A Proposed Model for Predicting Clamp Load Loss Due to Gasket Creep Relaxation in Bolted Joints

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An improved mathematical model is proposed for predicting clamp load loss due gasket creep relaxation in bolted joints, taking into consideration gasket behavior, bolt stiffness, and joint stiffness. The gasket creep relaxation behavior is represented by a number of parameters which has been obtained experimentally in a previous work. An experimental procedure is developed to verify the proposed model using a single-bolt joint. The bolt is tightened to a target preload and the clamp load loss due to gasket creep relaxation is observed over time under various preload levels. The experimental and analytical results are presented and discussed. The proposed model provides a prediction of the residual clamp load as a function of time, gasket material and thickness, bolt stiffness, and joint stiffness. The improved model can be used to simulate the behavior of creep relaxation in soft joints as the joint stiffness effect is considered. Additionally, a closed form solution is formulated to determine the initial clamp load level necessary to provide the desired level of a steady state residual clamp load in the joint, by taking the gasket creep relaxation into account. [DOI: 10.1115/1.4005387]

Keywords: *gasket creep relaxation, clamp load loss, gasketed bolted joints*

Introduction

Gaskets are often used to create and maintain a seal between two separable flanges to prevent joint leakage. Several design and analysis challenges are associated with gasketed joints. Among these challenges is the reaction of the gasket material to the sealed medium, the pressure that the gasket can withstand in the radial direction, the environmental effect on the gasket material such as temperature and humidity, and more importantly the change in the gasket thickness and stress over time, which is usually referred to as gasket creep relaxation [1].

Although the effect of gasket creep relaxation on the clamp load loss in bolted joints has been recognized in the literature, the subject remains a vital research area. Only a few papers address analytically the effect of gasket creep relaxation. Creep analysis of bolted connections is presented in Refs. [2–4], where steady creep was assumed for the joint but the gasket creep was ignored. However, recent studies [5,6] show that the gasket creep relaxation is more important than the bolt/joint material relaxation and cannot be ignored. Kraus [7,8] proposed a model to predict the time required for the bolts to relax from an initial stress level to a steady state level. However, the effect of the gasket and other joint structures was not considered. Most the previously mentioned work focused on the bolt/joint material relaxation and ignored the effect of gasket creep relaxation. Bazergui [9], Bouzid and Chaaban [10] considered the effect of gasket creep relaxation. Bazergui [9] showed based on experimental data that, for most types of gaskets, a linear relationship between displacement, due to creep, and the time could be constructed on a semilogarithmic plot. Bouzid and Chaaban [10] also adopted the same procedure to evaluate the relaxation in bolted flanged connections. The authors, in a previous work [11], developed a model for predicting gasket creep relaxation in which the clamped material was assumed to be infinitely stiff. This paper provides more accurate prediction of the residual clamp load by taking into account the joint stiffness. The model proposed in this paper predicts the residual clamp load as a function of time, gasket material, and geometric properties of the gasket, as well as the joint stiffness.

Mathematical Modeling of the Gasket

In a previous work [11], the authors adopted Maxwell model to investigate the behavior of gaskets when subjected to an external pressure. The authors considered the gasket material as viscoelastic as shown in Fig. 1. The gasket model consists of three mechanical elements in series. The first element is an elastic spring with stiffness K_1. When the gasket is compressed the spring K_1 compresses by the amountΔ_1. This element represents a pure elastic part of gasket behavior that is fully recoverable upon load removal.

The second element is pure viscous dashpot with damping rate C_1. When the gasket is compressed the viscous element with the damping coefficient C_1 will compress by Δ_2, however when the load is removed, this compression is not recovered. The clamp load lost because of this element is time-dependent and unrecoverable. This element of the model accounts for the long term asket creep relaxation.

The third element is a viscoelastic element, which consists of an elastic spring K_2 and a dashpot C_2 connected in parallel. When the gasket is loaded, this element compresses by Δ_3. This compression will be recovered after a period of time after removing the load; therefore, the compression of this element is time-dependent and fully recoverable after the load is removed. This element accounts for the short term gasket creep and relaxation behavior.

