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A simplified approach for the ultimate limit state analysis of three-dimensional reinforced concrete elements

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ABSTRACT

Several advanced constitutive models of concrete have been developed in recent decades, some of which are able to reproduce the behaviour of concrete structures with a high level of accuracy. Yet given their complex formulation, their application by most practitioners can entail some difficulties. This paper describes the adoption of an alternative, simplified comprehensible constitutive model for the ultimate limit state analysis of 3D reinforced concrete structural elements.

The proposed model is described and the undertaken assumptions are justified. Different uniaxial stress–strain models can be adopted, particularly neglecting the tensile strength of concrete permits to study the goodness of the stress field method and the strut-and-tie method for 3D elements.

This model was implemented into a non-linear finite element-based tool developed by the authors. The results of twelve four-pile caps and three socket base column-to-foundation connections are shown. The proposed approach facilitated the identification of the flow of forces and allowed a better understanding of the structural response.

1. Introduction

Computer software is widely applied in the analysis and design of reinforced concrete structures. In particular, the application of the finite element (FE) method has become most important in recent decades [1]. Although initially its use was limited mainly to the domain of researchers, today the FE method is an everyday tool in many structural design offices. The development of computing technology and FE programmes has contributed to this spread. Guidelines and recommendations have been edited to help practitioners define the models and analyse the results (e.g. [1,2]).

The FE method has permitted the development of advanced constitutive concrete models (e.g. [3–5]), which have been later implemented in FE software packages. On the one hand, the ability of some of these models to accurately reproduce the behaviour of concrete structures is doubtless. On the other hand, their complex formulation limits the number of potential users because only those who understand the fundamentals on which models are based should apply them. The calibration of model-related constants, some of which have no clear physical meaning and are difficult to understand [6,7], can also interfere with their application.

The methods that are included in concrete design codes, and have been traditionally applied in practice, adopt simplifications to deal with the complex behaviour of concrete. As stated by Schlaich et al. [8], design concepts should be clear and based on simple models that are understandable by designing engineers. The truss analogy [9,10], which became a practical and useful tool to understand the response of cracked reinforced concrete beams, is such an example. Schlaich et al. later developed the strut-and-tie method [8], which generalised the truss analogy to apply it to any part of any structure, including regions with statical and/or geometrical discontinuities (D-regions). One of its main assumptions is neglecting the tensile strength of concrete.

The stress field method [11] is also a simplified approach to design reinforced concrete structures. The tensile strength of concrete is neglected and a rigid-plastic constitutive behaviour is adopted in compression. Applications of the stress field method are similar to those of the strut-and-tie method. Strut-and-tie models can be viewed as discrete representations of stress fields. More detailed information about structural behaviour can be obtained from stress field models than from strut-and-tie models, but the former also require considerable computational effort.

Computer-based tools to balance the accuracy and adaptability of FE models, and the simplicity of design models and methods are of interest. Several computer-based tools have been developed to facilitate the use of strut-and-tie models [12–14] and stress field

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Nomenclature

E_{cm}	secant modulus of elasticity of concrete
f_{cm}	mean value of cylinder compressive strength of concrete
f_{cc}	modified compressive strength of concrete
f_{cp}	equivalent plastic strength of concrete
f_{ck}	characteristic value of cylinder compressive strength of concrete
f_{ct}	tensile strength of concrete
f_{sy}	yielding strength of steel
G_{ij}	tangential shear modulus
G_f	fracture energy of concrete
$\varepsilon_i,\ \varepsilon_j,\ \varepsilon_k$	strain in principal directions i, j, k
ε_{c1}	axial strain at unconfined concrete strength f_{cm}
ε^*_{c1}	axial strain at modified concrete strength f_{cc}
$\sigma_i,\ \sigma_j,\ \sigma_k$	stress in principal directions i, j, k

models [15,16]. These tools adopt simple concrete constitutive models, and are valuable for ultimate limit state analyses and for designing two-dimensional D-regions. However, no references of tools that have extended the use of simple concrete models to 3D have been found.

