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Bottle-shaped stress field solution for partially loaded reinforced concrete blocks

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Abstract

Most existing approaches for the design of partially loaded areas in reinforced concrete – including design rules in international codes – are purely empirical, and based on experimental tests on unreinforced concrete. In this paper, a bottle-shaped stress field solution for strip loading is presented and generalised for axisymmetric cases of partial area loading. The model is compared to experimental results as well as predictions obtained from existing models and design rules. While the correlation with the available experimental evidence is good, further experiments are required for verification, particularly for the case of heavily confined areas.

1 Introduction

Partially loaded areas occur frequently in engineering practice where concentrated loads are applied onto a concrete member over limited contact areas. The resulting internal compressive stresses spread with increasing distance from the loaded area until they eventually approach a uniform distribution over the entire cross-sectional area of the block. It can be distinguished between spatial (Fig. 1a) and plane (Fig. 1b and c) cases of partial area loading, depending on whether the load disperses in one or two directions, respectively [1], [2]. Plane cases of partial area loading can be further subdivided into plate (Fig. 1b, \( b_2 < 2d_1 \)) and strip loading (Fig. 1c, \( b_2 \geq 2d_1 \)).

Although this apparently simple problem has been studied for almost a century and a half, there is a remarkable knowledge gap regarding the mechanical modelling of partially loaded areas. This lacuna manifests in the fact that the design of partially loaded areas in most international codes relies on the following so-called “square-root equation”:

\[
\frac{f_{cc}}{f_{c0}} = \sqrt{\frac{A_{x1}}{A_{x0}}} = \sqrt{\frac{b_2d_2}{b_1d_1}}
\]

relating the average bearing capacity \( f_{cc} \) of the loaded area to the uniaxial compressive concrete strength \( f_{c0} \) and to the square root of the ratio of the maximum design distribution area \( A_{x1} \) (cross-section of block) to the loaded area \( A_{x0} \). Due to its purely empirical nature, standards typically restrict the use of Eq. (1) by several conditions, among which the geometric affinity of \( A_{x0} \) and \( A_{x1} \), and the

![Fig. 1 Cases of partial area loading: (a) Spatial case, (b) plate, and (c) strip loading. Adapted from [2].](image)
limitation of the strength increase to a factor of 3. The latter limitation is overly conservative for highly concentrated loads and for reinforced blocks (see Section 3.4). Moreover, because of the requirement of geometric affinity, these codes, strictly speaking, do not allow for a strength increase in plane cases of partial area loading. While this appears justified for partially loaded plates, it is overly conservative for strip loading [1], [2].

These observations provided the motivation for the authors to develop two new mechanical models, based on the lower-bound theorem of limit analysis, for reinforced concrete blocks under partial area loading: a wedge-and-fan type stress field [1] and a bottle-shaped stress field. In the present paper, the latter is developed for strip loading, generalised for axisymmetric cases of partial area loading, and finally compared to experimental results as well as existing models and design rules.

2 Confinement of the concrete region immediately below the loaded area

The dispersion of forces below the loaded area gives rise to transverse compressive stresses in the confined region immediately below the loaded area, and transverse tensile (bursting) stresses in the bursting region further away from it. Owing to the beneficial effect of confinement, the concrete below the loaded area can sustain compressive stresses several times higher than the uniaxial compressive strength. The confining stresses are caused by (i) the deviation of the compressive stress trajectories (geometric confinement), and (ii) the impediment of lateral expansion caused by the surrounding, axially unloaded part of the block (passive confinement). The reader is referred to [1] for a thorough description of the mechanical behaviour of partially loaded areas and their failure modes.

