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A Commentary on Improving the Design Rules for Thin Aluminium Shell Structures

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Abstract

For the design of aluminium shells, Eurocode 9 is heavily dependent upon the principles of steel shell design given in Eurocode 3. The persistent recourse in Eurocode 9 to Eurocode 3 can lead to designers being misinformed about the design process, or making incorrect assumptions when deciding which section of which Eurocode is appropriate and which material is being used. The present paper indicates ways in which Eurocode 3 requirements for shell design need to be incorporated into Eurocode 9 to reduce uncertainty when designing thin aluminium shells and to help ensure computer resources use only the appropriate analysis methods.

Keywords: aluminium design, design rules, Eurocode 3, Eurocode 9, shell buckling, shell theory.

1 Introduction

The structural resistance of a shell structure is based on its curvature. A shell is very efficient in resisting distributed loads but less so resisting concentrated loads as they introduce local bending stresses. In shells two modes of resistance are combined, membrane resistance to in plane forces and bending resistance to out-of-plane forces. Bending usually occurs at changes in boundary conditions, shell thickness, load types and where local instability occurs [1].

Shells resist loading initially by membrane action, but as the load increases, bending begins, becomes predominant and the shell buckles, often without warning, as a whole or in part depending upon the line of least resistance. The shell may still carry load beyond the buckling load but the magnitude of this load depends upon the load type, boundary conditions, shell shape and the relationship between buckling stress and the yield stress.

If a shell fails initially with multiple small local buckles, the critical load is little affected by the boundary conditions, but this is not the case if the buckles involve the whole shell. Further the buckling load is reduced by pre-buckling initial deformations and these must be taken into account [2]. For the design of complex shell structures finite element analysis (FEA) software is needed.

Initial shape imperfection, eccentricity of loading and residual stresses due to manufacture often occur causing apparently identical shells to collapse at different loads with a multiplicity of different buckling modes associated with the same bifurcation load. Non-linear behaviour may also be caused by changes in the geometry due to shell deformation. Consequently shells must be manufactured, fabricated and erected using strict quality control procedures.

2 Shell buckling complexity

Despite extensive research the knowledge on shell buckling is limited by to two main difficulties: a) the complexity of shell buckling and b) shell sensitivity to small geometric imperfections and locked in stresses induced in manufacturing, fabrication and erection.

An obvious difficulty a designer faces when using shell buckling FEA is how to convert the numerical buckling load based on any of the types of buckling analysis to the design strength of the structure.

Two approaches in use are:

- Linear elastic bifurcation buckling analysis to determine the bifurcation load of the perfect structure and then apply reduction factors to account for geometric and material non-linearity. This approach is familiar to designers and linear bifurcation analysis is uncomplicated to perform. The difficulty is determining the value of the reductions factors.
- Fully nonlinear analysis modelling the deflections, geometric and material non-linearity, but establishing the form and amplitude of the imperfections can be difficult [3].

Typical types of analysis are:

- Pre-buckling behaviour is assumed to be linear with the buckling stress corresponding to a bifurcation point found by eigenvalue analysis.
- Non-linear collapse analysis enables successive points on the non-linear primary equilibrium path to be determined until non-linear collapse occurs.
- Investigating bifurcation buckling from a non-linear pre-buckling state involves searching for the lowest bifurcation point.
- General non-linear collapse analysis of an imperfect shell consists of determining the non-linear equilibrium path and the limit point for the shell whose initial imperfections and plastic deformations are taken into account. The limit load causing the structure to snap-through

3 Steel buckling analysis strategy

There is research which proposes a FEA approach for predicting the buckling strength and load resistance of steel structures to verify the ultimate limit state (ULS) [4]. A similar procedure could be developed for aluminium shells.

The steel shell strategy consists of setting up FEA models, obtaining critical buckling modes from linear elastic bifurcation analysis (LBA), then using a linear combination of these modes as imperfection patterns for a geometrically and material nonlinear imperfection analysis (GMNIA).

The aim is to provide practical guidelines for using FEA for design and to predict anticipated failure mechanisms. A finer finite element mesh is required for nonlinear analyses than for a linear convergence study.

Although LBA critical buckling loads are not safe predictions of strength, LBA must precede nonlinear analyses for two main reasons:

- LBA critical buckling loads are an upper bound of actual strength and LBA is a fast, inexpensive analysis for evaluating alternative solutions.
- LBA buckling modes are used as initial imperfections for GMNIA and identify all possible failure mechanisms to ensure the critical failure mechanism is determined. Several buckling modes must be obtained as although the first buckling mode is the lowest critical buckling mode, a higher mode may be more critical.

