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- PACE-1450 - AN EXPERIMENTAL TEST SETUP FOR THE INVESTIGATION OF THE CRACK BEHAVIOUR OF PRESTRESSED CONCRETE CONTAINMENT WALLS

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ABSTRACT

Among other topics the crack initiation and the leakage through prestressed concrete walls of reactor containments are matters of particular interest for the safety of nuclear facilities. Experimental investigations under different loads which also include the limit state under accidental conditions are the basis for the implementation of these problems in finite element codes. The validity of models that are used in nonlinear calculations has to be verified by comparing their performance with experimental results. In order to determine the capability of simulations to predict the structural behaviour of realistic and representative structural parts these kind of complex tests are indispensable. The PACE 1450 experimental project is an intermediate sized experiment to investigate the behaviour of a curved specimen which is representative for the prestressed containment of a 1450 MWe nuclear power plant. The specimen is loaded by air pressure simulating the internal pressure within the reactor containment under inspection and accidental conditions. The resulting ring tensile stresses of the cylindrical part of the containment are applied externally by eight hydraulic jacks. The initial prestressing of the specimen is realised in such a way that a decreasing of the prestressing force for the purpose of simulating the aging of the structure is possible.

1 INTRODUCTION

In the last decade several civil engineering research and development programs dedicated to the analysis and behaviour of nuclear power plant containments have been carried out. Results for the comparison of numerical results with experiments are generally obtained by performing simple tests on small sized specimens. Regarding the material properties of prestressed reinforced concrete at least medium sized experiments are indispensable to reproduce the behaviour of the extremely inhomogeneous material. This aspect leads to very expensive tests and therefore they are usually financed by more than one research organization or company.

For the "PACE 1450 – Experimental Campaign" the R&D Department of EDF (Electricité de France) and the MPA Karlsruhe (Materials Testing and Research Institute of the Universität Karlsruhe (TH)) decided to cooperate in order to benefit from the experience of each single institution as well as of the experience that have been gained in past cooperations too. The MPA Karlsruhe owns a leakage testing facility which had been built up for a research project funded by VGB PowerTech and GRS (Gesellschaft für Anlagen- und Reaktorsicherheit) ([1], [2]) and used later in cooperation between EDF and MPA Karlsruhe for further leakage research projects ([3], [4], [5]). This facility has been reused in parts to build up a new and improved testing facility which is focused on the testing of prestressed, curved specimen under inspection and accidental conditions which has been already investigated by EDF in a numerical project [6]. Figure 1 shows the current program in the framework of past activities of different research works sorted in dimension and complexity starting with single cracks up to model containments and simulations in 1:1 scale.

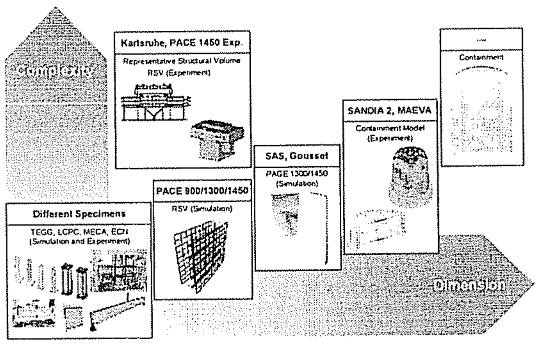

Figure 1. Current project in the framework of past research activities

2 EXPERIMENTAL SET-UP

2.1 BASIC IDEA OF THE EXPERIMENTAL SET-UP

As it is difficult to finance the building up of a closed ring with a inner radius of r = 21.9 m and a thickness of 1.2 m modelling a piece of a reactor containment as a pressure chamber under correct mechanical conditions in order to obtain a membrane stress state EDF and MPA decided to build up a facility to test a representative curved specimen (cut out of the cylindrical part of a containment) which has realistic dimensions and can be loaded very similar to a closed ring under internal pressure (see Figure 2).

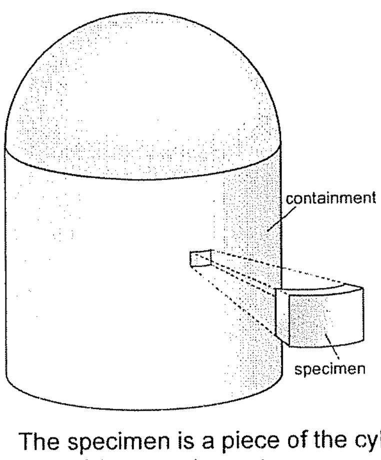

Figure 2. The specimen is a piece of the cylindrical part of the containment

The externally applied tensile force corresponds to the ring tensile force resulting from the internal pressure within the reactor containment under inspection or accidental conditions.

