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Contribution to pressure vessels design of innovative methods and comparative application with standardized rules on a realistic structure – Part I

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A B S T R A C T

Design of pressure vessels, which are subjected to various natures of loading, must prevent damage mechanisms occurrence. For a load applied or maintained with a given intensity, primary failure modes can appear, such as gross plastic deformation, plastic instability or buckling. For design-by-analysis, the reference methodology is based on an elastic stress calculation. During the last decade, studies have shown that this ingenious procedure could provide conservative design limits. They can become actually overly conservative in a context of increasing complexity of geometry and loading modelling. In parallel, technological and theoretical developments enabled limit analysis to be considered as an interesting design methodology. This is suggested in standards and codes (EN 13445, CODAP, Boiler and Pressure Vessels Code) since the early 2000's. In this first of two companion papers, a set of standardized and innovative procedures is introduced. These approaches rely on various concepts, such as elasticity, incremental elastoplasticity, or elastic compensation (Modified Elastic Compensation Method, Linear Matching Method). Each methodology is presented on theoretical aspects, eventually adapted so as to take into account safety margins. They are then applied on a model inspired from a real industrial reactor, using Abaqus. Results are compared to reference data from codes, in terms of accuracy and computing time. A final assessment underlines practical benefits that could be expected.

1. Introduction

Pressure vessel design consists in defining a structure, whose characteristics (shape, material, thickness, etc) will enable this to sustain a given service loading safely. The objective is to avoid the occurrence of failure modes, which can be classified in several categories [1].

This paper deals with failure modes of primary category, resulting from the application of loading at a given intensity. It focuses on one of them: gross plastic deformation.

The concept of gross plastic deformation applies to the overall vessel dimensions, such as diameters, length or angles. The definition of the relevant limit load refers to the plastic limit state, obtained for a material with an elastic perfectly-plastic behaviour. Under these conditions, some sections or whole regions reach the yield limit: no load increase beyond this limit might be possible for this fictitious material. Plastic instability may occur under increasing loading, when material reinforcement by hardening cannot compensate section reductions caused by plastic deformation. The related action at the onset of gross plastic deformation is an ultimate action, and burst and collapse are typical examples [2].

Extra primary failures modes should also be taken into account in a design operation.

Concerning the risk of ductile failure, local plastic deformations – which remain enough confined to exclude any risk of collapse – are allowed by the rules covering gross plastic deformation. However, parent material and welded areas should have a sufficient

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plastic deformation capacity. This requirement is covered when rules related to structure material ductility, welded joints achievement and their destructive tests are satisfied. In codes and standards, these rules are usually not specified in chapters related to design and conception, but rather in materials, fabrication, or inspection.

Buckling generally results from compressive stresses. This failure mode should be taken into account for all loading conditions causing this kind of stress fields. Specific calculations should be led, so as to check that applied loadings never exceed loadings causing collapse, with a safety factor.

Prevention of brittle fracture under static loadings is finally the subject of specific requirement, such as material selection, or also fracture mechanics.

Excessive deformation and rupture caused by creep usually affect pressure vessels, whose design temperature is high enough to cause gradual material yielding under constant loading. Risks related to this failure mode should be evaluated in normal operating conditions.

In design by calculations, two methodologies are usually described in pressure vessels codes. The first one, design-by-formula or design-by-rule, defines relations for standard geometries: when it is used with the design stress, it leads to the minimum thickness of the vessel or component. For design-by-analysis – which is related to the topic of this paper – a structure is checked through a global mechanical analysis, in order to avoid the collapse of a pressure vessel. Usually performed by Finite Elements Method, various methods and criteria have been proposed. Some of them, chosen for their relevance, are presented below.

2. Design methodologies

Design methodologies introduced in this paper correspond to a non exhaustive set of techniques. They are either standardized, or are applied according to publications. In this paper, all analyses are performed with the commercial finite elements software Abaqus. It proposes procedures which are used when they are suitable with the described methodologies. When it is not the case, they are implemented via user subroutines. The objective is the comparison of their performance in limit design against gross plastic deformation.

