The strain behaviour of prestressed concrete pressure vessels after 10 years operational experience

I.W.Hornby
Central Electricity Generating Board, Leatherhead, Surrey, UK
J.Holland
Rendel, Palmer and Tritton, London, UK
T.Willis
South of Scotland Electricity Board, Glasgow, UK

1 INTRODUCTION

In the U.K., all nuclear power stations with prestressed concrete pressure vessels undergo a surveillance programme to monitor their behaviour throughout their life (1),(2). Included in this programme are the recording and assessment of vessel internal strains under all operational load conditions. In the first two Advanced Gas-cooled Reactor (AGR) stations to be commissioned, at Hinkley Point in England and Hunterston in Scotland, several hundred vibrating wire strain gauges were cast in the four vessels during their construction. A selection of these gauges have been read regularly since reactor commissioning. Readings had been taken before start-up, particularly during prestressing and also at the proof pressure tests as part of the overall commissioning requirements of the stations.

In each vessel, every gauge has a duplicate diametrically opposite, so in many cases there are eight records (2 from each vessel) covering the strain history of any one location. This has enabled considerable confidence to be given to the measured data.

The measured strain histories are compared with a prediction based on the superposition of elastic strains and creep strains. The elastic strains are derived from finite element analyses, the creep strains from experimental data obtained from representative samples of the concretes used for the vessels at the two stations.

2 ELASTIC ANALYSES

The elastic stresses and strains resulting from prestress, pressure and temperature were derived from either axisymmetric finite element analyses using the BERSAFE suite of programs (3) or Dynamic Relaxation techniques (4). An elastic modulus of 41.4 KN/mm^2 was used for the concrete, with a reduction of this value by 63% for the stand pipe region of the top slab based on studies by Bailey and Hicks (5) and Abdul Wahab (6). The Poisson's ratio used was 0.18 for Hinkley B and 0.20 for Hunterston B.

The prestressing loads used in the analyses were the average of the lift-off measurements made at the 6 biennial inspections. The vessel operating gas pressure of 38 bar g and 'as measured' temperature distributions were used to derive the elastic stresses and strains used in the derivation of the strain history plots.

3 CREEP DATA

To obtain the stress/temperature/time relationship of the concrete, uniaxial tests on samples of Hinkley B mix concrete were undertaken. To simulate the conditions of most of the vessel concrete, the samples were sealed immediately after casting to prevent moisture loss and were subjected to a heat of hydration temperature cycle. The applied stress was 14 N/mm² at temperatures of 20°C or 60°C. From the data obtained, a specific creep/time/temperature relationship was derived. A similar relationship was also derived for the Hunterston mix based on this and other relevant data. Although the aggregates and cement were obtained from different sources, the two specific creep relationships were found to be very similar.

Assuming a linear temperature and a logarithmic time relationship, an equation for specific creep at any time is given in the form of:

$$s=A+[B+D(T-20)]\log_{10}(t+1)$$

(where: s=creep strain per N/mm², T=temperature (°C), t=time under load in days, while A,B and D are constants for the particular concrete in use). This does not take into account the age at loading, which has no significant effect over the time scale being considered.

The effect of triaxial loading on creep had been previously established by Hannant (7) who showed that the use of a Poisson's ratio of the same value as the elastic one was acceptable. In the same paper, Hannant also quantified the creep recovery resulting from a reduction of stress (i.e. the reduction of prestress stress by pressure loading during start-up). This has been taken as 25% of the elastic change (see next section).

4 STRAIN HISTORIES

To determine the strain history at any gauge position, the total strain can be divided into a number of components:

(i) Elastic strain resulting from prestressing loads.
(ii) Creep strain from prestressing to start-up.
(iii) Elastic strain from pressure loading.
(iv) Thermal strain.
(v) Creep recovery from change of stress at start-up where applicable.
(vi) Creep from start-up to 1986.

