or 3º).

- The more flexible the beam the greater the deformation, the smaller the area of contact and the greater the concentration of stresses close to the supports. The distribution of shear and vertical stresses, in these areas, may be represented in an approximate way by a triangular diagram.

The arching effect is conceptually a rearrangement of the resistant forces of the structure. A wall over an extremely rigid base has a uniform stress distribution and, on reducing the beam stiffness, this distribution of stresses tends to concentrate on the lower sides of the wall, a consequence of the arching effect, alleviating the load in the central region of the base of the wall.

Riddington and Stafford Smith (1978) and Davies and Ahmed (1978) proposed design methodologies, that is, ways to develop equations for the composite wall-beam action and, in these methodologies, they adopted stiffness parameters to express the relative stiffness of the wall and beam.

METHODOLOGY PROPOSED BY DAVIES AND AHMED (1978)

The authors consider the degree of concentration of vertical stresses on the lower sides of the wall, a consequence of the arching effect, the main reason for collapse in most of the cases analyzed. This concentration of stresses is influenced mainly by the stiffness in flexure. They propose a stiffness parameter defined by:

$$R = \sqrt[4]{\frac{H^3 t E_w}{I E_b}} \qquad 1$$

where I and E_b are the moment of inertia of the section and elastic modulus of the beam, and H, E_w and t are the height, elastic modulus and width of the wall, respectively.

The authors attribute to the stiffness parameter "R" the function of governing the vertical stress distribution along the contact surface and consider:

- $R \geq 7$ very slim beam where the distribution of stresses is triangular with great concentrations of vertical stresses on the supports;
- $5 < R < 7$ intermediate R values where the distribution of stresses along the contact surface is close to a simple parabola (quadratic);
- $R \leq 5$ relatively rigid beams where the vertical contact stress is extended to the center of the beam, with less concentration of stress on the supports. The distribution of stress approximates to a third degree parabola.

The three cases identified by the limits of the R parameter may be shown according to the diagram in Figure 2.

From the numerical results obtained from the finite elements analysis, Davies and Ahmed described through equations the concentration of vertical stresses in the wall, the maximum axial strength in the beam, the peak shear load along the wall/beam interface, the bending moment and the deflection in the beam, through the coefficients α, β and γ, obtained empirically as a function of the H/L ratio, according to the graph shown in Figure 3.

For the concentration of vertical stresses in the wall they proposed, as an alternative, its determination as a linear relation between the stiffness parameter R and the H/L ratio, according to Figure 4. From the analysis of the calculation methodology proposed by Davies and Ahmed (1978), it can be observed that:

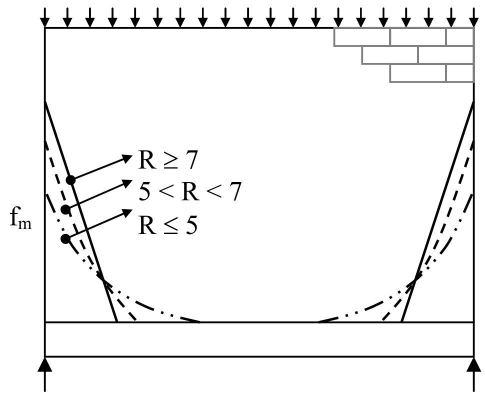

Figure 2. Distribution of vertical stress along the wall/beam interface. Source: Davies and Ahmed (1978)

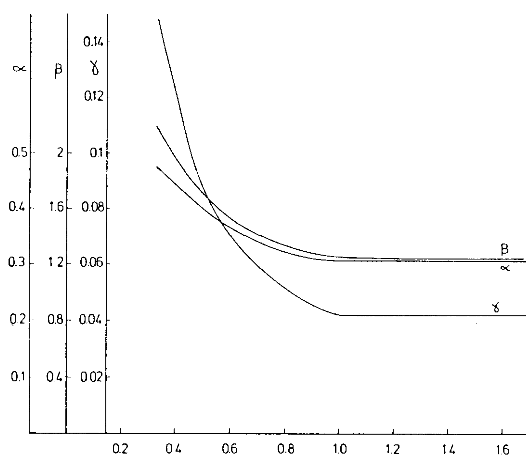

Figure 3. Variation of α, β and γ with H/L. Source: Davies and Ahmed (1978)

