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Containment Mock-up Tests at Walldorf, Germany

Rüdiger Danisch[1], Heribert Hansen[2], Christoph Stiepani[3], Holger Kolsch[2] and
Günter Liersch[4]

1) Siemens AG, KWU NAD, Germany
2) Hochtief AG, Germany
3) Siemens AG, KWU NW-O, Germany
4) Bayernwerk Kernenergie GmbH, Germany

ABSTRACT

The Walldorf project is to be seen in the framework of the different activities for the containment design of the European Pressurized Water Reactor (EPR). The research centers around pressure tests using a containment mock-up depicting the main features of a steel reinforced concrete containment with a fibreglass reinforced plastic (FRP) liner. Important questions and potential solutions that are of relevance for a real containment, for instance questions relating to reinforcing arrangements, the design of large penetrations, the application of FRP liners as well as the load carrying characteristics and deformation behaviour of the structure, crack development in steel reinforced concrete and, in particular, the effects of a system consisting of steel reinforced concrete and FRP liner on the leak tightness of containment in the case of large concrete deformations had been investigated.

THE WALLDORF MOCK-UP

The mock-up is located at the area of the testing facilities of the HOCHTIEF company in Walldorf, near Frankfurt, Germany.

Objective of Testing

The objective of this test effort was to use a large mock-up to investigate as many aspects as possible that are of relevance for a future containment:

- calculation and dimensioning of a steel-reinforced concrete mock-up with non-prestressed reinforcement at ultimate load
- application of composite liners
- load carrying characteristics and deformation behaviour of the steel-reinforced concrete mock-up at ultimate load.
- nonlinear behaviour of the reinforced concrete at the junction of the cylindrical wall to the end slabs (top and bottom) ; rotational capacity
- behaviour of composite liners on concrete in the case of multiaxial loading as well as large concrete deformations and crack widths
- influence of steel fibre concrete sections on cracking and behaviour at ultimate load

An extreme high internal pressure of 16 bar_{abs} was prescribed as the maximum load for the mock-up. The internal pressure was achieved by filling the mock-up with pressurized water. The main advantage of creating the pressure using water rather than air is that it offers high safety, even in the hypothetical case of sudden failure of the mock-up (which has to be ruled out). In addition, leaks can be detected more easily on account the moisture.

The loading/time curve was stepped with interim load alleviations and repeats. The individual load steps were selected to represent significant conditions for the mock-up or a containment. The hold times served primarily to check whether a state of equilibrium had set and whether leaks had occured.

Geometrie and Features of the Mock-up

The mock-up is constructed in steel-reinforced concrete with non-prestressed reinforcement. It depicts the main load carrying characteristics and deformation properties of a possible, real EPR containment. The geometric (dimensional) scale is 1:10. The mock-up has a volume of around 50 m³. Figures 1 and 2 each show a cross section and a view of the containment mock-up.