An example of such a strain history is included in the figures that follow. The datum from which all the plots and measurements are based is the condition immediately prior to the start of prestressing in 1972. The prestressing operation lasted 12 weeks and the order in which the tendons were loaded was predetermined to give the vessel as a whole, a smooth transition to full prestress. However, the rate of stress increase at any position was not necessarily linear and consequently the creep strain at the end of prestressing was not a simple stress/time function. Nevertheless, by the time of commissioning, the effect of this variation was insignificant and it could be assumed that the prestressing was instantaneous. It can be noted from the strain plots that no attempt has been made to predict, in detail, the strain/time behaviour during this early period. The

effects of pressure reductions at refuelling or shut-downs during the biennial maintenance, have been ignored.

As indicated above, the creep strain has been divided into two time intervals: prestressing to start-up (c.1340 days) and start-up to 1986 (5000 days). The creep strain/temperature relationship for these two periods can be approximated by linear functions as shown in fig.1.

During start-up, both an elastic strain from the internal pressure and a thermal strain from the new temperature distribution are imposed. After start-up, a strain recovery is included when the effect of the pressure is to reduce the compressive stress. This is taken as 25% of the elastic strain from gas pressure, as recommended in the studies by Hornby (2). The thermal strains were assumed to relax out completely over the first few years and so are not included in the final totals (see for example, reference 9).

When the concrete experiences an increase in temperature at start-up, the creep strain increment is determined by a transition between the two 'time' lines of the temperature/specific creep relationships. The dotted line of fig.1 is an example of a temperature change from 20 to 30°C, the value 'y' is the specific strain used to calculate the creep strain increment. This principle was established in previous tests on pressure vessel concrete (8).

This method of superposition of elastic and creep strains is based on the assumption that the temperature gradients (and hence creep gradients) are substantially linear and that no redistribution of stress occurs. Earlier work on predicted long-term stresses by England (9) showed that large redistributions could occur. His predictions, however, used thermal profiles with non-linear thermal gradients that would be found in uncooled thick concrete sections. The profiles generally occurring in the vessels considered are very much controlled by the cooling water system which, except for the area close to the liner, results in thermal gradients that are effectively linear. Nevertheless where a slight non-linearity does occur, it is possible that there will be a small amount of redistribution of stress in the long-term.

5 OVERALL ACCURACY

In an assessment of an earlier vessel (2), the accuracy of the vibrating wire strain gauge readings together with temperature measurements and corrections was shown to be within $\pm$10%. Taking into account a possible $\pm$10% in the accuracy of elastic and creep strain determinations, a maximum variation of 20% between the predicted and measured values could occur.

6 RESULTS

There are several hundred strain histories to study and it is impractical to include many examples in this paper. In a large number of cases the eight records of a particular gauge position demonstrate good correlation and fig.2 shows a strain history which included superimposed data from a number of gauges. (For clarity, data of combined records for only two years, 1983 and 1984, have been used). Note that in fig.2, the shut-downs of the vessels occurred at different times.

The strain histories show the measured values at prestress, proof pressure test and at regular intervals from start-up. The biennial shut-downs are apparent, as are the pressure reductions at fuel loading

when these coincided with the gauge reading. Superimposed on these plots are the calculated total strains at start-up (elastic strain from prestress + creep in the first 1340 days), the elastic strain from pressure at start-up, the creep recovery (when applicable), the thermal strain and finally the total strain at 5000 days.

7 DISCUSSION

Figs. 2 and 3 show the measured hoop strain histories of the inside and outside positions on the equator. Very good correlation between the measured and predicted strains was obtained. The predominance of creep is apparent in fig.2 where 237 μs of the 330 μs total strain is attributable to creep. This emphasises the importance of determining the creep component of the total strain if stresses are to be derived. A large proportion of this creep strain occurs between prestressing and start-up.

Fig. 4 shows the radial strain profiles, obtained from a number of gauges, through the thickness of the top slabs and again the correlation is within the expected limits. The readings support the view that the structural behaviour of the standpipe zones in the top slabs of the vessels is closely akin to that of the remainder of the vessels and that the original concern of a general stiffening of this complex region has not been substantiated.

