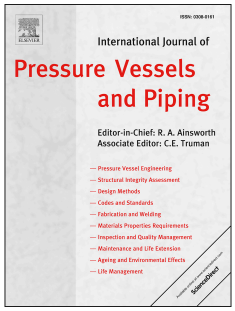


Analysis of a HDPE flanged connection with a time and temperature dependent constitutive behavior

A. Shahin, I. Barsoum, F. Korkees

PII: S0308-0161(21)00073-9

DOI: https://doi.org/10.1016/j.ijpvp.2021.104375

Reference: IPVP 104375

To appear in: *International Journal of Pressure Vessels and Piping*

Received Date: 8 October 2020

Revised Date: 1 March 2021

Accepted Date: 5 March 2021

Author Statement

Ahmed Shahin: Conceptualization, methodology, testing, analysis, modeling, Writing-original draft of the manuscript.

Imad Barsoum: Assisting with modeling, experimentation and supervision in all aspects of the work. Writing parts of the final draft of the paper.

Feras Korkees: Writing parts of paper and revising final version of paper.

Analysis of a HDPE Flanged Connection with a Time and Temperature Dependent Constitutive Behavior

A. Shahin [(1)] and I. Barsoum [(1),(2),*] and F. Korkees [(3)]

[(1)] Department of Mechanical Engineering
Khalifa University of Science and Technology
P.O Box 2533, Abu Dhabi, UAE

[(2)] Department of Engineering Mechanics
Royal Institute of Technology – KTH
SE-100 44, Stockholm, Sweden

[(3)] Materials Research Centre
College of Engineering, Swansea University
Swansea SA1 8EN, Wales-UK

* Corresponding author: imad.barsoum@ku.ac.ae

Abstract

High density polyethylene (HDPE) piping systems are used extensively in both industrial and societal infrastructure. However, their performance is sometimes impacted due to leakage through flanges, especially HDPE pipes with large diameters. Many factors affect leakage, including stress relaxation in the HDPE material and ambient temperature effects. Hence, this study investigates the effect of temperature on the leakage of a HDPE flanged connection with steel backing rings. It incorporates the effects of stress relaxation and temperature on the HDPE material and assesses the degradation of performance of the connection with time by means of finite element analysis (FEA). The temperature and time dependent mechanical properties of the HDPE material are determined experimentally through tensile, compression and relaxation testing conducted at various temperatures under isothermal conditions. The constitutive behavior of the HDPE material is modeled using the nonlinear visco-elastic plastic three network model (TNM), which predicts the mechanical behavior of HDPE markedly well. The calibrated TNM is used in the FEA study to investigate the leakage performance of the HDPE connection at various temperatures (23, 40, 60 and 80 °C) at isothermal conditions over a service time of one year. The FEA results reveal that the flanged connection can experience leakage at all temperatures due to insufficient bolt preload. It is also found that leakage occurs prematurely as temperature increases. To simulate a realistic scenario resembling an above ground piping system, an annual temperature profile for a selected geographic location was prescribed to the model to simulate leakage over a one year period. Based on the results, several bolt re-torqueing plans were explored and suggestions are made on the best bolt re-torqueing practice for preventing leakage over the service life of the HDPE connection.

Keywords: Bolted flange, HDPE, Three network model, Flanged connection, FEA, Temperature, Leakage, Torque.

1. Introduction

High density polyethylene (HDPE) pipes are common means for fluid transportation both in industrial and societal infrastructure, due to their lower cost, high corrosion resistance and high level of toughness. However, leakage is an issue that plastic pipes with large diameters can suffer from, which in some cases can be difficult to alleviate as these pipes are normally buried underground or submerged in water. In general, some of the major causes for leakage in plastic pipe connections include exposure to high temperatures [1], material stress relaxation [2, 3, 4, 5], loss of bolt preload due to elastic interactions [6, 7], insufficient bolt preload and inappropriate gasket selection in the design [8]. In response, many methods are used to prevent and deal with leakage which include retightening of bolts to higher torques and replacing the gasket altogether. Although retightening can prevent leakage, excessive retightening can lead to failure of the connection, especially at high operating pressures and temperatures [1]. Over the years, bolted flanges and their performance and tightness have been the subject of many studies, experimental and numerical ones.

Barsoum et al [1] conducted a finite element analysis (FEA) to study the performance and integrity of a HDPE stub-end bolted blind flange connection with a CNAF gasket. A temperature dependent elastic-plastic model was used for the HDPE material, whereas a non-linear through thickness compression behavior was used for their compressed non-asbestos fiber gasket. With the FEA they could assess the integrity and performance of the connection at different temperatures, bolt preloads and operating pressures through so called failure assessment charts (FACs). They concluded that as temperature increases, the window for safe operation becomes smaller and vanishes at 80 °C.

