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# A simplified finite element model for assessing steel fibre reinforced concrete structural performance

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ABSTRACT

The present numerical investigation offers evidence concerning the validity and objectivity of the predictions of a simple, yet practical, finite element model concerning the responses of steel fibre reinforced concrete structural elements under static monotonic and cyclic loading. Emphasis is focused on realistically describing the fully brittle tensile behaviour of plain concrete and the contribution of steel fibres on the post-cracking behaviour it exhibits. The good correlation exhibited between the numerical predictions and their experimental counterparts reveals that, despite its simplicity, the subject model is capable of providing realistic predictions concerning the response of steel fibre reinforced concrete structural configurations exhibiting both ductile and brittle modes of failure without requiring recalibration.


## 1. Introduction

A large number of finite-element (FE) models have been developed to date aiming to describe the nonlinear behaviour of reinforced concrete (RC) structural configurations under static and dynamic loading. The analytical formulation of such models is generally based on the combined use of [1,2]: (i) relevant experimental data and (ii) continuum mechanics theories (i.e. nonlinear elasticity, plasticity, visco-plasticity and damage mechanics). The latter formulation usually incorporates a number of parameters, the evaluation of which is essential for achieving close correlation between the numerically predicted nonlinear specimen behaviour and its experimentally-established counterpart. These parameters are usually associated with post-failure concrete behaviour (i.e. strain softening, tension stiffening, shear-retention ability) and their values are often established through calibration based on the use of experimental information at the structural – rather than at the material – level [3]. The use of such parameters tends to attribute ductile characteristics to plain concrete behaviour not compatible with its brittle nature and not justified by the relevant published test data [4–7]. This, in turn, can detrimentally affect the objectivity of the numerical predictions obtained since such parameters often require recalibration depending on the type of problem investigated [3,8,9]. Based on the above, the use of such models is considered generally too complicated for practical applications whilst the results obtained are not always accepted to be reliable and are frequently treated with skepticism. The generality of such models is also limited as they rely on the aforementioned calibration of several parameters for every case considered.

An FE model is generally considered capable of yielding realistic predictions concerning the nonlinear response of concrete structures when the deviation of the predicted values from their experimentally measured counterparts (of particular structural characteristics) does not exceed a value of the order of 20% [3,9,10]. Such structural characteristics usually include the load-bearing capacity, the relation between applied load and corresponding displacements, reactions or first-order deformation derivatives (e.g. rotations). So, in essence, a finite-element analysis (FEA) package is considered to be characterised by both objectivity and generality when it is capable of providing realistic predictions of structural behaviour for a wide range of structural concrete configurations, without requiring recalibration of the parameters employed by the concrete material model [3,8].

Further to the macro-models, which are widely employed for describing the behaviour of concrete and fibre reinforced concrete when assessing structural response, a number of micro-models have been also proposed which aim at providing an in-depth understanding of the effect of fibres on the material behaviour of

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structural concrete [49]. Such models essentially consider the fibres, the various constituents of concrete, as well as their interaction independently, thus offering a more detailed description of the structure of concrete as well as the micro and macro cracking process it undergoes when subjected to external loading [10]. In order to simplify the formulation of such models a homogenisation technique is often employed when modelling the concrete medium (due to its heterogeneous nature). However, it should be pointed out, that although micro-level models can be used for studying the behaviour exhibited by small specimens they cannot be easily employed for assessing structural performance. As a result such models are considered beyond the scope of the present work.

The present work is based on the use of a well-known commercial FEA program, ABAQUS [11], capable of carrying out three-dimensional (3D) static and dynamic nonlinear finite element analysis (NLFEA) which incorporates a simple brittle model (termed "brittle cracking model") in order to describe concrete material behaviour. The latter model is purpose-built for brittle materials the behaviour of which is dominated by tensile cracking [11]. This is largely true in the case of reinforced concrete (RC) flexural structural elements where cracks form due to the development of tensile strains within the concrete medium in the tensile region of the element considered. Such cracks gradually extend (into the compressive region) with increasing levels of applied loading, ultimately leading to structural failure and collapse. This is particularly useful for the present study on the performance of steel fibre reinforced concrete (SFRC) structural configurations as it allows for modelling the effect of steel fibres on the concrete tensile behaviour, especially after the onset of cracking.

