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Review

Plastic load evaluation for a fixed tube sheet heat exchanger subject to proportional loading

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ABSTRACT

The plastic load of pressurised components can be calculated based on both the twice elastic slope and tangent methods. Both methods are problematic since they rely on parameters that are localised and therefore have a strong dependency on the gradient of the stress–strain diagram in the plastic region. The criterion of curvature of plastic work is a suitable replacement for the above techniques. This method calculates total plastic work done on the structure and relates its change to the curvature of the load-plastic work plot. In this work the plastic load has been calculated for a fixed tube sheet exchanger according to curvature criteria using various hardening scenarios. Plastic loads calculated by other methods also have been reported. It has been indicated that tube sheet thickness calculated according to the classical ASME procedure can be significantly reduced when based on the curvature criteria.

1. Introduction

Heat exchanger tube sheets are a significant expense in power and process plant, where large numbers of heat exchangers may be used. The cost of a tube sheet is dependent on the basic thickness required to satisfy safety and functional considerations, not only in terms of material cost but also the added manufacturing costs associated with machining, drilling, welding and NDT. These costs rise greatly as tube sheet thickness increases and it is financially advantageous to minimise the required tube sheet thickness at the design stage.

Conventional tube sheet design is based on modified elastic plate bending theory, in which the perforated tube sheet is treated as a thin homogeneous plate with modified material properties used to simulate the structural effect of the perforations. In pressure vessel Design by Formula procedures, for example ASME VIII Div 1 and Div 2 [1,2], design factors are applied to the solid plate model to account for exchanger type, tube pitch and other geometrical information. The conventional approach is safe and functionally effective but may lead to over-conservative designs in which the plate thickness is greater than that required to safely contain the pressurised fluids in the heat exchanger. This conservatism can be reduced by basing the design on a more detailed stress analysis of the component through application of Code Design by Analysis (DBA) procedures. Codes such as ASME III [3], ASME VIII Div 2 and EN13445 [4] provide methodologies for design based on both elastic and inelastic analysis.

Fixed tube sheet exchangers are subject to a steady-state steady-flow loading during their normal operation and criteria of scheduled start-up to full shut-down, they also are also subject to an emergency shut-down mode. This work is based on the steady-state steady-flow mode and possible fluctuations in operating pressure and operating temperature from steady-state operation are not considered in this work, such a notion is treated in a separate paper dealing with fatigue characteristics of the tube sheet which encompasses the effect of above variations.

It should be further noted that tube sheet and reactors are protected against excess fluctuations and large variations in pressure and temperature from normal operating mode, fluctuations in pressure or temperature occurs not from design conditions but from operating parameters. Tube sheet and reactors are protected by continuous monitoring of the flow parameters both on the shell and on the tube side, shut-down logic will be activated if pre-set parameters are exceed (data sheet in Ref. [5]). This means the tube sheet will never experience non proportional loading, i.e., a rise in one parameter, for example pressure, in expense of the drop in the other one, for example temperature loads, beyond its protected range.

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The elastic design procedures use a stress categorisation methodology to guard against failure due to gross plastic deformation and progressive plastic deformation or ratcheting. In practice, 3D Finite Element Analysis is employed to calculate the elastic stress field, with a stress linearisation procedure employed to evaluate membrane and bending stresses for design assessment. This approach can yield a less conservative design than design by rule but does not lead to the most effective use of material possible. ASME VIII Div 2 A5.2.1.4 states "The structural evaluation procedures based on elastic stress analysis … provide an approximation of the protection against plastic collapse. A more accurate estimate of the protection against plastic collapse of a component can be obtained using elastic–plastic stress analysis to develop limit and plastic collapse loads." The EN13445 *direct route* and ASME inelastic design rules provide procedures for design based on inelastic analysis.

EN13445 restricts the material model to be used to elastic-perfectly plastic. When applied in a small deformation analysis, the calculated plastic collapse load is the limit load of the structure. In a structure exhibiting geometric weakening, EN13445 specifies use of large deformation theory and the evaluated collapse load is treated as a lower bound on the limit load for design purposes. Taking a C2-Hydrogenation reactor as an example on a specific petrochemical plant, Behseta and Schindler [5] showed that the direct route led to a thinner tube sheet design than that required by design by rule procedures (ASME VIII Division 1 and EN 13445-3 Clause 13 and Annex J).

ASME III and ASME VIII Div 2 also provide procedures for design based on limit analysis; that is, an elastic-perfectly plastic model and small deformation theory. In addition, these Codes also provide *plastic analysis* procedures for design based on an analysis incorporating material strain hardening and/or large deformation theory.

