CREEP AND RELAXATION BEHAVIOURS OF 304 STAINLESS STEEL PIPING ELBOWS

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Summary

In order to acquire information relative to the static strength design of the primary coolant piping system in LMFBR, collapse, creep and relaxation tests were carried out on 9 elbow specimens. The collapse test consists of tensile and compressive tests at ambient temperature and a compressive test at 600°C. Creep tests were carried out under three dead load conditions at 600°C. Relaxation tests were made under two constant deflection conditions and under the condition of stepwise increasing deflection. The tests made under constant deflection conditions were repeated in several cycles.

The specimens were made from type 304 stainless steel, and its 90° elbow part, of which dimensions were 165.2 mm in inside diameter, 3.4 mm in thickness and 228 mm in bend radius, was butt-welded at each end to a straight pipe leg of 500 mm in length. The specimen was heated with an electric furnace in case of creep tests and by four electric heating elements fixed inside the elbow specimen in the case of collapse and relaxation tests. In all the tests, readings from 12 thermo-couples welded to the outside surface of the elbow showed deviations of less than 5°C during the test at 600°C. Applied load, diametral displacements at the middle of the elbow and strain at the maximum circumferential stress point were measured with a load transducer, welded strain gauges and a strain gauge type transducer, respectively.

Conclusions obtained are as follows:

(1) For an elbow which is made from a material with low yield strength and high strain-hardening coefficient, such as type 304 stainless steel at elevated temperatures, the values obtained for the experimental collapse load defined by the deflection versus load curve were found to be approximately twice as large as the values obtained by the two methods described in ASME Boiler and Pressure Vessel Code, Section III.

(2) As for elbow creep deflection, no state in which the deflection rate is constant was found. Deflection rate decreased gradually and became nearly zero in the final stage. For example, creep deflection reached to a saturated value after 600 hours in the case of in which 410 kg load applied to a specimen. Creep deflections were represented by bilinear relations between deflection and time in a log-log plot. The point where the bi-linear curves meet is about 30 hours for every applied load. The creep deflection rate calculated by J. Spence's diagram is considerably larger than the one obtained in experiments. This discrepancy may result from disregarding stiffness in the joints where strainght pipes meet elbow ends.

(3) The load change as a time dependent phenomenon in each step in the relaxation test, using a stepwise increasing deflection method, showed nearly the same behaviour against time for all the steps in the test, when the load was normalized by dividing by the maximum load at the beginning of each step. On the contrary, relaxation strain diminishes by degrees with the steps.

1. Introduction

Creep and relaxation behaviours of an elbow may be one of problems in the assessment of structural integrity of piping system in Liquid Metal Cooled Fast Breeder Reactors, because the service temperature is high enough to cause creep. However, a few papers [1,2] describing experimental results have been reported on such mechanical behaviours as creep and relaxation of the elbow.

This paper deals with the results of experiments involving collapse tests, creep and relaxation tests of elbows (type 304 stainless steel. 6B Sch 10S) at 600°C, including discussion of monotonic collapse load and deflection behaviours. The results obtained were found to be available in demonstrating the reliability of inelastic computer programs and may be helpful in designing of piping systems in the LMFBR.

2. Test Specimens and Experimental Procedures

2.1 Elbow Specimens

The elbow specimens used in the experiments were approximately 1/5 the size of actual elbows in an LMFBR coolant piping system. The shape and dimensions of the elbow specimens are shown in *Fig. 1*. A short straight pipe is welded at each end of an elbow specimen. The outer diameter of the elbows and the straight pipes is 165.2 mm and the wall thickness is 3.4 mm (6B Sch 10S). Each elbow was constructed of two parts, which were formed from type 304 stainless steel plate with a hydraulic press, welded together and then heat treated in a solid solution (1,060°C for 25 min. and then water quenching).

Two types of testing machines were used in the tests. The servo-controlled hydraulic testing machine shown in *Fig. 2* was used in the monotonic loading, relaxation and fatigue tests. Specimens were heated with electric heaters, which were installed inside the specimens. The exteriors of speicmens were thermally insulated with glass fiber sheets 20 mm thick. Elbow temperatures were controlled to within ±5°C of a test temperature with thermocouples, which were percussion welded to the surfaces of the specimens. During the tests, elbow cross-sectional deformation was measured continuously at the middle of elbows (ψ=0) with a specially developed deformation device. The device was constructed of four linear differential transformers (LDT) and a support ring. It was placed on the outer surface of the thermal insulation covering an elbow and the LDT spindles were attached to the outer surface of the elbow itself, at θ=0, 45, 90 and 135 degs. A support frame of a special design was developed for the deformation device. Local strain was measured continuously with clip gauges developed by S. Kusumoto [3] and with the weld type strain gauge (GL=0.7 inch) that was welded to a specimen.