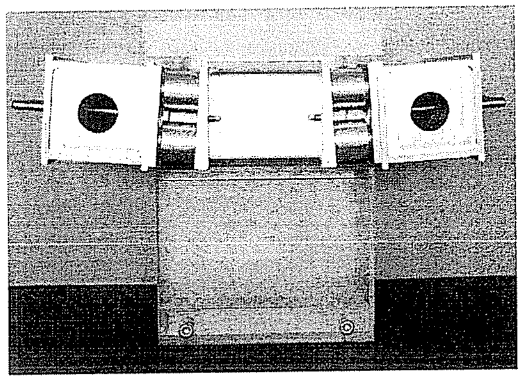

Figure 3. Model of the basic idea of the test set-up

This basic idea led to a facility which was first built up as a small model (see Figure 3) based on a three dimensional sketch which is shown in Figure 4 and which contents the specimen turned in a way that it is lying concave within the load frame. The membrane force that would occur in a closed ring under internal pressure is realised by hydraulic jacks pushing apart the so called "ears" which are transverse beams made of steel. They are connected to the specimen by reinforcement bars and load the specimen with the tensile force.

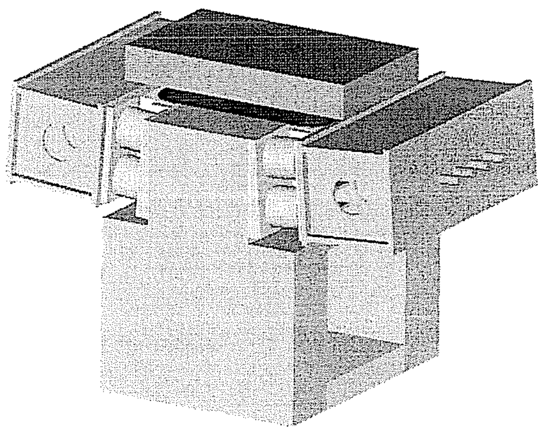

Figure 4. Three dimensional sketch of the principle of the mechanical part of the facility

A further important point regarding the integrity of a prestressed containment is the aging which does not only affect the concrete itself [7]. Also the remaining prestressing force will decrease during the lifecycle of a power plant. The following table gives the prestressing levels during the test campaign regarding the decreasing of the prestressing in order to simulate this prestressing loss.

Table 1. Test program

RUN	real age (years)	experimental age (days)	pressure (bar_{abs})	temp (°C)	prestressing (%)
0	0	60	1,43	20	25%
1	0	90	5,30	20	100%
2	10	120	5,30	20	80%
3	35	150	5,30	20	60%
4	60	210	7,00	180	60%

The RUN 0 is a test of the whole facility at a low level of prestressing and pressure. The test pressure and therefore the external force correspond to 10 % of the test pressure of 5.3 bar (absolute pressure) during RUN 1 to 3. For RUN 4 a pressure level of 7 bar (absolute pressure) with heated air (180 °C) and a corresponding external force is planned.

2.2 MECHANICAL PART OF THE SET-UP

The mechanical part of the set-up consists mainly of the prestressed specimen, the inner abutments, the ears at the left and the right hand side as well as the hydraulic jacks pushing the ears to the outwards. Additional parts are the cover which is also the pressure chamber and the foundations for the specimen and the abutments.

