AN INVESTIGATION ON A PRESTRESSED CONCRETE REACTOR VESSEL UNDER INTERNAL GAS PRESSURE. MODE OF RUPTURE

R. LENSCHOW,
Institutt for Betongkonstruksjoner,
Norges Tekniske Høgskole, Trondheim, Norway

ABSTRACT

The Cement and Concrete Research Institute, University in Trondheim, Norway, performed in February 1971 tests to rupture on 2 models of prestressed concrete pressure vessels. The main purpose with this project, which is planned for a series of 6 models, is to study the mode of rupture of the vessel, loaded by internal gas-pressure.

Model no. 1 is a model in scale 1/3.6 of the Scandinavian PCCV-model, except for the removable lid. The vessel has an inside diameter of 55 cm and an inside height of 111 cm. The cylindrical wall thickness is 30 cm and the top and bottom slabs are 33 cm. The reference pressure is 85 bar.

To simulate the effect of shear capacity of the steel tubes in the Scandinavian model, model no. 1 is supplied solid steel bars in the top and bottom slabs. The vertical prestressing system consists of prestressing bars (System Dywidag). In the circumferential direction there are 10 bands, consisting of 3/8" prestressing strands. The nominal prestressing forces in the tangential and axial direction are about 1.5 and 1.75 times the reference pressure load, respectively. In addition there is bonded reinforcement that can take up 0.6 and 0.8 times the reference pressure, respectively in the tangential and axial directions (at yield). The inside of the vessel is lined by a mild-steel lining (thickness 3 mm), welded in argon-atmosphere. The concrete in the models has an average cylinder strength of 430 kp/cm².

Model no. 2 is equal to no. 1, but has no bonded reinforcement in the cylindrical wall. The nominal prestressing forces in the tangential and axial directions are equal to model no. 1, but a greater amount of the prestressing reinforcement compensates for the absence of bonded reinforcement. (The influence of the bonded reinforcement on the mode of rupture is one of the parameters to be examined in the first stage of this project).

The models were instrumented with vibrating wire strain gauges in the concrete and electrical resistance strain gauges on the reinforcement and on the lining and thermocouples registered concrete temperature.

Both models were loaded with an internal gas-pressure to failure. Model no. 1 failed by an extensive leakage at 270 kp/cm², model no. 2, however, exploded at 267 kp/cm² internal over-pressure. Both models had significant deformations and cracks before failure. The maximum measured deflections were about 25 times the deflections by the reference pressure.

The tests results are interpreted and compared with computed values. Calculation of ultimate load is discussed.
The test program, some results and comments.

The main purpose of this project, which is planned for a series of 6 models, is to study the mode of rupture of the vessel, loaded by internal gas-pressure.

The Research Institute for Cement and Concrete performed in February this year tests up to rupture on 2 models of prestressed concrete pressure vessels. Model M1 is a model with a scale reduction of 1/3.6 of the Scandinavian PCRV-model, except for the removable lid and the penetrations in the bottom slab. The vessel has an inside diameter of 55 cm and an inside height of 111 cm. The cylindrical wall thickness is 30 cm and the top and bottom slabs are 33 cm. (See figure 1). The reference pressure is 84 kp/cm². To simulate the effect on shear capacity of the steel tubes in the bottom slab model M1 is supplied with solid steel bars in the top and bottom slabs.

The vertical prestressing system consists of prestressing cables (System Dywidag). (See photo 103 and 104). In the circumferential direction there are 10 bands, consisting of 3/8" prestressing strands.

The nominal prestressing forces in the tangential and axial direction are about 1.5 and 1.75 times the reference pressure load, respectively. In addition bonded reinforcement that can take up 0.6 and 0.8 times the reference pressure, respectively, in the tangential and axial directions (at yield). (See photo 101 and 102). The inside of the vessel is lined by a mild-steel lining (thickness 3 mm), welded in argon-atmosphere. (See photo 001). The concrete in the models has an average cube strength of 550 kp/cm² and \( E_b = 300000 \) kp/cm².

