# RESEARCH ON PCPV FOR BWR —PHYSICAL MODEL AS DESIGN TOOL— MAIN RESULTS

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## SUMMARY

ISMES (Experimental Institute for Models and Structures) is now carrying out a series of tests on physical models as a part of a research programme sponsored by DSR (Studies and Research Direction) of ENEL (Italian State Electricity Board) on behalf of CPN (Nuclear Design and Construction Centre) of ENEL with the the aim to experience a "Thin"-walled PCPV for "BWR".

The physical model, together with the mathematical model and the rheological model of the materials, is intended as a meaningful design tool. The mathematical model covers the overall structural design phase, (geometries) and the linear behaviour, whereas the physical model, besides of a global information to be compared with the results of the mathematical model, supplies a number of data as the non-linear behaviour up to failure and local conditions (penetration area etc.) are concerned.

The aim of the first phase of this research programme is to make a comparison between the calculation and experimental tests as the thicknesses of the wall and the bottom slab are concerned, whereas the second phase of the research deals with the behaviour of the removable lid and its connection with the main structure.

To do this, a model in scale 1:10 has been designed which symmetrically reproduces with respect to the equator, the bottom part of the structure. In the bottom slab the penetrations of the prototype design are reproduced, whereas the upper slab is plain.

This paper describes the model, and illustrates the main results, underlining the different behaviour of the upper and bottom slabs up to collapse.

## 1. INTRODUCTION

The research on physical model,object of the present paper,is to be envisaged in the frame of an agreement concerning a collaboration between ENEL (Ente Nazionale per l' Energia Elettrica of Italy) and the AB Atomenergi of Sweden, for the application of the PCPV concept to BWR. This research is developed at the ISMES (Istituto Sperimentale Modelli e Strutture) laboratories in Bergamo - Italy.

The physical model is considered, in the general design criteria philosophy, as a true calculation tool that being of the same material as the prototype is able to provide, in short time, a more realistic and a larger number of information for the whole range of required functional performances (from the elastic range to the collapse). These information are also cycled to the mathematical model for the refining of the mathematical simulation. [1]

In the schedule of research development, the first phase has been devoted to the design of the so-called "glass structure". The most important problem rised by this part of P.C.P.V. is related to the heavy presence of penetrations, namely in the bottom slab.

It was therefore deemed advisable to test a continuous model - see fig. 1 - (without the removable lid) in order to:

a) assess the difference of behaviour of the end cap slabs - with and without penetration - for refining the mathematical model, as well as, to know the behaviour of the cap slabs in the ultimate conditions.

b) assess the deformability of the cap penetration area in the pressure operating range.

c) control the collapsing sequence of the tendon systems as defined by the design philosophy. [2]

## 2. MODEL DATA

All the main data relating to: geometry, prestressing, cable-pattern, penetrations, are given in fig. 1. The scale of the model is 1 : 10. The choice of this scale is due to:

1) the size of the internal diameter of the PV (that for the Light Water Reactor is about 1/3 of the diameter required by Gas-Reactors).

2) the purpose of having exactly the same number of cables of the prototype making use of the same diameter of the wire (Ø7 and Ø8 mm.) in order to achieve the best simulations at reasonable cost.

3) the technological limit given by the pouring of the bottom slab penetration areas.

### 2.1. Prestressing.

The prestressing consists of the circumferential and vertical systems - sized in or der to have the structure "fully compressed" when an internal pressure of 85 Kg/cm$^2$ and a difference of temperature of $10^{\circ}$C across the walls are envisaged. All the tendons are monowire and equipped with BBR anchor-heads. The cables are anchored to twelve concrete buttresses spaced out at $30^{\circ}$. Each hooping system consists of four layers of cables type (a- b - c - d) each layer turned, one against the other, at $90^{\circ}$. One layer is formed by three cables covering with their curved portions three different angles (ENEL, Dr. Scotto patent - fig. 1).

