AN ANALYTICAL AND EXPERIMENTAL STUDY TO ESTABLISH ACRITICAL FLAW SIZES” FOR HIGH PRESSURE SEAMLESS CYLINDERS

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ABSTRACT

The objective of this study is to establish quantitative, critical flaw sizes for high pressure seamless steel cylinders that can be used for the periodic retesting of the cylinders. The “critical flaw sizes “ are defined as the depth and length or area of a flaw that will cause the cylinder to fail at a designated burst pressure. In this study, the performance of seamless steel cylinders was evaluated based on the principles of structural integrity analysis. The “critical flaw sizes” were established using the analytical procedures described in the American Petroleum Institute (API) “Recommended Practice 579, Fitness-for-Service”.

The effect of various types and sizes of flaws on the performance of seamless steel cylinders was evaluated experimentally by conducting hydrostatic burst tests on selected seamless steel cylinders. This was done for several types of flaws at (1) the designated service pressure (MAWP) and (2) the hydrostatic test pressure of the cylinder. The results of these hydrostatic burst tests were then used to verify that the (API) “Recommended Practice 579, Fitness-for-Service@ procedures could be used to reliably establish “critical flaw sizes” for seamless steel cylinders.

After the API 579 analysis procedures were verified by these experiments, the “critical flaw sizes” were determined analytically for a wide range of cylinder sizes by setting the assumed burst pressure of the cylinder to a fixed value and then calculating the depth and area or length of the flaw to cause failure of the cylinder at the designated burst pressure. This establishes a “critical flaw size” curve (depth versus area or length) for each type of flaw in any cylinder.

1 INTRODUCTION

The objective of this study is to establish quantitative, critical flaw sizes for seamless steel cylinders that can be used for the periodic retesting of seamless steel, high pressure cylinders. The Acritical flaw@sizes are based on an evaluation of the structural integrity performance of the cylinders.

Seamless steel cylinders that are used to transport high pressure gases are required to be periodically retested. Until recently, the retesting was done only by hydrostatic pressure testing. Typical flaws that can occur in high-pressure seamless gas cylinders during service are: corrosion pits, line corrosion, gouges, local thin areas of corrosion, and cracks. The sizes of any flaws in the cylinders that would cause the cylinders to be rejected by the hydrostatic test were essentially qualitative and were established from past service experience and were not based on a quantitative assessment of the cylinder performance.

More recently, ultrasonic methods have been developed for the retesting of cylinders that permit the quantitative determination of the sizes of flaws that are detected in the cylinders. However, to use these ultrasonic test methods, it is required that quantitative, critical flaw sizes be established to from the basis for setting acceptance/rejection limits for each type of flaw in the cylinders at the time of retesting.

2 ANALYSIS AND EXPERIMENTAL RESULTS

2.1 TECHNICAL APPROACH

In this study, the “critical flaw sizes” for seamless cylinders, are established by determining the effect of various types and sizes of flaws on the performance (i.e. burst pressure) of the cylinders. The “critical flaw size” is defined as the size (ex. depth and length or area) of a flaw that will cause the cylinders to fail at a designated pressure. The method of analysis used, determines how much the failure pressure of a cylinder containing a flaw is reduced compared to the failure pressure of a similar cylinder that does not contain a flaws. The performance of the cylinder is defined as the ratio of the failure pressure of a cylinders containing a flaw (P_f) to the burst pressure of a similar cylinder that does not contain a flaw (P_b), i.e. the ratio (P_f)/ (P_b). Failure of the cylinder may occur by bursting, by fracture, by leaking or other failure modes.

2.2 ANALYSIS OF FLAW SIZES

To establish "critical flaw sizes", an assessment of typical flaws that occur in seamless cylinders was carried out using the analytical procedures described in the American Petroleum Institute (API) "Recommended Practice 579 Fitness-for-Service" (API 579) [1]. For a cylinder containing a specified flaw (size and shape), this analysis is used to predict the amount the failure pressure of the cylinder will be reduced due to the presence of the flaw.

The API 579 methods of analysis permit three levels of assessment depending on the available data and on the accuracy of the evaluation that is required. The data required to conduct the "Fitness-for-Service" analysis of flaws in cylinders are: (1) the material properties (i.e. yield strength, tensile strength, fracture toughness, etc.), (2) the applied stress due to the pressure in the cylinder, and (3) the size, shape, location of the flaws to be evaluated. The "Fitness-for-Service" assessment procedures require the choice of the "acceptance criteria". The "acceptance criteria" is chosen for each specific case that is analyzed. The "acceptance criteria" may be (1) the "maximum allowable stress" (2) the "remaining strength factor", or (3) the "failure assessment diagram".

