Experimental study on macroscopic creep behavior of perforated plates

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1 INTRODUCTION

In the design of high temperature equipment containing perforated plates, such as the intermediate heat exchanger for the high temperature gas cooled reactor, creep analysis of perforated plates is required. The simplified method based on the equivalent solid plate concept (O'Donnell et al. 1982) is used for the creep analysis of perforated plates. In this case, the results of the analysis depend on the prediction methods of both equivalent solid plate properties and stress-strain concentration around a hole. In the previous paper (Igari et al. 1986), the authors proposed these prediction methods based on an analytical approach assuming the Norton's creep law. And, the experimental verification of the applicability of these prediction methods to real structural material which exhibits both primary and secondary creep, was left for future work.

Experimental study of macroscopic creep behavior of perforated plates is performed in this paper in order to verify the proposed prediction method of the equivalent solid plate properties. When discussing the macroscopic creep behavior of perforated plate, there is another approach based on the effective stress concept which is often used in damage mechanics (Kachanov 1958). First, in this paper, a relation between the equivalent-solid- plate stress and the effective stress is studied by analytical approach assuming the Norton's creep law. Secondly, the macroscopic creep deformation and failure behaviors are investigated by carrying out a series of the creep tests of both solid and perforated plates made of Hastelloy X at 800 and 950 °C. Finally, predicted results by the combination of the minimum creep rate of the flat plates and the prediction method of the equivalent solid plate property shown above, are compared with the experimentally obtained macroscopic minimum creep rates of perforated plates. And also, a possibility in predicting the macroscopic creep rupture data of perforated plates is studied by use of the effective stress mentioned above.

2 EFFECTIVE STRESS OF PERFORATED PLATES

2.1 Prediction method of equivalent solid plate property

The prediction method of the equivalent solid plate property proposed by the authors are summarized in the followings. Assuming that the creep properties of base material and equivalent solid plate are expressed by the eqs. (1) and (2), respectively,

(1) $\dot{\varepsilon}_c = A\sigma^n$ (Base material)

(2) $\dot{\varepsilon}_c^* = A^*\sigma^{*n^*}$. (Equivalent solid plate)

The authors proposed the next equation for A*, intending to extend the applicable range of exponent n by the previous work (Uragami et al.1981).

(3) $A^* = (\frac{0.591}{n} + 0.316)\eta^{-1.18n}A$. (η: ligament efficiency)

The relation for the special case of n=1 by this equation is expressed as follows by considering the Hoff's analogy.

(4) $A^*/A = E/E^*$

As for another property n* of equivalent solid plate, Uragami et al. has clarified that the exponent n* is equal to exponent n of base material.

2.2 Effective stress of perforated plates

Definitive equation of the effective stress of perforated plates is studied here, in connection with the predictive equation of equivalent solid plate property expressed by eq. (3) assuming the Norton's creep law.

Figure 1 schematically shows a base plate, a perforated plate and an equivalent solid plate. Each of them is subjected to the same force F and have same macroscopic creep behaviors. Gross section area S of the perforated plate is the same as that of the equivalent solid plate. On the other hand, a section area of $\bar{S}$ of the base plate, which is imaginary plate to clarify the physical meaning of the effective stress, is smaller than the area S of the other two plates.

Creep law of the base plate is expressible by eq (1) using σ_{Base} and $\dot{\varepsilon}_c^{Base}$. Creep law of the equivalent solid plate is expressed as follows;

(5) $\dot{\varepsilon}_c^* = A^*\sigma^{*n}$

The effective stress σ_{nom} of the perforated plate is defined as the stress related to the averaged creep strain rate $\dot{\varepsilon}_c^{nom}$ by the Norton's law of base material as the next equation,

(6) $\dot{\varepsilon}_c^{nom} = A\sigma_{nom}^{\ n}$

Since the creep rates of the three plates in Fig.1 are equal to each other by the definition as,

(7) $\dot{\varepsilon}_c^{Base} = \dot{\varepsilon}_c^{nom} = \dot{\varepsilon}_c^*$

the effective stress σ_{nom} is connected with the other two stresses as follows,

(8) $\sigma_{nom} = \sigma_{Base} = (A^*/A)^{\frac{1}{n}}\sigma^*$

and also, the effective section area $\bar{S}$ is expressed as,

(9) $\bar{S} = (A^*/A)^{-\frac{1}{n}}S$.

