BENEFICIAL EFFECTS OF HIGHER PRESSURE TESTING ON REDISTRIBUTION OF RESIDUAL STRESSES AND CRACK BLUNTING

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ABSTRACT

For testing Group 4 unfired pressure vessels designed according to the European Standard EN 13445, not subject to non-destructive testing other than visual inspection, the hydraulic proof test is expected not only to prove leak tightness but also to improve the vessel's reliability (500 full pressure cycles minimum fatigue life). In the HYDFAT research program two complementary approaches were combined to investigate the benefits of the hydraulic test pressure on the fatigue life. (1): Numerical modeling allowing for the determination of the critical weld defect size under various pressure test conditions, complemented by tests on wide plates and small-scale vessels (wall thickness 6 and 12 mm) containing weld defects. (2): Statistical investigation (multivariate analysis) of a series of experiments on thin-walled vessels (≤ 6 mm). It was concluded that the hydrotest pressure had to be as high as possible and ratios of test pressure to the maximum allowable pressure were proposed for ferritic and austenitic steels. However the maximum allowable peaking for testing Group 4 vessels should be lower than that currently allowed in EN 13445 for vessels of other testing Groups. These results have been implemented in the first edition of the European standard EN 13445 published in May 2002.

IIW-Thesaurus keywords: *Pressure vessels; Fatigue tests; Fatigue strength; Pressure tests; Pressure; Lack of fusion; Defects; Influencing factors; Lifetime; Design; Carbon manganese steels; Austenitic stainless steels; Thickness; Size; Statistical methods; Computation; Simulating; Critical values; Practical investigations; Standards; CEN; International activities.*

1 BACKGROUND AND OBJECTIVES

This paper presents an overview of the "Hydfat" research project dealing with the determination of the relation between fatigue strength and hydrotest pressure [1]. This research was performed in the framework of the Standards, Measurements and Testing Programme of the European Commission (Contract N° SMT4-CT96-2081) to support the activities of Technical Committee 54 "Unfired Pressure Vessels" of the European Committee for Standardisation (CEN TC 54).

As all national pressure vessel standards, the European standard for unfired pressure vessels (EN 13445) [2] uses the pre-service hydrostatic test as a means of checking the leak tightness and the integrity of the vessels under its design conditions. Beneficial effects of the pressure test are well known: lowering of residual stresses, correction of some shape imperfections, strain hardening, crack blunting etc. This is especially important for testing Group 4 vessels. These are extremely numerous and range from very small to relatively large ones. According to EN 13445, Group 4 vessels are not subject to any nondestructive test other than visual inspection.

The following conditions apply to testing Group 4 pressure vessels:
- Thickness is limited to 12 mm.
- Manufactured from either Group 1.1 low C-Mn steels with a specified minimum yield strength ≤ 275 N/mm², or Group 8.1 austenitic stainless steels with Cr ≤ 19% [3].
- Contain only group II fluids, non-dangerous fluids according to article 9 of the PED Directive [3].
- Maximum allowable design pressure, P_s, is 20 bar.
- Maximum allowable temperature T_{smax} is 200 °C for Group 1.1 steels and 300 °C for Group 8.1 steels.
- Minimum allowable temperature T_{smin} is - 10 °C for Group 1.1 steels and - 50 °C for Group 8.1 steels.

$P_S.V \leq 20\,000$ bar.L, when T_{smax} is above 100 °C.

$P_S.V \leq 50\,000$ bar.L, when $T_{smax} \leq 100$ °C.
- Designed assuming 90% level of the nominal design stresses used for other testing group -vessels, given at the calculation temperature T by:

$$\min\left[\frac{R_{p0,2/T}}{1,5};\frac{R_{m/20}}{2,4}\right]$$ for Group 1.1 C-Mn steels

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$\left[\frac{R_{p1,0/T}}{1,5}\right]$ or min $\left[\frac{R_{p1,0/T}}{1,2};\frac{R_{m/T}}{3}\right]$ for Group 8.1 austenitic stainless steels.

– No restriction on the welding procedure.

– NDT (10% of length) only for seams of conical shells with a cylindrical shell in the case of an angle > 30°.

– The nominal design stress under test conditions[1] shall not exceed:

$$f_{test} = \frac{R_{p0,2/T_{test}}}{1,05} \text{ for Group 1.1 C-Mn steels}$$

$$f_{test} = \max\left[\frac{R_{p1,0/T_{test}}}{1,05};\frac{R_{m/T_{test}}}{2}\right] \text{ for Group 8.1 austenitic stainless steels.}$$

– In prEN 13445-5:1999 [2a], the minimum test pressure shall be:

- $P_t = 1,75\ P_S \frac{f_a}{f_t}\ \frac{e_n}{e_n - c}$ for Group 1.1 C-Mn steels
- $P_t = 1,6\ P_S \frac{f_a}{f_t}$ for Group 8.1 austenitic stainless steels

where:

P_t is the test pressure

P_s is the maximum allowable pressure of the vessel

f_a is the nominal design stress for normal conditions at the test temperature

f_t is the nominal design stress for normal conditions at the maximum allowable temperature

e_n is the nominal thickness of the section under consideration

c is the corrosion allowance.

The ratio f_a/f_t to be used shall be the highest of the various components of the equipment, but considering only the main ones.

In addition:

– The joint efficiency shall not exceed the value of 0,7, since the equipment is not subject to NDT, except for visual inspection.

– EN 13445-3 requires that the minimum lifetime for pressure vessels in testing Groups 1, 2, 3 and 4 be 500 full pressure cycles (0 to P_s).

– For non-cyclic operation (maximum 500 full pressure cycles) larger deviations of the ideal shape are allowed in prEN 13445-4:1999: e.g. max. peaking ≤ 5 mm for $e / D \leq 10$ mm for $e / D > 0,025$.

The aim of this research project was to determine the test pressure conditions for hydraulic proof testing that would guarantee the integrity of the vessel throughout its lifetime, defined as 500 internal full pressure cycles for testing Group 4 unfired pressure vessels (a minimum target life of 1 000 cycles was chosen to allow for scatter in fatigue lives), even if these contained weld defects.

On the basis of the research, recommendations were made for the revision of the EN standards on unfired pressure vessels and industrial piping, taking particular account of the nominal stresses in design and service.

2 METHODOLOGY

Two distinct tasks were grouped allowing for different but complementary approaches to the problem. This resulted in a two-part work programme:

2.1 Part I – Analytical approach complemented by tests (medium wall thickness: 6 and 12 mm, Group 1.1 and 8.1 materials)

The overall approach was to investigate the fatigue performance of vessels containing weld defects that were just below the critical size for failure under the pressure test. Thus, Part I was based on the development of a numerical model for the determination of the critical weld defect size under pressure test conditions. The model included the influence of residual stresses due to welding. Small-Scale Pressure Vessels (SSPVs), 500 mm in diameter and 1,000 mm in length with forged elliptical ends (Fig. 1), in which the longitudinal weld contained deliberate weld defects of known size and up to 50% of the vessel wall thickness, helped to set up the numerical modelling. The small-scale pressure vessels were tested after hydrotest pressurisation to different P_t / P_s ratios ranging from 1 to 2,1 for Group 1.1 C-Mn steel and from 1 to 2 for Group 8.1 austenitic stainless steel. They were then submitted to cyclic loading.

2.2 Part II – Statistical approach (low wall thickness programme: 3 to 6 mm)

In Part II the work programme was based on a statistical investigation (multi-variant analysis) of a series of experiments on thin-walled (≤ 6 mm) vessels with

Fig. 1. Typical small-scale pressure vessels (MBEL).

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[1] For calculating the required thickness under test conditions a joint efficiency of 1 should be used.

defects in single-pass longitudinal welds. The results of the statistical analysis were compared with those of a parallel theoretical analysis using proven models for the various effects.

Two types of steels and three wall thicknesses were considered:
- Group 1.1 (C-Mn steels) and Group 8.1 (austenitic stainless steels) materials.
- Wall thicknesses of 3.5 to 4 mm, 6 and 12 mm.

3 REVIEW OF HYDROTEST CONDITIONS IN PRESSURE VESSEL STANDARDS

Based on a literature survey, it was found that the major European, American and Japanese codes were broadly similar in specifying hydrotest pressures between 1.25 to 1.5 times the design pressure, plus corrections for temperature and corrosion allowance. The requirements for testing Group 4 vessels in prEN 13445-5:1999 are more severe than those in any of the other codes examined.

All codes specify that the test pressure must be applied gradually. The test pressure hold time varies from 10 to 30 minutes. Internal (if possible) and external visual inspections of the vessels are specified. The vessels are checked for signs of plastic deformation in addition to leakage.

4 PART I – ANALYTICAL APPROACH COMPLEMENTED BY TESTS

Partners involved were:
- ISQ: define the welding procedures (WP) and design the welds containing calibrated lacks of penetration.
- IIS: qualify the WP and record thermomechanical data for input for the numerical modelling (IIS, University of Breda and IS).
- Ansaldo Energia Spa: manufacture the wide-plate test specimens (48) and the small-scale pressure vessels (SSPVs) (32) with welds containing “calibrated” defects.
- TWI and EMD: perform the wide-plate CTOD and fatigue tests.
- TWI: carry out residual stress measurements.
- MBEL: Group 8.1 steel small-scale pressure vessel (SSPVs) tests.
- MPA: Group 1.1 steel SSPV tests.

