EXPERIMENTAL STUDY OF A SPHERICAL PWR-CONTAINMENT WITH GEOMETRICAL IMPERFECTIONS AT THE WELDS

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It is the purpose of the experimental investigation described in this paper to study the influence of the additional stresses caused by a mismatch of the shell plates which cannot be avoided in real structures. The paper is an extract from [1]. The spherical shell model had a diameter of 2.6 m and a thickness of 30 mm. The load was internal pressure. High strength steel StE 51 with a minimum yield limit of 500 N/mm^2 was used. At one circumferential weld the plates had intentionally a mismatch between 1.0 and 4.6 mm. At a second circumferential weld a heart-shaped imperfection (necking) was intentionally induced using the same welding conditions. The deviation of the regular shape was between 3.8 and 6.3 mm based on a measuring length of 500 mm. Unfavourable welding conditions were chosen. Some of the basic electrodes used were not dried before welding.

The internal pressure was increased up to 1.62 times the test pressure of the containment. In this case with a maximum pressure of 220 bar the primary membrane stresses reached a value of 477 N/mm^2. Strains were monitored at the internal and external surfaces of the imperfect weld zones. In addition a complete analysis was performed based on the linear bending theory for thin shells. There was a satisfying correlation between the theoretical bending stresses and the stresses based on the strain control in the test.

The following conclusions may be drawn: Despite remarkably plastic deformations no damage could be recognized in any part. In large regions of the model the total strains measured reached values up to 0.7 percent. During the finishing process the thickness of one weld part was mistakenly reduced resulting in a maximum measured strain of 2.1 %. There too no severe damage could be recognized.

1. Scope of the Study

It is the purpose of the experimental investigation described to supplement to the regular acceptance tests usually performed under uniaxial conditions a test with a biaxial stress state giving a much better representation of the real structure. The spherical shell model consists of high strength steel St E 51 (BH 51 WS) with a minimum yield limit of 500 N/mm^2. The pressure load was increased to $\nu = 1.5$ times of the maximum service load (test pressure) without resulting in unacceptably large deformations or any kind of damage for the imperfect structure; a procedure in civil engineering corresponding to the usual design principle based on a second order analysis.

2. Description of the Model Sphere and the Geometric Imperfections

Figure 1 shows the spherical model shell together with its main dimensions. It was planned to increase the curvature of the panels beside the circumferential seam weld III getting a heat-shaped imperfection (necking) of 5 mm based on a measuring length of 500 mm. Finally in the specimen imperfections of 3.8 and 6.3 mm were measured at this weld.

Systematically the plates beside the circumferential seam IV should have a mismatch of 3 mm. In the model this value varied from 1.0 to 4.6 mm, in large parts of the weld from 3.4 to 4.0 mm.

3. Material

The model sphere was made out of 30 mm thick dished plates with unfavourable NDT-temperatures originally designated for the containment of a nuclear reactor plant.

Table 1 shows some data of the material used for the sphere. As filler material the basic Tenacito 60 electrodes (Oerlikon) were used. The electrodes should be used in two ways. Fully dried with 4 ml/100 g weld metal and also under "humid" conditions with about 7 ml/100 g weld metal. These humid electrodes were taken from special air-sealed containers and welded without drying usually done for two hours at a temperature of 300 °C. The average relativ humidity checked in the moisture-test was 5.2 ml/100 g weld material for the dry electrodes and 7.3 ml/100 g for the humid electrodes, respectively. The maximum value was 10.2 ml/100 g. The preheat temperature was taken as 100 °C, 150 °C and 220 °C.

For the model sphere 6 production test coupons varying the specified welding conditions were prepared. The base metal showed the lowest notch toughness. Like required by the ASME-code the energy absorbed of 68 J for the ISO-V transverse test specimen was reached in the upper plateau, however, the ambiant temperature was already in the transition zone. For the notch toughness of the weld metal and of the heat-affected zone the value of 68 J (in the upper plateau) was met for the dry and humid electrodes under all preheat conditions. The transition zone was much better than for the base material. Thus it can be stated that the 68 J are reached for the lowest temperature of $5^{o}C$ present at the pressure test. There was no distinct interdependence on the degree of humidity and preheat temperature. After all the C_V-T-curve of the humid electrodes showed up the lowest upper plateau for preheat temperatures of $100^{o}C$ and $150^{o}C$.

