

A review of design methods given in present standards and codes and design proposals for nozzles and openings in pressure vessels

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Contents

	Page
Foreword	ii
1 Introduction	1
2 Design basis	1
3 Pulsating pressure and external loads	5
4 Limitations and applicability	5
5 Design stresses and criteria	6
6 Planned future work	6
7 Discussion	7
8 Conclusions and recommendations	9
Appendix A Bibliography	15
Table 1 — Rules in Standards and Codes on effective replacement material	11
Table 2 — Vital statistics in Standards and Codes	12

Foreword

This is the second memorandum in the series being prepared by Committee E/-/3 and reviews the rules given in British Standards and other Codes concerning the amount and disposition of “compensation” around nozzles and openings in pressure vessels. It comments on the limits of application of the various rules and points to areas where further research is required.

This memorandum has been prepared by Mr. H. Porter and has been scrutinized and approved by the various committees responsible for particular British Standards for pressure vessels.

Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, pages 1 to 19 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

1 Introduction

Each British Standard or foreign Code concerned with the design of pressure parts contains a section describing the amount and disposition of “compensation” necessary for pressure vessel openings. The bases of the different rules in Standards and Codes vary from simple pressure strength considerations to rules which apply the results of complex analytical stress solutions albeit by the use of simply applied design curves. Yet others are based upon empirical formulae derived from experimental pressure vessel yielding or bursting tests. The amount and disposition of compensating material required varies considerably between Standards and Codes of different design basis and also in some cases between those of similar derivation.

Earlier Standards and Codes are primarily concerned with satisfying static pressure loading and it is specified only that the effects of externally applied loads “be considered”. More recent Standards and Codes, however, include explicit rules for the evaluation of the effects of external loads and for the evaluation of fatigue strength. In some cases it is necessary to refer to the literature for information on some aspects of design in order to satisfy the requirements of the Standard or Code.

More recently, design method proposals are being made which are based upon the results of extensive analyses by computer with comprehensive experimental verification.

The following sections describe briefly the basis and applicability of each pressure vessel Standard and Code. Practical limitations and detail differences between the Standards and Codes are discussed and summarized in Table 2.

References (indicated by numbers in parentheses) are made to a selected bibliography contained in Appendix A. A discussion compares the limitations of the various Standards and Codes and outlines the major conclusions to be drawn from the comprehensive subject literature.

A final section indicates the direction in which current developments in nozzle design methods are likely to lead and makes specific recommendations as to how these could be employed in conjunction with further tests where necessary to improve present day Standards and Codes. Consideration is at present being given as to how to tackle the work which has to be done before the improvements indicated can be effected in British Standards. In the meantime the paper and its recommendations are being openly circulated in the belief that the information contained will be generally useful.

2 Design basis

The bases of the current design Standards and Codes as regards compensation for openings may be divided into the following groups:

- 1) Equal area methods.
- 2) Experimental yield or bursting methods.
- 3) Elastic stress analysis.

Recent design method proposals are based upon

- 4) Limit analysis methods.
- 5) Experimental stress methods.

2.1 Equal area methods. The British Standards BS 1500¹⁾, BS 1113²⁾, ASME pressure vessel Codes and draft ISO proposals for pressure vessels and ISO/R 831³⁾ for boilers are based generally upon equal area methods. The principle of the method is to provide material local to a vessel opening equal in cross-sectional area to that which would be removed by the hole in a shell of the required unpierced thickness. This is an attempt to restore the general yield strength of the vessel. For the replacement material to be effective it must be placed in regions close to the edge of the hole. Early studies on biaxially loaded flat plates with pad reinforced holes (1) demonstrated that the distribution of compensating material around the hole had a substantial effect upon the stress concentration factor.

When an over-thick nozzle is welded into the hole, the Standards and Codes allow the excess material over some “effective” length of the branch to be taken as compensation. Excess material thickness of the shell for some distance from the hole may also be considered as compensation.

¹⁾ BS 1500, “Fusion welded pressure vessels for general purposes”, Part 1, “Carbon and low alloy steels”.

²⁾ BS 1113, “Water-tube steam generating plant (including superheaters, reheaters and steel tube economisers)”.

³⁾ ISO/R 831, “Rules for construction of stationary boilers”.

The major difference in “equal area” methods is in the nozzle and the shell lengths over which compensating material may be considered to be effective. Also, in recognition of the greater efficiency of compensation nearer the hole, the more recent ASME Section III Code requires two-thirds of the replacement material to be within a prescribed shorter distance. Draft proposals for the ISO pressure vessel Code apply a similar rule for the larger openings in the thin shells. These differences in Code rules are summarized in Table 1.

For the particular case of a hole without nozzle reinforcement, in a thickened or unthickened shell, some “equal area” Standards and Codes use an alternative approach. ASME Section I⁴⁾ and ISO/R 831⁵⁾ provide curves which give allowable hole sizes plotted for the parameters (DT) and (T^1/T) up to an arbitrary maximum of 8 in diameter. BS 1500, ASME Sections III⁴⁾ and VIII⁴⁾ more simply allow an unreinforced hole up to 3 in diameter, all other sizes requiring equal area compensation.

