

# Non-linear model of stress relaxation curve at high temperatures of Gr. 91 steel

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## ABSTRACT

Two non-linear models were proposed for modeling stress relaxation curves of high temperatures of Gr. 91 steel, which is used as structural materials of Gen-IV reactor systems. Stress relaxation data were obtained from a series of the SRTs conducted under a constant strain of 0.6% at 500, 550, 600, and 650°C. To model the stress relaxation curves well, a spring-dashpot model and Peleg's model were applied. The parameter values used in two models were determined through a nonlinear least square fit to experimental stress relaxation curves. The results showed that the spring-dashpot model was not in accordance with the experimental stress relaxation curves at 500 and 550°C, although it was agreement at 600 and 650°C. On the other hand, Peleg's model was in good accordance regardless of the temperatures, and the parameters followed temperature dependence well because its model was simple as four parameters. It is thus suggested that Peleg's can be used well to model the stress relaxation curves of Gr. 91 steel.

## 1. INTRODUCTION

Modified 9Cr-1Mo steel (ASME Grade 91, hereafter Gr. 91 steel) is regarded as a promising candidate for structural materials such as steam generators (SG), intermediate heat exchangers (IHX), and hot pipes in sodium-cooled fast reactors (SFR). The modified version is obtained by the addition of strong carbide/nitride forming elements such Nb and V and nitrogen in plain 9Cr-1Mo steel and is also known as 9Cr-1Mo-V-Nb steel designated as P91 or T91 by ASTM standards. The selection of Gr. 91 steel is mainly based on its high creep and low cycle fatigue resistance than those exhibited by its counterparts such as plain 9Cr-1Mo and 2.25-1Mo steels (Choudhary 2011, Mannon 2003, Raj 2010, Kim 2013, Srinivasan 2012). Presently, the KAERI (Korea Atomic Energy Research Institute) has established an R&D program to develop a Prototype Gen-IV SFR (PGSFR) by 2028, and key technologies for constructing its reactor are being developed step by step through a long-term R&D program (Kim 2011). The two main materials of the PGSFR consist of Gr. 91 and 316

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stainless steels. Its structural components will be designed for service of up to 60 years at elevated temperatures.

In order to design the components, the data for stress relaxation referring to a material response whereby stress under constraint is relaxed by creep strain are required. In a common experiment test, the total strain of a uniaxial test specimen is fixed and load (stress) is monitored as it is gradually reduced by conversion of elastic to inelastic strain at a constant temperature. The engineering applications of relaxation data cover a wide range of displacement or strain controlled loading such as bolted joint, thermal stresses giving rise to secondary loads or to a creep-fatigue cycle and welding residual stresses. In addition, stress relaxation offers a means of evaluating the deformation dynamics of materials. However, unlike creep rupture data which is used for design under primary stresses, most stress relaxation models are limited in applicability by either strain range, temperature or both. Therefore, it is necessary to investigate a suitable model for modelling relaxation data.

In the present investigation, the stress relaxation tests are conducted under a constant strain of 0.6% at 500, 550, 600, and 650°C for Gr. 91 steel. In order to well describe the stress relaxation curves experimentally obtained, two non-linear models of a spring-dashpot and Peleg's models are introduced among various models and applied to Gr. 91 steel. The parameter values used in two models are determined to give the best fit to experimental relaxation curves. A temperature dependence of the parameter values is investigated to find a suitable model describing well the stress relaxation behavior.

## **2. EXPERIMENTAL PROCEDURES**

A commercial grade hot-rolled Gr. 91 steel plate was used for the testing material. The heat treatment was normalized and tempered at 1050°C/1min/mm and 770°C/3min/mm. A stress relaxation test (SRT) is to perform by slowly applying a finite amount of initial strain,  $\varepsilon_0$  (total or global strain) to a specimen and then maintaining it constant. While the specimen is continued to be loaded to the initial constraint, the stress  $\sigma$  drops with time. In this study, the SRTs were carried out under a controlled constant tensile strain of 0.6% at the four temperatures of 500, 550, 600, and 650°C for Gr. 91 steel. The initial loading rate reaching up to 0.6% was applied with the strain rate of  $3.33 \times 10^{-4}$  (1/s). After reaching to the target strain level of 0.6%, the strain was a constantly maintained with a stop, and then the relaxation data with elapsed time were automatically obtained using PC. A three-zone furnace was used to provide the constant temperature environment. The jigs and pull rods attached to the specimen were used with Ni-based superalloy to prevent from the deformation during test period at the high temperature. The SRTs were performed according to the ASTM E328 procedures (ASTM 1986). The test specimens were prepared with a sufficient size recommended in the ASTM standard as a round type with 6.0 mm in diameter and 105 mm in gage length.