Figure 1: Sectional Drawing of EPR Mock-up

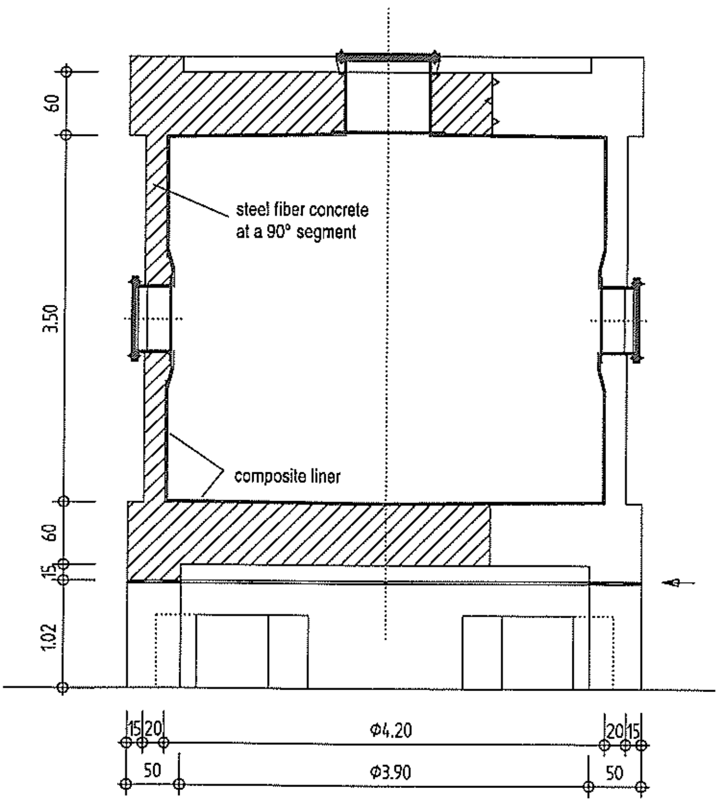
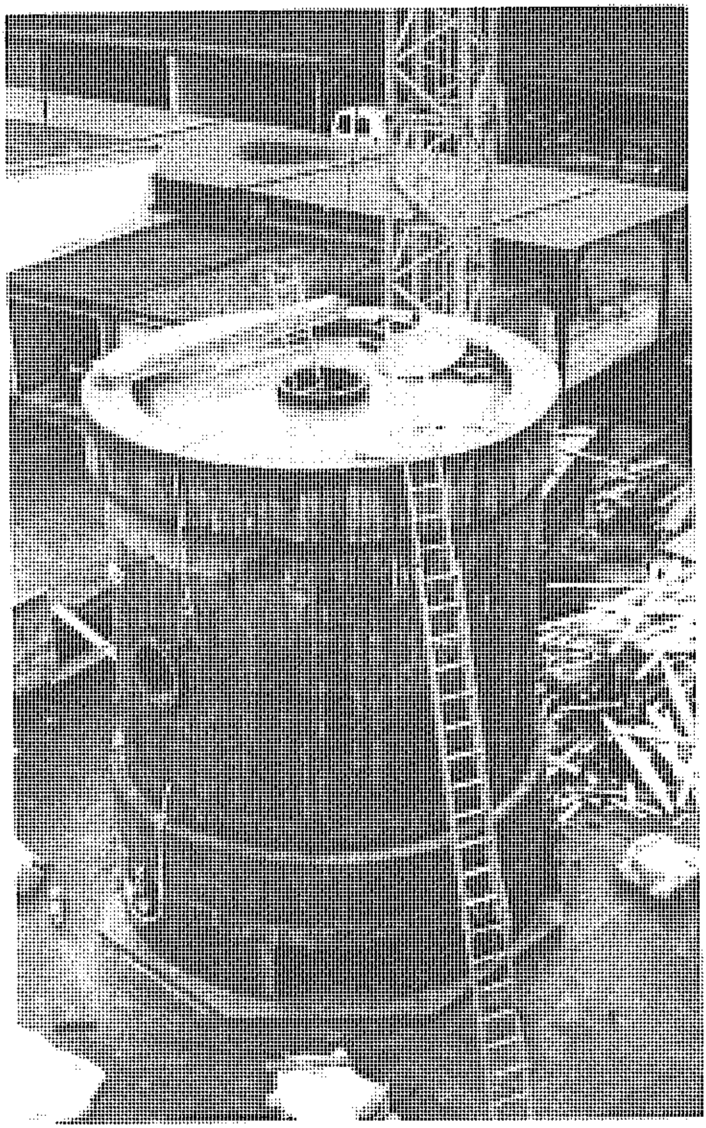


Figure 2: View of the Mock-up



The main features of the steel-reinforced concrete mock-up or, in other words, the similarities between the mock-up and a reinforced concrete containment are as follows:

- The mock-up experiences radial and tangential expansions in the cylinder wall which are similar to those that would occur in the real containment at the same load.

- The corner areas of the mock-up should not affect each other. The cylinder wall height is selected such that the cylinder wall is in fact a long shell. As a result, only membrane forces are effective in the central area.
- The end slabs (top and bottom) are much more rigid than the cylinder wall representing the base to wall thickness ratio similar to the real containment. The cylinder wall is fully restraint to the end slabs.
- Steel fibre concrete has much higher ductility and better crack distribution than normal concrete. One segment of the mock-up was therefore constructed in steel fibre concrete to test its improved behaviour as compared to normal concrete - also with respect to interaction with the composite liner.
- Openings are present in the mock-up. These areas are particularly interesting because local effects arise at these breaks in the otherwise homogeneous and symmetrical structure. The openings simulate the locks present in the actual containment.
- The reinforcement of the mock-up was selected in such a way that large crack widths were pre-programmed in the concrete. In addition, special measures were taken for the purposes of crack provocation and deformation concentration. In this way, the liner was to be subjected to extreme requirements in the test.