Namely:

| Prototype Slabs | Model Slabs |
|---|---|
| Three hooping systems pitch 88 cm. Total prestressing height: 264 cm (3 x 88). Cables type 163 wires Ø7 mm - UTS 1129 tons. Total cross sectional area of prestressing steel: 2258 cm$^2$.<br>Nominal prestressing: UTS · 0,7 | Four hooping systems that are: three systems monowire cables 8mm - UTS 8990 Kg. One system monowire cables Ø7 mm - UTS 7390 Kg. Working load: 6333 Kg Ø8 mm and 4848 Kg Ø7 mm (per each cable). Total prestressing height: 26,4 cm. Total cross sectional area of prestressing steel: 22,70 cm. |

| Prototype Barrel | Model Barrel |
|---|---|
| 14,5 hooping systems - pitch 100 cm, cables type 109 wires Ø7 mm - UTS 755 tons and 4 systems of cables pitch 141,5 cm. Cables type 121 wires Ø7 mm - UTS 838 tons. Total prestressing height: 2016 cm. Total cross sectional area of prestressing steel: 9533 cm$^2$. | 16 hooping systems - pitch 9,6 cm. Monowire cables Ø7 mm. 5 hooping systems - pitch 11,32 cm - monowire cables Ø7 mm. Total prestressing height: 261,6 cm. Total cross sectional area of prestressing steel: 96,97 cm$^2$. |

Average friction coefficient of the hooping cable: 0,15 (determined by experimental measurement on models).

Cable ducts: continuous mild steel pipe.

Vertical Prestressing

| Prototype | |
|---|---|
| 96 cables 139 wires Ø7 mm BBR anchor heads - UTS 962 tons-nominal prestressing 0,7 x UTS - arranged on two radii. | 96 monowire cables Ø8 mm arranged as on the prototype.<br>Working load: 6333 kg (per each cables). |

All prestressed cables are of the non-grouted type.

## 2.2. Liner.

The steel liner is replaced in the model by a 3 mm thick annealed copper bag, in order to allow the test up to the structural collapse, without any water leakage in the concrete. The bag is not anchored to the concrete.

The bottom slab embodies 161 control rod penetrations and 8 housing of Main Circulator Pumps. All these penetrations can be pressurized.

## 2.3. Concrete.

The model has been poured in one stage with a concrete having a maximum size of aggregates of 6 mm and has the following mechanical properties at the time of testing (March 75 - aged about 90 days):

- compressive strength (test specimen 16 x 16 x 16 cm) i $R_{cc}$ = 570 Kg/cm$^2$.
- tensile strength (cylindrical specimen ∅10 cm, h = 20 cm brasilian test): $R_{ct}$ = 40,5 Kg/cm$^2$.
- Young' modulus (up to 140 kg/cm$^2$ - test specimen 16 x 16 x 32 cm) $E_c$ = 370.000 - 350.000.
- Poisson' ratio: 0,175 - 0,185.

## 2.4. Instrumentation.

The model is equipped with the following instrumentation: (fig. 2)

| Type of Measurement | Type of Instrument | No. |
|---|---|---|
| Deflections of the cylindrical wall and slabs. | Inductive displacement transducers. Hottinger type W1 e W5 TK. | 88 |
| Strains measured on the outer surfaces. | Electrical resistence strain gauges SOKKI KENKYUJIO. | 116 |
| Pull check in the prestressing cables. | Load cells I.S.M.E.S. type. | 47 |
| Temperature distribution in the concrete. | "Thermoelectric" thermocouples type. | 28 |
| Internal model pressure. | Hottinger type extensimetric pressure cells P3M 100 P3M 200 P3M500 | 3 |

The scanning speed of the above instruments was of 1 point per second, (Hottinger type automatic switching and reading equipment). The readings are independently recorded on perforated tape and then processed on HP computer and plotted.

Due to the high danger of the ultimate test, they are carried out in a suitable bunker room provided with a remote control T.V. system.

## 3. TEST DATA

### 3.1. Scheduling.

All tests were performed as summarized in fig. 3.

### 3.2. Main Results.

Without going into details, the most significant results are summarized as follows:

#### 3.2.1. Comparison of the behaviour of perforated and non-perforated end cap slabs.

As can be seen in fig.4 no significant difference in behaviour appears to exist, for the short time tests, between the perforated (bottom) and non-perforated (upper) slab.

This result can be explained as being due to the compensatory effect given by the steel shutter tubes.

This kind of result was experienced also on the small scale PCPV. Models for HTR. [3] [4] [5] [6]

#### 3.2.2. Behaviour of the model in the overpressure range.

The first overpressure cycle was intended to determine the starting of the cracks, initially detected instrumentally and subsequently by visual observation.

At a pressure of about 115 ÷ 140 $Kg/cm^2$, the strain gauges on the external surface began to reveal the so-called "instrumental cracks". (fig. 5)

The overall behaviour of the structure is however almost linear up to about 140 $Kg/cm^2$, as shown by the pattern of the deflections $\Delta$ R at the equatorial area of the barrel, and $\Delta$ Z on the central area of the slabs. (fig. 6).

