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CONCEPT STUDY FOR A COMBINED REINFORCED CONCRETE CONTAINMENT

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ABSTRACT

A variety of different steel and concrete containment types had been designed and constructed in the past. Most of the concrete containments had been prestressed offering the advantage of small displacements and certain leak tightness of the concrete itself. However, considerable stresses in concrete as well as in the tendons have to be maintained during the whole lifetime of the plant in order to guarantee the required prestressing. The long-time behaviour and the ductility in case of beyond design load cases must be verified. In contrary to a prestressed containment a reinforced containment will only significantly be loaded during test conditions or when needed in case of accidents. It offers additional margins which can be used especially for dynamic loads like impacts or for beyond design considerations.

The aim of this paper is to show the feasibility of a so-called combined containment which means capable to resist both - severe *internal* accidents and *external* hazards mainly the aircraft crash impact as considered in the design of nuclear power plants in Germany.

The concept is a lined reinforced containment without prestressing. The mechanical resistance function is provided by the reinforced concrete and the leak tightness function will be taken by a so-called composite liner made of non-metallic materials. Some results of tests performed at SIEMENS laboratories and at the University of Karlsruhe which show the capability of a composite liner to bridge over cracks at the concrete surface will be presented in the paper.

The study shows that the combined reinforced concrete containment with a composite liner offers a robust concept with high flexibility with respect to load requirements, beyond design considerations and geometrical shaping (arrangement of openings, integration with adjacent structures). The concept may be further optimized by partial prestressing at areas of high concentration of stresses such as at transition zones or at disturbances around big openings. Such investigations are under way.

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1. INTRODUCTION

The German Nuclear Power Plants mostly have a spherical steel containment designed for Loss of Coolant Accidents (LOCA). The steel containment is covered by a secondary reinforced concrete containment to get a double confinement function. The design of this outer shell is governed by external events like aircraft impact and external explosion pressure wave leading to wall thicknesses of up to 2.00 m.

The Boiling Water Reactor of KRB II Gundremmingen has a prestressed concrete containment with a steel liner. The containment contains the reactor pressure vessel and the pressure suppression system. It is also covered by a secondary non prestressed reinforced concrete containment.

Based on the experience gained with these types of containments studies had been performed to find improved solutions.

The principal aim of the work presented here is to examine the feasibility of a so-called "combined containment" which means capable to resist both severe *internal* accidents and *external* hazards, mainly the aircraft crash impact as considered in the design of nuclear power plants in Germany.

2. RATIONALE OF THE CONCEPT

The proposed concept follows the idea to have a clear decoupling between the mechanical resistance function provided by reinforced concrete and the leak tightness function provided by a liner, which may be either made of steel or made of non-metallic materials - a so-called "composite liner".

Contrary to a fully prestressed containment (with or without liner), where considerable stresses in concrete as well as in tendons have to be maintained during the whole lifetime of the plant, a reinforced concrete containment will only significantly be loaded during test conditions or when needed in case of accidents.

The wall thickness and the tensile reinforcement needed for the pressure test at a design pressure of round about 5 bar (rel) being derived from a LOCA (Loss of Coolant Accident) is already high enough to carry loads due to the impact of the aircraft to be considered in Germany leading to protective reinforced concrete structures with wall thicknesses of about 1.60m to 2.00m.

Thus, a reinforced concrete containment designed for LOCA, already offers a robust concept for other accidental load cases as well. Due to the ductility of non prestressed reinforced concrete and a properly designed composite liner, there are additional margins for "beyond design" considerations with respect to ultimate bearing capacity and leak tightness. Such "beyond design" events are under discussion in combination with Severe Accidents as a consequence of hydrogen. For example, controlled leak tightness may be required after Severe Accidents, producing higher pressures than LOCA.

By adding additional reinforcement or replacing regular reinforcing steel by steel with higher ultimate bearing capacity the margins with respect to Severe Accidents can be extended as far as needed. In this concept study 15 bar (rel) internal pressure has been assumed as an upper bound at which leak tightness still has to be maintained.

3. GENERAL DESCRIPTION OF THE CONCEPT

The analysis and design of the containment concept is based on the configuration shown in Fig. 1. The containment is founded on the common foundation slab bearing also the annular building. The cylindrical part is closed by a hemispherical shell and connected to the outer structure of the annular building providing the protection against aircraft impact. The containment has an inner diameter of 45,00 m, an inside height at the centre line of 63,00 m, a wall thickness for the dome and cylinder of 2,00 m and a foundation slab thickness of appr. 4,00 m, depending on the soil conditions.

The leak tight barrier between the containment atmosphere and the environment is an internal liner.

