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Design by analysis versus design by formula of high strength steel pressure vessels: a comparative study

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Abstract

A comparative study for design by analysis and design by formula of a cylinder to nozzle intersection has been made using different finite element techniques. The cylinder to nozzle intersection investigated is part of a typical vertical pressure vessel with a skirt support. For the study the commonly used ductile P355 steel alloy and the high strength steel alloy P500 QT were considered. The comparative results clearly show disadvantages in terms of limit load capability when the design-by-formula procedures are used in the design of high strength steel pressure vessels. The FE results also clearly show advantages of the shell to solid sub-modeling technique, as it combines the accuracy of 3D-solid modeling with the affordable computing time of the 3D-shell modeling technique.

Keywords: Design by analysis; Design by formula; Limit load analysis; High strength steels; Shell-to-solid sub-modeling FEA

1. Introduction

Industrial pressure vessels are usually structures with complex geometry containing numerous geometrical discontinuities and are often required to perform under complex loading conditions (internal pressure, external forces, thermal loads, etc.). The design and manufacturing of these products are governed by mandatory national standards, codes and guidelines that ensure high safety performance. Most pressure vessel design codes (e.g. EN13445 [1], BS550 [2], ASME DivIII [3]) assume a membrane stress state condition for the determination of the minimum shell thickness and large safety factors at areas of geometric discontinuities such as openings, change of curvatures, nozzle intersections, thickness reduction, etc. It should be noted that large safety factors lead to increasing the material thickness, while safety is not necessarily increased; recall that fracture toughness decreases with increasing thickness, and stress corrosion cracking at components operating in corrosive environments is expected to be higher in thicker parts.

When using high strength steel alloys for pressure vessels it can be noted that according to EN13445 code the design stress is derived by the formula

$$f = \min\left(\frac{R_{p0,2/t}}{1,5};\frac{R_{m/20}}{2,4}\right),$$

where $R_{p0,2/t}$ and $R_{m/20}$ are the minimum yield strength or 0.2% proof strength at the calculation temperature t and the minimum tensile strength at 20 °C, respectively. Compared to the ASME code

$$f = \min\left(\frac{R_{p0,2/t}}{1,5};\frac{R_{m/20}}{2,14}\right)$$

it can be seen that design by EN13445 leads to more conservative products for high strength materials, e.g. with high yield to tensile strength ratio ($R_{p0,2/t}/R_{m/20}$), where $R_{m/20}$ determines the design stress. Therefore, investigations are necessary to examine the capability of high strength steels for design and manufacture of pressure vessels with increased levels of safety.

Up to the year 2000 finite element analysis was excluded from most national design codes. Only recently, a procedure

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for estimating the lower limit load by using finite element analysis has been introduced in Annex b of the Euro Norm EN13445 [1]. The procedure presented in annex b of EN13445 is referred to as 'Design by Analysis' (DBA), and will be followed in the present work. So far, the most commonly used techniques in finite element modeling involve linear elastic and linear elastic-ideal plastic analysis implemented in 2D and 3D-Shell element models or 3D-Solid element models.

The majority of finite element analyses used for the design of pressure vessels involve 2D and 3D shell element models [4–11]. The use of this type of element allows computation of the stress state of the component in affordable computing time. However, the derived values in areas with geometrical discontinuities (nozzle intersections, weldments, etc.), where stress singularities occur, are expected to include certain inaccuracies as such complex geometries cannot be modeled with shell elements and in addition, only stresses at limited surfaces (top-middle-bottom) may be derived. The use of 3D-solid element models currently remains limited [4]. Although the use of this type of elements results in an accurate derivation of the stress state, the FE-models are usually huge and require very large computing time.

In the present work a Finite Element Analysis of the cylinder to nozzle intersection of a pressure vessel has been made by developing a shell to solid finite element model to achieve sufficient accuracy in affordable computing time. The derived stress state of the nozzle to cylinder intersection is compared with results obtained by implementing traditional 3D-shell and 3D-solid models. Two different materials: the high strength steel P500 and the conventional low strength steel P355 have been considered for comparison.

2. Design by analysis of a cylinder to nozzle intersection

DBA, as defined in annex b of the European standard EN13445, provides design rules of any pressure vessel component under any action and it may be used as an alternative to design by formula, or as a complement to design by formula. The DBA procedure includes a check against gross plastic deformation (GPD). In the present case study the design action is internal pressure.

The principle that defines GPD states that for any load case the design action A_d, or the design effect E_d, shall not exceed the design resistance R_d:

$$A_d \leq R_d \quad \text{or} \quad E_d \leq R_d \tag{2.1}$$

Specifically, the design check for GPD may be conducted by means of two application rules specified in annex b of Ref. [1]. In application rule 1, the design action shall be less than the lower bound limit load divided by a partial safety factor γ_R. The lower bound limit load may be derived using

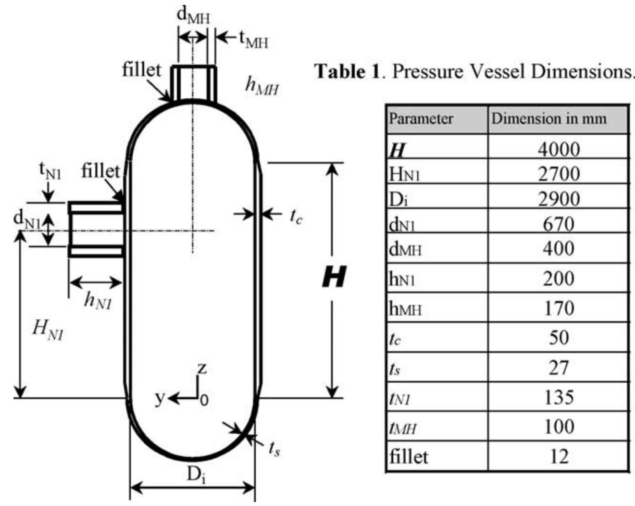

Fig. 1. Dimensions of the vessel input as parameters in the FE code.

the twice-elastic slope method [4] from the load displacement curve. An additional constraint in this procedure is that the absolute maximum principal strain shall not exceed the value of 5%. In application rule 2, the primary stress intensity defined by ($|\sigma_{max} - \sigma_{min}|$) at any location of the structure shall not be greater than RM/γ_R, σ_{max} and σ_{min} are the maximum and minimum principal stresses, respectively. The parameters RM and γ_R are obtained from Table B.9-5 of annex b [1] of EN13445.

2.1. Case specification

The example pressure vessel chosen was defined in the framework of the European research project ECOPRESS [12]. The geometry values of the pressure vessel shown in Fig. 1 are presented in Table 1. It is a typical vertical pressure vessel with a skirt support, and contains most of the usually encountered critical geometrical discontinuities. The pressure vessel was designed for material P355 at a design pressure of 8.25 MPa, according to the rules of 'Design by Formula' of the ASME design code.

Table 1
Pressure vessel dimensions

Parameter	Dimension (mm)
H	4000
H_{N1}	2700
D_i	2900
d_{N1}	670
d_{MH}	400
h_{N1}	200
h_{MH}	170
t_c	50
t_s	27
t_{N1}	135
t_{MH}	100
Fillet	12