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A density-dependent failure criterion for concrete

Jan Arve Øverli

Department of Structural Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway

HIGHLIGHTS

- An octahedral failure criterion for concrete.
- Includes the density of the concrete directly in the failure criterion.
- For low densities the compressive and tensile meridian tends toward a single curve.

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ABSTRACT

This work focuses on the large effect of small secondary stresses on the compressive strength of concrete. The strength and especially the ductility of structural concrete members depend on local triaxial stress conditions that inevitably develop in the compressive zone just prior to failure. A failure criterion for concrete, which accounts for the effect of a reduced density of the concrete on the strength under fully compressive triaxial stress states, is proposed. The criterion was derived by curve-fitting mathematical expressions to axisymmetric strength data from a test programme on concretes of different weights previously published. For the purpose of evaluation, it was compared to other triaxial compressive strength data for lightweight aggregate concrete available in the literature; and to the failure criterion in fib Model Code 2010. It was found that, contrary to the Model Code criterion, the failure criterion presented in this paper generally provides safe lower bound estimates for the strength levels attained in the experimental tests.

1. Introduction

Lightweight aggregate concrete (LWAC) has been used as a construction material for many decades, with the main objective for using LWAC normally being to reduce the dead weight of structures. Thus, with a low weight, the dimensions of the foundations in buildings can be reduced in areas with low bearing capacities, while the inertia actions are reduced in seismic regions, and it also enables an easier handling and transportation of precast elements. Even with the major advantage of a reduced weight and the high strength-to-weight ratio of the material compared to conventional concrete, the use of LWAC is still limited as a mainstream construction material in the building industry. However, for large and advanced structures such as high-rise buildings, bridges and offshore structures, it has been applied with great success [1–5]. The major disadvantage of LWAC is the brittleness in compression at the material level compared to normal weight concrete (NWC). However, the strength and especially the ductility of structural concrete members depend on local triaxial stress conditions that inevitably develop in the compressive zone just prior to failure.

Today non-linear finite element analysis (NLFEA) is often used in design and verification of reinforced concrete structures. However, various analysts often obtain widely diverting results when modelling the same structure using the same FE code due to the uncertainty connected to many of the material parameters going into the analyses [6]. The response is significantly affected by parameters describing mechanisms such as: compression softening due to transverse cracking, confinement effects, tension softening, tension stiffening and rebar bond slip. There are two main reasons for this lack of generality and objectivity when the FE method is applied to concrete structures. Firstly, the material models employed by many analysts do not realistically describe concrete as a material and, secondly, cracking of concrete may lead to numerical instabilities of the analyses if not adequate precautions are taken. In this respect it is interesting to note that remarkable good numerical results have been reported when applying a brittle triaxial material model which takes into account the increased transverse expansion of the concrete prior to failure [7].

E-mail address: jan.overli@ntnu.no

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The density dependent failure criterion presented in this paper was part of a research project where the goal was to get a better understanding of the ultimate behaviour of lightweight aggregate concrete at both the material and the structural level [8]. The working hypothesis was that the three key material characteristics generally dictating the ultimate response of concrete structures was: the large effect small secondary stresses have on the compressive strength; the abrupt increase of the transverse expansion at a stage close to, but not beyond, the peak stress level; and the rapid unloading of the material beyond the peak stress level. As a consequence of these features, the strength and especially the ductility of structural concrete members depend on local triaxial stress conditions that inevitably develop in the compressive zone just prior to failure rather than stress-redistributions owing to post-peak material characteristics as commonly believed. Confinement effects introduce the secondary stresses which increases the ductility of concrete as well as enhancing the concrete strength. Additionally, an active confinement from external stresses is more effective than a passive confinement, which is mobilized by an opposing transverse deformation from the Poisson effect. In reinforced concrete, the passive confinement from transverse reinforcement is the most common, and numerous researchers have investigated the effect of ordinary transverse steel reinforcement and the effect of adding fibres on the confinement in normal density concrete, both experimentally and theoretically [9–11].For lightweight aggregate concrete, similar effects have been reported [12–14]. The hypothesis in this work has previously been used with success to predict and explain the behaviour of normal weight concrete in the ultimate limit state [15,16]. Hence, when applied to lightweight aggregate concrete, a failure criterion, which accounts for the effect of a reduced density on the strength under fully compressive triaxial stress states was needed.