All the openings and penetrations are arranged at the cylindrical part of the containment. This area is covered by the annular building and will be maintained under subatmospheric pressure in order to allow an integral leakage control. The dome of the containment is not disturbed by any penetrations. If, nevertheless, a leakage control system should be arranged at the outer surface of the dome, this can be verified in combination with weather protection or by a thin outer shell of concrete, forming a controlled space between the containment wall and the environment. However, no resistance against aircraft impact is required for this cover.

4. STRUCTURAL ANALYSIS

4.1 Loading Conditions

Preliminary design calculations of the reinforced concrete containment were performed considering the following loading conditions. All pressure values are given in bar relative, that means 1 bar (rel) equals 0.1 MPa.

- Design pressure: p_d = 5.3 bar (rel)
- Subpressure: P_s = 0.2 bar (rel)
- Pressure at ultimate structural integrity: up to P_u = 15 bar (rel),
- corresponding temperature at liner surface: T_u = 150°C
- Aircraft impact: 110 MN peak load; 7 m² impact area; 70 ms impact duration (acc. to German guidelines)
- Design earthquake: a_h = 0,25 g; a_v = 0,125g
- Dead and live loads

4.2 Internal Pressure

A parametric study was carried out assuming that the most significant load for design of the containment is a pressure of 15 bar (rel) at ultimate structural integrity and at pertinent temperature. Due to the carrying disability of concrete subjected to tension, the total tensile force must be carried by rebars.

The values of strain at the ultimate bearing capacity are linked to the nominal yield point, which is for regular reinforcing (BSt 500 S) 2,38 ‰ and for special reinforcing (BSt 1100) 5,24 ‰.

Verifications at ultimate limit states, based on non-linear structural analysis methods or on a modified yield line theory are based on these strain values. These verifications will govern the design and supply the necessary amount of reinforcement. The working strains related to the design pressure of 5,3 bar (rel) are considerably lower.

4.3 Design Earthquake

Response-spectrum and time-history-modal-analysis were used to check the containment bearing capacity considering the before mentioned design conditions. Additionally, increased ground acceleration values up to 0,35g have been investigated.

With the large foundation slab and the integrated arrangement of containment and annular building, no problems with respect to earthquake design will occur.

4.4 Aircraft Impact

The aircraft impact analysis of the containment has been performed according to German practice. The provided thickness of 2,00 m ensures a full protection of the components against spalled pieces of concrete and against burning kerosene.

Several characteristic impact cases covering extreme vertical, horizontal and oblique impact directions were considered. In order to check the influence of non-linear effects at the impact zone, the linear-elastic time-history analyses were completed by corresponding non-linear analyses. The required reinforcement for any impact case is much lower than the reinforcement necessary to cover design pressure load cases.

4.5 Dimensioning Of Wall Thickness And Reinforcement

The required wall thickness is mainly determined by the construction, considering the spacing of reinforcement in order to ensure an efficient compaction of concrete.

The dimensioning had been performed according to the German rules, in particular DIN V 25459 German DIN-Norm "Reinforced and Prestressed Concrete Containments for Nuclear Power Plants".

A possible arrangement of the necessary reinforcing steel at the undisturbed area of the cylindrical part of the containment shell is shown in Fig. 2, using relatively small rebar diameters in order to achieve a good distribution of tensile cracks at the concrete surface, which carries the liner.

This arrangement is based on a design pressure of 5.3 bar (rel) using only regular steel BSt 500. The ultimate bearing capacity of such a design is round about 9 to 10 bar (rel). The shear reinforcement is mainly necessary for the aircraft impact and may be reduced at areas where a direct impact is not to be considered due to protecting adjacent structures.

For an ultimate bearing capacity of 15 bar (rel) the sole use of regular steel is no longer economic. A better solution is to replace it with special reinforcing steel BSt 1100 having an ultimate bearing capacity 2.2 times higher than regular steel. Such a steel is licensed in Germany. It has been mainly applied under economic reasons reducing the necessary amount of bending reinforcement in the structures designed against aircraft impact.

Using such steel BSt 1100 an ultimate bearing capacity of 15 bar (rel) can be achieved with the following reinforcement, being less than the amount shown in Fig.2:
Dome and cylindrical part (horizontal) 154 cm^2/m,

e.g.	2 layers ∅ 20 BSt 1100	a = 20 cm
	2 layers ∅ 28 BSt 1100	a = 20 cm
	4 layers ∅ 28 BSt 1100	a = 40 cm

Cylindrical part (vertical) 307 cm^2/m,
e.g. 10 layers BSt 1100 a = 20 cm

Similar reinforcement densities had been evaluated and executed for reinforced concrete containments in USA, designed according to ASME "Boiler and Pressure Vessel Code, Subsection CC, Concrete Containment" e.g. Ref. [2].

