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Division I

THE PACE-1450 EXPERIMENT – INVESTIGATIONS REGARDING CRACK AND LEAKAGE BEHAVIOUR OF A PRE-STRESSED CONCRETE CONTAINMENT

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ABSTRACT

The Materials Testing and Research Institute (MPA Karlsruhe) of the Karlsruhe Institute of Technology (KIT) and EDF started a cooperation in 2005 for the "PACE-1450 – Experimental Campaign" following up past joint research work. The subject of the project was to complement the variety of research programs of the last decades dealing with the crack and leakage behaviour of concrete containments of nuclear power plants under accidental conditions. The partners decided to build a facility for the testing of a representative curved pre-stressed specimen, which can be loaded as a closed ring under internal pressure.

The facility focuses on the testing of the pre-stressed concrete specimen under definded inspection and accidental conditions. This issue has also been partially investigated by EDF and MPA Karlsruhe in an intensive experimental and numerical work before and has partially been published at several occasions [Niklasch and Herrmann (2009)]. Theoretical investigations are not part of this paper, the description of relevant models and formulas can be found in [Niklasch et al. (2005)] and related publications cited therein.

The test campaign has been run with a specimen of realistic dimensions, reinforcement and pre-stressing. Leakage tests have been performed under different temperature and pressure conditions with varying media mixtures of air and steam. Supplementary investigations on the crack pattern of the used specimen have been started after the leakage test campaign and are still ongoing. This paper summarizes the results of the air leakage investigations at different temperatures as well as the first results of the crack investigations.

TEST PROGRAM, SPECIMEN AND EXPERIMENTAL SET-UP

The PACE-1450 experiment is an intermediate sized set-up and addresses the behaviour of a curved specimen representing a 1450 MWe nuclear power plant containment. The specimen's dimensions are 3.5 m (length), 1.8 m (width) and 1.2 m (height) corresponding to the thickness of the original containment wall (see Figure 1).

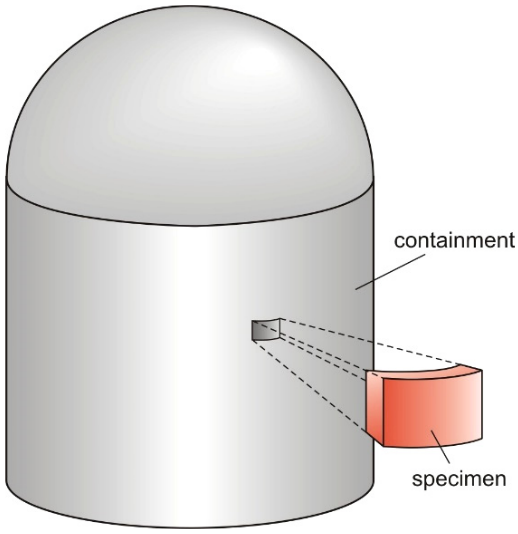

Figure 1. The specimen is a sector of the cylindrical part of the containment.

The reinforcement layout of the specimen mainly consists of meshes of bars near the inner and outer surface and four pre-stressing cables in the circumferential direction (see Figure 2 and Figure 3). During the tests of the campaign, the specimen is loaded by pressure, which simulates the accidental containment pressure of 5.2 bars or even more for research reasons (all pressure values in this paper are given in absolute terms). The resulting ring tensile stress (originally in the cylindrical part of the containment) is externally applied by hydraulic jacks. The initial pre-stressing of the specimen of 12 MPa is realized in such a way that a decrease of the pre-stressing for the purpose of simulating the aging of the concrete structure is possible.