This model shows that the equivalent overall gasket stiffness K_g becomes function of time once the compressive force is applied, which results in the creep (increase in the gasket compression $\Delta(t)$. with time when the load is held constant) and

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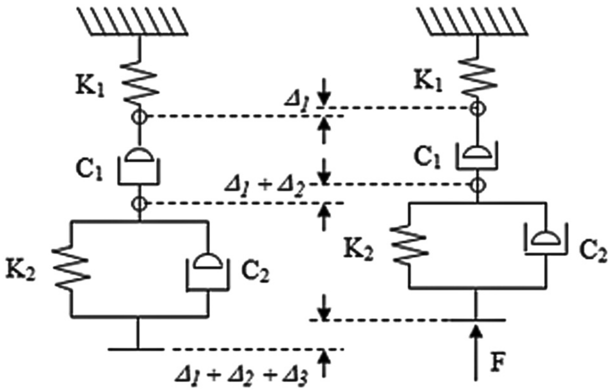

Fig. 1 Mechanical model of a typical gasket [1,11]

relaxation (decrease in gasket stress with time when the displacement is held constant). The equivalent gasket stiffness at any time t after compressing the gasket has been given by Alkelani et al. [11] as a function of the gasket constants presented in this model as follows:

$$K_g(t) = \frac{1}{\left[\frac{K_1+K_2}{K_1K_2} + \frac{t}{C_1} - \frac{1}{K_2}e^{-\frac{K_2}{C_2}t}\right]} \tag{1}$$

where the four constants K_1, K_2, C_1, and C_2 for specific gasket can be determined experimentally.

Mathematical Modeling of Gasket Creep Relaxation

Clamp load starts to decrease in a gasketed bolted joint right after tightening the bolts due to the combined effect of gasket creep and bolt relaxation. Gasket creep causes the gasket to become thinner; therefore, the bolt looses some of its elongation, which translates into a loss in the joint clamping force. Most of the standard gasket tests are conducted under constant force (pure creep) or constant deflection (pure relaxation). For accurate prediction of the clamp load loss in gasketed joints, however, the uncoupled relaxation and creep tests do not yield a reliable prediction [12]. Hence, a new gasketed joint model is introduced in this paper for predicting the clamp load loss due to gasket creep relaxation in a single-bolt joint. The model is shown in Fig. 2. The gasketed joint system is modeled as a set of springs and dashpots. The bolt is presented by a spring in parallel with the gasket and the flanges. Figure 2(*a*) shows the pretightening position for the different joint members. Figure 2(*b*) shows the gasket compression and the bolt elongation after the bolt is tightened. As time elapses, gasket creep relaxation takes place causing further gasket compression as illustrated by Fig. 2(*c*). This additional gasket compression is not completely recoverable even after the load is completely removed; permanent gasket deformation presents as shown in Fig. 2(*d*).

The clamping force applied to the three gasket elements shown in Fig. 1 at any time t is given as follows:

$$F(t) = K_1\Delta_1(t) = C_1\dot{\Delta}_2(t) = K_2\Delta_3(t) + C_2\dot{\Delta}_3(t) \tag{2}$$

The gasket compression $\Delta(t)$. at any time t is the sum of compression of the three gasket mechanical elements and it is given by

$$\Delta_1(t) + \Delta_2(t) + \Delta_3(t) = \Delta(t) \tag{3}$$

By differentiation of Eq. (3)

$$\dot{\Delta}_1(t) + \dot{\Delta}_2(t) + \dot{\Delta}_3(t) = \dot{\Delta}(t) \tag{4}$$

From Eq. (2), $\dot{\Delta}_1(t)$ and $\dot{\Delta}_2$ can be given as

$$\dot{\Delta}_1(t) = \frac{K_2}{K_1}\dot{\Delta}_3(t) + \frac{C_2}{K_1}\ddot{\Delta}_3(t) \tag{5}$$

$$\dot{\Delta}_2 = \frac{K_2}{C_1}\Delta_3 + \frac{C_2}{C_1}\dot{\Delta}_3 \tag{6}$$

