CREEP COLLAPSE OF A CYLINDRICAL SHELL SUBJECTED TO EXTERNAL PRESSURE AT HIGH TEMPERATURE

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As structures are exposed to increasingly high temperatures, creep collapse is no longer negligible in the design of structures, and thus the necessity has arisen to establish some standardized method of analyzing creep collapse.

The purpose of this paper is to qualify (1) the various methods of analysis proposed in the past for the prediction of creep collapse time of a cylindrical shell subjected to external pressures at high temperatures and (2) "C-BUCKL", a computer program for the analysis written by the present authors. The qualification is based on the comparison of theoretical analyses and test results. Much care was taken to use test tubes more closely identified than the ones used in any preceding similar test.

A new equipment was assembled for the creep collapse tests. It is capable of temperatures up to 1100°C and external pressures up to 100 kgf/cm^2, and has 400 mm long isothermal zone. The equipment is designed to measure collapse time by detecting sudden rise in the charged pressures in test tubes as well as electric contact between probe rod placed inside test tubes and inner surface of test tubes at the moment of creep collapse. The pressures of 7.5 to 19.0 kgf/cm^2 were applied by nitrogen gas on test tubes of Hastelloy-X, 60 mm in outer diameter, 2 mm in thickness and 400 mm in length, at temperatures of 800°C and 900°C. Some of the test tubes were intentionally deformed to have quasi-elliptical cross sections. Resultant initial imperfection in radius was approximately 0.39 to 0.49 mm. To have detailed data on the shapes of cross sections, measurement of radius and thickness were done at every 9° of circumferential angle on three separate cross sections of all test tubes. Creep and tensile data necessary for analysis were obtained by test using test specimens cut out of the same tubes as the ones used for the collapse test.

All the test tubes showed quasi-elliptical deformation mode. The test results were compared with theoretical predictions by (A) sandwich model analysis, (B) "C-BUCKL" and (C) simplified analysis. In the theoretical predictions, test tubes without being purposely deformed were considered as tubes having the shapes of equivalent quasi-elliptical cross sections. The theoretical predictions by (A) and (B) were in fairly good agreement with the test results. The test results showed higher reproducibility than the records in any preceding literature. Therefore the test results can be used as bench mark problems not only of the conventional methods adopting variation in radius as initial imperfections but also of method of analysis which treat variation of both radius and thickness as initial imperfections.

1. Introduction

Tubes subjected to external pressure at high temperatures are apt to show structual instability such as creep collapse. Creep collapse is induced by initial imperfection such as (1) deviation from perfect circularity and uniform wall thickness in the shape of the tube cross sections which is inevitably caused during the manufacturing and machining of the materials, and (2) the heterogenuity of materials. As the structures are exposed to increasingly higher temperature, the possibility of creep collapse has become no longer negligible. Thus the structures have to be designed so as to ensure the integrity against creep collapse during their life time.

The code case 1592 shows creep collapse as one of the time dependent failure modes of high temperature component. But they do not specify the method of analysis, leaving it to designer's choise. A series of analysis methods have been proposed, but to date none of them has been established as a standardized method partly for the lack of experiment data to be used as reference.

The purpose of this paper is to qualify various analytical methods, including the one designated "C-BUCKL" which the authors have written, for the prediction of creep collapse time of long thin-walled tubes subjected to high temperatures and external pressures. For this purpose, the authors measured creep collapse time using Hastelloy-X thin-walled tubes as test specimens and subjecting them to external pressures at temperatures of 800°C and 900°C by a newly assembled equipment. Uniaxial creep tests and uniaxial tensile tests were also conducted to obtain Young's moduli, Poisson's ratios and creep constitutive equations, based on which creep collapse time was computed theoretically and was compared with experimental one.