Two steels representative of testing Group 4 materials 1.1 and 8.1 were used for manufacturing the specimens:
- P265GH (EN 10028-2) [5], a normalised carbon-manganese steel, 6 and 12 mm.
- X2CrNi19-11 (EN 10088-3) [6], an austenitic stainless steel, 6 and 12 mm.

Chemical compositions and mechanical properties are given in Tables 1 and 2 respectively.

As a first step, wide-plate fatigue test specimens with welds containing deliberate natural defects of known and reproducible sizes were tested (Fig. 2). These preliminary tests aimed at providing experimental data to help to develop a numerical model.

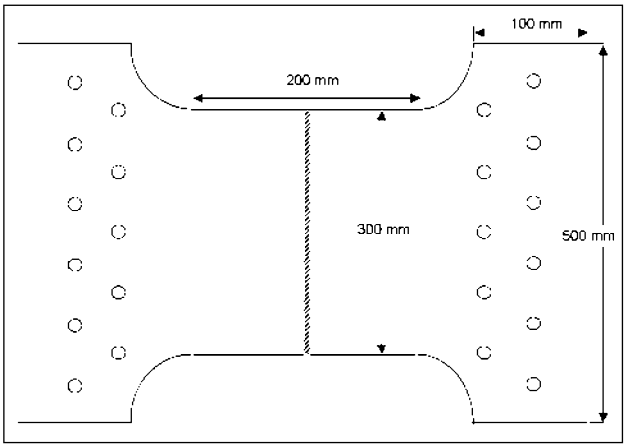

Fig. 2. Wide-plate test specimen (ISQ).

Table 1. Steel compositions (Part I).

P265GH													
	C	Si	Mn	P	S	Al	Cr	Cu	Mo	Nb	Ni	Ti	V
6 mm	0.14	0.17	0.98	0.011	0.004	0.032	0.060	0.018	0.015	0.002	0.027	0.016	0.002
12 mm	0.16	0.20	1.06	0.012	0.003	0.035	0.03	0.01	0.007	0.002	0.04	0.003	0.013

X2 CrNi19-11							
	C	Si	Mn	P	S	Cr	Ni
6 mm	0.026	0.38	1.33	0.037	0.004	18.23	10.20
12 mm	0.028	0.32	1.34	0.027	0.004	18.20	10.01

Table 2. Steel mechanical properties (Part I).

	Group 1.1 steel (P265GH)			Group 8.1 steel (X2CrNi19-11)		
	EN 10028-2	6 mm thick	12 mm thick	EN 10088-3	6 mm thick	12 mm thick
$R_{p0,2/20}$ (MPA)	265	333	295	200	260	250
$R_{m/20}$ (MPa)	410 to 530	450	400		570	550
E (MPa)		250,000	230,000		191,000	190,000
υ		0.3	0.3		0.3	0.3

As a second step, a series of small-scale pressure vessels (SSPV's) were manufactured with weld defects deliberately introduced into the longitudinal weld of the cylindrical shell. These SSPV's were tested after pressure testing with the aim of comparing calculated and experimental results and validate the numerical model.

4.1 Welding procedures

Welding procedures were developed to allow the introduction of sharp, constant-height lack of penetration (LOP) defects in the longitudinal seams of the 6 mm thick specimens or vessels (nominal defect height a = 1.5 and 3 mm) and embedded lack of penetration (LOP) defects in the 12 mm (nominal defect height a = 3 and 6 mm) (Fig. 3 and 4). In the case of the vessels, the weld defect length was about 75% of the longitudinal weld length to ensure that the ends were well away from the circumferential welds, thus avoiding any secondary bending moment due to the stiffness induced by these welds. Accuracy and reproducibility of the defect height of about ± 0.5 mm was required.

Automatic Gas Metal Arc Welding (GMAW) was used for all test specimens and SSPVs. Welding procedures were defined and qualified in each case. Each welded sample and SSPV was inspected by NDT for weld quality.

4.2 Numerical modelling (IS)

The study aimed at modelling the behaviour of longitudinal butt welds containing weld defects in 6 and 12 mm thick pressure vessels during the application of the test pressure. An elastic-perfect plasticity model was used for calculating the failure stress σ_{collapse}. The mesh size at the crack tip was 0.2 mm and all elements were under-integrated in order to satisfy the condition of plastic incompressibility.

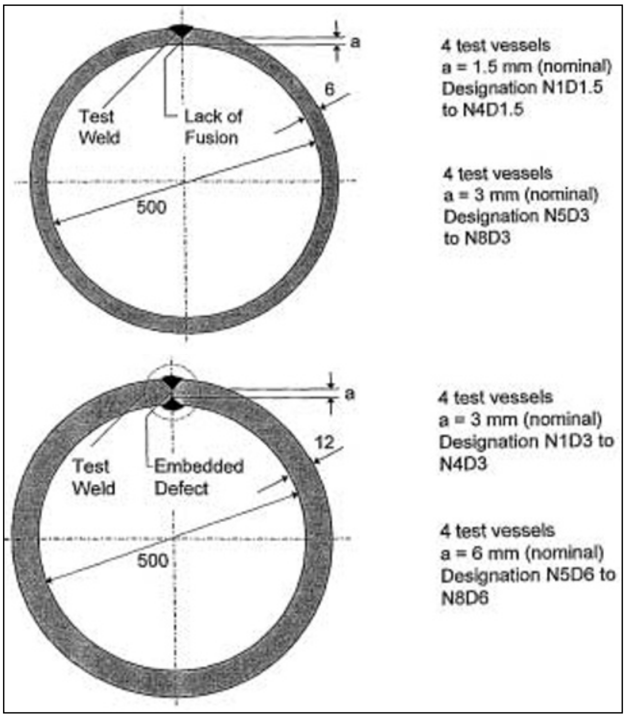

Fig. 3. Schematic representation of defect – SSPV (MPA).

As a first step, the stress intensity factor K_I was computed for both surface-breaking defects (wall thickness 6 mm, single V-groove) and embedded defects (wall thickness 12 mm, double-V groove), ignoring welding residual stresses. Then a non-linear mechanical analysis was performed to determine the evolution of the plastic zone at the tip of surface-breaking defects as a function of the test pressure.

The calculations were performed with:

- $\frac{P_t}{P_S} = 1{,}4$; 1.75 and 2.1 for Group 1.1 steel,
- $\frac{P_t}{P_S} = 1{,}6$ and 1.8 for Group 8.1 steel.

The nominal design stress corresponding to P_s was calculated using the following equations:

$$f = \frac{R_{p0,2/20}}{1{,}5} \,.\, 0{,}7.0{,}9 \text{ for Group 1.1 steel}$$

$$f = \frac{R_{p1,0/20}}{1{,}5} \,.\, 0{,}7.0{,}9 \text{ for Group 8.1 steel}$$

The resulting nominal stresses for the different test pressures used in the model are summarised in Table 3.

Table 3. Stresses used in the numerical model (IS).

Steel	Thickness (mm)	Stress based on	$P_t = P_s$ (MPa)	$P_t = 1.4.\ P_s$ (MPa)	$P_t = 1.75.\ P_s$ (MPa)
St1.1	6	Standard	115.5	161.7	202.1
St1.1	6	Actual	139.9	195.9	244.8
St8.1	6	Standard	75.6	105.8	132.3
St8.1	6	Actual	109.2	152.9	191.1
St1.1	12	Standard	115.5	161.7	202.1
St1.1	12	Actual	155.4	217.6	271.9
St8.1	12	Standard	75.6	105.8	132.3
St8.1	12	Actual	107.9	151.1	188.8

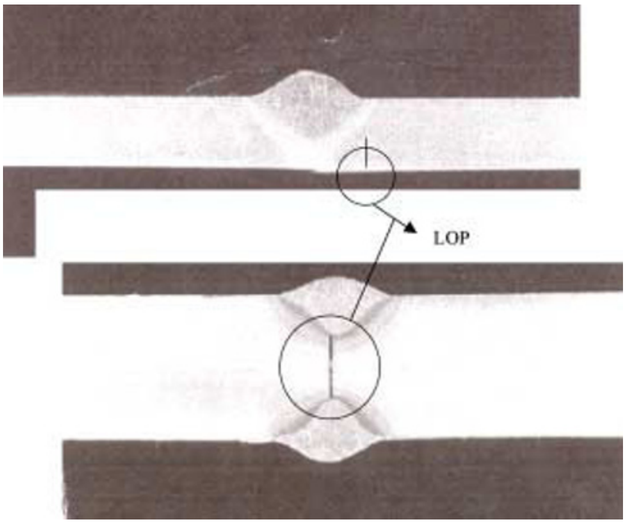

Fig. 4. Weld defects: lack of penetration min a single-sided (6 mm) and double-sided (12 mm) St1.1 steel sample (IIS).

