Two parameters modelling of clay brick masonry confinement

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Abstract

Confinement is a well-known structural application since ancient times. Its early applications involved mainly masonry elements or structures, however in recent times a lot of research has been performed experimentally on confinement of concrete columns, either cylindrical or prismatic. Only recently the research differentiated the behavior of plain concrete from reinforced concrete, and the number of available confinement models increased rapidly. Predictive models are usually quite different in nature; earlier developments involved sound mechanically based approaches, based on classical failure criteria, while moving from those outcomes, proposals deviated on best fitting and empirical approaches, up to recent neural network approaches. In this framework, even if masonry confinement was the pioneer application, masonry confinement modelling has been usually borrowed from concrete confinement, which was vastly tested in the last decades.

However concrete and masonry have some crucial differences in their behavior, mainly related to their nature. Masonry is characterized by non-isotropic and non-linear behavior also for reduced strain levels. The behavior can vary significantly from masonry to masonry depending on its composition, i.e. the type and aggregation of the artificial or natural resistant elements and the type of mortar. Under uniaxial loading, masonry material exhibits a brittle behavior characterized by tensile strength far lower than compressive strength. If this is similar to concrete, the variability of the ratios between tensile and compressive behavior is notably wider for masonry. In fact ordinary concrete performance can be usually fully defined by the cylindrical compressive strength, as it is the only parameter used to individuate the confinement performance of concrete after the lateral confining pressure is known.

Authors are working on theoretical modelling of masonry confinement aiming at include other features characterizing the masonry behavior on a solid mechanics base (e.g. recently CNR guidelines added empirically the specific weight of masonry as an index for the confinement efficiency). In the present work, a failure criterion is considered containing the mean, or hydrostatic stress, able to promote the difference between compressive and tensile strength. This criterion is defined in the principal stress field and the mean stress (or first invariant) is crucial to the failure in brittle and compacting porous materials. Criteria of this kind are particularly useful not only to introduce non-uniform stress states, as those developed in non-axisymmetric confined elements, but also to be implemented in finite elements applications.

The validity of the adopted failure criterion has been checked against actively confined clay brick masonry experimentally tested under accurately known lateral pressure levels.

Keywords: **Clay Brick masonry, Confinement, Failure criterion, Triaxial Hoek cell**

Introduction

The confinement is the application of a wrapping around an object with the aim of limiting or preventing the lateral deformations and the failure. In the construction industry, the application of confinement is used both to confine individual structural elements either entire buildings or parts of them. Since ancient times the confinement was well-known and adopted in various fields, for instance for the vaults, the columns and the domes.

The research on the physical-mechanical characterization of materials has led to the evolution of the confinement techniques, refining methodologies and sizing. The basic idea is that, by increasing the lateral compression in an axially loaded element, a three-dimensional stress state is obtained, beneficial in terms of the ultimate load, as it is well known from the application of the classical failure criteria to the building materials.

Despite masonry confinement applications have been among the first to be developed, the wider part of confinement research of the last decades was focused on ordinary concrete elements. The two materials share the quasi-brittle nature and the relevant difference between compressive and tensile strength. However concrete and masonry have some crucial differences in their behavior, mainly related to their nature. The behavior can vary significantly from masonry to masonry depending on its composition. Masonry is characterized by non-isotropic behavior due to the type and aggregation of the bricks/blocks and the type of mortar/joints. Confinement also has unquestionable advantages in the case where the heterogeneity of the materials (such as in masonry with alternating mortar and bricks) induces tensile stresses in one of the components.

Outlining the differences between masonry and concrete is out of the scope of this work, however the recent trend to extend confinement models developed for concrete to the case of masonry elements imposes a careful re-evaluation of the theoretical bases.