## **3. RESULTS AND DISCUSSION**

### *3.1 Proposition of non-linear stress relaxation models*

Here, two non-linear stress relaxation models of a spring-dashpot and Peleg's model are considered to model the stress relaxation behavior for Gr. 91 steel. The non-linear equations for the two models are described as follows.

First, the spring-dashpot model (Lubahn 1961)) was derived from a single paralleled spring-dashpot combination, as shown in Fig. 1 (a). Under a constant strain condition, the equation of the spring-dashpot model can be given by

$$S + S_a = eE + \left[ \frac{e_a}{a(1 - \exp(-t/\tau))} \right] \quad (1)$$

where,  $S$  is the elastic part of the stress and  $S_a$  is the anelastic part. This equation was derived by converting into stress from strain basically. In addition, Eq. (1) can be modified into multi terms to determine the correct parameter values in a non-linear least square fit (NLSF). The modified equation can be given by

$$S + S_a = eE + \left[ \frac{e_a}{a(1 - \exp(-t/\tau))} + \frac{e_a}{a(1 - \exp(-t/\tau))} \right] \quad (2)$$

$$y = p_1 + \left[ \frac{p_2}{p_3(1 - \exp(-t/\tau))} + \frac{p_5}{p_6(1 - \exp(-t/\tau))} \right] \quad (3)$$

Eq. (2) means that metal behaves in the same way as a spring in series with two parallel spring-dashpot combination, as shown in Fig. 1 (b). The stress relaxation values of y-axis can be obtained with the time variations of x-axis by determining the values for seven parameters:  $P_1, P_2, P_3, P_4, P_5, P_6,$  and  $P_7$ , as given in Eq. (3).

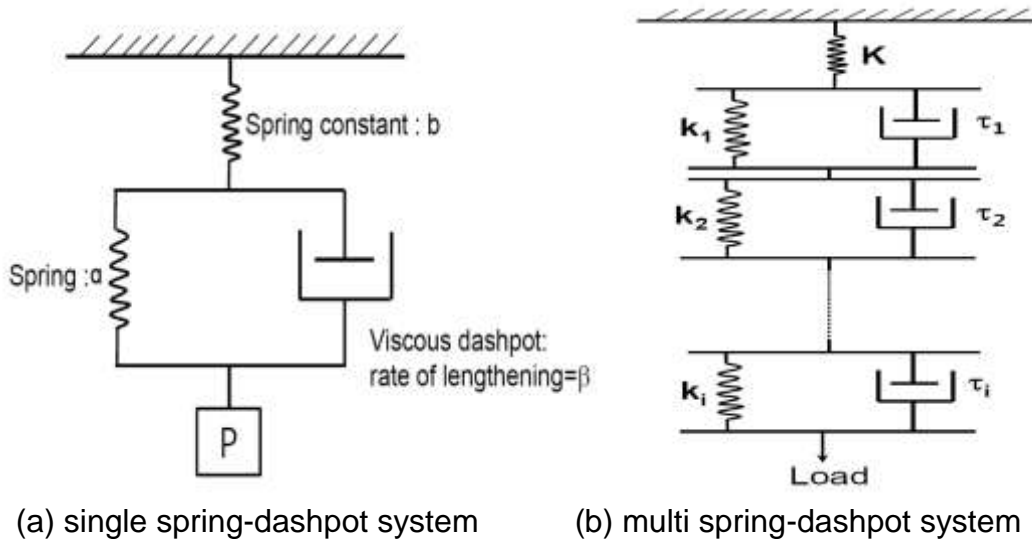


Fig. 1 Schematic drawing of simplified spring-dashpot analogue to anelastic strain