4.2.1 Failure risk assessment

The “two-criteria method” defined by PD6493 [7] was used to assess the fracture susceptibility of the defects. Two cases were considered for modelling:

– minimum material properties as given in the respective reference standard (EN 10028-2 or 10088-3),

– actual properties (actual yield strength, *E* and *n*).

This method is based on the interpolation of the two limiting criteria analyses of failure, i.e. analysis by linear or non-linear elastic fracture mechanics and limit analysis (σ_{Collapse}). It is assumed that failure occurs when the load reaches the lower value of the two predicted to be critical, either by linear or non-linear elastic mechanics or by plastic mechanics.

The failure curve is characterised by two parameters: K_r and S_r, defined as[2]:

$K_r = K_I / K_{Ic}$ or $K_r = K_J / K_{Ic}$,

$S_r = \sigma_{00}$ (total applied load) / σ_{collapse} (plastic flow load).

Where:

– K_I is the stress intensity factor defined at the crack tip by numerical calculation,

– K_J is the stress intensity factor defined by J integral, obtained numerically,

– K_{Ic} is the toughness of the material,

– σ_{00} is the nominal stress in the vessel (circumferential stress),

– σ_{collapse} is the nominal stress which produces net section yielding.

For surface-breaking defects the two parameters are related by the following equation, based on the Dugdale model, in a failure assessment diagram (FAD):

$$K_r = S_r \left\{ \frac{8}{\pi^2} \ln \left(\frac{1}{\cos \frac{\pi S_r}{2}} \right) \right\}^{\frac{-1}{2}}$$

A second-degree envelope curve is thus obtained. The region below the (K_r, S_r) curve is the safe area corresponding to a probability of failure of about 1 to 2.5%. One example of a FAD is given in Fig. 5.

The resulting maximum allowable defect sizes are given in Tables 4 and 5. The values from numerical modelling are safe, although less conservative than those derived from the PD 6493 two-criteria approach. This is due to the simplified assumptions made in the latter: net section strain hardening is not taken into account, and the base metal yield strength, which is lower, is used instead of the value for the weld metal. If the actual base metal properties are used, the critical defect sizes are about 50% higher than those calculated using the minimum standard properties. However, these results show that the actual weld defects in the SSPVs are sub-critical at the different test pressures.

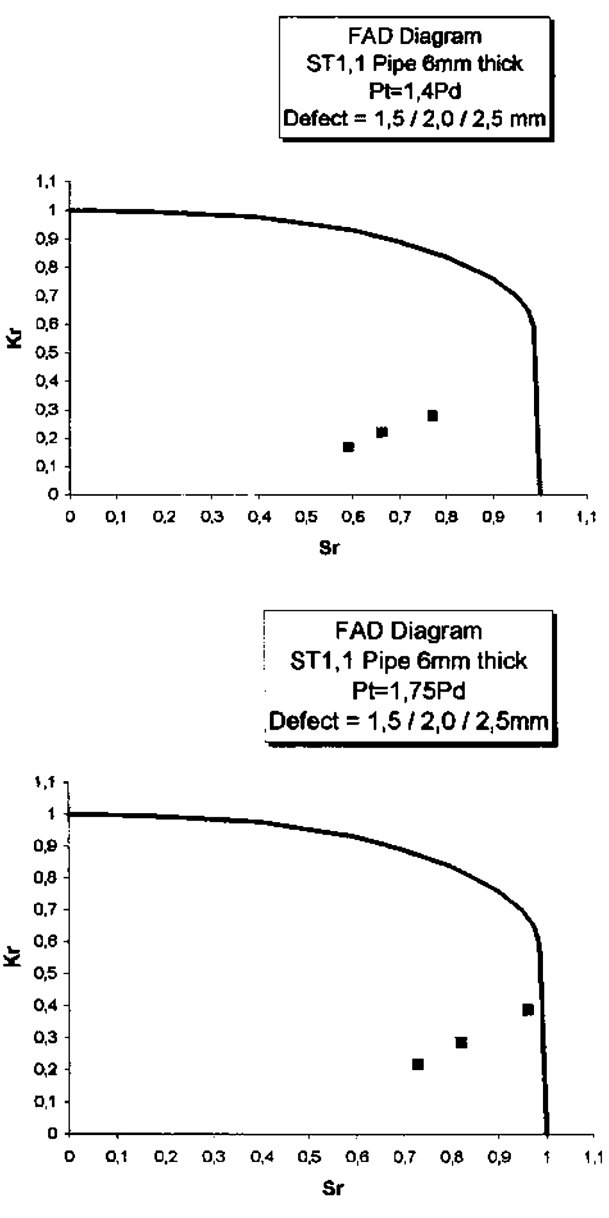

Fig. 5. Example of failure assessment diagram (FAD).

It is confirmed that peaking has a marked effect: K_J increases and σ_{collapse} decreases. The respective influences of peaking and out-of-roundness are summarised in Tables 6 and 7. For instance, under the above assumptions, for a 500 mm diameter vessel with a lack of penetration nearly half the wall thickness, the maximum allowable peaking is 4 mm. In contrast, it was verified that out-of-roundness has a negligible effect on K_J and σ_{collapse}.

Table 4. Computed critical defect size at test pressure. Standard minimum mechanical properties (IS).

Steel	Thickness (mm)	P_t / P_s	Numerical Analysis	BSI PD 6493:1991
St1.1	6	1.4	a_{critical} = 2.5 mm	a_{critical} = 2.5 mm
St1.1	6	1.75	a_{critical} = 1.8 mm	a_{critical} = 1.6 mm
St1.1	12	1.4	$2a_{\text{critical}}$ = 5.6 mm	$2a_{\text{critical}}$ = 4.6 mm
St1.1	12	1.75	$2a_{\text{critical}}$ = 3.5 mm	$2a_{\text{critical}}$ = 3.0 mm
St8.1	6	1.4	a_{critical} = 2.5 mm	a_{critical} = 2.5 mm
St8.1	6	1.75	a_{critical} = 1.8 mm	a_{critical} = 1.6 mm
St8.1	12	1.4	$2a_{\text{critical}}$ = 5.8 mm	$2a_{\text{critical}}$ = 5.0 mm
St8.1	12	1.75	$2a_{\text{critical}}$ = 3.6 mm	$2a_{\text{critical}}$ = 3.0 mm

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[2] Residual stresses are not taken into account in these calculations.

Table 5. Computed critical defect size at test pressure. Actual mechanical properties (IS).

Steel	Thickness (mm)	P_t / P_s	Numerical Analysis	BSI PD 6493:1991
St1.1	6	1.4	$a_{critical}$ = 3.3 mm	$a_{critical}$ = 3.0 mm
St1.1	6	1.75	$a_{critical}$ = 2.5 mm	$a_{critical}$ = 2.4 mm
St1.1	12	1.4	$2a_{critical}$ = 9.0 mm	$2a_{critical}$ = 5.5 mm
St1.1	12	1.75	$2a_{critical}$ = 6.5 mm	$2a_{critical}$ = 5.0 mm
St8.1	6	1.4	$a_{critical}$ = 4.0 mm	$a_{critical}$ = 3.4 mm
St8.1	6	1.75	$a_{critical}$ = 3.0 mm	$a_{critical}$ = 2.9 mm
St8.1	12	1.4	$2a_{critical}$ = 9.2 mm	$2a_{critical}$ = 5.4 mm
St8.1	12	1.75	$2a_{critical}$ = 6.9 mm	$2a_{critical}$ = 5.1 mm

Table 6. Peaking effect (IS).

6 mm thick, Group 1,1 steel, P_t = 2.1, P_s		
Size	**K_J (MPa$\sqrt{m}$)**	**$\sigma_{collapse}$ (MPa)**
Peaking = 6 mm LOP = 0.5 mm	150	150
Peaking = 6 mm LOP = 1.5 mm	235 (30*)	114 (275*)
Peaking = 2 mm LOP = 1.5 mm	87 (30*)	217 (275*)

* Values referring to vessel without peak effect.

4.2.2 Modelling integrating welding residual stresses for Group 1.1 material

The Sysweld+® finite element calculation software was used. It allows the simulation of welding, taking into account the associated thermal, metallurgical and mechanical aspects. A preliminary thermo-metallurgical calculation allowed the temperatures and the metallurgical transformations of Group 1.1 material to be determined at any time and every point. Residual stresses and distortion were then calculated. The thermal simulation takes into account the variations in thermal conductivity, specific heat and density in terms of temperature. The simulation included:

– Phase proportions dependence on mechanical properties.

– Volume changes associated with the metallurgical transformations.

The results show that the crack tips are under a compressive stress of about 200 MPa, for both 6 mm thick Group 1.1 and 8.1 steels (surface-breaking defect) and about 400 MPa for the 12 mm thick Group 1.1 steel (embedded defect). For the 12 mm thick Group 8.1 stainless steel the inner side crack tip is under a compressive stress (about 300 MPa), but the crack tip on the outer side is under a tensile residual stress of 300 MPa.

An example of transverse residual stress distributions is given in Fig. 6. Radial residual stresses after welding were also calculated. The limited experimental residual stress measurements fitted rather well with the calculated values.