As buckling may be a combination of both geometric and material nonlinearity, both must be considered.

Due to initial imperfections and geometric and material nonlinearity, GMNIA is recommended for reliably understanding the behaviour, predicting all possible failure mechanisms, evaluating strength and assessing the vulnerability of steel structures. It is useful to carry out a separate material nonlinearity imperfection analysis (MNIA) and a geometric nonlinearity imperfection analysis (GNIA), to identify the prevailing failure mechanism. The ultimate strength evaluation should always be based on GMNIA [4]. MNIA is not covered in EN1993-1-6 or in EN1999-1-5 and neither is GNIA covered in EN1999-1-5 [5,6].

Important aspects of an equilibrium path include:

- Slope of its initial part, representing the structure's initial stiffness.
- Maximum value of the external actions, representing the structure's strength.
- Displacement corresponding to the maximum value of the external actions, indicating serviceability problems.
- Maximum deformation at failure representing the structure's ductility.

The proposed steel shell strategy consists of having an appropriate FEA model, obtaining critical buckling modes from LBA and then using linear combinations of these modes as imperfection patterns for GMNIA to obtain a load–displacement curve [4].

4 Eurocode 9 Part 1-5 [6]

EN1999-1-5 is drafted on the EN1993-1-6 model with the buckling analysis organised on the lines of the ECCS Recommendations on buckling of steel shells [5,6,7,8]. However, in EN1999-1-5, EN 1993-1-6 is supplemented by specific provisions for aluminium shells, which include inelastic buckling, imperfection sensitivity, effect of welding etc. General shell-loading combinations are allowed in EN 1999-1-5 provided fully non linear FEA is used for imperfections and for geometric and material non-linearity effects. This presents designers with decisions regarding which imperfections and geometric and material non-linearity effects to include.

Type of analysis		Shell theory	Material law	Shell geometry
Membrane theory of shells	MTA	membrane equilibrium	not applicable	perfect
Linear elastic shell analysis	LA	linear bending and stretching	linear	perfect
Linear elastic bifurcation analysis	LBA	linear bending and stretching	linear	perfect
Geometrically non-linear elastic analysis	GNA	non-linear	linear	perfect
Materially non-linear analysis	MNA	linear	non-linear	perfect
Geometrically and materially non-linear analysis	GMNA	non-linear	non-linear	perfect
Geometrically non-linear elastic analysis with imperfections	GNIA	non-linear	linear	imperfect
Geometrically and materially non-linear analysis with imperfections	GMNIA	non-linear	non-linear	imperfect

Table 1. Eight types of shell analysis in EN1999-1-5 [B]

The analysis of thin aluminium shells has been widely investigated and the complexity of the shell analysis methods has been simplified in EN1999-1-5 [6,7]. As EN1999-1-5 lists eight types of shell analysis, designers would benefit from a commentary on where each type of analysis gives the most accurate results and in what combination and order of precedence each type of analysis is to be used. In this way designers would be able to select the analysis best suited to a particular application. The eight types of shell analysis are given in Table 1, but there is some confusion over GNIA. Section 5.5 of EN1999-1-5 indicates that design should be based on one or more of the eight types of analysis, but then says GNIA is not covered in EN1999-1-5, but is listed to give a complete presentation of types of shell analysis. Reference is made to EN 1993-1-6 for more details.

EN 1999-1-5 applies to the structural design of aluminium structures, stiffened and unstiffened, that have the form of a shell of revolution or of a round panel in monocoque structures and to axisymmetric shells and associated circular or annular plates and beam section rings and stringer stiffeners [6]. Supplementary information is given in EN 1993-1-6 and the relevant application parts of EN1993 which include: Part 3-1 for towers and masts, Part 3-2 for chimneys, Part 4-1 for silos, Part 4-2 for tanks and Part 4-3 for pipelines [5,9]. When using material nonlinearity, the appropriate stress-strain curve has to be selected from Annex E of EN 1999-1-1 where the idealization of the stress-strain relationship of aluminium alloys takes account of the actual elastic-hardening behaviour of aluminium [10]. The stress-strain relationships have different levels of complexity according to the calculation accuracy required. The designer then has to choose which model is most appropriate for the analysis under consideration and which FEA software is suitable.