The preliminary analysis showed that the failure of the steel cylinders that were tested could be evaluated by the calculating the remaining strength factor (RSF) for the cylinders containing flaws. For these cylinders, the fracture toughness was sufficiently high that failure of the cylinders containing flaws failed by bursting when the stress in the cylinder wall causes failure by plastic collapse as the internal pressure was increased.

For the seamless steel cylinders evaluated here, the "remaining strength factor" (RSF) defined in the API 579 methods of analysis was found to be the suitable failure criteria. The RSF is defined as the ratio of the limit load or plastic collapse load of a cylinder containing a flaw to the limit load or plastic collapse load of a cylinder that does not contain flaw. The RSF may also be defined as the ratio of the failure pressure of a cylinder containing a flaw and the failure pressure of the same cylinder without a flaw, that is: RSF = (P_f)/ (P_b). The RSF is calculated as:

$$RSF = R_t / ((1-(1/M_t)(1-R_t))$$

Where: M_t is the stress magnification factor

R_t is the remaining thickness ratio = t_{mm} /t

2.3 EXPERIMENTAL RESULTS

As part of a program being conducted by the International Standards Organization (ISO), Technical Committee 58 (TC 58) /Subcommittee 4 (SC 4)/ Working Group 1 (WG 1) on "Rejection Criteria for Metal Cylinders", steel cylinders containing machined flaws were tested by monotonic, hydrostatic pressurization until failure occurred by bursting [2]. The cylinders contained machined flaws on the exterior of the cylinder (OD flaws). The cylinders had flaws that simulated notches, round local thin area (LTA), rectangular LTA, and pits (small round flaws). The results of these tests were used to verify that the API 579 methods of analysis can be reliably used to predict the failure pressure of cylinders containing flaws.

2.4 VERIFICATION OF THE FLAW SIZE ANALYSIS

To demonstrate that the API 579 "Fitness-for-service" methods of analysis could be reliably be applied to evaluating flaws in seamless cylinders, a limited number of seamless steel cylinders containing flaws of different types and sizes were tested in another study by hydrostatically testing the cylinders to failure by bursting. To verify that the API 579 methods of analysis reliably predict the performance of cylinders containing flaws, the results of the burst tests described above were compared with the burst pressures predicted by the API 579 analysis results.

For this verification analysis, both local thin area (LTA) types of flaws and notch type flaws were evaluated. A local thin area type of flaw is one in which the length and width of the flaw are approximately equal.

This type of flaw represents a typical area of wall thickness reduction due to corrosion in the cylinder. A notch type of flaw is one which is V shaped and in which the length of the flaw is many times greater than the width of the flaw. This type of flaw represents a crack like flaw in the cylinder. The RSF values of each tested cylinder were calculated using Equation 1. The ratio of the measured failure pressure (P_f) of a cylinder with a flaw to the measured failure pressure of similar cylinders, (P_f/P_b) is defined as the “measured RSF” for the tested cylinders. A comparison of the measured RSF to the calculated RSF is shown in Figure 1.for the cylinders that were tested. Figure 1, shows that the measured and calculated values lie along a 45^o line. This indicates that the API 579 analytical procedures can be used to reliably calculate the RSF and therefore to calculate the failure pressure of cylinders containing flaws. This analysis is suitable for use to evaluate the effects of notches, cracks, local thin area, pits, and general wall thinning due to corrosion. Therefore, the API 579 methods of analysis can be used to calculate the “critical flaw sizes” for these types of flaws in seamless steel cylinders.

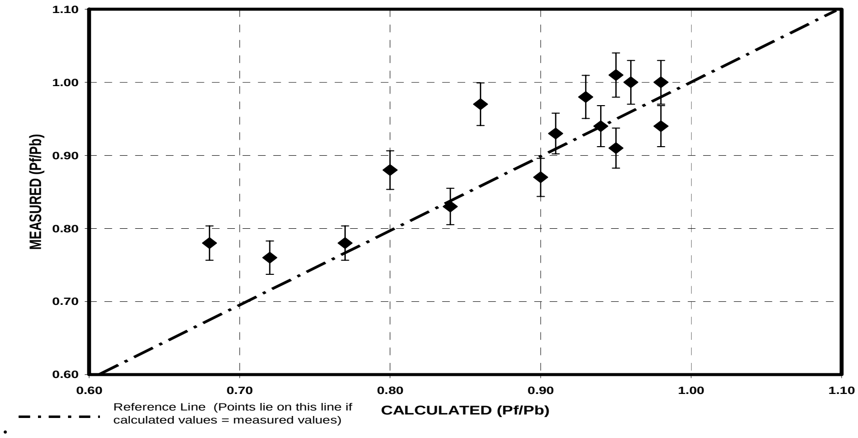

Figure 1:Verification of API 579Analysis for Seamless Steel Cylinders

2.5 CRITICAL FLAW SIZE ANALYSIS AND VERIFICATION

The development of “critical flaw size” requirements that can be used for the retesting of cylinders requires that the length or area and the depth of flaws that will cause the cylinder to fail at a designated pressure must be established. These requirements are most conveniently shown as curves of the flaw depth (defined as a/t ratio) versus the length or diameter of the flaw for designated failure pressure. As shown above, the API 579 method of analysis can reliably be used to calculate the failure pressure of seamless steel cylinders containing various types and sizes of flaws.