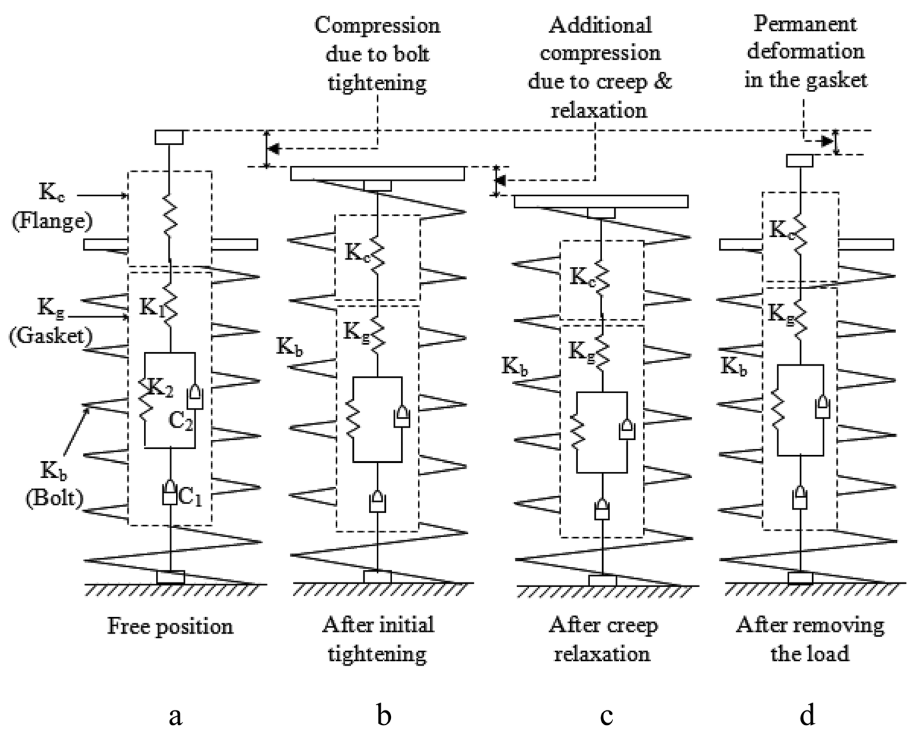

Fig. 2 Mechanical model of single-bolt gasketed joint [11]

By substitution Eqs. (5) and (6) into Eq. (4)

$$\frac{C_2}{K_1}\ddot{\Delta}_3+\left(1+\frac{K_2}{K_1}+\frac{C_2}{C_1}\right)\dot{\Delta}_3+\frac{K_2}{C_1}\Delta_3=\dot{\Delta} \tag{7}$$

The clamping force $F(t)$ experienced by the three joint components (gasket, bolt, and clamped material) is always equal. This yields

$$F(t)=K_g(t)\Delta(t)=K_b\delta_b(t)=K_c\delta_c(t) \tag{8}$$

where K_b is the bolt stiffness, K_c is the joint stiffness, $\delta_b(t)$ is the bolt elongation, and $\delta_c(t)$ is the joint compression.

Figure 2 shows that, after the bolt is tightened, the change in the bolt elongation is equal to the summation of the changes in the joint and gasket thicknesses as follows:

$$d\delta_b(t)=d(\Delta(t)+\delta_c(t)) \tag{9}$$

Substituting Eq. (9) into Eq. (8) yields

$$\begin{aligned}F(t)&=K_b(\delta_b(0)-d\delta_b(t))\\&=K_b(\delta_b(0)-\Delta(0)-\delta_c(0)+\Delta(t)+\delta_c(t))\end{aligned} \tag{10}$$

Substituting for the bolt elongation and gasket compression, and by manipulation Eq. (10) can be written as

$$\left(1-\frac{K_b}{K_c}\right)F(t)=K_b\left(\frac{F(0)}{K_b}-\frac{F(0)}{K_g(0)}-\frac{F(0)}{K_c}+\Delta(t)\right) \tag{11}$$