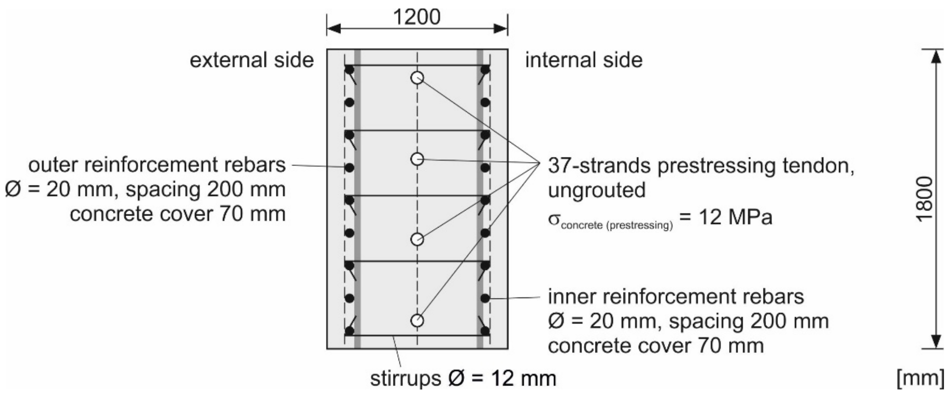

Figure 2. Section of the specimen as part of the containment.

The design of the test facility allows for the cracking of the specimen and for leakage measurements at different controlled crack widths, which can be varied during the tests. The specimen is equipped with embedded optical fibre strain and temperature sensors and an acoustic emission for recording the crack initiation. At the extrados of the containment segment an optical fibre bonded to the surface is installed allowing for crack detection, with laser and inductive displacement sensors monitoring the crack opening and anemometers for air velocity measurement at the crack outlet. The displacement of the specimen's edges is measured with the help of inductive sensors.

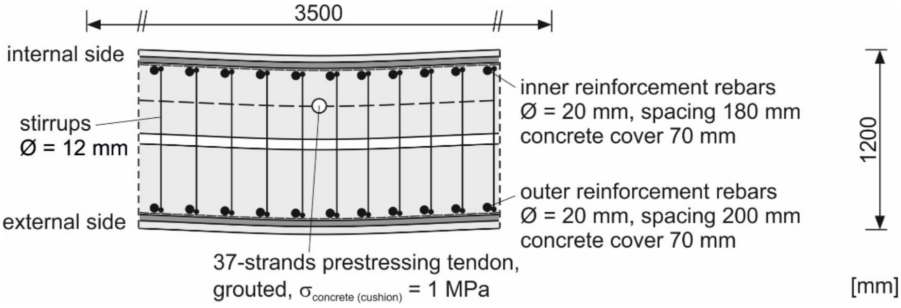

Figure 3. Vertical section in longitudinal direction of the specimen.

Concrete creeping varies with the mix design but it shall not result in a significant loss of pre-stressing that would jeopardize the containment structural integrity during an over-pressurization scenario (integrated standard leak rate test or accidental situation). For practical purposes, the pre-stressing in the campaign was gradually decreased to simulate the creeping of the concrete and its effects on the post-tensioning system. The test pressure during RUN 1 to RUN 3 was 5.3 bars. For RUN 4 to RUN 6 a pressure level of 6 bars was chosen and RUN 7 to RUN 12 have now been successfully performed at a pressure level of 5.2 bars taking into account also hot air and air-steam mixtures as in accidental scenarios. The goal of these tests is to steer desired leakage rates and get knowledge of the relation of these rates between cold air, hot air and air-steam-mixtures. This paper focuses on the comparison of tests with cold air and heated air, namely RUN 7 and RUN 10. Table 1 gives an overview of the full test campaign.

Table 1: Test program.

RUN	**real age (years)**	**pressure (bars)**	**temp. (°C)**	**media**	**pre-stressing (%)**	**remarks/idea (see also text)**
0	0	1.43	20	air	25	testing of facility
1	0	5.30	20	air	100	first day of plant operation
2	10	5.30	20	air	80	leak tightness test after 10 years of operation
3	35	5.30	20	air	60	leak tightness test after 35 years of operation
4	60	6.00	20	air	60	accident after 60 years of operation/ cracking
5	60	6.00	20	air	60	First leakage test (all cracks)/accident after 60 years
6	60	6.00	20	air	60	second leakage test (all cracks)/accident after 60 years
7	60	5.20	20	air	60	third leakage test (single crack, varying crack width
8	60	5.20	140	air	60	fourth leakage test (single crack, fixed crack width)
9	60	5.20	140	air	60	fifth leakage test (single crack, adjusted crack width)
10	60	5.20	140	air	60	sixth leakage test (single crack, adjusted crack width)
11	60	5.20	140	air-steam	60	seventh leakage test (single crack, adjusted crack width)
12	60	5.20	140	air-steam	60	eighth leakage test (single crack, adjusted crack width)