However, the API 579 method has not previously been used to develop “critical flaw size” requirements for cylinders. To establish “critical flaw size” requirements for cylinders, the failure (burst) pressure (P_f) of a cylinder containing a flaw is specified. The ratio (P_f/P_b) is then calculated, where P_b is the failure pressure of the same type and size of cylinder that does not contain a flaw. This ratio (P_f/P_b), can now be defined as the “residual strength factor”(RSF) as shown in Equation 1 above. An inverted form of Equation 1 is then used to back calculate the flaw depth and length or area that is expected to cause the cylinder to fail at the designated pressure.

In the present study, the failure pressure (P_f) of the cylinder was specified as (1) the designated service pressure (MAWP) or (2) the hydrostatic test pressure of the cylinder. The “critical flaw size” curve (depth versus area or length) for each type of flaw in any cylinder was then calculated. The “critical flaw size” curves for failure at the designated service pressure of the cylinder shows the size of flaws that would cause the cylinder to fail in service. The “critical flaw size” curves for failure at the hydrostatic test pressure of the cylinder shows the size of flaws that would cause the cylinder to fail during the traditional hydrostatic pressure test. This shows the size of flaws that could be expected to have been left in the cylinder after performing the traditional hydrostatic pressure test. Examples of “critical flaw size” curves calculated in this manner are shown in Figure 2.

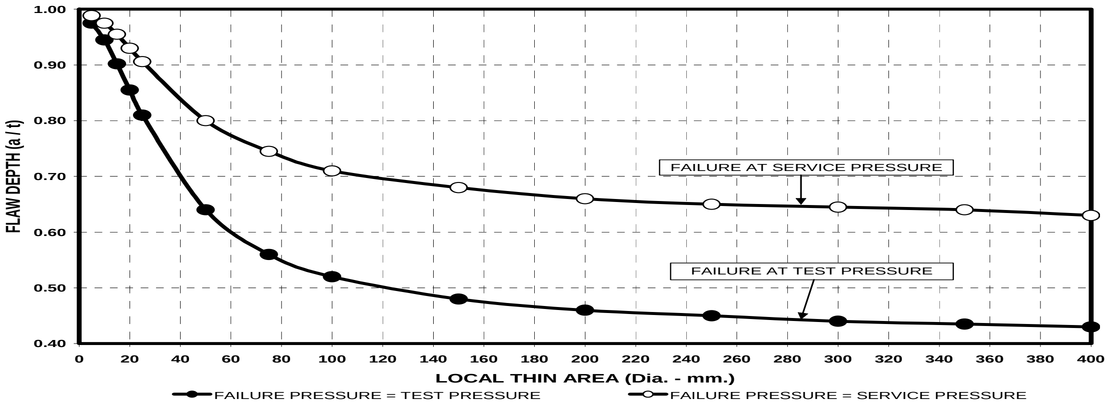

Figure 2: Critical Flaw Sizes for Steel Cylinders

To demonstrate that the API method of analysis reliably predicts the critical flaw sizes for cylinders, a comparison was made between the analytical predictions and experimental test results from the ISO TC 58/SC 3/WG 14 on “Toughness and acceptance levels of steels of strength levels above 1100 N/mm^2 “ [3]. Selected results from the WG14 test program are shown in Figures 3. Figure 3 shows that the measured flaw sizes for the flaws are all equal to or larger than the calculated “critical flaw sizes” for a failure pressure at the service pressure of the cylinders.

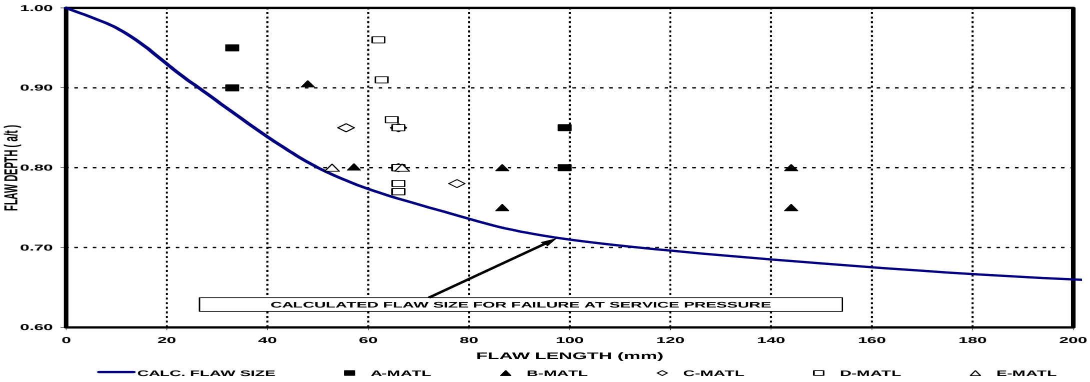

Figure 3: Calculated and Measured Flaw Sizes for Cylinder Failure at Service Pressure