5. LINING SYSTEM

The leak tightness will be ensured by a liner which may be a conventional steel liner, fixed to the concrete wall by means of mild steel anchorage.

Investigations are in progress to find non-metallic materials to be alternatively used as a so-called composite liner. Several lining materials consisting mainly of glass-fibre reinforced plastics (GRP) have been evaluated and tested.

One promising material is based on Palatal which is a registered trade mark of BASF. Palatal is a reactive resin based on unsaturated polyesters (UP), vinyl esters (VE) and a monomer usually styrene. It is a so-called thermosetting reactive resin. As compared to thermoplastics which can be re-used after they have solidified simply by heating them again, thermosets under go a chemical reaction during moulding, called curing after which they can no longer be moulded. Thermosets mouldings are distinguished for their high resistance to mechanical, physical and chemical influences. They can be tailored to most requirements.

Based on theoretical investigations an upper bound of crack widths to be expected at ultimate bearing capacity at a pressure of 15 bar (rel) lies in the order of 3 mm. This value may be further reduced by crack distributing reinforcement consisting of small diameter rebars arranged at the outer concrete surfaces or by concrete with higher strength.

In order to check the capability of the composite liner to bridge over cracks at the concrete surface, series of tests at SIEMENS laboratories and at the University of Karlsruhe have been performed. The test installation used at the University of Karlsruhe is shown on Fig. 3 and 4. Pictures of the liner during testing at different crack widths are presented at Fig. 5 and Fig. 6.

Typical results, showing the relationship between strain of the liner material and crack width at the concrete surface, are presented in Fig. 7.

It could be demonstrated that cracks up to 8 mm width could be bridged over if the liner has been properly built up.

6. CONSTRUCTION TIME OF THE REACTOR BUILDING

A total construction time of seven months is evaluated for the reactor building raft. The polar crane can be installed after 22 months and the heavy components can be erected after 25 months. The concreting work of the reactor building including the annular building will be finished after 37 months. The outer thin shell above the dome is not considered, as it can be constructed later without interference to other activities.

7. POSSIBLE DESIGN MODIFICATIONS

7.1 Integration With Adjacent Structures

Several alternatives have been studied with respect to the arrangement of adjacent structures. Besides the annular building concept a design with rectangular shaped adjacent buildings is considered. In order to protect these structures against aircraft crash they will be covered by reinforced concrete walls and roofs decoupled from its inside structure in order to reduce induced vibrations in case of an impact.

From a civil engineering point of view an annular building with an outer ringwall and a roof shaped as a through-going flat disc integrated to the containment shell at the transition from the cylindrical to the spherical part as shown in Fig. 1 is the optimum solution.

The main benefits of such a design are:

- Avoiding or minimizing stiff corners being detrimental with respect to dimensioning against induced vibrations in case of aircraft impact.
- Saving supporting structures which otherwise would be necessary to transfer the dead loads and the aircraft impact loads via the roof of the annular building to the foundation slab.

- Higher resistance of the integrated structural system in case of extreme earthquake loads.

However, it is obvious that prior to a decision with respect to an integration other aspects like layout and costs had to be assessed. A combined free-standing containment without integration to surrounding structures is feasible as well.

It should be mentioned, that an integrated reinforced concrete containment for an Advanced Boiling Water Reactor is under construction in Japan since 1991, Ref. [1].

7.2 Partial Prestressing

From economic point of view it may be beneficial to partially prestress the reinforced concrete containment at areas of high concentration of loads such as at transition zones or at disturbances around big openings. Another aspect may be the wish to keep the major part of the concrete under compression during the pressure test in order to limit early cracking.

In horizontal direction the forces due to internal pressures are twice as high as in vertical direction and as in the containment spherical part. Therefore it might be economic to partially prestress only in the horizontal direction bearing in mind that the dome and the integrated roof of the annular building already provide certain vertical prestressing forces due to their dead load.

The amount of partial prestressing depends on a variety of boundary conditions, e.g. load scenarios, test conditions, licensing requirements and last but not least cost evaluation.

