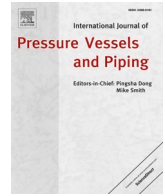




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Enhancing non-metallic gasket performance with shape memory fibers

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ABSTRACT

This study aims to enhance the sealing performance of non-metallic gaskets by incorporating shape memory fibers. The analytical exploration focuses on analyzing the thermomechanical behavior of Nitinol fibers in their woven state within the gasket. Specifically, the investigation examines the variation of phase transformation zones across the wire cross-section with changes in temperature. Subsequently, a series of SMA fiber-reinforced gasket samples were fabricated, and experimental investigations were conducted to assess the impact of Nitinol fibers on composite gaskets using a helium gas leak test. The results demonstrate that the integration of shape memory alloy wires into the composition of gaskets can significantly improve their sealing performance. Moreover, this study examines a number of pivotal factors such as fiber volume fraction, temperature application, woven fiber arrangement, leakage rates, gasket deformation, contact stress, and structural bending. These comprehensive investigations may provide valuable insights into the efficacy of Nitinol fibers in enhancing gasket sealing performance.

Nomenclature

A_g	Contact area of gasket
A_s	Austenitic start temperature at zero stress
A_f	Austenitic finish temperature at zero stress
A_c	Contact area between woven wires and active gasket layer
$a_{1,2,3}$	Hartl model parameters
c	Specific heat capacity
d_i	ID of contact surface of gasket
d_o	OD of contact surface of gasket
d_2	Basic pitch diameter of the thread
D_e	Effective bearing diameter of the nut face
d_{on}	Outer bearing diameter of the nut face
d_{in}	Inner bearing diameter of the nut face
E^M, E^A	Young's modulus in the martensitic state and austenitic state, respectively
F_{bolt}	Axial force in the bolts
f^t	Hardening function
f_0	Profile functions of the cross-section of the beam
G	Specific Gibbs free energy
H^{cur}	Maximum transformation strain at current stress
H^{cur-r}	Maximum current transformation strain at the reversal of forward transformation
h	Half of the height of the beam cross-section
k	Instantaneous curvature of the bent beam
K	Dimensionless curvature of the beam
K_m	Dimensionless amplitude of the curvature pulse

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K^E	($= 1 + K^{AM}, K^M = 1 + K^{MA}$)
K^{AM}, K^{MA}	Critical dimensionless curvature at initiation of austenitic and martensitic state
L	Measured leak rate of gasket
M_f	Martensitic finish temperature at zero stress
M_s	Martensitic start temperature at zero stress
m	Temperature sensitivity of the superelasticity limit at simple tension
M	Bending moment
M_d	Dimensionless bending moment
$n_{1,2,3,4}$	Hartl model parameters
P	Test pressure
p	Pitch of the thread (1/number of thread per inch.)
R, R_i	Radius of curvature
R_H	Radius of curvature at the end of martensitic phase to austenitic state during unloading
r_c	Radius of the wire cross-section
S	Material compliance
s_0	Specific entropy at the reference state
T	Temperature
T_0	Reference temperature
T_{bolt}	Total tightening torque
u_0	Specific internal energy at the reference state
V	Chamber volume
W_l	Lifting weight by temperature changes
y^{AM}, y^M	Mobile phase interfaces during loading half-cycle

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(continued)

y_0, y_e	Mobile phase interfaces during the unloading half-cycle
y	Dimensionless cross-section coordinate of the beam
α	Thermal expansion coefficient tensor
δ	Dimensionless coherency energy
δ_g	Arithmetic mean value of thickness changes of gasket
ΔP	Pressure decay
Δt	Elapsed time
$\varepsilon^t, \varepsilon^{t-r}$	Transformation strain tensor
$\varepsilon, \varepsilon_{11}$	Macroscopic uniaxial strain
Λ	Transformation tensor
μ_t	Coefficient of friction for the threads
μ_n	Coefficient of friction for the nut face or bolt head
ξ	Total martensitic volume fraction
π	Thermodynamic force
ρ	Mass density
σ_{max}	Maximum gasket stress
σ_c	Contact stress of gasket
$\sigma_{\Delta T}$	Stress generated from woven SMA wire due to the temperature rise
σ	Uniaxial macroscopic stress
Y	Critical value for thermodynamic force to cause transformation
Φ	Phase transformation function

1. Introduction

Today, shape memory alloys are known as one of the important alloys due to their two properties: shape memory and superelasticity. The characteristics to recover the remaining mechanical strains by a temperature change is called the shape memory effect, and the ability to experience elastic deformations due to phase changes well beyond other metals is called the superelasticity. The use of Nitinol fibers within a matrix of another material improves its mechanical properties due to the overall composite action and the excellent characteristics of the SMA fibers.

In industrial contexts, flange connections are among the most important and widely used joints/connections in piping systems and transmission lines. The area where pipes, pumps, and industrial valves are connected to each other by flanges are equipped with gaskets to fully fill the space between the non-ideal contacting surfaces. In other words, these types of connections are expected to transform the non-ideal contact surfaces, which include voids, indentations, and protrusions, to a perfect fluid-impermeable joint. In the flange connection set, the sealing elements are strongly stressed, and various types of elastic and plastic behaviors may occur at different points. One of the most important loadings is the bending on flange connections, which might be caused by changes in the support conditions of pipeline due to pipe vibrations, lack of concentricity of flanges when closing, non-uniformity in the force of closing bolts, and even earthquakes and landslides. As a result, non-uniform distribution of contact stresses on the gaskets occurs, which may eventually result in a leakage. It should be noted that the importance of gaskets is further revealed when the safety of the industrial environment is compromised either due to the leakage of flammable fluid from the flange connections, or due to the loss of highly valuable fluid by leakage from an improper sealing.

Having known the consequences of leakage from gaskets, the goal in this study is set to examine how can shape memory fibers contribute to the improvement of gasket performance? Firstly, shape memory fibers have a low elastic modulus in a relatively large region of their stress-strain diagram, beginning from the martensitic phase transformation and extending to the complete martensite in the loading path. As a result, incorporation of shape memory wires into the fiber-elastomer sheet does not restrict the deformability of gasket particles to fill the existing voids and indentations, and to create a proper contact load on flange surfaces.

Secondly, shape memory wires possess the capacity for superelasticity. By properly arranging fibers within the composite, transverse stress across the gasket thickness may be generated; improving the sealing performance and ultimately reducing the leak. Moreover, its flexibility to return to its original shape after a deformation could

improve the sealing performance of gaskets.

Several prior investigations have contributed valuable insights on the deformation of Nitinol specimens. Orgeas and Favier [1] conducted experimental research into the compressive behavior of shape memory alloys, unveiling significant discrepancies between the tensile and compressive responses of Nitinol. On the other hand, Raniecki et al. [2] analytically derived moment-curvature equations of the Nitinol beam subjected to pure bending. Their approach involved segmenting the beam cross-section into three distinct parts, and deriving the moment-curvature equations for each part. Bartzela et al. [3] conducted experimental investigations to study the deformation of Nitinol wires under bending, particularly in dentistry applications. Shang and Wang [4] employed the first shear deformation theory to derive the governing equations of the cantilever shape memory beam and then numerically solved them. Ahrari et al. [5] studied the impact of chemicals on dental wire properties under bending. Considering the superelastic conditions, Mirzaeifar et al. [6] investigated the bending behavior of Nitinol beams to address the asymmetric effects of tensile and compressive behaviors and Rao [7] employed two different approaches for modeling the bending of such Nitinol beams (and wires). The asymmetric behavior of Nitinol tubes in bending, both in compressive and tensile regions, was examined by Reedlunn et al. [8] by both numerical simulations and experimental investigations. More recently, Zamani and Botshekanan [9] analyzed the shape memory beams by considering both material and geometrical nonlinearity effects.

Several studies have examined flanged joints and investigated innovative approaches to enhance the sealing performance. Among them, Sakai et al. [10] conducted experiments to evaluate the performance of rubber seals. Their research scrutinized the surfaces involved and their influence on the seal's leak effectiveness. Another study employed the finite element method (FEM) to analyze the behavior of flanges [11]. Shoji and Nagata [12] introduced a method to model nonlinear response of gaskets by the ANSYS software. Abid and Nash [13] examined how flange surface profiles affect the mechanical behavior of flanges through the finite element analysis. In a separate study, Lee et al. [14] investigated the contact stress distribution on gaskets and cylinder heads under various loading conditions using FEM. Sato and Kado [15] investigated the elastic plastic behavior of dissimilar material flanges with a metal ring joint gasket operated at elevated temperature using FEA.

Researchers have also examined the behavior of gaskets. Abid and Nash [16] conducted experimental studies to analyze stress in various types of gasketed and non-gasketed flanges. On the other hands, Krishna et al. [17], employing FEM, examined the gasket performance by considering its nonlinear behavior. Choi and Sankar [18] investigated the effect of cryogenic cycling on the gas permeability of various composite laminates for cryogenic storage systems, and Kobayashi [19] investigated the gasket performance, with a focus on spiral gaskets, in various fluid leakage scenarios through an extensive 3-h test involving 11 loading stages. Kondo et al. [20] numerically examined the role of bending in flange connection leakage. The dynamic response of piping systems with gasketed flange connections at various temperatures was explored by Mathan and Prasad [21]. Omiya and Sawa [22] studied the effects of cyclic thermal conditions on pipe flange connection sealing performance and mechanical properties using FEM, and Kobayashi [23] explored the viscoelastic behavior of gaskets during loading and its impact on flange bolt residual forces. In an analytical and experimental research, Wasmi et al. [24] developed a mathematical model to predict creep and relaxation behaviors in flange gasket connections. Shen et al. [25] studied the wear mechanism of rubber materials in gaskets.

More recently, the properties of protective tunnel sealing gasket materials were investigated by Yang et al. [26] with proposed improvements for gasket performance. Another experimental study examined the fretting wear and frictional mechanism of interface between spiral wound gasket and flange [27]. Gawande [28] explored the finite element analysis of flange-bolted joints in gearboxes. The

experimental study, conducted by Jaszak [29], illustrated that the inclusion of an elastic core in the gasket would result in a consistent force distribution. Yang et al. [30] applied the graphene rubber composite for monitoring the contact pressure of the sealing rings. Yang et al. [31] modeled the two-dimensional assembly of the radial metal seal by the cantilever beam assumption, and Wang et al. [32] evaluated the sealing performance of sealing structures based on multiscale contact analyses. The performance of three-layer gaskets was analyzed by Karohika and Haruyama [33] both numerically and experimentally, with significant results emerging from the leakage test of three-layer copper gaskets. Furthermore, Huang et al. [34] examined the rubber gaskets in concrete structures by FEM.

While various studies have explored gasket behavior and sealing techniques, only a few have focused on the application of shape memory alloys (SMAs) in gasket construction. Lu et al. [35] investigated the effect of ambient temperature on compressibility and recovery of NiTi

shape memory alloys as static sealing elements. In another work, a self-sealing nickel-titanium (NiTi) alloy double corrugated composite gasket was designed and tested [36]. The results showed that self-sealing composite gasket had better sealing performance. He et al. [37] manufactured the shape memory alloy corrugated gaskets which could adapt to fluctuating working conditions due to their superelasticity (SE) and shape memory effect (SME), making them excellent sealing components. Later, Zhu et al. [38] proposed a novel approach by integration of Nitinol sheets into a three-layer smart gasket, capable of generating force in response to temperature changes. They assessed the mechanical properties of the proposed gasket design and conducted leakage tests to evaluate its performance.

