PACE 1450 - Experimental investigation of the crack behaviour of prestressed concrete containment walls considering the prestressing loss due to aging

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1 ABSTRACT

As an intermediate sized experiment the "PACE 1450 - Experimental Campaign" aims to investigate the behaviour of a curved specimen which is representative for a 1450 MWe nuclear power plant containment under accidental loading conditions. The reinforcement layout of the specimen is very similar to the original geometry and consists mainly of meshes of reinforcement bars near the inner and outer surface and four prestressing cables, each of them consisting of 37 strands within ducts in the circumferential direction. An initial prestressing of the specimen of 12 MPa in this direction is realised in such a way that decreasing the prestressing force for the purpose of simulating the aging of the structure is possible. In order to obtain information about the behaviour of the containment wall segment under the chosen conditions, the specimen is equipped with embedded optical fibre strain and temperature sensors and a sound detection system to record the initiation of cracks. Additionally the displacement of the edges is measured by inductive sensors. The paper explains the setup in detail and presents results of the ongoing test series.

2 INTRODUCTION

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 for the "PACE 1450 – Experimental Campaign" in order to benefit from the experience of each single institution as well as from the experience that have been gained in past cooperations. 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) (Eibl et.al. (2001), Herrmann et.al. (2002)) and used later in cooperation between EDF and MPA Karlsruhe for further leakage research projects (Niklasch et.al. (2005), Stegemann et.al. (2005), Herrmann (2006), Niklasch et.al (2008).

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 would have been difficult in control as well as in crack and leakage detection, not to mention the high costs. Therefore, EDF and MPA decided to build up a facility to test a representative curved specimen with realistic dimensions and can be loaded very similar to a closed ring under internal pressure. The above mentioned old 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 (Jason et.al. (2005)).

The following Fig. 1 shows the current program in the framework of previous activities of different research works sorted in dimension and complexity starting with single cracks up to full scale model containments and simulations.