A very flexible system to provide additional prestressing, especially in the horizontal direction, is the DYWIDAG monostrand unbonded post-tensioning system, see Fig.8. This system uses individually sheathed and greased bare or galvanised strands directly embedded in the concrete cross section with the advantage of minimal prestressing losses due to friction. Opposite ends of the tendons are anchored in a floating steel block which is embedded within a pocket at the inside of the concrete shell. The main features of such a system are:

- Simultaneous stressing and anchoring of up to 20 individual strands
- Elimination of buttresses
- Minimum size of blockout
- Saving of material due to minimal prestressing friction losses

8. CONCLUSIONS

The following conclusions are drawn based on the performed concept study of a combined reinforced containment:

- The containment design with the assumed integrated configuration is feasible and capable to withstand the postulated loading conditions (pressure, temperature, earthquake, aircraft impact).

- The reinforced containment wall, as designed for design pressure conditions (in the range of 5 bar (rel)), can also withstand an aircraft impact as specified by German rules, without additional bending reinforcement.

- Based on the studies performed to date, non-metallic liner materials seem to be more beneficial than conventional steel liners, constructed up to now in Germany.

- The combined reinforced concrete containment means a robust concept, offering high flexibility with respect to load requirements, "beyond design" considerations, and geometrical shaping (arrangement of openings, integration with adjacent structures).

- Partial prestressing may be beneficial.

REFERENCES

[1] Saito H. et al.," Post-Test Analysis of a 1:10 - Scale Top Slab Model of ABWR/ RCCV Subjected to Internal Pressure ", Fifth Workshop on Containment Integrity, Washington DC 1992, NUREG/CP-0121 SAND-0173 pp.227-243.

[2] Sawhney P.S. et al., "Integrated Reactor Building/Containment Design of a Simplified Boiling Water Reactor (SBWR) Plant", 10th SMiRT Vol.H pp.61-66 .

FIGURES

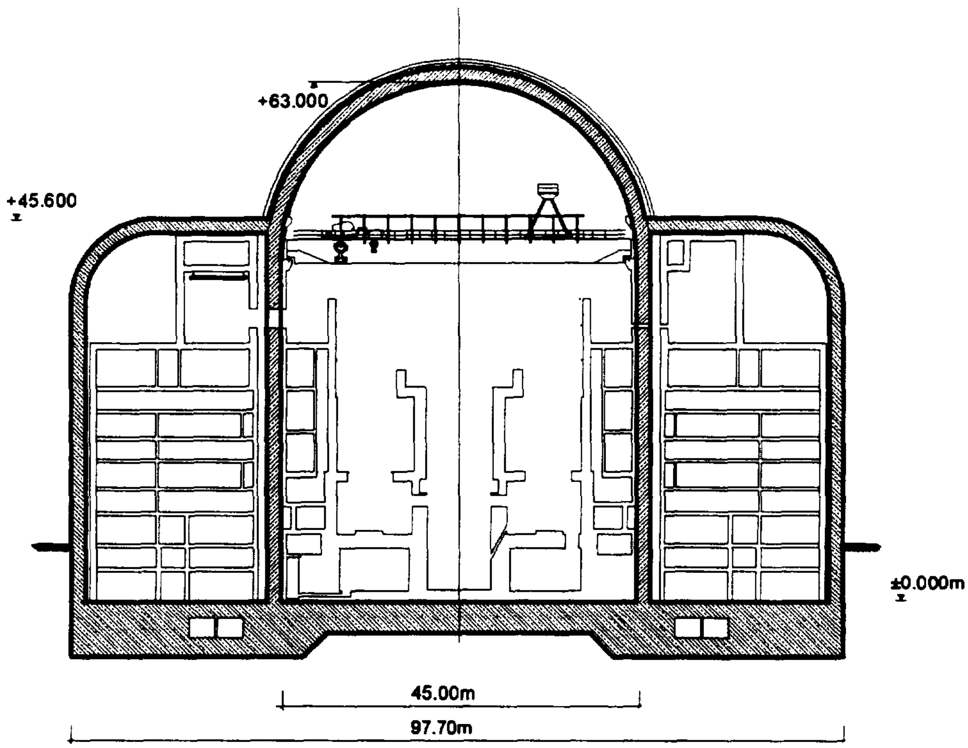
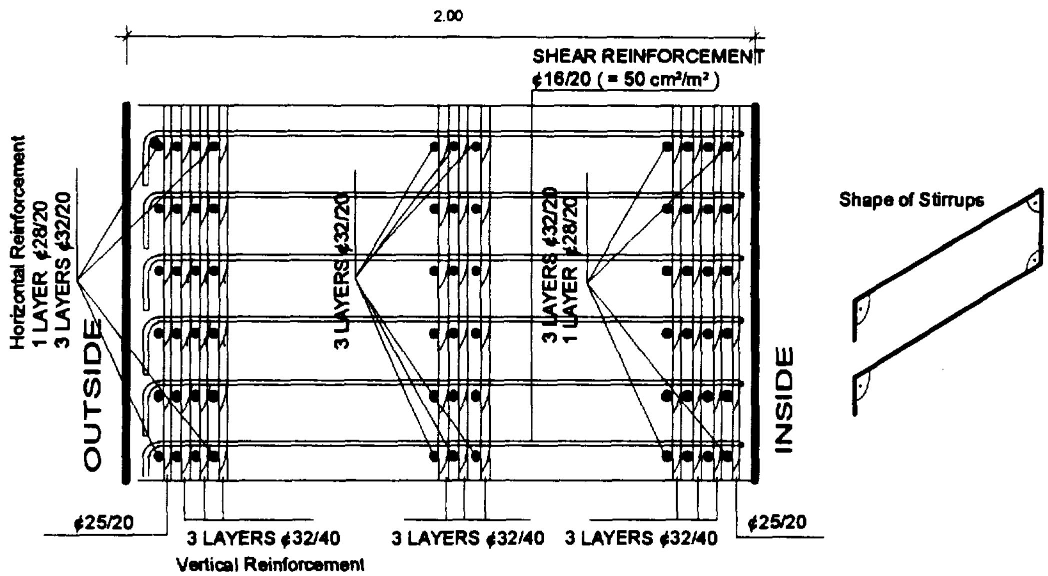