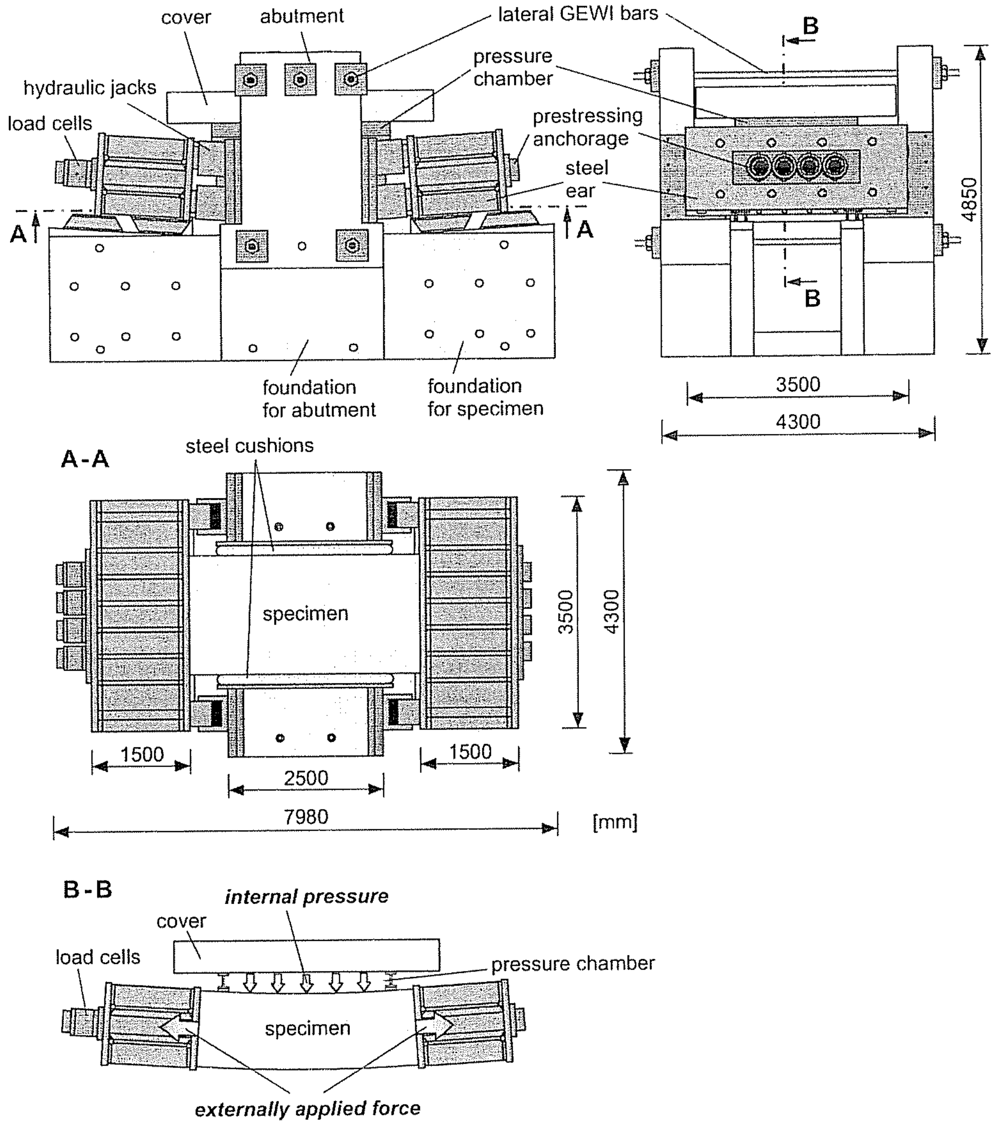

Figure 5. Drawings of the mechanical part of the facility, in section B-B the internal pressure and the externally applied force is shown in principle

The specimen is lying between the front and the backmost abutment (see also drawings in Figure 5) and is connected to the ears by 128 GEWI reinforcement bars on each side. It is loaded with a tensile force corresponding to the internal pressure that is realised with the help of the pressure chamber lying atop of the specimen. This tensile force is applied to the ears by the hydraulic jacks who have their support at the abutments on each side of the specimen. Due to the connection between the ears and the specimen by the GEWI reinforcement bars the specimen is put under tension at the moment when the externally applied force exceeds the prestressing force. Theoretically this situation will occur the first time during RUN 3. Lately during RUN 4 there is the possibility of getting a global transversal crack through the whole specimen. In order to simulate a prestressing in the original vertical direction of the containment steel cushions are placed between the specimen and the abutments. These cushions can be set under pressure up to 1 MPa. In the case of an appearing crack these cushions serve also for the purpose of securing the sealing of the specimen in a way that an occurring leakage could be collected and measured beneath the specimen. For taking the load of the cushion pressure the abutments are held together in lateral direction by 5 tension rods of a diameter 63.5 mm.