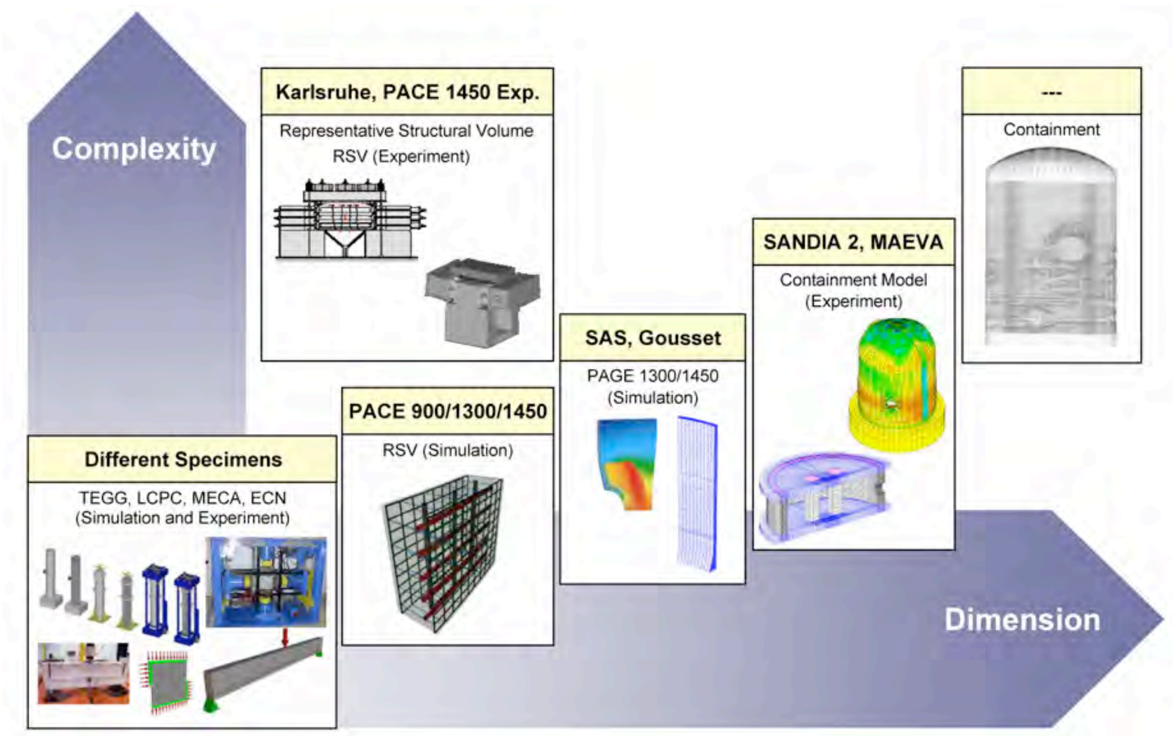

Figure 1. Current project in the framework of previous research activities

3 BASIC IDEA OF THE EXPERIMENTAL SET-UP

The specimen having realistic dimensions is to be loaded very similar to a closed ring under internal pressure. It is designed as a cut out of the undisturbed cylindrical part of a nuclear reactor containment (see Fig. 2).

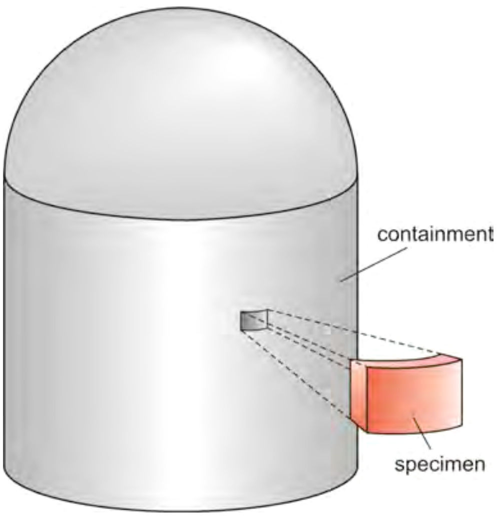

Figure 2. The specimen is cut out of the cylindrical part of the containment

The tensile force which is to be applied externally in the tests corresponds to the ring tensile force resulting from the internal pressure within the reactor containment under inspection or under accidental conditions. This basic idea led to a facility which was first built up as a small model based on a three dimensional sketch containing 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.

A further important point regarding the integrity of a prestressed containment is the aging which does not only affect the concrete itself due to creep and shrinkage (Le Pape et.al. (2006)). Also the remaining prestressing force will decrease during the lifecycle of a power plant. The following Table 1 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	20	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 bars (absolute pressure) during RUN 1 to 3. For RUN 4 a pressure level of 7 bars (absolute pressure) and a corresponding external force is planned.

4 EXPERIMENTAL SET-UP

4.1 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 outwards. Additional parts are the cover which is also the pressure chamber and the foundations for the specimen and the abutments. An additional steel construction is needed to hold down the cover during the tests when the pressure chamber is loaded.

The specimen is lying between the front and the rear abutment (see drawings in Fig. 3) 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 occurs 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 pressurised 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 five tension rods with a diameter of 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 five seconds during a test and every six hours between the tests. In order to keep the drawings in Fig. 3 clear the steel construction for holding down the cover is not shown. The holding construction can be pushed down with eight hydraulic jacks and be fixed with screws at eight tension rods with a diameter of 63.5 mm taking the load of the applied pressure inside the pressure chamber.

Fig. 4 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.

