A Systems Approach to the Avoidance of Brittle Fracture in Pressure Vessels

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1. Introduction

Under the assumption that the components have been dimensioned and fabricated so that no yielding occurs in the overall cross section under loading in the proximity of the biggest possible defect located anywhere, questions relating to the fracture safety under static loading will be examined.

Any stress peaks exceeding the locally applicable yield strength are reduced by plastic deformation as long as adequate ductility is assured. If on the other hand, only negligible permanent deformation occurs prior to rupture, under tensile stressing for example, the following brittle fracture criterion is valid:

$$\sigma_R \leqslant \sigma_{max} \qquad \text{resp.} \qquad K_{Ic} \leqslant K_I$$

σ_R : true tensile strength; K_{Ic}: fracture toughness (opening)
σ_{max} : maximum tensile stress occuring locally; K_I: stress intensity, perpendicular to the plane of the defect.

2. Dimensioning - adequate ductility

It is necessary to assume an homogeneous isotropic medium of constant material characteristics for the conventional application of stress analysis principles. Experience shows this to be a reasonable assumption in those cases of sufficient ductility. There are numerous regulations for dimensioning vessels, some of them standardized - such as the German AD directives (Arbeitsgemeinschaft Druckbehälter), the French SNCT (Syndicat National de la Chaudronnerie, de la Tôlerie et de la Tuyauterie Industrielle)and the ASME code(American Society of Mechanical Engineers). They give simplified dimensioning rules, but no determination of the stress pattern is provided for; local stress peaks are accepted.

The procedure is shown in Fig.1. With weldable fully killed ferritic structural steels of any thickness, adequate ductility is generally assumed in the received condition above 100 °C - even under multiaxial stress and high deformation rate.

With suitable choice of welding materials and processes this also applies to the weld metal and the heat affected zone.

3. Indeterminate fracture behaviour

Dimensioning is performed first in the usual manner. If adequate ductility does not appear to be assured, however, brittle fracture tests are made in order to judge the fracture behaviour. With the procedure suggested in Fig.2(1) the brittle fracture tests arranged according to their information value are inserted in stages. Upon reaching the requisite criteria, dimensioning in the usual fashion is enough. In this way the problem can be related to the particular conventional regulations. If on the other hand, satisfactory ductility of the parent metal, weld metal and heat-affected zone is not verified in the stages of the statistically supported, limit value and adapted tests, then a rather brittle behaviour is to be expected. In the following, the main principles of this systems approach will be outlined.

3.1 The major feature of "Statistical Procedures" is Notched Bar Impact Testing. Welded fabrications may be judged as to their resistance to brittle fracture by ensuring the following conditions:

a) Testing with Charpy-V or with other specimens, whose constraint is equal to or higher than that of the Charpy-V specimen.

b) Impact velocity ≥ 5 m/sec.

c) A steel which could be evaluated by these specimens would be one which had undergone no important manufacturing changes during a prolonged period of production. The final properties to be expected will be well known from data collected over the years.

d) The results of such testing would only be applied to fully-documented constructions where service conditions were thoroughly understood from data compiled over many years.

Note: The term "service conditions" is taken to include the initial proving test, since this often tends to be more stringent than the subsequent service loading.

If the above conditions cannot be fulfilled or defect sizes have to be treated, then such testing can only be used as a

measure of quality control, if possible coupled with a superior and correlated test procedure, e.g. the Wells Wide Plate Test in conjunction with Charpy-V testing(2). Also in the event of the values obtained being insufficient, then the next procedure should be adopted.

3.2 In "Limiting Value Procedures" we include such tests as Pellini Drop Weight, Fatigued Charpy, and for common structural steel the Schnadt Pressed Notch Test of root radius $r \leq 0.01$ mm. The conditions during testing should be far more stringent than those expected in service e.g. high notch acuity and high deformation rate. These "limit values" may be used to assess brittle fracture safety provided the following conditions are met:

a) The test loading system is really more stringent than expected in service.

b) Wall thickness criteria are taken into account, e.g. Pellini Test; Battelle Test.

c) Specimen manufacturing procedure to have no important influence on the test results, e.g. brittle weldments on quenched and tempered base metal.

d) Any extrapolation of data from NDT temperature to service temperature must be proved reliable and show a sufficient increase in ductility with increasing temperature.

If such a system is inapplicable, if more accurate defect evaluation is needed or the set standards are not met, then the next procedure can be applied which attempts to simulate actual service conditions wherever possible.

3.3 "Adapted Procedures" are concerned with the testing of specimens machined near to wall thickness. These will be tested either statically or dynamically dependant upon service conditions, with due regard to other criteria such as strain rate etc. The following information should be available:

a) For welded constructions the test specimen should exhibit a fatigued notch unless the equivalence of other notch geometry has been proven.

b) Comparable loading rate and testing temperature.

c) The safety margin to be applied to the results of such tests.

d) If defect size evaluations are envisaged relations between the slit or notch geometry with actual defects have to be established.