In this study, an innovative concept is introduced based on the use of SMAs in non-metallic gaskets to enhance their sealing capabilities. Nitinol wires in a woven configuration are incorporated into the gasket middle layer. The superelastic properties of shape memory wires are

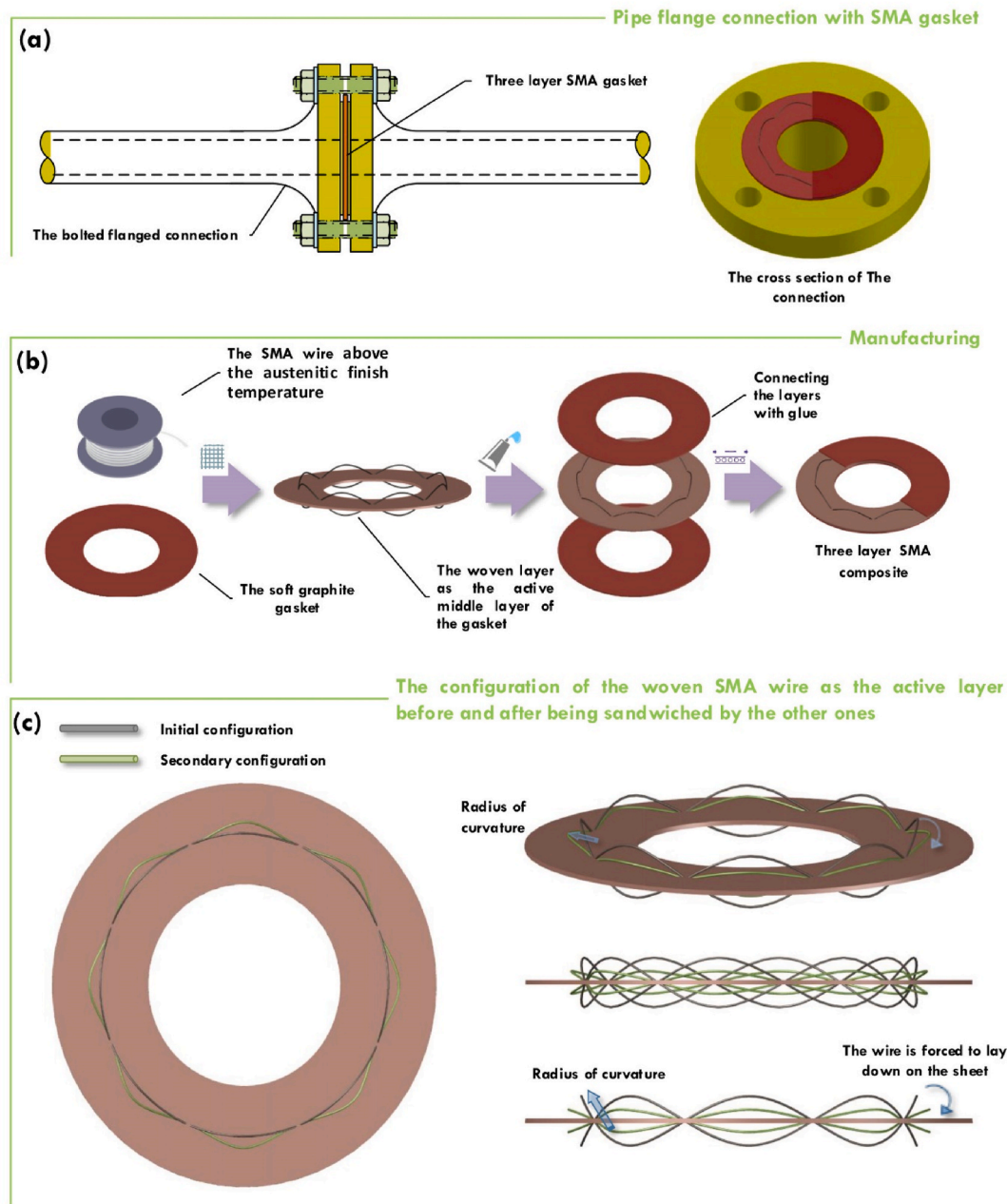


Fig. 1. (a) Overview of the three-layer gasket woven with shape memory wires and its placement on a face flange; (b) Sequential manufacturing steps for the three-layer gasket; (c) Schematic depiction of fiber bending within the sandwiched layers.

employed to improve the gasket sealing performance. To predict the superelastic behavior of the woven fibers, the Hartl-Lagoudas model is employed. The accuracy of proposed model is validated by comparing the analytical results with existing experimental findings in the literature. Subsequently, a series of smart gaskets with varying SMA fiber volume fractions, wire diameters, and woven fiber patterns are fabricated, and their impact, along with various operational conditions such as bending loading, are examined on the leakage rate of the Helium leakage testing. This study marks a significant advancement in gasket technology by employing shape memory alloy wires to enhance non-metallic gasket performance. It provides valuable insights into their behavior under different conditions.

2. Materials and methods

In this section, thermomechanical behavior of woven SMA wire on active layer, including the SMA constitutive model and pure bending analysis are discussed first, and then the experimental investigations, including gasket fabrication and gasket performance testing procedure, are examined.

2.1. Thermomechanical behavior of woven SMA wire on active layer

Fig. 1 illustrates the concept of integrating SMA wires into the composition of a three-layer non-metallic gasket. It provides an overview of how the wire is utilized within the gasket, offering a general depiction of the three-layer gasket woven with shape memory wires and its positioning on the flange face. In Fig. 1-b, the steps involved in making the three-layer gasket are schematically presented. Fig. 1-c illustrates how the fibers (SMA wires) bend when placed between the other two layers. The woven fibers are depicted in a darker shade before being sandwiched and in a lighter shade after bending due to the sandwiching process. Additionally, it illustrates the arrangement of woven Nitinol wires on the middle active layer of the gasket.

This section aims to investigate the stress levels experienced by the fibers while they are woven in the middle of fiber-elastomer sheet. Additionally, it explores the theoretical effects of certain parameters, such as temperature, which may not be readily studied in experiments. It is assumed that woven Nitinol fibers are in a state of pure bending.

Furthermore, it is assumed that the fibers exhibit the same behavior under tension and compression. Consequently, the neutral plane is positioned at the center of the wire cross section. The cross-section of the Nitinol wire can be divided into three regions: complete austenite, complete martensite, and a phase combination. Typically, the regions farther from the neutral layer are more likely to experience the complete martensite phase. Fig. 2 schematically illustrates the distribution of stress in the cross-section of the woven Nitinol wire. When the wire undergoes the maximum bending state, its cross-section experiences single-phase austenite, single-phase martensite, and mixed regions. As the wire curvature decreases under lower load-levels, the single-phase martensitic region gradually diminishes until the entire cross-section becomes single-phase austenitic.

These phase transformations occur within a temperature range higher than the austenitic finish temperature, a state referred to as the superelastic property of the alloy. In the superelastic state, the temperature during loading becomes crucial. In shape memory alloys, the stress required for the phase transformation is highly temperature-dependent. At higher temperatures, a greater stress level is needed to initiate the phase transformation. This implies that different zones of phase distribution are formed across the cross-section of the wire at two different temperatures. While the temperature is influential in the shape memory property of Nitinol fibers, it also plays a crucial role in its superelastic property.

2.1.1. The SMA constitutive model

The constitutive model employed in this study is the Hartl-Lagoudas model. Its most prominent characteristic is the smooth transition in temperature and mechanical responses. This model was developed

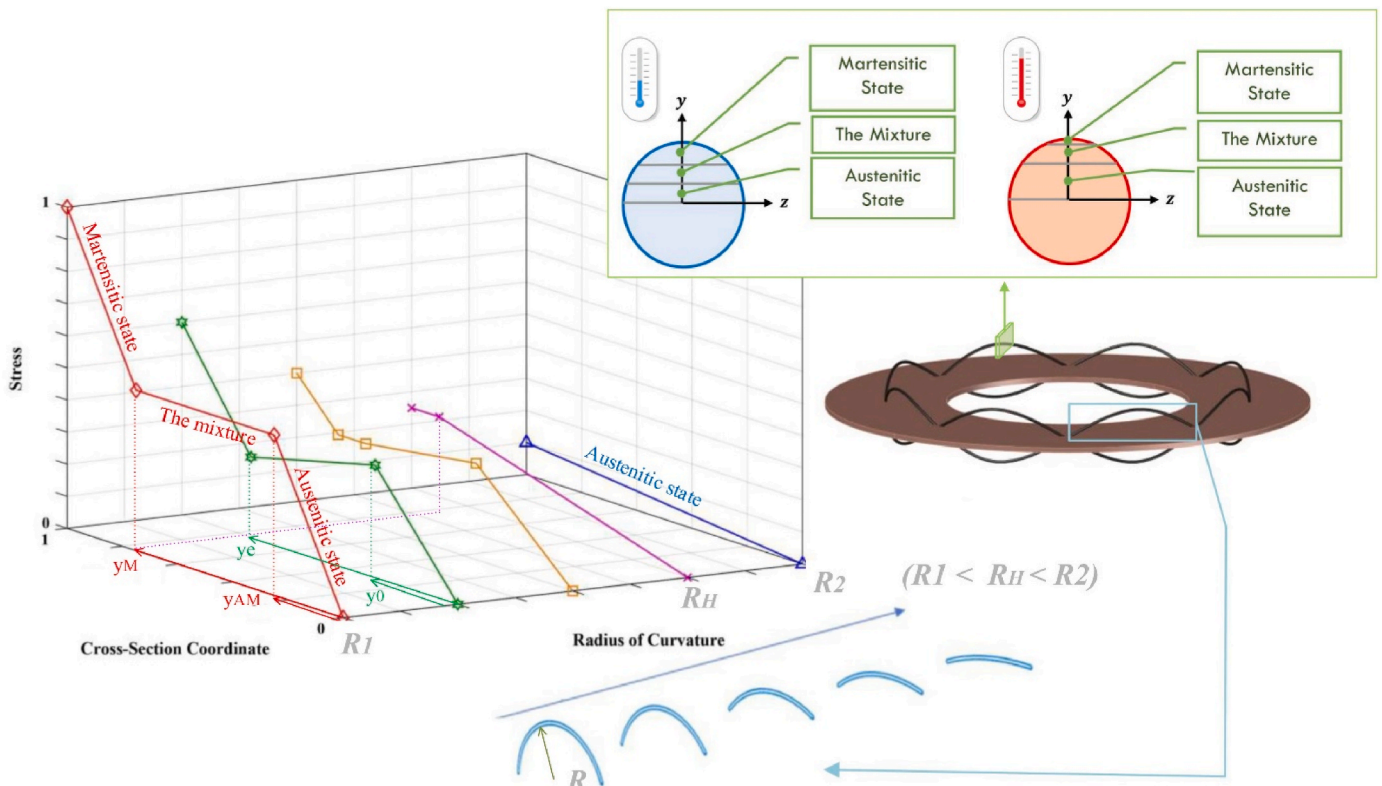


Fig. 2. Illustration of potential evolution of phase zones within the SMA wire cross-section in response to different curvatures and temperature.

through the integration of experimental findings and the definition of thermodynamic quantities, such as the Gibbs potential energy. In the reduced one-dimensional model, the stress-strain relationship is described by the following equation [39]:

$$\varepsilon_{11} = \varepsilon = S\sigma + \alpha(T - T_0) + \varepsilon^t, \quad (1)$$

where ε is the strain, σ is the stress, α is the coefficient of thermal expansion, S is the material compliance, T is the temperature, T_0 is the reference temperature and ε^t is the phase transformation strain. Moreover [39]:

$$\dot{\varepsilon}^t = \Lambda \dot{\xi}, \quad (2)$$

$$\Lambda = \Lambda_{11} = \begin{cases} H^{cur}(\sigma) \operatorname{sgn}(\sigma); & \dot{\xi} > 0, \\ \varepsilon^{t-r}/\dot{\xi}; & \dot{\xi} < 0, \end{cases} \quad (3)$$

where Λ is the transformation tensor, ξ is the martensitic volume fraction, H^{cur} is the maximum transformation strain at the current stress and ε^{t-r} is the transformation strain during the martensitic to austenitic phase transformation. Finally, the scalar function Φ^t for the forward phase transformation is defined as [39,40]:

$$\Phi_{fwd}^t(\sigma, T, \xi) = (1 - D)|\sigma|H^{cur}(\sigma) + \frac{1}{2} \left(\frac{1}{E^M} - \frac{1}{E^A} \right) \sigma^2 + \rho \Delta s_0 T - \rho \Delta u_0 - f_{fwd}^t(\xi) - Y_0^t = 0 \quad (4)$$

and during the reverse phase transformation:

$$\Phi_{rev}^t(\sigma, T, \xi) = -(1 + D)\sigma \varepsilon^{t-r}/\dot{\xi} - \frac{1}{2} \left(\frac{1}{E^M} - \frac{1}{E^A} \right) \sigma^2 - \rho \Delta s_0 T + \rho \Delta u_0 + f_{rev}^t(\xi) - Y_0^t = 0 \quad (5)$$

where ρ is the density, c is the specific heat capacity, E^M is the modulus of elasticity in the martensitic phase, E^A is the modulus of elasticity in the austenitic phase, Y_0^t is the critical value for the thermodynamic force to cause transformation, s_0 is the specific entropy at the reference state, u_0 is the specific internal energy and f^t is the following set of hardening functions, defined to facilitate a smooth and continuous transition from the elastic region to the phase transformation region [39]:

$$f_{fwd}^t(\xi) = \frac{1}{2} a_1 (1 + \xi^{n_1} - (1 - \xi)^{n_2}) + a_3. \quad (6)$$