However, it should be underlined that the first clearly visible craks ($>$ 0,13 mm) appears at a pressure of 155 $Kg/cm^2$ (a few vertical cracks which affect the equatorial areas of the barrel for length of about 4 ÷ 5 cm), (cfr. fig. 13).

Fig. 7 illustrates the outside deflections of the model up to a pressure of 150 $Kg/cm^2$ (covering also the non-linear behaviour of the structure).

#### 3.2.3. Tests in the cracking pressure range.

These tests are done in the so-called concrete small deformation pressure range, that is under the pressure at which the first prestressing steel wire reach its yielding limits. This limit is checked by the records of many load cells applied to the anchor heads of the two prestressing systems.

Fig. 8 shows the radial deflections, at the equator up to 180 $Kg/cm^2$. The patterns of the $\Delta R$ deflections, as well as the pull of the equatorial cables, during the first two overpressure tests are pratically coincidental up to about 115 Kg/cm$^2$ (1,35 times 85 Kg/cm$^2$ fully compressed structure condition). In turn, the pull of the vertical cables show the same behaviour over the entire pressure range, probably due to the fact that the cracks are mainly of vertical type.

It should be underlined that, due to a redistribution of the friction forces along the cables, the pull measured at the anchor heads at the end of the test up to 180kg/cm$^2$ has a lower value with respect to the initial one (fig. 10).

The subsequent tests in the operational pressure range, (5 ÷ 75 Kg/cm$^2$) - - fig. 9 - show that the structure is still able, after having experienced an internal pressure of 180 Kg/cm$^2$ ($\Delta$T 10° C) to "reverse" in the elastic conditions (that is "reverse" in the original operative fully compressed condition).

This is due to the fact that the steel of the prestressing cables is still elastic (figs. 10 ÷ 11), and the cracks, reclosed by prestressing, affect only a cortical limited region of the PCPV (cfr. fig. 13).

### 3.2.4. Collapse

The structural failure was due to the collapse of the central barrel hooping cable system (fig. 14). This was expected, as the design assigned to this part a lower safety factor.

The central barrel hooping system reached its yield limits at a pressure level of about 230 Kg/cm$^2$. At that pressure level the vertical system was near to its yield limits. With the pressure at 236 Kg/cm$^2$ the first hooping tendon collapsed; 11 seconds later (237 Kg/cm$^2$) several central barrel hooping cables failed within 4 seconds. As result the central part of the barrel was severely damaged (fig. 14) while both the cap slabs were still intact. The prestressing hoop system of the cap slabs and part of the barrel didn' t reach their yield limits (cfr. fig. 12).

## 4. CONCLUSIONS

On the basis of the previously described results, the following conclusions can be drawn:

- the tests on the physical model show that the structure behaviour is fully satisfactory, as far as the barrel and the bottom slab are concerned, in the high overpressure range.
- The collapsing sequence of the cable systems (see point 1. c) agrees with the design philosophy criteria.
- It has been possible to infer with great accuracy the structural behaviour on the basis of the results obtained in the previous PCPV models for Gas Reactors. This once more confirms the complete reliability of the "thin - walled" design concept.

[1] Riccioni R.; Robutti G.; Scotto F. L. "Finite Element Structural Analysis of a PCPV for BWR". 3rd Int. Conf. on Structural Mechanics in Reactor Technology. London, England (September 1 - 5, 1975).

[2] Scotto F. L. "Thin walled" Concept and a new top lid applied to BW Scandinavian PCRV. 3rd Int. Conf. on Structural Mechanics in Reactor Technology. London, England (September 1 - 5, 1975).

[3] Fumagalli E.; Verdelli G. "Small Scale Models of PCPV For High Temperature Gas Reactors - Modelling Criteria and Typical Results". IABSE Seminar, Bergamo, May 17 - 19, 1974.

[4] Scotto F. L. "Concrete Behaviour under Combined Stresses up to Failure. Test Result on Small Dimension Prestressed Concrete Pressure Vessel Models". ACI Seminar "Concrete for Nuclear Reactors" - Berlin 5 - 9 October, 1970.

[5] Fumagalli E.; Verdelli G. "Static Tests on a small Model of Prestressed Concrete Pressure Vessel for THTR Nuclear Reactor. Safety Aspects of PCPV". Delft, December 1970.

[6] Fanelli M.; Riccioni R.; Robutti G. "Finite Element Analysis of PCPV". IABSE Seminar, Bergamo May 17 - 19, 1974.