Jacobsson et al [2] studied the tightness of HDPE pipe flanges at ambient temperature with aid of FEA, and utilized a creep model with potential hardening to describe the constitutive behavior of the HDPE material. Based on their findings they report that most relaxation of bolt loads and, consequently relaxation in contact stress, occur in the first thousand hours. This numerical study was followed by an experimental investigation by Jacobsson et al [3] to validate the FEA model. It was concluded that the bolt forces are rather unevenly distributed and the use of the simplified bolt force relationship can be misleading. Moreover, the numerical analysis was found to be unrepresentative of the experiments as the bolt forces were assumed to be uniform, and they were much higher than that of the experiments. Sallstrom et al [4, 5] studied the water tightness of HDPE flange joints both numerically and experimentally. The FEA model uses a linear viscoelastic material definition for HDPE and a hyperelastic with strain hardening creep material definition for the rubber gasket. It is concluded that the joints with rubber gaskets remain tight for the simulated period of hundred years.

Many studies have assessed the leakage performance in steel flanges. Estarda [9] studied the leakage in bolted joints with an axisymmetric FEA model to investigate the evolution of contact stress in a steel flange with a gasket. The FEA results were compared with analytical calculations, which predicted pressure penetration distance values in agreement with the FEA results. Sawa et al [10] conducted a numerical study on the sealing performance of a steel box-shape flange gasketed connection subjected to internal pressure. The leakage rate obtained from the numerical results are compared to leakage rate obtained from experiments. It was concluded that the sealing performance is maximized with minimizing gasket width and flange cover thickness. Bu et al [11] analyzed numerically the contact stress in a gasketed full-face stainless-steel flange for hydrogen pipelines. The gasket used was a ring-shaped stainless-steel gasket with two conical faces on both sides, and found that the contact stress is concentered over a narrow ring on the conical surface of the gasket. Sawa et al [12] studied a stainless steel flange connection with a spiral wound gasket under internal pressure numerically, analytically and experimentally. A good agreement was reported between the analytically calculated contact stress distribution and that of the numerical model. Luyt et al [13] studied the effect of gasket creep-relaxation on steel flange through FEA. A linear visco-hyperelastic material definition was used for the gasket material, whereas the flange was modeled as a linear elastic material. It was concluded that the axisymmetric model over predicts the reduction in contact pressure with time in comparison to the full model used.

It is evident from the aforementioned studies that the majority of previous work relate to metallic flange. There seems to be a lack of studies on the combined effect of temperature and time dependent behavior on the tightness of HDPE flanged connections. Hence, the aim of the current work is to calibrate a material model to account for the time and temperature dependent behavior of HDPE. The model is used to describe the constitutive behavior of the HDPE material to predict the leakage performance over prolonged times of a HDPE flange accounting for temperature effects. The effect of bolt re-torqueing on tightness is also studied and re-torqueing time intervals are deduced from the results at various temperatures to avoid leakage due to the effect of relaxation in the HDPE material.

2. HDPE material testing and modeling

The HDPE material used in this study is BorSafe HE3490-LS [14], commonly used in pressurized HDPE plastic pipes. In the following section, the mechanical testing conducted and the constitutive model calibration based on the experimental results are presented.

2.1. Experimental setup and results

Four sets of experiments were conducted in this study to characterize the effect of temperature on the mechanical properties of the HDPE material at isothermal conditions and temperatures ranging from 23 to 80 °C. The quasi-static tensile and compression short term tests were conducted at loading rate 10 mm/min. In addition, both tensile and compression relaxation long term tests were conducted at a constant stress level of 10 MPa. The stress level was reached in 3 min and was kept constant for 1 min, after which the displacement was held constant for 8 hours to measure the relaxation force during the test. The experimental setup for both the short and long term tests is shown in Figure 1. Specimens used during testing are shown in Figure 2.