2.1. Elastic stress classification (ESC)

Nowadays, this method is proposed in most codes, and has been used in the Boiler & Pressure Vessels Code (ASME) since 1964. This consists in checking the strength of a structure through the analysis of elastic calculations. This method requires an interpretation of stress levels in accordance with the applied loading [3].

The first step of analysis is the definition of supporting line segments, as shown on Fig. 1. This usually corresponds to the shortest segment between the inner and outer surface of a wall. There exist more specific definitions in case of shape discontinuities. After this selection, a coordinate system is associated to the segment. Its origin is at mid-length of this segment, and the direction $\overrightarrow{x_3}$ coincides with its direction.

The stress field can be separated into a linear stress and a nonlinear stress as follows:

$$(\sigma_{ij}) = (\sigma_{ij})_{linear} + (\sigma_{ij})_{nonlinear} \tag{1}$$

$$(\sigma_{ij})_{linear} = (\sigma_{ij})_m + (\sigma_{ij})_b \tag{2}$$

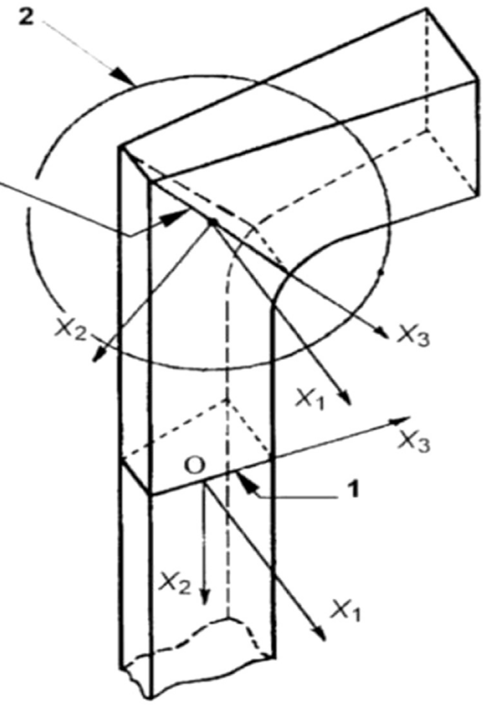

Fig. 1. Supporting line segments definition [4].

For this unique decomposition:

◆ $(\sigma_{ij})_m$ represents an average component, known as membrane stress, and is defined – with t the length of segment – as:

$$(\sigma_{ij})_m = \frac{1}{t}\int_{\frac{-t}{2}}^{\frac{+t}{2}} \sigma_{ij}\cdot dx_3 \tag{3}$$

◆ $(\sigma_{ij})_b$ represents a linear bending component, whose bending moment is equal to the bending moment generated by the real stress field, and is defined as:

$$(\sigma_{ij})_b = \frac{12x_3}{t^3}\int_{\frac{-t}{2}}^{\frac{+t}{2}} \sigma_{ij}\cdot x_3\cdot dx_3 \tag{4}$$

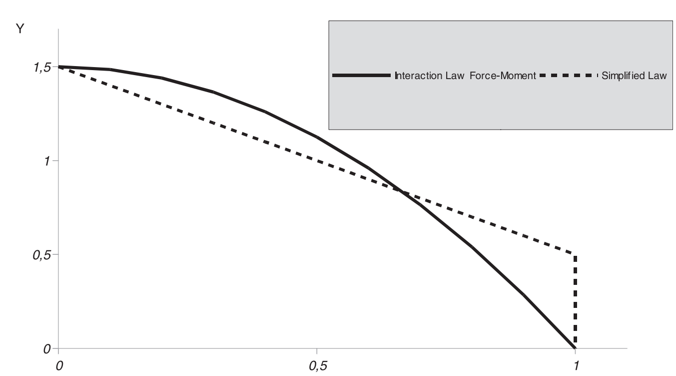

Fig. 2. Definition of the simplified force–moment interaction law [5].