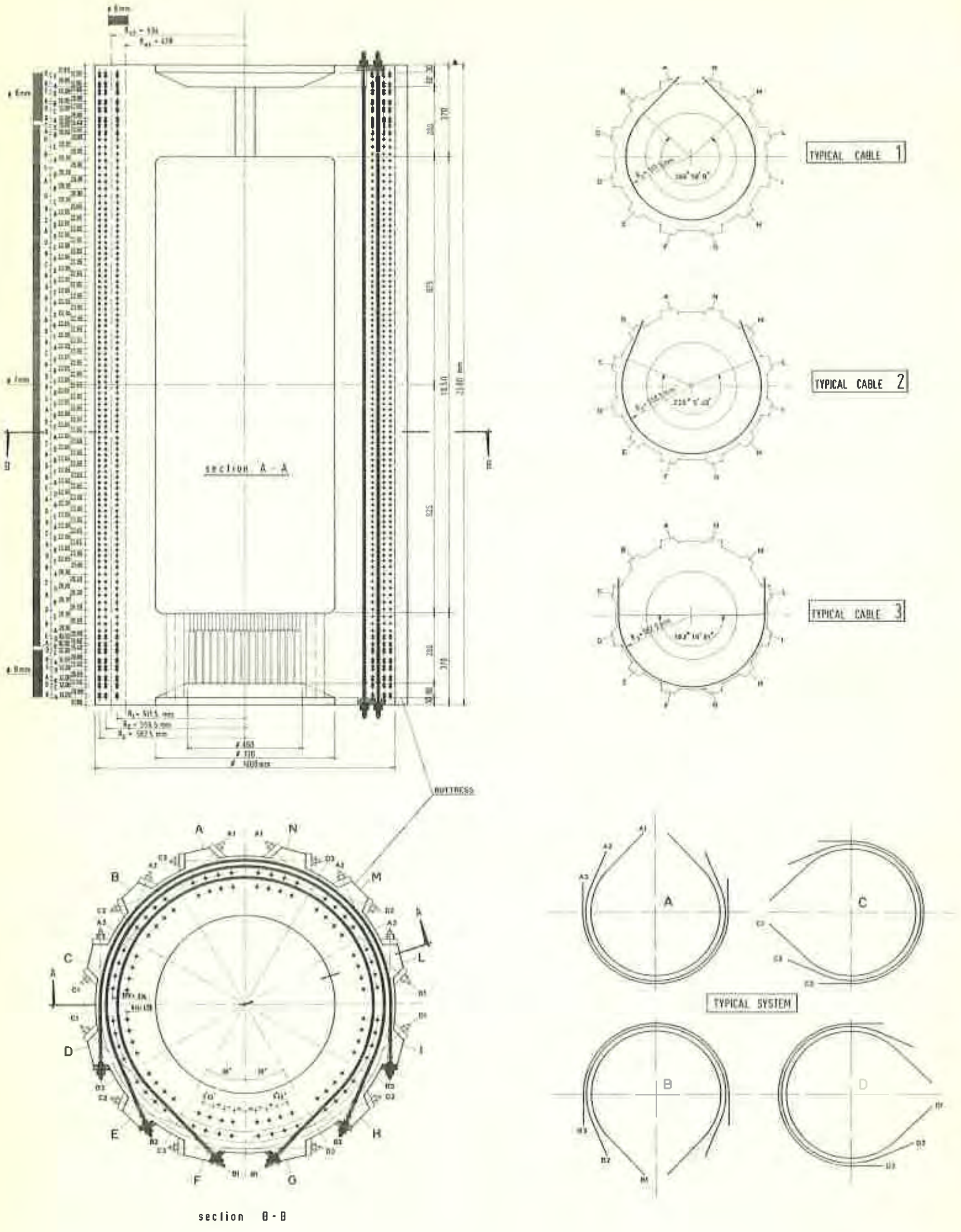


Fig. 1: 1:10 PCPV for BWR continuous model main data.