The quality test for the concrete used for the containment mock-up resulted in values of between 55 and 66 N/mm². A concrete steel of quality 500 S was selected for the reinforcement.

THE LINER OF THE EPR MOCK-UP

A variety of different plastics are available for consideration as materials for the containment liner, such as polyurethane, polyester, vinyl ester and epoxy resins.

After extensive investigations and consultations with plastics manufacturers and users of coatings, fibreglass-reinforced vinyl ester resin systems were selected. These systems meet all the requirements indicated above, and have previously been used with success in a wide variety of applications. For example, these systems have been successfully used for many years in boat construction and in the automobile industry, and as a material for pipelines and containers such as flue gas scrubbers and jet fuel tanks which are exposed to severe chemical attacks.

Typically, the composite systems consist of a primer which functions as an anchoring agent on the concrete substrate. The next layer consists of a flexible putty coating acting as an equalizing and buffer coating in the event of crack formation in the concrete. A complex laminate, which consists of plies of complex glass fabrics, is applied on top of that. The final cover laminate consists of a ply of glass matting with glass fibre wool to achieve a uniform surface. The coating is then sealed to create a smooth, non-porous surface.

Coating of the EPR mock-up was carried out by the companies Keramchemie and Tankbau[1].

RESULTS OF PRETESTS

The mechanical behaviour of different composite liner systems coated on concrete beams had been investigated by tension tests and bending tests similar to those performed 1992 at the university of Karlsruhe [Ref. 1].

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1 Keramchemie GmbH, Berggarten 1, D-56427 Siershahn. Tankbau GmbH, Fabersweg 1, D-22848 Norderstedt.

During the tests the following items had been measured and observed:

- the crack pattern in the concrete and the crack width bridged by the composite liner
- the interaction of the liner with a concrete specimen
- the strain behaviour of the liner
- the delamination of the liner from the concrete surface
- the failure mechanismen of the composite liner

The main results had been as follows:

The adhesion of all the liner systems to the concrete surface has been excellent and mostly higher than the tension resistance of the concrete. The treatment of the concrete surface, for example by brushing and sandblasting or the application of different shuttering materials had had no significant effect on the liner performance.

The liner behaved like an external reinforcement increasing the bearing capacity of the test specimen and influencing the crack pattern.

The composite liner systems were able to bridge very large concrete deformations and single cracks up to five to six millimeters. The following figures 3 to 4 give an impression of the bending and tension tests with the composite.