By Substituting $F(t)$ from Eq. (1) and differentiation, Eq. (11) maybe rearranged as follows:

$$\left(\frac{1}{K_b}-\frac{1}{K_c}\right)\left(K_2\dot{\Delta}_3(t)+C_2\ddot{\Delta}_3(t)\right)=\dot{\Delta}_1(t)+\dot{\Delta}_2(t)+\dot{\Delta}_3(t) \tag{12}$$

Using Eqs. (5) and (6) to substitute for $\dot{\Delta}_1$ and $\dot{\Delta}_2$ in Eq. (12) yields

$$\ddot{\Delta}_3(t)+\left(\frac{\frac{K_2}{K_b}-\frac{K_2}{K_1}-\frac{C_2}{C_1}-\frac{K_2}{K_c}-1}{\frac{K_1C_2(K_c-K_b)-K_bK_cC_2}{K_bK_cK_1}}\right)\dot{\Delta}_3(t)-\left(\frac{K_bK_cK_1K_2}{K_1C_1C_2(K_c-K_b)-K_bK_cC_1C_2}\right)\Delta_3(t)=0 \tag{13}$$

Equation (13) is a second order ordinary differential equation in the form $\ddot{\Delta}_3+B\dot{\Delta}_3+G\Delta_3=0$

where $B=\left(\dfrac{\frac{K_2}{K_b}-\frac{K_2}{K_1}-\frac{C_2}{C_1}-\frac{K_2}{K_c}-1}{\frac{K_1C_2(K_c-K_b)-K_bK_cC_2}{K_bK_cK_1}}\right)$,

$G=-\left(\dfrac{K_bK_cK_1K_2}{K_1C_1C_2(K_c-K_b)-K_bK_cC_1C_2}\right)$

The solution for this second order differential equation is in the form

$$\Delta_3=A_1e^{\lambda_1t}+A_2e^{\lambda_2t} \tag{14}$$

where: The roots λ_1 and λ_2 are given by

$$\lambda_{1,2}=\frac{-B\pm q}{2},\quad q=\sqrt{B^2-4G},$$

A_1 and A_2 are constants that are determined from the initial conditions as follows

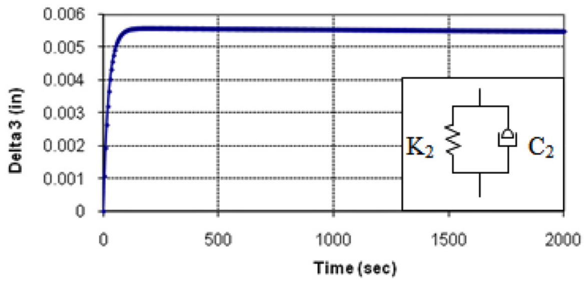

Fig. 3 Behavior of the gasket viscoelastic element K_2,C_2

$$\left.\begin{aligned}&\Delta_1(0)=\Delta(0),\ \dot{\Delta}_1(0)=\dot{\Delta}(0)-K_1\Delta(0)\left(\frac{1}{C_1}+\frac{1}{C_2}\right)\\&\Delta_2(0)=0,\ \dot{\Delta}_2(0)=\frac{F(0)}{C_1}=\frac{K_1\Delta(0)}{C_1}\\&\Delta_3(0)=0,\ \dot{\Delta}_3(0)=0+\frac{F(0)}{C_2}=\frac{K_1\Delta(0)}{C_2}\end{aligned}\right\} \tag{15}$$

The solution for Δ_3 in Eq. (14) becomes

$$\Delta_3=\frac{F(0)}{C_2(\lambda_1-\lambda_2)}\left(e^{\lambda_1t}-e^{\lambda_2t}\right) \tag{16}$$