Table 7. Out-of-roundness (O of R) effect (IS).

6 mm thick, Group 1,1 steel, P_t = 2.1, P_s		
Size	**K_J (MPa$\sqrt{m}$)**	**$\sigma_{collapse}$ (MPa)**
O of R = 6 mm LOP = 0.5 mm	15.8	300
O of R = 6 mm LOP = 1.5 mm	37 (30*)	277 (275*)
O of R = 3 mm LOP = 1.5 mm	32 (30*)	278 (275*)
O of R = 6 mm LOP = 3.0 mm	134	165
O of R = 3 mm LOP = 3.0 mm	127	173

* Values referring to vessels without out-of-roundness.

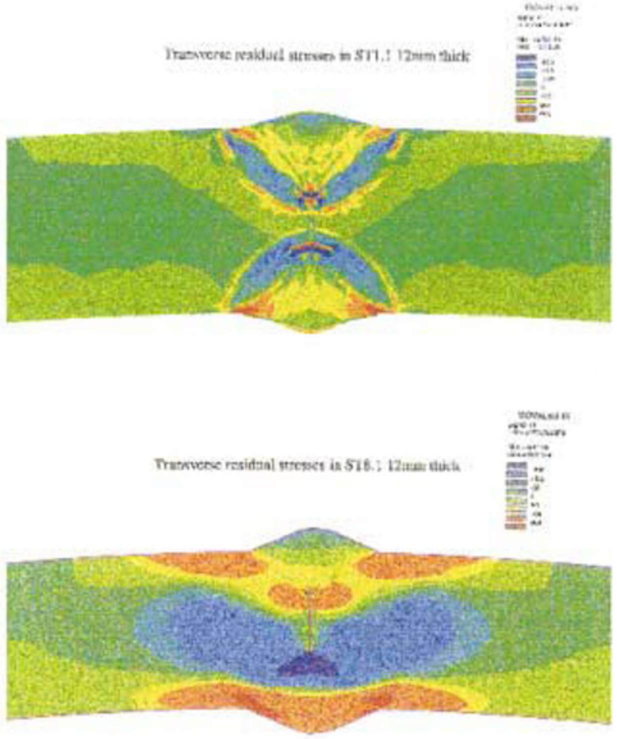

Fig. 6. Transverse weld residual stress field. As-welded.

Residual stress effect – FAD application domain

The residual stress field after pressure testing (P_t = 2.1 P_S) was computed with and without weld residual stresses. It was shown that:

– The initial weld residual stress field is modified by the pressure test: compressive stresses increase. However, at the crack tips, the stress distributions are very similar, whether weld residual stresses are present or not.

– The residual stresses are reduced significantly. Furthermore the material has a ductile behaviour for the service temperatures.

In conclusion, the residual stresses do not alter $\sigma_{collapse}$ significantly. Furthermore, since the initial residual stresses have no influence on the crack tip stress field, it is considered that the FAD diagrams in Fig. 5 may be used to assess the risk of failure.

4.2.3 Discussion and conclusions

– For the materials used in this study, under a test pressure $P_t = 2.1\ P_S$, the critical defect dimensions were approximately equal to or higher than half of the wall thickness for 6 mm thick vessels with surface-breaking defects (e.g. lack of penetration – LOP) and 75% of the wall thickness for 12 mm thick vessels with embedded defects (e.g. LOP).

– Based on the minimum $R_{p0.2}$ required by the material standards, the critical LOP dimension was reduced to around one third of the wall thickness for 6 mm thick vessels and half of the wall thickness for 12 mm thick vessels.

– Peaking has an important effect on the performance of longitudinal welds, as shown by the few calculations made with values ranging from 4 to 6 mm (for 500 mm-diameter vessels) depending on the tensile properties of the material. These values were in good agreement with experiments.

– Out-of-roundness effects are negligible.

– For the welding conditions used, residual stresses at the defect tips were in compression for both 6 and 12 mm thicknesses and both steels.

– Weld residual stresses did not have a detrimental effect on the failure resistance because they were compressive. In addition the pressure test improves the initial residual stress field at the crack tip by increasing both the magnitude and extent of the compressive stress field.

– Increasing P_t / P_S increases the extent of the plastic deformation at the defect tip, which further improves the fatigue life. However, for long surface-breaking defects, with depths very near the respective critical sizes, the required minimum of 500 cycle-fatigue life may not be achieved.

– Fatigue life could not be predicted because the Paris law is only valid for high-cycle fatigue (number of cycles greater than 100,000) and the application of the Manson-Coffin law requires that the strain amplitude at the defect tip be determined. This was out of the scope of this study.

4.3 Wide-plate test results

Two series of welded test coupons were manufactured from both 6 mm and 12 mm thick plates for both Group 1.1 and 8.1 steels. Two sets of 24 wide-plate test specimens were machined from the welded coupons (Fig. 2). The test procedure included a preliminary proof loading to simulate the pressure test. This was based on the minimum tensile properties according to the relevant standards to simulate a material, which would just meet the specified minimum tensile properties.

The pre-loading values were as follows:

– Group 1.1 steels, 1.43 and 1.75 times the maximum allowable pressure, corresponding respectively to 177 N/mm^2 and 217 N/mm^2 nominal stresses (54% and 67% of measured parent metal yield strength).

– Group 8.1 steel, 1.43 and 1.6 times the maximum allowable pressure, corresponding respectively to 151 N/mm^2 and 169 N/mm^2 nominal stresses (60% and 67% of measured parent metal yield strength).

Residual stress measurements were carried out on one sample of each series.

4.3.1 Fatigue test results on wide-plate

Because the edges of the LOP defects in the 6 mm thick specimens were bonded together during welding the defects did not open during pre-loading. As a consequence, no fatigue test could be carried out.

For the 12 mm thick test specimens, welded from both sides, fatigue tests were performed for both series. The fatigue stress range corresponded to the full design stress, giving $\Delta\sigma$ = 24 N/mm^2 for Group 1.1 steel and $\Delta\sigma$ = 106 N/mm^2 for Group 8.1 steel.

Because of the high yield strength of the weld metal, at least 50% higher than that of the parent metal, collapse of the ligaments on either side of the flaws was not expected. A significant crack growth (Δa >1 mm) occurred only after 10^5 cycles. There was no clear distinction between results from plates subjected to a high proof stress (1.6 and 1.75 times the design stress) and those subjected to a lower proof stress (1.43 times the design stress). The experimental results are summarised in Table 8.

4.3.2 Surface residual stress measurement

Weld residual stresses were measured before and after simulated proof loading, in both the 6 mm and 12 mm thick specimens. The effect of proof loading on transverse residual stresses was not consistent, possibly

Table 8. Results of 12 mm thick wide-plate fatigue tests (TWI).

Specimen ID	Measured flaw height (mm)	Proof load ratio	Number of cycles (x 10^4)	Δa_{ave} mm
W01-01	4.0	1.75	1.3	0.06
W01-02	3.7	1.43	1.3	0.03
W01-03	3.7	1.75	1	< 0.01
W01-04	4.0	1.43	1	< 0.01
W01-05	3.5	1.75	1.3	0
W01-06	3.7	1.43	1.3	0.025
W02-01	4.1	1.75	1.3	< 0.01
W02-02	4.8	1.43	1.3	0.05
W02-03	5.0	1.75	1.3	0.02
W02-04	4.8	1.43	1	< 0.01
W02-05	4.7	1.75	1	0.05
W02-06	4.7	1.43	1.3	< 0.01
W03-01	4.01	1.6	1.3	0
W03-02	4.05	1.43	1.3	0
W03-03	3.84	1.6	10	0.2
W03-04	4.09	1.43	10	0.6
W03-05	3.13	1.6	50	0
W03-06	3.94	1.43	50	0.03
W04-01	4.16	1.6	1.3	0
W04-02	4.57	1.43	1.3	0.03
W04-03	4.95	1.6	10	1.1
W04-04	–	not tested	–	–
W04-05	4.05	1.6	2.5	0
W04-06	4.45	1.43	2.5	0.02

because of unintended variables (misalignment, angular deviation). The measured values were used to check the numerical model.

4.4 Small scale pressure vessel tests

4.4.1 Test vessels

A total of 32 vessels, 8 for each steel and each thickness, were manufactured. The central cylindrical section contained a longitudinal weld along its whole length. To simulate a weld defect, each vessel contained a 760 mm length of Lack of Penetration (LOP).

The 6 mm thick vessels contained an internal surface-breaking defect arising from lack of penetration in a single-pass weld. Two nominal defect depths were simulated: 4 vessels with a 1.5 mm deep defect and 4 with a 3 mm deep defect. An embedded defect arising from lack of penetration in a double-sided weld was simulated in the 12 mm thick vessels. Again, two nominal defect depths were simulated: 4 vessels with a 3 mm deep embedded defect and 4 vessels with a 6 mm deep embedded defect. More details are given in Fig. 3.