The final alternative methods of assessment concern the real quantitative evaluation of fracture resistance and the corresponding defect size which can be tolerated in the construction.

3.4 Quantitative Procedures: Studies of the stress field around a defect allow the Fracture Toughness and/or Crack Opening Displacement theories to be applied to the assessment of resistance to sudden and catastrophic failure. The following conditions must be fulfilled to apply such methods:

a) The load stress distribution in the vessel must be known and any residual stress estimated.
b) The position, geometry and distribution of any defects above certain limits should be established.
c) The characteristic Fracture Toughness or C.O.D. at the lowest service temperature should be established for the least favourable microstructure in the weakest direction, or for some direction of special interest.
d) Static or dynamic tests should be performed dependant upon service conditions.
e) If the test fracture process is wholly elastic, relatively small specimens may be used provided it can be shown that increasing thickness does not dangerously decrease the toughness value.
f) If the fracture process is partly plastic, the effect of specimen thickness should be established.
g) C.O.D. measurements should take account of any non-linearity of opening along the length of slit up to the fatigue crack. A single measurement of displacement on the front face of the specimen may only be used in the case of general yield.
h) The influence of slit length in comparison with the evaluated defect size from C.O.D. measurements should be accounted for (relation defect length-opening displacement).

4. Application

Amongst others, there were vessels built for service at 680

atm g and -30°C. The i.d. was 1.6 m, overall length 40 m; weight 550 metric tons. The construction was multiwall with single wall flanges and bottom ends. An example of multiwall-multiwall circular seam is given in Fig.3.

Literature:

1. T. Varga: Ein Bewertungssystem der Sprödbruchsicherheit. Schweiz. Bauzeitung, to be published.
2. Working Group 15 of ISO/TC 11/SC 2(Chairman W.A.Derungs)

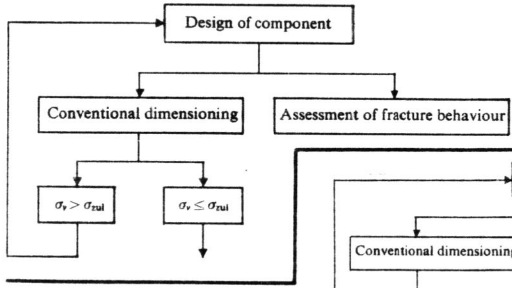

Fig. 1

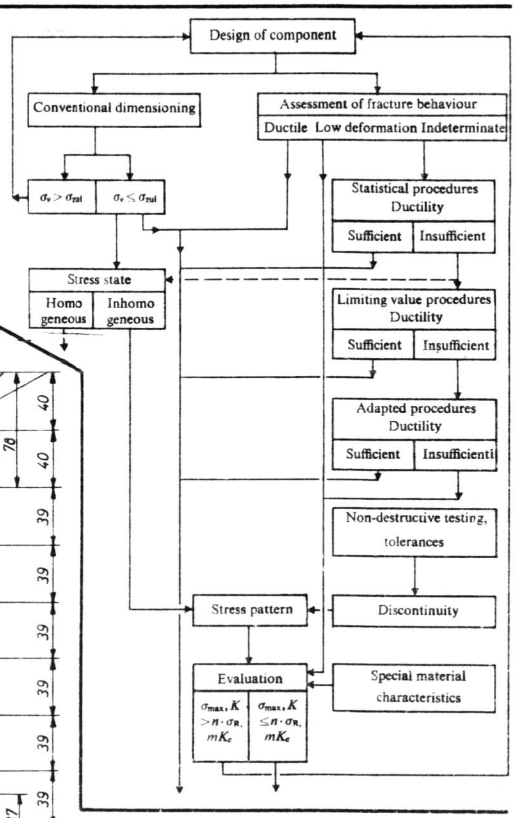

Fig. 2

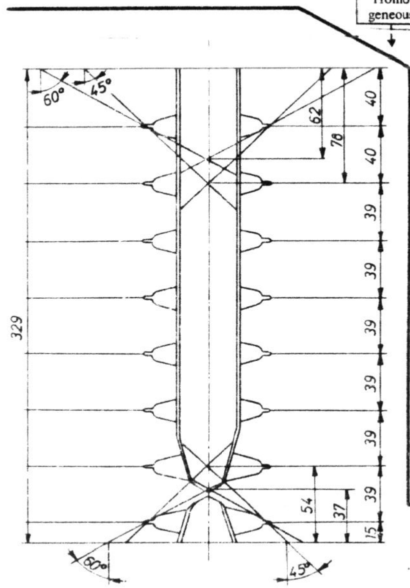

Fig. 3