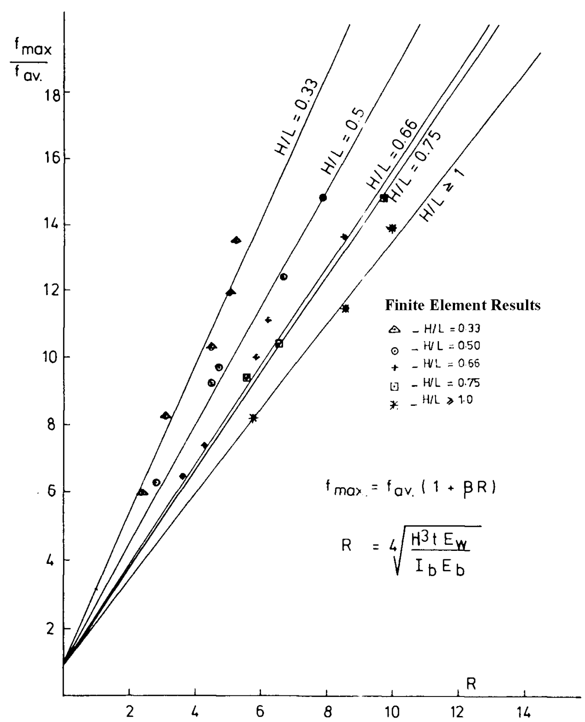

Figure 4. Concentration factor for the vertical stresses.

- the increase in the resistance of the blocks (f_{bk}) implies an increase in the relative flexural stiffness (R), resulting in an increase in the stress concentration factor (C) and, consequently:
- an increase in the maximum vertical compression stress in the wall (f_{max});
- an increase in the value of the relative axial stiffness parameter (K), causing a reduction in the maximum axial force in the beam (T);
- a reduction in the bending moments of the beam.

A reduction in the H/L ratio of the wall (always kept above 0.6), on the other hand, implies a reduction in the relative flexural stiffness parameter (R), resulting in a reduction in the stress concentration factor (C) and consequently, in a reduction in the maximum vertical compression stress in the wall (f_{max}), in a reduction or an increase in the value of the relative

axial stiffness parameter (K), and the maximum axial force in the beam (T), respectively, and in an increase in the bending moments of the beam.

METHODOLOGY PROPOSED BY RIDDINGTON AND STAFFORD SMITH (1978)

The studies by Riddington and Stafford Smith are characterized by the adoption of a characteristic parameter K, to express the relative stiffness of the wall and beam:

$$K = \sqrt[4]{\frac{E_w t L^3}{EI}} \qquad 2$$

where E, I and L are the elastic modulus, moment of inertia of the section and beam span, and E_w and t are the elastic modulus and the wall thickness, respectively.

Based on Burhouse's observation that the minimum wall height should be greater than 60% of the beam span and that the distribution of stress in the wall and the interaction mode of the structure are, for practical purposes, independent of the height above this value, Riddington and Stafford Smith decided on a design methodology with the value (K) - relative stiffness of wall and beam – being independent of the height of the wall.

The determination of the effective contact length, that is, the lengths of the regions where the loads are transferred from the wall to the beam is proposed through the expression:

$$\alpha = \frac{BL}{K} \qquad 3$$

where L is the span, K is the characteristic parameter, determined by equation (2), and B is a calibration constant whose value is obtained from the experimental data, obtained from the analysis of various test programs in real scale and in the models.

Analysis of the experimental results was used to verify the theoretical analysis of the stress distributions between the wall and the beam over the contact region. These theoretical and experimental studies showed that the compression and shear load distributions along the contact length behave according to the diagrams in Figure 5 (a) and (b). For simplification, considering that the results were very close to those of the real stress distributions, the authors adopted a triangular distribution, as shown in Figure 5(c).

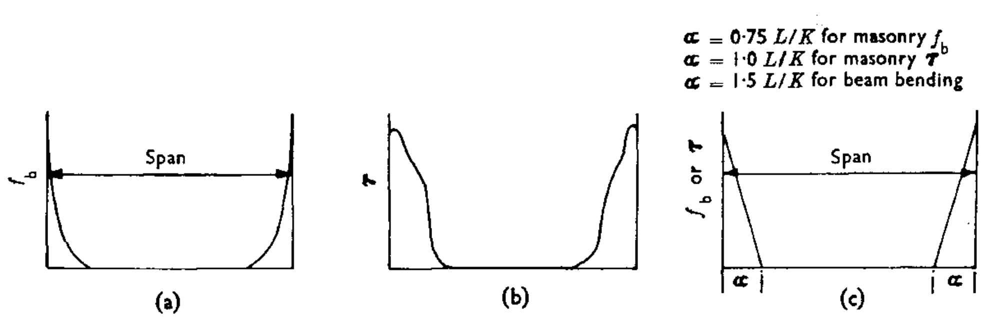

Figure 5. Stress distribution: (a) typical vertical stress distribution; (b) typical shear load distribution; (c) distribution adopted for the vertical and shear loads. Source: Riddington and Stafford Smith (1978).