Figure 3: Test Setup for Bending Tests

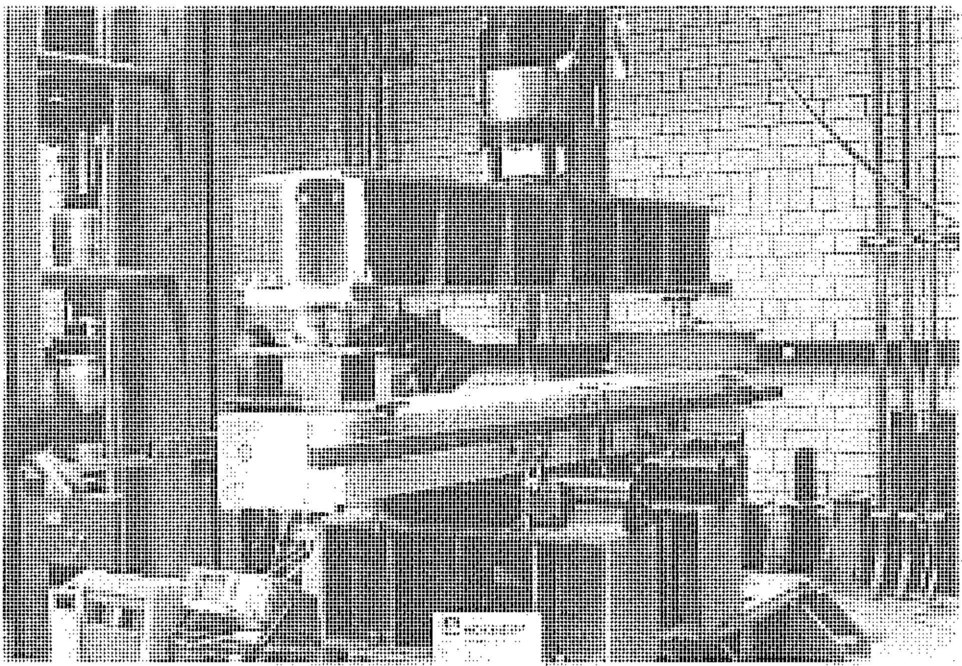
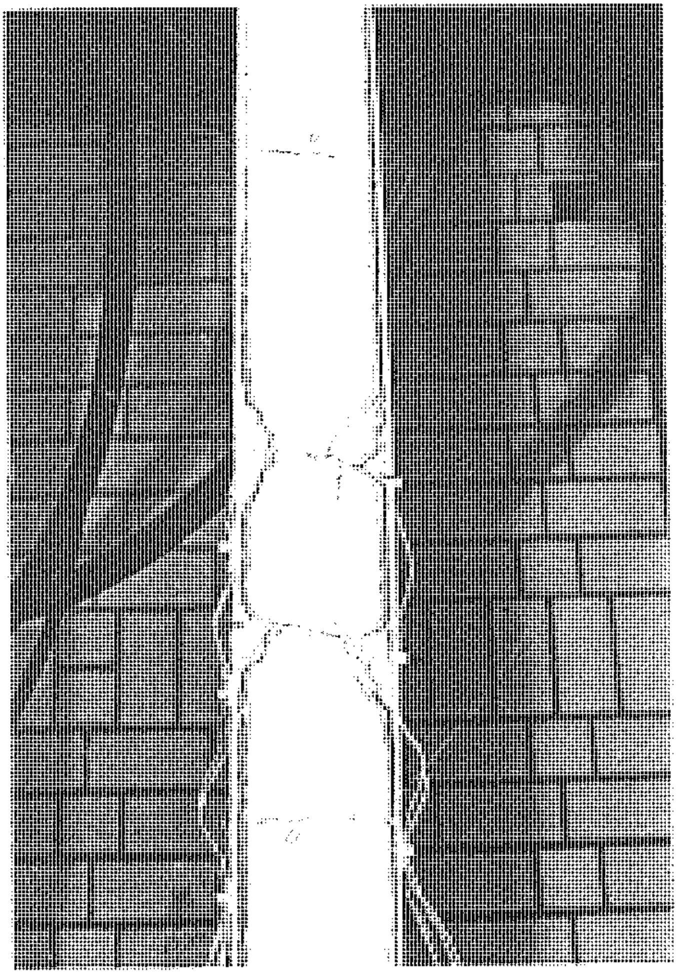


Figure 4: Branching of Cracks



INTERMEDIATE RESULTS OF THE MOCK-UP TESTS

To date, one test series conducted at pressures of up to 6.5 bar_{abs} has been performed and two test series at up to 11 bar_{abs} which is two times as much as the design pressure at which the steel reinforcement reached its elastic limit. In the areas of crack provocation and deformation concentration, crack widths in the concrete measuring up to 1.7 mm were observed. There was no indication of liner separation from the concrete substrate, nor any large leaks occurred, thereby verifying the crack bridging properties of the composite liner. The fundamental feasibility of the composite liner functioning as leaktight barrier was thus confirmed.

In all three test series, however, isolated minute local leaks developed due to isolated ruptures in the liner despite the fact that quality checks by electrical brush testing were conducted prior to each test series.

Subsequent to draining the mock-up, it was determined in each case that the cause of these local leaks was a small number of individual pores which apparently first formed under the given pressure test conditions. This phenomenon may well be explained as follows: In the manufacturing process, small air bubbles become entrained within the resin. In addition, individual glass fibres may display incomplete adhesion to the resin. Based on expansion concentrations at high internal pressures, individual minute bubbles may burst and lead to minute ruptures, if these are joined with points of defective contact within the fibreglass.