4.4.2 Test procedure

4.4.2.1 Dimensional measurements, nondestructive testing (NDT)

A dimensional survey of each vessel was made before and after hydraulic testing (12 mm vessels only) and after final failure. After completion of all tests a thickness measurement was made using a micrometer. High elongation strain gauges of 3 mm and 20 mm gauge length were attached circumferentially across the centreline of the weld at mid-length. An AC Potential Drop (ACPD) system was used as a means of identifying crack growth from the defect.

On receipt of the vessels, manual ultrasonic testing (0°, 70°, 80° probes) was performed to examine the simulated defects. The aim had been to establish that the defects were of the correct size range and locate the deepest part of the defect. The Time Of Flight Diffraction (TOFD) technique originally intended to be used was not accurate enough, and was therefore discontinued in the remainder of the test programme. Defect sizes were checked a posteriori by metallographic examinations. For the stainless steel vessels, the ultrasonic technique was able to confirm whether the defect was 1.5; 3 or 6 mm in depth, but could not be used for accurate sizing or location of the deepest point.

4.4.2.2 Hydraulic test

The hydraulic pressure test was conducted using water as the pressurising medium, the pressure rise being limited to ≤ 20 bar/min. The initial pressure increment was to 50% of the test pressure with subsequent increments of 10% up to the maximum test pressure. The maximum test pressure was held for the required 30 minutes as specified in the standard. On completion of the hold period, the pressure was reduced to 50% of the test pressure and the vessel visually inspected for any sign of leakage.

The vessels were subjected to variable test pressure according to modelling requirements. The pressure test was computed as per EN 13445 formulas:

$$P_t = r\,P_S\,\frac{f_a}{f_t}\,\frac{e_n}{e_n - c} \quad \text{for 1.1 steel, with } 1.75 \le r \le 2.1$$

$$P_t = r\,P_S\,\frac{f_a}{f_t} \quad \text{for 8.1 steel, with } 1.43 \le r \le 1.6$$

To investigate the effect of the hydraulic test pressure on the fatigue life, some of the vessels were tested at different factors of the maximum allowable pressure (see Tables 9 and 10).

4.4.2.3 Internal pressure fatigue test

All vessels underwent an internal pressure fatigue test. The majority of the vessels were cycled from a nominal zero (determined by the system) to the calculated maximum allowable pressure as determined by the stan-

Table 9. Group 8.1 austenitic stainless steel vessels. 6 and 12 mm wall thickness (MBEL).

Mark	Wall t (mm)	Defect depth (mm)	Peaking (mm)	P_t (bar)	P_s (bar)	$\frac{P_t}{P_s}$	Nr of cycles to failure
N1D1.5	5.94	2.1	- 0.91	73	70.4	1.037	1,225
N2D1.5	5.9	1.38	2.44	32.3	20.2	1.6	> 10,000
N3D1.5	5.95	1.63	0.96	48.5	20.2	2.4	> 10,000
N4D1.5	5.68	1.22	1.34		20.2	0	> 10,000
N5D3	6.03	2.5	0.51	73	70.4	1.073	390
N6D3	5.98	1.8	1.18	32.3	20.2	1.6	> 10,000
N7D3	5.91	1.9	1.38	48.5	20.2	2.4	> 10,000
					60.8	0	739
N8D3	6.05	1.96	3.09		20.2	0	> 10,000
N1D3	11.57	2.23	3.48	64.5	40.3	1.6	> 5,000
N2D3	12.09	7.15	- 1.14	64.5	40.3	1.6	> 5,000
N3D3	11.95	7.55	4.29	64.5	60.5	1.06	2,000
N4D3	12.09	7.22	3.27	83.8	80.8	1.037	1182
N6D6	12.22	8.58	- 0.27	64.5	40.3	1.6	> 5,000
N7D6	12.03	8.96	2.92	64.5	60.5	1.06	1,254
N8D6	12.16	9.04	-0.05	83.8	80.8	1.037	99
N5D6	11.83	3.03	2.87	64.5	40.3	1.6	> 5,000

Table 10. Group 1.1 C-Mn steel vessels, 6 and 12 mm wall thickness (MPA tests).

Mark	Wall e (mm)	Defect depth (mm)	Peaking (mm)	P_t (bar)	P_s (bar)	$\frac{P_t}{P_s}$	Nr of cycles to failure
N1D1.5	6.1	1.5	< 1	73	32.8	2.22	5,584
N2D1.5	6.1	2	1.5	57.4	32.8	1.75	1,833
N3D1.5	6.0	0	2	57.4	28.1	2.04	>10,000
N4D1.5	6.1	2.4	< 1	57.4	32.8	1.75	1,587
N5D3	6.1	2.8	< 1	57.4	32.8	1.75	1,560
N6D3	6.2	2.8	2	40.8	23.3	1.75	3,380
N7D3	6.1	2.8	1	57.4	28.1	2.04	3,616
N8D3	6.1	2.8	1	0	32.8	0	720
N5D6	12.5	2.8	1.5	107.9	56.8	1.9	>10,000
N2D3	12.6	6.5		107.9	56.8	1.9	>13,400
N3D3	12.6	8		75			
N4D3	12.6	7		74	48.2	1.53	1,696
N6D6	12.5	9.4		75	48.2	1.53	797
N7D6	12.6	9		89.4			

dard. The pressure cycling rate was limited to ≤ 5 cycles/min. If fatigue failure had not occurred after 10,000 cycles (6 mm vessels) or 5,000 cycles (12 mm vessels), the test was stopped.

As part of the investigation of the relationship between the hydraulic test pressure and the fatigue life, some Group 8.1 steel vessels were tested or received additional cycles beyond 10,000 cycles at a maximum pressure greater than the maximum allowable pressure (i.e. by factors of 1.5; 2.01; 3.0 and 3.49).

ACPD and strain/clip gauge outputs were monitored during this test.

4.4.2.4 Burst test

Vessels that did not fail by fatigue were subsequently subjected to a burst test to establish their maximum capability with respect to their maximum allowable pressure. The pressurising rate was limited to ≤ 20 bar/min.

ACPD and strain/clip gauge outputs were monitored during this test.

4.4.3 Summary of results and discussion

4.4.3.1 Group 8.1 steel pressure vessels

The out-of-roundness, generally less than 1%, was well within the allowable values given in most standards. The peaking local to the weld was generally insignificant at around 1 mm or less for the 6 mm vessels and around 3 mm for the 12 mm vessels. A summary of the main measurements from the dimensional survey and metallographic examinations are presented in Table 9.

Only two of the 12 mm vessels were tested as double-sided welds with an embedded defect as originally intended. The six remaining vessels had the outer surface weld slit down to the level of the embedded defect, effectively making it an outer surface-breaking defect. The fracture faces of both vessels that failed by fatigue and by burst test were metallographically examined both optically and, where appropriate, by scanning electron microscopy. The fracture faces were viewed to determine the actual depth of the simulated defects, the extent of any subcritical crack growth, which might have occurred during hydraulic or fatigue testing and the final ductile failure. Macro and micrographs were taken from a cross-section of the weld (at the centre of the failure). Hardness measurements (HV10) were taken across the section local to the defect tip.

The results in Table 9 show that all vessels that were hydraulically (standard test, i.e. $P_t = 1,6\ P_s$) and subsequently fatigue tested at the maximum allowable pressure (P_s) completed at least 10,000 cycles (6 mm thick vessels) and 5,000 cycles (12 mm thick vessels). This is one order of magnitude greater than the 500 cycles required by the European standard. The only vessels that failed by fatigue were those which, regardless of the hydraulic pressure applied, were fatigue tested at pressures greater (by at least a factor of 2) than the design pressure. The burst pressures for those vessels that survived the internal pressure fatigue test are consistent between vessels of differing defect depth and geometry and ranged from 75 bar for a 6 mm thick, 1.5 mm defect vessel to 197.9 bar for a 12 mm thick, 3 mm embedded defect vessel.

Metallographic examination

The defect depth measurements taken from the fracture faces generally showed that the separation between the two nominal defect sizes was not as great as intended. The fractographic examination showed a combination of fatigue and ductile tearing. Fig. 7 is an example of a typical failure after fatigue testing of a stainless steel SSPV. Some, but not all, vessels showed evidence of “diffusion bonding” at the point of fracture initiation. The deeper defect produced a greater opening and hence greater bending, resulting in more compressive strains on the outer surface local to the weld. Similarly, increased levels of hydraulic test pressure produce greater defect openings resulting in more compressive strains local to the weld. The dimensional measurements showed that for the surface-breaking defects local deformation (peaking) existed at the weld seam and may have contributed to the reduction in tensile strain due to the introduction of additional bending stresses. The two double-sided 12 mm thick vessels tested in this programme do not confirm the relationship between reduc-

a) Fracture Face Exhibiting Both Fatigue and Ductile Fracture b) Fatigue Striations

: Vessel N1D1.5 - Position 'B' Fractographic Examination

Fig. 7. SEM micrographic examination of a SSPV failure after fatigue testing – St8.1 steel (MBEL).

tion in tensile weld strains and increased peaking (confirmed by numerical modelling).