In the WG 14 test program, several hundred monotonic hydrostatic, flawed-cylinder burst tests were conducted. The flaw type in all of these tests was a longitudinal notch type of flaw. The cylinders tested ranged in tensile strength from less than 750 MPA to more than 1250 MPA. The cylinders tested represent the full range of strength levels and sizes of cylinders currently used in the world. From this test data, the results of tests in which the measured failure pressure was near the marked service pressure were selected. The measured flaw sizes from these tests that caused failure at the marked service pressure were compared with the calculated “critical flaw sizes” for failure at the marked service pressure as shown in Figure 3.

In addition, similar results were obtained using test data from the WG 14 test program in which the measured failure pressure was near the cylinder test pressure were selected. These results show that for failure at both the marked service pressure and the test pressure, the measured flaw sizes were larger than the calculated “critical flaw sizes”. Therefore, critical flaw sizes can be reliably calculated using the API 579 assessment procedure and used to establish “critical flaw sizes “ for all steel cylinders currently in use

3 DISCUSSION

3.1 SIGNIFICANCE OF THE ANALYSIS

For steel cylinders at all strength levels, the API 579 methods of analysis have been shown to be reliable for calculating “critical flaw sizes” for failure of the cylinders at all pressures. The predicted failure pressures and the predicted flaw sizes that were obtained by the analysis were in agreement with extensive experimental test results.

For the steel cylinders that were evaluated, it was shown that the failure mode due to the internal pressure in the cylinder was by bursting due to ductile, plastic collapse of the cylinder wall in the region of the flaw. Other failure modes that could result from the pressure in the cylinder, such as fracture, were shown to not be significant for the steel cylinders evaluated in this study. It was found to be sufficient to analyze the flaws in the cylinders using only a two dimensional model. That is, the circumferential dimension of the flaws did not significantly affect the predicted failure pressure of the cylinder.

The flaw size analysis conducted in this study and the experimental verification of the analysis shows that for steel cylinders the “critical flaw sizes” can be reliably determined by the analytical modeling alone. The verification of the analysis is sufficient so that it should not be necessary to conduct additional experimental tests to determine “critical flaw sizes” to be used for setting acceptance/rejection criteria for use at the time of retesting.

3.2 SIGNIFICANCE OF “CRITICAL FLAW SIZE”

The “critical flaw size” evaluation is the starting point to be used for setting acceptance/rejection criteria for use at the time of retesting. The “critical flaw sizes” are the flaw sizes that are expected to actually cause failure at the specified pressure. The “critical flaw sizes” at the service pressure show the flaw size that would be expected to cause a failure of the cylinder while in service. Once this flaw size is established, “allowable flaw sizes” can be established to ensure that no flaw will grow to reach the critical size while the cylinder is in service.

The “critical flaw sizes” at test pressure determine the flaw size that is expected to cause failure of the cylinder during the traditionally used hydrostatic pressure test. The significance of the “critical flaw sizes” at test pressure is that flaws of these sizes could have been left in the cylinder at the end of hydrostatic testing. Because cylinders that have been in service after being retested only by hydrostatic testing have not been found to fail in service in significant numbers, it can be concluded that cylinders that contain flaws that are as large as the “critical flaw sizes” at the test pressure have an adequate safety margin.

4 SUMMARY AND CONCLUSIONS

1. The API 579 Recommended Practice 579 “Fitness-for-Service” methods of analysis have been shown to reliably define the “critical flaw sizes” for flaws in seamless steel cylinders.

2. Extensive hydrostatic, flawed-cylinder burst test data were used to verify the use of the API 579 methods of analysis for defining “critical flaw sizes” in seamless steel cylinders.

5 REFERENCES

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2. ISO/TR 22694 Gas cylinders- Acceptance/Rejection criteria for requalification of monolithic steel and aluminum cylinders, The International Standards Organization, Geneva, Switzerland, (in press).

3. ISO/TR12391-2, Gas cylinders Refillable seamless steel Performance tests Part 2: Fracture performance test Monotonic burst tests@, The International Standards Organization, Geneva, Switzerland, 2002.