Substituting Eq. (16) in Eqs. (5) and (6) yields Δ_1 and Δ_2 as follows:

$$\Delta_1=\frac{K_2}{K_1}\frac{F(0)}{C_2(\lambda_1-\lambda_2)}\left(e^{\lambda_1t}-e^{\lambda_2t}\right)+\frac{F(0)}{K_1(\lambda_1-\lambda_2)}\left(\lambda_1e^{\lambda_1t}-\lambda_2e^{\lambda_2t}\right) \tag{17}$$

$$\begin{aligned}\Delta_2=&\frac{K_2}{C_1}\frac{F(0)}{C_2(\lambda_1-\lambda_2)}\left(\frac{1}{\lambda_1}e^{\lambda_1t}-\frac{1}{\lambda_2}e^{\lambda_2t}\right)\\&+\frac{F(0)}{C_1(\lambda_1-\lambda_2)}\left(e^{\lambda_1t}-e^{\lambda_2t}\right)-\frac{K_2}{C_1}\frac{F(0)}{C_2(\lambda_1-\lambda_2)}\left(\frac{1}{\lambda 1}-\frac{1}{\lambda 2}\right)\end{aligned} \tag{18}$$

Finally, the residual gasket compression $\Delta(t)$ at any time t may be determined by substituting for Δ_1, Δ_2, and Δ_3 from Eqs. (16)–(18) into Eq. (3). The corresponding residual clamp load at any time t (from initial tightening) is obtained by using Eqs. (2) and (16), which yields $F(t)$ in terms of the initial preload $F(0)$ as follows:

$$F(t)=\left(\frac{K_2}{C_2(\lambda_1-\lambda_2)}\left(e^{\lambda_1t}-e^{\lambda_2t}\right)+\frac{1}{(\lambda_1-\lambda_2)}\left(\lambda_1e^{\lambda_1t}-\lambda_2e^{\lambda_2t}\right)\right)F(0) \tag{19}$$

Equation (19) provides a closed form solution for the residual clamping force $F(t)$ in a single-bolt gasketed joint at anytime t. This equation can also be used to determine the initial clamp force

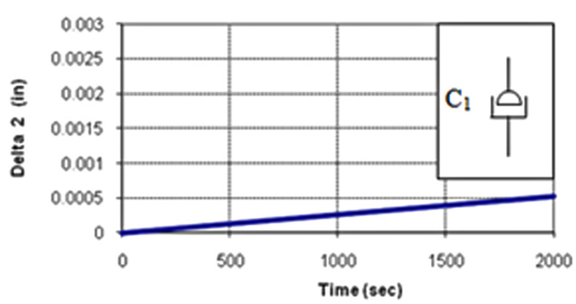

Fig. 4 Behavior of the gasket viscous element C_1

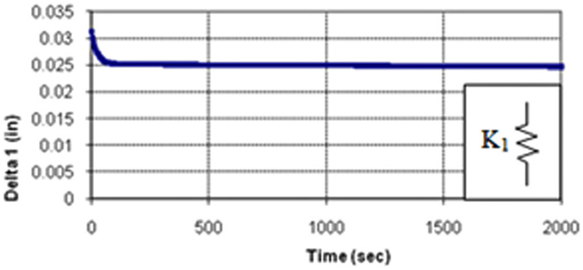

Fig. 5 Behavior of the gasket elastic element K_1

$F(0)$ required to achieve any desired level of residual clamp load $F(t)$ after gasket creep relaxation takes place as $t \to \infty$.

Gasket Behavior Analysis

In this section, the behavior of the three main elements in the gasket model is discussed; namely, the elastic element represented by the spring K_1, the viscoelastic element represented by the parallel combination of K_2 and C_2, and the viscous element represented by C_1.

Figure 3 shows the behavior of the viscoelastic element represented by the spring and dashpot elements (K_2 and C_2). As soon as the external load is applied, the displacement Δ_3 starts to increase, mainly due to the dashpot in this element. As time passes by, the displacement increases and the resistance from the spring increases as well, until a steady state is reached. This element accounts for the short term creep relaxation.

Figure 4 shows the behavior of the viscous element represented by the dashpot C_1 which accounts for the long term relaxation. The displacement from this element Δ_2 increases with time causing gradual relaxation in the long term. The magnitude of relaxation in the long term is highly dependent on the gasket material.

Figure 5 shows the behavior of the elastic element represented by the spring K_1. The displacement Δ_1 in this element is highly dependent on the amount of relaxation caused by the other two gasket elements in the model, namely the viscoelastic element and viscous element. As can be seen in Fig. 5 the displacement in this element stabilizes with time.