Confinement modelling

First models proposed at the beginning of last century were based on solid mechanics, e.g. one of the pioneers was by Richart et al. [1] dating back to 1929 for concrete confinement. Its form was quite simple as it provided a linear formulation between masonry confined compressive strength, f_{mcd}, and lateral pressure, f_l, respectively, normalized with respect to masonry unconfined compressive strength, f_{md} and proportional to a coefficient *k'*:

$$\frac{f_{mcd}}{f_{md}} = 1 + k' \cdot \frac{f_l}{f_{md}} \tag{1}$$

Further models followed on an empirical base, assuming the following format:

$$\frac{f_{mcd}}{f_{md}} = 1 + a\left(\frac{f_l}{f_{md}}\right)^b \tag{2}$$

and the coefficients (or sometimes functions) *a* and *b* were repeatedly calibrated based on regression analyses, hence aiming at best fitting the experimental available data on masonry confinement. In these processes, two different uncertainties combine together: (i) the variability of masonry performance, hence a simple format involving only the compressive (unconfined) strength is weak; (ii) the former tests (on concrete only) involved passive confinement by means of steel jackets, hence the lateral pressure, et least close to the peak, was simply related to the (constant) yielding stress value of the steel material, however hundreds of further tests were based on fiber reinforced plastics (FRP) confinement. Such a confining material has a linear elastic behavior up to failure, so that the lateral pressure is continuously variable, and depends on the compatibility with lateral deformability of the confined member. Assuming the ultimate stress of FRP as the relevant value to estimate the lateral pressure has been demonstrated to be non-conservative and many reasons for this were provided [2][3].

Furthermore many tests are conducted on non-axisymmetric elements, so that the confining pressure is not uniform and the correlation between lateral pressure and increase of compressive strength is even more complicated. Conventional approaches, like as parabolas and volumetric efficiency factors, have been provided (e.g. [4]), as long as more refined approaches taking into account the pointwise variability of lateral pressures not equal even in two orthogonal directions in the plane of the cross section [5][6].

To solve some of the issues remarked previously (i.e. on effective lateral pressure and cross sectional shape effect), in this work focus is made on circular masonry elements and for the validation, actively loaded cylindrical masonry specimens tested in triaxial compression device (Hoek cell) only were considered [7].

It is remarked that the extension of concrete models to masonry is weak because there are many differences between the two materials and the main intent is to avoid experimentally calibrated models, that do not reflect the intrinsic variability in masonry performance (apart providing a calibrated model for each masonry type), but to provide solid mechanic based models that can be implemented satisfactorily in Finite Element Models (FEMs), too, and allows to account also for non-uniform lateral pressures. Such models are necessarily multi-parameters. For instance CNR DT200R1 [8] suggests that the effects of lateral pressure on masonry confinement are proportional to the mass-density of the masonry, in the sense that heavier masonry has higher increases of compressive strength from the same amount of lateral pressure. This means that a in equation (2), according to [8], is proportional to the masonry mass density expressed in ton/m^3. In this way the model is based on two parameters: unconfined compressive strength and mass density of masonry. Similarly, another two-parameters model was proposed [9], derived from the Mohr Coulomb failure criterion, including friction angle, Φ, and cohesion, c, to characterize different masonry materials (e.g. compared to [8], it is expected that two masonries having the same mass density, behaves differently according to other mechanical parameters). In that model [9], two independent parameters, out of the three (i.e. f_{mcd}, Φ and c), are used, e.g. k' in equation (1) is $(f_{md}/2c)^2$. However the definition of friction angle and cohesion for masonry is not always straightforward.

Recently some of the authors proposed [10] to extend the ultimate strength surface, based on five parameters, proposed by Argyris et al. [11] to masonry. This surface was previously adopted by Mander et al. [12] to calibrate their well-known solid mechanic based model for concrete confinement (and inserted also in international Codes, e.g. ACI440.2R-02 [13]). Despite its derivation is based on five parameters, the final form and coefficients, in particular, depend implicitly on the input parameters depicting the masonry behavior; the approach should be repeated for each masonry to provide the relevant confinement models. For instance the confinement equation proposed in ref [10] for clay brick masonry is as follows:

$$\frac{f_{mcd}}{f_{md}} = -1.07 + 2.07\sqrt{1 + 7.56\frac{f_l}{f_{md}}} - 2\frac{f_l}{f_{md}} \qquad (3)$$

To have a more flexible, solid mechanic based model, authors propose the following explicit two-parameter approach, based on the general failure surface developed by Stassi for hollow cylinders and hollow spheres [14].