The overall correlation obtained supports the view that little stress redistribution has occurred. This is a departure from earlier thinking (10), where it was assumed that a stress distribution corresponding to the steady state of stress approach would be achieved within a few years of commissioning. This steady state is undoubtedly an asymptotic bounding condition, but there is no evidence that the four vessels under discussion have approached this condition of stress. It is not the purpose of this paper to offer a rationale for the fact that steady state of stress conditions have not apparently been achieved. A possible explanation can be derived from the concept of limited creep potential, the available creep capacity having been exploited in the early life of the vessels before commissioning. The vessels were then at substantially higher compressive stress levels than they have experienced after pressurisation. This explanation is offered tentatively - more to prompt discussion, since it is accepted by the authors that the concept is contrary to recognised thermal theory.

A significant implication of the above is that contrary to conservative asumptions made during the design stage as to loading conditions in later life, the proof pressure test is in fact likely to be the most onerous stress regime that the vessel would experience.

8 CONCLUSIONS

Results from the majority of the embedded strain gauges indicate that the vessels, by according closely to the formula derived from the concrete creep tests, have experienced very little stress redistribution.

In all cases the strain readings obtained during the 10 years of operation indicate the existence of satisfactory overall compressive stress conditions.

9 ACKNOWLEDGEMENT

This paper is published with the permissions of the Central Electricity Generating Board and the South of Scotland Electricity Board.

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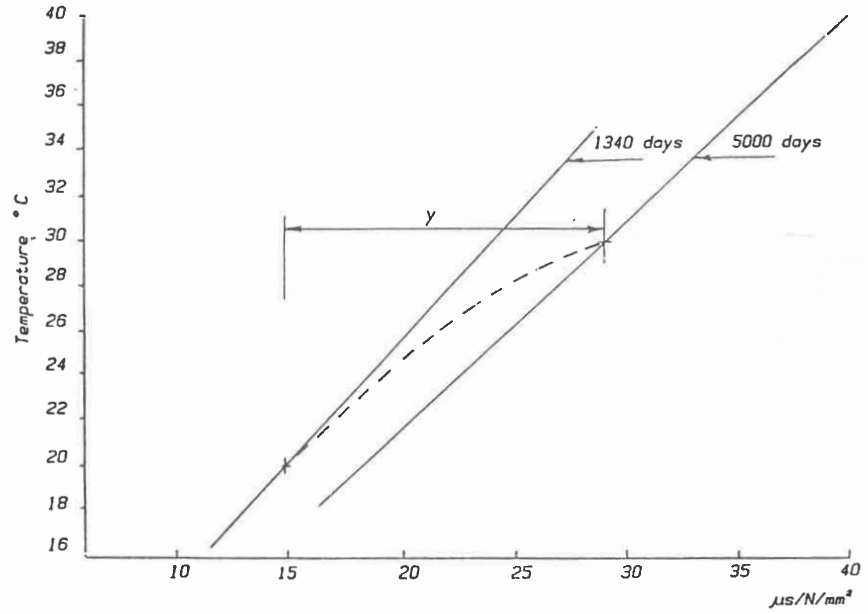

Fig. 1. Specific creep strain against temperature.