Fig. 1 Arrangement of the combined reinforced concrete containment



HORIZONTAL REINFORCEMENT	VERTICAL REINFORCEMENT
2 Outer Layers ϕ28/20	2 Outer Layers ϕ25/20
9 Inner Layers ϕ32/20	6 Inner Layers ϕ28/40
(= 423 cm²/m)	3 Inner Layers ϕ32/40
	(= 202 cm²/m)

Fig. 2 Typical arrangement of reinforcement at the cylindrical part

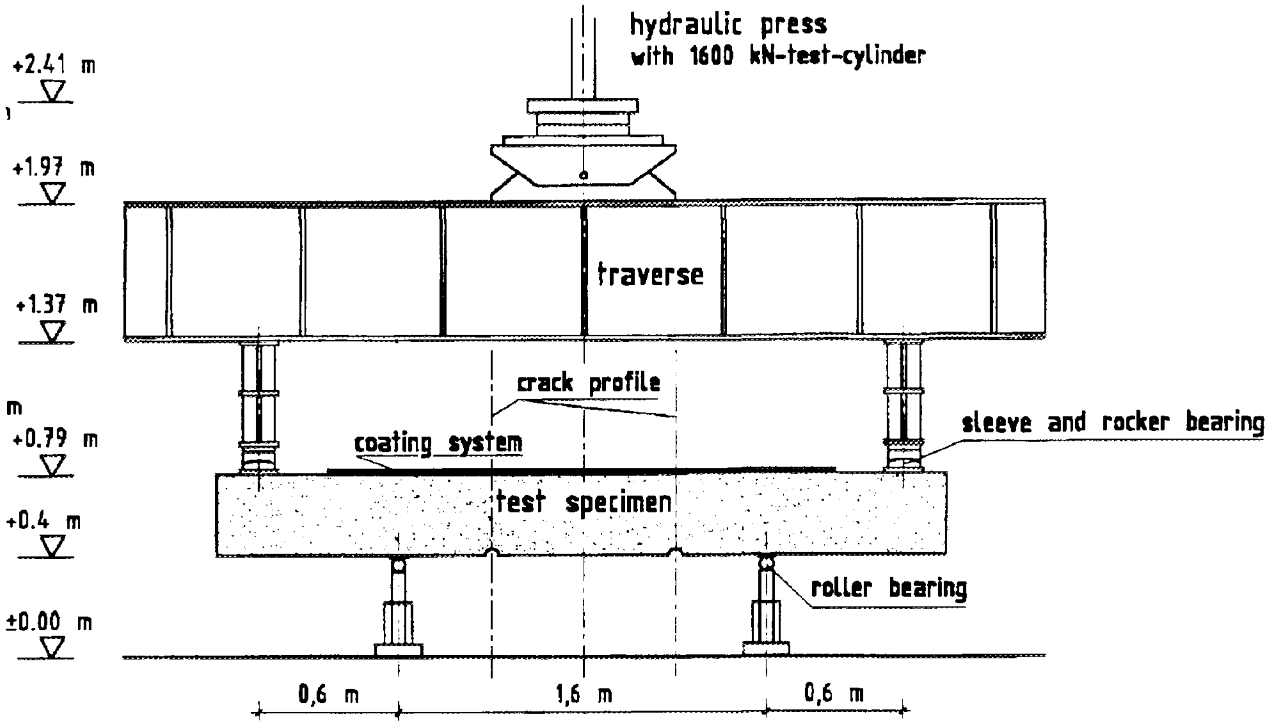


Fig. 3 Composite liner test installation

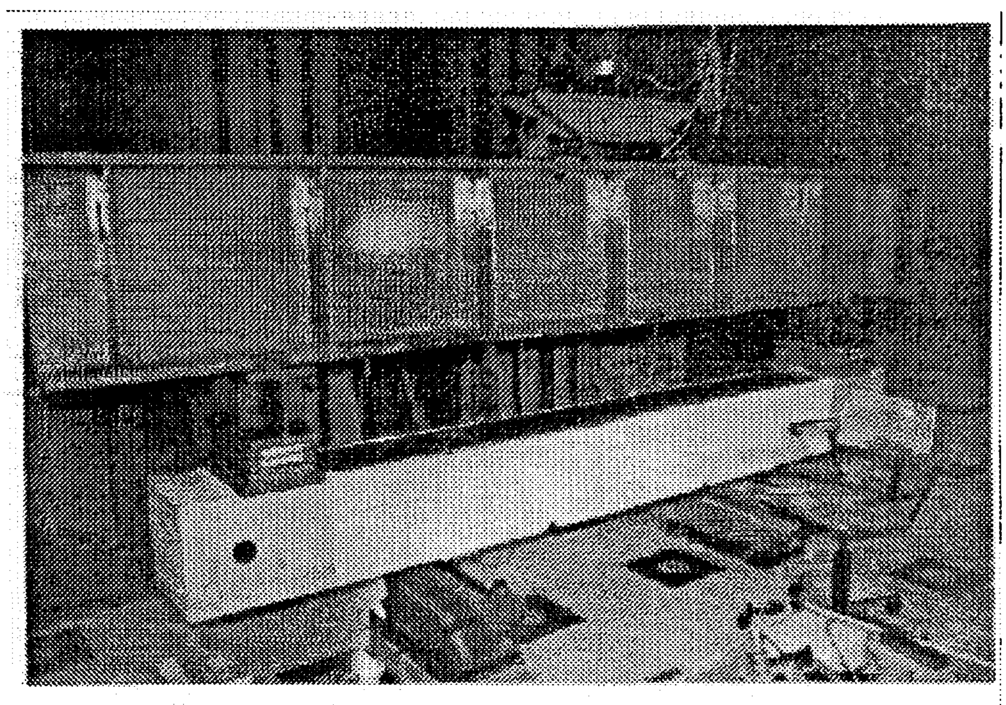