$$f_{rev}^t(\xi) = \frac{1}{2} a_2 (1 + \xi^{n_3} - (1 - \xi)^{n_4}) + a_3. \quad (7)$$

where a_i and n_i are the Hartl model parameters. Four key points exist where the temperature and the martensitic volume fraction in the stress-free state can be incorporated as known parameters within the equations. These points correspond to the boundaries between the elastic region and the phase transformation from austenite to martensite (both the starting and ending points), as well as from martensite to austenite (both the starting and ending points). This consideration is made under the assumption that all internal and external variables return to their initial state following a full cycle of phase transformations [39], leading to:

$$a_1 = \rho \Delta s_0 (M_f - M_s) \quad (8)$$

$$a_2 = \rho \Delta s_0 (A_s - A_f) \quad (9)$$

$$a_3 = -\frac{a_1}{4} \left(1 + \frac{1}{n_1 + 1} - \frac{1}{n_2 + 1} \right) + \frac{a_2}{4} \left(1 + \frac{1}{n_3 + 1} - \frac{1}{n_4 + 1} \right) \quad (10)$$

$$\rho \Delta u_0 = \frac{\rho \Delta s_0}{2} (M_s + A_f) \quad (11)$$

$$Y_0^t = \frac{\rho \Delta s_0}{2} (M_s - A_f) - a_3 \quad (12)$$

where M_s , M_f , A_s and A_f represent the martensitic start and finish temperatures and the austenitic start and finish temperatures, respectively. Variations of c , s_0 , u_0 , α and S with respect to the martensitic volume fractions are assumed as [39]:

$$c(\xi) = c^A + \xi \Delta c \quad (13)$$

$$s_0(\xi) = s_0^A + \xi \Delta s_0 \quad (14)$$

$$u_0(\xi) = u_0^A + \xi \Delta u_0 \quad (15)$$

$$\alpha(\xi) = \alpha^A + \xi \Delta \alpha \quad (16)$$

$$S(\xi) = S^A + \xi \Delta S. \quad (17)$$

For further details on SMA constitutive law see Refs. [40,41].

2.1.2. Pure bending analysis of an ideal superelastic SMA wire

The circular cross-section of the Nitinol wire under pure bending condition can be divided into three regions: austenite, martensite and a mixture of the two, as depicted in Fig. 3. The challenge in pure bending lies in the evolution of phase zones across the cross-section as the applied moment changes.

In this section, the Müller-Zhou fundamental equations are employed under the assumption of an ideal superelastic state. In this ideal state, the tensile and compressive behaviors of the Nitinol are considered to be similar. Consequently, the neutral axis locates on the horizontal diameter of the circular cross-section. Accordingly, the moment-curvature relationship in the wire can be derived from the global equilibrium equations [2]:

$$\int_{-h}^h \sigma f_0(x_1) dx_1 = 0 \quad (18)$$

$$M = 2 \int_{-h}^h \sigma x_1 f_0(x_1) dx_1 \quad (19)$$

where σ is the normal stress, M is the bending moment and h is half of the height of the wire cross-section, which is equal to radius of the wire cross-section. The shape of the cross-sectional profile is indirectly defined by the function $f_0(x_1)$. Under the assumption of an ideal superelasticity state, Eq. (18) is automatically satisfied. Fig. 3 schematically illustrates the zones of phase transformation in the cross-section of the Nitinol wire.

The dimensionless parameters are defined as $y = \frac{x_1}{h}$, $K = \frac{hk}{E^A}$, $f(y) \equiv \frac{f_0(hy)}{h} = \sqrt{1 - y^2}$. The strain can then be expressed in terms of the dimensionless variables [2]:

$$\varepsilon = \frac{L_{CD} - L_{AB}}{L_{AB}} = \frac{(R + x_1)\theta - R\theta}{R\theta} = yhk(t) \quad (20)$$

where $k(t)$ is the instantaneous curvature of the bent wire. Putting Eq. (20) into Eq. (1) and using Eq. (19) by assumption of ($\Delta T = 0$), the basic relations describing the overall $M - K$ characteristic of the wire is obtained [2]:

$$\frac{M}{4I_0 E h^3} = kh - H^{cur} \frac{1}{I_0} \int_0^1 \xi y f(y) dy \quad (21)$$

where I_0 is the characteristic shape function of the beam cross-section (defined later in Eq. (30)). Moreover [2]:

$$\xi(y, K) = \langle Ky - K^{AM} \rangle - \langle Ky - K^E \rangle \quad \text{for loading} \quad (22)$$

$$\xi(y, K) = \langle \xi_m - \langle K^{AM} + (1 - \delta)\xi_m - yK \rangle \rangle \quad \text{for unloading} \quad (23)$$

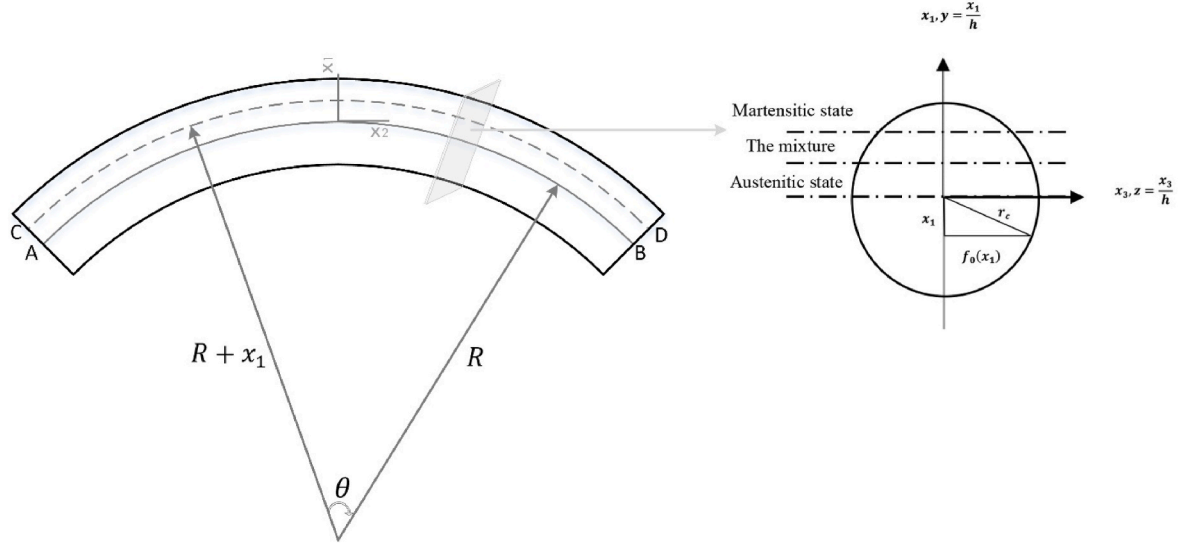


Fig. 3. Illustration of the phase zones in the circular cross-section of the wire.

$$\xi_m = \langle yK_m - K^{AM} \rangle - \langle yK_m - K^E \rangle \quad (24)$$

Also [2],

$$K^{AM} = \frac{m}{EH^{cur}} (T - M_s^0) \quad (25)$$

$$\delta = K^{AM} - K^{MA} \quad (26)$$

where K is the dimensionless curvature, K^{AM} and K^{MA} are critical dimensionless curvature at initiation of austenitic and martensitic states, respectively, T and m are the temperature and the temperature sensitivity of the superelasticity limit at simple tension, respectively. δ is the dimensionless coherency energy and K^E is equal to $(1 + K^{AM})$ [2]. Fig. 4 defines some of the main variables of the present model on typical M - K responses.

The moment-curvature relationships for the Nitinol wire vary between the loading and unloading stages, resulting in separate relationships for each stage. Substituting Eqs. (22) and (23) into Eq. (21) leads to $M_{d-forward}$ for the loading stage [2]:

$$M_{d-forward} \equiv \frac{M}{4I_0 H^{cur} E h^3}$$

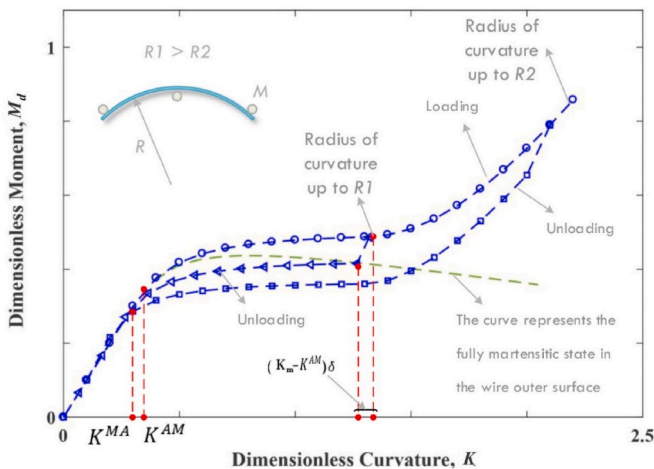


Fig. 4. Definition of some of model variables on typical M - K responses.

$$= K \{ 1 + I_2 [y^{AM}(K)] - I_2 [y^M(K)] \} - I_1^t + I_1 [y^M(K)] + K^{AM} \{ I_1 [y^M(K)] - I_1 [y^{AM}(K)] \} \quad (27)$$

To characterize the bending behavior of the Nitinol wire during unloading, the return path is determined by the following two relationships [2]:

$$M_{d-reverse(1)} \equiv \frac{M}{4I_0 H^{cur} E h^3} = K - I_1^t + K^E \delta I_1 (y_0^M) + K^M I_1 (y_e) - K^{AM} (1 + \delta) I_1 (y_0) - \delta K_m I_2 (y_0^M) - K I_2 (y_e) + (K + K_m \delta) I_2 (y_0) F; \quad R_1 \leq R \leq R_H \quad (28)$$

$$M_{d-reverse(2)} \equiv \frac{M}{4I_0 H^{cur} E h^3} = K I_2 (y_0) + K^{MA} [I_1^t - I_1 (y_0)]; \quad R_H < R \leq R_2 \quad (29)$$

M_d is the dimensionless bending moment, K_m is the dimensionless amplitude of the curvature, and $y_0, y_e, y^{AM}, y^M, R_1, R_H$ and R_2 shown in Fig. 2, are the distances that specify the geometries of different phase zones and the radius of curvatures. K^M represents the beam curvature at the moment when the outermost point of the cross-section of the wire exits the complete martensitic state. Each of the reverse equations forms part of the return path.

To establish the moment-curvature relationship, the following dimensionless specific shape functions are derived for the circular cross-section in this study:

$$I_0(y) = \int_0^1 f(y) y^2 dy = \frac{\pi}{16} \quad (30)$$

$$I_1(y) = \frac{1}{I_0} \int_0^y f(y) y dy = \frac{1}{I_0} \left[-\frac{1}{3} (1 - y^2)^{3/2} + \frac{1}{3} \right] \quad (31)$$

$$I_2(y) = \frac{1}{I_0} \int_0^y f(y) y^2 dy = \frac{1}{I_0} \left[\frac{1}{8} \sin^{-1}(y) + \frac{y}{8} (2y^2 - 1) \sqrt{1 - y^2} \right] \quad (32)$$

$$I_1^t = I_1(1) \quad (33)$$

Also, the essential relationships for the boundary distances that define the phase zones are given by Ref. [2]:

$$y^{AM}(K) = 1 - \langle 1 - K^{AM} / K \rangle \quad (34)$$

$$y^M(K) = 1 - \langle 1 - K^E / K \rangle \quad (35)$$

$$y_0(K) = \left\langle \frac{K^{AM}(1 + \delta)}{K + K_m\delta - K^{AM}(1 + \delta)} + \frac{K^{MA}}{K - K^{MA} + K^{MA}} \right\rangle \quad (36)$$

$$y_e(K) = \frac{K^{AM}\delta}{K^{AM}\delta + \langle K + K_m\delta - K_m - K^{AM}\delta \rangle} - \left\langle \frac{K^{AM}\delta}{K^{AM}\delta + \langle K + K_m\delta - K_m - K^{AM}\delta \rangle} - \frac{K^M}{K^M + \langle K - K^M \rangle} \right\rangle \quad (37)$$

Furthermore, the angle brackets $\langle \rangle$ is defined as:

$$\langle A \rangle = \begin{cases} A & A > 0 \\ 0 & A \leq 0 \end{cases} \quad (38)$$

The green dashed line in Fig. 4 is the state in which the outer surface of the wire experiences fully martensitic phase. This line is [2]:

$$\frac{M(K_m)}{4I_0H^2curEh^3} = K^{AM}(1 + \delta) \left[I_1^t - I_1 \left(\frac{K^{AM}(1 + \delta)}{K^{AM}\delta + K_m} \right) \right] - \delta K_m - (K^{AM}\delta + K_m)I_2 \left(\frac{K^{AM}(1 + \delta)}{K^{AM}\delta + K_m} \right) + (K + K_m\delta)I_2(y_0) \quad (39)$$

where

$$K = K_m(1 - \delta) + K^{AM}\delta \quad (40)$$

2.2. experimental study

In this section, the effects of utilizing shape memory fibers on the sealing performance of fiber-elastomer gaskets are experimentally investigated. First, the gasket fabrication process is explained, followed by a description of the test setup used to examine the sealing performance.