The displacement of the specimen during the tests is recorded by displacement transducers at all edges of the specimen. Also the force in each prestressing cable is recorded at any time of the test. Therefore load cells are placed on one side below the anchorage system. The data is registered every 5 seconds during a test and every 6 hours between the tests. In order to keep the drawings in figure 5 clear the holding construction for the cover is not shown there. Figure 6 gives an impression of the steel construction that is needed to fix the cover on the top of the specimen in a way that a lifting off is impossible. The holding construction can be pushed down with 8 hydraulic jacks and be fixed with screws at 8 tension rods of diameter 63.5 mm taking the load of the applied pressure inside the pressure chamber.

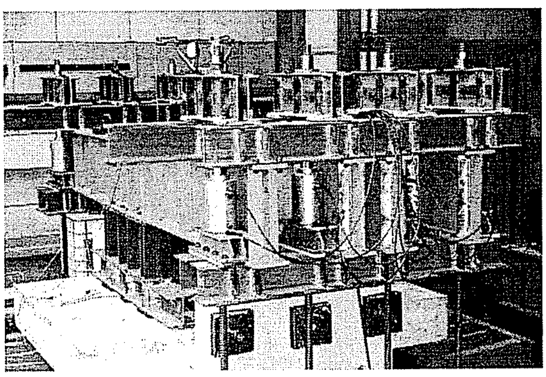

Figure 6. Steel construction fixing the cover

Figure 7 shows the whole mechanical set-up of the facility during RUN 1. The computers for controlling, steering and data recording are located in the floor below for safety reasons. The thermo-hydraulic part of the set-up is placed near the old leakage testing facility which still can be operated.

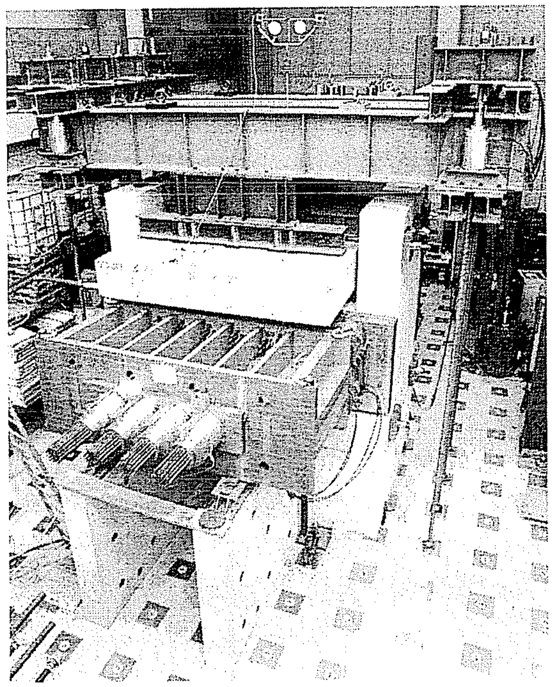

Figure 7 Complete mechanical test set-up

2.3 THERMO-HYDRAULIC PART OF THE SET-UP

The thermo-hydraulic mixing facility of a former leakage project with another mechanical set-up is used for the current campaign. It has been built up in order to be able to realise stable complex air-steam mixtures for highly time dependent accidental scenarios. To fulfil the predefined accidental scenarios it is necessary to regulate the parameters temperature, partial pressure of steam and partial pressure of air. These three parameters describe the physical state completely at any time. The production principle of the air-steam-mixture is shown in Figure 8. The main parts of the air-steam mixing facility are compressor, boiler, static mixer, air heater, steam super-heater and three pneumatic valves and the flow measurements described below. There are two input channels (for air and steam) which converge to the air-steam-mixture channel and an output channel for the eventual leakage measurement.

Unlike temperature, the partial pressure air and partial pressure steam parameters are not available for direct measurement. It is necessary to define the system state in equivalent measurable parameters. With the help of flow measurements in each of the input channels the relation between air and steam can be adjusted and taken as control parameters. Together with the temperature and the pressure measured within the pressure chamber the physical state is known.