Second, the Peleg's model was proposed by Peleg (1976). This model was known as a rheological model of non-linear stress relaxation. The equation is given by

$$S(t) = S_{max} \left( 1 - \frac{t^n}{k_1 + k_2 t^n} \right), \quad (4)$$

where,  $S_{max}$  is the maximum stress,  $t$  is the time, and  $k_1$ ,  $k_2$ ,  $n$  are the rheological parameters. This model has been known to well describe viscoelastic properties of materials (Myhan 2015)). In the present investigation, the parameter values for the two models were determined using the NLSF method on the results of the SRTs obtained under a constant strain of 0.6% at 500, 550, 600, and 650°C for Gr. 91 steel. Each model was compared and evaluated to investigate a better model for Gr. 91 steel.

### 3.2 Application of two models

Fig. 2 shows the stress relaxation curves obtained under a constant strain of 0.6% at 500, 550, 600, and 650°C for Gr. 91 steel. The four relaxation curves present the temperature dependence well. The stress drops abruptly at initial stage, and then the stress decrease slightly. The recovery amount of elastic stress is very large for of Gr. 91 steel. The recovery of anelastic stress occurs largely from an initial stage, and then the stress relaxation by creep recovery is smooth with time variations. As the temperature increases, the recovery rate is fast: a low temperature of 550°C is slower in the recovery rate than a high temperature of 650°C. Based on the results of the stress relaxation curves, Optimum values of each parameter for two models considered in the present study are determined using the NLSF method to give the best fit to experimental data.

