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IMPACT AND BENEFIT OF THE PRE-STRESSING SYSTEM ON THE INNER CONTAINMENT OF THE PRESSURIZED WATER REACTOR (EPR™ Type)

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ABSTRACT

The inner containment of the pressurized water reactor (EPR™ type) is a pre-stressed concrete shell equipped with a steel liner on the inner side. The concrete shell is designed to withstand the loads from internal accidents. The steel liner ensures the containment leak tightness.

The pre-stressing tendon ducts are injected with grout. The used pre-stressing type is therefore pre-stressing with bond. An integrated monitoring system enables the documentation of the containment long time behavior regarding deformation, temperature, humidity and pre-stressing forces.

The alignment of tendons, the state of concrete compression and the bond between tendons and concrete create many advantages in the containment integrity, in the consideration of failure events and in material deterioration processes. The maintenance of the pre-stressing system during the operation of the nuclear power plant is optimized.

The evaluation of measurement results of a containment in operation for a long time proves that the monitoring system is able not only to verify the functionality of the pre-stressing system, but also to reproduce the ageing behavior of the containment structure and to provide additional margins regarding the containment life-time by the reconsideration and assessment of the material design parameters.

1. CONTAINMENT STRUCTURE AND PRE-STRESSING SYSTEM

The reactor building of the pressurized water reactor (EPR™ type) consists of two concrete shells and a steel liner. The outer containment is a conventional reinforced concrete shell. Its function is to protect the reactor building against external hazards like airplane crash.

The inner containment is a pre-stressed concrete shell. It can be divided into the cylindrical part and the dome part, see Figure 1.

The cylindrical part includes numerous openings, the equipment hatch being the major one. Both containment parts are pre-stressed crosswise with three groups of tendons, see Figure 2. The internal side of the wall is covered with a steel liner.

After erection and pre-stressing of the containment structure grout is injected in the tendon ducts. The bond between the tendon strands and the grout, between the grout and the tendon duct and between the duct and the walls concrete enables the transfer of forces in longitudinal tendon direction.

2. MONITORING SYSTEM

The containment long-time behavior as well as the behavior during the pressure tests is monitored by a wide diversity of measurement devices. Regarding the deformations pendulums at the exterior of the inner containment are installed at different levels of the cylindrical part.