In the similar experiments done in the past, measurement on the shape of the cross sections of test tubes were only inadequately done, and initial imperfection was not paid due attention. In the present study, detailed measurement of radii and thicknesses was done on cross sections of all the test tubes to identify the shapes. To study the effect of initial imperfection, some of the test tubes were purposely deformed to have quasi-elliptical cross sections. To ensure that the test tubes for creep collapse tests and the test specimens for uniaxial creep and uniaxial tensile tests are of the same material property, thick-walled tubes of the same manufacturing lot were used for both creep collapse tests and uniaxial creep and uniaxial tensile tests, being machine-processed for the former tests, and cut out for the latter tests. In the uniaxial creep tests, creep curves were obtained within the range of stress applied to test tubes in creep collapse tests so as not to require the extrapolation of stress term in creep constitutive equations.

2. Experiments

2.1 Test apparatus

A new apparatus was assembled for experiments. It is capable of studying the characteristics of instantaneous and creep collapse of tubes subjected to external pressures at high temperatures. This test apparatus is designed to apply external pressure by gas on test tubes at high temperature. In instantaneous collapse tests, critical pressure can be measured, while in creep collapse tests collapse time can be measured. The photograph of the test apparatus and flow diagram are shown in Fig. 1 and Fig. 2 respectively. Principal specification is shown in Table 1. The test apparatus is an autoclave in which electric furnace is placed. As seen in Fig. 2, a test tube is placed upright through the electric furnace. It is ensured that the part to be tested of the test tube is placed in isothermal zone in the central part of the furnace. The upper end of the test tube is fixed, while the lower end is sealed by O-ring to allow axial elongation.

External pressure is applied by gas fed from gas cylinder, being regulated by pressure control unit composed of pressure transducer, setter and electro-magnetic valve. The pressure is continuously recorded by recorder. By regulation system, the pressure is controlled to within ±1%.

The furnace has three separate heaters. With thermocouple and temperature control unit, an isothermal zone 400 mm in length can be produced at desired temperature. Temperatures of gas are measured at three separate positions, i.e. the center of the isothermal zone, 200 mm above and below the center of the isothermal zone, and are recorded by recorder throughout the experiments. The temperatures are controlled to within ±3°C at above-mentioned three positions along the length of the test tube.

As the pressure applied inside the apparatus increases, the convection of gas inside the furnace becomes activated, and this may cause the variation of temperature and heat loss. The apparatus was so designed to minimize such convection.

Collapse time is measured by detecting sudden rise in the charged pressure in test tubes as well as electric contact between probe rods (steel inserts) placed inside test tubes and inner surfaces of test tubes at moment of creep collapse. Collapse time recorded by these two detection systems were found almost identical to each other.

2.2 Test pieces

The material for the test specimens is nickel-based supperalloy "Hastelloy-X" hot extruded tubes, 75 mm in outer diameter and 11.5 mm in wall thickness, subjected to solution treatment of 1140°C x 35 min. (W.C.). Its grain size is ASTM No. 4.5. Its chemical composition is shown in Table 2. Test specimens for uniaxial creep tests and uniaxial tensile tests were cut out of the tubes and machined. As for the test tubes for the creep collapse tests, the Hastelloy-X tubes were machined, and tubes, 60 mm in outer diameter, 2 mm in wall thickness and 400 mm in length, were obtained. Some of these tubes were purposely deformed to have quasi-elliptical cross section shape. The rest of them were used without such tube upsetting. These tubes are the parts to be tested and type 316SS tubes, 62 mm in outer diameter and 10 mm in thickness, were welded to the both ends of all these Hastelloy-X tubes, to make test tubes 1800 mm in total length. The shape of the test tube is shown in Fig. 3.