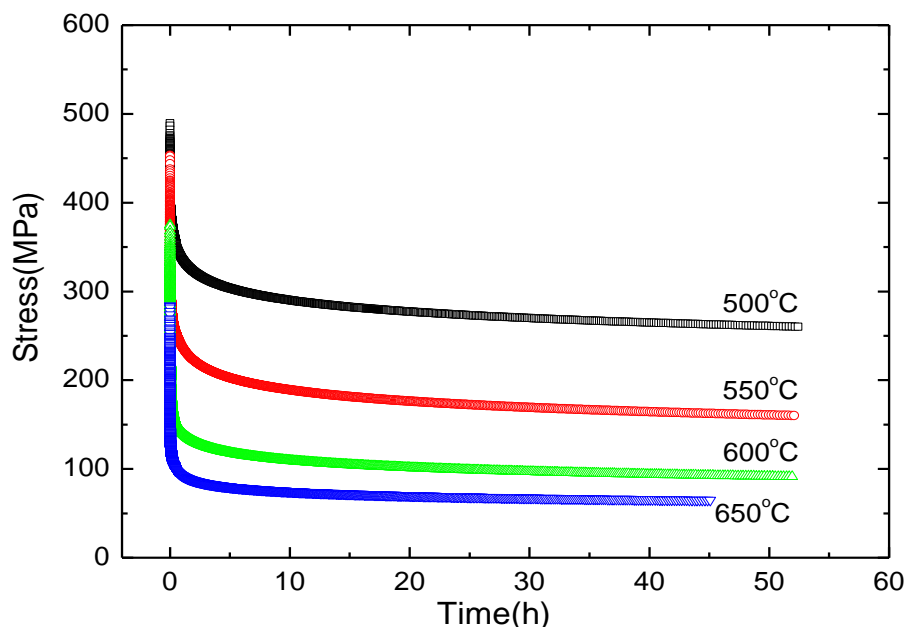


Fig. 2 Stress relaxation curves obtained at each temperature

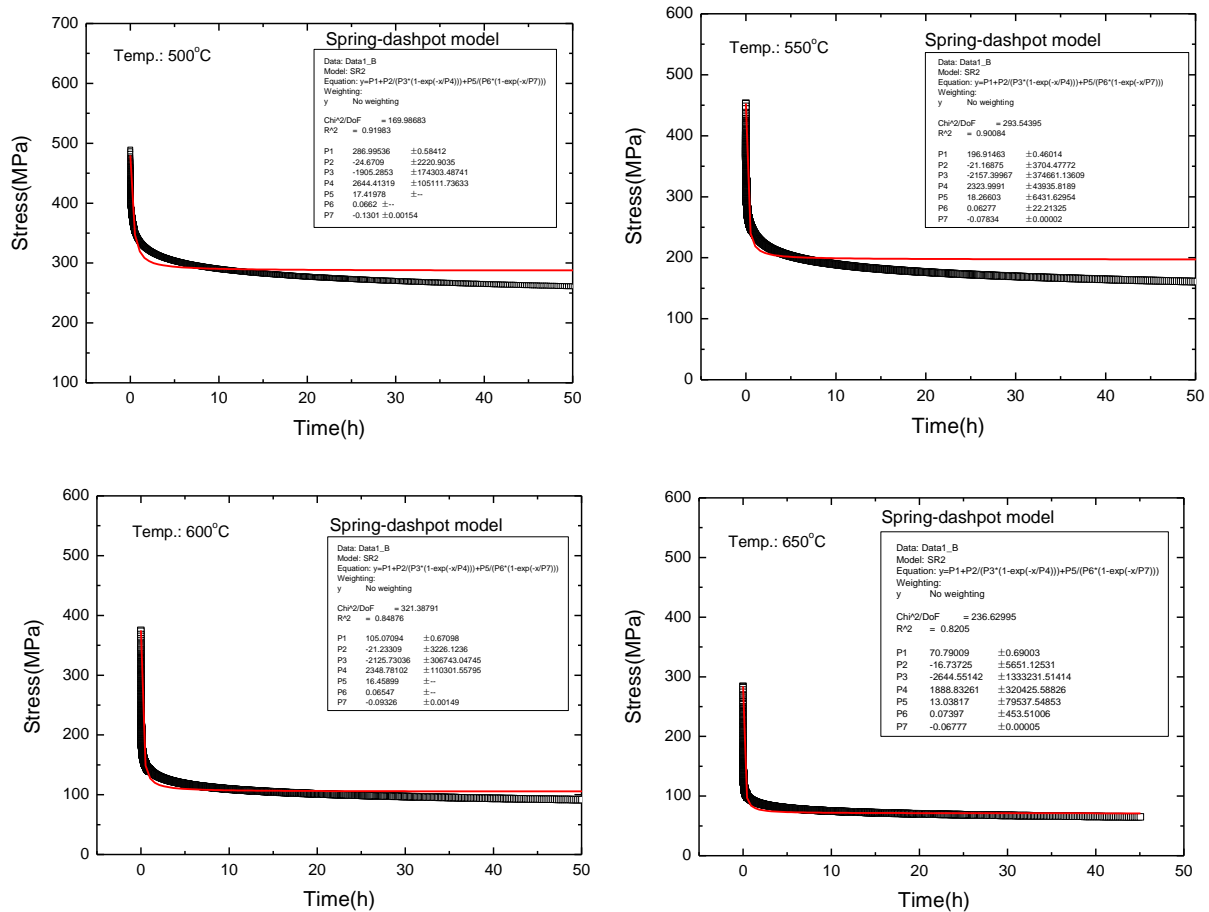


Fig.3 NLSF results of the spring-dashpot model to experimental data at 500, 550, 600 and 650°C of Gr. 91 steel

Figs. 3 and 4 show the NLSF results of the spring-dashpot model and Peleg's model to experimental data at 500, 550, 600 and 650°C of Gr. 91 steel. For the spring-dashpot model, although the NLSF results shows good agreement with the experimental data at 600 and 650°C, but the results do not match with the experimental at 600 and 650°C. It was also investigated that seven parameters did not obey the temperature dependence well. On the other hand, for the Peleg's model, the NLSF results reveal good match with the experimental data for all the temperature regardless of four temperatures, as shown in Fig. 4. Thus, it is found that the Peleg's model was superior in modeling of the stress relaxation curves of Gr. 91 steel to the spring-dashpot model. From the results, the optimum values for each parameter in the Peleg's model were drawn through many iteration processes to give the best regression to the experimental data. The summary of the parameter values of  $S_{max}$ ,  $k_1$ ,  $k_2$ , and  $n$  is given in Table 1. As listed in Table 1, the  $R^2$  value (coefficient of determination, COD) is closer to unity. It means that the Peleg's model can describe well the stress relaxation curves of Gr. 91 steel. Using the results of Table 1, the temperature dependence for