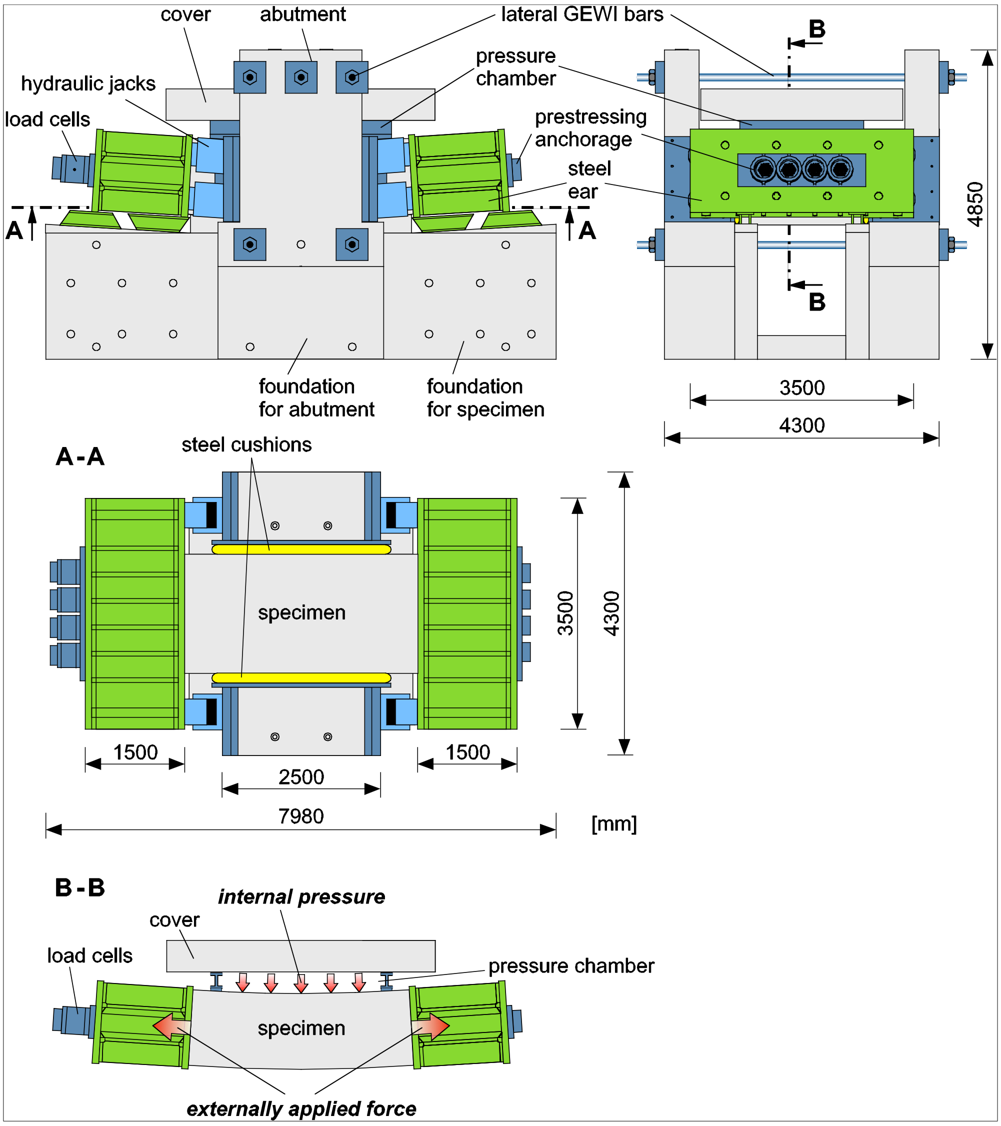

Figure 3. Drawings of the mechanical part of the facility, in section B-B the internal pressure and the externally applied force is shown in principle

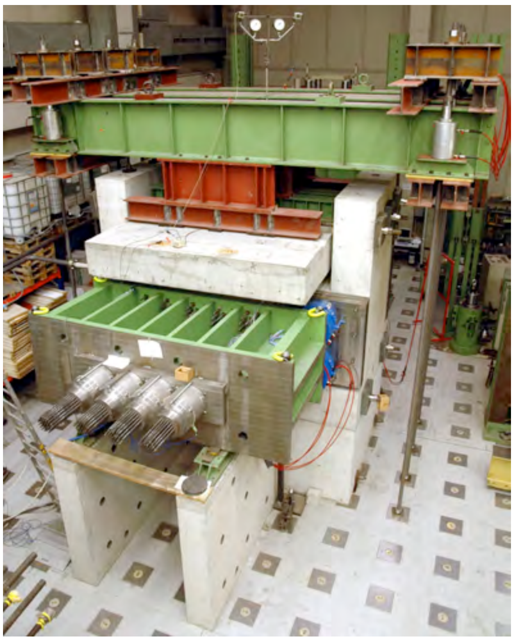

Figure 4. Complete mechanical test set-up

4.2 Thermo-hydraulic part of the set-up

The thermo-hydraulic mixing facility of a former leakage project is used again for the current campaign. It has been built up in order to be able to realise complex but stable 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 main parts of the air-steam mixing facility are compressor, boiler, static mixer, air heater, steam super-heater and three pneumatic valves as well as the flow measurements. There are two input channels (one for air and one for steam) which converge to the air-steam-mixture channel and an output channel for the eventual leakage measurement. With the help of the flow measurements in each of the input channels the relation between air and steam can be adjusted and taken as control parameter. Together with the temperature and the pressure both measured within the pressure chamber the physical state is known. The details of the production principle of the air-steam-mixture can be found in Herrmann et.al. (2008).

