Construction and Building Materials 170 (2018) 66–77

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Failure modes and buckling capacity of thin cylindrical reinforced cementitious shells under axial compression

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HIGHLIGHTS

- The buckling behavior of an axially compressed cementitious cylinder is studied.
- The tolerance measurement proposed by EC3 seems to cover cementitious cylinders.
- The capacity curve for different imperfection amplitudes is numerically obtained.
- Three different failure modes are identified.
- The capacity curve is approximated by the same buckling parameters used by EC3.
- A simplified design approach similar to that of EC3 seems possible.

ARTICLE INFO

Article history:
Received 20 April 2017
Received in revised form 18 January 2018
Accepted 28 February 2018
Available online 23 March 2018

Keywords:
Thin cylindrical cementitious shells
Buckling
Capacity curve
Failure modes

ABSTRACT

High performance cementitious composites have made possible the manufacturing of thin cementitious shell structures which are prone to buckling. Perhaps the most comprehensive design procedure for such shells is provided by the design recommendations issued by the International Association for Shells and Spatial Structures (IASS) which, however, are inconsistent with the modern European design framework. The scope of this paper is to contribute to the development of a design methodology similar to the one recommended by Eurocode 3 part 1–6, which is based on a capacity curve that represents all the possible failure states. In this respect, the capacity curve of an axially compressed cylinder is produced by geometrically and materially nonlinear analyses for different fabrication quality classes, which are in the sequel approximated by parametric capacity curves based on parameters determined following the concept of Eurocode 3.

1. Introduction

Due to their structural efficiency as well as their aesthetic elegance, shells have been the choice of engineers when high efficiency was needed, such as the covering of long spans. Some of the applications of concrete shells include shell roof systems, silos and tanks as well as cooling towers. Concrete shells, which are one of the oldest structural systems, witnessed a blooming period between the 1920 and 1980. After this period, the interest in concrete shells suddenly faded, as the industry turned towards alternative structural systems and materials such as steel. This had a direct impact in the development of analysis and design methodologies for concrete shells, as the lack of extensive research after 1980 created a gap in design guidelines between concrete and steel shells.

Perhaps the most comprehensive design guidelines for cementitious shells are provided by the International Association for Shell and Spatial Structures (IASS) [1]. Published in 1979, more than 35 years ago, the IASS design recommendations were prepared by a working group as a guideline for both the analysis and design of shell structures as well as their construction. The design recommendations were mainly based on the research work of Kollár and Dulácska [2] and include a procedure of applying reduction factors on the theoretical buckling load of the shell, in order for its elastic-plastic capacity to be obtained. Each step of the procedure intends to take into consideration a different factor that affects the capacity. These different factors are initial imperfections, creep, cracking and plasticity. The final load is further reduced by a global safety factor. Facts such as the lack of a clearly defined tolerance measurement method, the lack of recommenda-

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https://doi.org/10.1016/j.conbuildmat.2018.02.215
0950-0618/

tions regarding the imperfection pattern used in numerical analyses and the use of a global safety factor rather than partial ones, lead to inconsistencies with the modern European design framework of Eurocodes.

An alternative design approach can be achieved by the use of the general provisions of Eurocode 2 [3] regarding second order analysis. However, these provisions do not provide a comprehensive and complete design methodology for reinforced concrete shells. Thus, the capacity of a concrete shell can only be determined by geometrically and materially nonlinear analysis of the imperfect structure. The design by performing a geometrically and materially nonlinear analysis of the imperfect structure (GMNIA) found in Eurocode 3 part 1–6 [4] (normative requirements for steel shells) seems to be an appropriate method for the analysis of cementitious shells as well. However, besides the fact that such a highly nonlinear analysis is not easily performed by everyday engineers, its results cannot be always interpreted or trusted without a reference solution, obtained by simpler methods.

A simplified approach that has been proved very convenient for the design of steel shells is based on the general capacity curve for shell structures, a curve that represents the reduction of the compressive resistance of the structure due to its slenderness. The method adopted by Eurocode 3 part 1–6 [4] is an extension of the classical buckling curves that are used for the design of linear structural members. The capacity curve, in its simplest form, is defined by four distinct parameters, each of which represents a characteristic part of the behavior of the structure [5]. In more detail, the first parameter is the squash limit relative slenderness $\bar{\lambda}_0$, which is the slenderness below which the plastic axial capacity is achieved $(\chi = 1)$. The second one is the plastic range factor β, that defines the point $(\bar{\lambda}_p, 1-\beta)$, beyond which the shell will buckle elastically. The third parameter named "interaction exponent η" controls the curvature of the elastic-plastic branch of the capacity curve, and thus expresses the intensity of the interaction. The fourth parameter is the elastic imperfection reduction factor α, which expresses the impact of geometric nonlinearity and imperfection sensitivity on the elastic buckling stress and is calculated as the factor of the characteristic buckling stress of the imperfect elastic shell R_{rk} to the elastic critical stress R_{cr}. A visual representation of the classic buckling curve as well as the modified portrayal [5] are shown in Fig. 1.

