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Towards a better understanding of the ultimate behaviour of LWAC in compression and bending

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ABSTRACT

There is a general scepticism regarding the use of lightweight aggregate concrete (LWAC) for structural applications. This concern is attached to the more brittle post-peak material behaviour and smoother crack surfaces of these concretes compared to normal density concrete (NWC). In this research, the post-peak material behaviour and the force transfer across cracks were considered to be unimportant, regardless of the weight of the concrete. The working hypothesis was that the three key material characteristics that generally dictate the ultimate response of concrete structures are: the large effect small secondary stresses have on compressive strength; the abrupt increase of 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. It follows from these features, that the strength, and especially the ductility, of structural concrete members depend on the local triaxial stress conditions that inevitably develop in the compressive zone just prior to failure, rather than on stress-redistributions due to post-peak material characteristics, as is commonly believed. In the verification process, results from experimental programmes reported in the literature were carefully examined using three-dimensional nonlinear finite element analysis. The somewhat lower ductility of LWAC members with decreasing density can be explained by a lower degree of stress triaxiality in the compressive zone compared to NWC. This seems to be a result of the often quite modest transverse expansion of LWAC concretes prior to failure and linked to a limited degree of micro-cracking within the material. Nevertheless, the load-carrying capacity of LWAC members is often similar to that of corresponding NWC members. The high strength-to-weight ratio of LWAC compared to conventional concrete means that increased use of the material would be both economical and environmentally friendly. A better understanding of the ultimate behaviour of LWAC in compression and bending can help increase the use of LWAC in structural applications.

1. Introduction

Lightweight aggregate concrete (LWAC) has been used as a construction material for many decades, normally with the aim of reducing the dead weight of structures. This allows the dimensions of the foundations of buildings to be reduced in areas with low bearing capacities, inertia actions are reduced in seismic regions, and it is easier to handle and transport precast elements. In large and advanced structures, such as high-rise buildings, bridges and offshore structures, it has been applied with great success [1–5]. Yet, even with the major advantage of its reduced weight and high strength-to-weight ratio compared to conventional concrete, the use of LWAC is still limited as a mainstream construction material in the building industry.

The finite-element (FE) approach is a numerical method which can be used to assess the deformational and strength response for any geometry, boundary conditions and material during the entire loading history of a structure. It can be used in the design of new structures, especially those with complex geometries, or as an inexpensive alternative to experiments for the development of innovative and efficient building products and more accurate design rules, because it allows for a multitude of tests to be carried out numerically, with only a small number of laboratory tests needed to check the theoretical findings. These areas of application, however, have rarely been appreciated for concrete. The reason for this is at least twofold. Firstly, concrete behaviour is often 'tuned' to specific types of structure, in which the material parameters must be 'retuned' depending on the problem type. Secondly, different analysts often obtain widely differing results when modelling the same structure using FE code due to the uncertainty connected with many of the material parameters going into the

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analysis [6–8]. This is awkward, since knowing the answer beforehand is almost a prerequisite for the success of the calculations. 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 can lead to numerical instabilities in the analysis if adequate precautions are not taken. In this respect, it is interesting to note that remarkably good numerical results have been reported when a brittle triaxial material model is used that takes into account the increased transverse expansion of the concrete prior to failure [9]. Unfortunately, anyone familiar with FE modelling of concrete structures knows that the common line of action is to use uniaxial models in which the post-peak material behaviour is characterised by a gradual loss of load-carrying capacity. Moreover, when triaxial material data actually are implemented in these models, it is normally without a proper description of the abrupt transverse expansion of the concrete prior to failure, which is what actually gives rise to the triaxial stress conditions in the structure.

The majority of concrete researchers do not accept the assertion that concrete is a fully brittle material. Instead they rely heavily on the description of the post-peak behaviour of the concrete at the material level. In this respect, it is important to remember that the FE method works by breaking the structure into a finite number of elements, so that its overall deformational and strength response for arbitrary boundary conditions can be calculated through mathematical equations related to the behaviour of each individual element. What is needed, therefore, is a mathematical description of the response of a representative element of the material under well-defined states of stress. This means that the material data must have been established independent of any effects from the testing equipment. The neglect of this requirement is probably the main reason for the lack of a proper understanding of concrete at both the material and the structural level. If this is true, this must inevitably hamper the development of rational design rules and generally valid FE models for concrete. To make a leap forward in structural concrete research, it was therefore considered to be of crucial importance to first evaluate whether concrete really behaves as it is assumed to do, both as a material and in a structure.