Standards and Codes based on the equal area design method do not generally discriminate between nozzles in spheres or in cylinders, singly or grouped. For multiple openings and irregular constructions most of the other types of design Standards and Codes revert to this method.

The main objections to the method are that it does not provide a uniform factor of safety against plastic collapse over the full range of vessel/branch geometries and that stress concentrations may be high in some configurations. Consequently the amount of compensating material may be excessively large in some cases and some arrangements may be unduly inefficient as regards fatigue strength.

2.2 Experimental yield or bursting methods.

BS 806⁶⁾ is concerned with pipework where vessel openings will be generally of one type. Branch/vessel ratios may be up to unity and equal area compensation methods inapplicable or inconvenient. In the course of work on alternative forms of reinforcement (2) experimental results were obtained for the yield and bursting strengths of various branch/pipe configurations. From these results it was concluded that the “pressure strength ratio” of various size-ratio branch connections could be represented by a simple equation. For branches at 90°, with diameters equal to or less than half the main size it was also concluded that there was no reduction in pressure strength. BS 806 applies these results by means of a factor in the formula for thicknesses required for branched pipes at a given design pressure. Adjustment to the thickness is provided for branches inclined other than 90° to the main and for the effects of mutually interfering connections.

The ISO/R 831⁵⁾ incorporates the methods of BS 806⁶⁾ for the design of pipework branches.

Somewhat similar methods form the basis of the German AD Merkblatt B9 pressure vessel specification. A series of pressure tests was made on cylindrical pressure vessels having openings and nozzles of various dimensions. Pressures required to produce a 0.2 % strain at the nozzle/shell junctions were used to derive “weakening” factors which could be used in the basic shell thickness formula. These factors are displayed in the specification by curves plotted for nozzle thickening ratios and vessel geometry. Rules are given for minimum nozzle and pad length. For nozzles which protrude into the shell, an arbitrary reduction of 20 % is allowed on the indicated nozzle thickness. For multiple openings the specification reverts to equal area methods.

⁴⁾ ASME, “Boiler and pressure vessel code”, Section I, “Power boilers”, Section III, “Nuclear vessels”, Section VIII, “Unfired pressure vessels”.

⁵⁾ ISO/R 831, “Rules for construction of stationary boilers”.

⁶⁾ BS 806, “Ferrous pipes and piping installations for and in connection with land boilers”.

2.3 Elastic stress analysis methods. The compensation design methods of BS 3915⁷⁾ for isolated openings are based upon an elastic stress analysis made for a “thin” nozzle connected radially into a spherical vessel (5). From computed results over the range of practical nozzle/vessel geometries curves are provided which give the shell and/or branch thickening which is necessary to reduce the maximum elastic stress concentration factor to a value of 2.25. When used with vessels designed for the nominal Code stress of 1/1.5 times proof stress this stress concentration factor (SCF) implies, of course, that the computed peak stresses are above yield and fictitious. The computed above yield elastic stresses may, however, be considered to be a measure of the amount of plastic strain. For uniaxial stresses in a perfect elastic-plastic material it may readily be shown (4) that if the peak calculated elastic stress is limited to twice yield, residual stresses after the first pressurization will limit subsequent behaviour to the true elastic range. More rigorous treatment (6) (7) has shown that, over the range of practical geometries, nozzles designed to BS 3915 for a SCF of 2.25 will “shake-down” to elastic behaviour with a consequent high strength against low cycle fatigue. It has also been shown (8) that with branches so designed general plastic collapse will not occur at the specified test pressure of 1½ times design pressure.

From the available experimental evidence (43) the present rules assume that the cylinder/sphere analysis provides a reasonable estimate of shell stress concentration in nozzle to cylinder connections and the design curves are intended to be used similarly for each case. (More recent experimental work is beginning to demonstrate differences in cylindrical shell behaviour — see Discussion.) The same analysis is assumed to provide an estimate of maximum stress concentration factor (SCF) for oblique nozzles up to 50° of obliquity although in such cases the SCFs predicted may not be strictly accurate. This assumption is probably adequate in predicting the pressure to yielding.

The curves presented in BS 3915⁷⁾ are extended to the case where there is no nozzle thickness and they may be used therefore to determine the maximum size of unreinforced hole which may be permitted in a thickened or unthickened shell. By specifying a minimum distance from the edge of the hole for the thickening to be effective, the curves may be used to design openings with pad reinforcement. Logical but somewhat arbitrary rules are given for “compressing” the indicated amount of reinforcement into a more compact rim around the hole to suit some practical applications.

There are considerable differences between the amounts of compensation required by BS 3915 and that indicated by equal area considerations. Generally the nozzles complying with the requirements of BS 3915 carry less compensation for smaller branch/shell diameter ratios in thick shells and considerably more (up to twice) the amount for larger openings in thin shells.

Being based upon a “thin” shell analysis the effects of local geometry such as fillet welds are not included and these may require separate consideration in applications where pressure cycling is involved (51).