The mechanical test bench comprises of the specimen, foundations, abutments, steel beams and a cover with its fixing construction enclosing the needed pressure chamber (see Figure 4). The specimen itself lies between the sidewise abutments and is connected to the beams by 128 GEWI bars at each side. Hydraulic jacks supported on the abutments at each side of the specimen apply the tensile force corresponding to the internal pressure. Due to the connection between the beams and the specimen, the specimen is initially put under tension at the very moment when the externally applied force exceeds the pre-stressing force. During RUN 4 the concrete was put under a tension load beyond the value of its tensile strength for the first time and therefore, four transversal global cracks through the whole specimen appeared. The specimen's crack pattern and the thermo-hydraulic mixing facility have been already described in other publications [Herrmann et al. (2015), Niklasch and Herrmann (2009)]. For the purpose of simulating the pre-stressing of the containment in the original vertical direction steel cushions are placed between the specimen and the abutments. These cushions can be set under pressure up to 1 MPa and also serve for sealing the specimen in a way that the total leakage could be collected and measured beneath the specimen. For the sake of clarity the fixing construction for the cover is not shown in Figure 4, it can be seen in the photo on the concrete cover.

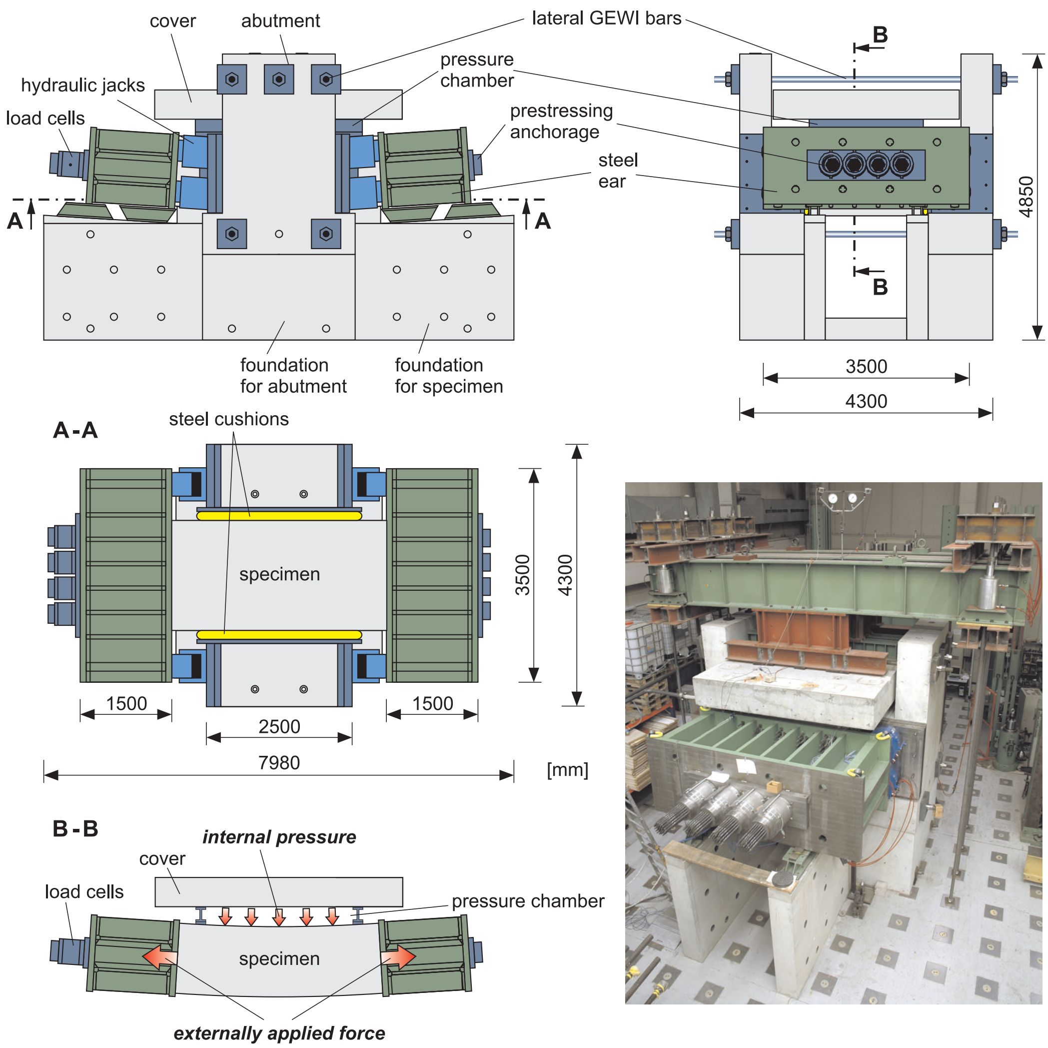

Figure 4. Drawings of the mechanical part of the facility (in section B-B the applied force is shown in principle) and photo of the mechanical set-up.

TEST SCENARIOS AND MEASUREMENTS