2.2.1. Gasket fabrication

The gasket under examination in this study falls into the category of non-metallic gaskets crafted from fiber-elastomer material. Depending on the specific flange dimensions and the nature of the surfaces involved, the shape and dimensions of gasket are cut from a fiber-elastomer sheet. In this investigation, gaskets are fabricated for installation on 2-inch ASME B16.5 Class 150 raised-face welding neck flanges. The gasket is composed of three layers, each serving a distinct purpose. The active layer acts as the foundation for the embedded SMA fibers, which are woven into it. The remaining two layers are securely sealed on both sides of the gasket using RTV silicone adhesive, resulting in a fully assembled and ready-to-test gasket. The thickness of the middle layer is 1 mm, while the thickness of the inner and outer layers is 0.5 mm each.

Typically, fiber-elastomer gaskets commonly employ wires (though not shape memory wires) to maintain gasket integrity and prevent failure under high stress conditions. Fig. 5 is a typical diagram comparing the mechanical behavior of shape memory alloys with stainless steel [42,43]. Fig. 6 illustrates the stress-strain characteristics of compressed non-asbestos fiber sheets used as gaskets [19,44].

Two types of three-layer gaskets are studied in this research, including those woven with Nitinol wires and wire-free gaskets. Two variants of shape memory wires with 0.3 mm and 0.5 mm of diameters are utilized. During the weaving process, the Nitinol wires must be maintained at a temperature above the austenitic finish temperature, so their geometry tends to remain a straight line. This wire shape during weaving offers a notable advantage in the manufacturing process, as it eliminates the need for shaping and complex heat treatments.

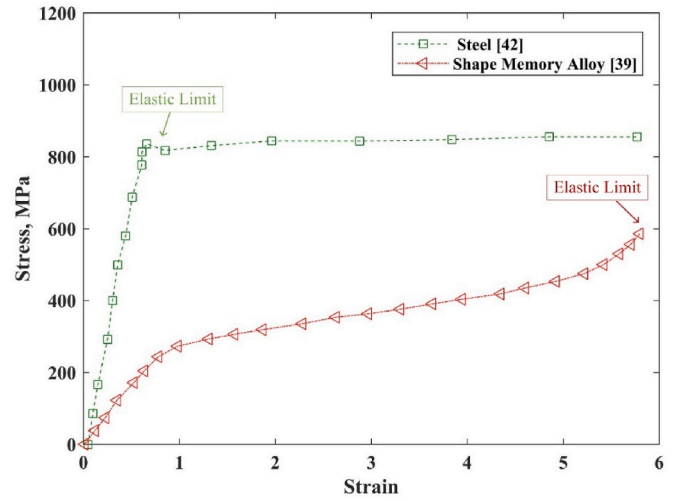


Fig. 5. Stress-strain diagram for stainless steel and Nitinol.

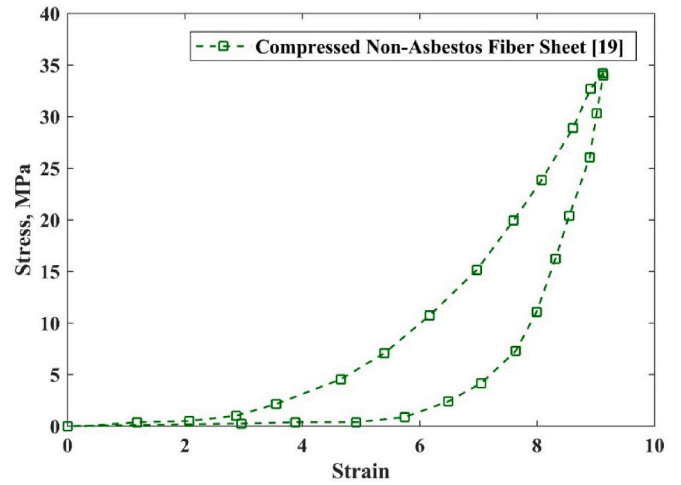


Fig. 6. Stress-strain diagram for compressed non-asbestos fiber sheet.

Fig. 7 illustrates the process of weaving the fibers onto the active layer. Two methods of weaving Nitinol wire on the fiber-elastomer sheet are the single-wire discontinuous form (Fig. 7-a) and the two-wire continuous form (Fig. 7-b). In this study, due to the limitation of the gasket area, only a single row of woven wire is implemented within the gasket design. The wires are used in the mean diameter of the gasket to ensure there is enough space to lay them on the sheet. It should also be noted that the presence of fibers in the middle diameter of the gasket makes it easier to attach the other two layers on both sides. For scenarios involving larger contact surfaces and dimensions, two or more rows of fibers may be employed.

Fig. 8 shows the two types of the gaskets that are fabricated and tested in this study and Fig. 9 represents the glued layer and completed three-layer gasket.

2.2.2. Gasket sealing performance testing procedure

Fig. 10 illustrates the experimental test setup used in the study. The experiment employed two 2-inch ASME B16.5 Class 150 raised-face welding neck flanges made of ASTM A105, paired with two Schedule 40 carbon steel pipes, each 3.81 mm thick, conforming to ASTM A53 standards. The stud bolts, fully threaded and with a nominal size of 5/8 inch, were selected in accordance with ASME B18.31.2 and ASTM A193. Fig. 11 displays the dimensions of the flanges and stud bolts. This setup can withstand pressures up to 270 psi at ambient temperature; however,

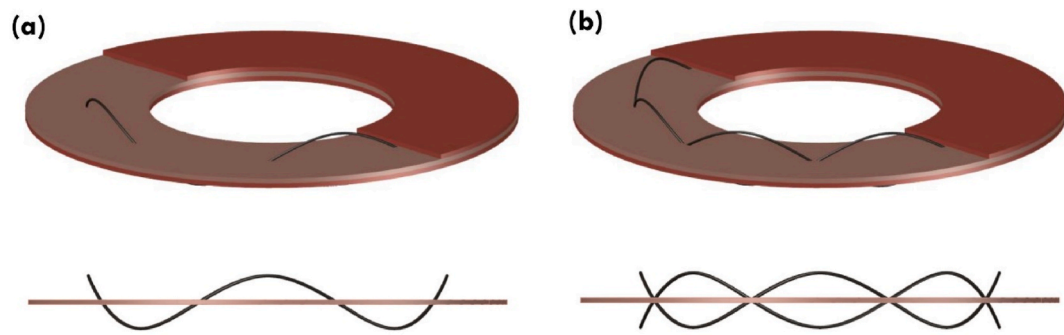


Fig. 7. Two methods of weaving Nitinol wire on the middle (active) layer: (a) single-wire discontinuous form (type I); (b) two-wire continuous form (type II).

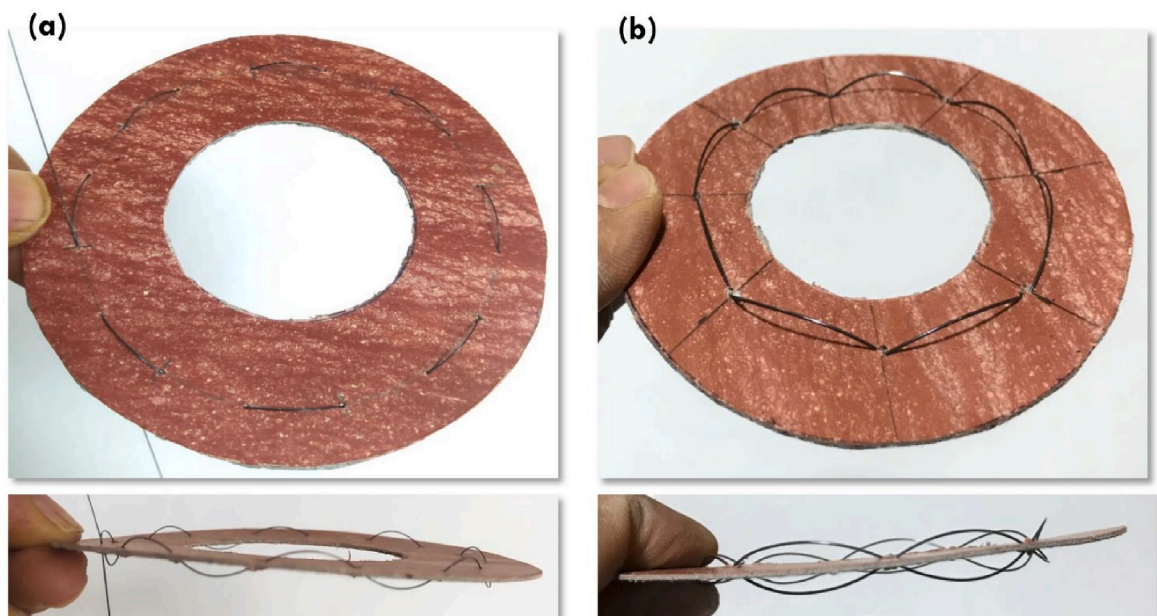


Fig. 8. Fabricated gaskets: a) single-wire discontinuous form (type I); b) two-wire continuous form (type II).

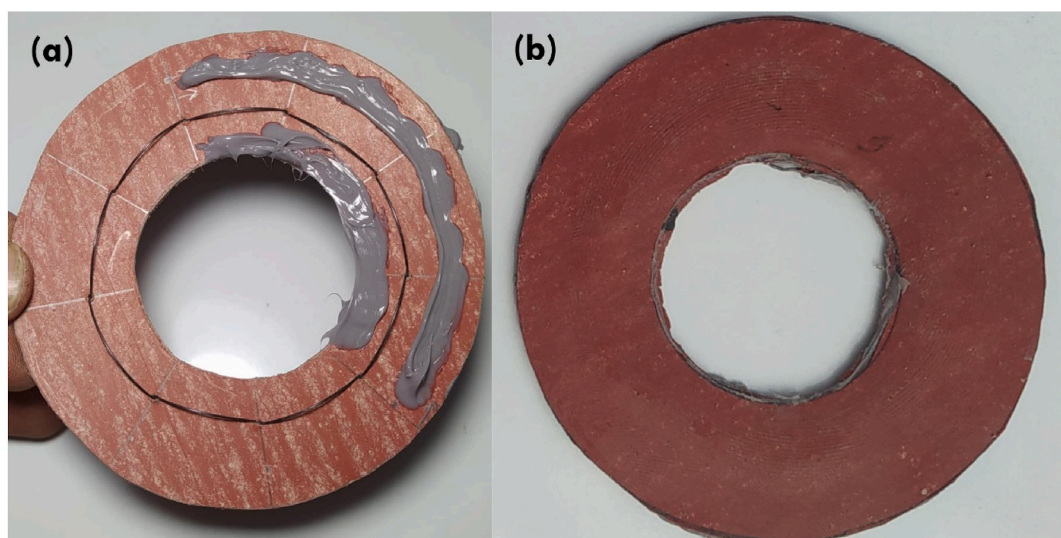


Fig. 9. Fabricated gaskets a) Glued layer b) Completed three-layer gasket.