For the weld material specimen the NDT-temperatures lie in between $- 60^{o}C$ and $- 70^{o}C$. Controlling the heat affected zone the results of only two specimen could be considered. In all other specimen the crack initiation could not be attained in the heat affected zone. The NDT - temperatures of $- 50^{o}C$ and $- 60^{o}C$ were considerably better than the temperatures of the base material where $- 5^{o}C$, $- 20^{o}C$ and $- 30^{o}C$ were obtained. The range of temperatures was $- 35^{o}C$ and $- 55^{o}C$ for those specimen in which the crack initiation was not definitely located in the heat affected zone. Probably they were influenced by the base material.

A definite numerical correlation of NDT-temperature and notched bar impact strength is obviously problematic. Just the plate with the worst NDT-temperature of $- 5^{o}C$ showed generally the best impact strength in a later test of the dished plates.

The hardness obtained in the weld material of the specimen reached HV 10 values between 205 and 245. The corresponding values in the base material were a little bit lower. Extreme hardness was found in the coarse-grained part, especially on the surface layer. Here values between 309 and 376 HV 10 were obtained despite a welding procedure based on the temper-bead-technique. Even an extreme value of 440 HV was measured in a weld of the model sphere welded with humid electrodes. But also in regions where dry electrodes were used values of more than 380 HV 10 were found.

4. <u>Test Data</u>

The test pressure of the containment transformed to the size of the model comes to $p_{Pr} = 136$ bar. Taking the $\nu = 1.5$ times load increase this results in the required internal pressure of $p_V = \nu \, p_{Pr} = 1.5 \cdot 136 = 204$ bar. In addition this pressure was increased to $p_V = 220$ bar during the test. This signifies a load increase of $\nu = 220/136 = 1.62$ instead of the required 1.5. The maximum primary membran stress comes to $\sigma_V = \frac{220/10 \cdot 130}{2 \cdot 3.0} = 477 \ N/mm^2$. The yield stress of the base material obtained in the tests meets with 517 and 498 N/mm^2 (see table 1) the specified value of 500 N/mm^2. Thus $\sigma_V/ß_{0.2} = 477/500 = 0.95$ referred to this yield limit which means that 95 % of the yield stress was reached in large areas of the unreinforced shell during the test. Even yielding occurred in many locations of the model sphere before the yield limit found in tension tests was obtained; a fact which could be observed at several strain gauges attached to the shell far away from weld seams or discontinuities.

At the circumferential weld III the strains were monitored at three meridian sections with imperfections (necking) of 5.0, 6.0 and 6.2 mm. During the reloading all strain control points showed a nearly linear characteristic so that elastic total stresses up to 850 N/mm^2 could be determined at the meridian 8. The yield limit of 500 N/mm^2 is exceeded by 850/500 = 1.70, i.e. 70 %; this is slightly above the allowable stress of $2.0/1.2 \cdot ß_{0.2} = 1.67\ ß_{0.2}$ recently introduced in Germany when primary and secondary stresses occur simultaneously.

The graphs of loading and reloading show a positive behaviour with only a slight hysteresis. Thus in the sense of a shake-down response the maximum loading conditions could occur several times without damaging the structure. Smaller elastic total stresses were observed at the lower welding seam IV with the systematic mismatch of the neighbouring plates. Still maximum stresses of more than 700 N/mm^2 were measured. In larger parts of the intentionally imperfect welds total strains up to 0.7 % were measured.

Accidentally during the grinding process the thickness at the circumferential weld II was locally reduced about 7.5 mm. Here the pressure - strain plots for loading and reloading showed again nearly straight characteristic. Thus it may be concluded that at a sharply notched weld some loading cycles are allowable even if the sum of primary and secondary "elastic" stresses exceed two times the yield limit. In this case the total strains measured were 2.1 %.

When the maximum load of 220 bar was applied the temperature in the shell plates was between 4,9°C and 5,5°C. Hence this corresponds to the lowest temperature of 5°C at which the pressure test of the real containment is performed.

5. Comparison of the Experimental and the Analytical Results

A linear elastic finite element analysis [2] was performed for the imperfect spherical shell. The calculation of the circumferential weld III was done for the geometry of the meridian 27 shown in figure 2 a. The calculated stresses in meridional direction are plotted in figure 2 b. The experimental data at the external surface of the meridian 27 is also added. The geometric deviations of meridian 13 with a maximum distortion of 2.9 + 1.7 = 4.6 mm (shown in figure 3 a) were taken for the circumferential weld IV. Experimental and analytical meridional stresses of both internal and external surfaces of the shell are shown in figure 3 b.