Fig. 4 Test specimen at the laboratories of Karlsruhe University

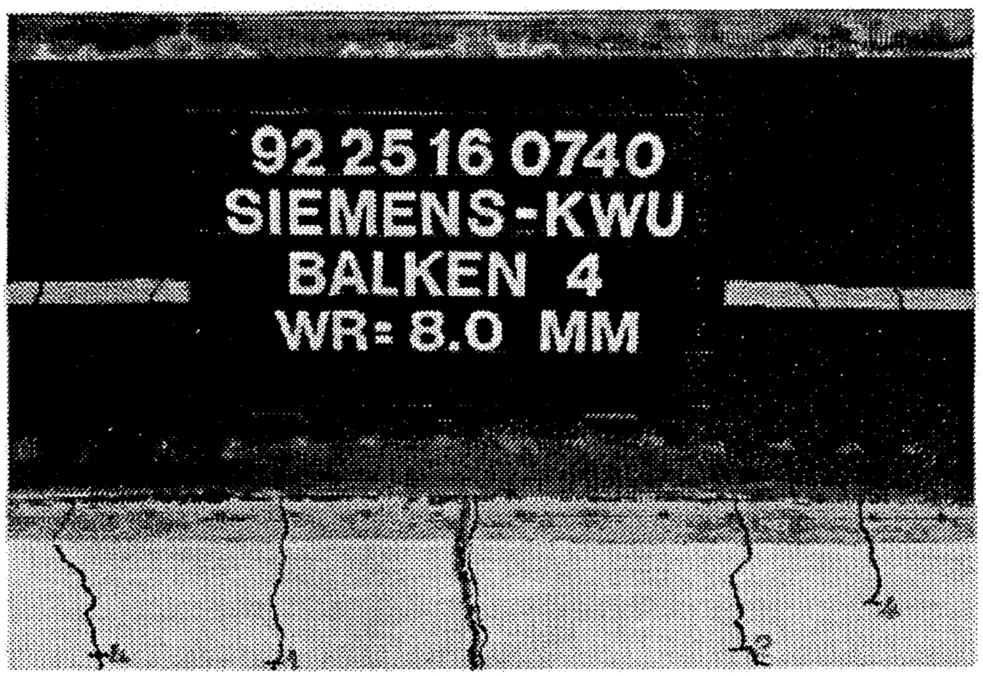


Fig. 5 Composite liner during test - crack width of 8 mm without failure

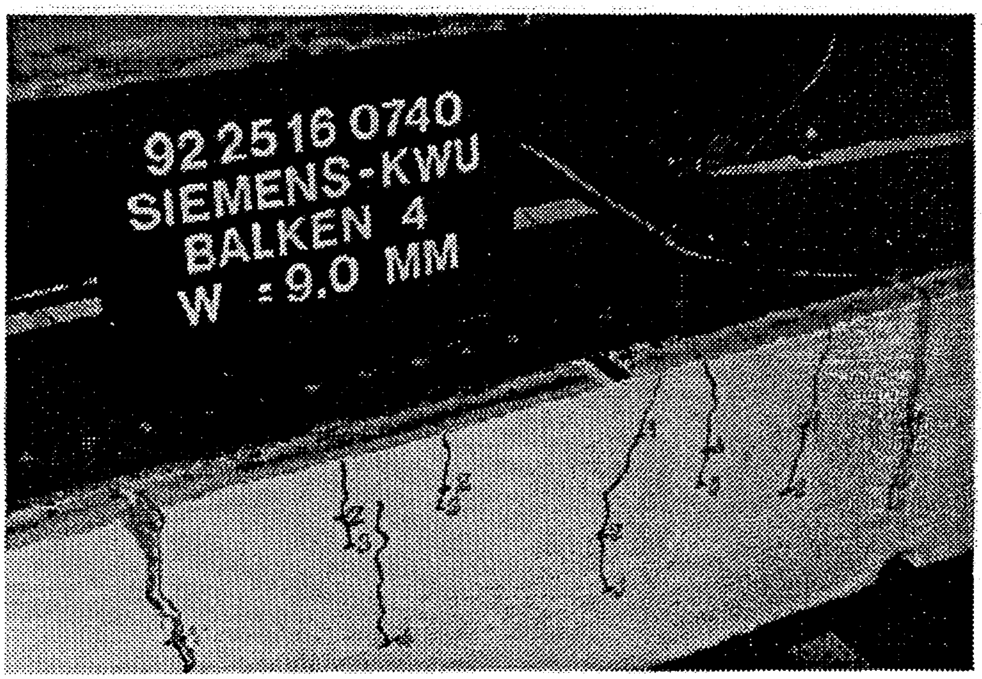


Fig. 6 Composite liner during test - crack width of 9 mm after failure