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 cracking. A further test of the current specimen under an air-steam-mixture load is not yet decided.

4.3 Design of the specimen

The specimen itself is prestressed by four cables consisting of 37 strands each. The prestressing force in each 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 circumferential reinforcement consists of bars with a diameter of 20 mm with a spacing of 200 mm as shown in Fig. 5 where the specimen is presented in the position as a part of the original containment. For the tests it is turned in the way as shown in the drawings in Fig. 3 and Fig. 6.

The spacing between the originally vertical bars now lying horizontally is 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 too (see Fig. 6).

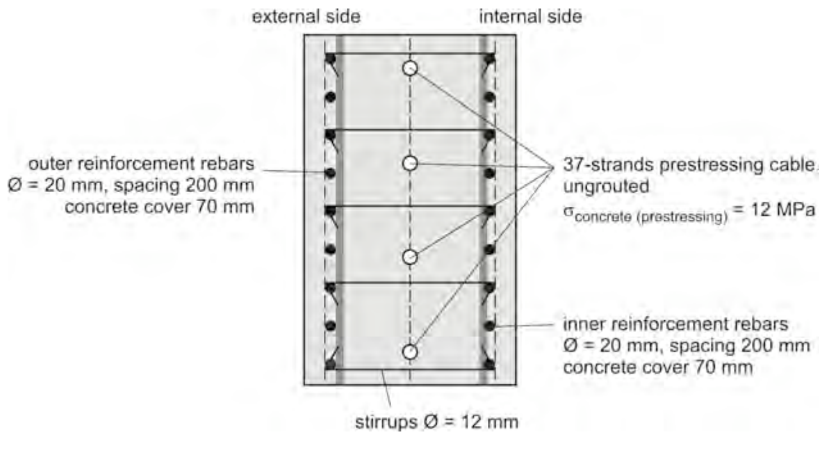

Figure 5. Section of the specimen as part of the containment

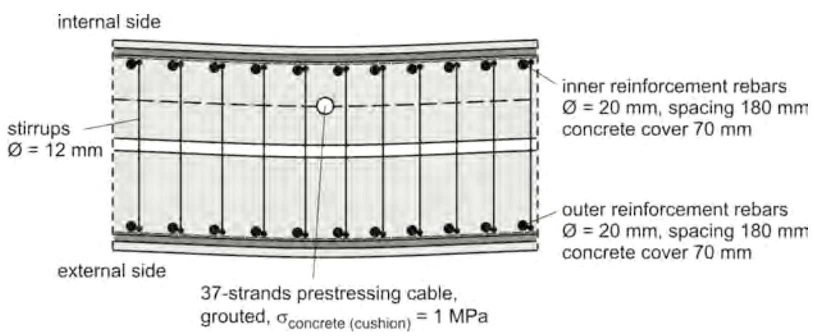

Figure 6. Vertical section of the specimen in longitudinal direction positioned as in the tests

As mentioned in the description of the mechanical part of the facility the specimen is coupled to the ears by GEWI reinforcement bars. The surface of the specimen in the direction to the ears is built with a steel plate in order to ensure full contact between these two parts. For the compensation of slight inaccuracy between the surfaces a thin hardboard is put between the steel surfaces. The ears were slowly moved in position whilst inserting the reinforcement bars into the designated holes in the flange of the ears. After contact the GEWI bars are fixed with nuts placed within the ear.

4.4 Test scenario and measurements

The test scenarii during the campaign follow the standard pressure tests which are performed for the checking of the leakage tightness of containments in France. The duration of one test is much shorter than in reality but long enough to ensure achieving a steady state. The peak pressure which is reached by increasing the pressure in steps is 5.3 bars absolute at ambient temperature. The starting pressure is chosen to 1.15 bars in order to ensure an exact control of the external force which is coupled to the applied pressure (see Fig. 7). The right part of the figure shows the characteristics of the control parameters pressure and externally applied force using hydraulic pressure. 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.