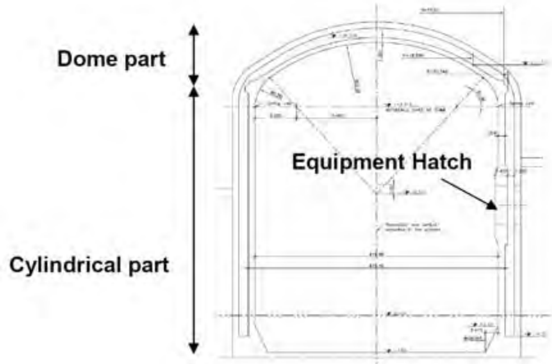

Figure 1: Inner and outer containment of the EPR™

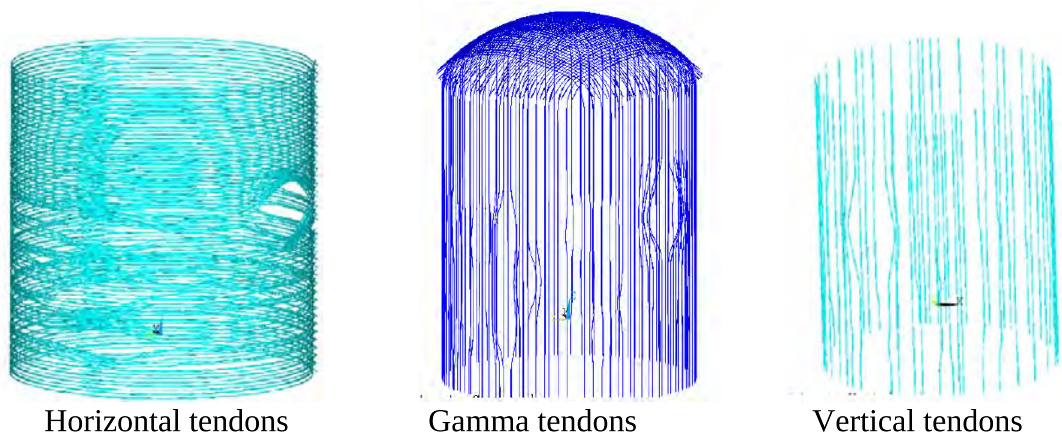

Figure 2: Tendon groups of the inner containment

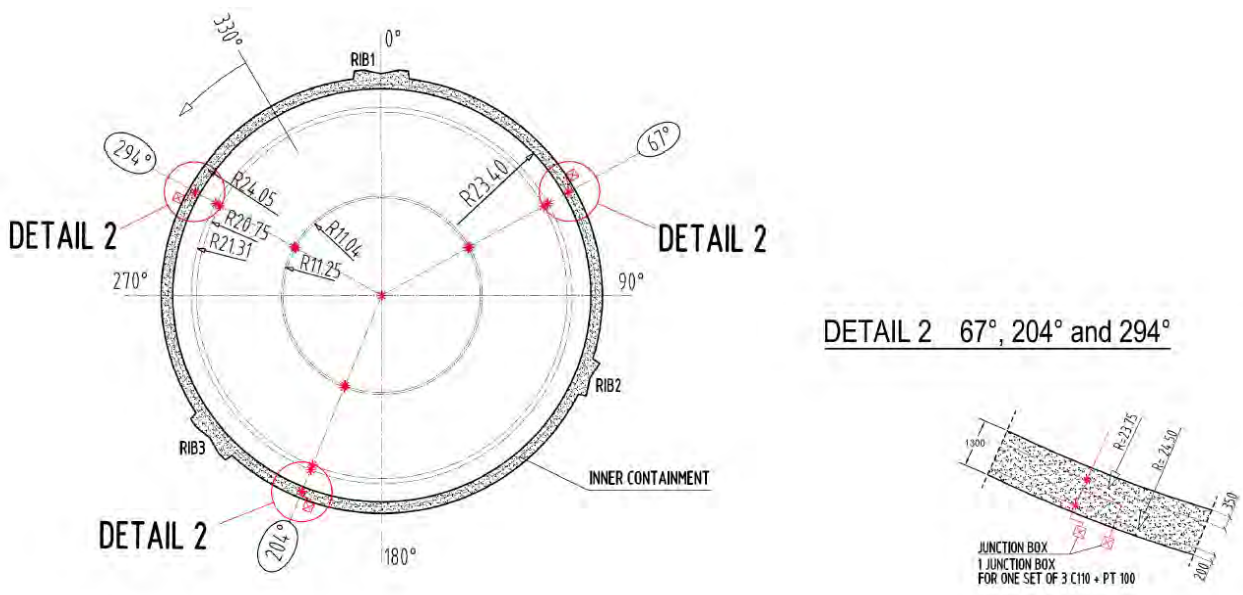

Figure 3: Location of measurement devices in cylindrical part and in dome

In addition strain gauges are embedded in the concrete wall of the cylindrical part and in the dome wall at different angles of the containment, see Figure 3. Strain gauges are also embedded in the base slab. The measurement system is supplemented with humidity and temperature devices at the same locations in order to ensure full control of the measurement results.

3. ADVANTAGES OF THE PRE-STRESSING SYSTEM

3.1 Advantages in the Containment Integrity

The amount and the density of the pre-stressing tendons are chosen in such a way that during pressure test the mean concrete stresses of the containment wall remain compressive in both directions. In consequence the approximate linear behavior of the containment structure is ensured even in this decisive load combination and concrete cracks are virtually avoided. Also progressing concrete cracks due to regularly repeated pressure tests and a deteriorating deformation and stress state of the containment structure is averted. The leak tightness of the liner is not endangered by increasing deterioration of the concrete wall in which the liner is anchored.

3.2 Consideration of Failure Events

The bond between the tendon and the concrete enables the transmission of forces longitudinal to the tendon. Besides the small forces which occur since the grouting of the tendon also higher forces appearing in failure events like strand ruptures can be transferred. A strand or a tendon failure remains therefore a local effect. The influence length is double the tendons re-anchoring length which is the force transfer length between the tendon and the concrete. In Figure 4 the re-anchoring length for the horizontal tendon is depicted as an example.