Proposed two-parameters confinement model

Stassi [14] proposed a failure surface of general character that may be adopted for both soft and hard materials. The failure surface is expressed by the following equation:

$$J'_2 + \alpha \cdot I_1 = \beta \tag{4}$$

as a linear combination of first and second stress invariants, I_1 and J'_2, respectively. The mean, or hydrostatic stress (i.e. I_1), is able to promote the difference between compressive, f_{md}, and tensile, f_{td}, strength and it is crucial to the failure in brittle and compacting porous materials. The parameters α and β have been related to f_{md}, and tensile, f_{td}, strengths (i.e. the failure surface passes through uniaxial strength points). Normalizing the principal stresses σ_1, σ_2, σ_3 (compression is positive) with respect to f_{md} and introducing the ratio $\rho_t = f_{td}/f_{md}$, the failure surface, F=0, becomes:

$$\begin{gathered} F\left(\frac{\sigma_1}{f_{md}}, \frac{\sigma_2}{f_{md}}, \frac{\sigma_3}{f_{md}}\right) = (\rho_t - 1)\left(\frac{\sigma_1}{f_{md}} + \frac{\sigma_2}{f_{md}} + \frac{\sigma_3}{f_{md}}\right) + \\ + \left[\left(\frac{\sigma_1}{f_{md}}\right)^2 + \left(\frac{\sigma_2}{f_{md}}\right)^2 + \left(\frac{\sigma_3}{f_{md}}\right)^2 - \frac{\sigma_1\sigma_2}{f_{md}^2} - \frac{\sigma_2\sigma_3}{f_{md}^2} - \frac{\sigma_1\sigma_3}{f_{md}^2}\right] - \rho_t = 0 \end{gathered} \tag{5}$$

The three-dimensional failure surface is plotted in Figure 1, assuming ρ_t changing from 0 to 1 with a step of 0.2. Equation (5) becomes a particular case, in fact it is the Von Mises failure criterion, when ρ_t=1.

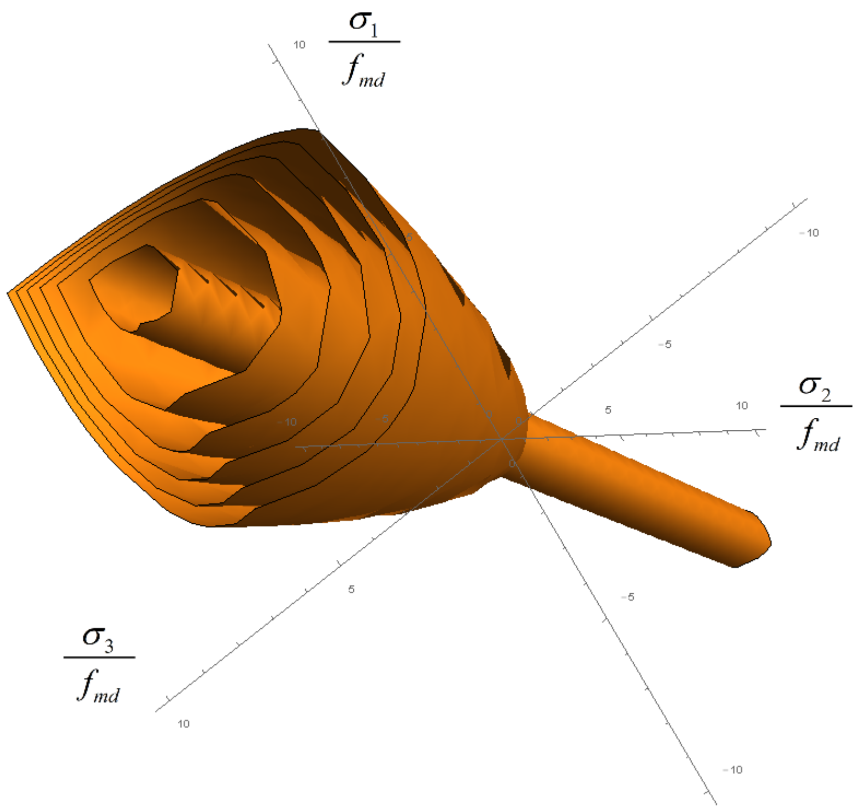

Figure 1. 3D failure surface assuming ρ_t changing from 0 to 1 with a step of 0.2