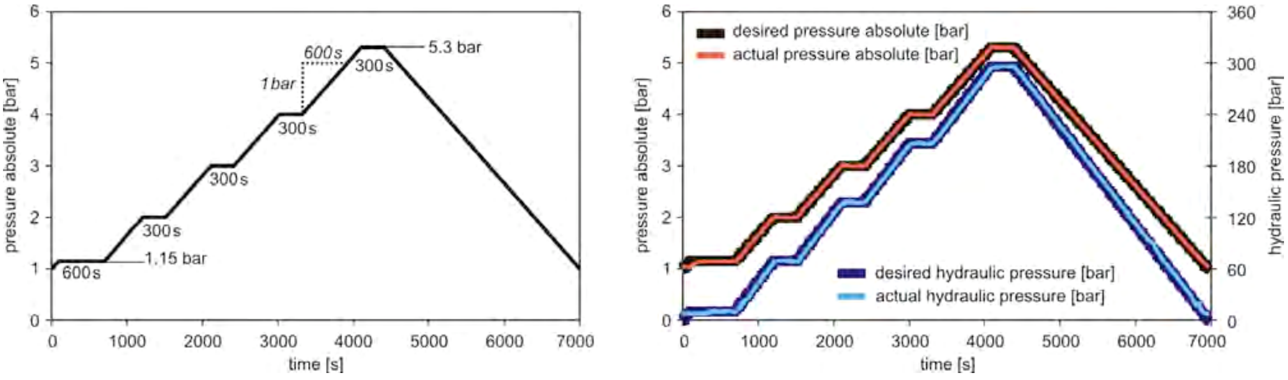

Figure 7. Pressure scenario for RUN 1 to RUN 3 (left), example for control (right)

For RUN 0 a peak pressure of 1.43 bars was used. This RUN 0 served as a set-up check only. For RUN 4 a peak pressure of 7 bars is planned.

The specimen itself is equipped with different measurement devices as well as the relevant parts of the facility. 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 at different locations and directions. Additionally a conventional strain measurement with encapsulated strain gauges and a temperature measurement with PT100 sensors are embedded. Some of the results are presented in the following chapter.

For the registration of appearing cracks a sound detection system is embedded within the specimen. The system consists of eight microphones which are located in a way that localization of developing micro cracks is possible. Up to RUN 3 not much events could be registered with this system but the functionality could be proven. For the following RUN 4 interesting results on crack development are expected which will be published in the near future.

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. These measurements show the global behaviour of the specimen and allow for observing any asymmetric movement.

For the recording of the force every prestressing cable is equipped with an individual load cell. These load cells have been used starting with the prestressing procedure and are still in use for the control of the prestressing decrease and the force level during the tests. Results of these measurements are displayed in the following chapter too.

5 RESULTS

RUN 0 to RUN 3 have been successfully performed at the time of writing this paper. In the following a short overview of results is given. Some exemplary results from the internal strain measurement during RUN 2 and RUN 3 are shown in Fig. 8 in normalised terms (set to zero at the start of the scenario). The transducers S1 and S5 show the measured strain in the longitudinal (circumferential) direction and the transducer S8 shows the lateral strain. Negative values mean compression and positive elongation. S5 and S8 are located near the internal surface while S1 lies beneath the external surface of the specimen. The starting values of S1 and S5 in absolute terms are between 1100 μm/m and 1400 μm/m which shows the compression of the specimen corresponding to the starting value of the prestressing (80 % for RUN 2, 60 % for RUN 3) while the sensor S8 shows 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 curves of hydraulic pressure and external force respectively is recognizable.