On the other side a tendon failure in an unbonded pre-stressing system influences the containment stress and strain state along the whole tendon length (green line in Figure 4). Due to the so called global effect a considerably higher area of the containment wall is affected.

The high energy released by a postulated tendon failure cause considerable dynamic effects as temporary accumulation of additional strand and tendon forces. The material of the pre-stressing steel is already utilized not far from the yielding strength. Such dynamic effects can trigger a chain reaction of strand and tendon failures. The adjacent tendons in respective parallel direction are concerned by additional loads and chain failure.

The probability of a chain reaction from a first to a second failure depends on the influence length of the failure. By comparing the influence lengths in case of bonded tendons with those in case of unbonded tendons the probability rate called “rate 1” of a chain reaction between both cases can be calculated. It is possible to calculate the rate, even if the probability of a tendon failure itself is not known. Equally the probability of a chain reaction from a second to a third failure can be quoted, called “rate 2”.

The tendon re-anchoring length depends on many boundaries as the used injection grout material, the surface of the tendon duct and the tendon curvature, but does not differ far from those in the following used best estimated values.

The results are summarized in Table 1 for the different tendon types. It is clearly visible that the danger for chain reaction is reduced in case of bonded tendons. With each additional tendon failure the probability rate between bonded and unbonded tendons gets considerably lower.

It is obvious that the here discussed consideration of failure events influences also the probability safety of the containment ultimate strength capacity.

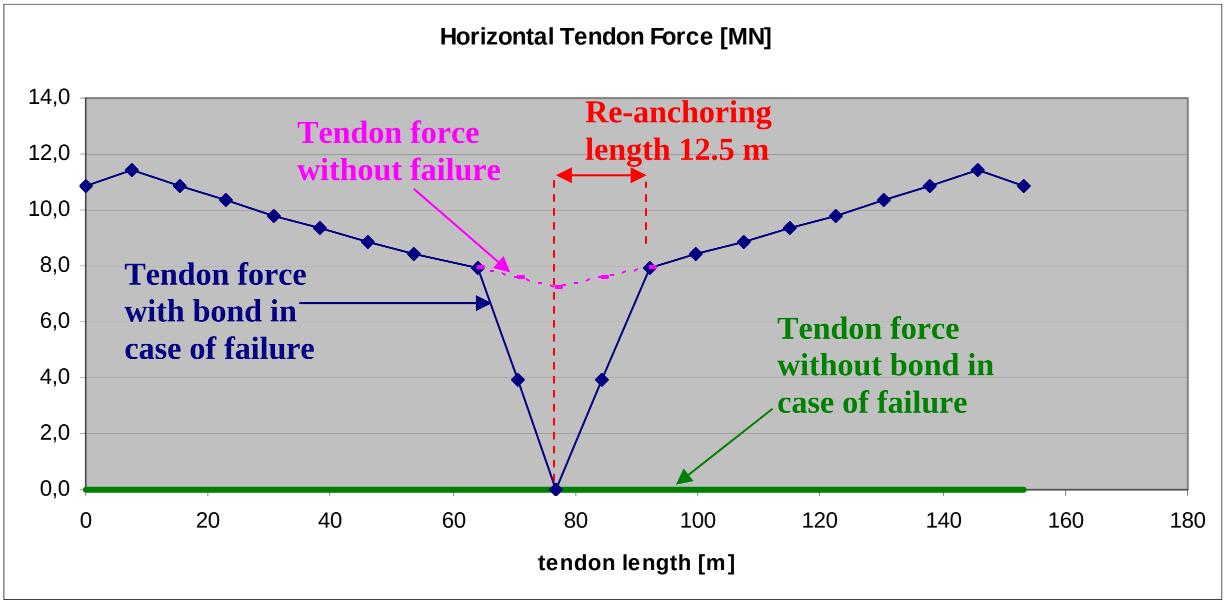

Figure 4: Tendon force and re-anchoring length

Table 1: Influence lengths in case of bonded and unbonded tendons

Tendon type	Influence Length for bonded Tendons (double re-anchoring length) [m]	Influence Length for unbonded Tendons (overall length) [m]	Rate 1 [%]	Rate 2 [%]
Horizontal	25	158.0	15.8	2.5
Gamma	30	110.2	27.2	7.4
Vertical	30	60.9	49.3	24.3

From Table 1 it is clearly visible that the rate after each failure step converges fast to zero independent of the tendon type. The advantage of pre-stressing with bond compared to without bond is therefore obvious.