In this paper a simplified, comprehensible 3D constitutive model for concrete is proposed and its fundamentals are described. This model characterises the 3D response of concrete by using uniaxial stress–strain laws, such as those proposed in concrete design codes, which are familiar to practitioners. Input variables are scarce and the parameters required to define the model have a clear physical meaning which allows the engineer to focus on the analysis and/or design of the structure rather than on the definition of the model. The undertaken simplifications limit the scope of the model to the ultimate limit state.

This model has been implemented into a non-linear FE-based tool developed by the authors (FESCA 3D: Finite Elements for Simplified Concrete Analysis in 3D). Two examples of applications are provided: firstly, the results obtained for 12 four-pile caps are presented and discussed. Conclusions are drawn for applying strut-and-tie models to these elements; secondly, the stress fields obtained for three socket base column-to-foundation connections demonstrate that this approach may be of interest to understand the structural behaviour of elements with complex geometries and for proposing suitable strut-and-tie models.

The proposed approach automatically allows the generation of three-dimensional stress fields from which three-dimensional strut-and-tie models can be easily developed. This feature is of interest because, for certain cases, the selection of an appropriate 3D stress field or strut-and-tie model is much more complicated than in 2D. Currently, and as addressed in fib bulletin 61 [17], there is scarce or absolutely no guidance about applying the strut-and-tie method to D-regions that display a three-dimensional behaviour. The results obtained with FESCA 3D could motivate the further study of the strut-and-tie method for 3D elements.

2. Adoption of a simplified model for concrete

2.1. On modelling concrete behaviour

Concrete is a brittle aggregate material, and its behaviour depends on its components and their interaction. Some degree of idealisation is required and justified to characterise the non-linear response of concrete structures at a macroscale level. The inherent complexity of concrete, linked to the aspiration of accurately capturing its behaviour, has encouraged the development of various constitutive models in the last few decades. By means of different approaches, these models include diverse factors that affect concrete behaviour, such as cracking, confinement, crushing, and degradation. Although the accuracy of some of these models is unquestionable, their application can generally entail some difficulties for most practitioners given their complexity. Therefore, idealisation of concrete response is necessary for common engineering issues.

Some common idealisations in design codes (like in MC 2010 [18], EC 2 [19], ACI 318-14 [20]) include: (i) linear elastic behaviour, i.e. assuming uncracked cross-sections, a linear stress–strain relationship and a mean modulus of elasticity value; (ii) plastic behaviour, like the strut-and-tie method and the stress field method; and (iii) non-linear behaviour by adopting adequate non-linear law for concrete. Although these models entail some loss of accuracy, it may be admissible for the sake of simplicity and safety in general practice.

The use of uniaxial stress–strain laws to characterise concrete behaviour is a common practice in the analysis and design included in plane and spatial problems. In compression, this relationship can be easily obtained from uniaxial compression tests. Standardised compressive stress–strain equations are also proposed in codes. Obtaining the stress–strain relationship in tension is also feasible, but is not as straightforward [21]. Standardised tension laws are found in the literature [22]. Notwithstanding, the lower tensile strength value of concrete compared to compressive strength, and the fact that stress drops abruptly after cracking, mean that neglecting tensile strength of concrete is common practice.

Reducing the number of parameters required to define a model is also important since it reduces the risk of making mistakes while defining them or interpreting the results, and allows engineers to focus on the analysis and/or design. In design codes, concrete compressive strength is the main parameter from which the other variables, such as modulus of elasticity or tensile strength, can be derived. The effect of transverse cracking in compression zones and confinement can be considered by modifying concrete strength.

After considering the above-mentioned issues, the authors propose a simplified, comprehensible behaviour model for concrete that adopts uniaxial stress–strain laws, such as those proposed in design codes, to characterise the response of 3D structural elements.

2.2. Model description

The adoption of an orthotropic model for concrete permits the 3D response to be split into three directions and to treat each direction separately. In this way a uniaxial stress–strain relation can be employed to model a three-dimensional phenomenon. Orthogonal models are suitable for smeared crack representations [23], where concrete is treated as a continuum, even after cracking.

As proposed by Cope et al. [24], the axes of principal strain are taken as axes of material orthotropy (Fig. 1a) and coaxiality between the principal strain and principal stress directions is enforced (Fig. 1b). The adoption of this model is justified for its simplicity, but some limitations must be addressed. The assumption of coaxiality is only valid when sufficient shear stress transfer takes place along the crack planes. This is not the case in high