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Research paper

A computational strategy to establish algebraic parameters for the Reference Resistance Design of metal shell structures

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ABSTRACT

The new Reference Resistance Design (RRD) method, recently developed by Rotter [1], for the manual dimensioning of metal shell structures effectively permits an analyst working with only a calculator or spreadsheet to take full advantage of the realism and accuracy of an advanced nonlinear finite element (FE) calculation. The method achieves this by reformulating the outcomes of a vast programme of parametric FE calculations in terms of six algebraic parameters and two resistances, each representing a physical aspect of the shell's behaviour.

The formidable challenge now is to establish these parameters and resistances for the most important shell geometries and load cases. The systems that have received by far the most research attention for RRD are that of a cylindrical shell under uniform axial compression and uniform bending. Their partial algebraic characterisations required thousands of finite element calculations to be performed across a four-dimensional parameter hyperspace (i.e. length, radius to thickness ratio, imperfection amplitude, linear strain hardening modulus).

Handling so many nonlinear finite element models is time-consuming and the quantities of data generated can be overwhelming. This paper illustrates a computational strategy to deal with both issues that may help researchers establish sets of RRD parameters for other important shell systems with greater confidence and accuracy. The methodology involves full automation of model generation, submission, termination and processing with object-oriented scripting, illustrated using code and pseudocode fragments.

1. Introduction

Shells are widely recognised to exhibit the greatest complexity of any structural form, a consequence of a behaviour governed by local buckling, global nonlinear collapse, plasticity and sensitivity to various imperfection forms, in addition to a myriad of possible geometries and load conditions [2]. The power of modern computing, coupled with the recent development of a powerful framework to characterise the results in a uniform manner, have led to the development of Reference Resistance Design (RRD) [1]. Without this framework, every problem must be treated in an ad-hoc manner. However, RRD requires a huge volume of nonlinear calculations required to support it. This paper presents a new and highly efficient technique to achieve that goal.

Although early advances in the analysis of shell buckling problems were made through algebraic studies [3–5], it did not take long for the set of shell structural systems that could be processed in this manner to become exhausted and recourse had to be made to numerical methods, first in the solution of the equations and ultimately by finite element analysis. The history of progress in shell buckling thus runs in parallel with the history of the development of modern scientific computing [6–8]. While the earliest computational endeavours saw researchers develop their own finite element solvers (e.g. BOSOR [9] and NEPAS [10]), the era of writing software from scratch has now largely passed as the range and complexity of the problems under investigation have burgeoned. A look at the modern engineering research literature reveals a widespread use of extensive 'general' FE software suites, both proprietary (e.g. ABAQUS [11]) and open-source (e.g. OpenSees [12]), that have benefited from years of continuous development. Many more design-focused FE packages are used by industry.

2. An overview of Reference Resistance Design

The state-of-the-art European Standard on the Strength and Stability of Metal Shells EN 1993-1-6 [13] was the first in the world to prescribe two formal methods governing the computer-aided

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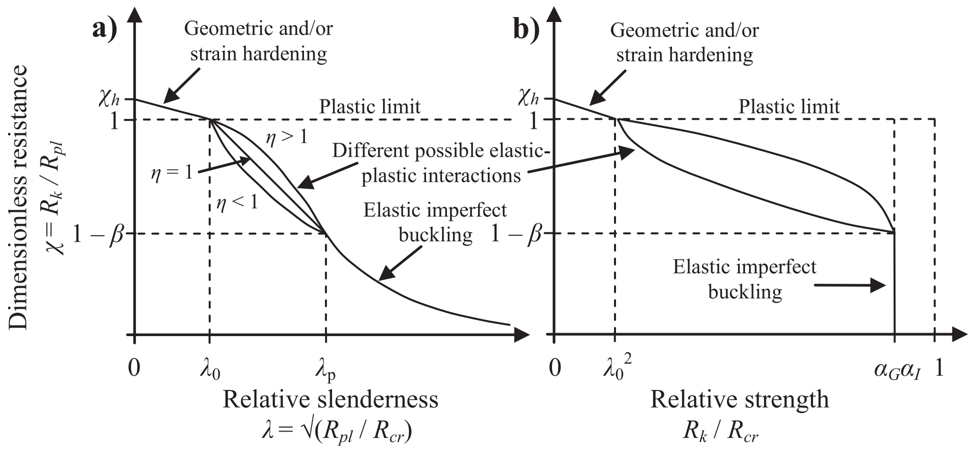

Fig. 1. a) Generalised and b) modified capacity curves [17].