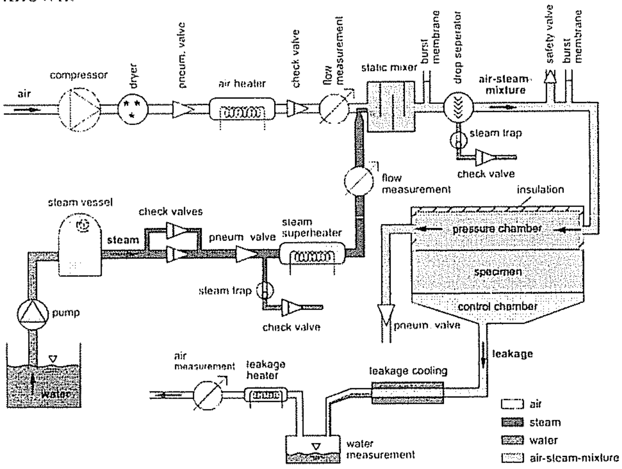

Figure 8. Principle of the thermo-hydraulic set-up

For the PACE 1450 experimental campaign only the air channel of the mixing facility is used. As it is uncertain if a crack through the specimen will appear the control chamber will be attached only for the case of occurring cracking. A later use of the steam and mixture channels for the currently tested specimen is not yet decided.

3 THE SPECIMEN

The specimen itself is prestressed by four cables consisting of 37 strands each. The prestressing force in every cable is chosen to a level which leads to a stress state of 12 MPa in the circumferential direction of the specimen. The inner and outer reinforcement in this direction consists of horizontal bars with a diameter of 20 mm with a vertical spacing of 200 mm as shown in figure 9.

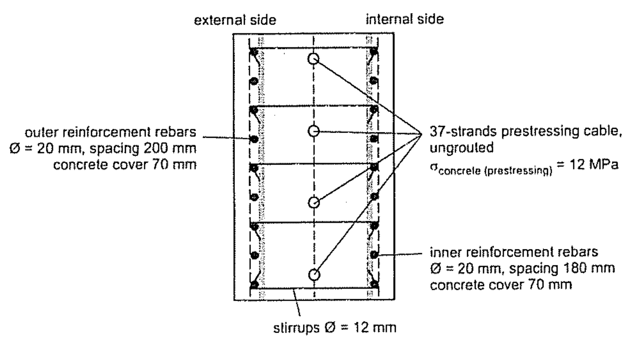

Figure 9. Section of the specimen as part of the containment

The spacing between the outer vertical bars is 200 mm in horizontal direction and at the internal side the spacing is reduced to 180 mm. The inner and outer mesh layers are connected by stirrups and additional hooks with a diameter of 12 mm. Within the specimen one prestressing cable in the original vertical direction is realised lying horizontally because of the turning of the specimen as it is shown in chapter 2 (see figure 10).

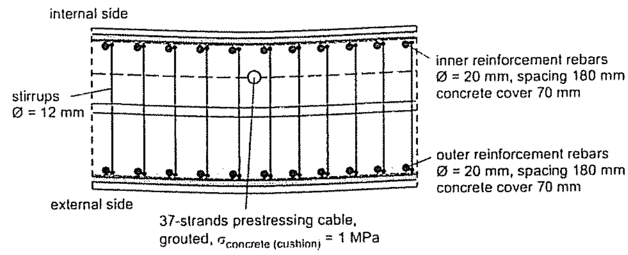

Figure 10. Vertical section in longitudinal direction of the specimen

As mentioned in the description of the mechanical part of the facility the specimen is coupled to the ears by GEWI reinforcement bars. These bars can be seen in figure 11 which shows the specimen being set onto the foundations between the abutments. The surface of the specimen in the direction to the ears is built with a steel plate in order to guarantee a tight coupling between these two parts. For the compensation of slight inaccuracy between the surfaces a thin wooden plate is put between the steel surfaces. The ears were slowly moved in position by inserting the reinforcement bars into the designated holes in the ear's surface and after form closure being fixed with nuts placed within the ear.