ADDITIONAL TESTS

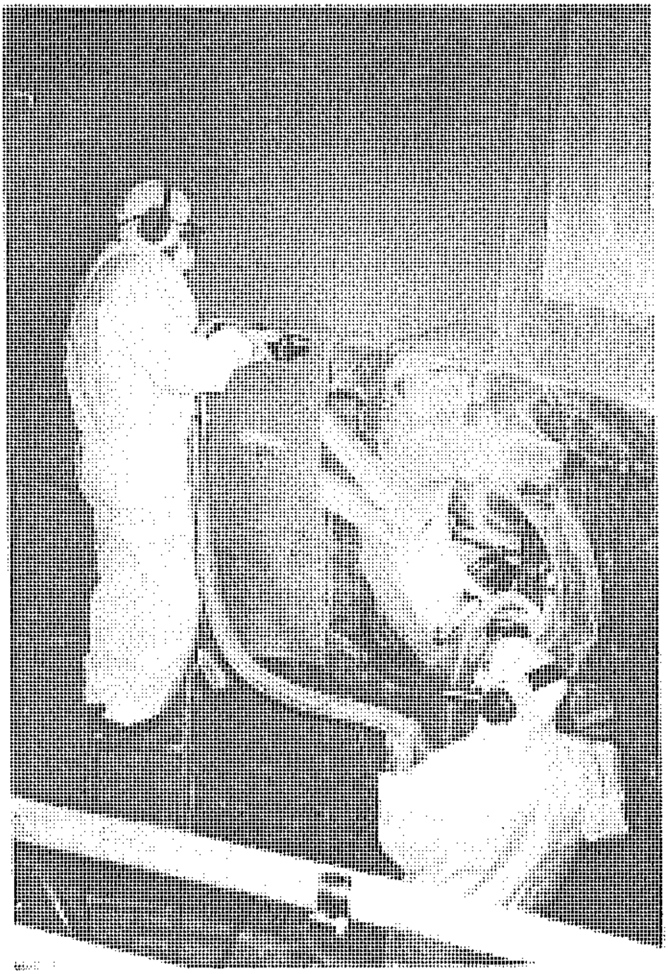
It has been decided to perform test with further liner systems for the purpose of controlling the problems associated with minute isolated ruptures as explained before. The idea is to improve the electrical conductivity of the liner substrate in order to allow better quality control by applying the electrical brush procedure. Two corresponding systems had been tested at Siemens KWU Group's laboratories. Metallic films had been laminated into the liner substrate providing excellent conductivity and resistance against diffusion of steam and gases. However, these systems had problems providing enough adherence after treated by LOCA tests. Although it could be possible to improve the adherence by chemical treatment or mechanical treatment of the metallic surfaces it was decided to abandon this idea. One reason was that competent suppliers for metallic films had not been found which were willing to support equivalent research work.

The procedure finally selected for further testing was to improve electrical conductivity by applying graphit powder or graphit fabrics within the liner substrate. The system selected by Keramchemie involved graphit fabrics whereas the system selected by Tankbau involved graphit powder.

STATUS AT WALLDORF MARCH 1999

In the meantime the composite liner of the Walldorf mock-up had been removed and one half of the concrete surface had been recoated with the modified Keramchemie liner as mentioned before. Figure 5 gives an impression on the old liner surface after exposure with two times the design pressure and on the procedure how to remove a liner. It was possible to peel off the liner without distroying the concrete surface.

Figure 5: Removing the Liner



The coating of the second half of the concrete surfaces has been postponed. At the time being modified liner systems are being tested which are able to better resist extreme loading conditions by steam. During the mock-up tests at Civaux which are being performed in parallel to the Walldorf tests the vinyl ester liner failed after a pressurization of the mock-up with steam during five days with temperatures between 140 and 165 °C and a pressure of 6.5 bar_{abs}. Additional research work is underway in order to improve the chemical performance of the putty layer and the resins. It is foreseen to resume the tests in Walldorf at autumn 1999 up to the ultimate bearing capacity of the mock-up which is expected around 16 bar_{abs}. The results will be reported accordingly.

REFERENCES

[1] "Discussion on Recent Concrete Containment Designs"
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