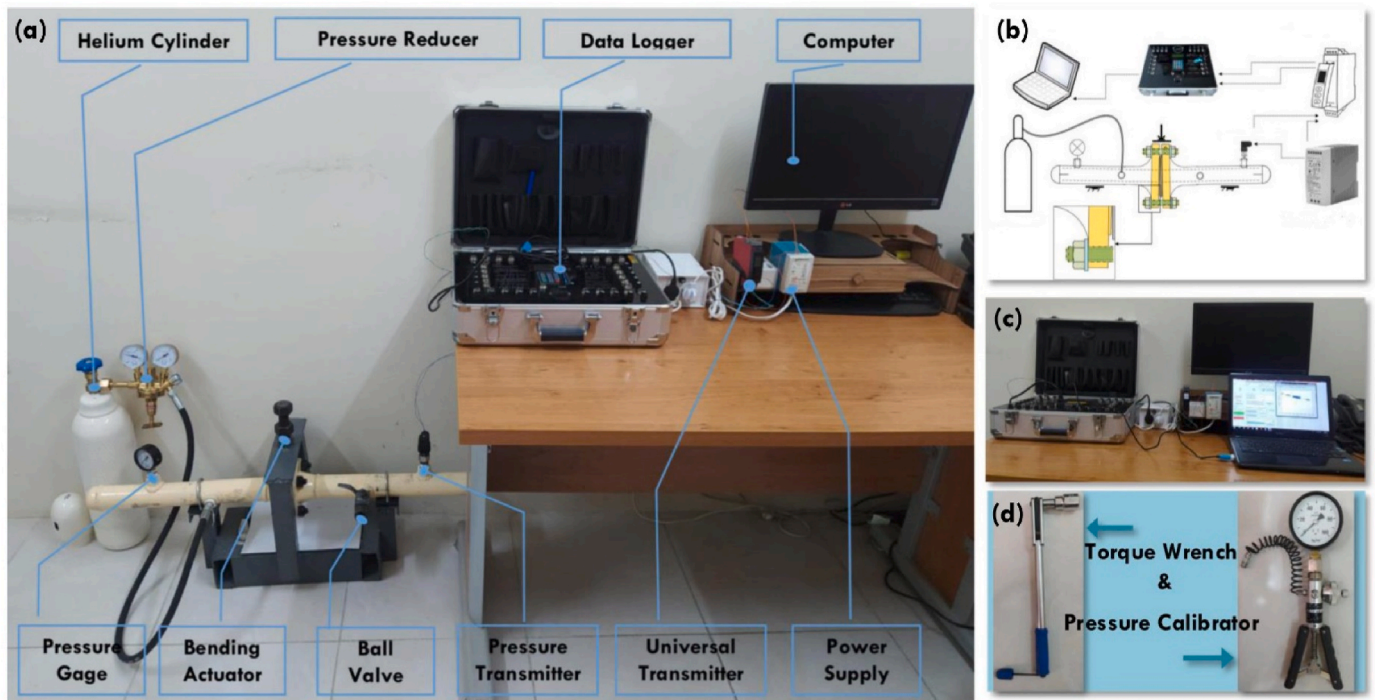


Fig. 10. (a) Experimental test setup; (b) Schematic view; (c) Data logger connected to the Laptop; (d) Torque wrench and Calibrator.

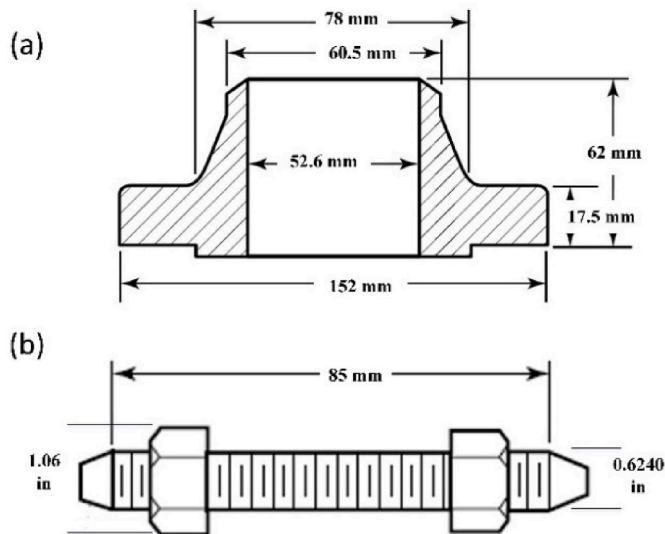


Fig. 11. Dimensions of a) 2-inch ASME B16.5 Class 150 raised-face welding neck flanges b) ASME B18.31.2 stud bolts.

for this study, the maximum pressure was limited to 160 psi.

Helium gas was employed as the trapped fluid in these experiments. A helium gas cylinder supplies the initial pressure for the leakage testing. An analog pressure gauge was used to compare the pressure with the data recorded by the data logger and providing mean values for the results. The electronic circuit included a pressure transmitter, power supply, signal converter, data logger, and computer to record pressure values over time.

Several design considerations are crucial when designing bolted flange connections, including pressure rating, flange surface finish, gasket thickness, bolt tightening and load capacity, flange rigidity, and joint assembly. ASME provides codes to guide the design of bolted flange connections, considering these factors. The choice of gasket material

depends on temperature, pressure, and fluid compatibility. In this study, compressed asbestos fiber sheets were used to fabricate the gaskets. These non-metallic gaskets are economical, easy to handle, and suitable for general fluids such as water, steam, and oil (ASME B16.21).

Bolts were inserted through the flanges and gasket and tightened to a specific torque value as per the design standard, using a torque wrench. For the simple gaskets used, the maximum gasket contact stress was 40 MPa [19]. The manufactured gaskets consisted of three glued layers, requiring special gaskets to be made and their maximum contact stress determined experimentally. The maximum contact stress required to achieve a leak-free state at a pressure of 160 psi was determined experimentally. By applying a torque of 35 Nm to each bolt, a leak-free condition was achieved, and this was considered the maximum contact stress.

As mentioned before, the main objective of this research is to examine the effect of SMA wires on the leakage performance of sheet gaskets. To do this, it is necessary to create leakage conditions to compare the performance of gaskets with and without SMA wire. Although the tightening torque applied to the bolts/nuts adhered to ASME PCC-1 standard conditions, to bring the assembly to the threshold of leakage and shorten the test time, the target torques on the bolts were set lower than the standard condition, at 35 Nm per bolt. Hand torque wrenches were used to adjust the torque values applied to the bolts.

The test setup is designed to examine the sealing performance of gaskets in two scenarios: with and without the application of bending. When a flange connection is subjected to bending, the gasket experiences high contact stress on one side while losing contact with the flange surfaces on the opposite side. The significant impact of the bending moment on the distribution of contact stress across the gasket surfaces increases the likelihood of leakage on the side where the flange edges diverge. As illustrated in Fig. 12, applying an upward bending moment decreases the contact stress in the lower part of the gasket due to the tension effect, increasing the likelihood of leakage in this area. The non-uniformity of gasket stress distribution along the radial direction reduces the effective sealing width [45,46].

The tightening torque on the power screw to apply bending moment on the piping is chosen in such a way that the assembly reaches the

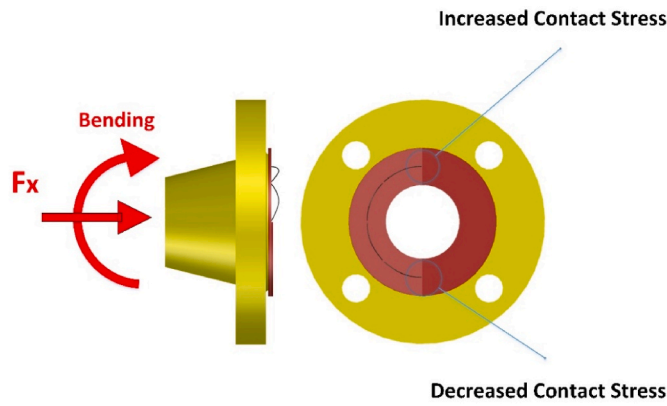


Fig. 12. Change of gasket contact stress distribution in the connection subjected to external bending.

threshold of leakage. The amount of this torque, which is applied using the hand torque wrenches, is determined experimentally. The torque starts from zero and increases until impending leakage occurs. This value for the applied torque is 70 Nm, which corresponds to the compressive force of 9000 N according to the power screw specifications. According to Fig. 13, this compressive force results in a bending moment of 1125 Nm applied to the flange-bolted connections.

To evaluate the performance of fabricated gaskets, a series of tests are performed. Initially, the gaskets are subjected to the maximum contact stress imposed by the flange surfaces through the tightening of flange bolt (In this step, the helium gas pressure is zero). Subsequently, the axial force on the bolts is carefully reduced using a torque meter to induce a controlled increase in the leakage rate, thus creating the necessary conditions for data collection. The maximum contact stress and a lower contact stress are achieved by applying specific torques of 35 Nm and 21 Nm, respectively, to the bolts. The maximum contact stress is determined through the experimental means, ensuring that a balance is struck to prevent both excessive stress on the bolts and flanges while preventing leakage [19,23].

The experiments are conducted under two distinct conditions: without and with the application of bending. In both scenarios, the initial internal pressure within the structure is maintained at the

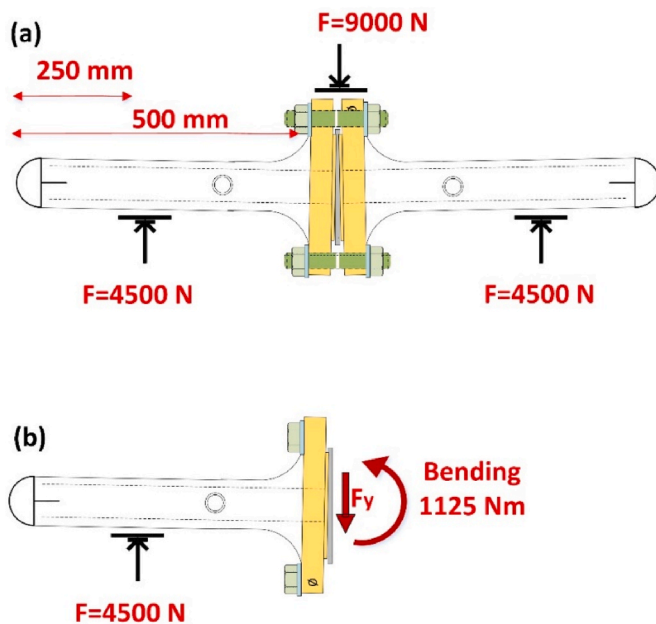


Fig. 13. Free body diagram of the flange-bolted connection under bending.

constant 160 Psi (1103 kPa). The standard thickness of gaskets within this pressure range typically falls between 1 and 5 mm [19,23].

The test duration for each sample is determined by monitoring the pressure drop within the structure. In most cases, two samples of each gasket type are fabricated. The average data obtained from data loggers and analog pressure gauges are utilized for clarity and precision.

Fig. 14 shows the values of the contact stress on the gasket, which are caused by the torque applied to the bolts. Steps 1, 2, and 3 respectively correspond to the following conditions: maximum contact stress (ideal condition), reduced contact stress without the presence of bending loads (non-ideal condition), and reduced stress when bending is applied on the flanges (non-ideal condition with bending). In the first stage, the gasket experiences high stress and actual deformations. At this stage, the leakage rate is zero or very low and the condition is ideal. By loosening the bolts and reducing the contact stress, the second step begins. The first step is only performed to put the gasket under real deformations/stresses before the testing. Afterwards, the bolts are completely loosened and then tightened again to 60 % of the maximum stress to start the second stage. The value of 60 % stress is chosen due to compliance with the Japanese industrial standard (HPIS Z104) [19]. The first and second step contact stresses are achieved by applying specific torques of 35 Nm and 21 Nm, respectively, on the bolts. The amount of bolt tightening is measured by a torque meter. The pressure of nitrogen gas tested in this study is 160 psi, which is lower than the pressure tolerance of class 150 connections, which is about 270 psi at ambient temperature. According to the gasket specifications, the minimum design seating stress is 11 N/mm² and the gasket factor is 2, so the amount of 35 Nm is appropriate as the target torque of the bolts to consider as the maximum contact stress. It is simulated under non-ideal conditions, which represents the increased leakage rate. The third step is similar to the second stage, with the difference that the flange joint and the pipe are under bending. It should be noted that the first step is only performed to put the gasket under real deformations/stresses before the testing, and all the results presented in this article are related to the second and third steps.