In table 2 the maximum stresses calculated in the 30 mm plates are compiled for the imperfect circumferential welds classified as membrane and bending stresses.

The maximum stresses calculated fairly agree with the stresses of the experiment. Only the maximum values at the equator weld III deviate. Here the experimental bending stresses reach values in between 320 and 370 N/mm^2. The smaller bending stresses of the analysis are caused by the smoother model used for the geometric imperfection.

6. Summary

The model shell was completely welded by hand. The conditions were the same existing on site during the erection of the real containment. The preheat temperatures of $100^{\circ}C$, $150^{\circ}C$ and $220^{\circ}C$ lie within the range of the corresponding temperatures during construction. One part of the welds was manufactured with perfectly dried electrodes based on the requirement of the specification. The other part was welded with improperly dried so-called "humid" electrodes. The existing geometric imperfections were somewhat larger than specified. This is valid for both the heart-shaped imperfection (necking) as well as the mismatch of the adjacent plates.

The maximum internal pressure applied in the model test was p_V = 220 bar. The test pressure of the containment was insofar increased to the value of $\nu = 1.62$.

Within the experiment extreme stress and strain situations were produced. The membrane stresses of the unreinforced shell nearly reached the yield limit of the high strength steel used. The bending stresses in large parts of the weld zones come to more than 50 % of the yield stress. Total strains up to 0.7 % were measured at several welds. Even a total strain of 2.1 % was found in one portion of a weld where the thickness was accidentally reduced.

Although the degree of hardness measured in the coarse-grained parts of the weld seams reached the maximum values of 440 HV 10 no damage could be observed during the test.

Finally it may be concluded that with this test the official requirement for civil engineering structures with a safety factor of $\nu \geq 1.5$ could be satisfied whereby the limits of all relevant manufacturing conditions were considered.

References

[1] BORNSCHEUER, F. W., "Gutachten über die Verwendung des Stahles BH 51 WS für die Sicherheitshülle des Kernkraftwerks Süd", 10. Zwischenbericht vom 17.3.1978 und Schlußbericht vom 27.4.1978.

[2] BORNSCHEUER, F. W. und J. M. SÄTTELE, "Modellkugelversuch aus Werkstoff W St E 51 für den Reaktorsicherheitsbehälter des Kernkraftwerks Süd 1 vom 12.2.1978".

Table 1: Material data taken from [1]

Plates No.	8035	8179	8179	
$ß_{0,2}$ [N/mm²]	(T) 550 * (H) 558 *	(T) 551 535 * (H) 572 552 *	longitudinal transverse	⟨517⟩ ** ⟨498⟩ **
$ß_B$ [N/mm²]	(T) 735 * (H) 755 *	(T) 751 724 * (H) 777 747 *	longitudinal transverse	⟨710⟩ ** ⟨625⟩ **
C_V (ISO-V transverse) at - 20°C [J]	(T) 50/40/38 33/30/37 (H) 54/50/52 33/43/41	(T) 31/32/32 30/26/33 (H) 35/42/24 28/34/32		⟨42⟩
NDT - temperature	- 5°C	- 20°C		⟨- 30°⟩

(T) ≡ tail }
(H) ≡ head } taken from the dished plates
⟨ ⟩ taken from the production test coupon

*) diameter of specimen 14 mm
**) diameter of specimen 10 mm

Table 2: Calculated stresses - dimension: N/mm²

	Weld III	Weld IV
meridional direction		
membrane stress	479,7	479,7
bending stress	± 252,7	± 234,0
hoop direction		
membrane stress	561,0	507,7
bending stress	∓ 76,0	∓ 56,7