The potential advantage of design based on plastic analysis is that including material strain hardening may result in calculation of a *plastic load* higher than the limit load of the structure. However, in practice the evaluated plastic load is dependent on the criterion of plastic collapse used in the design assessment. The object of this paper is to investigate the effect of different strain hardening models on the evaluated plastic load and hence design pressure of the reactor tube sheet investigated in Ref. [5].

2. Plastic design procedure

The material model specified by the designer for ASME III plastic analysis may vary in complexity from simple bilinear hardening models to more complex curves defining the actual stress–strain curve. Small deformation theory or large deformation theory may be used, at the discretion of the designer. The ASME III *plastic collapse load* is determined by applying the *twice elastic slope criterion*, a graphical technique for establishing the plastic load from a load–deformation relationship obtained by plastic analysis. The load is plotted as the ordinate and the deformation parameter – deflection or strain – as the abscissa, as illustrated in Fig. 1. The load–deformation curve is initially linear but becomes non-linear when the limit of proportionality is reached. The plastic collapse load is defined by plotting a straight *collapse limit line* from the origin with twice the **slope** of the initial elastic response: that is $\tan\phi = 2\tan\theta$ in Fig. 1. The twice elastic slope load $\mathbf{P}_{\phi}$, corresponding to the intersection point of the load–deformation curve and the collapse limit line, is taken as the plastic collapse load in DBA (subject to a maximum strain and triaxiality check).

The twice elastic slope criterion load and deformation parameters are required to characterise the plastic behaviour of the vessel, especially the formation of collapse mechanisms. The choice of type and location of the parameter is at the discretion of the designer.

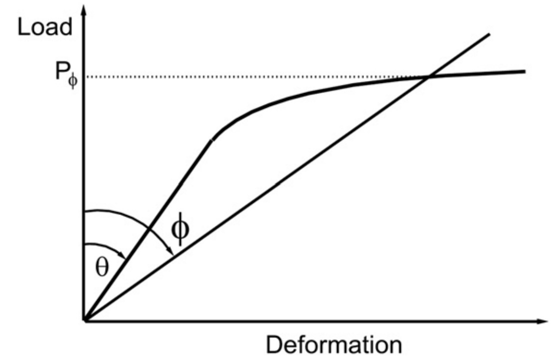

Fig. 1. Twice elastic slope criterion.

Prior to 2007, the ASME VIII Div 2 guidelines for plastic analysis were similar to those in ASME III. The 2007 ASME III Div 2 plastic analysis procedures are significantly different to previous versions; most notably, the von Mises yield criterion is specified as the design stress basis (as opposed to the Tresca criterion used in ASME III), large deformation theory must be used and two *Acceptance Criteria* are specified in place of the twice elastic slope criterion. In addition, an optional true stress–strain curve that can be wholly derived from standard ASME material data is specified in Appendix 3.D. When using this model, the hardening behaviour is included up to the true ultimate stress and perfect plasticity behaviour assumed beyond this limit.

The two *Acceptance Criteria* are a *Global* criterion that requires demonstration that the design does not experience overall structural instability (plastic collapse) under the specified design load cases, indicated by *convergence failure* in the analysis, and *Service criteria* that limit the potential for unsatisfactory performance under the allowable loads evaluated according to the global criterion. In addition to designing against global plastic collapse, a local strain limit failure criterion is defined.

Several workers have proposed alternative plastic collapse criteria to those currently used in the ASME procedures. Two which will be considered in this investigation are the tangent intersection (TI) criterion and Plastic Work Curvature (PWC) criterion. The TI criterion is an alternative graphical construction method applied to the load–deformation curve used in the TES criterion as shown in Fig. 2 [11].

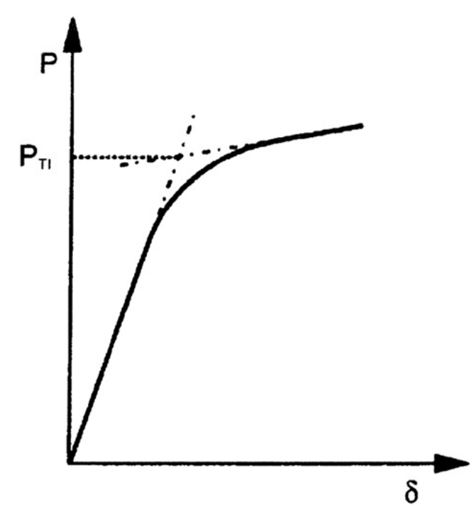

Fig. 2. Tangent intersection criterion.