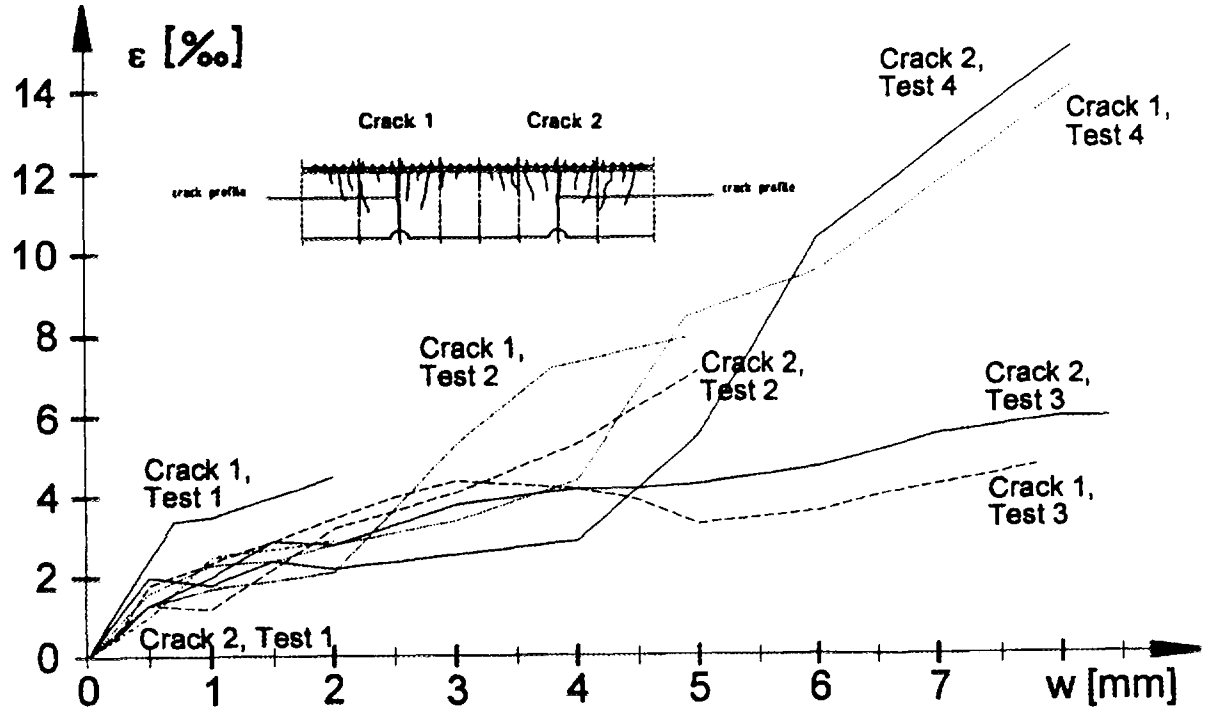


Fig. 7 Strain in the composite liner as a function of crack width

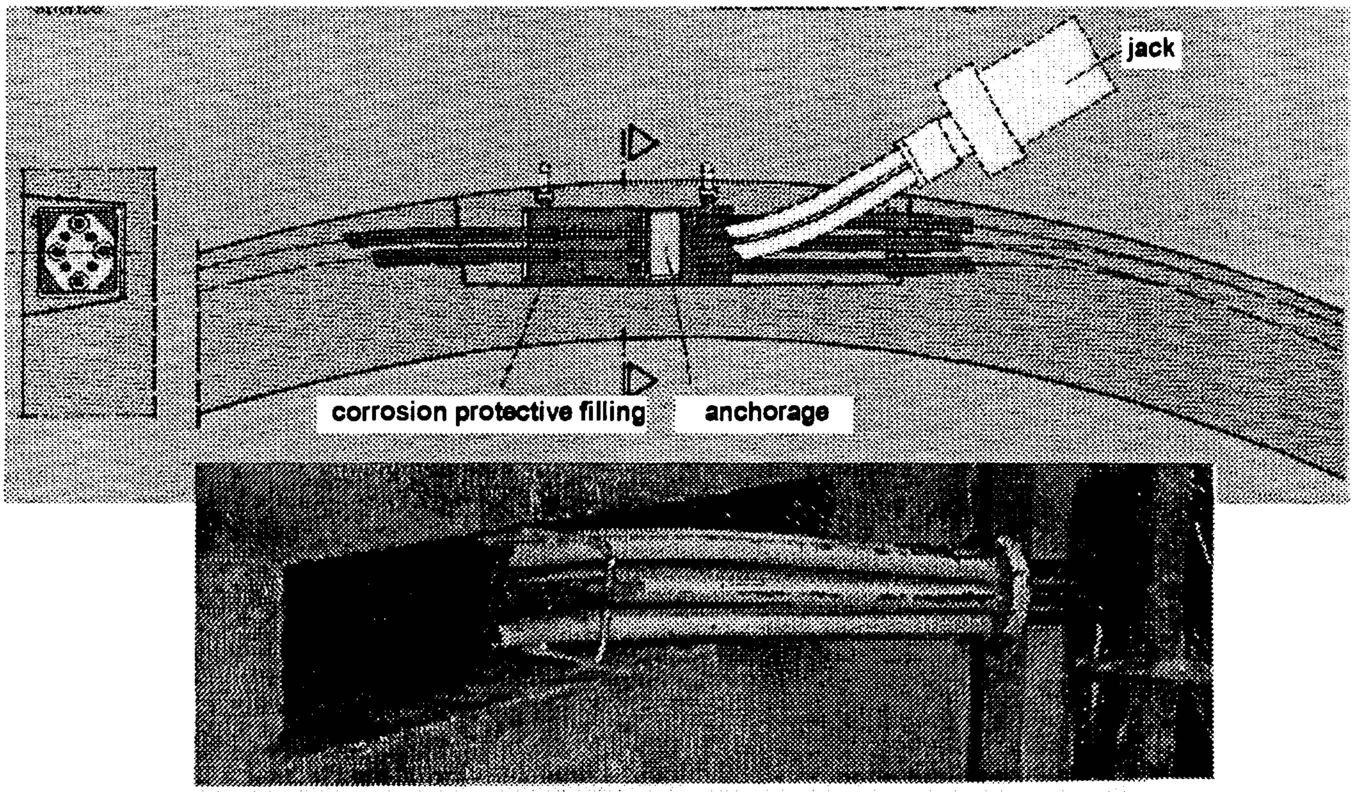


Fig. 8 Monostrand post-tensioning system of DYWIDAG