four parameters was investigated as shown in Fig. 5. The parameter  $S_{max}$  follows the 2<sup>nd</sup> polynomial, and the parameters of  $k_1$ ,  $k_2$ , and  $n$  follows a linear relation well when given by semi-log coordinate. Therefore, it is suggested that this result was reasonable because the parameters of the Peleg's model follows the temperature dependence well. Each equation on temperature dependence of four parameters was obtained as follows,

$$S_{max} = - 603.4622 + 4.93966 T - 0.0055 T^2 \quad (5)$$

$$\text{Log}(k_1) = 3.60155 - 0.00686 T \quad (6)$$

$$\text{Log}(k_2) = 0.54185 - 6.79297E-4 T \quad (7)$$

$$\text{Log}(n) = -1.03594 + 0.00104 T \quad (8)$$

Using the four equations obtained on the temperature dependence, it can be estimated for the stress relaxation curves at different temperature ranges for Gr. 91 steel.

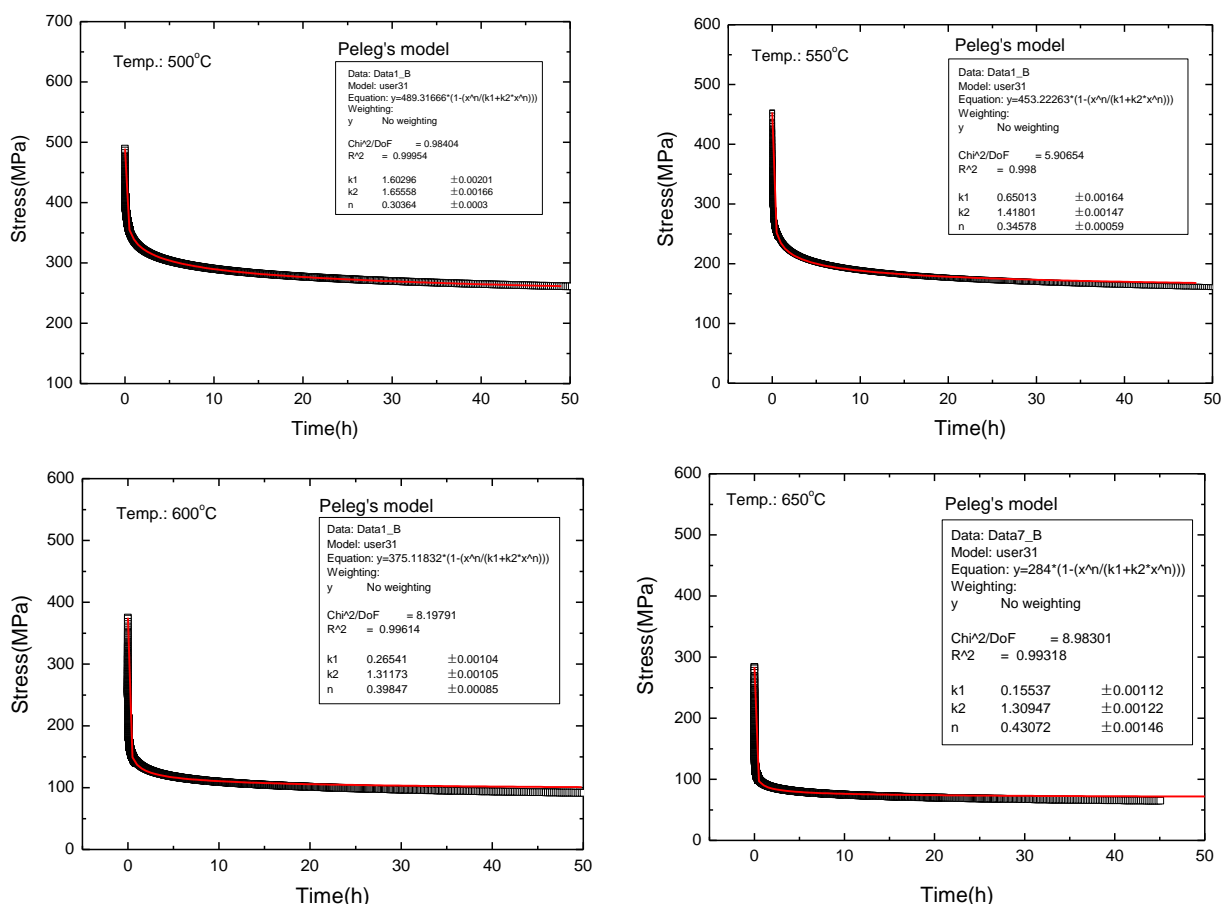
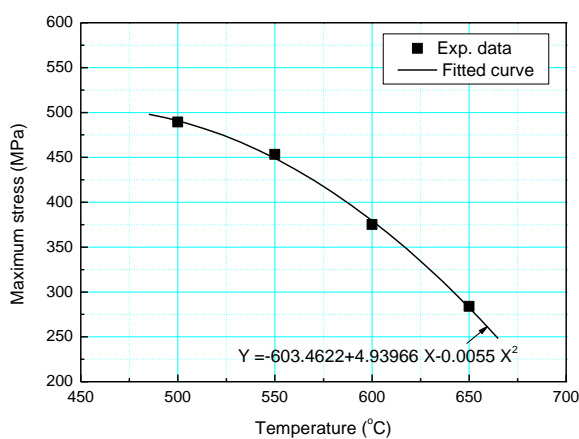