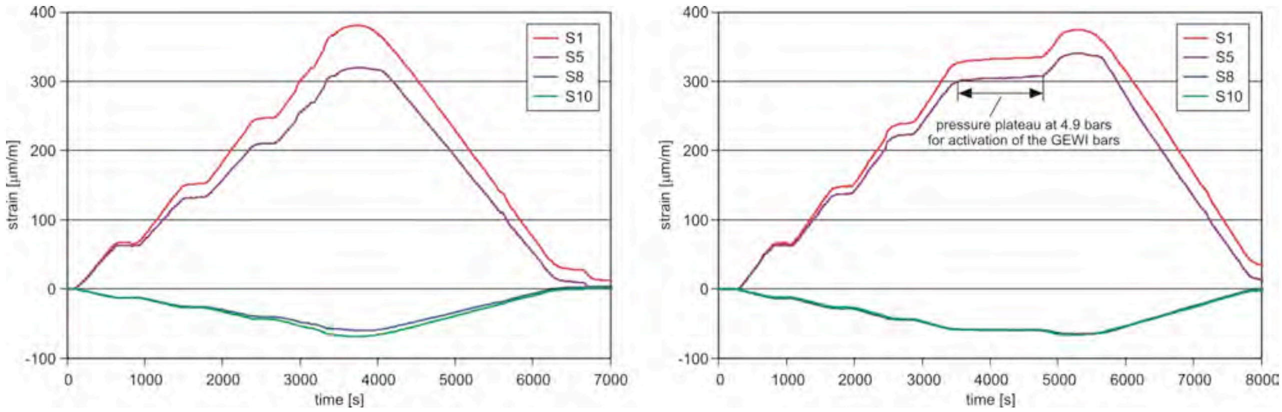

Figure 8. Internal strain measurements during RUN 2 (left) and RUN 3 (right)

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 sensor S8.

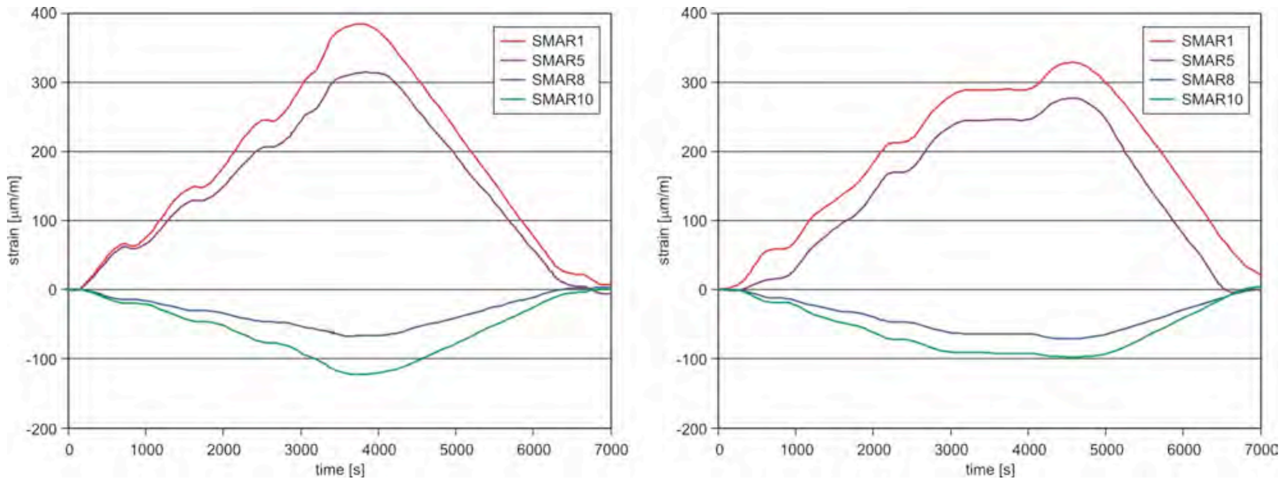

Figure 9. Internal strain measurements by the SMARTEC-sensors during RUN 2 (left) and RUN 3 (right)

The strain measurements in Fig. 8 correspond nearly perfectly to the strain measurement by the SMARTEC sensors that are shown in Fig. 9. The positions of the sensors SMAR1, SMAR5, SMAR8 and SMAR10 are geometrically comparable to the sensors S1, S5, S8 and S10 in Fig. 8. The global behaviour and the level of strain are very similar and quite promising for this kind of sensor prototype. As these sensors are chains with multiple strain and temperature sensors within one optical fibre the problem in many cases is that each sensor has only a very narrow frequency window in which the signal can be detected. In many cases the signal went temporary out of range but often shifted back into the window during the test.

