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**COMPARISON OF RESIDUAL
STRESS PROFILES IN ANNEX K
OF PD6493:1997(DRAFT) AND
SINTAP TASK 4 ANNUAL
REPORT**

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SINTAP Task 4.2

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1. Background

The SINTAP Task 4 Annual Report (Achon, 24 April 1997) and Annex K of the Draft PD6493:1997 (BSI, 3 September 1997) both contain recommended residual stress profiles for a range of common joint geometries. Both sets of profiles have been developed from the Nuclear Electric compendium (Mathieson, 1991), and both have taken account of the ongoing review of the NE compendium by AEA Technology (Sanderson, June 1996). However, there are some differences between the two sets of profiles. The participation of relevant organisations (AEA Technology, NE, IS and TWI) in the SINTAP project provides an opportunity to attempt to resolve these differences and obtain an agreed set of profiles.

This note summarises the differences between the current versions of the two documents.

In addition, I have taken the liberty of expressing my opinion on areas where further work is necessary. These comments are given in italics.

2. Surface residual stress profiles

The Task 4 report gives 'surface profiles', i.e. the variation of residual stresses across the face of the weld, for each joint geometry. Annex K does not give surface profiles.

Longitudinal stresses

The surface longitudinal stress profiles shown in Figs 1(a) to 9(a) of the Task 4 report for nine different joint geometries have various different shapes (parabolic, rectangular, trapezoidal and 'top hat'). The width of the profiles outside the weld is variously related to $\sqrt{(q/v)}$, (q/v) or t , and is zero for repair welds (this is unconservative). I do not think that there is any good reason for the differences between the recommended profiles: they are all idealisations, and could be idealised to the same shape. I would recommend a trapezium of width $(w+2r)$. For ferritic welds in thick plates, $r = \sqrt{(122(q/v)/\sigma_y)}$. The derivation of this formula is given in Equations 1 to 4 of my paper at ICRS5 (1997) – a copy is enclosed. Alternative formulae can be derived for other materials or for thin plates.

The formula for r in Figs 1(a), 3(a) and 5(a) is applicable for 316 stainless steel. It should be $r = \sqrt{(122(q/v)/\sigma_y)}$ for ferritic steels.

Transverse stresses

I do not think that it is necessary to specify the variation of transverse stress outside the weld: longitudinal weld defects are always located in the weld or very close to it, where the transverse stress is at yield. If the profiles are retained, then I think a total width of the tensile zone of $(w + 2t)$ would be adequate for butt, t-butt or repair welds in unrestrained flat plates. The width in cylinders, nozzles and domes should be related to the parameter \sqrt{Rt} .

3. Through-thickness residual stress profiles

Figures K1 to K4 of Annex K were made for an early draft and contain many errors. Most of the profiles shown in Figs K1a and K1b do not correspond to the formulae in the text. A hand-corrected version of Fig K1 is attached. Figs K2 to K4 refer to a non-existent section 3.2.

In the Task 4 report, transverse residual stresses are normalised with respect to the lesser of the weld or parent metal yield strengths, except for (1) defects in repair welds, (2) defects at weld intersections and (3) shallow defects of depth less than one weld run, where they are normalised to the greater of the two yield strengths.

I agree with using the greater yield strength at weld intersections, but I think it is over-conservative for repair welds and for shallow defects.

The section headings and numbering below correspond to those used in the Task 4 Report, with the corresponding section numbers of Annex K of PD6493:1997 in brackets.

3.1 Plate Butt Welds (K.1.1)

Although the normalised profiles in the Task 4 report and Annex K are the same, there are some differences in the definition of the normalisation parameters.

The Task 4 report allows the peak transverse stress to be reduced for thicknesses greater than 75mm.

Annex K states that z is measured from the side welded last, but this is not specified in the Task 4 report.

The formula for reducing the peak transverse stress in the Task 4 report is misquoted from Sanderson(1996). It should be $A = 1 - 0.004(t - 75)$. I am very dubious about reducing the peak transverse stress in thick plates. The formula gives zero peak stress at $t = 325\text{mm}$ (which is clearly wrong and unsafe) and negative peak stresses at greater thickness (which is absurd).

I think it would be worth investigating whether the data on longitudinal stresses in austenitic and ferritic steels could be combined to give a single upper bound line.

3.2 Plate T-Butt Welds (K.1.4)

The Task 4 report recommends bilinear profiles expressed as a function of z/t . These have been fitted to experimental and computed data.