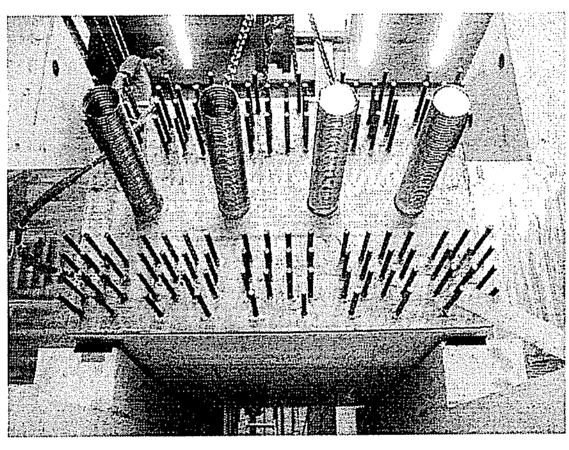

Figure 11. Specimen being set onto the foundations between the abutments

4 TEST SCENARIOS AND MEASUREMENTS

The test scenarios during the campaign are mainly geared by the standard pressure tests that are performed for the checking of the leakage tightness of containments in France. The test duration is much shorter than in reality but long enough to ensure the setting up of a steady state. The peak pressure which is reached by increasing the pressure in steps is 5.3 bar absolute at ambient temperature. The starting pressure is levelled to 1.15 bar in order to ensure an exact steering of the external force which is coupled to the applied pressure (see figure 12).

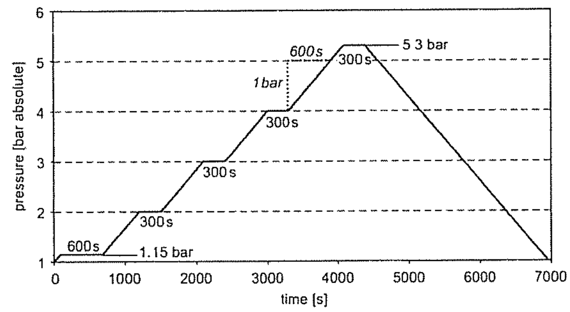

Figure 12. Pressure scenario for RUN 1 to RUN 3

For RUN 0 a peak pressure of 1.43 bar was used. This RUN 0 served as a set-up check only. For RUN 4 a peak pressure of 7 bar and a temperature of 180 °C are planned.

The specimen as well as the relevant parts of the facility is equipped with different measurement devices. Different transducers are placed within the specimen for the registration of strain, temperature and cracking events. One measurement system is manufactured by SMARTEC from Switzerland basing on an optical fibres Bragg network. It provides information on temperature and strain in different locations and directions. Additionally a conservative strain measurement with encapsulated strain gauges and a temperature measurement with PT100 sensors are embedded.

For the registration of appearing cracks a sound detection system is embedded within the specimen. The system consists of 8 microphones which are located in a way that localization of developing micro cracks is possible.

The global behaviour of the specimen is registered by displacement transducers that are placed at all edges of the specimen in longitudinal and horizontal direction and additionally in vertical direction at the top edges.

For the force recording every prestressing cable is equipped with an individual load cell that has been used for the prestressing procedure and is in further use for the control of the prestressing decrease and the force level during the tests.

5 FIRST RESULTS

At the moment of the writing of this paper RUN 0 and RUN 1 have been successfully performed. A short overview on the first results of RUN 1 is given in the following. Figure 13 shows the characteristics of the steering parameters pressure and the externally applied force. It can be seen that the measured pressure data follows precisely the desired levels of pressure. The behaviour of the force control is exactly the same.

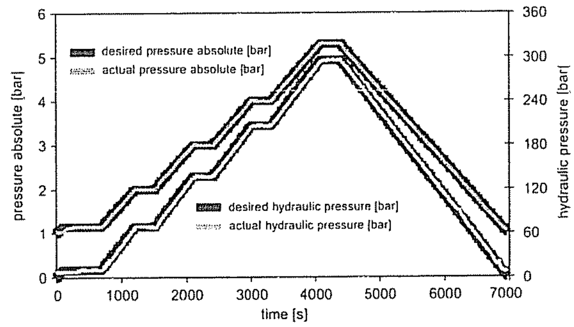

Figure 13. Pressure control during RUN 1

Some results from the internal strain measurement during RUN 1 are shown in absolute terms in the following figure 14. The transducers S1 and S5 show the measured strain in the longitudinal (circumferential) direction and the transducers S4 and S8 show the lateral strain. Negative values mean compression and positive elongation. S5 and S8 are located near the internal surface while S1 and S4 lie beneath the external surface of the specimen. The starting values of S1 and S5 at the level between 1100 µm/m and 1400 µm/m show the compression of the 100% prestressing while the sensors S4 and S8 show the lateral strain due to the prestressing. The sensor S10 shows the strain that leads to a thickness change of the specimen. In the strain curves a similar shape as in the hydraulic pressure and in the external force respectively is recognizable.