In order to study the initial geometric imperfection in the shape of cross sections, outer radii and wall thicknesses were measured at every 9° of circumferential angle of three separate cross sections, i.e. a cross section at the length center of Hastelloy-X tube and two cross sections each 100 mm off the length center of the test tube. Fig. 4 shows one of the results of the measurement on purposely deformed tubes. It was derived from these results that the approximation of out-of-roundness could be done by $w_0=w_1\cos 2\theta$ and that w_1 for all test tubes was in the range of 0.39 to 0.49 mm. The scattering of radius of test tubes not deformed is ±0.01 to ±0.02 mm. The radius/thickness ratios of the test tubes are about 15.

Residual stress caused by tube upsetting was released before experiments. The change of the cross section shape was within the error margin of measurement, and was therefore negligible.

2.3 Test procedure and results

The test tubes were placed in such a way that the Hastelloy-X parts were exactly in the isothermal zone. The lower end of the test tubes were supported in free-end condition as shown in Fig. 2. Temperature were measured by three thermocouples (PR 13%). External pressure was applied on test tubes by nitrogen gas.

In actual procedure, after the temperature of gas was set as prescribed, the test tubes were pre-heated for over 20 hrs. at the same temperature. Then nitrogen gas was applied, and prescribed pressure was obtained. This was recognized as the starting time of the experiments. Creep collapse time was defined to be the time from the starting time to the moment at which creep collapse was detected by the detection systems.

The experiments were conducted under two different temperature conditions, and under three different pressure conditions. For the temperature of 800°C, tests were done with effective external pressures of 15.0, 17.0 and 19.0 kgf/cm^2 separately. (effective external pressure = external pressure - internal pressure) For the temperature of 900°C, tests were done with effective external pressures of 7.5, 8.5 and 9.5 kgf/cm^2 separately. Internal pressure of the test tubes, by which collapse is to be detected, was 0.5 kgf/cm^2 for all the tests.

The conditions of the tests and results are shown in Table 3. Experiments Nos. 1, 2, 3, Nos. 4, 5 and Nos. 6, 7 are carried out under identical conditions respectively to study the reproducibility of test results. Good reproducibility was observed as seen in Table 3. The shapes of cross sections of test tubes after creep collapse invariably showed two-lobed deformation mode (n = 2). Maximum radius deformation was recorded at the position where initial imperfection in radius was largest. The photograph of a test tube after creep collapse is shown in Fig. 5.

In uniaxial creep tensile tests, a lever type creep testing machine was used. Creep curves were obtained at the temperature of 800°C and the stresses of 2.5, 4.0, 6.0, 6.8, 7.8, 9.0 kgf/mm^2 and at the temperature of 900°C and the stresses of 1.0, 2.0, 3.4, 4.0, 4.8, 6.0 kgf/mm^2 separately. The results are shown in Figs. 6 and 7. The results are fitted by Norton's creep constitutive equations $\dot{\varepsilon}^c = A\sigma^m$. The Young's moduli, the Poisson's ratios were studied by electro-hydraulic low cycle fatigue testing machine at 800°C and 900°C. Table 4 shows material properties obtained.

3. Theoretical Analysis

3.1 "C-BUCKL" theoretical formulation

The authors have written an economical computor program to predict creep collapse time of tubes with arbitrary initial imperfection. In this program, equilibrium equations are solved by finite difference method, and step-by-step computation is performed by incremental procedure. It is assumed that within each computation period Δt stress varies linearly by $\Delta\sigma$, and that creep constitutive equations are of Norton. The following is the general outline of the theoretical formulation.

According to Cry and Teter [1], if creep constitutive equations are in accordance with Norton's law, the relation between the incremental stress $\Delta\sigma$ and the incremental strain $\Delta\varepsilon$ within Δt is;

$$\Delta\sigma = [C + C_c]^{-1} (\Delta\varepsilon - \Delta\hat{\varepsilon}^c - \Delta\varepsilon^0) \tag{1}$$