The elbow creep testing machine shown in *Fig. 3* was used in creep tests. An elbow specimen was put in an electric furnace, in which electric heaters were mounted on the inside wall of a thermally insulated structure. The temperature of a specimen was controlled to within ±2°C of a test temperature. A constant tensile load was applied to a specimen using weights and a compound pulley (a load was 4 times as large as a weight). During the creep tests, diametral deformation at the middle of elbows (ψ=0) was measured continuously with deformation devices and local strain was measured with a weld type strain gauge.

The test parameter of all the specimen were summarized in *Table 1*.

3. Test Results and Discussion

3.1 Monotonic Load Tests

An increasing monotonic load was applied to elbow specimens at room temperature and at 600°C. The load P vs. deflection δ and P vs. diametral deformation d curves, where the deformation is at the middle of elbow ($\psi=0$), are shown in *Figs. 4* and *5* respectively. As the applied load increases, the deflection in compressive tests becomes greater than that in tensile tests. This means that, with respect to large deflections, elbow flexibility under tensile deformation is different than that under compressive deformation. R. Roche et al. [4] shows that this difference in elbow flexibility can be determined in a shell type analysis which takes into account the diametral deformation of an elbow. In the case of the load vs. diametral deformation curves, the maximum stress on the outer surface of an elbow equals the yield stress at the point, P=280 kg, where the tensile curve for the elbow separates from the compressive one. This separation occurs under a smaller load than is the case with the load vs. deflection curves.

3.2 Collapse load

There are many ways of defining the collapse load of an elbow as illustrated in *Fig. 6:* (1) the load at which the maximum strain reaches 0.2% (0.2% off-set method), (2) the load at which deflection is twice that at the point where the relation between load and deflection departs from linearity (ASME Code, experimental method), (3) the load at the intersection of a line in the elastic region and a line drawn tangent to the straight line portion of a curve in the plastic region (two tangent method), (4) the load at the intersection of a load-deflection curve and the line which forms an angle equal to twice the angle α (twice the angle α method) and (5) the load at the intersection of a load-deflection curve and the line which forms an angle equal to 1/2 times the angle β (one half the angle β method).

Using these different methods, the collapse loads obtained from the experimental results are shown in *Table 2*. The definition for the collapse load of an elbow which is given in the ASME Boiler and Pressure Vessel Code gives collapse load that are lower than the actual values for type 304 material, because the strain hardening coefficient of the material is large, while the one-half the angle method seems to give a more realistic approximation of collapse load in the case of materials with a large strain hardening coefficient.

3.3 Creep Tests

Creep tests were carried out with loads of P=410, 500 and 600 kg at 600°C. *Figures 7* and *8* show deflection δ vs. creep time, and *Fig. 9* shows diametral deformation vs. creep time, where the deformation is at the middle of an elbow ($\psi=0$). *Figure 10* shows circumferential strain vs. creep time curves at the maximum strain point of an elbow.

For loads of 500 and 600 kg, creep deformation is rapid for the first 100 hours, but after that it increases slowly and constantly. For a load of 410 kg, creep deformation is rapid for the first 100 hours, but after that it increases slowly and after about 600 hours it is almost constant. In *Fig. 7* initial deflections are 12, 20 and 30 mm for load of 410, 500 and 600 kg respectively. These deflections are smaller than the values obtained in the monotonic loading test (7 mm for 410, 30 mm for 500 and above 70 mm for 600 kg). This is because in the creep test the load was tensile and in the monotonic loading test the load was compressive. This decrease in the rate of creep deformation occurs because diametral deformation caused by tensile loading causes a decrease in elbow flexibility and a relaxation in stress near the point of maximum stress, which results in uniforming stress distribution curve. Upon a closer investigation of test data, it is found that, for a given load, log δ is related to log t by two straight lines and that creep time at the point where the two lines meet is about 30 hours, as shown in *Fig. 8*. After 30 hours creep time, the creep deflection rate, which decreases as creep time increases, is proportional to $t^{-0.9}$

J. Spence's analysis [5] is often used to calculate the stationary creep deflection rate of elbows. The results obtained in creep deflection rate calculations with this method are shown in *Fig. 7*, to allow comparison with the results obtained in experiments. The calculated values are considerably larger than the experimental ones, because "end effect", i.e. the reinforcement of the ends of elbows by the straight pipes that were welded to them, was not considered in the calculations.