The summation of the three displacements from the three elements represents the behavior of the actual gasket compression with time $\Delta(t)$, as shown in Fig. 6. It can be noticed that for the studied gasket material, short term gasket creep relaxation is dominant where most of the creep relaxation takes place during the first 3 min after the tightening. Long term creep relaxation continues but at a much slower rate.

Experimental Verification of the Creep Relaxation Model

Figure 7 shows the test setup used for the experimental verification of the proposed gasket creep relaxation model in a single-bolt

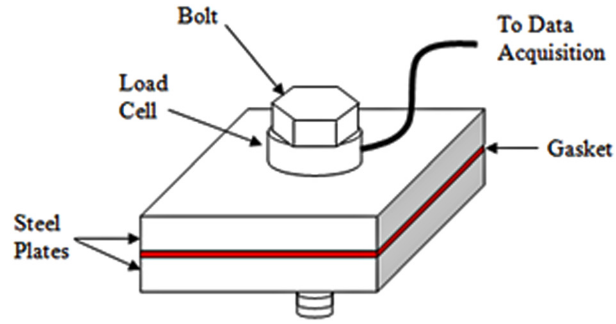

Fig. 7 A single-bolt gasketed joint test setup [11]

gasketed joint. The gasket material selected for this study is styrene butadiene rubber. It is a low cost gasket material that offers moderate to good performance for low pressure applications. It conforms easily to uneven flange faces. Three different gasket thicknesses are used, namely, 1/16 in., 1/8 in., and 3/16 in. A single tightening pass is used to tightening the joint to different load levels within the gasket limits. The bolt is tightened using an electric tool at 127 rpm to minimize the amount of gasket creep relaxation that takes place during the tightening process itself. A load cell is inserted between the bolt and the upper plate to monitor the clamping force during the test. After tightening, the joint is left for 40 min, during which the clamp load is recorded using a data acquisition system.

The gasket constants for different gasket thicknesses of styrene butadiene rubber have been obtained experimentally in a previous work [11]. It was found that the gasket constants are dependent on the thickness of the gasket used in the test, however, for the same gasket thickness the constants were found independent of the stress level applied on the gasket within its loading limits. Figures 8–10 show the analytical results from the proposed creep relaxation model (Eq. (19)) in comparison with the experimental data, for a single-bolt gasketed joint. Both short term and long term clamp load losses can be noticed on both experimental and analytical curves. The results show good correlation between the experimental data and the analytical model for all stress levels and gasket thicknesses considered in this study. The slight difference of $\pm 5\%$ between the model results and the experimental data could be due to normal variation in the gasket mechanical properties and/or experimental error. Hence, the proposed mathematical model can be used to predict the gasket creep relaxation behavior in a single-bolt gasketed joint, provided that the gasket constants have been experimentally determined and used in the model. The new creep relaxation model may also be used to estimate the