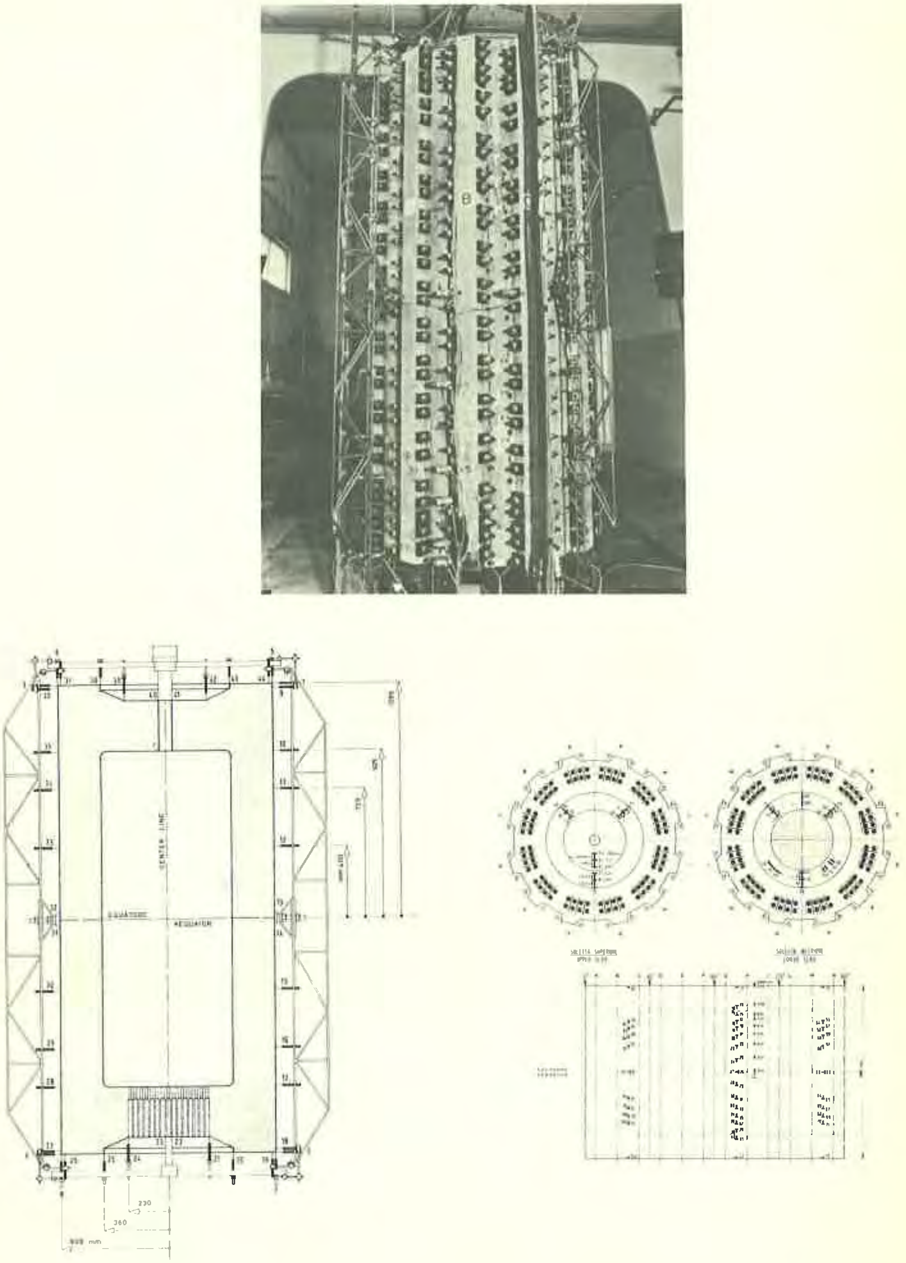


Fig. 2: Layout of strain gauges and displacement transducers.

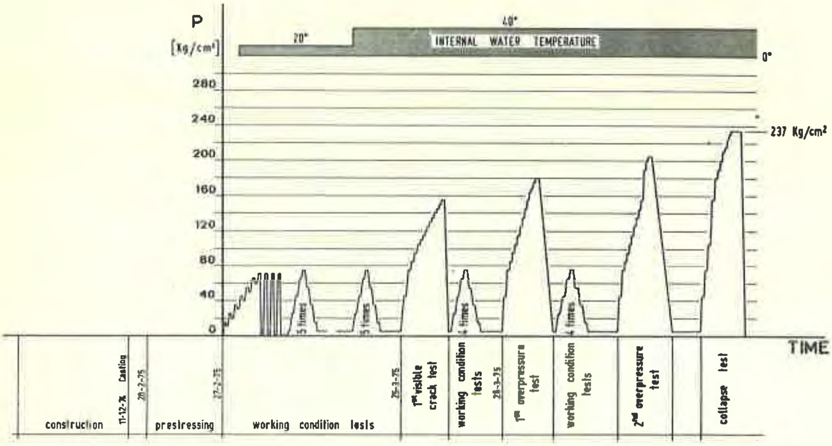
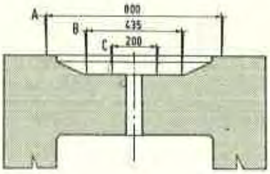