The ratio of diametral deformation of the horizontal diameter ($-d_H$) to that of the vertical diameter (d_V), which is shown in *Fig. 9*, is larger in the case of creep deformation (about 1.6 to 1.8, after a creep time of 100 hours) than in the case of monotonic loading (about 1.4 to 1.5, t=0 in *Fig. 9*).

Compressive circumferential creep strain $\varepsilon_{\theta C}$ on the outer surface at the maximum stress point increases, but the strain rate $\dot{\varepsilon}_{\theta C}$ decreases, as creep time increases (*Fig. 10*). Contrary to expectations, the larger the applied load, the smaller the creep strain $\varepsilon_{\theta C}$ is. The reason for this is probably that the larger the applied load, the greater the stress relaxation near the maximum stress point is.

The relation between circumferential strain and deflections during creep tests is shown in *Fig. 11*. Strain concentration during creep deformation is a little smaller than that during elastic or plastic deformation. This is due to a redistribution of the stress at the middle of an elbow.

3.4 Relaxation tests

The results of the short term relaxation test are shown in *Figs. 12, 13* and *14* and those of the long term test in *Figs. 15* and *16*. The short term test was carried out at 600°C by increasing the compressive deformation in steps of 1.7 to 10 hours in length (*Fig. 12*). *Figure 13* shows the relaxation behaviour of the resultant load and the circumferential strain at the point of maximum strain for several load steps. The relaxation rates of the resultant load and the strain of a given load step are smaller than those of the immediately preceding step. Strain and stress relaxations occur, but diametral deformation appears to be almost constant throughout the relaxation steps (*Fig. 14*). In *Fig. 15*, early relaxation of specimen A-5-1 is less pronounced than that of the other specimens. The reason for this is that, in the case of specimen A-5-1, early relaxation has already occurred to some extent as a result of the previous step-up relaxation test.

The results of the long term relaxation test are shown in *Fig. 16*, where the relation between log P_{in}/P and log t is represented by two straight lines. Relaxation time at the intersection of the two lines is about 20 hours. After 20 hours, the relation between resultant load and relaxation time can be expressed as follows.

$$P = A \cdot P_{in} \cdot exp\ \{t^{-0.15}\}$$

where, A is a material constant dependent on the previous loading history and P_{in} is the initial resultant load.

4. Conclusion

Collapse, creep and relaxation tests were carried out on elbow specimens made of type 304 stainless steel at ambient temperature and at 600°C. The main results obtained in the tests are as follows.

(1) At elevated temperatures, the experimental collapse loads obtained for elbows made from a material with a low yield strength and a high strain-hardening coefficient, such as type 304 stainless steel, are approximately twice those obtained with the two methods described in the ASME Boiler and Pressure Vessel Code, Section III, while the one-half the angle method gives a better prediction.

(2) The creep deflection rate of an elbow is not constant, but decreases gradually to almost zero. In the case of 410 kg load, for example, creep deflection is almost saturated after 600 hours. Creep deflection is represented by bi-linear relation between log δ and log t. The length of the period from zero to the point where the two lines meet is about 30 hours for every load that was applied. The creep deflection rate calculated with J. Spence's diagram is considerably larger than the experimental rate. This is probably because the reinforcement of the ends of the elbow by the straight pipes that were welded to them, is not considered in the calculations.

(3) When deflection is increased in a step-like pattern, the normalized load (P/P_{in}) of each step is nearly the same, but the normalized strain ($\varepsilon_\theta/\varepsilon_{\theta in}$) is different. The P/P_{in} can be represented as a function of log t.