C : elastic strain-stress matrix

C_c : creep matrix

$\Delta\varepsilon$: incremental total strain

Equilibrium equations for a thin-walled tube subjected to external pressure in incremental formulation by Timoshenko [2] are;

$$\frac{\partial\Delta N_y}{\partial\theta} - \frac{\partial\Delta M_y}{R\partial\theta} = 0 \tag{2}$$

$$\frac{\partial^2\Delta M_y}{R\partial\theta^2} + \Delta N_y - pR\left(\frac{\Delta w}{R} + \frac{\partial^2\Delta w}{R\partial\theta^2}\right) = 0 \tag{3}$$

ΔN_y : incremental sectional force per unit length in circumferential direction (θ)

ΔM_y : incremental sectional moment

p : uniform external radial pressure

R : mean radius of middle surface of tube

u : displacement of tube in axial direction (x)

v : displacement of tube in circumferential direction (θ)

w : displacement of tube in radial direction (z)

where,

$$\Delta N_y = \Delta\sigma_y dz \tag{4}$$

$$\Delta M_y = \Delta\sigma_y z dz \tag{5}$$

Compatibility equations are

$$\Delta\varepsilon_x = \frac{\partial\Delta u}{\partial x} - z\frac{\partial^2\Delta w}{\partial x^2} \tag{6}$$

$$\Delta\varepsilon_y = \frac{\partial\Delta v}{R\partial\theta} - \frac{\Delta w}{R} - \frac{z}{R^2}\left(\Delta w + \frac{\partial^2\Delta w}{\partial\theta^2}\right) \tag{7}$$

Substituting eqs. (1), (4), (5), (6), and (7) for eqs. (2) and (3), and adopting generalized plane strain assumption, we obtain simultaneous differential equation with unknown quantities Δw and Δv.

In this computer program, instantaneous displacements are solved by the method proposed by Pan [3]. Afterwards, incremental displacements are obtained by solving the simultaneous equation by finite difference method.

3.2 Theoretical prediction of creep collapse time

Collapse time was computed for all the test tubes that underwent creep collapse tests on the basis of the dimensions of the test tubes and the test conditions by several methods including "C-BUCKL", Hoff's method [4] based on Sandwich model and simplified approach proposed by Chern [5]. The results are shown in Table 3. As regards the input data for the computation, the figures in Table 4 were employed as material properties. Initial imperfections were obtained by $w_0=w_1\cos2\theta$ indicated in Fig. 4 for purposely deformed test tubes. For the other test tubes, $w_0=w_1\cos2\theta$ was also applied with w_1 defined as the maximum deviation from perfect circularity. In the Hoff's method, stress index in Norton's creep constitutive equations are limited to integral numbers. Therefore, in this study, interpolation of stress index was performed where stress index was not integral numbers.

4. Discussion and Conclusions

Creep collapse time of thin-walled tubes subjected to constant temperatures and constant external pressures has thus been measured. The results show significant reproducibility, and therefore are applicable as bench mark problems for creep collapse analysis of tubes subjected to external pressures.

The theoretical predictions by "C-BUCKL" and Hoff's method have been found in fair agreement with the test results as seen in Table 3. The "C-BUCKL" is capable of theoretical prediction of creep collapse time of tubes whose collapse mode is $n>2$, although complex numerical method with computor is required. In Hoff's method, computation is very complex when stress index of Norton's creep constitutive equation exceeds 5, and it is only applicable where collapse mode is $n=2$. In Chern's method, computation is rather simple, and computer is not essential, although it produces predictions excessively on the conservative side in relation to the test results.

In the authors' earlier computations, Norton's creep constitutive equations based on the creep data for higher stresses were employed. This led to theoretical predictions on the non-conservative side. In other words, the computations were done with creep constitutive equations based on the creep curves for stresses of 3.4 to 6.0 kg/mm^2, while the average circumferential stresses applied to the test tubes for the major part of test period are 1 to 2 kg/mm^2 at the experiment temperature of 900°C. The resultant predictions were very much on the non-conservative side. Subsequently, the authors based creep constitutive equations on the stresses of 1.0 to 6.0 kg/mm^2 which cover the above-mentioned average circumferential stresses of 1.0 to 2.0 kg/mm^2 applied in actual creep collapse tests. In this manner, the theoretical predictions were found in fairly good agreement with the test results. Therefore, it has been concluded that it is inappropriate with the creep constitutive equations based on the high stress creep curves to predict creep collapse characteristics of tube under low stress during the major part of test period.