Fig. 3: Test history.

radial strains for pressure 5 ÷ 70 Kg/cm² ( ε · 10⁵ )

| GAGE LENGTH | UPPER SLAB | BOTTOM SLAB |
|---|---|---|
| A | 48 | 5.0 |
| B | 10.5 | 9.7 |
| C | 153 | 123 |

---HEAVILY PERFORATED
—NON PERFORATED



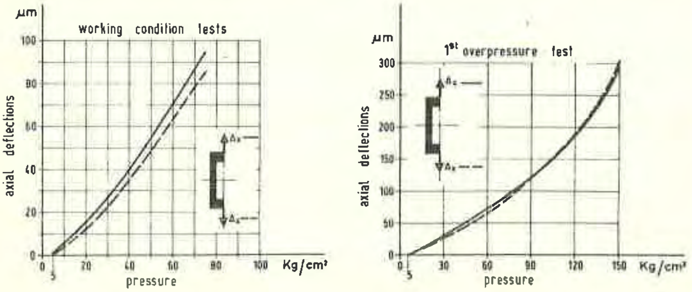


Fig. 4: Comparison between perforated and not perforated cap slab behaviours.

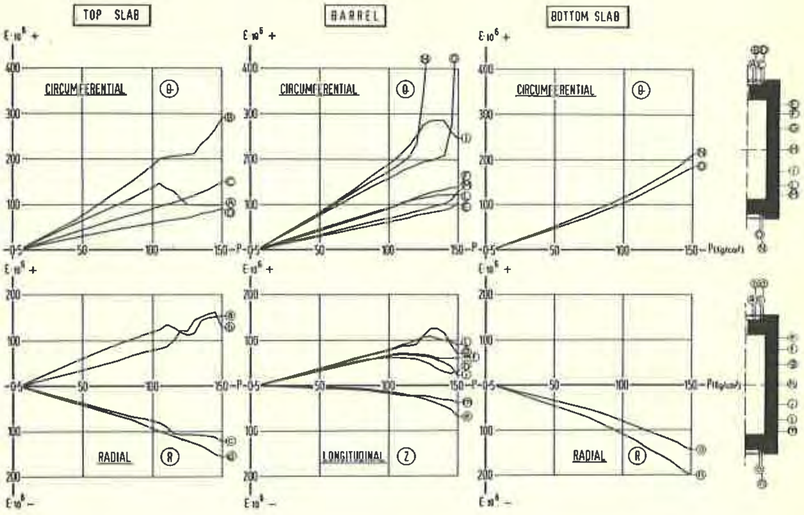


Fig. 5: Instrumental crack range as revealed by strain gauges.

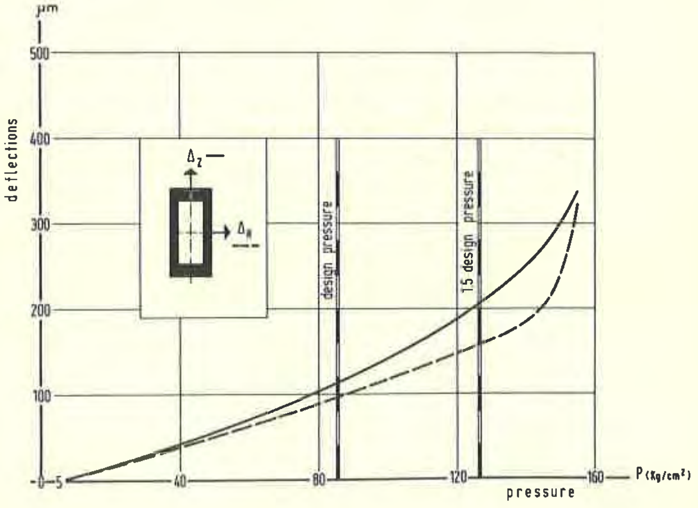
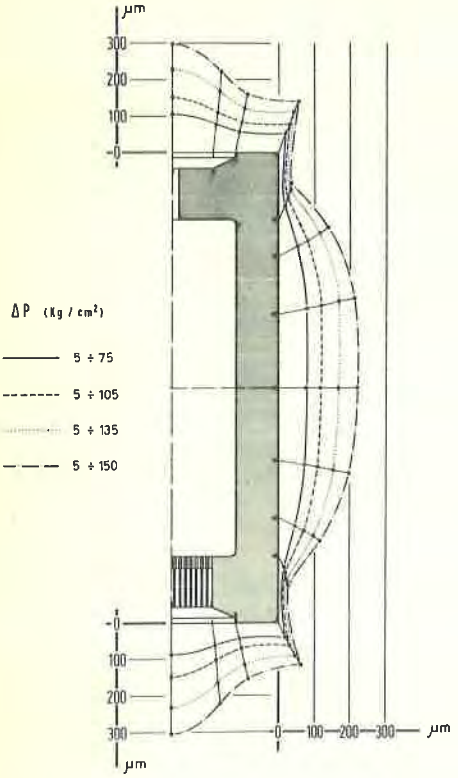