Fig. 2 illustrates possible ways of modelling and quantifying passive confinement. The lateral dilatancy of the axially loaded concrete is initially impeded by the surrounding uncracked concrete mass. This pre-cracking passive confinement is difficult to reliably quantify for strip loaded members (Fig. 2a) and will be neglected in the development of the stress field. For the spatial case, however, it can be estimated by considering a thin horizontal section near the loaded surface of the block and assuming circumferential stresses amounting to the concrete tensile strength $f_{ct}$ in the concrete surrounding the loaded area (Fig. 2c):

$$\sigma_{\text{conf,pre}} = f_{ct} \left( \frac{d_1}{d_t} - 1 \right) \quad (2)$$

After cracking, a properly dimensioned and detailed amount of transverse reinforcement in the immediate vicinity of the loaded area can provide passive confinement of the surrounding concrete. This post-cracking passive confinement can be estimated for strip loaded members (Fig. 2b) as [3]:

$$\sigma_{\text{conf,post}} = \frac{A_{s,x} f_y}{b_s s_c} \quad \text{or} \quad \frac{A_{s,y} f_y}{a_s s_c} \quad (3)$$

where $A_s$ = total cross-sectional area of confining reinforcement in the considered direction, $f_y$ = yield strength of the reinforcement, and $s_c$ = reinforcement spacing in $x$-direction. For the spatial case (Fig. 2d) the same approach yields confining stresses of $(A_s f_y) / (s_c d_t)$; these stresses are transferred radially through the uniaxially stressed zone to the border of the loaded area, where they amount to:

Fig. 2 Modelling of passive confinement for partially loaded concrete blocks.
\[ \sigma_{\text{conf,post}} = \frac{A f_y}{s_i d_i} \frac{d}{d_i} = \frac{A f_y}{s_c d_i} \]  

Whether the extremely high confining stresses obtained from Eq. (4) for very concentrated loading \((d_i/d_s \leq 1)\) can be activated has not been experimentally verified to the authors’ knowledge.

3 Bottle-shaped stress field

3.1 Main assumptions

The bottle-shaped stress fields are based on the consideration of compression bands whose width is adjusted to account for the increase in concrete strength caused by the confinement produced by both geometric as well as passive confinement. To account for the confinement, a modified Coulomb failure criterion with a zero tension cut-off is used for the concrete, using \(\tan \phi = 0.75\) and \(c = f_c/4\) for the angle of internal friction and the cohesion, respectively.

Each band \(i\) is loaded with a compressive force \(n_i\) and its curvature results in deviation stresses \(u_i(x)\). If the latter are assumed to act horizontally (i.e. in the \((y,z)\)-plane), equilibrium of an infinitesimal band element (Fig. 3a) requires that the vertical \((x)\) component \(n_{ix}\) of the band force is constant along the entire band length, and the deviation forces are

\[ u_i(x) = n_{ix} \frac{\partial \tan \phi}{\partial x} = n_{ix} \frac{d^2 y}{dx^2} = n_{ix} y_{ix}(x) \]  

where \(y_{ix}(x)\) defines the geometry of the axis of compression band \(i\).

3.2 Strip loading

Consider a slice of a long concrete block \((b_i \geq 2d_i\), Fig. 1c), delimited by two vertical planes orthogonal to the longitudinal \(z\)-direction. By symmetry, it is sufficient to consider half of the slice \((y \geq 0)\). The \(z\)-axis is assumed to be a principal direction of stress and strain. The longitudinal stress \(\sigma_z\) can basically be freely chosen and may vary in the \((x,y)\)-plane. Sufficient and adequately detailed longitudinal reinforcement must be provided in the immediate vicinity of the confined zone in order to ensure that the assumed value of \(\sigma_z\) can be activated (as post-cracking passive confinement) [1]. In the present paper, the principal stress \(\sigma_z\) is chosen such that it does not govern concrete failure, i.e. equal

Fig. 3 Bottle-shaped stress field: (a) first compression band and infinitesimal element; (b) complete stress field; (c) transverse confining and bursting stress distribution along \(x\)-axis; (d) Superposition of the bottle-shaped stress field with the passive confining stress; (e) determination principal stresses with Mohr’s circle.
to the confining stress in the \((x,y)\)-plane in the regions of the stress field where confinement is required, and equal to zero in the remaining regions.