Geometrical deviations of the shell surface, such as: out-of-roundness, eccentricities and local dents should be considered and shell design must be based on one or more of the types of analysis given in Table 1 with further details given in EN 1993-1-6 [5]. EN1999-1-5 links the types of analysis with design requirements as follows [6]:

• Design values of stresses use	MTA, LA, GNA
• Design by numerical analysis use	MNA, GMNA
• Buckling strength use	LBA
• Buckling resistance of unstiffened welded shells use	GMNIA
• Design by numerical analysis use	GMNIA
• Geometry and joint offset use	LBA

5 Eurocode 3 Part 1-6 [9]

EN 1993-1-6 gives basic design rules for plated steel structures that have the form of a shell of revolution. It defines the characteristic and design values of the resistance of structures for the ultimate limit states of: plastic limit, cyclic plasticity, buckling and fatigue. It applies to axisymmetric shells and associated circular or annular plates and to beam section rings and stringer stiffeners where they form part of the complete structure. Cylindrical and conical panels are not explicitly covered. Although EN 1993-1-6 is intended for steel shells it may be used for shells of other metals provided the appropriate material properties are considered [9].

General procedures for computer calculations of all shell forms are covered. For the limit state of buckling one or more of the following methods are used.

• Checking for axisymmetric conditions only use	MTA
• Minimum requirement for stress analysis under general loading conditions use	LA
• Shells under general loading conditions if the critical buckling resistance is used use	LBA
• Shells under general loading conditions if the reference plastic resistance is used use	MNA
• Using appropriate imperfections and calculated calibration factors use	GMNIA MNA LBA GMNA

As strength under buckling depends on quality of construction, this must be considered.

It may be assumed that primary stresses control buckling but buckling may be affected by secondary stresses. Where the stress design approach is used, the limit states should be assessed in terms of three categories of stress: primary, secondary and local. The categorisation is usually performed with the von Mises equivalent stress, but buckling stresses cannot be assessed using this value.

For direct design:

• Determine the primary stresses using	MTA

For global numerical analysis:

• Determine the critical buckling resistance using	LBA
• Determine the plastic reference resistance, as part of the assessment of buckling using	MNA
• Determine the elastic buckling load of the perfect structure using	GNA
• Determine the elastic buckling load of the imperfect structure using	GNA GNIA GMNIA
• Determine the collapse loads for the perfect structure using	GMNA
• Determine the collapse loads for the imperfect structure using	GMNIA GMNA

Considerable research has been carried out into thin shell theory and the stress and the strain response of thin aluminium shells subjected to buckling. This research also identified that the analysis methods used to determine the buckling response of thin aluminium shells give significantly different results with the most accurate analysis being GMNIA, the most complex analysis method given in EN1999-1-5 [6]. GMNIA requires large amounts of computer time and resource input; a critical factor in deciding if this analysis method is used.

6 Discussion

EN1999-1-5 is heavily reliant upon the principles of steel thin shell design given in EN1993-1-6 with additional specific design studies and research formulated for aluminium [5,11]. However the behaviour of aluminium is different to steel; aluminium shells are more susceptible to buckling, fatigue, strain hardening, imperfections and welding. Further there is strongly different behaviour in the transition region between the elastic and the plastic range imperfections and post buckling performance recovery. Also thin aluminium shells are particularly susceptible to material and geometrical imperfections. Additionally EN1999-1-5 cannot be used without persistent reference to EN1993-1-6 to accommodate and use correctly the analysis methods in EN1999-1-5 [5,11]. The persistent recourse in EN1999-1-5 to EN1993-1-6 can lead to designers being misinformed about the design process, or making incorrect assumptions when deciding which section of which Eurocode is appropriate and which material is being use.

7 Conclusion

The European Commission, Enterprise and Industry Directorate-General, sent to CEN the Programming Mandate M/466 EN concerning the Structural Eurocodes [12]. Part of the mandate referred to further development of EN1999 related to the design and construction rules for shells which the mandate said required further guidance to make them easier for practical application [12]. This included Work Package 5 for the improvement of design rules for shell structures.

Previous research by the author has identified ways of improving the use of Eurocode 9 [13,14]. The present paper indicates ways in which the EN1999-1-6 requirements for shell design need to be incorporated into EN1999-1-5 to reduce confusion when designing thin aluminium shells and to help ensure computer resources use only the appropriate analysis methods.

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