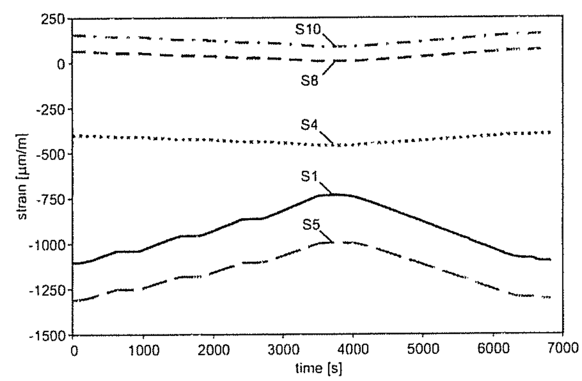

Figure 14. Internal strain measurements during RUN 1

The external force acts versus the prestressing force and decreases the compression of the specimen. This effect can be seen vice versa in the lateral strain sensors S4 and S8 with sensor S4 having a shift of the signal and therefore not registering positive strain as the other lateral sensors.

In order to show the relative strain the sensors described above are normalised in figure 15. In this diagram the curves for S4 and S8 are almost identical so that S8 is mainly hidden behind S4.

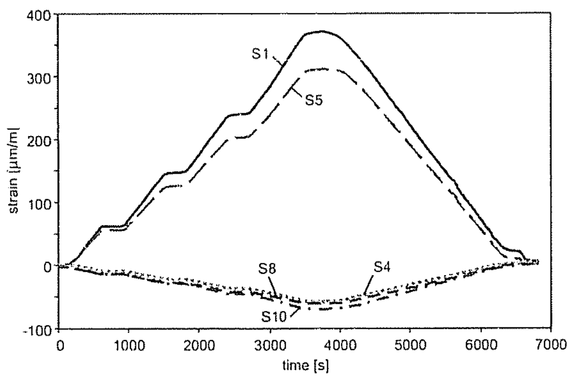

Figure 15. Normalised internal strains during RUN 1

As the GEWI reinforcement bars connecting the ears with the specimen are not yet activated during RUN 1, only a passive elongation of the specimen occurs. These GEWI reinforcement bars will be activated for the first time during RUN 3 when the externally applied force will exceed the remaining prestressing force in the specimen. As shown in table 1 the prestressing force for RUN 3 and RUN 4 will be 60% of the starting level of the prestressing force used in RUN 1. As a consequence of GEWI bars not having been activated yet and the concrete of the specimen not having been under tensile load during RUN 0 and RUN 1 the sound detection did not register any damage event during the tests so far. The functionality of the sound detection system has been checked permanently while the tests were running.

Furthermore leakage detection was not necessary up to now. For the case of a crack appearing and leakage coming through the cracked specimen a control chamber is available which can be fixed below the specimen in order to collect gaseous and fluid leakage. The amount of leakage of both phases can be measured separately by cooling down the leakage to force the condensation of water and registering afterwards the air volume by a flow meter as shown in figure 8.

The results of the measurement by the sensors of SMARTEC as well as the external displacement measurement is not yet evaluated but will serve as basis for numerical studies in the future. These sensors are based on optical fibres and are very sensitive on mechanical disturbances that are inevitable. At the time of RUN 1 five out of 150 of the measurement positions in the multi-channel sensors by SMARTEC seem to have been damaged or disturbed since the casting of the specimen.

More results will be published later as the campaign is still running and the evaluation of data is still ongoing at the moment of finishing the paper.

6 CONCLUSION AND OUTLOOK

For the "PACE 1450 – Experimental Campaign" a new leakage testing facility for prestressed curved specimen has been built up. The test campaign has been successfully started and is still running. A description of the experimental set-up is given in this paper as well as first results of RUN 1. Within the current project the specimen will be tested in four Runs which culminate in a test with a pressure of 7 bar absolute at a temperature of 180 °C. Further tests with air-steam-mixtures are possible but not yet decided. The mechanical part of the facility is designed in a way that with only slight modification also specimen with a different curvature can be tested under similar conditions within the capabilities of the set-up.

ACKNOWLEDGMENTS

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