The geometric boundary conditions for the development of the stress field are the width \(d_i\) of the loaded strip, the total block width \(d_x\), and the extension of the discontinuity region \(x_d\) at whose end a state of uniform uniaxial compression \((\sigma_y = \sigma_{ud}, \sigma_x = 0)\) over the width \(d_x\) is assumed. The height \(x_d\) is chosen in accordance with Saint-Venant’s Principle to be approximately equal to the block width \(d_x\). The bearing capacity is determined by determining the stress \(\sigma_{ud}\) at the end of the discontinuity region for which the concrete capacity at the loaded surface \((x = 0)\) is reached.

The stress field is developed starting from the compression band corresponding to the outermost stress trajectory \(y_i(x)\), whose geometry defines the shape of the stress field (Fig. 3a). Any mathematical function with a plausible shape (“bottle” with inflection point within \(x_d\)) and a sufficient number of parameters to satisfy the boundary conditions

\[
y_i(x = 0) = \frac{d_i - \Delta y_{0,i}}{2}, \quad y_i(x = x_d) = \frac{d_i - \Delta y_{ud}}{2}, \quad y_i'(x = 0) = 0, \quad y_i'(x = x_d) = 0
\] (6)
can be chosen, where \(\Delta y_{0,i}\) and \(\Delta y_{ud}\) are the widths of the compression band at \(x = 0\) and \(x = x_d\), respectively. According to the lower-bound theorem of limit analysis, any solution is on the safe side, i.e. the one yielding the highest ultimate load is preferred. One possible function is described by:

\[
y_i(x) = e^{C_i \sigma} C_{2i, \sin (C_{3i}, x + C_{4i}) + C_{5i}}
\] (7)

and will be used by way of example in the following. In Eq. (7), four of the constants \(C_{ij}\) to \(C_{5i}\) are determined by the boundary conditions given in Eq. (6) (suitably adapted for \(i > 1\) as described below) and the remaining constant is optimised in order to maximise the ultimate load. This function was chosen because it results in bursting stress distributions that are in good agreement with Elasticity Theory (Fig. 3c), which can also be achieved with polynomial functions.

Being the vertical component of the band force \(n_{x,i} = \sigma_{ud} \Delta y_{ud}\) constant over the entire length of the compression band, the width \(\Delta y_{ud} = n_{x,i} / f_{c0}\) at \(x = 0\) follows from the condition that the uniaxial concrete compressive strength \(f_{c0}\) is reached at \(x = 0\).

The deviation stresses – obtained from Eq. (5) – are equilibrated by the concrete surrounding the compression band. Depending on the sign of \(y_i''(x)\), they create (i) bursting stresses that are resisted by tension in the concrete or reinforcement (before and after cracking, respectively) or (ii) confining stresses producing horizontal compression in the concrete inside the compression band \((y < y_i)\) and a corresponding increase of the axial concrete strength.

Based on the shape of the first compression band \((i = 1)\) the following bands \((i > 1)\) are determined using the same mathematical function, but adapting its parameters in order to satisfy the different boundary conditions. While – as for the first compression band – the slope at both ends of the discontinuity region must be vertical, \(y_i'(x = 0) = 0\) and \(y_i'(x = x_d) = 0\), the position of compression band \(i + 1\) at \(x = x_d\) and \(x = 0\) follows from the position of compression band \(i\) and the following conditions: (i) all compression bands have the same width \(\Delta y_{ud}\) at \(x = x_d\), and (ii) the axial stress in each compression band is equal to the confined concrete strength at \(x = 0\), i.e. \(\sigma_{co,i} = f_{c0,i}\). Hence, all compression bands carry the same vertical force \(n_{x,i} = n_{x,i}\) since \(\sigma_{ud}\) is constant, and the widths \(\Delta y_{ud} = n_{x,i} / f_{c0,i}\) of the compression bands at \(x = 0\) decrease towards the middle of the block (i.e. with increasing \(i\)) in inverse proportion to the concrete strength \(f_{c0,i}\), which increases in this direction along with the confining deviation stresses caused by the outer compression bands \((1..i-1)\) as illustrated in Fig. 3b. Note that this leads to a distribution of axial stresses at \(x = 0\) that differs significantly from elastic solutions, where the peak stresses are obtained at the edges of the loaded area. If the stress \(\sigma_{ud}\) at the end of the discontinuity region \(x = x_d\) is increased, the width \(\Delta y_{ud}\) used by the compression bands at \(x = 0\) grows until the bearing capacity

\[
\frac{\sigma_{ud}}{f_{c0}} = \frac{\sigma_{ud}}{f_{c0}} \frac{d_i}{d_1}, \quad \text{where} \quad \frac{\sigma_{ud}}{f_{c0}} = \frac{2}{d_1} \sum_i (\sigma_{ud,i} \cdot \Delta y_{ud,i}) = \frac{2}{d_1} \sum_i n_{x,i}
\] (8)
is reached when the compression bands take up the entire width \(d_i\) of the loaded area at \(x = 0\).