The equations necessary for determining the level of stress on the gasket, resulted from the applied torque on the bolts, are briefly outlined. The contact gasket stress (σ_c) can be obtained from Ref. [19]:

$$\sigma_c = \frac{4F_{bolt}}{A_g} - \frac{(\pi/4)d_i^2 P}{A_g} \quad (41)$$

$$A_g = \frac{\pi}{4} (d_o^2 - d_i^2) \quad (42)$$

where A_g is the contact area of gasket, P is the test pressure, d_o^2 and d_i^2

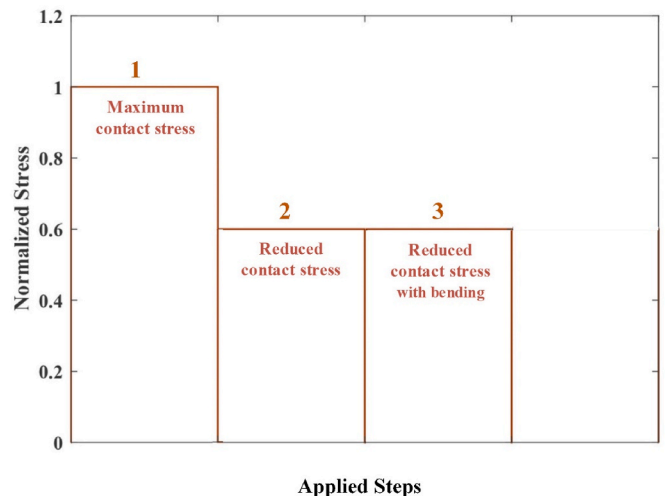


Fig. 14. Normalized stress versus applied steps.

represent the outer and inner diameters of the gasket, respectively and F_{bolt} represents the axial force in the bolts. Tables are available to convert the torque applied to the bolts into the axial force for each bolt based on the lubrication conditions (See Eq. (49)) [19,23]. For the present setup conditions, a torque of 21 Nm (equivalent to a tensile axial force of 6000 N) is applied to the bolts, leading to a contact stress of 4.5 MPa on the gasket in the unpressurized state (Eq. (41)).

The leakage rate (L) can also be determined from Ref. [19]:

$$L = \frac{\Delta P \cdot V}{\Delta t} \quad (43)$$

where ΔP represents the pressure difference within the trapped volume (V) during the time interval Δt .

In the following, the analytical relations for approximating the effect of temperature on gasket behavior are presented. In order to calculate the deformation of the gasket (δ_g) analytically, the contact stress of gasket can be obtained from Ref. [19]:

$$\sigma_c = F \delta_g^{b_b} \quad (44)$$

where F is obtained from the maximum gasket stress (σ_{max}):

$$F = (\sigma_{max})^{(1-b_B/b_A)} a^{(b_B/b_A)} \quad (45)$$

where the constants of the gasket (a , b_A , b_B , c , d) represent gasket deformation characteristics, based on the type and material of the gasket [19]. The leakage rate is calculated analytically with the help of gasket deformation obtained from Eq. (44) [19]:

$$L = ce^{-d\delta_g} \quad (46)$$

In order to investigate the effect of temperature on Nitinol gaskets, the temperature related stress, generated by the SMA wire, can be obtained experimentally and is added to the contact stress of the gasket:

$$\sigma_c = \frac{4F_{bolt}}{A_g} - \frac{(\pi/4)d_i^2 P}{A_g} + \sigma_{\Delta T} \quad (47)$$

where $\sigma_{\Delta T}$ is the stress generated from woven SMA wire due to the increase in temperature. Also, $\sigma_{\Delta T}$ can be experimentally determined:

$$\sigma_{\Delta T} = \frac{W_l}{A_c} \quad (48)$$

where W_l is the lifting weight, which can be approximated from the displacement test shown schematically in Fig. 15 and A_c is the contact area between the woven wires and active gasket layer.

With the help of Eqs. (44) and (47), the deformation of the gasket (δ_g) is obtained and then by putting δ_g in Eq. (46), the leakage rate (L) is determined. In order to serve the purpose, Fig. 16 is presented, which demonstrates the history of the stress applied to the gasket. In the first step, the gasket is under stress by the flanges, which varies depending on

the amount of torque applied to the bolts. In the next step, helium gas is injected into the closed volume of the connection to reach a constant pressure. The final step is increasing the temperature of SMA wire reinforced gasket to generate internal stress in the direction of the thickness.

According to ASME PCC-1, the mathematical model relating the applied torque and tension in the stud bolt is generally expressed as

$$T_{bolt} = F_{bolt} \left[0.16p + 0.58\mu_t d_2 + \frac{\mu_n D_e}{2} \right] \quad (49)$$

where T_{bolt} and F_{bolt} are the total tightening torque and bolt preload, respectively; p is the pitch of the thread (1/number of thread per inch); μ_t and μ_n are the coefficients of friction for the threads and for the nut face or bolt head, respectively; d_2 is the basic pitch diameter of the thread; and D_e is the effective bearing diameter of the nut face, calculated as $\frac{d_{on}+d_{in}}{2}$, where d_{on} and d_{in} are the outer and inner bearing diameters of the nut face. The first term represents the torque needed to stretch the bolt, the second term accounts for the torque to overcome the thread friction, and the last term addresses the torque required to overcome the face friction.

2.2.3. Testing procedure for investigating the effect of temperature on the woven SMA wire

To experimentally examine the performance of SMA gaskets at different temperatures, two experimental tests were designed. The first test setup, as shown in Fig. 17, is used to evaluate the ability of woven Nitinol wires (Type II) to lift a kilogram of calibration weight as the temperature increases. The gasket contains two woven wires in a continuous form, and the amount of lift was investigated under two conditions: when the temperature increased from 263K to 323K and from 300K to 323K. The gasket is placed under the load of the calibration weight, and a dial indicator measures the lifting of the weight as the temperature rises.

Another experimental set up was designed to measure the effect of temperature on the force generated by woven SMA fibers. As shown in Fig. 18, a digital hot plate, electronic balance, and seesaw mechanism were used to measure the force produced as the temperature increased. The temperature was set between 320 K and 410 K. The measured force includes an additional kilogram calibration weight lifted by the woven fibers. It is important to note that in this experiment, the force effects due to the thermal expansion of the equipment must be subtracted from the force effects produced by the fibers.

3. Results and discussion

In this section, the results obtained from both the analytical solution and the experimental tests are presented and discussed. The analytical results explore the behavior of the woven wire on the active layer, considering it as pure bending element. The experimental tests

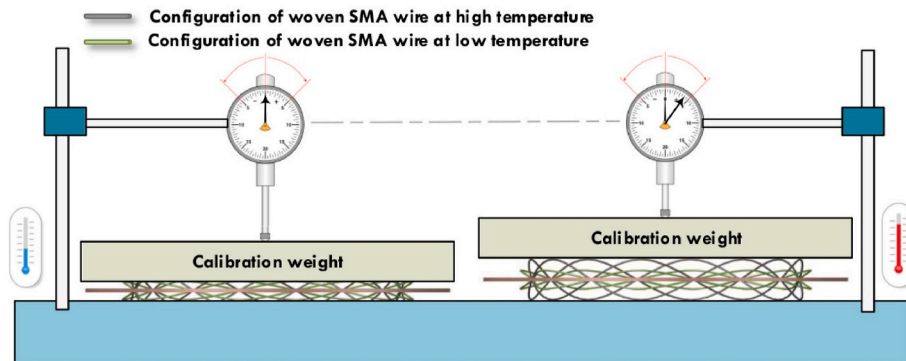


Fig. 15. Schematic illustration of displacement test to examine temperature effect on the active layer.

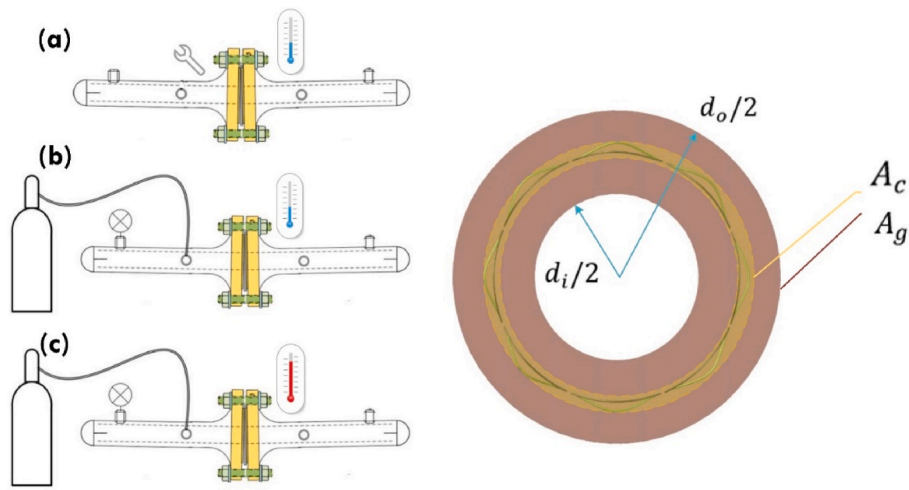


Fig. 16. History of the contact stress on SMA gasket at different stages; (a) tightening four bolts of the flanges; (b) pressurizing the structure with helium gas; (c) heating the structure.

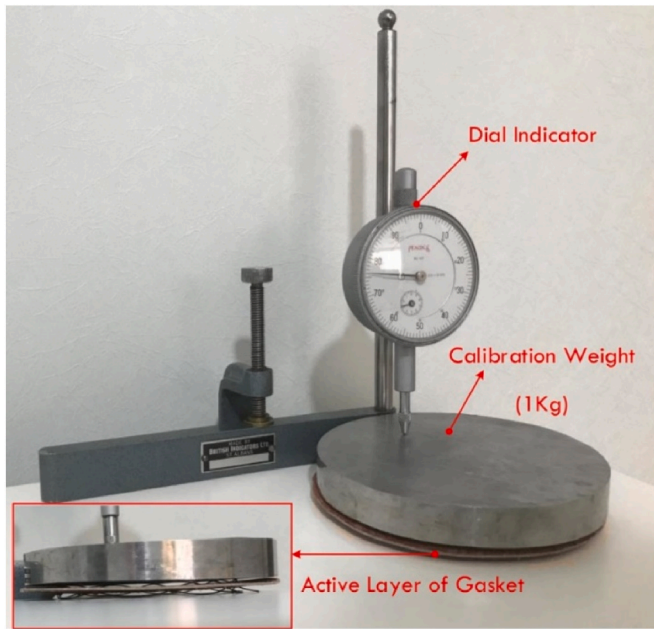


Fig. 17. Displacement test by using dial position indicator.

examined the effects of fibers on gasket performance in the helium gas leakage test.

3.1. Analytical results

In this section, the pure bending behavior of the SMA fibers are studied. Table 1 provides the thermomechanical specifications of the wire and Table 2 demonstrates the characteristics of fiber-elastomer gasket. Table 3 shows the parameters of the mathematical model relating the applied torque and tension in the bolt.

Validation of the analytical formulations for the circular Nitinol wire behavior is investigated in Fig. 19. The figure compares the results of the current analytical model and the reference experimental moment-curvature data. Generally, a good agreement between the trends of the analytical solution and experimental data is observed. Expectedly, there exist some differences, which may be related to special test conditions

Table 1
Material parameters of Ti-Ni alloy [2,39].

$E^A = 32.5$	$E^M = 23.0 \text{ GPa}$	$\nu = 0.33$
$\rho = 6500 \text{ kg/m}^3$	$\alpha = 22.0 \times 10^{-6} \text{ K}^{-1}$	$m = 10 \text{ MPa/K}$
$c = 400.0 \text{ J/(kg.K)}$	$\delta = 0.04$	$\rho \Delta s_0 = -0.115 \text{ MJ/(m}^3\text{K)}$
$H^{cur} = 0.033$	$T_0 = 313 \text{ K}$	$A_s = 217 \text{ K}$
$A_f = 290 \text{ K}$	$M_s = 264 \text{ K}$	$M_f = 160 \text{ K}$
$n_1 = 0.17$	$n_2 = 0.27$	$n_3 = 0.25$
$n_4 = 0.35$	wire dia. = 0.5 mm	

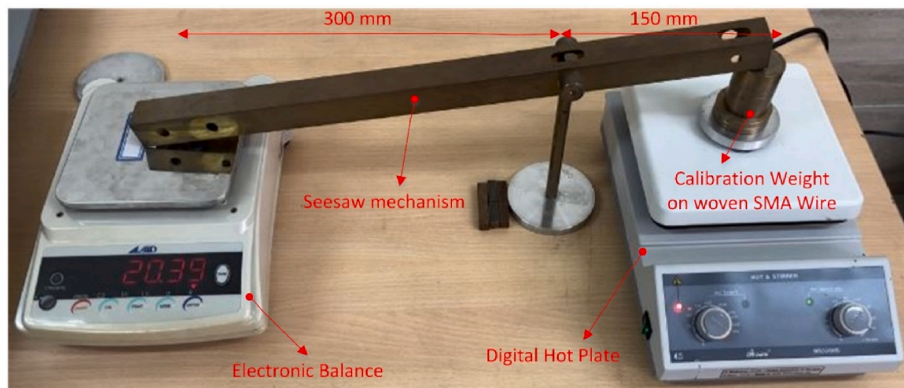


Fig. 18. Experimental set up designed to measure the effect of temperature on the force generated by woven SMA fibers.

Table 2

Compressed Non-asbestos fiber Gasket constants [19].