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Table 1 Summary of test parameter

Test	Spec. code	Temp. (°C)	Load P or deflection δ
Collapse	A-1-1	R.T.	Monotonic compression
	A-1-2	R.T.	Monotonic tension
	A-2-1	600	Monotonic compression
Creep	A-4-1	600	P = 410 kg, t_h = 600 hr
	B-2-3	600	P = 500 kg, t_h = 300 hr
	B-2-2	600	P = 600 kg, t_h = 200 hr
Relaxation	A-5-1	600	Step-up δ, t_h = 1 to 3 hr
	A-5-2	600	Cyclic δ, ±35 mm, t_h = 200 hr
	E-4-1	600	Cyclic δ, ±35 mm, t_h = 24 hr

Table 2 Collapse loads by different methods

Method	Collapse load P_c (kg)		
	600°C (Comp.)	R.T. (Comp.)	R.T. (Ten)
0.2% offset	540	690	880
ASME Sec III (Exp.)	320	560	540
Two tangent	540	790	810
Twice the angle α	590	710	-
One-half the angle β	560	860	-
ASME Sec III (limit analysis)	282	582	582

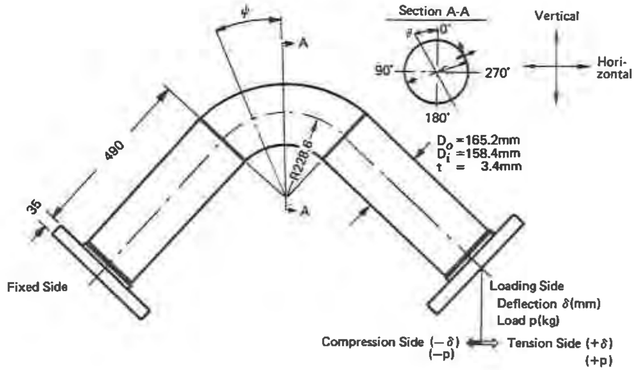

Fig. 1 Details of elbow specimen

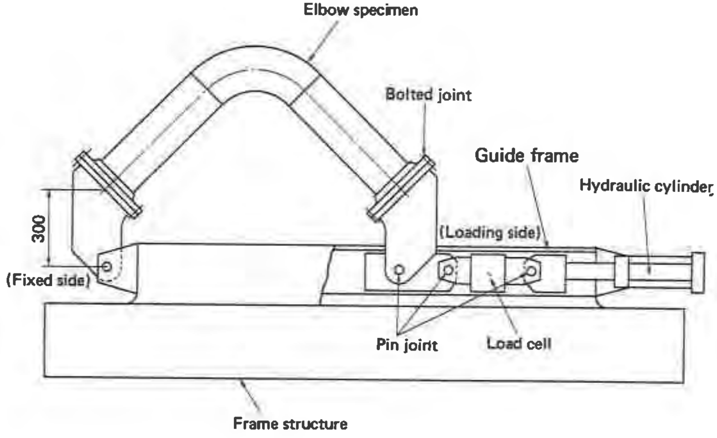

Fig. 2 Elbow collapse and relaxation test machine

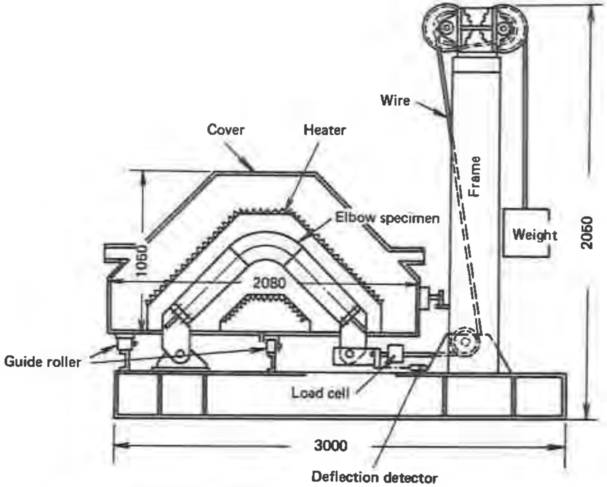

Fig. 3 Elbow creep testing machine

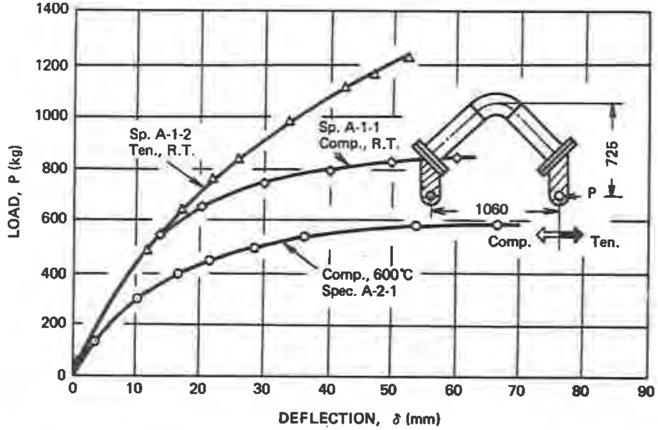

Fig. 4 Load-deflection curve

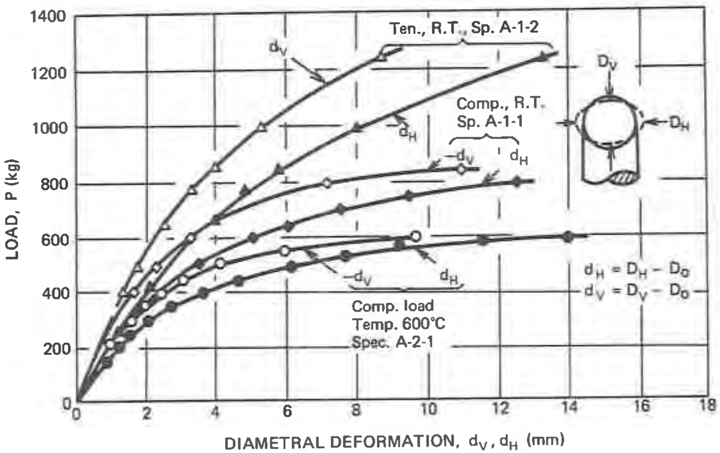

Fig. 5 Load-diametral deformation curve

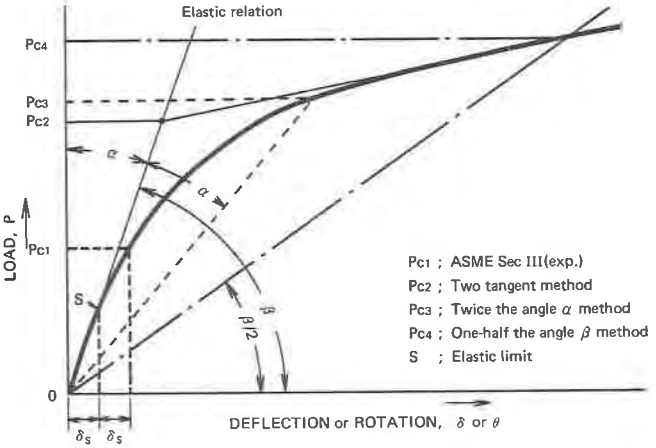