Fig. 3b illustrates the complete stress field obtained following the procedure described above. The bursting reinforcement can be determined from the distribution of transverse stresses (sum of deviation forces of all compression bands for given \(x\)) along the x-axis (Fig. 3c). In order to account for the beneficial effect of a transverse confining reinforcement in the immediate vicinity of the loaded area,
a uniaxial compressive stress field in the y-direction, with compressive stresses corresponding to the confining stresses caused by the reinforcement (see Section 2), can be superimposed to the bottle-shaped stress field as shown in Fig. 3d. Thereby the axial concrete strength, and accordingly the ultimate load, is further increased. Note that to be able to resist the resulting higher load, the bursting reinforcement must be increased accordingly.

Depending on the expression used to define the geometry of the compression bands, the concrete failure criterion may be governing along a compression band rather than at \( x = 0 \) as assumed above. This can be verified by computing the principal stresses and checking the failure criterion at each point of the compression bands, as shown in Fig. 2e. If the failure criterion is infringed, the value of \( \sigma_{ud} \) must be adjusted, while keeping the geometry of the stress field unchanged, until the failure criterion is respected throughout the entire block.

### 3.3 Spatial case of partial area loading

In this section, the bottle-shaped stress field is adapted to axisymmetric problems. Consider the cylindrical block of diameter \( d_y \), centrally loaded over an area of diameter \( d_i \), using cylindrical coordinates \((x, r, \theta)\) with the x-axis corresponding to the block axis. The procedure to develop the bottle-shaped stress field is essentially the same as in the plane case; however, here a sector of the block with a central angle \( d\theta \) is considered (Fig. 4a). The compression band corresponding to the outermost principal stress trajectory \( r_i(x) \), with a radial width of \( \Delta r_{ad} \) at \( x = x_d \), carries an axial force of:

\[
n_{s,i} = \sigma_{ud} d A_{sd,i} = \sigma_{ud} \Delta r_{ad} r_i(x = x_d) d\theta
\]  

(9)

Being the vertical component of the band force constant over the entire length of the compression band, and assuming that the uniaxial concrete strength \( f_{c0} \) is reached at \( x = 0 \), the following relationship for the radial width \( \Delta r_{0,i} \) at \( x = 0 \) is obtained:

\[
\Delta r_{0,i} = \Delta r_{ad} \frac{r_i(x = x_d)}{f_{c0} r_i(x = 0)}
\]  

(10)

Substituting \( r_i(x = 0) = (d_i - \Delta r_{0,i})/2 \) and \( r_i(x = x_d) = (d_2 - \Delta r_{ad})/2 \) into Eq. (10), a quadratic equation for \( \Delta r_{0,i} \) is obtained.

The deviation forces along the axis (= trajectory \( r_i(x) \)) of the compression band can be calculated according to Eq. (5). Dividing the deviation forces by the arc length \( ds_i(x) = r_i(x) d\theta \) of the compression band at any point of its axis results in following expression for the deviation stresses:

\[
u_i(x) = \sigma_{ad} \Delta r_{ad} \frac{r_i(x = x_d)}{r_i(x)} r_i''(x)
\]  

(11)

The deviation stresses act in a radial direction. Equilibrium for an axisymmetric disc loaded in its plane (Fig. 4b) requires that:

\[
\frac{\partial \sigma_r(r)}{\partial r} + \frac{\sigma_r(r) - \sigma_\theta(r)}{r} = 0
\]  

(12)