Fig. 6: Typical average radial and axial deflections during the first overpressure test (5 ÷ 155 Kg/cm$^2$).



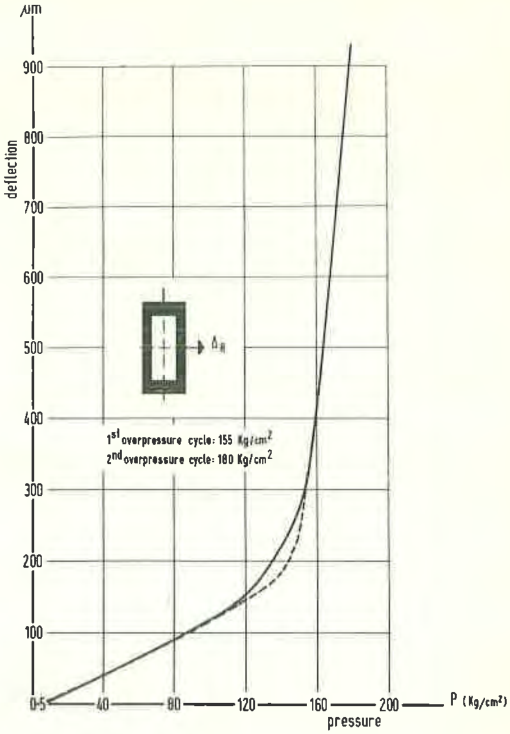


Fig. 7: Outside average deflections in the range (5 ÷ 150 Kg/cm$^2$).

Fig. 8: Average radial deflection during the second overpressure test (5 ÷ 180 Kg/cm$^2$).

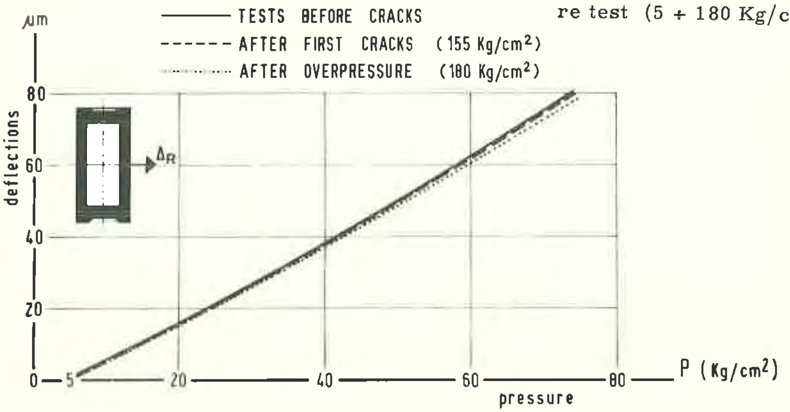


Fig. 9: Test of reversibility in the operating range (radial deflections).

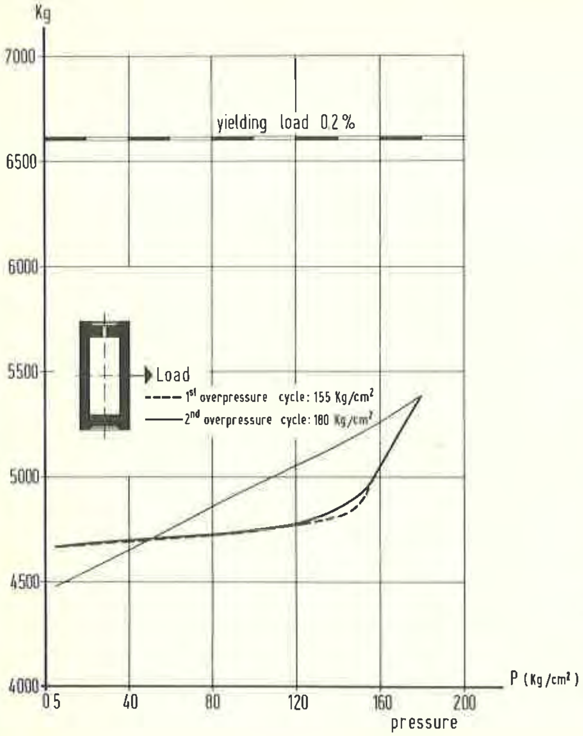


Fig. 10: Hooping cable system - Increasing of the anchor head load during the overpressure tests.