Annex K recommends bilinear profiles expressed as a function of z/z_0 , where z_0 is a function of weld heat input and plate yield strength. The profile is based on a simple theoretical model of heat flow and yielding at a weld on a thick plate, with some experimental validation.

Both sets of profiles show a turning point in the profile at some distance below the plate surface. I maintain that the position of the turning point is a function of welding conditions and material properties, and hence the Task 4 profiles are likely to be inaccurate when these factors are different from those that have been investigated. The Annex K profiles are intended to be an upper bound, and may be over-conservative for thinner plates. Under SINTAP, I will extend the validation of the Annex K profiles, and investigate the potential for making them less conservative by allowing for the flexibility of the base plate.

The parameter z_0 used for T-butt and repair weld profiles is the same as the parameter r used for surface longitudinal profiles (also known as y in PD6493:1991 and as r_p in my paper at ICRS5). For consistency, we should have one symbol: I prefer r_p or r_γ but as these are used for the crack tip plastic zone size, I suggest r_0 .

The Annex K profiles apply to T-butt welds and fillet welds. The sketches of the joint in Fig 2 of the Task 4 report show a T-joint with very small welds which could be a partial penetration T-butt weld or high penetration fillet welds. Do the Task 4 recommendations apply to fillet welds? Do they apply to full penetration T-butt welds?

3.3 Pipe Butt Welds (K.1.2)

The profiles in the Task 4 report and Annex K are the same, except for σ_{outer} for transverse stresses in ferritic steels at low heat inputs, where Annex K uses a function of R/t taken from earlier versions of the NE compendium, while the Task 4 Report uses a function of $q/(vt)$ taken from the latest proposed revisions of the Compendium.

The Task 4 formulation removes a clear error in the older version, which suggested that the transverse stresses would be zero at $R/t = 5$. Annex K should be updated.

I propose to carry out a thorough review of residual stresses at circumferential butt welds in pipes as part of my contribution to SINTAP, and hope to produce a more consistent approach applicable for a wide range of geometries, materials and welding conditions.

3.4 Pipe T-Butt Welds (K.1.4)

The Task 4 profiles are expressed as polynomial functions of z/t . The text states that if the radii of the brace and chord differ by a large amount (say a factor of 5) then the profiles presented for plate T-butt welds should be considered as a good alternative.

Annex K uses the same profiles as for plate T-butt welds.

The comments above for plate T-butt welds also apply here. The Task 4 profiles are entirely tensile. The background data (see Task 4 Ref 7) shows that the stresses always drop to zero or below somewhere within the thickness of the chord. The Annex K profiles are likely to be less conservative,

particularly for thicker chords, and also for thinner chords if they can be modified to allow for the flexibility of the chord wall.

3.5 Pipe Seam Welds (K.1.3)

The Task 4 report recommends that the longitudinal stress are equal to the yield stress and gives a polynomial profile for the transverse stresses.

Annex K uses the same profiles as for plate butt welds.

The restraint conditions at an axial seam weld are similar to those in a typical plate butt weld. The Task 4 profiles are based on measurements in two pipes only. I think it is more appropriate to consider the plate butt and seam weld data as a single dataset.

3.6 Nozzle-Cylinder Welds

This geometry is not considered in Annex K.

The Task 4 profiles vary linearly through the thickness from $0.63\sigma_y$ or $0.75\sigma_y$ at the outside to σ_y at the inside. The text of the Task 4 report recommends that the pipe T-butt profiles might be used as an alternative.

The residual stresses at a nozzle-cylinder weld are very sensitive to whether it is a set-on or set-through nozzle, to the component dimensions (particularly nozzle wall thickness) and to whether the weld is displaced from the corner using a forged nozzle. Fig 6(b) and 6(d) of the Task 4 report suggest a forged set-through nozzle. Task 4 Fig 6(e) suggests a nozzle set-on to a stub on the cylinder. The recommended distribution of transverse stresses is entirely tensile, which would be appropriate for a set-through nozzle, but over-conservative for a set-on nozzle. The fact that the stress is at a maximum at the inside suggests that the weld was completed at the inside surface, but the sketch seems to show a single V weld made from the outside.

I suspect that there may not be enough data in existence to provide reliable profiles for nozzle welds. If this profile is to be included, then details of the geometry and welding conditions on which it is based should be given.