As the GEWI reinforcement bars connecting the ears with the specimen were not activated yet during RUN 1 and RUN 2, only a passive elongation of the specimen occured. These GEWI reinforcement bars have been activated for the first time during RUN 3 when the externally applied force exceeded the remaining force in the specimen. As shown in Table 1 the prestressing force for RUN 3 and RUN 4 is 60 % of the starting level of the prestressing force used in RUN 1. As a consequence of GEWI bars not having been activated and the concrete of the specimen not having been under tensile load during RUN 0, RUN 1 and RUN 2 the sound detection did not register any damage event during these tests. The functionality of the sound detection system could be confirmed during RUN 3 and the data is still under evaluation. For RUN 4 the detection of micro-crack development is expected. The possibility of localisation of crack development is still an open question.

The following Fig. 10 shows the development of the prestressing force measured by the load cells which are mounted under the anchorage plates of the horizontal cables. It can be seen that the prestressing force follows exactly the scenario of the internal air pressure and also the externally applied force. Note that the vertical axis starts with a pressure level of 3 000 kN per jack and that the scenario of RUN 3 has an additional plateau at 4.9 bars to give time for the activation of the GEWI bars by fixing the nuts within the steel ears.

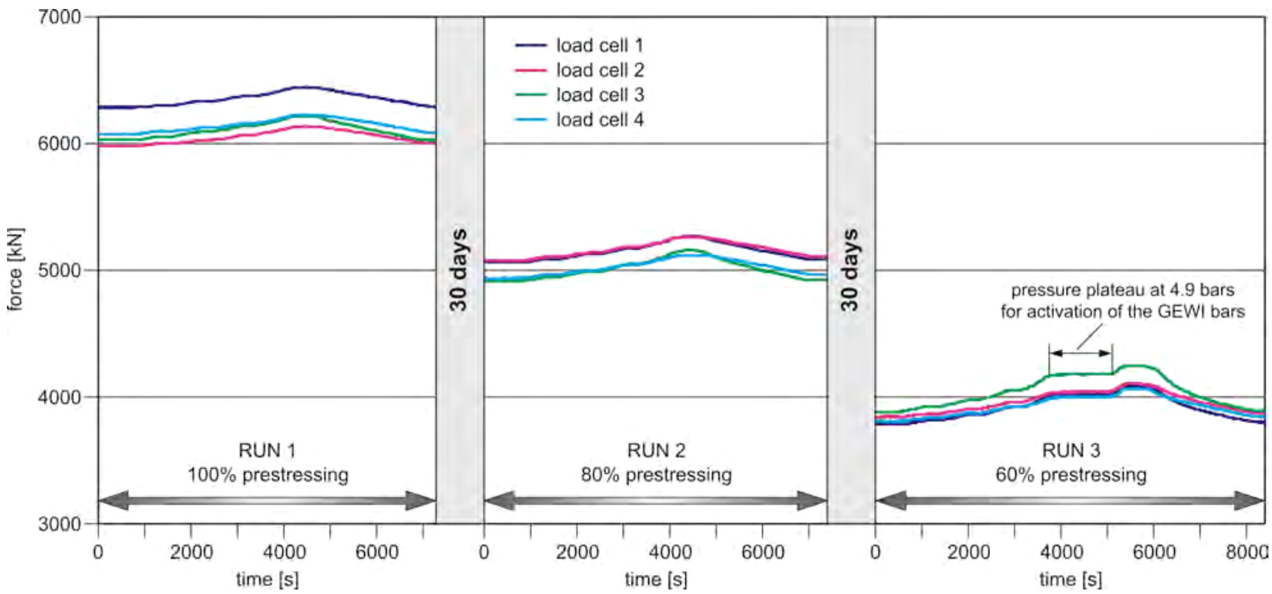

Figure 10. Change in the prestressing force during RUN 1, RUN 2 and RUN 3

As displayed in Fig. 11 first cracks appeared in RUN 2 (green) which developed further during RUN 3 (blue). After RUN 2, two types of cracks can be distinguished: (i) cracks located around the loading introduction zone and (ii) longitudinal cracking near existing casting joints.