Standard integrated leak rate tests in France mainly geared the chosen test scenarios. The duration in the lab was shortened as a steady state is obtained much faster than in reality. The peak pressure of 5.2 bars was reached with an increase rate of 0.2 bars/minute after the starting pressure was levelled to 1.15 bars in order to ensure for an exact steering of the external force coupled to the applied internal pressure. In the following RUN 7 and RUN 10 are discussed for which a scenario was chosen that gave the opportunity for adjusting the leakage rate to different values as it was done in RUN 7 and to steer the leakage rate to a desired value and increase the temperature as in RUN 10. In RUN 10 this was done with heated air of 140 °C while in RUN 7 the temperature has been kept stable to 20 °C (see Figure 5).

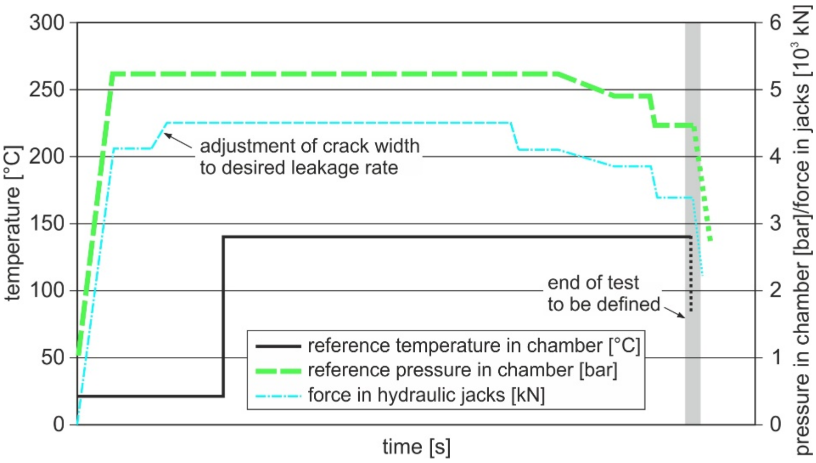

Figure 5. Principle pressure scenario for RUN 7 (temperature kept to 20 °C) and RUN 10 (reference temperature 140 °C after reaching the desired crack width).

The adjustment of the leakage rate was done by varying the crack width due to manually increasing the tension force independently from the physical relation between the inner containment pressure and the resulting ring tensile stress. After measuring a stable leakage rate, the tension force was reduced again to the correctly calculated physical level. The first decreasing ramp for reaching a plateau at 4.9 bars was defined with a decrease rate of 0.5 bars/hour. The next ramps for reaching further pressure plateaus of 4.5 bars, 4.0 bars etc. were performed with a faster rate of 0.2 bars/minute. The end of the test was decided between the project partners for the case that no further changes in the measured leakage rate was observed. All relevant parts of the facility as well as the specimen itself are equipped with transducers for monitoring strain and temperature. The force in the pre-stressing cables is measured by individual load cells.