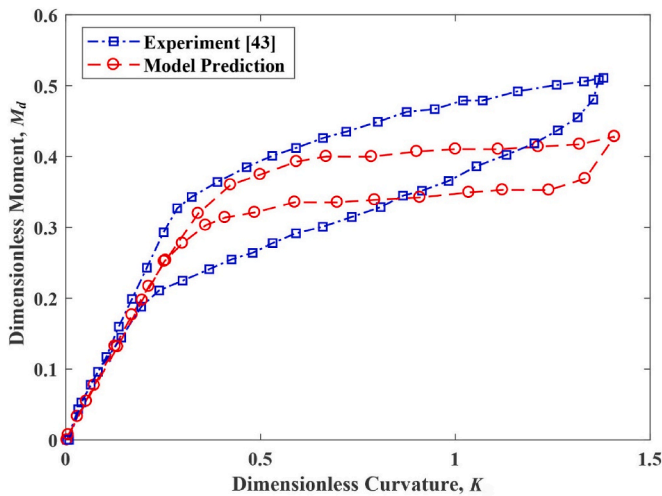
Stress - Deflection			Leak - Deflection		Compressibility ^a	Leakage ^a (Pa· $\frac{m^3}{s}$)
a	b_A	b_B	c	d	%10	0.0006–0.003
6170	2.12	9.02	1.24	86.8		

^a Leakage data at a tightening stress of 19.6 MPa and an internal pressure of 0.98 MPa (for N₂ gas) and compressibility data at a stress of 34.3 MPa, for a thickness range of 1–3 mm.

Table 3

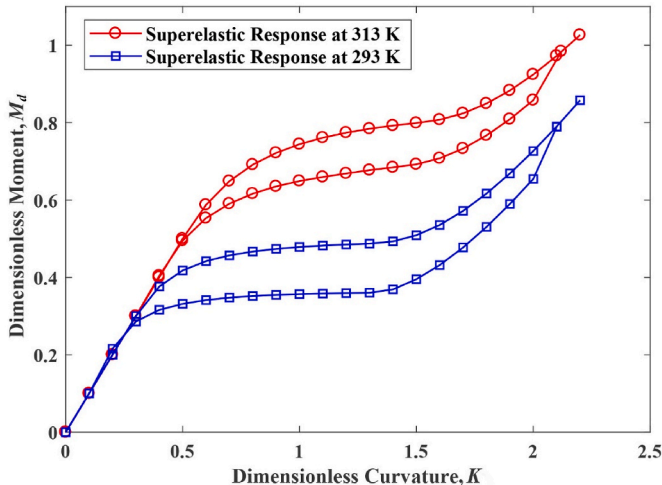
Parameters of the mathematical model relating the applied torque and tension in the bolt (Eq. (49)).

p	μ_t	$\frac{d_2}{d_1}$ (inch)	μ_n	$\frac{d_o}{d_i}$ (inch)	$\frac{d_i}{d_o}$ (inch)
1/11	0.12	0.566	0.16	1.06	0.624

**Fig. 19.** Comparison of the current analytical solution and the experimental superelastic M - K results at 298 K.

and the simplified assumptions of the analytical derivation [43,46].

Fig. 20 illustrates the effects of the bending moment applied to the Nitinol element at two distinct temperatures, namely 293K and 313K. The applied moment is continued until a complete phase transformation

**Fig. 20.** Effect of temperature on M - K loops.

from austenite to martensite occurs during the loading, and vice versa during the unloading. At higher temperatures (ct. 313K), the stress levels required for the phase change would elevate, causing whole response to shift towards higher values.

In order to further classify the way the SMA wire response evolves with rising temperature, the Lagoudas model is employed. As depicted in Fig. 21, it is evident that stress exhibit a substantial increase at 313K in contrast to the material behavior at 293K. Similar changes are also evident in the moment-curvature diagram.

Table 4 presents the ratio of bending moments for two methods of weaving Nitinol wire on the active gasket layer at two distinct temperatures. Since the radii of curvature of the woven wires on the gasket are not exactly the same at different points, a range of curvature radii are assumed, as defined in Table 4. It is observed that an increase of up to 36 percent is expected in constant curvature due to a temperature rise of 20K. Moreover, with an increase in temperature, a larger area of the cross-section remains in the austenitic phase, thereby allowing for higher moment capacity at any specific curvature.

In order to examine the SMA gasket performance at different temperatures, a test setup presented in Fig. 17 is used to examine the ability of woven Nitinol wires (type II) to lift a kilogram of calibration weight, when the temperature rises. According to Table 5, it seems that in the case where the initial temperature is 263 K, compared to the case with the initial temperature of 300 K, the woven fibers possess a lower load bearing capacity. As a result, the fibers bend more under the external weight and deform to a larger extent after heating, pushing the weight upward further. It can be mainly attributed to the phase transformation from the mixture state to the austenitic state. In this section, 1 kg of weight (equal to 10 N) is assumed as W_l in Eq. (48).

Fig. 22 illustrates the diagram of leakage rate versus gasket deformation induced by applied stress for two cases of with and without the effect of temperature. It is mainly because of increased deformation of the gasket layers at areas where the wires are laid (see A_c in Fig. (16)). Also, in the cases where the bolts are tightened with a higher torque (from 600 N to 6600 N in each bolt), the positive effect of temperature increase of SMA wires decreases.

The woven wires are restricted in terms of curvature during the heating (displacement control approach). So, an increase in temperature transforms a larger volume of wire from the mixture phase to the stiffer austenite state, allowing it to withstand more caliber weight. For further details on the superelastic behavior of Nitinol under pure bending see Refs. [45,47]. The load or displacement control types of the loading are important in studying the bending of Nitinol wires. In other words, there can be control either over the bending moment of the wire or its curvature.

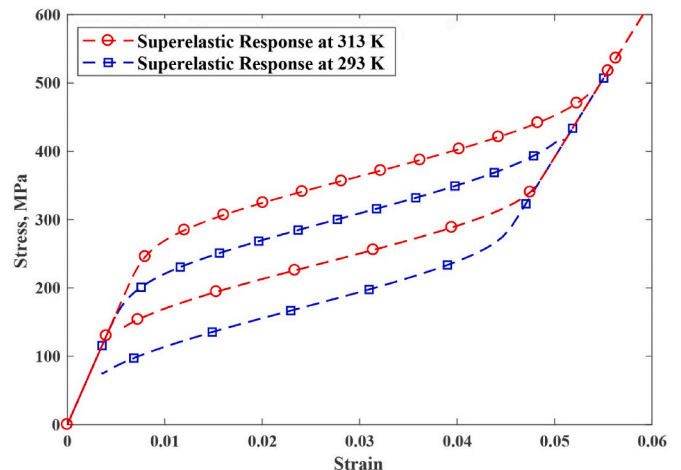
**Fig. 21.** Stress-strain response of NiTi wire in different initial temperatures.

Table 4

Dimensionless bending moments for the weaving Nitinol wire on the active layer at two distinct temperatures.

Type of gasket	K	$M_d(293\text{ K})$	$M_d(313\text{ K})$	$\frac{M_d(293\text{ K})}{M_d(313\text{ K})}$
Single-wire	0.80	0.46	0.69	0.67
discontinuous form	0.90	0.47	0.72	0.65
(type I)	1.00	0.48	0.74	0.64
Two-wire	0.37	0.38	0.41	0.92
continuous form	0.5	0.40	0.47	0.85
(type II)	0.75	0.42	0.64	0.65

Table 5

Results of the displacement test.

Type of gasket	lifting weight (Kg)	T_1 (K)	T_2 (K)	lifting height (mm)
Two-wire	1	263	323	0.07
continuous form (type II)	1	300	323	0.03

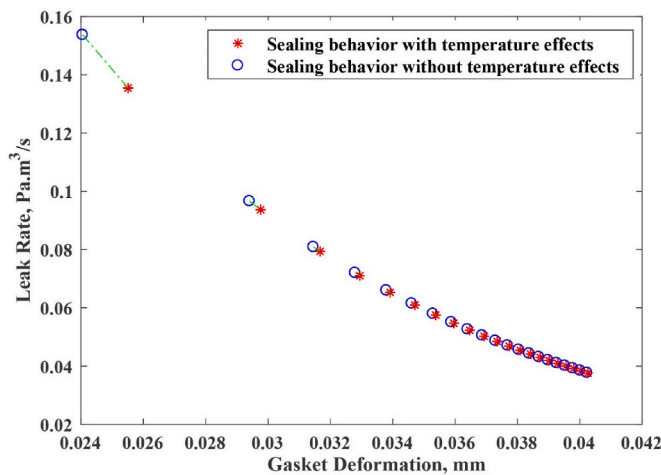


Fig. 22. Comparison of the sealing behavior of the SMA gasket with and without temperature change in 21 cases of initial tightening bolts (Fig. 16-a).

3.2. Experimental results

The primary goal is to examine the sealing performance by applying the superelastic effect of Nitinol shape memory alloy wires, which are woven into the gasket. Each SMA fiber-reinforced gasket is installed in the test setup, and its performance is evaluated using a helium leakage test.

3.2.1. Comparison of simple and SMA gaskets

In this section, the performance of a gasket reinforced with Nitinol fibers is compared with that of a conventional simple gasket. Both types consist of three layers of fiber-elastomer gaskets with thicknesses of 0.5–1.0–0.5 mm. In the case of SMA gasket, Nitinol wires with a diameter of 0.5 mm are utilized in the two-wire continuous form (Fig. 8-b, type II).

The results of this comparison are illustrated in Figs. 23–26. According to Fig. 23, the use of Nitinol fibers results in a minimal pressure drop (approximately 5 Psi (34.5 kPa)) after 9000 s. In contrast, the simple gasket exhibits a pressure drop of approximately 35 Psi (241 kPa) in identical conditions and over the same duration. This improvement in leakage performance is even more remarkable when the connection is subjected to bending. In such cases, the pressure drop with Nitinol gaskets is 22 times lower than that with simple gaskets after

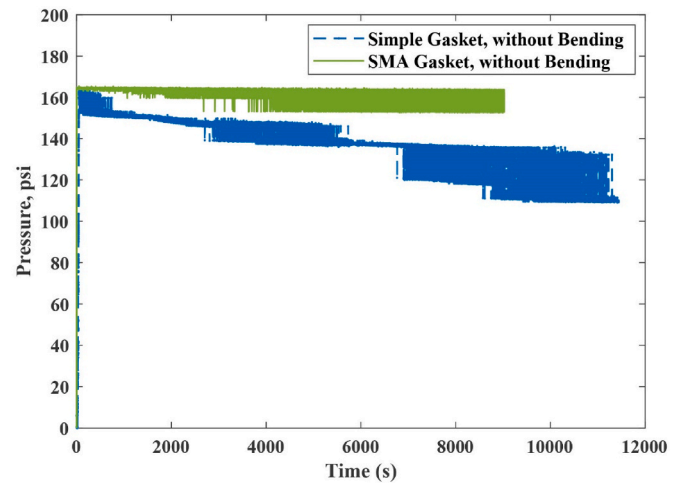


Fig. 23. Variations of pressure with time for SMA and simple gaskets (without bending).

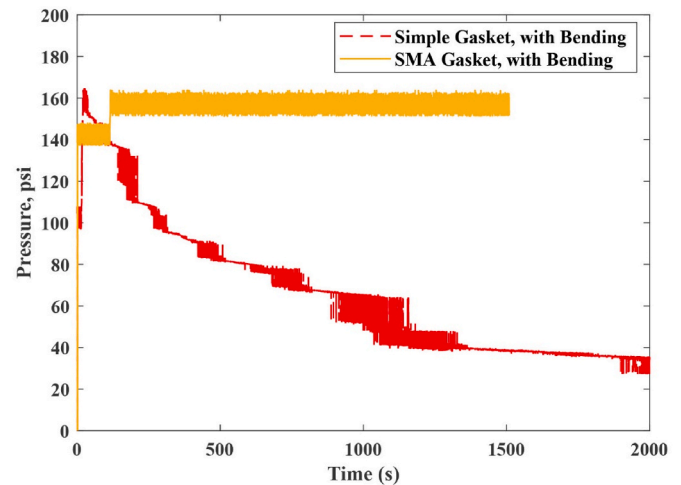


Fig. 24. Variations of pressure with time for SMA and simple gaskets (with bending).