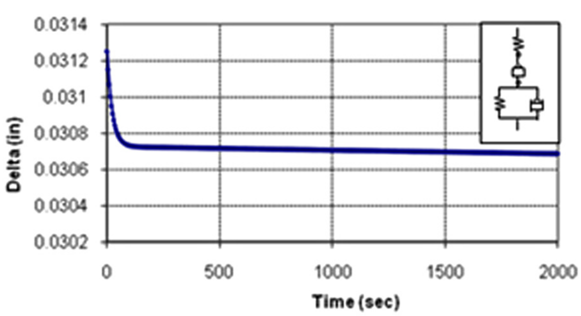

Fig. 6 Behavior of the gasket—compression with time

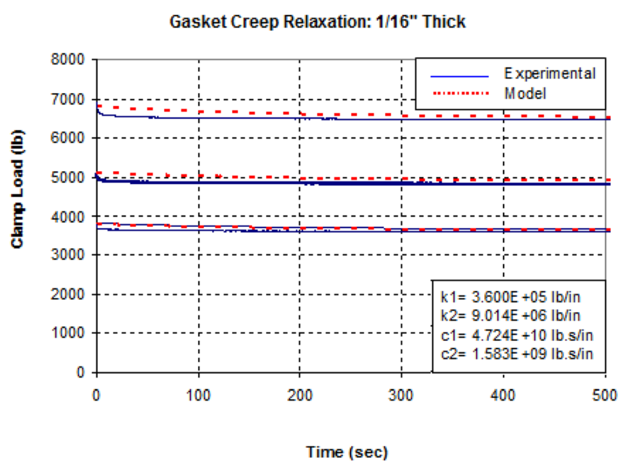

Fig. 8 Experimental and analytical clamp load results for 1/16 in. thick gasket

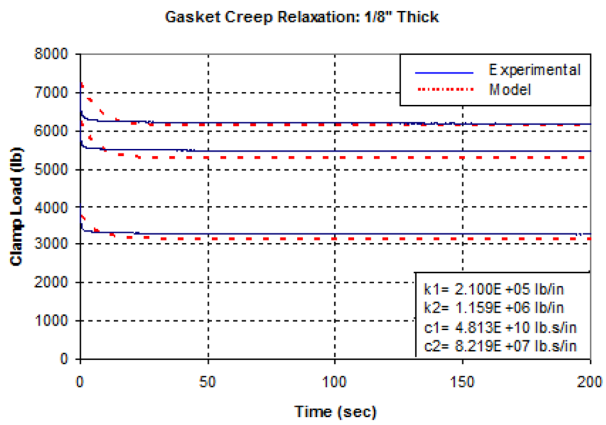

Fig. 9 Experimental and analytical clamp load results for 1/8 in. thick gasket

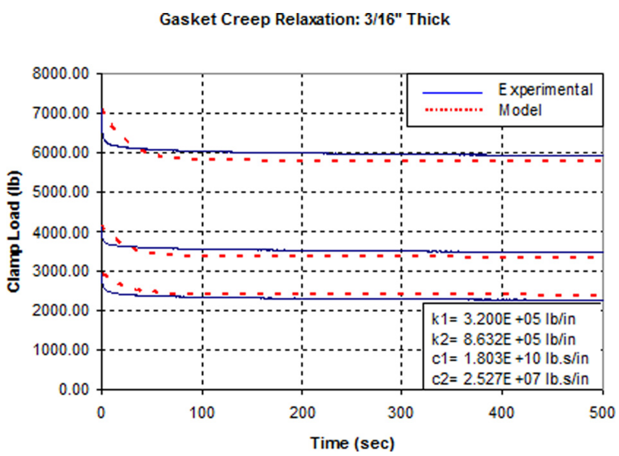

Fig. 10 Experimental and analytical clamp load results for 3/16 in. thick gasket

initial clamp load $F(0)$ needed to produce a desired level of a steady state residual clamp load F, by taking the gasket creep relaxation into consideration (Eq. (19)).

Although the model presented in a previous work [11] provides good correlation with the experimental results, the model works only for hard joints as the effect of joint stiffness was neglected. The model proposed in this work will provide more accurate results for both soft and hard joints as it takes the joint stiffness into account.

Red rubber gasket is used for the experimental verification of the model. It should be pointed out here that the model is not exclusive for red rubber and a different gasket type or material could be used. When using the model for a different gasket material, the constants for that gasket have to be experimentally obtained from a creep test as explained previously and then used as input for the model.

Conclusions

An improved mathematical model is presented to predict the gasket behavior at room temperature after the bolt is tightened in a single-bolt gasketed joint. The model takes into consideration the gasket material and geometry, bolt stiffness, as well as joint stiffness which were assumed infinite in a previous work [11]. The improved model can be used to simulate the behavior of creep relaxation in soft joints.

The residual clamping force is significantly affected by the gasket creep relaxation behavior of the joint. A closed form solution is formulated for the clamp load as a function of the time elapsed after the initial tightening of the joint. The clamp load formulation can also be used to determine the initial clamp load level that is necessary to provide the desired level of a steady state residual clamp load in the joint, by taking the gasket creep relaxation into account. The good agreement between the mathematical model results and the experimental data (within $\pm 5\%$) suggests that the proposed model can be used to accurately describe the gasket behavior and the clamp load loss due to gasket creep relaxation.

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