Many consider the major disadvantage of LWAC to be its brittleness in compression at the material level compared to normal density concrete. The requirement of adequate strength, which can easily be fulfilled with lightweight concrete, is not the only design criterion, because adequate ductility is essential for safety in overload situations [10–13]. Ductility is of great importance in the redistribution of forces, and is also a major consideration in the design of structures in seismic areas. It is possible to achieve ductile structures by adjusting reinforcement ratios and proper detailing. However, some structures, e.g. large offshore shell concrete structures, are often heavily reinforced to satisfy other criteria than ultimate capacity. In such cases the brittle behaviour of concrete needs to be considered. The assumed limited post-peak behaviour of LWAC can help explain the limited use of the material, and requests for energy dissipation and/or controlled behaviour after peak load can therefore exclude LWAC as the preferred material. The main objective of this research was to increase our understanding of the ultimate response of LWAC members in compression and bending [14]. The background was that the common explanations for the differences between LWAC and NWC were not entirely satisfactory. Very often the experimental results seemed to be in conflict with the current way of thinking [15]. The hypothesis underlying this study was that the three key material characteristics that generally determine the ultimate response of concrete structures are: 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. It follows from these features that the strength, and especially the ductility, of structural concrete members depend on local triaxial stress conditions that inevitably develop in the compressive zone prior to failure, rather than on stress-redistributions due to post-peak material characteristics, as is commonly believed. This hypothesis has previously been used with success to explain and predict the behaviour of NWC members in the ultimate limit state [16,17]. This research aimed to find out whether it can be used to explain the experimental results that seem to be in conflict with the current theoretical understanding of the ultimate response of LWAC members. So the main goal of this work was to investigate the explanatory power of the alternative hypothesis when applied to LWAC. In this respect, a large variety of experimental data reported in the literature were examined. Existing triaxial strength data were used as the basis for the development of a novel failure criterion taking into account the density of the concrete. Finally, a three-dimensional nonlinear FE model with the proposed failure criterion was developed for the verification of the hypothesis.

2. Fundamental behaviour of concrete at material level

2.1. Underlying reasons for the differences between LWAC and NWC

Aggregates make up the highest volume fraction in a concrete. The primary reason for mixing aggregate with cement paste is to reduce the cost of the material, since aggregates are cheaper than cement. Moreover, aggregates reduce shrinkage and creep, give better volume stability in the concrete, and enhance its durability. In NWC, the strength of the aggregate is rarely a problem, and the properties of the aggregates therefore do not determine the performance of the concrete. The lower overall density of LWAC is achieved by replacing the conventional gravel aggregates with lighter and, therefore, softer and weaker types. So the aggregates in LWAC are more prone to affect the performance of the concrete, and will in many cases become the decisive factor. The porous nature of the lightweight particles means that the cement paste tends to penetrate inside the aggregates, resulting in little or no transition zone between the component phases. So what primarily sets LWAC apart from NWC is: a lighter, softer and weaker aggregate compared to the mortar, combined with an often higher bond strength between these two components.

Concrete can be separated into two classes determined by the properties of the two components, aggregate and mortar [18]. In the first class of concretes, including ordinary NWC and some lightweight concretes, the concrete composite can be considered as a two-phase material in which stiffer and stronger particles are embedded in a softer and weaker matrix. The short-term strength is a function of the strength of the mortar only, which predominantly depends on the water-cement ratio of the mix and the strength of the cement. In the second class of concretes, where softer and weaker particles are embedded in a stronger and stiffer matrix, the influence of the aggregates on the strength must be taken into account. The effect of the aggregates on the overall compressive concrete strength can be evaluated by comparing the relationship between the strength of the mortar and the strength of the concrete made with this mortar, as illustrated in Fig. 1.

Up to a certain limit, the compressive strength of the concrete will be governed by the compressive strength of the mortar. The limit marks the shift from what can be defined as a class one to a class two concrete. Below the limit strength, a lightweight concrete behaves in the same way as an ordinary concrete. However, above the limit strength, the stress distribution within the concrete