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A proposed new pressure vessel design class

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ABSTRACT

Leveraging off riveted pressure vessel design methods, a factor to account for the likelihood of defects in a partial volumetric inspected weld was introduced into the design approach for welded vessels. This approach is universally adopted in all known pressure equipment codes around the world. Of interest is the use of 0.7 and 0.85 weld efficiency factor for a weld having no volumetric inspection and partial volumetric inspection respectively. To the authors' best knowledge, these have gone unchallenged for the past 88 years.

This paper gives the historical background to how these weld efficiencies were developed. The statistical significance of partial volumetric inspection is explored, considering the implications on the safety of the design. The comparative safety of partially volumetrically inspected welds and non-volumetrically inspected welds is challenged. A proposal is made for the introduction of a new design class based on a fabricator nominated weld efficiency and hydrostatic pressure testing to near yield conditions without volumetric inspection. While the paper is not conclusive in its findings, its purpose is to challenge the understanding of weld efficiencies and to encourage new developments.

1. Introduction

It does well to critically appraise the development of pressure vessel design; where it has been and where it is now. Arguably pressure vessel design is mature and with maturity complacency can set in with the feeling that it is all “done and dusted” and as such ongoing development is hindered. It is believed this is the case with the development and use of weld efficiencies in welded pressure vessel design. In this section, the development of the weld efficiency is briefly reviewed. This sets the background for challenging the use of weld efficiency factors and opens the way for future development discussed further in the paper.

1.1. Arc welding

To understand the introduction and development of weld efficiencies in pressure equipment design one must also understand the introduction and acceptance of arc welding as an alternative and eventual replacement of riveted construction. The use of the term arc welding is deliberate as joining of metals by forging had been a practice introduced over 1000 years ago. Modern arc welding was ushered in by the developments in electricity and in particular, arc lights in 1881. From there development was rapid and Davy [1] notes that towards the end of the First World War, there was considerable interest in welded vessels but only for attaching branches. It was not until 1931, that the all-welded steel boiler drum was endorsed and this was constructed in accord with the newly released requirements of the Boiler Code of the American Society of Mechanical Engineers (ASME). Fish [2] reinforces this noting that fusion arc welding had been applied in the United States for the construction of pressure vessels since the 1910's and that “*literally 1000's of pressure vessels* [3]” had been fabricated during the interim period up to the 1930's. Fish goes further to note that the unreliability of welding resulted in numerous failures and obtaining insurance protection was problematic.

1.2. Development of the welded pressure vessel

The introduction of fusion welding in the ASME Boiler Code of 1931 had its inception in the 1920's [3] being spurred along by the rapid use of fusion welding for pressure vessel fabrication and associated failures that ensued as a consequence. It is of particular interest that this would appear to be one of the first times that weld efficiency was defined; being the ratio of calculated membrane

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Nomenclature

C	Coverage for weld inspection (%)
l	Length of weld considered
n	Number of weld defects in a specified length
P_d	Proportion of weld containing defects (%)
R_e	Minimum guaranteed yield strength of material at ambient temperature
R_m	Minimum guaranteed tensile strength of material at ambient temperature
SF	Safety factor against ultimate tensile strength, typically 3.5 for a medium strength design or 2.4 or 2.35 for a high strength design
S_h	Membrane stress induced by hydrostatic test pressure
t	Plate thickness
T_{app}	The upper temperature for which the results of the hydrostatic test can be deemed applicable
x	Weld strength reduction factor = (1-η)
η	Weld efficiency factor
λ	Weld defect severity parameter
ρ	Average density of weld defects (per length)

stress at the actual burst pressure to the ultimate failure stress of the parent metal as measured from tensile testing. An early reference [4] notes that joint efficiency of 80% could be achieved for the combination of relatively thin plate and double-covered which was formed by use of a plate both side of the main shell and double-riveted or two rows of rivet each side of the joint. By 1927, Haven and Swett [5] reports on a complicated quadruple-riveted joint with a joint efficiency of 95% for relatively thin plate. De Jonge [6] undertook the enormous task of compiling all the known work related to riveted joints to that date. The review spanned from 1837 to the time of publishing which was 1947. By that time, welded joints were already prevalent owing to the alluring simplicity in comparison with the complex and labour-intensive riveted joint, as well the recognition that leakage through the riveted joint was limiting the operating pressure (e.g. Ref. [8]).