The maximum strain level reached during the standard hydraulic test was < 0.1%. Even with a hydraulic test pressure 2.4 times the design pressure, the induced strains were only 0.1%. These are low for austenitic steels. Only when testing at pressures close to the burst pressure did the strains come anywhere near the 1% proof strain of the material.

No vessel submitted to a standard hydraulic pressure test and fatigue tested to its maximum allowable pressure failed in fatigue. To obtain fatigue failures it was necessary to go to fairly extreme test conditions. Pressures between 1.5 and 3.48 times the maximum allowable pressure were required.

No vessel showed any sign of initiation after 10,000 cycles. This is an indication that there may be an upper limit to an effective hydraulic test pressure.

Four vessels (N1D1.5, N5D3, N4D3, N8D6) hydraulically tested close to their burst pressures (83% and 92%) survived the hydraulic test, but in three of them subcritical crack growth was found to have occurred.

None of the vessels fatigue tested at their maximum allowable pressure showed fatigue damage. This reinforces the conclusion drawn from the test work that a vessel, which passes the standard hydraulic test and is cycled at its design pressure, is unlikely to fail in less than 500 cycles.

4.4.3.2 Group 1.1 steel pressure vessels

The fatigue test results for the Group 1.1 steel vessels are presented in Table 10 and in Fig. 8. With these steels in testing Group 4, if the vessels survive the pressure test, an endurance of more than 500 cycles is assumed for defect sizes up to 50% of the thickness (6 mm). For 12 mm vessels with embedded defects, the critical size is likely to be significantly higher. Fatigue cycling without the pressure test clearly led to disadvantages. For all these tests fatigue crack initiation could be observed at approximately 70% of the cycles to failure, but without the hydrostatic proof test (test N8D3) crack initiation was immediate. In addition the number of cycles to rupture was less than 500 for this vessel.

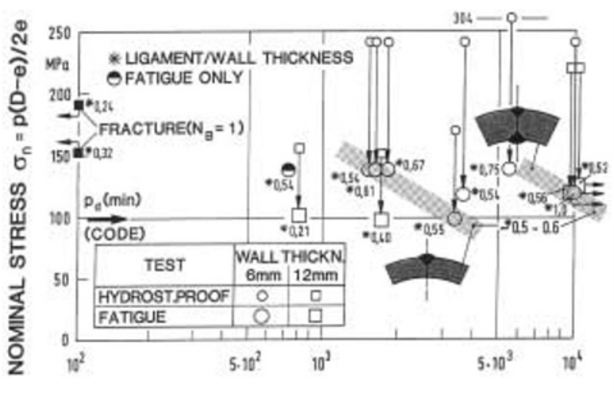

Fig. 8. Summary of St1.1 steel SSPV testing (MPA).

5 PART II – STATISTICAL APPROACH

Partners involved were:

- Loos International, Gunzenhausen.
- SNAM, Milan – Südpetrol München.
- TÜV Süddeutschland, Munich (TÜV-B).
- TÜV Austria, Vienna (TÜV-A).
- Technical University, Vienna (TUW: A and AB).

5.1 6 mm thickness, variable weld and shape defect vessel series

5.1.1 Test vessels

Using the experience from more than 100 pre-tests on specimens with P_t = 40.47 bar, ***a series of pressure vessels was manufactured as follows:***

- Flat ends, diameter 500 mm, length 960 mm, 6 mm wall thickness in Group 1.1 steel (P235 GH – EN 10028-2).
- All vessels one-side welded from the outside.
- Intentional weld defects in the form of lack of penetration over the length of the longitudinal weld with ligaments at the weld joint. Defect 1,5 to 2,22 mm (LOP 66 to 75% of the wall thickness).
- Peaking ranging from 0 to 7.5 mm.

5.1.2 Test procedure

The pressure test procedure was different from that described above. Here two consecutive loadings with holding time 10 min were applied instead of one loading with 30 min holding time. P_t / P_s ratios ranged from 1.8 to 2.28.

The calculations, which were made in strict compliance with prEN 13445, resulted in P_t = 40.17 bar and P_s = 19.13 bar. The hydrotest pressure P_t was varied. Hydrotests and measurements of peakings and strains were made at the various stages of the pressure and cyclic tests. Details of the results are given in Tables 11 and 12.

Table 11. St1.1 steel vessels, 6 mm wall thickness (TÜV-B).

Mark	Wall e (mm)	Defect depth (mm)	Peaking (mm)	P_t (bar)	P_s (bar)	$\frac{P_t}{P_s}$	Nr of cycles to failure
G12	6		6.8	30	19.2	1.8	218
G13/1	6		7.43	40.1	19.2	2.1	739
G13/2	6		6.94	40.1	19.2	2.1	841
G14	6		5.64	40.2	19.2	2.1	1,032
G15	6	4.3	3.93	36.3	19.2	1.9	230
G20	6	3.78	2.85	43.6	19.2	2.28	8,043

Table 12. Results of tests with pressure vessel 500 x 6 mm; Group 1.1 (from TÜV-B).

Mark	P_{lim} (bar)	Mean peaking at 0 bar in mm (angle between breaking sides)		Number of cycles 0.1/19.2 bar	Net section after hydrotest	Strain [%] at the nearest (mm) gauge to leak (mm)
		Before hydrotest	**After hydrotest**			
G 01	24.7	h = 6.44 (154.3°)				
G 02/1	32.3	h = 5.90 (155.30°)	h = 1.37 (168°)			
G 02/2	≤ 35	h = 137 (168°)				
G 02/3	≤ 35	h = 1.37 (168°)			1.7	
G 11	39.8/ 35,1	h = 4.75 (157.8°)	h = 1.51 (167.4°)		2.0	
G 12	34 (expected)	h = 6.8 (153.6°)	h = 4.53 (158.3°)	218	1.55	0.47% (60 mm)
G 13/1	40.1	h = 7.43 (152.4°)	h = 4,3 (158.9°)	739	2.2	0.51% (leak under strain gauges)
G 13/2	40.1	h = 6.94 (153.3°)	h = 3.63 (160.6°)	841	2.1	0.444% (10 mm)
G 14	40.2	h = 5.64 (155.9°)	h = 3.21 (161.7°)	1,032	2.05	0.383% (70 mm)
G 15	36.3	h = 3.93 (161.2°)	h = 1.92 (165.8°)	230	1.7	0.309% 15 mm
G 16/1	36.8	h = 3.95 (159.8°)				
G 16/2	32.5				1.9	
G 20	43.6	h = 2.85 (162.8°)	h = 1.76 (166.45°)	8,043	2.22	0.141% (30 mm)
G 21	43.6	h = 2.76 (163.0°)			2.2	

Notes: P_{lim} = limit pressure;
P_s = 19.13 bar (cyclic pressure);
$P_t = 1.75\,\frac{6}{6-1}\cdot P_s = 40.17$ bar; see G 13/1 G 13/2 – G 14 (test pressure according to part 5 of prEN 13445).

The performance of nozzles with poor welds could not be investigated. It was impossible to produce equivalent small welds, which just did not burst under the effect of a certain test pressure.

The tests were intentionally performed under the worse conditions, with large peaking, high strength weld metal, with subcritical crack growth by high pressurising at the *real limit pressure* and low frequency during cyclic tests. The out-of-roundness of the pressure vessels was below 0.2%.

The cyclic tests were performed after the hydrotests with the same maximum allowable pressure P_s, calculated in compliance with EN 13445. The frequency of the cyclic tests was 0,004 Hz or 4 minutes per cycle.

5.1.3 Summary of results and discussion

Tests with high overloads on test specimens with cracks always resulted in beneficial effects for the prolongation of the lifetime (number of cycles). The results are summarised in Table 12.

After a test pressure of $P_t = 1{,}48\, P_S \frac{f_a}{f_t} \frac{e_n}{e_n - c}$

218 cycles were reached.

After a test pressure of $P_t = 1{,}58\, P_S \frac{f_a}{f_t} \frac{e_n}{e_n - c}$

230 cycles were reached.

In 3 cases the test pressure required by prEN 13445, $P_t = 1{,}75\, P_S \frac{f_a}{f_t} \frac{e_n}{e_n - c}$ was reached as a real limit pressure for the defects. The lifetimes reached afterwards were only 739, 841 and 1,032 cycles. With a hydrotest pressure of $P_t = 1{,}48\, P_S \frac{f_a}{f_t} \frac{e_n}{e_n - c} = 2{,}28\, P_S$ and with a strongly reduced peaking (peaking < 3 mm and no out-of-roundness) the lifetime reached was 8,043 cycles with $\Delta P = P_s = 19.1$ bar. In this case the safety margin to the required minimum of 500 cycles is large enough.

All fractures and crack propagation in the pressure vessels occurred in the weld metal. In some cases squeezing lines and the start of necking zones at polished locations showed the proximity to the burst pressure (limit pressure), better than the measured strain values. Altogether 46 strain gauges were attached. All measured strains at the outside were negative. The peaking measurements showed that the size of the remaining peaking after the hydrotests was reduced with increasing test pressure.