Here, the following solution of Eq. (12), yielding a safe value of the bearing capacity in accordance with the lower-bound theorem of limit analysis, is chosen:

\[
\sigma_r(r) = \sigma_\theta(r) = u_i , \quad \text{for } 0 \leq r \leq r_i
\]

(13)

\[
\sigma_r(r) = \sigma_\theta(r) = 0 , \quad \text{for } r_i < r \leq d_2/2
\]

Accordingly, uniform biaxial stresses \( \sigma_r = \sigma_\theta = u_i \) result inside the corresponding circle of radius \( r_i \), without affecting the state of stress outside. While the bursting deviation stresses produce tension that must be resisted by tensile stresses in the concrete or reinforcement, the confining deviation stresses are carried by the concrete, resulting in an increase of the concrete strength.

The following compression bands \((i > 1)\) are computed as in the plane case. However, in the axisymmetric case, the magnitude of the axial forces \( n_{s,i} \) decreases towards the block axis since all compression bands have the same radial width \( \Delta r_{ad} \) at \( x = x_d \), see Eq. (9). The radial widths \( \Delta r_{0,i} \) at \( x = 0 \) are computed consecutively using Eq. (10), using adapted values of radii \( r_i(x = 0) \) and \( r_i(x = x_d) \), and confined concrete strengths \( f_{c0,i} \) at \( x = 0 \). The ultimate load
\[
\sigma_{\text{ed}} = \sigma_{\text{ed}} \left( \frac{d_2}{d_1} \right)^2, \quad \text{where} \quad \sigma_{x0} = \frac{8}{d_1} \sum_i \left( \sigma_{\text{ed},i} \Delta r_{\text{ed},i} r_i (x = 0) \right) = \frac{8}{d_1} \sum_i n_{x,i} \tag{14}
\]

is reached for the value of \( \sigma_{\text{ed}} \) at the end of the discontinuity region \( x = x_d \) for which the compression bands takes up the entire radial width \( d_1 \) of the loaded area at \( x = 0 \).

As in the plane case, the failure criterion can be checked by computing the principal stresses at each point of the stress field. The favourable effect of the pre-cracking or post-cracking passive confinement can be accounted for by superimposing – similarly to Fig. 3d – the passive confinement stresses to the above described bottle-shaped stress field. At every height \( x \) the pre- and post-cracking passive confinement can be computed using Eqs. (2) and (4), respectively, using the diameter \( 2r_i (x) + \Delta r_i (x) \) of the stress field at the considered height instead of \( d_1 \).

The axisymmetric stress field can also be used to estimate the ultimate load of more general spatial cases of partial area loading, as long as the cross section of the block and the loaded area can be represented reasonably by circles of equal area.

![Diagram](a) (b)

Fig. 4 Bottle-shaped stress field for axisymmetric problems: (a) circular sector of the block with the first compression band; (b) thin disc concentrically loaded by deviation stresses.

### 3.4 Comparison with existing approaches and test results

Fig. 5a compares the bearing capacity predictions of strip loaded blocks obtained using the bottle-shaped stress field solution with existing design recommendations and a recently developed wedge-and-fan stress field [1]. Contrary to the existing approaches, both stress field solutions allow to consistently account for the favourable effect of transverse confining reinforcement: higher values of \( \sigma_{\text{conf}} \) lead to higher bearing capacities. It can be seen that the empirical “cube-root equation” (essentially Eq. (1) with a cube root instead of the square root), proposed almost 150 years ago by Bauschinger [4] based on strip loaded sandstone specimens and still used today [2], correlates well with the predictions obtained from the stress field solutions for low values of \( \sigma_{\text{conf}} \) and \( \sigma_i \) (with \( \sigma_i \) being the bursting stress in the wedge-and-fan stress field [1]). For small load concentration ratios \( d_i / d_2 < 0.2 \) the bottle-shaped stress field yields considerably lower ultimate loads than both the wedge-and-fan stress field and Leonhardt’s empirical formula for the design of one-way concrete hinges [5] (in Fig. 5a the updated version proposed by [6] is plotted). Trajectory shapes differing from Eq. (7) causing a more uniform confining stress distribution (e.g. parabolic trajectories) are expected to yield better ultimate load estimates for \( d_i / d_2 < 0.2 \). For load concentration ratios above 0.2 the stress field solutions envelop Leonhardt’s equation; the differences between the approaches diminish as the ratio \( d_i / d_2 \) approaches unity.
In Fig. 5b, the results from several test series on unreinforced concrete blocks under partial area loading are compared with predictions using different approaches. Only cylindrical and square specimens centrally loaded over a circular and square area, respectively, and with a height $h$ (in $x$-direction) equal or greater than the width $d_2$ are considered. The rather large scatter in the experimental results is due to the differences in the test setups, concrete properties, and block geometries. The predictions by the bottle-shaped stress field (with pre-cracking passive confinement and limiting the maximum bursting stress to $\sigma_{c,\text{max}} = f_c = 0.10f_{c,0}$), as well as Eq. (1) used in most international standards (in spite of lacking substantiation by a mechanical model), match well with the test data. As in the plane case, the chosen trajectory shape leads the bottle-shaped stress field solution to underestimate the bearing capacity for very concentrated loads ($d_1/d_2 < 0.2$).