The authors used three methods to determine the practical values for the B constant in Equation 5. The first was a direct measurement of the contact length; considered not very accurate given the difficulty of defining the limits of the separation cracks. The second was obtained from the measurement of the vertical deformations of the wall above the beam extremities. These were used to calculate the stresses and, once the total applied load is known and adopted in the triangular distribution of stresses, enabled the calculation of the contact length. The third method involved a similar calculation to the second, but using the collapse load of the wall and the resistance to compression of the masonry unit.

Since the value of B controls the degree of conservatism of the design procedures for the various limitation criteria, it can be modified to values higher or lower than its initial value, to ensure that each procedure produces a reliable result. The authors analyzed four effects particularly related to the arching and which must be considered in the development of a design method, and based on these results they adopted a value for the B constant of:

Estimate of maximum compression stress in the wall	B = 0.75
Estimate of maximum bending moments in the beam	B = 1.5
Estimate of shear load at the interface	B = 1.0
Beam deformation	$h_v \geq \ell /25$

One of the characteristics of the proposal by these authors is the search for a stiffness of the beam which makes the maximum stress in the masonry equal to its admissible stress. With this procedure they attempted to ensure a stress which can be supported by the masonry.

The beam stiffness is found through the parameter $K = \sqrt[4]{\frac{E_w t L^3}{EI}} \quad \Rightarrow \quad I = \frac{E_w}{E}\frac{tL^3}{K^4}$ 4

where W_w is the total load applied, through the equilibrium of the vertical forces, assuming a triangular distribution of stresses, [Fig. 3(c)].

$W_w = f_b \ \alpha \ t$, and since $\alpha = \frac{0,75L}{K} \quad \Rightarrow \quad W_w = \frac{0,75 f_b L t}{K} \quad and \quad K = \frac{0,75 f_b L t}{W_w}$ 5

where t is the width of the wall and f_b is its maximum compression stress. Substituting (5) in (4):

$$I = \frac{E_w}{E} \cdot \frac{W_w^4}{0,75^4 \ f_b^4 \ L \ t^3} \qquad 6$$

and the inertia of the beam is obtained by substituting the maximum compression stress of the masonry by the admissible stress.

$$I \leq \frac{E_w}{E} \cdot \frac{W_w^4}{0,75^4 \ f_{b,adm}{}^4 \ L \ t^3} \qquad 7$$

In sequence, the authors continue with the development of the equations to describe the flexion, shearing, etc.

CONSIDERATIONS

These two calculation methodologies, proposed thirty years ago, have been accepted by a consensus among the technical and scientific community, for the development of equations to describe the stresses due to the action of the arching effect.

It can be observed in the literature that there is a preference for the proposal by Davies and Ahmed, although, in a recent study Hardy (2000) opted for the proposal by Riddington and Stafford Smith. The research by Hardy forms part of a continuing project involving analytical and experimental investigations on the composite action of steel beams and masonry walls, and the researcher, after analyzing the proposals of Riddington and Stafford Smith and of Davies and Ahmed considers that, in the research of Davies and Ahmed, the loss of contact is not modeled and, consequently, the estimates of the vertical stress in the wall and the bending moment of the beam are significantly lower than those obtained using the method of Riddington and Stafford Smith. These authors, due to the difficulty of measuring experimentally the contact length, obtained a great variation in the values from these experimental tests, and ended up using an average value in their design method.

Both of the proposals admit different materials for the support beam – concrete, steel, wood, etc., however, the methodology proposed by Riddington and Stafford Smith was developed particularly for structures with masonry walls and steel beams.

The preference for the proposal of Davies and Ahmed to the detriment of that of Riddington and Stafford Smith, is due, in principle to:

- the fact that the latter involves a calibration constant B, with a value proposed from experiment data, and a very significant interval of variation, giving some uncertainty to the calculation.
- the proposal by Riddington and Stafford Smith being considered conservative, overestimating the results by 30 to 40%.