The highest hydrotest factor with the highest allowed stress of $\frac{R_{p0,2}}{1{,}05}$ was:

$$P_t = 2{,}267\, P_S \frac{f_a}{f_t} \frac{e_n}{e_n - c}$$

Tensile tests with notched specimen showed that the tensile strength in the ligament was about 23% higher than in the smooth specimen. The tensile strength in the ligament of pressure vessels were calculated with 0.82 $R_{m,\,weld}$ or 1.20 $R_{m,\,shell}$.

In nozzle welds real limit defects could not be produced in a defined manner.

Serial tests with high overloads on test vessels with cracks always resulted in beneficial effects for the prolongation of the lifetime (number of cycles). This is valid for overloads applied before cyclic operation and for repeated overloads between cyclic operations, as long as the overloads are less than the burst loads. Examples of actual large weld defects are shown in Fig. 9. During overloads subcritical crack growth (tearing) was observed. Investigations with coloured crack surfaces and with scanning electron microscopes showed that the subcritical crack growth varied from 0.5% to 3.3% of the ligament. The high lifetime prolongations corresponded with the larger subcritical crack growth values. The material needs time for yielding, also for developing the Bauschinger effect. After a quick pressure rise the strains lag. The same can be observed after a quick pressure release. The strain gauge measurements showed that hold times of 2 × 10 minutes (minimum) are necessary as a fading time for yielding and creeping during the hydrotests.

During the operational pressure cycles it was determined that the strains at the maximum allowed pressure P_s were nearly constant after 1 to 2 minutes. This confirmed that the pressure-time conditions for the cyclic test were well chosen.

5.2 3.5 and 4 mm thick vessels – variable fatigue loading conditions

Several vessel series were manufactured using 3.5 mm thick Group 1.1 steel and 4 mm thick Group 8.1 steel with different combination of weld and shape defects. The work programme was split into three parts:

- A statistical multivariate analysis of series of experiments on rather thin-walled vessels (3.5 mm) with defects of different sizes in single-pass longitudinal welds and shape imperfections.
- A fracture mechanics investigation to help the interpretation of the test results in order to separate the structural effects from the material effects.
- Shakedown limits.

Other groups of vessels were included in the study.

5.2.1 Test vessels

Cylindrical vessels (flat ends) with 3.5 mm wall thickness, manufactured in Group 1.1 steel (St 52.3 – DIN 17100, YS 301 – 313 MPa, UT 421 – 457 MPa, % Elong. 35.1 – 41.1%):

- Series 1, BB series (323 mm): 25 vessels.
- Series 2, BC series (351 mm): 22 vessels.
- Series 3, BC series vessels with variation in the most important parameters (by reducing the net rest section at the crack tip or by increasing the size of the weld defect by fatigue).

Defect in a single layer weld (MAG) and peaking.

Defect in a single layer weld (MAG), welded on a cooled copper bar.

Fig. 9. Examples of actual large weld defects in pressure vessels (TÜV-S).

- Series 4 (BD series) of six 8.1 stainless steel vessels was manufactured with dimensions: 323 mm, wall thickness 4 mm, length of the longitudinal weld 500 mm. The 8.1 steel mechanical properties were YS (0.2%) 333 MPa, UT 673 MPa.

In all vessels, the excess weld metal was ground off and shape and dimensions were recorded. Peaking was about zero but some offset caused asymmetry.

5.2.2 Test procedure

A burst test was carried out with the first vessel of every series to determine a suitable break-off criterion to obtain a hydraulic test pressure close to the limit pressure or to have a limit defect for a specific hydraulic pressure.

A pressure test and afterward a fatigue test were carried out on the remaining vessels in the following way:

- In the pressure test the pressure was increased near the bursting pressure.
- The vessels were pressurised cyclically until failure or 10,000 cycles were achieved. If no crack growth was detected the cyclic load was increased for another 10,000 cycles and so on.

Acoustic emission and strain gauge measurements were carried out in all tests.

5.2.3 Summary of results and discussion

5.2.3.1 Fatigue tests

Pre-tests of the BB series resulted in very low fatigue lives.

In the case of the BC series the numbers of cycles were quite satisfactory (a minimum of 8,500 cycles, lack of penetration up to 57% the thickness). All of these tests (BB and BC series) were performed with the longitudinal excess weld metal ground off.

The essential differences between the BB and BC series were:

- For BC series the pressure difference in the fatigue test was considerably smaller than the test pressure (factor 2.45).
- For BC series the test pressure was much closer to the burst pressure.
- There was almost no peaking in the case of the BC series, but there was considerable peaking in the BB series vessels.
- The crack pattern and the kind of incipient crack were different.
- The position of the cusp of the cutting edges was different in both series.

The average stress at the rest section at burst is in both series between the ultimate strength of the base material and 110% of that value.

For vessels with welds not ground the question of how to consider the excess weld is still open. It was shown by numerical modelling that if peaking is negligible (no bending), the excess weld has a negligible influence on the K_I value, e.g. on 6 mm thick vessels, excess weld metal ranging from 0,6 to 2,4 mm, had no effect on K_I for a 1.5 mm deep LOP and produced a 9% variation for a 2.5 mm deep LOP.

For 8.1 steel series (ground weld) the average stress at burst is lower.

Crack growth, stretched zone or blunting was produced during the pressure test. In addition, a reduction of the net section due to necking at the pressure test near the burst pressure is possible. But despite the large number of experiments no detrimental effect due to a high test pressure was recognised.

5.2.3.2 Fracture mechanics calculations

Fracture mechanics calculations have shown that the influence of peaking is of the same order of magnitude as the remaining section thickness influence (surface-breaking defect).

The plastic deformation has a very important influence. But there was a big difference between computed and measured shape alterations.

It was not possible to obtain some general formulas by finite element calculation due to the large number of variables and the unknown material parameters at weld failure.

5.2.3.3 Shakedown limit calculations with technical beam theory

For the thin walled vessels, it seems the reason for the low number of cycles to failure is that shakedown limits were exceeded during pressure cycling. Two shakedown limits were calculated for the weakest vessel section. One is given by the $2R_M$ criterion and one can be calculated using the plastic hinge theory. With these formulas relationships were obtained between the ratio of the burst pressure to the cyclic pressure, the shape deviation, a material parameter and the net section, allowing for avoiding exceeding the shakedown limits. These formulas seem to work well with the investigated vessels and the limit according to the $2R_M$ criterion seems to give conservative results.

With these formulas allowable positive peaking values were obtained for the Group 1.1 steel vessels. The allowed peaking values have a minimum for 3 mm wall thickness; this minimum is lowered when a 1 mm excess weld is considered.

These allowed peaking values strongly depend on the ratio between the stress in the area outside the weld during the pressure test and the yield strength or the ultimate strength of the weld metal. An upper limit has to be specified for the steel strength.

From these formulas one can deduce that the test pressure has to be very high – as high as allowed – and the peaking has to be very small.

6 RESULTS OF HYDFAT

The complementary scientific approaches within the project (Parts I and II) led to a good agreement. The use of as high as possible pressure proof tests has several beneficial effects that can improve significantly the fatigue life of pressure vessels. These beneficial effects were modelled and quantified including shape imperfection effects.

The conclusions of the analytical approach (Part I) related to critical defect sizes may be considered as conservative. However a fair quantification of the beneficial pressure test effects is obtained. In addition, the analysis of defect shape influences, although few cases were investigated, led to predictable effects in good agreement with the experimental data.

The statistical approach faced the difficulties related to the multi-parameters individual and crossed influence analysis. However the great number of vessels, the partners' experience and the support of finite element analysis led to a good understanding of the influencing variables (material and pressure test procedures) and allowed to identify the separate effects of the most important ones.

Formulas for predicting some of the pressure test effects seem to work fairly well for peaking and out-of-roundness effect predictions.

Sharing the partners' experience and skill resulted in a deeper knowledge of pressure test effects versus the different parameters and allowed the quantification of these effects. Very useful conclusions were obtained; they will serve as guidance for improving prEN 13445:1999.

The following sections summarise the detailed conclusions and recommendations.

6.1 Hydraulic test pressure

6.1.1 Requirement of 500 full pressure cycles

For testing Group 4 vessels, which are not subjected to any nondestructive testing other than visual inspection, it may be assumed with a reasonable confidence that the 500 cycles required by the new European standard should be exceeded after hydraulic testing at a high test pressure.

6.1.2 The pressure test of Group 1.1 steel pressure vessels must be as high as possible

The test pressure can be as high as P_t / P_s = 2.3 (without corrosion allowance) or 2.7 (with 1 mm corrosion allowance for 6 mm wall thickness) to comply with the $R_{p0.2}$/1.05 allowable stress for test conditions. Below P_t / P_s = 1,5 there is no significant effect on the subsequent fatigue life.

6.1.3 Critical weld defect sizes for bursting

Under pressure test conditions the limit weld defect sizes for bursting (critical sizes) are very large; the net section at the defect tip is very small. Should a near-critical size weld defect be present (such as an exceptionally continuous large lack of penetration would have been rejected after visual inspection) the vessel would survive the pressure test, but the minimum life (500 cycles) under cyclic loading at the design pressure might not be obtained, depending on the steel properties.