The physical meaning of the effective stress σ_{nom} is found to be the stress of the base plate. The effective stress σ_{nom} is concretely defined by use of equation (3) and the equivalent-solid-plate stress of perforated plates.

3 CREEP TESTS OF PERFORATED PLATES

3.1 Test method

The test material is a 5mm-thickness-plate made of Hastelloy X (ASTM B435-77). Examples of the test piece are shown in Fig.2. Figure 2 (a) is a flat plate to obtain properties of base material, on the other hand, Fig.2 (b) and (c) are perforated plates with triangular penetration pattern of circular holes loaded to different directions (X-load and Y-load). A gage length of all specimens for measuring macroscopic strain is 50mm, and a gross section area of all specimen is the same to each other. Two kinds of η ,0.5 and 0.7, are adopted by changing a diameter of holes, and by keeping a hole pitch p constant to be 4mm. All test conditions are listed in Table 1, test temperatures being 800 and 950°C. Creep tests were performed up to a macroscopic rupture, under constant loads.

3.2 Test results

Examples of creep curves of the flat plate and perforated plates under the same stress value of σ and σ^*, that is to say, under the same loads, are indicated in Fig.3. The perforated plate of η =0.5 shows the largest creep strain, while the creep strain exhibit smaller value in the order of the perforated plate of η =0.7 and the flat plate. Minimum creep rates of the flat plates and perforated plates are compared to each other in Fig.4, by taking ordinate as σ (flat plates) and σ^* (perforated plates). Minimum creep rate for the perforated plates with η of 0.5 is the largest, while the smallest for the case of the flat plates. Macroscopic creep rupture data of the flat plates and perforated plates are shown in Fig.5, with the same ordinate as in Fig.5. Creep rupture time of the perforated plates with η of 0.5 is the shortest, while the longest for the case of the flat plates.

4 PREDICTION OF MACROSCOPIC CREEP BEHAVIOR OF PERFORATED PLATES

4.1 Prediction of minimum creep rate

A trial to predict the macroscopic minimum creep rates of perforated plate from those of the flat plates was performed here, by use of the eqs. (3) and (5) assuming the Norton's law.

Prediction for the case of the temperature of 800°C is compared with experiments in Fig. 6 following the next procedure :the minimum creep rates of the flat plates are expressed as the following equation as shown in the figure,

(10) $\dot{\varepsilon}_c^{min}=1.225\times10^{-17}\sigma^{7.597}$ (800°C)

the minimum creep rates are predicted and shown as the dotted line in the figure, using eqs. (3) and (5). The prediction coincides well with the experiment in the figure. The equation (3) is found to be applicable to the prediction of the macroscopic minimum creep rates of perforated plates, based on those of the flat plates.

An applicability of the eq.(3) is also studied, from a view point of the definitive equation of the effective stress. Data in Fig.4 are re-arranged as shown in Fig.7, by taking the ordinate as the effective stress σ_{nom} defined by the eq. (3). In the figure, the next equation is used for the creep data of the flat plates at 950°C,

$$\dot{\varepsilon}_c^{min}=2.995\times10^{-11}\sigma^{5.806} \qquad (950^\circ C) \tag{11}$$

The macroscopic minimum creep rates of perforated plates are found to coincide with those of the flat plates. This fact indicates that the definitive equation of the effective stress of perforate plates is reasonable.

4.2 Prediction of creep rupture property

The process of creep rupture of perforated plates is considered to proceed from the creep-crack initiation around holes to the final macroscopic rupture by connecting these creep cracks. In this paper, a trial to predict this macroscopic creep rupture was made by use of the effective stress σ_{nom} which was defined as the effective stress from a view point of creep deformation in the eq.(8). The reason to use this effective stress of creep deformation as that of creep rupture is as follows in addition to the relationship between minimum creep rates and creep rupture properties (Monkman et al. 1956).; the macroscopic creep rupture data in Fig.5 show the same tendency as those of the macroscopic minimum creep rates of perforated plates giving the data group parallel to the data of the flat plates.