RESULTS

Here, only results of the second part of the test campaign (RUN 7 to RUN 12) are shown. Only one of the four main cracks that appeared in RUN 4 was kept open for these tests. This crack is displayed in Figure 6 with marked positions of the displacement sensors A, B and C at the crack inlet before the seal for the other cracks had been put in place. The later mentioned displacement sensors D, E and F were located at the crack outlet at the lower side of the specimen. All cracks beside the middle crack were sealed with a steel sheet being mounted on the top surface of the specimen and therefore, these other cracks had no influence on the leakage results. The sealing sheet is shown in Figure 7 after fixation on the top surface of the specimen. Only the chosen centre crack of a length of 1.5 m was accessible to the media.

In order to avoid condensed water from blocking the chosen centre crack, a notch surrounded the open area with the possibility of collecting condensed water around the open crack in a cavity at the lowest area of the specimen within the crack box. With the help of a condensation catcher this water was led out of the pressure chamber.

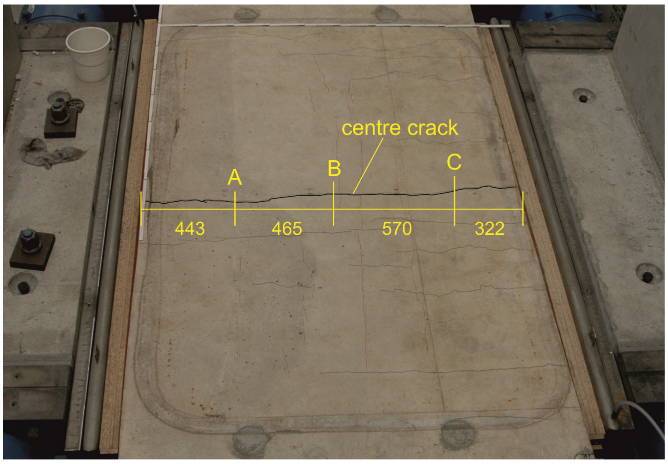

Figure 6. Centre crack with marked positions for displacements sensors A, B and C.

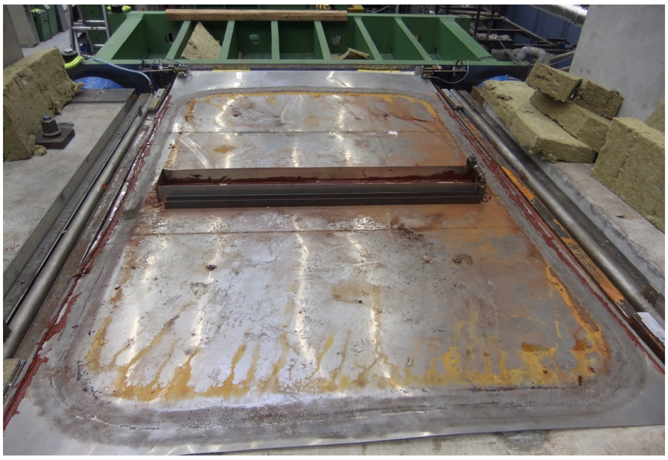

Figure 7. Steel sheet sealing all but the centre crack with notch around the crack

As the crack path within the specimen could not be traced regarding to possible bifurcations, the collection chamber covering the whole observation area of the lower surface was used again below the specimen in order to catch all leakage. The target value for the starting leakage rate was defined after RUN 7 for the other tests by EDF based on the results of observations at real power plants. In this paper RUN 7 (cold air) and RUN 10 (hot air) have been chosen for publication of relevant results. Both were performed according to the principle scenario displayed in Figure 5.

In Figure 8 the characteristics of RUN 7 are displayed. First, the air pressure was increased and the hydraulic force was steered according to the physical relation, which resulted in an average crack width at the internal surface of approximately 0.1 mm (see reddish lines A, B and C in Figure 9). After the observation of a stable leakage of ca. 5 kg/h at the top surface, the hydraulic force was increased in order to open the crack to a width of ca. 0.2 mm and a leakage of ca. 20 kg/h. In additional steps, the force was increased to reach a leakage of ca. 30 kg/h at a crack width of ca. 0.3 mm and finally up to nearly 65 kg/h at little less than 0.5 mm of average crack opening. Shortly before reaching the last hydraulic force level a secondary leakage (probably at the sealing of the cover) occurred after ca. 7300 s of runtime. The problem could be fixed after ca. 9000 s by adjusting the cover construction. After ca. 9800 s the test was finished, the last peaks after this time were only steered for test reasons of the facility.