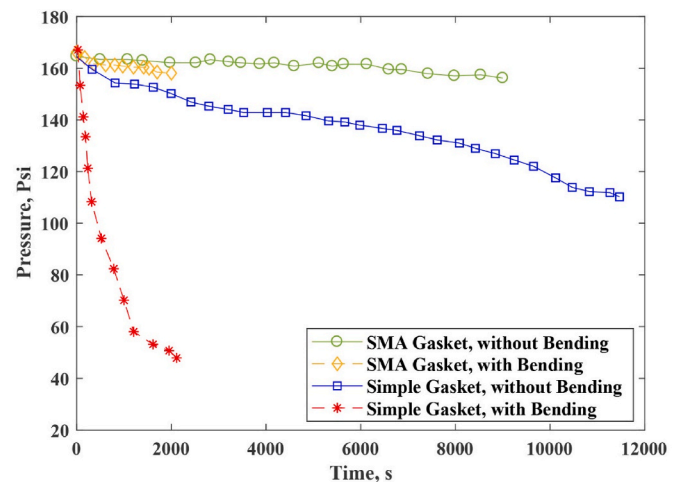


Fig. 25. Variations of average pressure with time for SMA and simple gaskets.

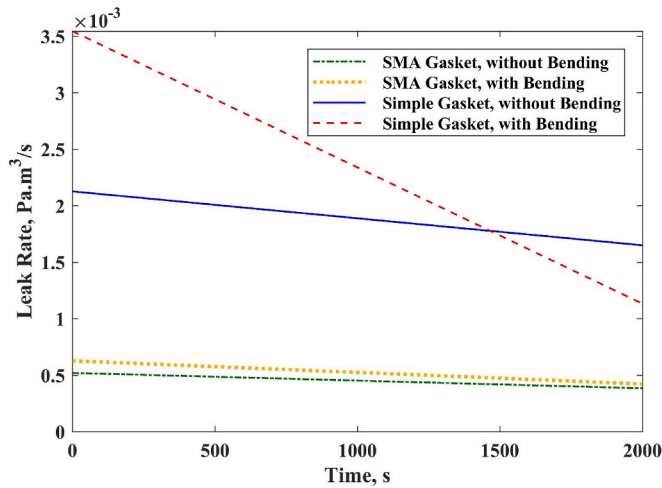


Fig. 26. Variations of average leak rate with time for SMA and simple gaskets.

approximately 2000 s, as shown in Fig. 24. Fig. 25 provides a comparative overview of the average results obtained from the tested samples. Furthermore, Fig. 26 highlights that the maximum leakage rate occurs with simple gaskets under bending loading conditions, which significantly differs from other scenarios.

To look deeper into this matter, the Nitinol gasket is disassembled after undergoing the helium leak test. Upon inspection, it becomes evident that the shape memory wire has retained its original shape and has not entered the plastic deformation region. Furthermore, it still exhibits a tendency to open and move away from the surface of the middle layer. The behavior of SMA wires, particularly their superelastic property, has significantly contributed to improvement of the gasket performance. The reason can be attributed to the application of force in the direction of gasket thickness to enhance better sealing.

3.2.2. Effect of SMA wire diameter

In this section, the effect of different shape memory fiber diameters on gasket performance is explored, as demonstrated in Figs. 27–30. The specifications of three fiber-elastomer layers are the same as the previous section. In these gaskets, shape memory wires with thicknesses of 0.3 mm and 0.5 mm are employed, as shown in Fig. (8-a, type I) and Fig. (8-b, type II), respectively.

The gasket with the 0.3-mm wire features a single-wire discontinuous form on the active layer (Fig. 8-a, type I), with closely spaced points

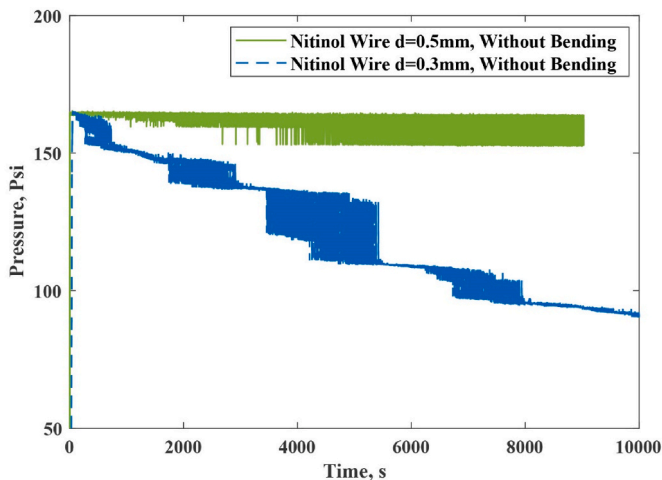


Fig. 27. Variations of pressure with time for SMA gaskets with different fiber diameter (without bending).

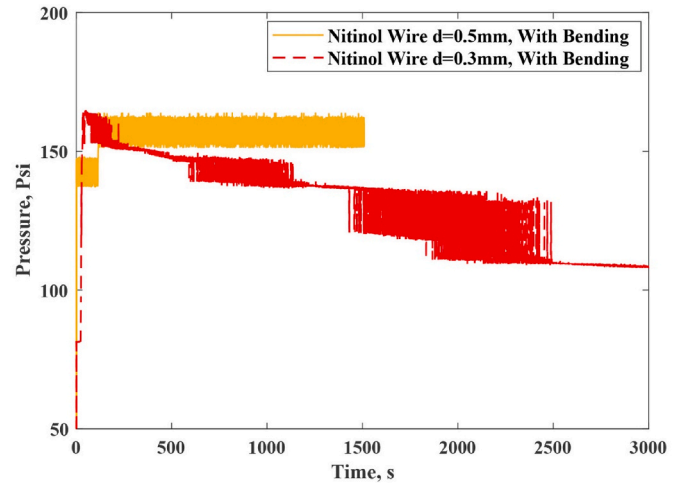


Fig. 28. Variations of pressure with time for SMA gaskets with different fiber diameter (with bending).

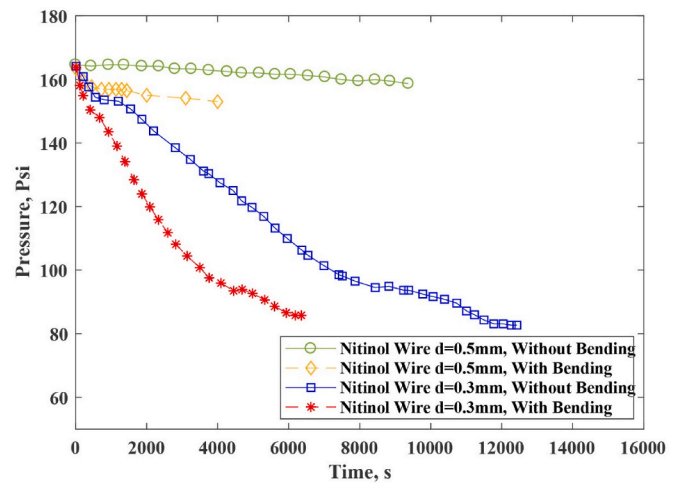


Fig. 29. Variations of average pressure with time for SMA gasket with different fiber diameters.

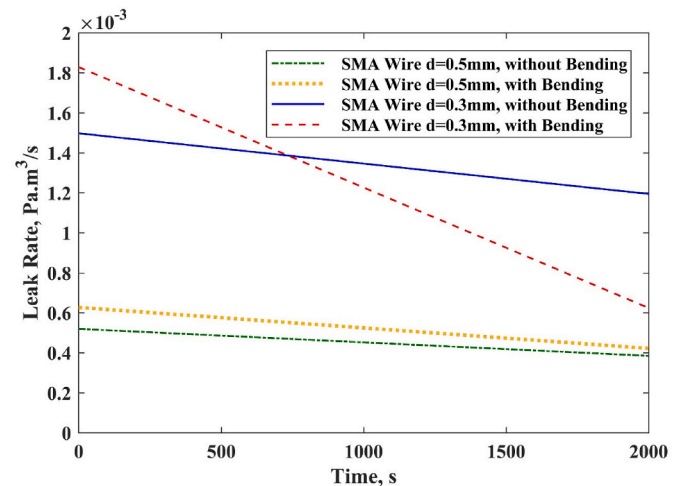


Fig. 30. Variations of average leak rate for SMA gasket with different fiber diameters.

passing through the middle layer. However, this design does not significantly improve the sealing performance, as demonstrated in Figs. 27 and 28. In contrast, significantly higher improvements are observed when a 0.5-mm shape memory wire is woven in a two-wire continuous form on the middle layer (Fig. 8-b, type II).

It is essential to note that the thickness of gasket, wire diameter, and wire weaving pattern must be carefully considered to ensure that they generate a proportional force across the thickness without causing delamination or any other types of damage to the gasket. Improper application of shape memory fibers could even reduce the contact area between the gasket and flange surfaces. The contact area between the flange and gasket directly affect the sealing performance, as shown in Figs. 29 and 30, which display the average data and leakage rates.

3.2.3. Effect of temperature on the woven SMA wire behavior

Fig. 31 illustrates the results of temperature changes versus the forces produced in the test setup described in Fig. 18. The values of the loads in this figure exceed the 1-kg calibration weight. The results indicate that greater forces are generated with increasing temperature, although the rate of change decreases. Generally, convection heat transfer is preferred for heating the SMA wire, as the conduction method can reduce accuracy due to the thermal expansion of other materials. In this study, the effect of the superelasticity of SMA fibers at different temperatures was investigated. It is expected that by utilizing the shape memory effect of SMA fibers, higher generated stress will be observed with increasing temperature.

4. Conclusion

The effect of woven Nitinol fibers on the performance of fiber-elastomer gaskets are explored in this study. Each gasket is composed of three layers, connected using RTV silicone adhesive, and with the middle active layer containing the Nitinol fibers. Both analytical and experimental studies are performed. In the analytical phase, the behavior of Nitinol wires in a woven state and subject to bending conditions is analyzed, with specific attention given to the superelastic properties of Nitinol wire. In the experimental phase, several SMA gaskets are fabricated and tested to investigate the effects of various parameters on their performance through the helium gas leakage tests.

The findings reveal that the gaskets reinforced with shape memory fibers experience an increase in stiffness and resistance to deformation due to the forces generated by the shape memory wires across the thickness. When subjected to the compression of flange faces, gaskets enter the plastic deformation region. In such cases, if the contact stress applied to the gasket from the flange decreases for any reason, such as bolt loosening or pipe bending, leakage may occur, due to gasket plastic deformation and its weakness to fill the void space between the flange surfaces. Consequently, having an active layer in the middle of the gasket that continues to remain elastic and to exert forces across the thickness can significantly enhance the sealing performance. This is precisely achieved through the use of superelastic Nitinol wires.

In summary, the following key conclusions can be made.

- An increase in the temperature leads to an increase in the contact stress of the SMA gasket, which, as a result, enhances the sealing performance.
- Despite lower volume fraction of Nitinol fibers compared to fiber-elastomer, proper arrangement of Nitinol fibers can substantially enhance the sealing performance of the composite gasket.
- Nitinol fibers prove more effective when the pipe connection experiences bending moments.
- The gasket design proposed in this study is considered cost-effective compared to previous models that utilized a SMA sheet in the gasket structure. In addition to its lower volume fraction, the superelastic wire can be readily used in a straight initial shape and does not necessitate complex shaping with special heat treatment.

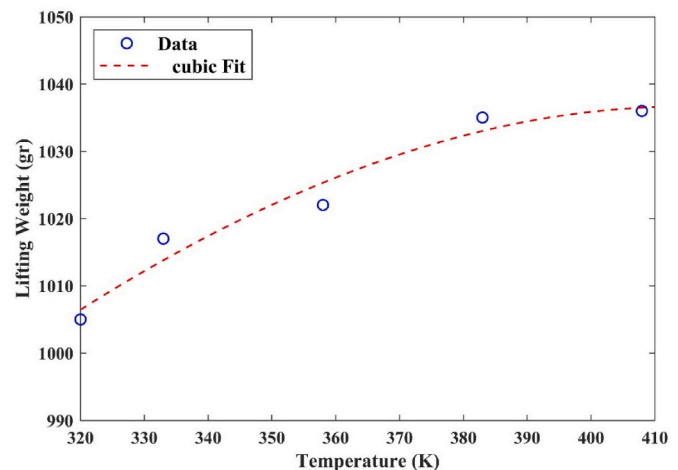


Fig. 31. Load generated from the woven SMA wire versus the applied temperature.

CRediT authorship contribution statement

Amin Ardali: Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **Jafar Rouzegar:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Soheil Mohammadi:** Writing – review & editing, Supervision, Conceptualization. **Saeede Sharifnejad:** Writing – original draft, Investigation, Data curation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to only to improve language and readability of the text. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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