Assuming the creep rupture data of the flat plates at 800 and 950°C as follows,

$$tr=B\sigma^m=4.656\times10^{14}\sigma^{-6.077} \qquad (800^\circ C) \tag{12}$$

$$tr=B\sigma^m=3.214\times10^{10}\sigma^{-5.164} \qquad (950^\circ C) \tag{13}$$

the macroscopic creep rupture properties were predicted by this equation,

$$tr^*=B\sigma_{nom}{}^m=B(A^*/A)^{\frac{m}{n}}\sigma^{*m} \tag{14}$$

All data in Fig.5 are re-arranged in Fig.8, with the ordinate of the effective stress σ_{nom} defined in eq.(8). All data for the perforated plates are found to coincide well with the data of the flat plates. This fact indicates that this effective stress σ_{nom} acts as the effective stress for the macroscopic creep rupture of the perforated plates.

4.3 Simplified prediction of the effective stress

Fig.9 shows the relation between 1/n and $(A^*/A)^{1/n}$, which is necessary in defining the effective stress discussed above. The ratios of young's modulus of the flat and the perforated plats E/E* shown in A-8000 are also found in the figure. These ratios, which are related to $(A^*/A)^{1/n}$ for the case of n=1, coincide with the solid lines of $(A^*/A)^{1/n}$ at around the range of "1/n=0.1~0.2". Consequently, the effective stress σ_{nom} in this range corresponding with the range of n=5~10, which is often found in the case of real structural materials, can be simply predicted by the following equation,

$$\sigma_{nom}=E/E^*\sigma^* \tag{15}$$

5 CONCLUDING REMARKS

Applicability of the prediction method of equivalent solid plate property by the authors was experimentally clarified. That is to say, macroscopic minimum creep rate and macroscopic creep rupture time of perforated plates were successfully predicted by using the effective stress defined from the proposed prediction method. Simplified predictive equation of the effective stress was also shown.

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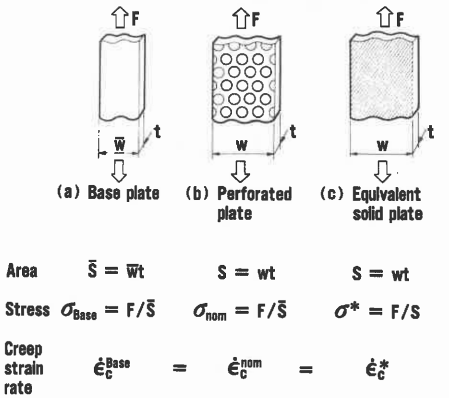