3.3 Material Deterioration Processes

The most critical material deterioration process in the pre-stressing system is the danger of strand corrosion. Explanations in the present publication will therefore be restrained on this item.

The injection of the tendon ducts with grout offers the best conceivable corrosion protection for the tendon strands. The chemical properties of the grout are examined in order to limit the exposure to impairing substances as chlorides and oxygen. Even more important is the injection procedure regarding the grouting velocity and pressure. As the timing of grout mixing and injecting in connection with the grouting equipment and the staff is a challenge on site, the grouting procedure is tested in full-scale mock-ups in advance. By cutting the mock-ups the number and distribution of resilient air voids in critical duct locations can be checked and evaluated. Voids can't be avoided totally, because a tiny amount of gas is produced from the cement setting process. The limitation of the voids precludes efficiently the corrosion of the strands.

The ends of the tendons are protected with metallic grouting caps which are also injected with grout after tensioning. Tendons are hence completely sealed and protected from external affecting conditions.

3.4 Maintenance of the Pre-stressing System

For the maintenance of the pre-stressing system during the operation of the nuclear power plant the required effort is minimized. There is no re-tensioning of the tendons needed because the tensioning forces are designed at a level which ensures remaining concrete compression until end of the containment life time even during periodical pressure tests.

The performance of re-tensioning measures would be detrimental to the maintenance of the nuclear power plant. The duration is longer than the usual outage periods. In addition clearance is needed at every pre-stressing anchor and access is required in order to move and place the pre-stressing jack.

4. EVALUATION OF MEASURING RESULTS

4.1 Creep and Shrinkage Deformations

The containment long time behavior is dominated by creep and shrinkage of the concrete due to the compression forces applied by the pre-stressing system. The evaluation of the containment measuring results regarding its deformation development opens the possibility to verify the functionality of the pre-stressing system, but also to check the assumptions in material design parameters which are the basis for the design calculations.

Strain gauges embedded in the concrete wall are part of the monitoring system. The concrete strain development is measured starting from a zero measurement after the finalization of pre-stressing.

In Figure 5 the measured strains are compared with the values calculated with the design material parameters for the cylindrical part in horizontal and in vertical direction and for the dome. The calculated values are generally higher, because they are based on the design material parameters which have been determined conservatively. The result of the comparison is the basis to assess the real material parameters and to recalculate the containment in order to predict its behavior more accurate.

4.2 Force Balance in Wall Section

Figure 6 delivers a view on the force balance between the different components in the wall section. The force balance is shown for the cylindrical part in horizontal direction, calculated with design material parameters. The loss of compression in concrete is transferred to compression forces in the conventional reinforcement, the tendons and the liner. The increasing bracing between concrete compression loss and compression of the other components is clearly visible. In case of using assessed material parameters the bracing is in this example at about 10% less pronounced. The respective curve for concrete is denoted with a dotted line.

4.3 Concrete stress Development

The resulting concrete stress development is indicated in Figure 7. Stress peaks due to pressure tests are marked in purple color. The concrete stresses calculated with design material parameters are indicated with a straight line, those with assessed parameters with a dotted line. In the present example the concrete stress peak during the pressure test decreases by using the assessed material parameters.