During RUN 3, the global tensile regime was reached. As a result, cracks developed in the lateral direction. None of these cracks went through the entire section of the specimen. As a separating crack is expected for RUN 4 a steel ball grid has been installed in the observation area in order to measure the opening crack width during RUN 4 and later on the remaining crack width without any externally applied force. The displacement between two steel ball measuring points can be measured mechanically.

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 leakage. It is designed in a way that detection of a fluid phase would also be possible. The amount of leakage of different phases can then be measured separately by cooling down the leakage to force the condensation of water and registering the air volume afterwards by a flow meter. In the actual test series simple gas measurement is sufficient.

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

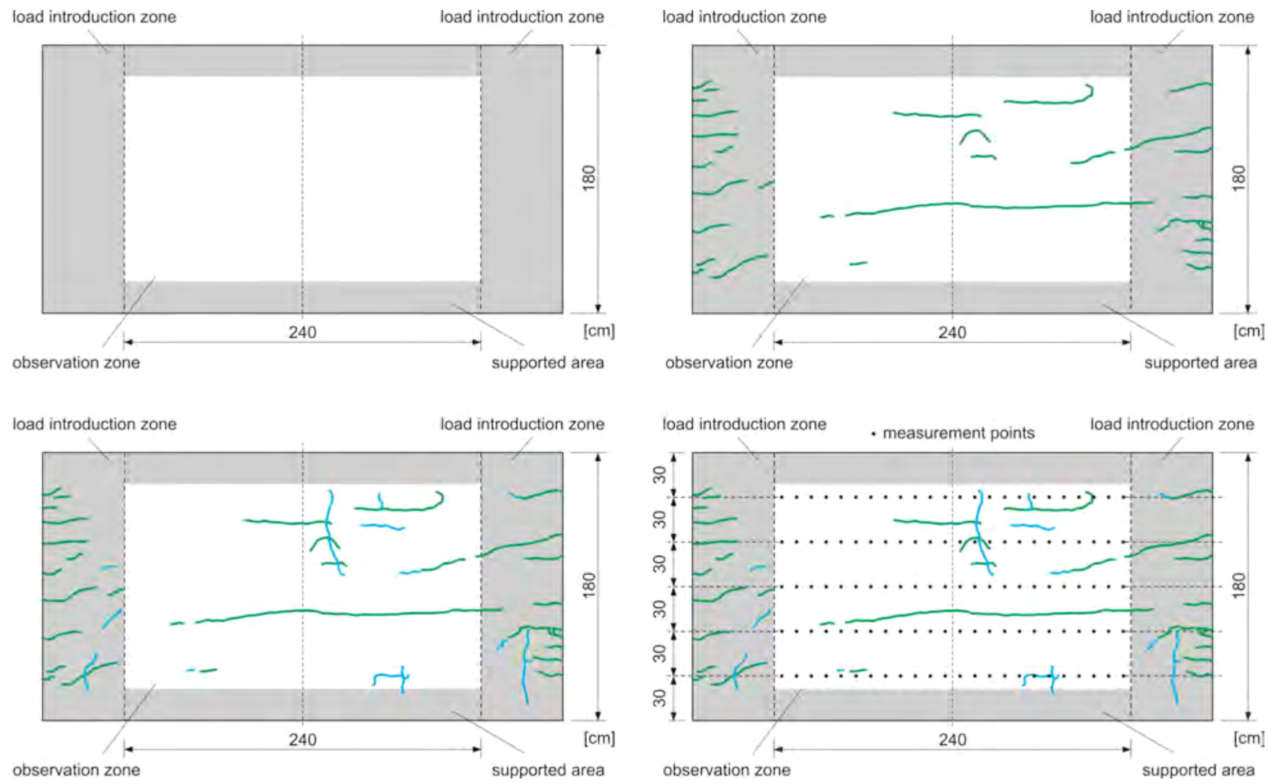

Figure 11. Crack development at the lower surface of the specimen after RUN 1 (top left), RUN 2 (top right), RUN 3 (bottom left) and the prepared steel ball grid for RUN 4 (bottom right)

6 CONCLUSION

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, RUN 2 and RUN 3. Within the current project the specimen will be tested in four runs with an eventual RUN 5 for leakage detection. 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.

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