In future studies, it will be necessary to qualify by experiments the law of linear cumulative damage on which creep collapse analysis under varying load and temperature is based. The establishment of simpler, more accurate method for the theoretical prediction is also called for to alleviate the complexity of computation now required for creep collapse anaysis.

5. References

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Maximum operating temperature	1100°C
Length of isothermal zone	400 mm
Variation of set temperature	± 3 °C
Maximum operating pressure	100 Kg/cm^2
Variation of set pressure	± 1 %

Table 1 Specification of test apparatus

C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	Ni
0.07	0.44	0.49	0.010	<0.005	21.37	0.99	8.82	0.51	8.47	Bal

(wt %)

Table 2 Chemical composition of Hastelloy-X

No.	T (C)	p (kg/cm^2)	R (mm)	h (mm)	w_1 (mm)	h** (mm)	t_{cr} (hr)			
							Actual	C-BUCKL	Hoff et al	Chern***
1*	900	12.0	29.03	2.00 (1.96)	0.015	0.08	96.8	98.0 (86.0)	60.8 (54.3)	40.7 (35.9)
2*	900	12.0	29.05	2.01 (1.99)	0.015	0.05	148.0	100.0 (94.0)	62.3 (58.9)	41.8 (39.3)
3*	900	12.0	29.02	1.99 (1.96)	0.010	0.08	109.5	104.0 (94.0)	65.0 (59.7)	42.8 (39.0)
4	900	9.5	28.96	2.01 (1.99)	0.468	0.03	27.2	35.5 (30.0)	28.2 (26.5)	4.52 (4.13)
5	900	9.5	29.01	2.01 (1.92)	0.390	0.20	21.5	42.0 (29.0)	32.9 (24.8)	6.49 (4.35)
6	900	8.5	28.98	2.01 (1.95)	0.440	0.10	40.3	58.0 (44.5)	43.1 (35.6)	7.95 (6.10)
7	900	8.5	28.96	2.00 (1.98)	0.445	0.05	44.5	55.0 (50.0)	41.5 (39.0)	7.48 (6.85)
8	900	7.5	28.93	2.00 (1.97)	0.455	0.06	93.2	86.0 (76.0)	62.3 (56.6)	11.7 (10.3)
9	800	19.0	29.03	1.99 (1.98)	0.463	0.02	51.2	39.0 (37.0)	47.9 (46.4)	3.92 (3.71)
10	800	17.0	29.08	2.04 (2.00)	0.485	0.07	131.0	70.0 (70.0)	76.3 (67.5)	7.54 (6.11)
11	800	15.0	29.09	1.99 (1.98)	0.458	0.03	353.5	104.0 (104.0)	104.0 (100.7)	11.6 (11.0)

* Tube undeformed purposely, w_1: Maximum deviation from circularity

** h; Maximum thickness - minimum thickness

*** Simplified approach that uses the secant modulus method

( ) Minimum thickness was used

Table 3 Experimental and theoretical results

°C	E (Kg/mm)	ν	A	n
RT	19900	0.32	—	—
700	15700	0.33	—	—
800	15000	0.34	1.6×10^{-7}	3.7
900	14200	0.35	3.4×10^{-6}	3.6
1000	12500	0.37	—	—

E : Young's modulus   ν : Poisson's ratio
A : Constant in Norton's creep law
n : Stress index in Norton's creep law