Fig. 6 Schematic diagram for collapse load determination

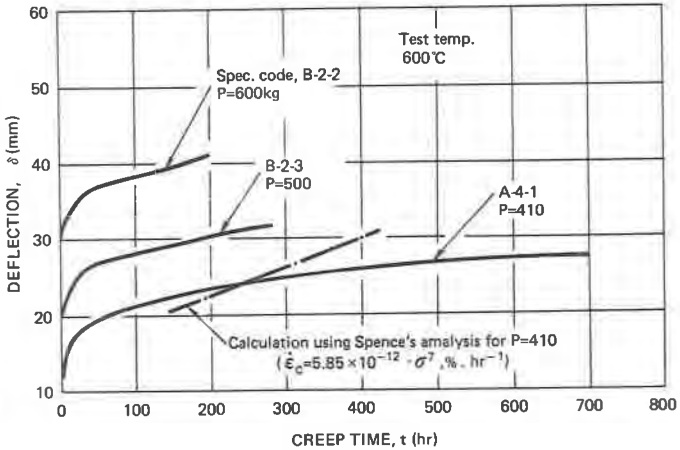

Fig. 7 Creep deflection characteristics

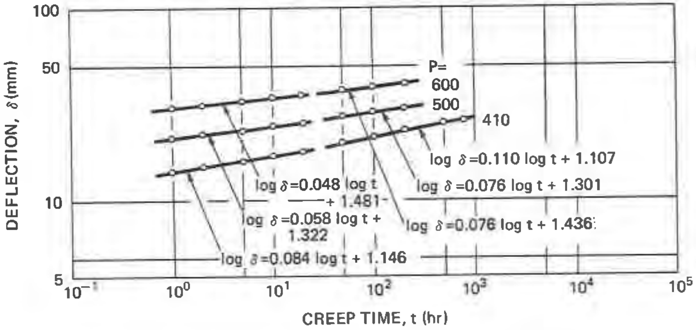

Fig. 8 Analytical expression of creep deformation behaviour

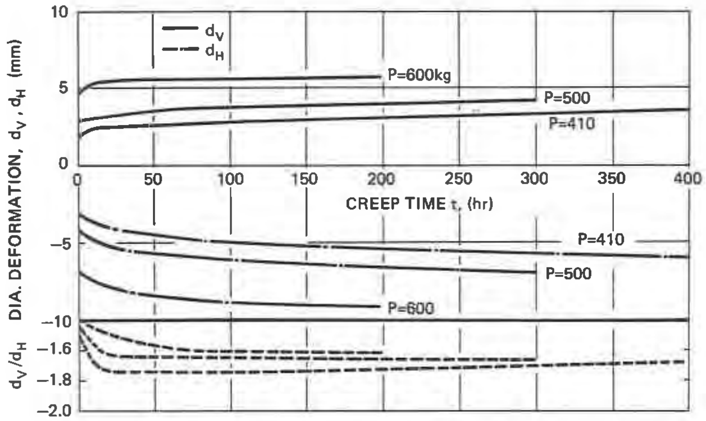

Fig. 9 Diametral deformation behaviour during creep test

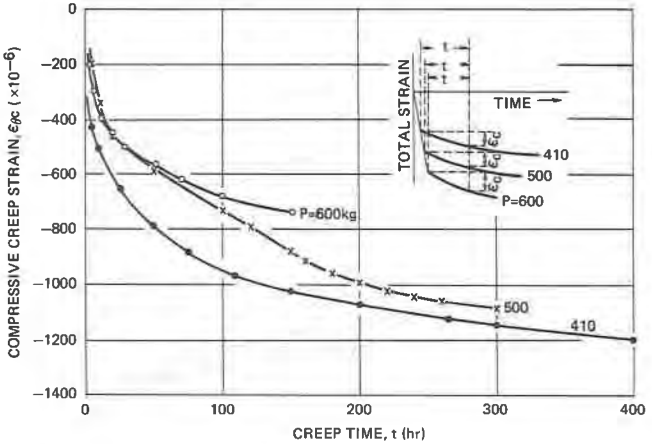

Fig. 10 Dependence of creep strain on applied load

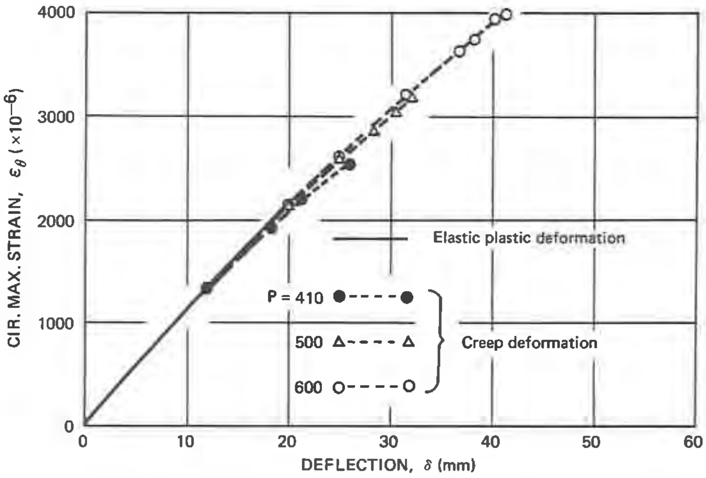

Fig. 11 Relation between circumferential maximum strain and deflection in creep and elastic plastic deformation