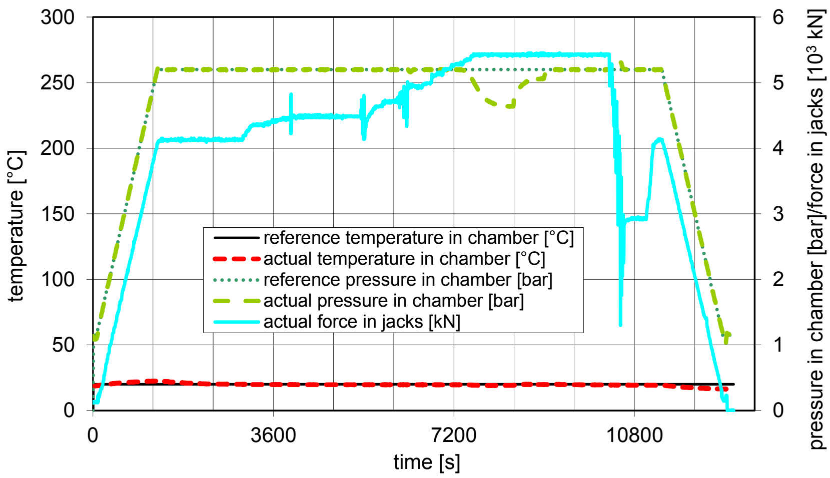

Figure 8. Temperature, pressure and force during RUN 7

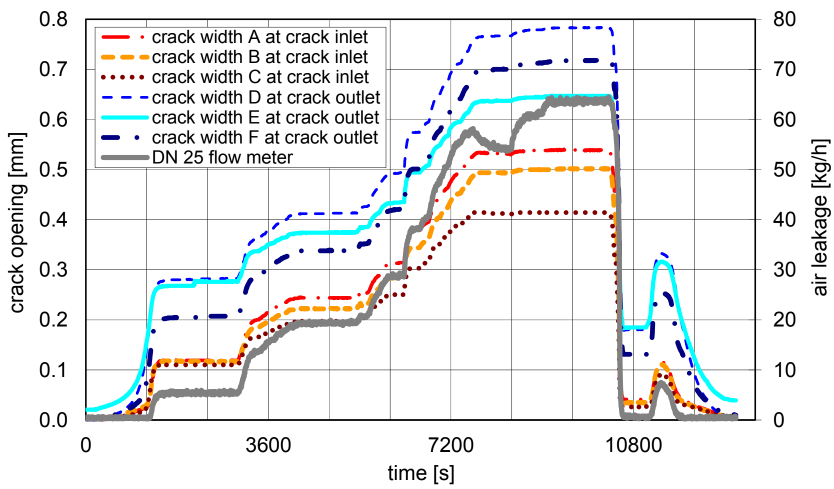

Figure 9. Crack width and leakage measurement during RUN 7

For RUN 10 the desired starting value for the leakage rate was chosen to ca. 12.9 kg/h per meter of crack length at the top surface, which would have resulted in a value of 19.4 kg/h for the crack being investigated. During the scenario the target leakage had been changed to 24 kg/h. This adjustment can be seen in the light blue curve in the following Figure 10. First the shape of the force increase in the jacks follows perfectly the pressure scenario for the pressure chamber (green lines in Figure 10) resulting in a crack width at the upper surface of the specimen of approximately 0.1 mm (reddish lines A, B and C in Figure 11). After ca. 2600 s of runtime the force in the jacks had been increased manually in order to reach the mentioned leakage rate which led to a crack width of approximately 0.2 mm at the intrados of the specimen. At the extrados this adjustment also resulted in a doubled crack opening.