The suggestion in the text of the Task 4 report of using the pipe T-butt profiles instead is worth considering. These would only be relevant to the stresses in the cylinder wall due to a set-on nozzle. The T-butt profiles are likely to be conservative, because they were based on measurements at tubular intersections with no cut-outs: nozzle joints have cut-outs and hence are less highly restrained and are likely to have lower stresses.

3.7 Cylinder-Dome Welds

This geometry is not considered in Annex K.

As for the previous section, the joint geometry is unclear. The profile for transverse stresses may be appropriate for a set-on nozzle, but would be unconservative for a set-through nozzle.

3.8 Weld T-Intersections

This geometry is not considered in Annex K.

3.9 Transition Welds

This geometry is not considered in Annex K. The Task 4 report gives surface profiles only.

3.10 Repair Welds (K.1.5)

The profiles in the Task 4 report and Annex K are the same.

3.11 PWHT

Recommendations for residual stresses after PWHT are given in Section 7.2.1.3 of PD6493:1997(Draft). PD6493 and the Task 4 report both recommend that the longitudinal stresses acting on a transverse flaw after PWHT should be assumed to be 30% of the yield strength of the material that contains the flaw. PD6493 recommends that the transverse stresses acting on a longitudinal flaw should be assumed to be 20% of the lesser of the yield strengths of the weld and parent metal: the Task 4 report recommends 15% of the lesser yield strength.

PD6493:1991 recommended that the transverse stresses should be assumed to be equal to 15% of the weld metal yield strength. This was changed to 20% of the lesser yield strength in PD6493:1997 to be more consistent with the treatment of as-welded stresses. I think it would be logical to make the Task 4 recommendation the same as the PD6493:1997 recommendation.

It should be stated that the recommendations for residual stresses after PWHT do not apply to transition welds, where additional stresses are generated during cooling after PWHT due to mismatch in coefficients of thermal expansion.

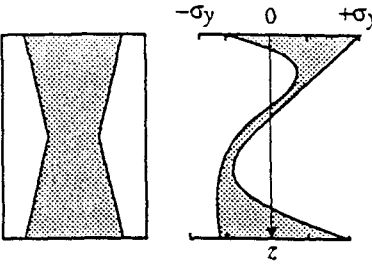
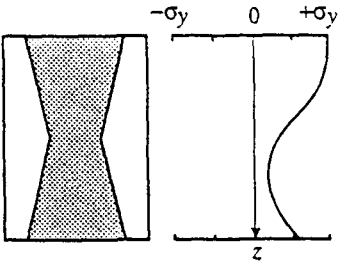
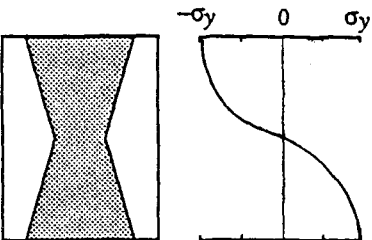
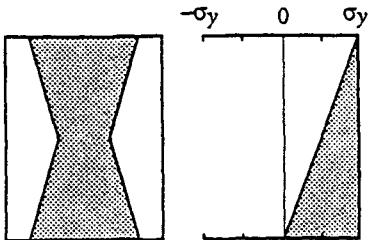
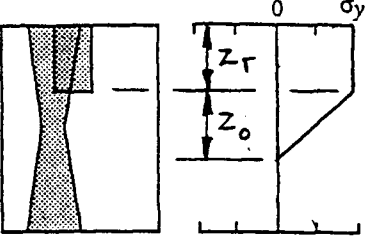
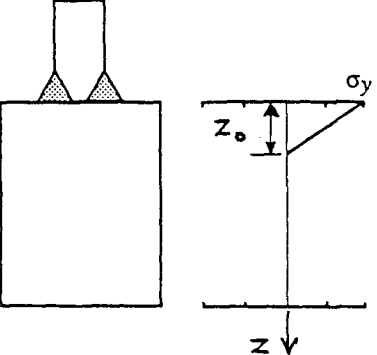
Joint Geometry	Transverse Residual Stress Distribution	Longitudinal Residual Stress Distribution
<p>Plate butt welds and pipe axial seam welds</p>		
<p>circumferential Pipe/butt welds</p>	 <p>This profile is for ferritic steels with high heat input</p>	
<p>Repair welds</p>		<p>(As transverse)</p>
<p>and fillet T-butt welds</p>		<p>(As transverse)</p>

Figure K1 Typical residual stress distributions in welded joints