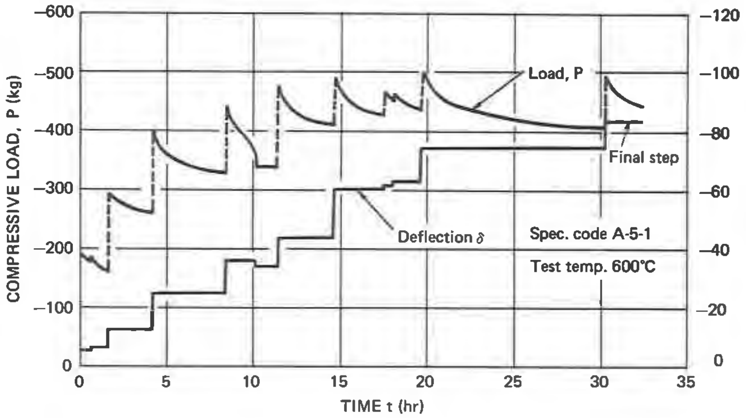

Fig. 12 Load relaxation behaviour in step-up deflection test

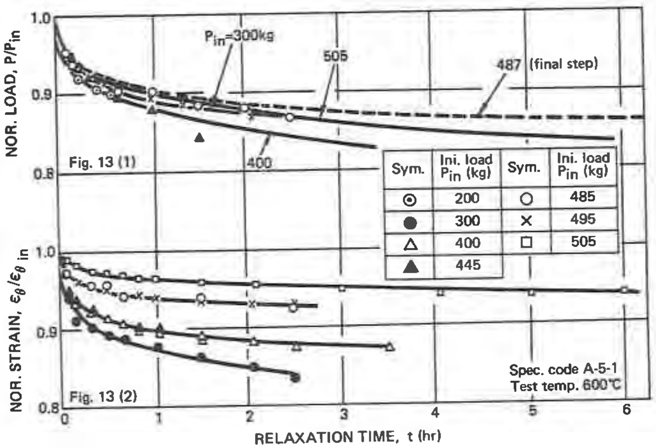

Fig. 13 Normalized strain and load behaviour in step-up relaxation test

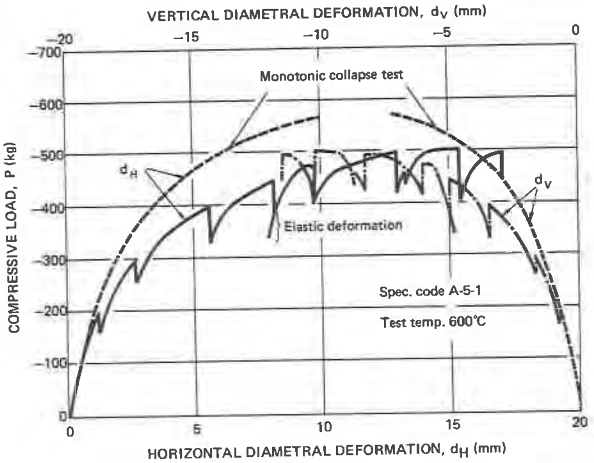

Fig. 14 Diametral deformation in step-up relaxation test

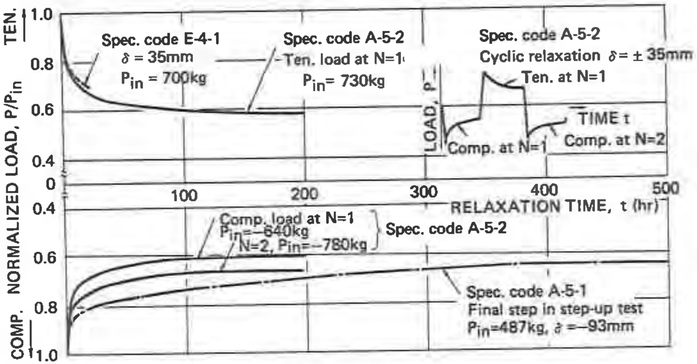

Fig. 15 Normalized load behaviour in long term relaxation test

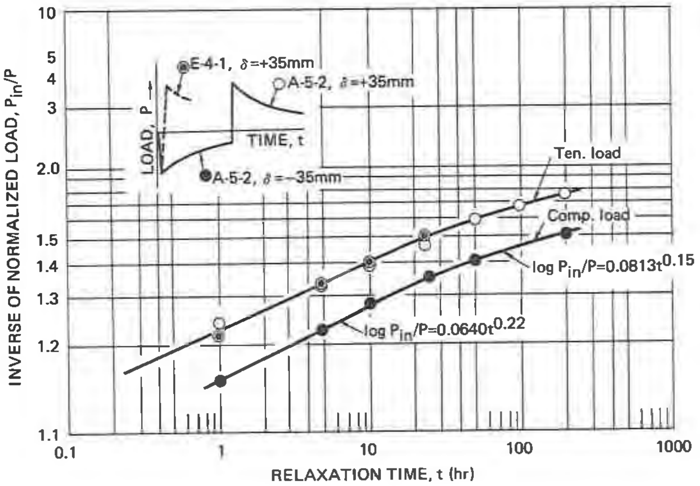

Fig. 16 Analytical expression of load relaxation behaviour