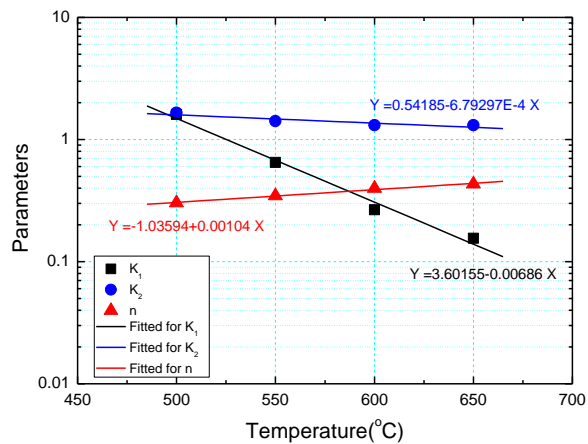
Fig. 4 NLSF results of the Peleg's model to experimental data at 500, 550, 600 and 650°C of Gr. 91 steel

Table 1 Summary of each parameter of Peleg's model

Temp. (°C)	$S_{max}$	$K_1$	$K_2$	$n$	$R_2$
500	489.316	1.602	1.655	0.303	0.999
550	453.222	0.650	1.418	0.345	0.998
600	375.118	0.265	1.311	0.398	0.996
650	284.000	0.155	1.309	0.431	0.993



(a)  $S_{max}$



(b)  $k_1$ ,  $k_2$ , and  $n$

Fig. 5 Temperature dependence of  $S_{max}$ ,  $k_1$ ,  $k_2$ , and  $n$  in the Peleg's model

#### 4. CONCLUSIONS

Stress relaxation data were obtained from a series of the SRTs conducted under a constant strain of 0.6% at 500, 550, 600, and 650°C. Using the experimental data, to model the stress relaxation curves well, a spring-dashpot model and Peleg's model were applied. The parameter values in two models were reasonably determined through a nonlinear least square fit to experimental stress relaxation curves. The results showed that the spring-dashpot model was not in accordance with the experimental data at 500 and 550°C, although it was agreement at 600 and 650°C. On the other hand, the Peleg's model was in good accordance with the experimental data regardless of the temperatures, and the parameters followed temperature dependence well because its model was simple as four parameters. It is thus suggested that Peleg's can be used well to model the stress relaxation curves of Gr. 91 steel.

#### ACKNOWLEDGEMENTS

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