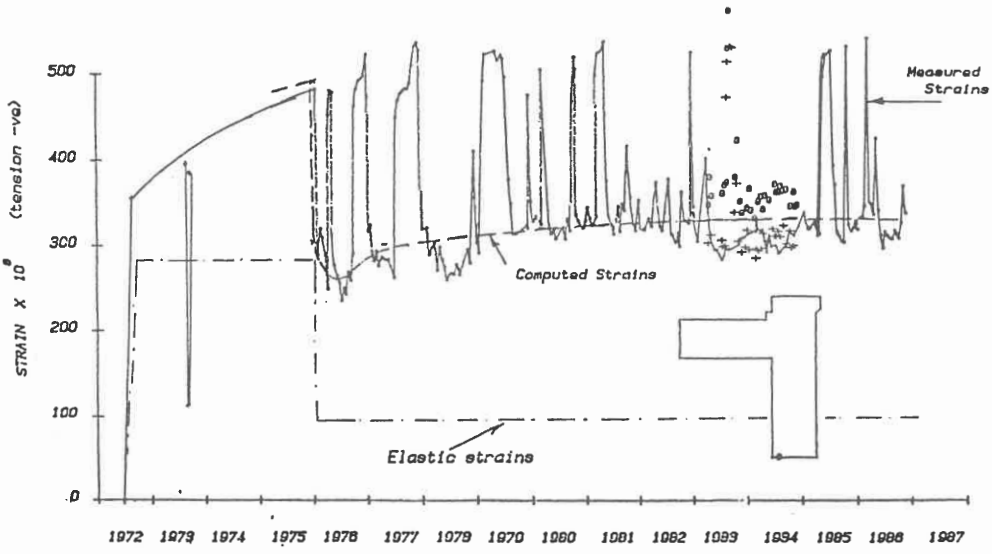

Fig. 2. History of hoop strains on inner face of equator.

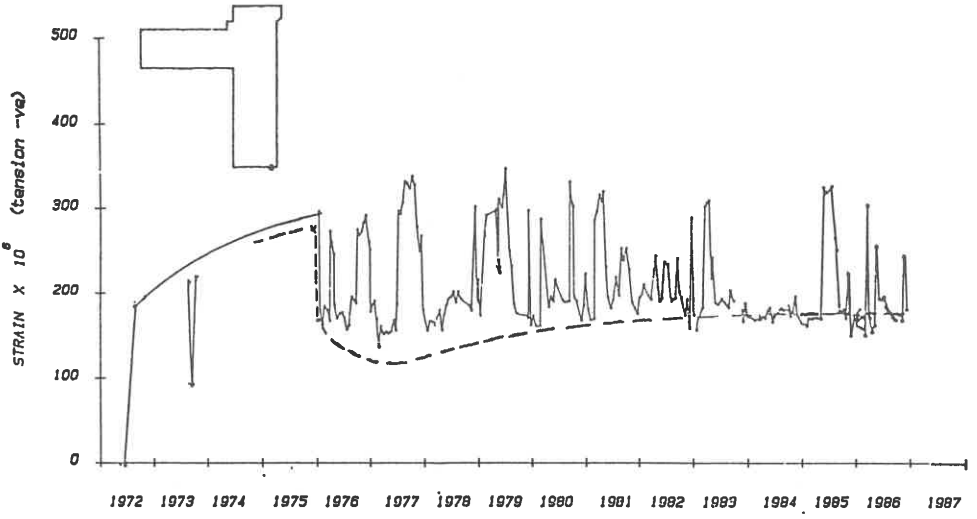

Fig. 3. History of hoop strains on outer face of equator.

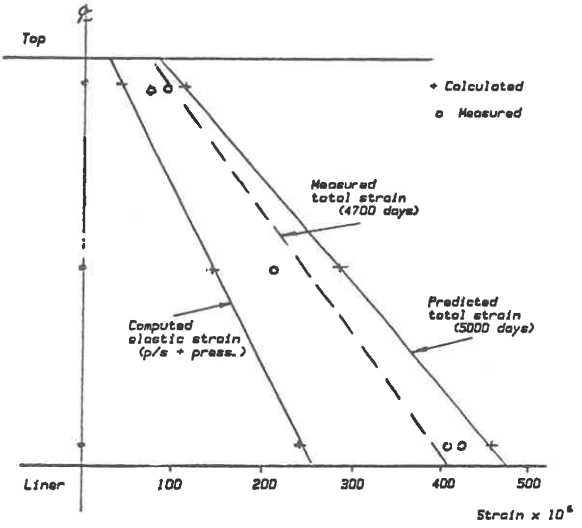

Fig. 4. Radial strain profile across top slab.