BS 3915 includes design curves for both flush and protruding nozzles. The method of BS 3915 is now used in BS 1515-1⁸⁾ and BS 1515-2 with design curves plotted in terms of the basic geometry parameter $(d/\sqrt{DT})$. This allows branch and shell thickness to be determined directly without a series of trial readings as is needed using BS 3915.

2.4 Limit analysis methods. Much experimental work has been carried out recently to determine the plastic collapse strengths of both spheres and cylinders with welded-in nozzles (9) (10) (11) and there has been much effort spent in formulating a more rigorous “limit analysis” for the prediction of safe values of internal pressure (14) (15).

The results of one such analysis (13) has been used in work for the American Welding Society Pressure Vessel Research Committee (16) (17) (18) on the formulation of design code proposals for nozzles in spherical shells. From the results of a lower bound limit analysis, these proposals give design curves which show the thickening required on shell or nozzle to produce a design which has a safety factor of 1.5 against plastic collapse. For the practical case where both shell and nozzle thickening may be applied, an approximate equation is given which allows simple adjustment of the indicated shell and nozzle thicknesses.

⁷⁾ BS 3915, “Carbon and low alloy steel pressure vessels for primary circuits of nuclear reactors”.

⁸⁾ BS 1515, “Fusion welded pressure vessels for use in the chemical, petroleum and allied industries”, Part 1, “Carbon and ferritic alloy steels”, Part 2, “Austenitic stainless steel”.

The factor of 1.5 is chosen as being in agreement with the basic design criteria of the ASME Section III nuclear vessel Code and to meet the Code general requirement on shakedown behaviour the proposed nozzle designs are also analysed on an elastic basis (12). Over the range of practical geometries it is demonstrated that elastic SCFs will be less than three times the normal Code design stress (i.e. twice yield).

The method is extended to the case of a nozzle reinforced by large fillets or compact reinforcement local to the nozzle/shell junction. Simple formulae are given for the area and for the limits within which such compensation must lie.

For shell or nozzle thickened designs the proposals give generally somewhat more conservative amounts of reinforcements than designs to BS 3915⁹⁾. The relationship to equal area amounts is also similar to that of BS 3915. The areas of required "compact" reinforcement are substantially less than those required by equal area methods for the smaller openings. For multiple interfering openings the proposals revert to equal area methods.

Nozzle in cylinder design is excluded from the proposals. Recent experimental work (10) has indicated that due to geometry changes no pattern of plasticity occurs which can be associated with a true limit pressure. Analytical work is being carried out (19) to develop a lower bound analysis for openings in cylinders.

2.5 Experimental stress methods. Considerable effort is being made to develop an elastic analysis for the non-axisymmetric case of a cylinder to cylinder connection (20). A large number of experimental stress results on nozzles in cylindrical vessels is, however, available at the present time. A recent Central Electricity Generating Board (C.E.G.B.) design proposal for such nozzles is that a correlation of experimental results for maximum SCF with vessel geometry (21) be used as an interim measure until the results of theoretical analyses become available. An empirical curve is given for the maximum SCF which encompasses within a scatter band of $\pm 10\%$ the results of 50 tests.

A design curve for nozzle thickness is proposed which uses these results to obtain a maximum SCF of 2.5 to ensure shakedown in arrangements of small branch/vessel diameter ratio.

For larger openings it is appreciated that side-wall stresses may become governing and the proposals suggest limitations on the amount of branch thickening to be allowed. Recommendations on combined shell and branch thickening, depending upon opening size, are made. The proposals suggest supporting experimental evidence that nozzles so designed will not suffer gross distortion under test pressure and will have adequate fatigue life.

2.6 Other proposed design methods. Over the past years various approximate methods have been suggested for the design of nozzles subject to pressure loading and although not incorporated in any Code some have been used in practical design work.

In one piping design manual (22) a "pressure area" method is described for determining the thickness of tees and other fittings. Average stresses in the region of the junction are found by dividing the pressure area by the cross-sectional area of metal contained within assumed effective main and branch lengths. In this case the effective lengths are taken to be approximately equal to the inside radius of the main.

Using the elastic decay lengths $\sqrt{dt}$ and $\sqrt{DT}$ as measures of the effective lengths the method was later applied to nozzles in cylindrical vessels (23). When adjusted to predict 0.2 % strain values the method was found to give quite good agreement with the experimental curves derived from the AD Merkblatt B9 specification. More recently it has been suggested that a value of 0.8 times the decay length would be more appropriate (24). Some other workers have proposed using the method with somewhat more refined methods of determining the effective lengths (25).

An approximate calculation for the elastic SCF of a cylinder/cylinder connection was at one time proposed which used a two part solution (26). The SCF for a pad or rim reinforced hole in a biaxially loaded flat plate was added to the SCF due to the branch end load calculated by using an approximate cylinder/cylinder analysis. A comparison was made between results by the method modified to apply to nozzles in spheres with those obtained by a more exact elastic analysis (3). This was found to give a reasonable amount of agreement.

⁹⁾ BS 3915, "Carbon and low alloy steel pressure vessels for primary circuits of nuclear reactors".