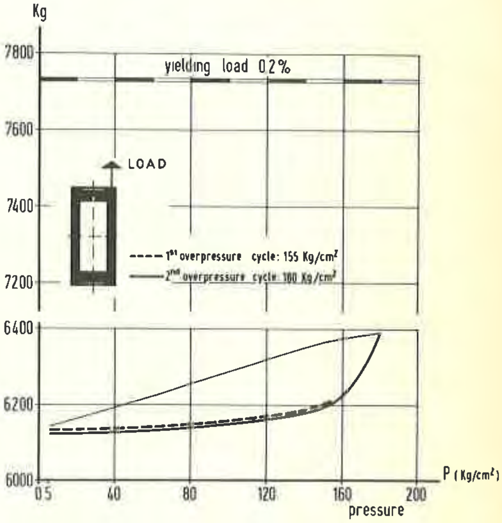


Fig. 11: Vertical cable system; increasing of the anchor head load during the overpressure tests.

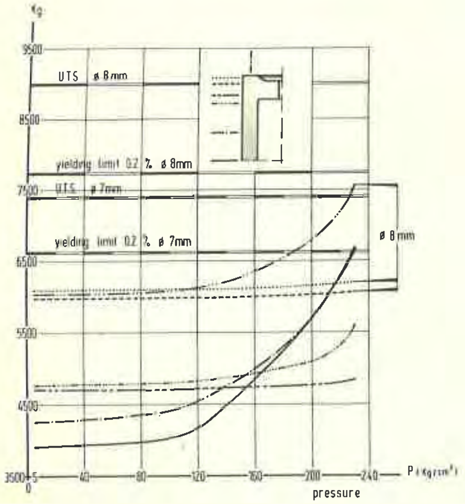


Fig. 12:

Loads at the anchor heads of tendon systems during the collapse test.

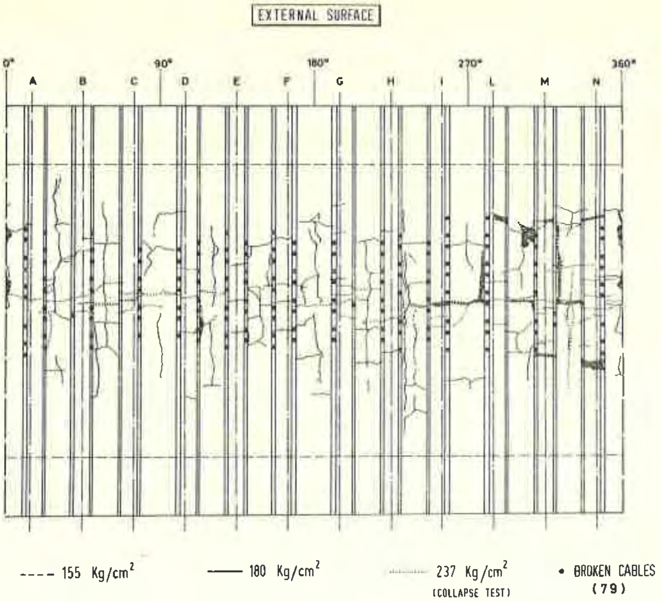


Fig. 13: Crack pattern at different upper levels of the overpressure tests.

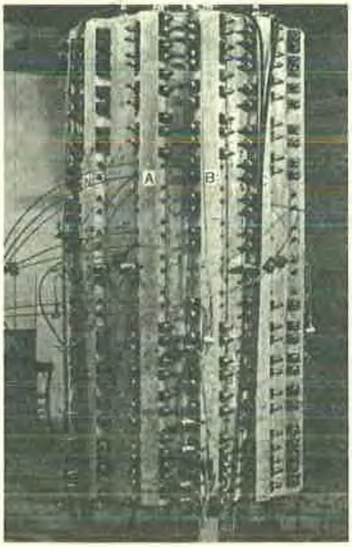


Fig. 14: Model after collapse test.