Table 4 Material properties

Fig. 1 Test Apparatus

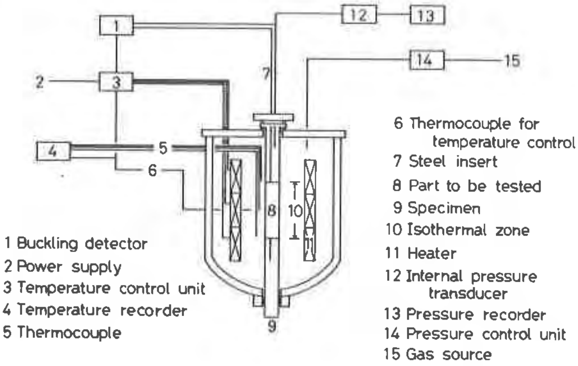

Fig 2 Schematic diagram of test apparatus

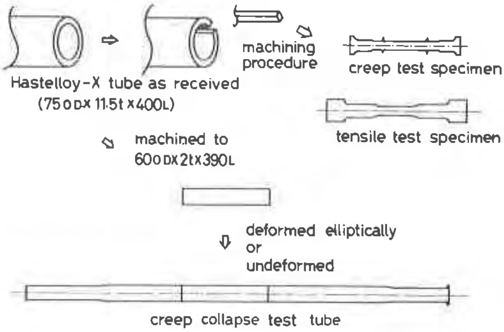

Fig. 3 Test specimens

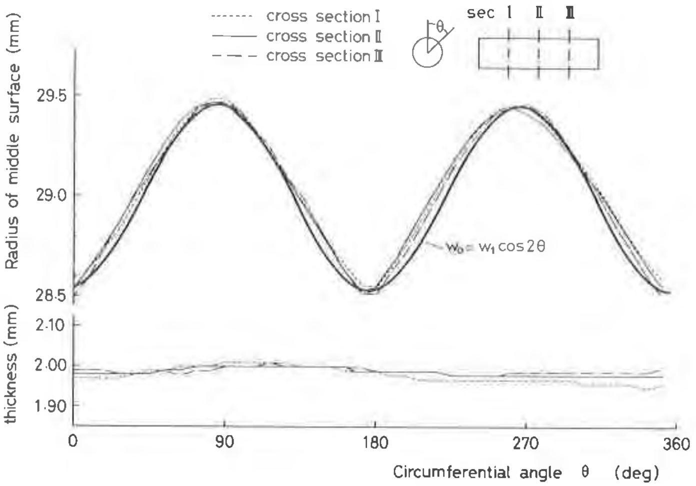

Fig. 4 Radii and thicknesses of creep collapse test tube

Fig. 5 Tube after creep collapse

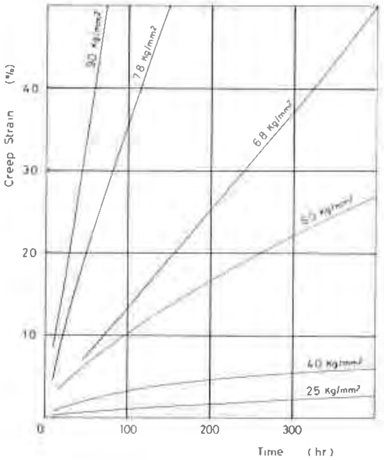

Fig 6 Creep curves at 800 °C

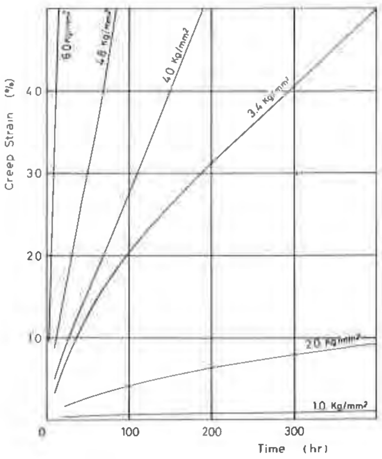

Fig 7 Creep curves at 900 °C