Model M2 is equal to M1, but has no bonded reinforcement in the cylindrical wall. The nominal prestressing forces in the tangential and axial directions are equal for the 2 models, but greater amount of the prestressing reinforcement was added to compensate for the absence of bonded reinforcement. (The influence of the bonded reinforcement on the mode of rupture was one of the parameters to be examined in the first stage of this project). Photo 002 shows the models without circumferential prestressing reinforcement.

After testing in the laboratory (pressure 30 kp/cm²), the models were transported to a testing field for explosives.

Photo 105 shows the test set up. The models were tested with almost identical test-procedures.

Test 1: 0 - Reference pressure - 0
Test 2: 0 - Ref. p. - working pressure - 1.5 times the Ref. p. - 0
Test 3: 0 - 2 times the Ref. p. - Ref. p. - 3 times the Ref. p. - 0
Test 4: 0 - Failure
The registered pressures during the tests were as follows:

<table>
<thead>
<tr>
<th>Test</th>
<th>Model M1</th>
<th>Model M2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 87 0</td>
<td>0 85 0</td>
</tr>
<tr>
<td>2</td>
<td>0 89 63 130 0</td>
<td>0 88 70 130 0</td>
</tr>
<tr>
<td>3</td>
<td>0 169 94 265 0</td>
<td>0 170 90 266 0</td>
</tr>
<tr>
<td>4</td>
<td>0 - 270</td>
<td>0 - 267</td>
</tr>
</tbody>
</table>

Model M1 failed by an extensive leakage at 270 kp/cm², model M2, however, exploded at 267 kp/cm² internal over-pressure. The photos 106 and 107 show the visible cracks for Model M1 at 265 and 270 Ato.

Photo 203 shows the visible cracks on Model M2 at 266 kp/cm² pressure, this is only 1 kp/cm² before explosion. The actual mode of explosion is shown in photos 204 and 207.

Model M2 was supported on 4-15 cm cubes which were completely destroyed under the explosion. In the nearest surroundings of the vessel only small fragments were found. The greater fragments had been thrown up to 200 m away from the model. The top slab was found about 80 m from the vessel. It is remarkable that the circumferential prestressing reinforcement in the upper band and parts of the surrounding concrete ring were lying close to the great slab fragments. This is astonishing because these fragments must have been separated under the explosion by the anchorage plates which remained in place.

After the pressure was released it was not possible to get a pressure higher than 20 kp/cm². We have reasons to believe that the failure took place at the corner as for Model M2.

As shown in Figure 2 the failure was progressive and the failure deformation was about 25 times the deformation at the ref. pressure. By inspection of the model after test 3 (cycle to 170 kp/cm²), visible cracks were not observed, though the instruments indicated the first cracks at about 130 kp/cm². (See figures 3, 5, 6 and 13). The plastic deformations became significant for pressures over 150 kp/cm².

As expected the same behavior was observed by model M2 up to 150 kp/cm². For higher pressures accelerating deformation took place in the middle of the top slab. (See figures 7, 8 and 9). In figures 10 and 11 the explosive failure has been attempted reconstructed. A couple of seconds before the explosion a leakage was registered in the lining. Under the explosion the supporting concrete cubes were crushed.

The pressure force on the top part of the lining was at failure 0.267 · π · \( \frac{55^2}{4} \) = 635 Mp.

With an average compressive strength of the supporting cubes of 630 kp/cm² transformed with the factor 1.3 to dynamic compressive strength, we get a minimum explosion reaction of 1.3 · 0.620 · 4 · 15² = 725 Mp. This indicates that gas pressure occurs in the cracks of failure.
The capacity of the reinforcement at yield is in axial direction, 850 Mp, equal for the 2 models. The lining has in the same direction a yield capacity of 100 Mp, which amounts to a total capacity of 960 Mp. Adding the yield force in the lining to the axial prestressing force (480 Mp) and comparing it with the measured ultimate force on the top of the lining, following results are obtained:

\[ P_v, \text{calculated} = 110 + 480 = 590 \text{ Mp equal for M1 and M2} \]