Fig. 1 Definition of stress of perforated plates

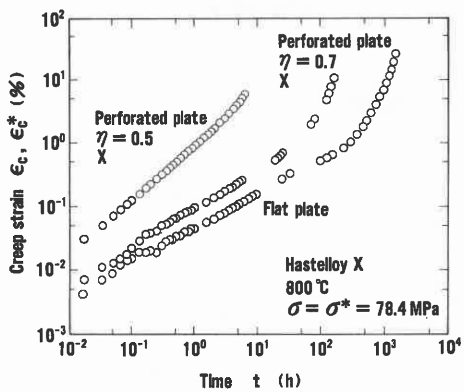

Fig. 3 An example of creep curves of flat and perforated plates

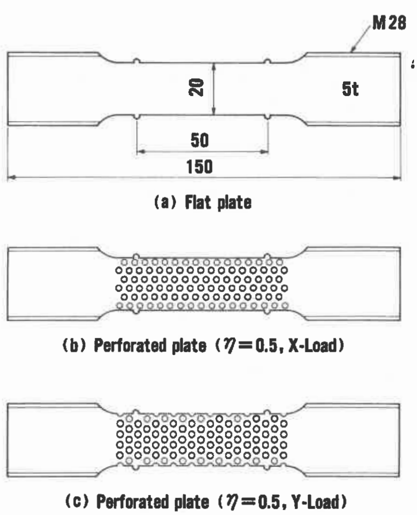

Fig. 2 Test specimens

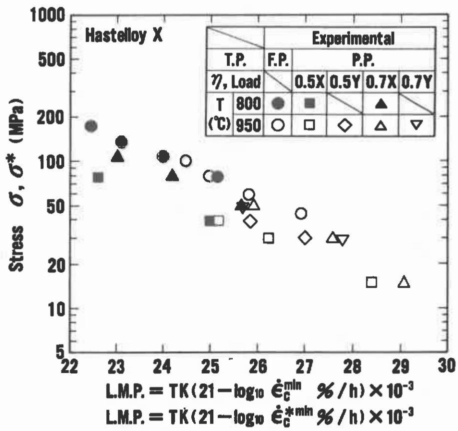

Fig. 4 Minimum creep rates of flat and perforated plates

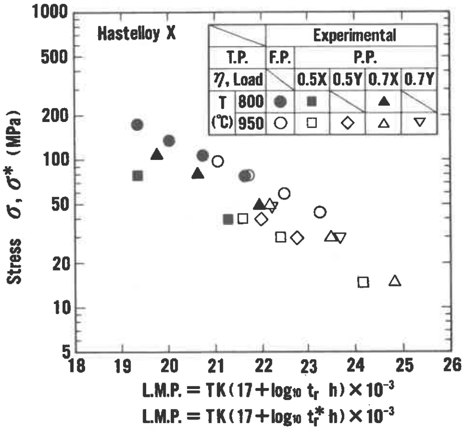

Fig. 5 Creep rupture data of flat and perforated plates

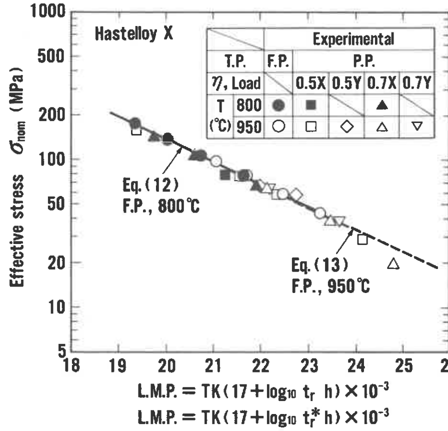

Fig. 8 Prediction of creep rupture data of perforated plates by effective stress σ_{nom}

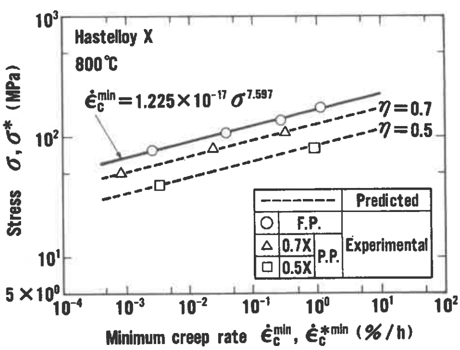

Fig. 6 Prediction of minimum creep rates of perforated plates (800℃)

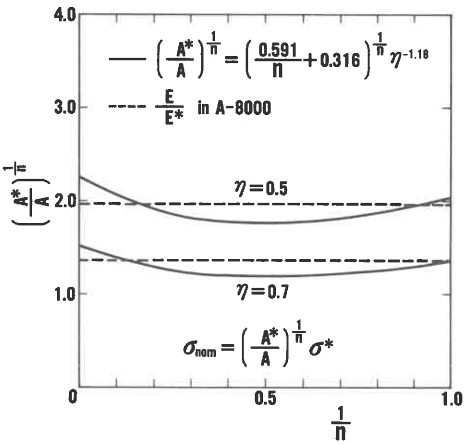

Fig. 9 Simplified prediction of effective stress σ_{nom}

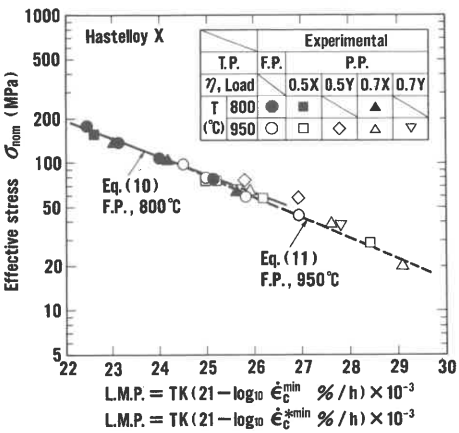

Fig. 7 Prediction of minimum creep rates of perforated plates by effective stress σ_{nom}

Table 1 Test condition

	Load	η	T (℃)	σ (for F.P.), σ^* (for P.P.) (MPa)
Flat plate (F.P.)			800	176.4, 137.2, 107.8, 78.4
			950	98.0, 78.4, 58.8, 44.1
Perforated plate (P.P.)	X	0.5	800	78.4, 39.2
			950	39.2, 29.4, 14.7
		0.7	800	107.8, 78.4, 49.0
			950	49.0, 29.4, 14.7
	Y	0.5	950	39.2, 29.4
		0.7	950	49.0, 29.4