The scope of this paper is to demonstrate that the extension of the above methodology for the design of an unstiffened axially compressed reinforced cementitious cylinder cementitious shells is feasible. The work is numerically elaborated, by means of the FEM and appropriate models are developed using layered shell finite elements. The case of a cementitious cylinder is systematically investigated, starting from geometrically nonlinear analyses that target to the determination of the most appropriate types of imperfections that must be considered in the design and their characteristics (imperfection length and amplitude). In the sequel, both material and geometric nonlinearities are considered to identify the possible failure modes. A model capacity curve combining the identified failure modes is proposed, specifically for the case of cementitious shells. In the sequel, numerical capacity curves are generated, for three different fabrication quality classes. Finally, a procedure is presented for the determination of the parameters that may be used for the approximation of the numerical capacity curves by means of parametric curves. Thus, the present work, apart from an elaborate numerical investigation of the behavior of a high performance axially compressed cementitious cylinder, is also a "proof of concept" that cementitious shells can be treated within the capacity curve framework of Eurocode 3 part 1–6 after certain enhancements and modifications.

2. Formulation of the numerical models

The structure under investigation is an axially compressed cementitious cylinder with radial (w), axial (u) and circumferential (v) displacements restrained at both edges, and a length-to-radius ratio equal to 4. It should be mentioned that the aforementioned length-to-radius ratio was selected in order the cylinder to be long enough so that the boundary conditions do not have an impact on the final capacity of the shell. The analyses were carried out using the MSC Marc Finite element analysis software [6]. For the formulation of the numerical model four-node thick-shell elements were used. All models were solved using large strain theory and the arc-length load incrementation method [7], with convergence testing based on residual stresses. In order to reduce the computational cost, half of the cylinder was simulated by imposing the appropriate symmetry conditions along two opposite meridionals. The cylinder was assumed to be manufactured by a high performance cementitious material (mortar) similar to ferrocement [8] with reinforcement ratio equal to 3.4% per direction. The mortar was considered to be of C60 grade and the reinforcing meshes of B500c steel. For the simulation of the reinforced composite section, layered shells were utilized. Reinforcement rods and meshes were simulated by equivalent reinforcement layers that had stiffness only in the direction of the reinforcement, while the cement mortar was simulated by isotropic material layers. Fig. 2 presents the reinforcing pattern of the cylinder as well as the corresponding composite layered shell.

As far as material nonlinearity is concerned, the provisions of Eurocode 2 [3] were followed regarding the material properties. For nonlinear structural analysis, the stress-strain relationship proposed by Eurocode 2 for the mortar is shown in Fig. 3. The tensile

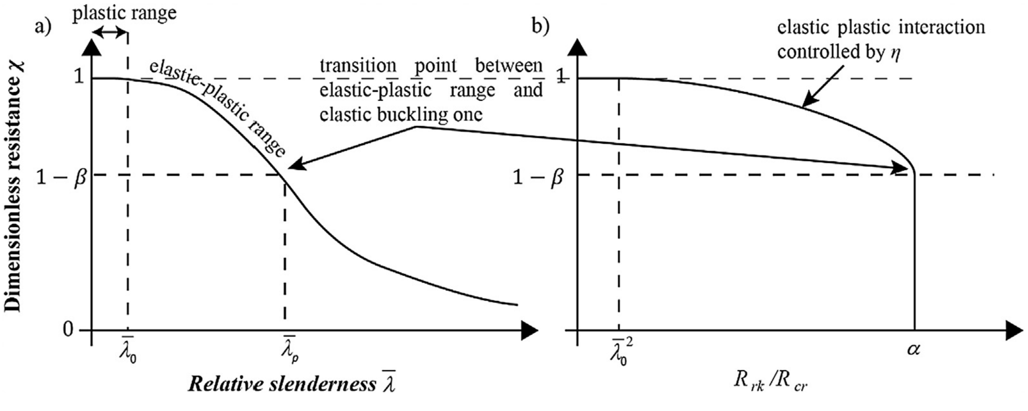

Fig. 1. (a) Classic and (b) Modified capacity curves.