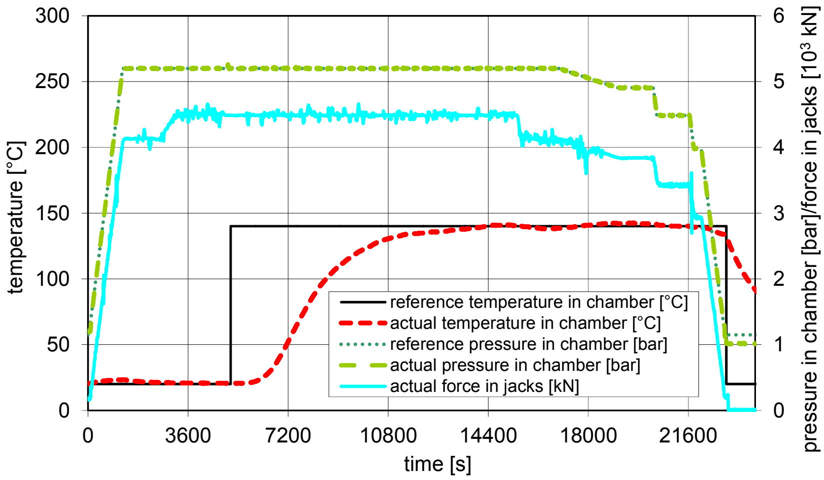

Figure 10. Temperature, pressure and force during RUN 10

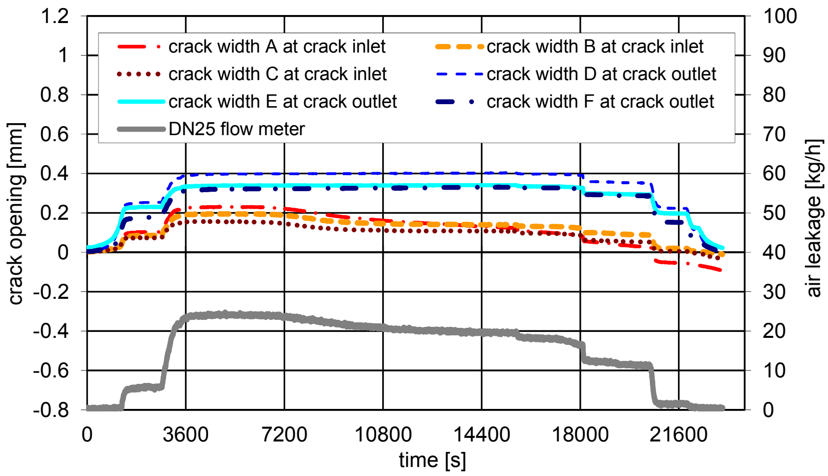

Figure 11. Crack width and leakage measurement during RUN 10

In Figure 10 also the reference as well as the actual temperature in the pressure chamber is shown. The heating only with air was very slow and it took nearly two hours to reach the target temperature of 140 °C due to the small heat capacity of air and the large volume of the concrete parts of the facility, mainly the cover and the specimen itself. In Figure 11 a reduction of the crack width at the inlet nearly back again to an average of 0.1 mm caused by the increase of temperature can be seen. Negative crack values (sensor A at crack inlet) are due to a contact of the steel sealing to the sensor at the end of the test. The corresponding leakage (grey line in Figure 11) decreased from a value of 24 kg/h to less than 20 kg/h. Afterwards the force adjustment was retracted without causing a significant effect. This may result from the cracks having already been nearly totally closed.

A slow decrease of the air pressure had been steered until 4.9 bars were reached and then the values 4.5 bars and 4.0 bars have also been investigated. At the 4.0 bars plateau it was decided to end the test as no more relevant leakage was registered.

POST-MORTEM ANALYSYS OF THE CRACK PATTERN

In order to understand how the cracks inside the specimen developed, it was cut into 18 blocks. The blocks were numbered, those in the central part have numbers from 7 to 12 (see scheme in Figure 12). After cutting, cracks were identified with the naked eye and marked in black in order to make them clearly visible. Photos of five of the six surfaces of each block were taken.

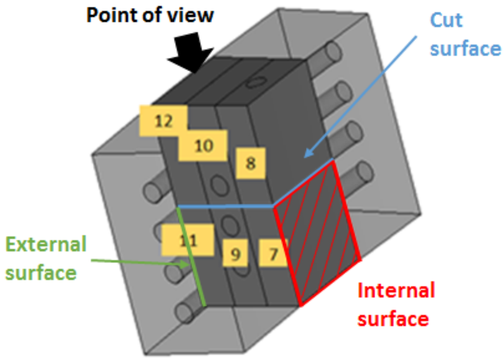

Figure 12. Central blocks after cut of PACE 1450.