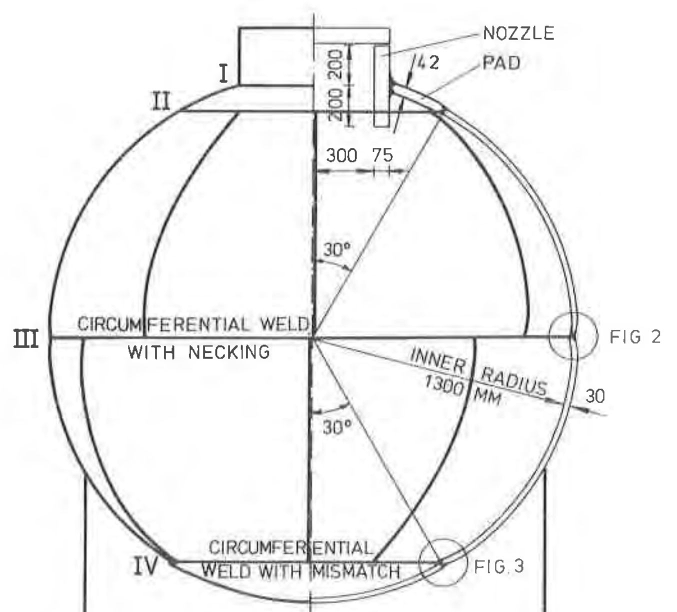

FIG 1 SPHERICAL MODEL SHELL

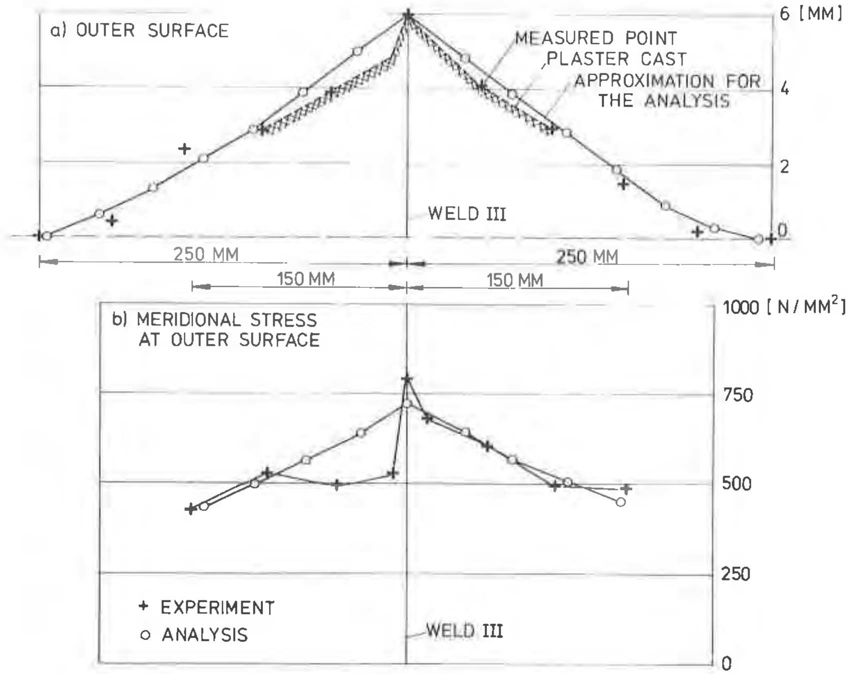

FIG. 2 COMPARISON EXPERIMENT / ANALYSIS FOR WELD III (MERIDIAN 27)

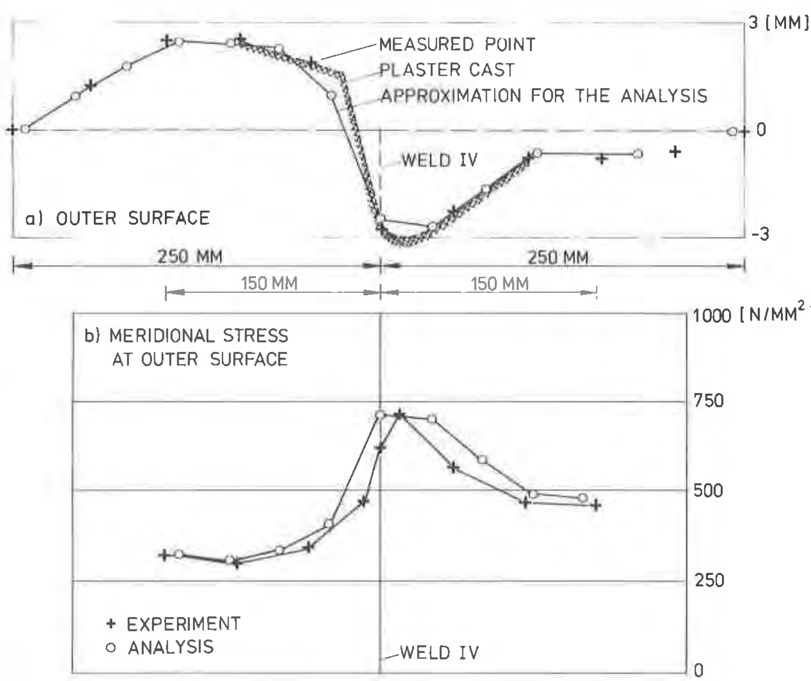

FIG. 3 COMPARISON EXPERIMENT / ANALYSIS FOR WELD IV (MERIDIAN 13)