This failure surface was first used for finite element modelling of masonry structures by Sparacio and Russo Spena in 1980 [15], however it is still particularly suitable to derive a confinement model both accounting for uniform and non-uniform biaxial lateral confining pressure.
In the same format of previous equations for confinement modelling, the following positions can be assumed: axial stress $\sigma_1=f_{mcd}$ and lateral stresses $\sigma_2=\sigma_3=f_l$. Equation (5) of the failure surface can be then solved with these assumptions, yielding to

$$\frac{f_{mcd}}{f_{md}}=\frac{1-\rho_t}{2}+\sqrt{\left(\frac{1+\rho_t}{2}\right)^2+3\left(1-\rho_t\right)\frac{f_l}{f_{md}}}+\frac{f_l}{f_{md}} \quad (6)$$

hence an explicit two-parameter model, in terms of f_{md} and the ratio $\rho_t=f_{td}/f_{md}$ is provided.
The proposed confinement model, based on equation (6) is plotted in Figure 2, assuming ρ_t changing from 0 to 1 with a step of 0.1. It is worth noting that, according to the proposed model, the lower is the ratio between tensile and compressive strength and the higher is the confinement effectiveness, i.e. given a lateral pressure, the increase of compressive strength is higher.

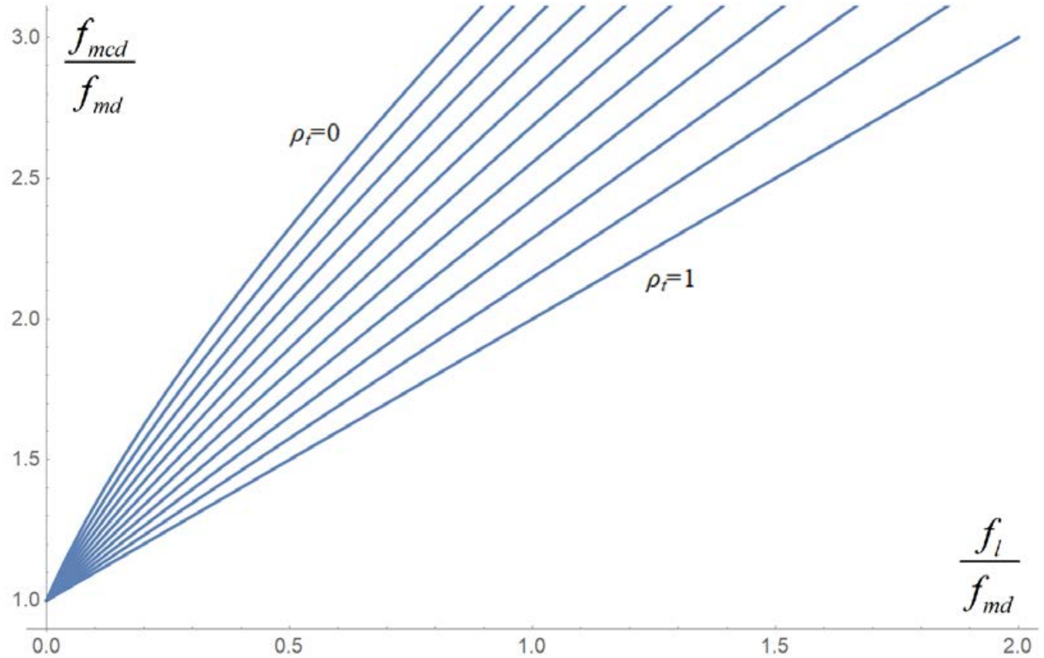

Figure 2. Proposed confinement model assuming ρ_t changing from 0 to 1 with 0.1 step