design of metal shells under the generic title 'design by global numerical analysis' [14]. The first and simplest method is 'LBA-MNA' [15], where the designer must use a computer calculation to determine the reference elastic critical buckling and plastic collapse resistances of the perfect shell from a linear bifurcation (eigenvalue) analysis (LBA) and an ideal elastic-plastic materially nonlinear but small displacement analysis (MNA) respectively. The second method is termed 'GMNIA' [16,17] and involves full geometrically and materially nonlinear analyses with explicitly modelled imperfections. Analyses of intermediate complexity are also defined in this Standard, termed GNA, GMNA and GNIA, where 'G' and 'M' indicate the inclusion of geometric and material nonlinearity respectively, while 'I' indicates the presence of imperfections. Neither of these computer-aided methodologies come easily to many practitioners, who may lack the training, the time or the software necessary to undertake nonlinear FE analyses on anything but the most important of designs. Indeed, the ECCS European Design Recommendations on the Buckling of Metal Shells [14] offers a commentary on EN 1993-1-6 and devotes much discussion to how such analyses should be conducted, illustrating many of the potential pitfalls that can make a calculation go wrong or be badly misinterpreted.

$$\chi(\lambda) = \begin{cases} \text{Fully plastic}: \chi_h - \left(\frac{\lambda}{\lambda_0}\right)(\chi_h - 1) & \text{when } \lambda \le \lambda_0 \\ \text{Elastic-plastic}: 1 - \beta\left(\frac{\lambda-\lambda_0}{\lambda_p-\lambda_0}\right)^{\eta} & \text{when } \lambda_0 < \lambda < \lambda_p \\ \text{Fully elastic}: \frac{\alpha_G\alpha_I}{\lambda^2} & \text{when } \lambda_p \le \lambda \end{cases}$$

$$\text{where } \lambda_p = \sqrt{\frac{\alpha_G\alpha_I}{1-\beta}} \quad (1)$$

The new method termed Reference Resistance Design (RRD) was recently devised by Rotter [1,2,18] to permit analysts to take advantage of advanced computational predictions without having to perform these themselves. RRD is built around a capacity curve which describes the base relationship between a shell's nonlinear characteristic resistance normalised by its reference plastic collapse resistance ($\chi = R_k / R_{pl}$) and its dimensionless slenderness ($\lambda = \sqrt{(R_{pl} / R_{cr})}$), where R_{cr} is the reference elastic critical buckling resistance). The entire relationship is characterised by six independent algebraic parameters α_G, α_I, β, η, λ_0 and χ_h, each one containing information about a real physical effect as described shortly. The most recent formulation of the capacity curve [17] is given in Eq. 1 and illustrated schematically first as a classic buckling curve in Fig. 1a and again in a modified form [19] in Fig. 1b. A detailed account of background to the capacity curve and proposed further enhancements may be found in Rotter [15] and Doerich and Rotter [20].

In Eq. 1, α_G and α_I are separate adjustments on R_{cr} to respectively account for the influences of geometric nonlinearity and imperfection sensitivity in slender shells that fail elastically. As most shell systems under simple load conditions suffer from pre-buckling geometric softening and detrimental imperfection sensitivity, α_G and α_I are usually less than unity. However, more complex systems such as cylindrical silos under unsymmetrical eccentric discharge pressures may exhibit beneficial changes of geometry leading to geometric stiffening and/or strengthening 'imperfections' [21,22], such that α_G and α_I may become greater than unity. In theory, this very general formulation supports both possibilities. Although $\alpha_G \ge 1$ cannot be avoided if the beneficial geometric nonlinearity relates to the fundamental mechanics of the system, a situation where $\alpha_I > 1$ usually signifies that an inappropriate 'imperfection' has been chosen and it is likely that a more carefully-chosen deviation from the perfect geometry will lead to $\alpha_I < 1$ [22].

The 'plastic range factor' β identifies the point $(\lambda, \chi) = (\lambda_p, 1 - \beta)$ on the capacity curve at which plasticity first begins to have a noticeable effect on the behaviour and marks the onset of the 'elastic-plastic' region. The 'interaction exponent' η controls the curvature of the relationship in this region of Fig. 1a, with $\eta < 1$, > 1 and $\equiv 1$ allowing convex (positive curvature, indicating a strong elastic-plastic interaction), concave (negative curvature, indicating a weak interaction) and idealised linear (zero curvature) relationships respectively in the χ vs λ plane. The 'squash limit' λ_0 defines the slenderness at which the reference full plastic conditions R_{pl} is reached, while $\chi_h \ge 1$ defines the projected intercept of the vertical axis for a fictitious shell with zero slenderness, allowing for resistances higher than R_{pl} for very stocky shells due to geometric or strain hardening.

In effect, RRD permits an analyst working with only a calculator or a spreadsheet to take full advantage of the accuracy and realism of a GMNIA, on the understanding that the six algebraic parameters that account for the complex nonlinear phenomena have already been established *a priori* for all practically relevant parameter ranges. While it is possible in theory to establish these on the basis of laboratory testing, the expense involved in doing so for all systems and parameter ranges would be absolutely prohibitive and difficult to justify in the modern age of limited budgets, powerful software and cheap computing power. A computational programme using a validated and robust FE model remains the only defensible option. The significant reduction in uncertainty in the structural resistance model obtained through RRD should reduce the need for excessive compensation through high partial safety factors, permitting more economic designs.