After having developed the bottle-shaped stress field solution, the authors discovered a little-known publication of Kupfer [11] using a similar approach, i.e. principal stress trajectories accounting for the strength increase caused by confining deviation stresses. While lacking rigour and generality since simplified shapes of the trajectories and approximate values of the deviation stresses were used, and although neither bursting nor confining reinforcement is accounted for, Kupfer’s approach is elegant, leading to solutions with reduced computational effort, and was innovative at its time. Kupfer’s solution is also plotted in Fig 5b and shows to match reasonably well with the test data, though overestimating the bearing capacity.

Fig. 5c shows that the total bursting force resulting from the bottle-shaped stress field is slightly lower than the one obtained by Mörsch using a simple strut-and-tie model [12] and Leonhardt’s subsequent modification [5]. The excessive conservatism of the chosen trajectory shape for very concentrated loads is evident by the extreme growth of the corresponding total bursting forces for $d_1/d_2 < 0.2$.

Table 1 compares the ultimate loads of reinforced specimens with the prediction by the proposed stress field solution. Again, only cylindrical and square specimens centrally loaded over a circular and square area, respectively, and with $h \geq d_2$ are considered. For the predictions, the average mechanical transverse reinforcement ratio $\omega$ over a distance $d_1$ from the loaded area was used to calculate the post-cracking passive confinement. The correlation with the experimental data is good and represents a significant improvement compared to current design standards. However, further experiments are required for verification of heavily confined blocks, as experimental evidence seems to indicate that the confining reinforcement cannot be fully activated (e.g. specimens 126 and 130 of [13]).
Table 1 Comparison of test results for centrically loaded reinforced concrete blocks with the prediction by the proposed stress field and square-root equation.

<table>
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<tr>
<th>Author</th>
<th>Specimen</th>
<th>$d_1/d_2$ [-]</th>
<th>$\omega$ [-]</th>
<th>$f_{ce}/f_{co}$ [-]</th>
<th>Test Bottle-shaped SF</th>
<th>International codes</th>
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</table>

* Average value of test results.

4 Conclusion

A new stress field solution for strip loaded concrete blocks is presented and adapted for axisymmetric cases of partial area loading. Contrary to existing empirical design rules, the new mechanical model consistently accounts for the behaviour of concrete under multiaxial compression as well as the favourable effect of transverse confining reinforcement in the loaded area. Hence, the bottle-shaped stress field represents an interesting and mechanically consistent way of tackling the problem of partial area loading. However, for the plane case of partial loading, the wedge-and-fan stress field presented in [1] is shown to correlate better with test results and to be more suitable for practical use. On the other hand, the bottle-shaped stress field can be adapted relatively easily to axisymmetric problems (Section 3.3). Here, the correlation with plain and reinforced concrete experiments shows a satisfactory agreement and a significant improvement compared to current design standards. Further experiments are required for verification of the stress field solutions, particularly regarding higher resistances of heavily confined areas as compared to existing design rules. Such experiments are currently being undertaken by the authors.

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