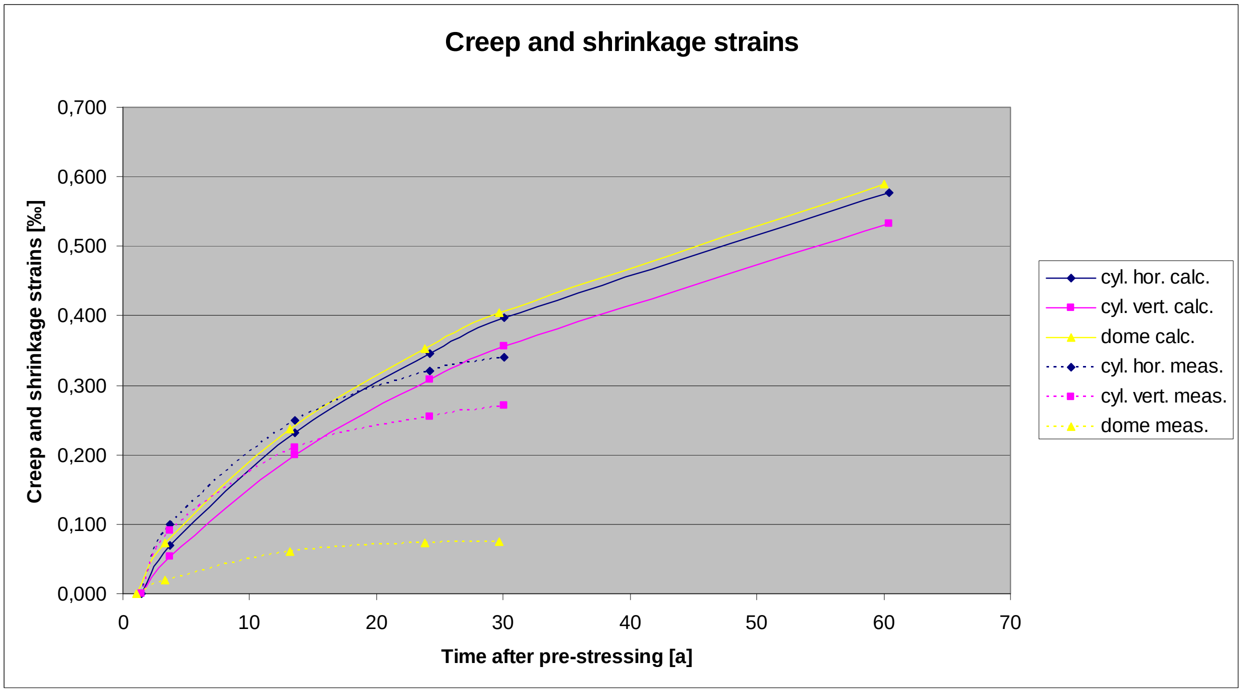

Figure 5: Calculated and measured creep and shrinkage deformations

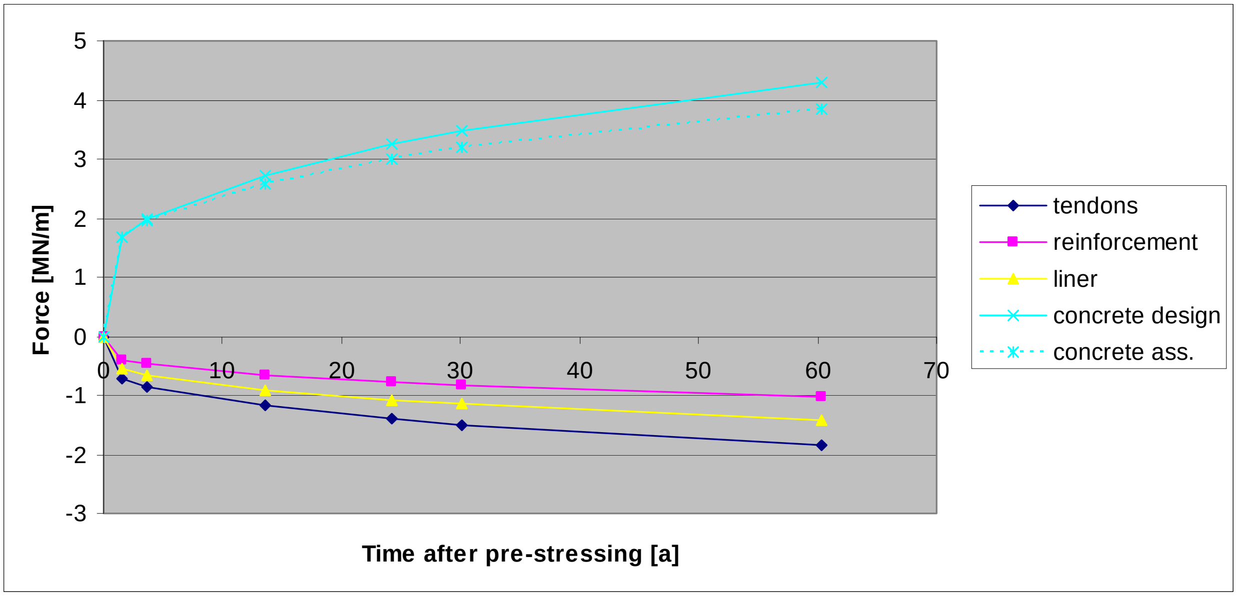

Figure 6: Force balance for the cylindrical part in horizontal direction

The maximum containment life time is linked with the criterion of concrete tensile stress limit. Maximum tensile stresses occur during the regularly scheduled pressure tests. The evaluation of concrete stresses with assessed material parameters based on measured results has shown that the maximum tensile stresses decrease compared to the calculation with design material parameters. In consequence, this comparison opens the possibility of a life time extension of the containment. In a calculation with assessed material parameters, the concrete tensile stress limit will be reached at a later date.

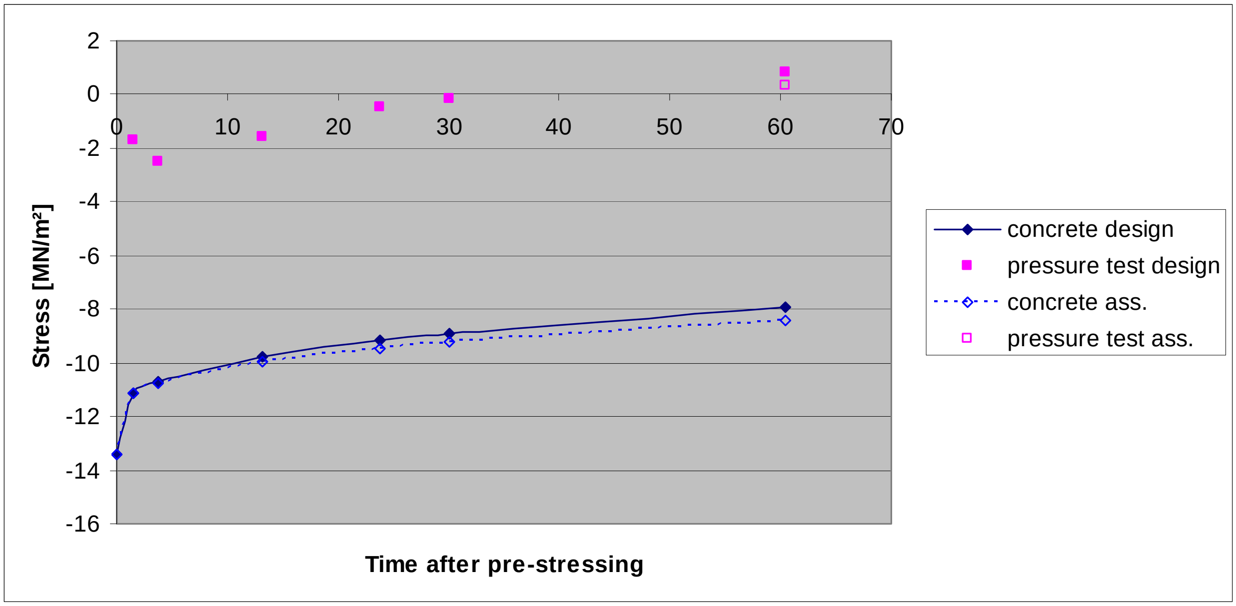

Figure 7: Concrete stress for the cylindrical part in horizontal direction

5. CONCLUSION

The advantages of the bonded pre-stressing system of the pressurized water reactor (EPR™ type) inner containment have been demonstrated. The alignment of tendons, the state of concrete compression and the bond between tendons and concrete are beneficial in the containment integrity, in the probabilistic consideration of failure events and in material deterioration processes. In addition, the pre-stressing system consisting of grouted tendons optimizes the maintenance during the operation of the nuclear power plant and induces long term economical advantages.

The measurement results of a containment in operation have been evaluated. The results verify the functionality of the applied pre-stressing system.

By using assessed material parameters instead of the design values, the containment ageing behavior has been recalculated. Due to additional margins in the containment concrete stress during pressure a life time extension of the containment can be envisaged.

REFERENCES

Wienand, B., Ostermann, D. and Krumb, C. (2012). "Not a Mystery – Inner Containment of the Pressurized Water Reactor (EPR™ Type)", *Annual Meeting on Nuclear Technology*, Germany