Within structural concrete, the stresses frequently act in more than one direction [17,18]. Hence, since the pioneering work of Richart, Brandtzæg and Brown [19], a large amount of research has been undertaken to describe the strength properties of concrete under combined states of stress. This has led to several acceptable formulations for the failure of concrete under general short-term loading. However, none of them account for the density of the concrete. Admittedly, the criterion implemented in fib Model Code 2010 (MC-10) [20] differentiates between normal weight concrete and lightweight aggregate concrete, although the density of the concrete is not a parameter. For normal density concrete the strength under multiaxial stress can be expressed with the uniaxial compressive strength since the failure can be considered as a function of the strength of the mortar. However, for lightweight concrete the influence of the aggregate must be taken into account since the failure can be governed by splitting of the aggregates. The most common and easiest available parameter for LWAC is the mass density of the concrete, which can be an input parameter in the formulation for the failure. Another option could be to make the failure dependent on e.g. the porosity of the aggregate.

Only a few researchers have examined the behaviour of LWAC under combined states of stress [21–27]. The most comprehensive investigation is a study performed by Hanson in 1963 [21], in addition a not so well-known test programme conducted at ‘Ente Nazioanale per l‘Energia Electrica’ (ENEL) in 1984 [26]. Since the latter forms the basis for the strength criterion proposed in this paper and the results are not so easily accessible, it is briefly summarized in the next section.

2. The ENEL test programme

2.1. Experimental details

The result from this test programme were first presented at the ’International conference on concrete under multiaxial compression’ held in Toulouse in 1984 [26]. The laboratory at ENEL was part of a joint test programme [28,29] were it proved to provide reliable results. Four different types of concretes were examined: one heavyweight, one normalweight and two types of LWAC. The composition of the mortar was the same for all concretes, i.e. only the weight of the coarse aggregate particles varied. For all concretes, approximately 40% of the total volume consisted of coarse aggregate, while the remaining 60% of the volume was occupied by the mortar. The observed differences in strength and deformational behaviour could therefore solely be attributed to the properties of the aggregate. The heavyweight aggregate was a crushed mineral with a high specific density (Barite); the normal weight aggregate was from a natural source of alluvial gravels (Vailata), while the lightweight aggregate was either sintered pulverized fuel-ash (Lytag) or expanded clay (Leca). The details of the mix design are given in Table 1. The total weight and the uniaxial compressive strengths established from the triaxial compression tests with zero confining pressure are also included in the table.

The strength and deformational behaviour under axisymmetric triaxial compression were studied by bringing 100 mm of cubical specimens to failure by following two different load paths: a hydrostatic loading up to a predetermined load level with a subsequent increase of the stress in either the vertical direction (triaxial compression) or equally in the two horizontal directions (triaxial extension). The load was applied through steel platens, which were lubricated by polyethylene sheets with grease in-between to minimize friction, a test method that has earlier been proven to provide reliable results [28,29]. Four different confining stress levels were examined for each load path, with three replications of each, resulting in a total number of 120 test specimens in the test program. Obviously, a confining stress level equal to zero leads to the special cases; uniaxial compression and equibiaxial compression for load path 1 and load path 2 respectively.

2.2. Experimental strength data

Fig. 1 depicts the strength data from the triaxial compression tests (upper points) and the triaxial extension tests (lower points), with the data normalized by the uniaxial compressive strength f_c (established from the triaxial compression tests with zero confin-

Table 1
Composition of the different concretes and the reference mortar utilized in the test programme [26].

	Barite (kg/m^3)	Vailata (kg/m^3)	Lytag (kg/m^3)	Leca (kg/m^3)	Mortar (kg/m^3)
Portland cement 425	350	350	350	350	583
Effective water	175	175	175	175	292
Absorbed water	–	–	80	45	–
Sand	700	700	700	700	1167
Aggregate (8–15 mm)	1850	1150	625	250	–
Total weight (kg/m^3)	3075	2375	1930	1520	2042
Concrete strength (MPa)	41.6	40.2	38.7	15.5	44.5