It is interesting to note that in the "brittle cracking model", the behaviour of concrete in compression is modelled essentially as "linear elastic" through the use of an equivalent elastic modulus approximately equal to 50% of secant value of the modulus of elasticity $E_{cof}$ concrete for stress levels between 0 and $0.4f_c$. The adoption of the latter assumption/simplification safeguards the numerical stability and robustness of the solution process allowing emphasis to be focused on realistically describing the all-important tensile material behaviour of concrete. Although the above assumption may appear at first unreasonable and not representative of concrete material behaviour, one should consider that concrete behaviour within the compressive region of a flexural member approaching its ultimate limit state is characterised by significant triaxiality [13]. This triaxiality is the result of the penetration of flexural cracking deep into the compressive zone resulting in a certain degree of confinement being imposed onto the 'uncracked' concrete of the compressive zone [12,13] (see Fig. 1). Due to this triaxial state of stress the stress–strain curve adopted by concrete design codes to describe concrete material behaviour under uniaxial compression which is also used to describe the stress-distribution along the depth of the compressive zone is, at the very best, an approximation which does not describe the true stress distribution in the above region [12,13]. As a result the behaviour of concrete in the compressive region of flexural elements differs considerably to that established under uniaxial compression [12] exhibiting a higher load-bearing capacity (approximately 50% higher compared to its counterpart under uniaxial compression) and stiffness. The present investigation reveals that although the model assumes elastic behaviour in compression (mainly for numerical stability purposes), this does not seem to affect accuracy as the predictions obtained concerning certain important aspects of structural response which are in good agreement with their experimentally established counterparts (as discussed in the present study). As a precaution, the compressive strains were also monitored especially when exceeding the ultimate value of 0.0035.

The "brittle cracking" material model employed (using ABAQUS software) is originally intended for *plain* concrete and was thus modified in order to account for the effect of steel fibres on the cracking processes that concrete undergoes when subjected to tension. The attention of the numerical investigation is focused on: (i) validating the predictions obtained concerning important aspects of the nonlinear behaviour (up to failure) for a wide range of SFRC structural configurations and (ii) investigating their generality and objectivity. The structural configurations considered herein include a wide range of SFRC specimens ranging from simply-supported SFRC beams with no conventional reinforcement to more complex (statically indeterminate, consisting of more than one structural elements and subjected to a combination of axial and lateral loading) SFRC structural configurations fully reinforced. It should be pointed out that although some of the case studies are presented herein for the first time, others have formed the basis for parametric investigations carried out recently assessing the effect of the fibre-content on RC structural responses [14–20]. The reason for presenting all the cases in the present article is to show the objectivity of the numerical model employed. Based on the

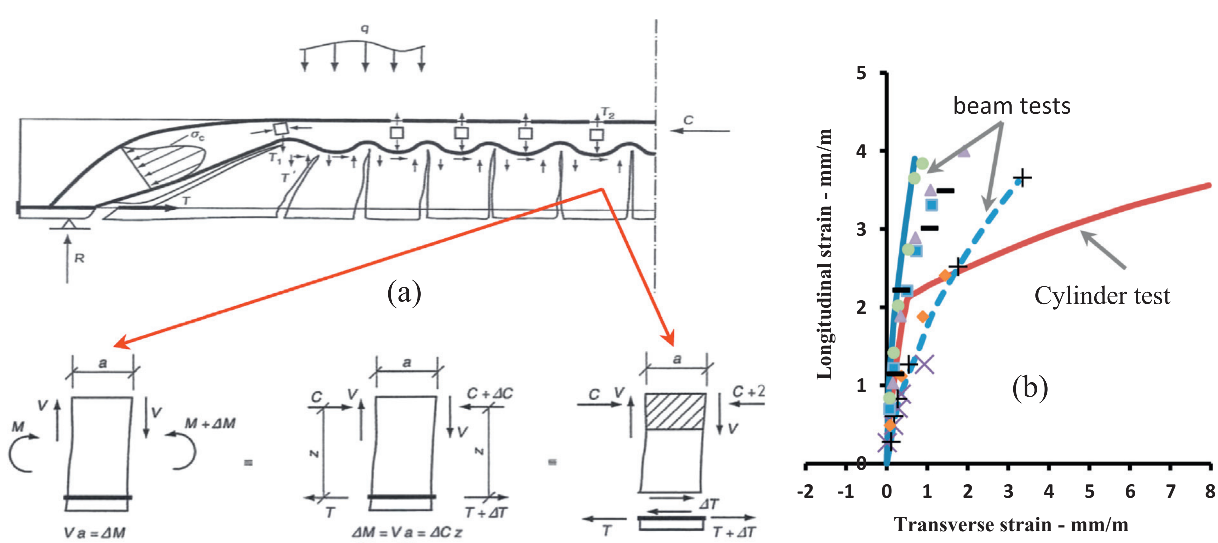


Fig. 1. (a) Internal actions developing within RC beams resulting in the development of a triaxial state of stress within the compressive zone [13] and (b) its effect on concrete material behaviour [12].