6.1.3.1Critical size for Group 1.1 steel

For Group 1.1 steel with tensile properties near the minimum values required by EN10028-2, critical sizes of very long weld defects under pressure test conditions are:
– 33% wall thickness for surface-breaking defects (6 mm thick vessels),
– 50% wall thickness for embedded defects (12 mm thick vessels).

However, these values are very conservative, e.g. for present Group 1.1 steels the critical defect sizes would be significantly higher, up to 60%. For example the yield strength of the P265GH grade steels of the study was about 40% higher than the standard requirement. In this case, with the same pressure test as above, the calculated critical sizes are respectively increased to 3 mm (50% wall thickness) and 9 mm (75% wall thickness).

6.1.3.2 Critical weld defect size for Group 8.1 steel

For Group 8.1 stainless steels the respective critical defect sizes are 50% higher than for Group 1.1 steels for similar vessel dimensions and P_t / $P_s \geq 1.6$. The project tests show that fatigue propagation is very low and no significant crack growth is reasonably expected if a vessel survives the pressure test, e.g. with P_t / P_s = 1.6 the fatigue life is always above 10 000 cycles for internal defects of up to 50% (wall thickness) or for embedded defects of up to 75% wall thickness. Even for a defect size up to 75% of the thickness (12 mm thickness vessel with inside weld removed) the required minimum number of cycles to rupture is obtained (also including the effect of moderate peaking of about 2 mm max).

6.1.4 Both defect size and peaking are to be considered together

For a given P_t / P_s ratio, the higher the peaking, the lower the acceptable defect size, and vice versa. For example for 500 mm diameter vessels with P_t / P_s = 1.75 and weld defect size less than 0,1 mm allowable peaking is 6 mm (calculated); for a defect size 50% wall thickness, peaking must be less than 3 mm (calculated). Shape imperfection effects are detailed below.

6.1.5 Weld residual stresses

Weld residual stresses have negligible effects for the ferritic material of the study.

6.2 Influence of shape deviations

6.2.1 Experimental results, confirmed by numerical modelling, show the peaking effect is very important and also excess weld metal at a minor degree

Other shape defects (out-of-roundness, misalignment) have a comparatively negligible effect. Negative peaking is favourable (compressive stress at the defect tip). Positive peaking generates additional bending stress, which increases the fatigue crack propagation rate.

6.2.2 Peaking has an important effect on the pressure test and the subsequent life of the vessels

It is shown that, depending on base material and weld properties (yield strength and ultimate strength), peaking must be less than 4 to 6 mm for 500 mm diameter vessels pressurised at $P_t = 2.1\ P_s$. Allowable peaking depends on the vessel wall thickness. It is minimum for a 3 mm thickness.

6.2.3 Peaking allowance should be reduced to a reasonable minimum

In view of the above results, peaking allowance as accepted by draft standard prEN 13445-4:1999 should be reduced to a reasonable minimum to take account of manufacture limits.

6.2.4 Potential improvement of shape deviation by the pressure test

The improvement of the shape deviation by the pressure test decreases with an increasing difference between the real and the nominal yield strength during the hydraulic test.

6.3 Pressure test procedure

Experimental results have shown that the pressure test procedure has a high influence on the subsequent fatigue life (pressure rise rate, hold time, number of test cycles). Two different procedures have been used, one consisting of one holding time of 30 minutes, the other two holding times of 10 minutes each. Both improve the fatigue life at sufficient P_t / P_s. However the present study does not allow to determine the best one, nor whether other procedures should improve the hydraulic proof test. This parameter should be investigated in another work.

7 RECOMMENDATIONS TO THE STANDARDISATION COMMITTEE

Concerning prEN 13445-5:1999 the following proposal is made for the performance of hydraulic test in testing Group 4:

7.1 Main recommendations

7.1.1 The hydrotest pressure factor has to be as high as possible

The following ratio of test pressure P_t to maximum allowed pressure P_s is proposed:

- For Group 1.1 steels $P_t = 2{,}2\ P_S \dfrac{f_a}{f_t}\ \dfrac{e_n}{e_n - c}$
- For Group 8.1 steels $P_t \geq 1{,}6\ P_S \dfrac{f_a}{f_t}$

7.1.2 Additionally, the maximum allowable peaking for longitudinal welds in testing Group 4 vessels should be lowered

For testing Group 4 vessels, values below those given in Table 5.4-2 (for static loads) in prEN 13445:1999 are recommended. Further details for maximum peaking values are recommended in the report.

7.1.3 Importance of visual inspection

Hydraulic pressure tests give a reasonable confidence in a lifetime of min. 500 cycles if they are performed in conjunction with a thorough visual inspection (inside and outside). In-service inspections can be developed to a predictive testing procedure and help to fulfil PED, Annex I, Clause 3.1.2: *"joints must be free of any surface or internal defects detrimental to the safety of the equipment".*

7.2 Further recommendations

7.2.1 Measurement of peaking

The 20° peaking gauge specified in prEN 13445-4:1999, clause 5.4.4, is not long enough if the peaking is more than $0{,}0075.d$ high. Draft standard prEN 13445 should be revised at this point.

7.2.2 Welded joints for nozzles

One-sided welded seams for nozzles or sleeves with outside diameters 65 mm are allowed, if the thickness of the weld is at least 1,5 times the thickness of the thinner part. In the case of two-sided welding, the weld thickness shall be ≥ 0.7 times the wall thickness of the thinner part.

7.3 Further work

Several important aspects would require further work. It is recognised that the beneficial effects of hydrotesting may be improved by further optimisation of the procedure. The roles of holding time and of the number of pressurisation cycles on yielding completion should be investigated.

8 DECISION OF THE STANDARDISATION COMMITTEE

Working Group E of CEN/TC 54 agreed upon the following alternative:

10.2.3.3.2 *For testing group 4 vessels the test pressure shall not be less than that determined by the following equations:*

For Materials of the Group 1.1:

if $c < 1$ mm

and (measured peaking + 0.5 excess weld) $\leq 0.5\ .\ e_{min}$

$$P_t = 2{,}2\ P_S \frac{f_a}{f_t}\ \frac{e_{min}}{e_{min} - c} \qquad \textit{(10.2.3.3.2-1)}$$

or

if $c \geq 1$ mm

and (measured peaking + 0.5 excess weld) $\leq 0.75 \,.\, e_{\min}$

and measured peaking $\leq 0.5 \,.\, e_{\min}$

and measured excess weld $\leq 0.75 \,.\, e_{\min}$

$$P_t = 2{,}0\, P_S \frac{f_a}{f_t} \frac{e_{\min}}{e_{\min} - c} \qquad (10.2.3.3.2\text{-}2)$$

where

$e_{\min}$ *is the minimum possible fabrication thickness of the section under consideration, as indicated on the drawings, see 5.2.3 of EN 13445-3:2002.*

c is the corrosion allowance, as indicated on the drawings.

For other symbols see 10.2.3.3.1.

The peaking may be measured after the hydrostatic test and the excessive weld may be measured after grinding if applied before the hydrostatic test.

For Materials of the Group 8.1:

if (measured peaking + 0,5 excess weld) $\leq 0.5 \,.\, e_{\min}$

$$P_t = 1{,}85\, P_S \frac{f_a}{f_t} \qquad (10.2.3.3.2\text{-}3)$$

9 CONCLUSION

HYDFAT has shown that it is possible to build safe pressure vessels for testing Group 4, meeting the requirement of sustaining 500 full pressure cycles or equivalent, by increasing the test pressure and reducing certain manufacturing tolerances, if the vessels are single-compartment and there is no risk of medium or environmentally assisted corrosion. The investigation was reasonably complete for vessels made of Group 1.1 ferritic steels, and it was possible to make firm recommendations. However, more tests on Group 8.1 austenitic stainless steel vessels would be necessary to justify the above recommendations.

In their deliberations, the Standardization Committee members have considered the combined effect of the two parameters, the test pressure and the manufacturing tolerances. Only further practice will enable the best combination to be chosen, because to date there is no systematic evaluation of the manufacturing tolerances for a given production unit. Experience feedback of other countries would be extremely useful.

The first edition of EN 13445 published in May 2002 includes the revised paragraph on the pressure test of testing Group 4 unfired pressure vessels. This is a remarkable example of cooperation between EPERC and CEN, with the support of the European Commission.

The adoption of an increased test pressure does not, in general, lead to an increase in the thickness of components if they are designed with a joint efficiency of 0.7. However, it will require an increase in thickness for all other components. This clearly shows that the manufacturer has two possibilities to build safe pressure vessels: performing a high pressure test with a reduction in manufacturing tolerances without NDT, or performing NDT and building thinner pressure vessels under other testing Groups than 4. His goal will be to choose the best solution for his particular equipment and experience.

In its instructions for use, the manufacturer of a testing Group 4 vessel should recommend that the vessel be visually inspected when the allowable number of 500 full pressure cycles or equivalent is reached, followed by a pressure test at a pressure equal to that used for the initial pressure test. This sequence may be repeated as long as the visual inspection reveals no evidence of fatigue cracking and the pressure vessel passes the pressure test.

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