The ratio \[ P_v, \text{measured} / P_v, \text{calculated} = \frac{635}{590} = 1.08 \text{ (Model M2)} \]

For M1 is \[ P_v, \text{measured} = 0.270 \cdot \pi \cdot \frac{55^2}{4} = 640 \text{ Mp} \]

and the ratio \[ P_v, \text{measured} / P_v, \text{calculated} = \frac{640}{590} = 1.09 \]

Assuming that the bonded reinforcement close to lining follows the deformations of the lining:

\[ P_v, \text{calculated} = 590 + 68 = 658 \text{ Mp} \]

which gives the ratio 640/658 = 0.97.

The concrete

A standard Portland Cement was used in mixing the concrete batches. Aggregate composed of natural sand and crushed gravel. Plastiment V was added to the cement (0.25 o/o of the cement weight). A batch was proportioned:

- Cement 90 kp
- Sand 155 kp
- Gravel 190 kp
- Water 41 kp

Interpretation of test results and experience from test.

In the evaluation of the behavior of reactor vessels reliable instrumentations are of great importance. A brief description of instruments used in the tests and interpretation of the test-results will be presented in the following. Some problems during the test period will also be mentioned. The instrumentation consists of transducers and equipment for registration and recording. In this paper only the transducers will be dealt with.

The following physical quantities were to be measured:

1. Internal air pressure
2. Prestressing forces
3. External deformations
4. Surface strains and internal strains
5. Temperature
6. Time
7. Sound level (at cracking)
Description of instruments used during the test:

Table 1 is a survey of all the instruments which were mounted in or on the two models M1 and M2. In all, there were 92 instruments mounted on M1 and 83 instruments mounted on M2. The number of active instruments got drastically reduced during the construction of the models while welding and casting and also during their transportation to the test site. The reduction was particularly severe for the electrical resistance strain gauges. Also, one vibrating wire strain gauge became inactive before the models were tested. In figure 12 the position of all internal transducers are shown for model M1.

The choice of instruments was dependant on their availability and earlier experience with different gauges.

Before the models were transported to the testfield, the instrumentation functioned satisfactorily. An example can illustrate the special conditions in the field. The solder-bits could not reach the necessary temperature for soldering when the air-temperature was below -15°C.

From earlier short term tests, carried out in the laboratory, we have, by and large, only good experience in using electrical resistance strain-gauges. For model M1 and M2 electrical resistance strain-gauges were fixed on the lining and the reinforcement, while vibrating wire gauges were embedded in the concrete. So were the epoxy type Japanese "concrete strain gauges". Judging from the results of the various types of instruments, the electrical resistance strain-gauges seem to be the least reliable. Moreover, several strain-gauges were damaged during the casting and during transportation of the models to the test site. The vibrating wire gauges and the inductive transducers, on the other hand seem to be very reliable, although these types are not completely free from problems either. Test results from vibrating wire gauges are all referred to the start of test cycle 1.

The test-results indicate, first of all, a good correlation between the two models within the range of elastic response. Figure 4 shows measured strains in tangential direction for vibrating wire VW1 and VW4 by testcycle 2 for models M1 and M2. The fact that the plotted curves are nearly linear and that they are repeatable demonstrates the reliability of the gauges. The results of inductive transducers which measured relative deformations in radial directions are in agreement with those of the vibrating wire strain gauges.

Figure 3 shows deformations measured by inductive transducer no. 2 at model M1. There is good agreement between the results shown in Figure 3 and those shown in Figure 4, particularly before cracking. The accuracy of the results obtained from the vibrating wire equipment has to be checked by comparison with some other reliable results. This is done by comparison with the results from epoxy strain gauges and these are shown in Fig. 6. This shows that there is good correlation between the results up to the stage of cracking. Figure 14-16 show the theoretically computed and the experimentally obtained results of tangential stress at mid height of the model, through the thickness of model wall from the lining. The calculations are based on element methods.
REFERENCES:

1. Manon, S.: Presentation of the Scandinavian PCRV - Model at the Seminar in Delft (4.12.1970) arranged by the Commission of European Communities and TNO.