> the results of the finite elements for the contact length and the maximum stress in the masonry are reasonably similar to those obtained by Riddington and Stafford Smith (1978). The approximate method proposed by these researchers clearly overestimates the maximum flexion stress [...] Hardy (2000)

- the proposal of Davies and Ahmed having a formulation which has a wider reach, and is more detailed and more accessible to the user.

FINAL CONSIDERATIONS AND SUGGESTIONS

In Brazil, the arching effect in structures with structural masonry has drawn the attention of designers and researchers since the design of buildings on reinforced concrete stilts is very common.

It was verified that the composite wall-beam action produces a substantial increase in the compression stresses in the masonry close to the supports, this being one of the main factors which can cause the structure to collapse. On the other hand, it causes a substantial reduction in the bending moment of the support beam, allowing a great reduction in its dimensions, that is, the support beams which would have the same characteristics as the transition beams, with

the consideration of the arching effect, can have much smaller dimensions, with significant gains both in terms of costs and aesthetics.

It is precisely this problem which is currently occurring. The imposing of the arching effect as a way to reduce the dimensions of the support beams is already found in some guidelines for design in structural masonry and even in scientific studies. The arching effect is conceptually a rearrangement of the resistance forces of the structure which can lead to distress manifestations, mainly those resulting from the great concentration of the compression stresses on the lower sides of the wall or substantial relief of these stresses on the central part of the wall/beam interface. Although experience is lacking, in engineering the possibility for the appearance of the possible defects should be predicted and combated in the project conception, thus avoiding, their appearance and, in the case studied here, the designer is advised to adopt the arching effect as a design concept.

In the technical literature some safeguards are found in relation to the idealization of the experimental modeling, that is, the relationship of the structure to be tested to the real one. Riddington and Stafford Smith (1978) in their conclusions cite some situations found in real structures which are not considered in the experimental model. Jagadish and Ramachandra (2000) also observed that "the beams are not normally simply supported, they are fixed at the extremities or are continuous with one or more intermediate supports or the beam is part of a global structure [...] consequently, these common wall/beam systems are less critical than the idealized case analyzed".

The issue relating to the idealization of the experimental model, practically not approached in the technical literature, needs further reflection. The support beams used for the numerical and/or experimental model as a rule of thumb are simply supported beams, with some exceptions where continuous beams are used and it is worth noting that the arching effect is to some extent relieved, since they undergo deformations which are much smaller than those of simply supported beams.

The most notable fact is that studies carried out so far have been focused on isolated elements, considered separately from the structure, that is, the interactions between the walls, or between the walls and columns (of masonry), so common in structures made of structural masonry, have not been analyzed. In structural masonry the walls may be considered without flanges (buttresses), as isolated panels, although they are commonly associated with flanges in a "C", "L", "T", "I" or "Z" form.

With regard to the walls interacting with flanges, we may ask, in what way are the stresses concentrated close to the supports? Is there no partial absorption of these stresses by the flanges? And is the stiffness of the wall not significantly increased with the contribution of the flanges?

Another issue to be observed is in relation to the beam stiffness. It has been verified that the consideration of the arching effect with the concentration of stresses close to the supports results in a substantial reduction in the bending moment and, consequently, in the section height however, the total applied load remains the same, that is, it maintains the designed shear load, although the resistant shear load undergoes a reduction proportional to the section height. In other words: the section reduction enabled by the arching effect is restricted by the crushing of the connecting bars of the concrete.

Davies and Ahmed (1978) attribute to the stiffness parameter "R" the function of governing the distribution of vertical stress along the contact surface. The authors identify three cases given by the limits of parameter R ($R \geq 7$. $5 < R < 7$ and $R \leq 5$; respectively, for very slim beams, intermediate values and relatively rigid beams). However, although the parameter R is dependent on the characteristics of the wall and support beam, it can be concluded that, in the case of walls/concrete beams, the restriction in the section reduction due to compression of the concrete bars rarely leads to the intermediate or slim situation, that is, we work with relatively rigid beams.

The reduction of the beam sections is important, and thus, even more important is to deepen the studies in order to better our understanding of the arching effect. With the consideration of the interaction of the wall with other structural elements we seek to improve our understanding of the composite wall-beam action, with a greater fidelity between the real and test structures.

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