Cracks in concrete structures may have complicated paths, due to the kind of loadings or to heterogeneities. Here, loading is quite homogeneous and one would expect (more or less) straight cracks from the inner to the outer side. However, the pre-stressing cables are quite large compared to the overall dimensions of the specimen and can be viewed as rigid inclusions.

In this paper, cracks patterns are analyzed with respect to possible leakage paths, from the inner surface where injection is done (red in Figure 12) to the outer surface (green in Figure 12). The trace of the cracks on the cut surface (in blue) give an idea of their configuration in the thickness. In Figure 13 the development of the lower (central) part of the specimen (blocks 7, 9 and 11) is displayed. The cut surface is seen from above (point of view in Figure 12).

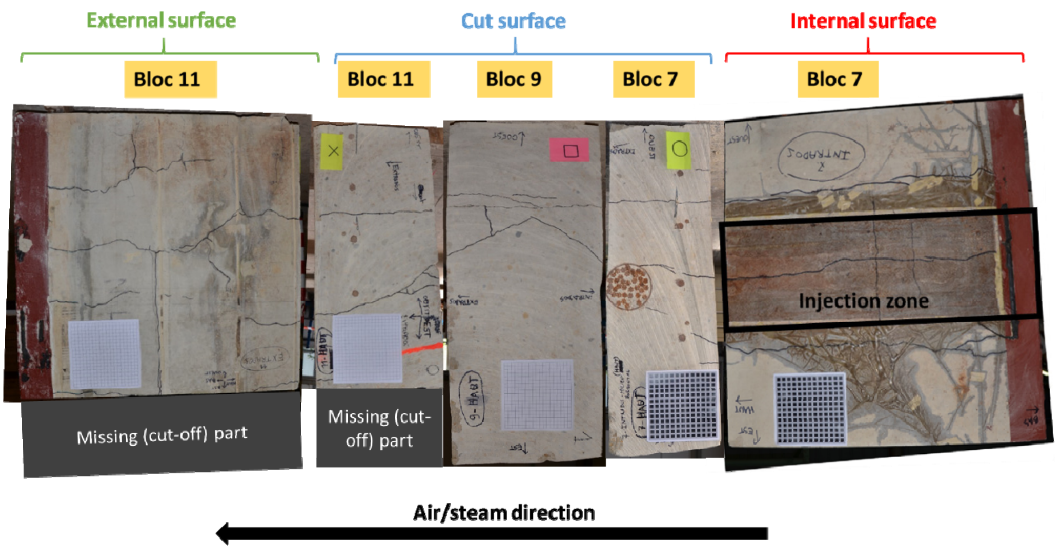

Figure 13. Development of lower central part of PACE 1450 (Blocks 7, 9 and 11).

The chosen representation allows for seeing the fluid inlet ("injection zone") as well as possible outlets and paths in the thickness. Indeed, cracks are not straight, so air or steam must undergo a complicated path from the inside to the outside.

More into details, the central crack used for air/steam injection is strongly deviated from the inner side to the outer side by the vertical cable. This is important for leakage predictions because sharp deviations may give rise to localized losses in kinetic energy. Moreover, due to bifurcations, knowing the real air/steam path from geometrical crack path is not straightforward. In fact, the injected fluid would follow preferably the crack with the widest opening.

CONCLUSION AND ACKNOWLEDGEMENT

For the "PACE-1450 – Experimental Campaign" a leakage testing facility for pre-stressed curved specimen has been built and tests have been successfully performed. Tests with cold air, hot air and air-steam-mix were performed. Further evaluation of the test data and the crack pattern is still ongoing and therefore, no final conclusion on the influence of the gained results on the maintenance of existing structures or the design of new structures can already be given at this time. The research work was done within the framework of the cooperation project "PACE-1450 – Experimental Campaign" of MPA Karlsruhe and the EDF departments R&D and SEPTEN. A complete publication covering all gained results and final conclusions is planned for the near future.

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