   Cement and Concrete Research Institute
   Technical University of Norway 20.4.1971.
<table>
<thead>
<tr>
<th>TABLE 1.</th>
<th>MODEL M1</th>
<th>MODEL M2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>1.1 Strain gauges on steel - half bridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1.1 on lining</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rosettes 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single strain gauges 4</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>1.1.2 On the reinforcement steel</td>
<td>18</td>
<td>14</td>
</tr>
<tr>
<td>1.1.3 On the longitudinal prestressing steel</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>1.1.4 On the ring prestressing steel</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.2 Epoxy strain gauges embedded in concrete</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>1.3 Instruments based on the strain gauges - full bridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3.1 Pressure transducers</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.3.2 Deformation gauges</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Inductive transducers calibrated for ± 2 mm</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>1.5 Vibrating wire strain gauges</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1.6 Extensometer measuring points</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>1.7 Thermocouples</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>SUM:</td>
<td>76</td>
<td>75</td>
</tr>
</tbody>
</table>

A The number of strain gauges and transducers actually installed in the model before its casting
B The number of strain gauges and transducers found in fact after the casting of the model
C The number of strain gauges and transducers found usable after transportation to the test site of Raufoss
FIGURE 1

SECTION THROUGH MODEL

FIGURE 2

RELATIVE DEFORMATION IN RADIAL DIAMETER - CONSTRUCTION 12X1 AND 4X4 AT MODEL M1 BY TEST 1 (Test cycle M1-100)

(def. = 0 when p = 0)

FIGURE 3

RELATIVE DEFORMATION IN RADIAL DIAMETER - CONSTRUCTION 12X1 AND 4X4 AT MODEL M1 BY TEST 2

FIGURE 4

STRAIN/PRESSURE IN TANGENTIAL DIAMETER FOR VIBRATING WIRE TEST 1 FOR MODEL M1 (0-00-00-100 and 0-100-00-100 and 0-00-100-00)

(See Figure 5 from p=0 by test 1)
Comparison between measured and computed values (stresses in kp/cm²)

Comparison between measured and computed values (stresses in kp/cm²)
PHOTO 001
LINING WITH TUBES

PHOTO 002
MODEL M1 AND M2 BEFORE APPLYING CIRCUMFERENTIAL PRESTRESSING REINFORCEMENT
PHOTO 101
MODEL M1:
BONDED REINFORCEMENT AT
THE LINING IN THE CYLINDRICAL
WALL

PHOTO 102
MODEL M1:
TOTAL BONDED REINFORCEMENT
IN THE CYLINDRICAL WALL
PHOTO 103
MODEL M1:
TOTAL STRUCTURAL REINFORCEMENT EXCEPT THE 25 MM BARS IN THE TOP AND BOTTOM SLABS

PHOTO 104
MODEL M1 BEFORE CASTING
PHOTO 105
TEST SET UP

PHOTO 106
CRACKS AT 265 ATO
INTERNAL PRESSURE

PHOTO 107
CRACKS AFTER FAILURE
(INTERNAL PRESSURE 270 ATO)
PHOTO 203
CRACKS AT 266 ATO INTERNAL PRESSURE

PHOTO 204
MODEL M2 AFTER FAILURE (INTERNAL PRESSURE 267 ATO)
PHOTO 207
THE TOP OF MODEL M2 AFTER FAILURE
R. D. BROWNE, U. K.

Q Was there an increase in vertical prestress load recorded during the explosive failure of the model without bonded reinforcement since gas present in the crack would cause a substantial increase?

A R. LENSCHOW, Norway

1. We were not able to measure the strain in the vertical prestressing cable at the moment of explosion. To get an idea of maximum stress in the cables, pieces of the cables were afterwards tested in order to see from the stress-strain curve whether the steel had been up in the non-proportional region.

2. The model vessel was supported by 4x15 cm cubes of concrete. These were completely crushed. From the strength of the cubes it has been concluded that the pressure on the "inner" slab alone is not sufficient to cause the mentioned reaction force.