Experimental validation

The proposed confinement model provided by equation (6) is dependent on the two parameters f_{md} and ρ_t. The model is validated by means of comparison with experimental tests, where the two parameters are required, i.e. knowledge on compressive and tensile strengths. To reduce uncertainties related to the (lateral) confining pressure estimation, in particular those related with the linear elastic confining materials, like as FRP substituting the traditional steel hoops, an experimental program on cylindrical columns of 54 mm in diameter and 85 mm high, with 0.25 cm thick joints was considered [7].
The short dimensions of specimens are due to confine them actively by means of a triaxial compression device (Hoek cell) and reproduce a 1:4 scaled masonry column (however it

cannot be excluded that some size effect occurred). Three unconfined specimens were tested to assess the compressive strength and f_{md}=13.58 MPa with a CoV=6.22 %. Afterwards ten specimens were subjected to a uniform stress, ranging from 0.4 to 7 MPa, by a hydraulic pressure generator applied to the lateral surface of cylindrical specimens contained in a rubber tube.
Unfortunately nothing is said on the tensile strength of the masonry apart that the lime mortar was made of one portion of cement, one portion of hydrated lime, eight portions of sand, and two portions of water. In this case, on safe side, a ρ_t =0.1 has been assumed and the ten experimental results have been plotted as red squares to be compared with the confinement solid curve in figure 3. The comparison allows to satisfactorily validate the proposed confinement model, even if supplementary results are required to further validate the model, however usual experimental tests available in scientific literature, with confinement made by FRP, add the aforementioned uncertainties on the effective confining pressure f_l and eventually the cross sectional shape effects.

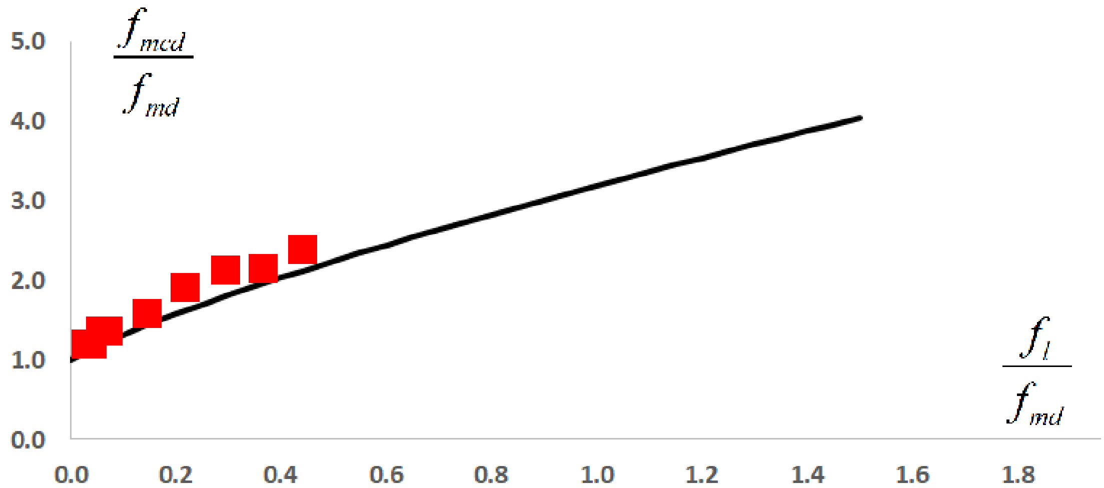

Figure 3. Experimental [7] validation of the proposed confinement model: Eq. 6 with ρ_t=0.1

Conclusions

Confinement of masonry is derived for similarity from concrete confinement, however many differences between the two materials can be outlined, as long as the parameters required to describe their behavior. Concrete confinement models are usually one-parameter models, as the knowledge of concrete behavior is usually comprehensive once given its cylindrical compressive strength; conversely masonry should be usually described by means of more parameters. Some attempts have been made to base the masonry confinement models on solid mechanics, hence to include as much information as possible on the masonry behavior.
In the present case, focus is made on two parameters, in particular tensile and compressive strengths, to characterize the masonry. A failure surface of general character is adopted as a linear combination of first and second stress invariants. The first invariant promotes the difference between compressive and tensile strength and is crucial to depict the failure in brittle and compacting porous materials. This confinement model adds up to few other models, mainly empirical in nature, relating the uniform lateral pressure to the increase of masonry compressive strength, however its nature allows to use its underlying failure criterion in FEM (hence including naturally the effects of confinement) and to evaluate confinement configurations where the confining stress is not uniform (hence in the case of

prismatic, non-circular elements). The proposed confinement model has been validated against few experimental tests, however there is lack of tests where the lateral pressure is known with reasonable accuracy without introducing further uncertainties on the effective confining pressure, commonly found in usual FRP confined tests.

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