1.3. *Weld efficiency*

In contrast to the riveted joint, the weld efficiency cannot be calculated, and a controlled range of vessels were fabricated and pressurised to failure. Reference [3] reports variation from as low as 60% through to 112% in the measured weld efficiency for 25 welded vessels selected from a variety of fabrication shops. Double sided welding returned much more consistency with the lowest recorded as 90%.

Additional testing was also carried out on purposely welded vessels to introduce known defects. Welds were described as bad, poor, fair and good. A bad weld was a single sided weld with only 1/3rd penetration while a poor weld was also one sided but with 2/3rd penetration. It is not entirely clear, but it would appear a fair weld was welded both sides, but with incomplete penetration; apparently with a nominal 1/3rd lack of penetration in the centre of the plate. It is difficult to imagine how this was controlled. Nonetheless, results reported are seen in Table 1.

Notwithstanding the results of testing seen in Table 1, the committee of the day [3] decided that the weld efficiency should be set at 80% and that all longitudinal welds would be doubled-sided V prep welds. It is also of interest that the factor of safety at that time, was set to 5 against ultimate failure, making the effective factor of safety which included the weld efficiency as 5/0.8 = 6.25. It is important to note that at this stage, there was no mention of weld inspection other than visually.

Table 1
Results taken from Ref. [3].

Weld quality	Average	Lowest	Greatest
good	102%	87%	115%
fair	85%	76%	96%
poor	51%	32%	65%
bad	43%	19%	61%

There is scant reference to trace how the progress to full radiography of welds occurred. It is likely that concern was raised regarding the variation in results typified by Table 1, which varied from as low as 76%, if it is assumed that “fair” is taken as acceptable. However, by 1930, the modern principles of weld procedure qualification, volumetric inspection and stress relieving had been developed. This then led to the introduction of the ASME Boiler Code of 1931, based on the proving of the rules by destructive testing of a pressure vessel designed and fabricated to the new rules. Undertaken by Combustion Engineering (CE), it marked a significant event which saw CE been recognised with an historical landmark award [7].

Fish also introduces the concept of weld classes; these being the highest, the middle and the lowest. As expected and consistent with modern construction, the highest requires 100% X-ray. Fish only gives the weld efficiency of the middle class as 80% and notes that it is higher for the higher class and lower for the lower class.

1.4. *The modern pressure vessel*

Contributed nearly 80 years ago, Hodge [8] is definitive in his description of what is now considered modern welding and design practice. He notes that “*X-ray was developed to ensure welds were defect free and that post weld heat treatment was introduced to eliminate all fabrication stresses*” [8]. He also introduces weld qualification and the recognition that production weld coupons for higher classes of vessel were required. He notes that tests to destruction were undertaken on quite a number of vessels to establish the ASME Boiler Code principles. Finally, he notes that maximum weld efficiency granted under the ASME Code of the day for a fully X-rayed and heat relieved vessel was 95% which is not surprising given that the highest riveted construction was also 95%. Moreover, acceptable defects in those days are significant and one example is given [8] of a slag inclusion running principally in the plane of the plate, as being acceptable if it was less than 1/3rd of the plate thickness. The acceptable width of this slag inclusion is not noted.

Hodge quotes residual stress measurements using strain gauges and a number of other techniques which regrettably Hodge does not describe which aligns surprisingly well with recent research. Stresses up to and beyond yield were measured. Fabrication is then concluded by undertaking a hydrostatic pressure test of 1.5 or even twice the design working pressure followed by magnetic particle inspection; all surprisingly modern.

At some point in time, the weld efficiency was upgraded from 95% to 100% for full radiography as it is currently [9,10]. More significantly we now have 70% for no inspection and 85% for spot inspection which is typically 10% of the total length of welds. While it may be reasonable to accept the use of weld efficiency of 100% if the weld is fully inspected, the use of 85% and 70% for 10% inspection and no inspection respectively could be questioned. Knowing that the basic premise for weld efficiency is the weakness

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