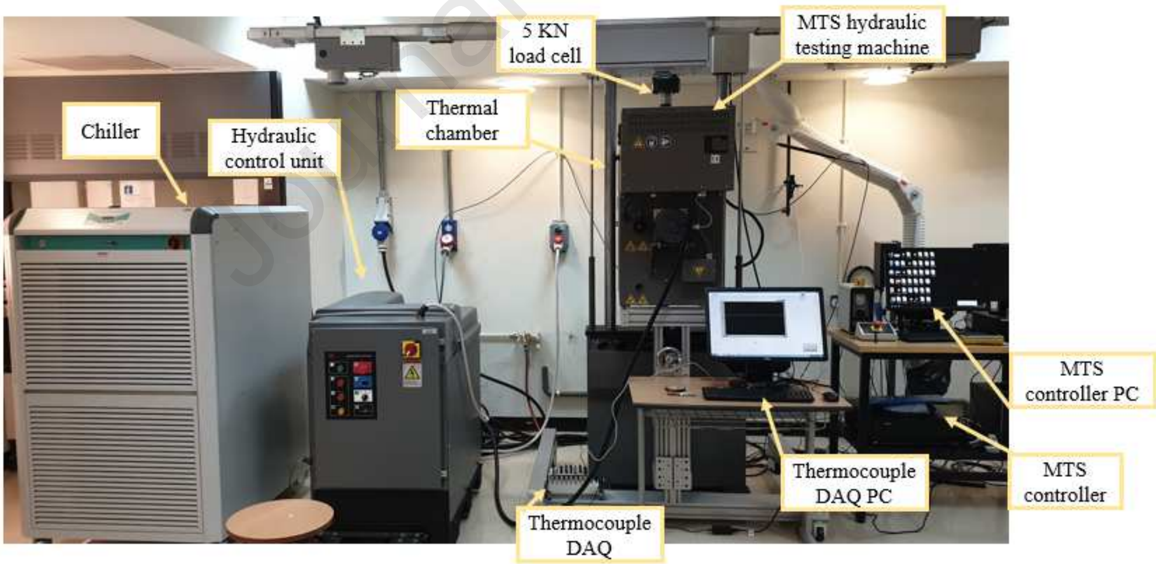


Figure 1: Experimental set up.

(a) (b) (c)

Figure 2: Test specimens used for: (a) short term tensile test, (b) short and long term compression test, and (c) long term tensile test.

All specimens were manufactured from a square slab using a CNC machine. For the short term quasi-static tensile tests as shown in Figure 2(a), a modified version of ISO 527 type BA specimen [15, 16] with 20 mm gauge length, 5 mm width and 3 mm thickness. The dimensions of the short and long term compression test specimens shown Figure 2(b), are based on ASTM D695 [17] and are solid cylinders with nominal diameter and height of 30 mm. The long term tensile tests were conducted on ISO 527 type A1 specimen [15, 16], as shown in Figure 2(c), having a gauge length of 80 mm, a width and thickness of 10 mm.

The short term tensile tests were conducted at each temperature up to the yield strength, and the short term compression tests were conducted up to 25% strain. All tests were conducted in an environmental chamber at isothermal conditions with temperatures 23, 60, 40 and 90 °C. The short term tensile and compression stress-strain curves are shown in Figure 4, whereas the stress vs. time response for the long term compression and tensile stress relaxation tests are shown in Figure 5.

2.2. Constitutive model calibration

The three network model (TNM) is an elastic-viscoplastic model and is chosen to represent the mechanical behavior of HDPE due to its versatility, accuracy, and suitability for thermoplastics in general [18, 19, 20], and HDPE in particular [21]. The TNM model is a further refinement of the hybrid model developed by Bergstrom et al [22, 23] for enhanced accuracy and numerical efficiency. Three parallel branches or networks are the bases of the TNM model, which are rheologically represented in Figure 3.

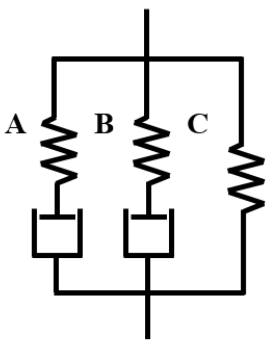


Figure 3: Rheological representation of the three network model (TNM).

The total stress over the three networks is the sum of each stress component experienced by each network. The total deformation gradient $\boldsymbol{F}$ on the TNM model consists of a mechanical and a thermal expansion component as follows

$$\boldsymbol{F} = \boldsymbol{F}^{(m)}\boldsymbol{F}^{(th)} \quad (1)$$

where $\boldsymbol{F}^{(m)}$ is the mechanical component of the total deformation gradient, and $\boldsymbol{F}^{(th)}$ is the thermal component. The mechanical component of the deformation gradient of network A and B can be decomposed into an elastic and a visco-plastic component

$$\boldsymbol{F}^{(m)} = \boldsymbol{F}_n^e \, \boldsymbol{F}_n^v \quad (2)$$

where the subscript *n* indicates either network A or B, $\boldsymbol{F}_n^e$ is the elastic deformation gradient and $\boldsymbol{F}_n^v$ is the visco-plastic deformation gradient. The Cauchy stress acting on network A and B can be expressed by the temperature-dependent version of the eight-chain model and is given in the following form [24]:

$$\boldsymbol{\sigma}_n = \frac{\mu_n}{J_n^e \bar{\lambda}_n^{e*}}\left[1 + \frac{\theta - \theta_o}{\hat{\theta}}\right]\frac{\mathcal{L}^{-1}\left(\frac{\bar{\lambda}_n^{e*}}{\lambda_L}\right)}{\mathcal{L}^{-1}\left(\frac{1}{\lambda_L}\right)}\mathrm{dev}(\boldsymbol{b}_{\mathrm{n}}^{\mathrm{e}*}) + \kappa(J_n^e - 1)\boldsymbol{I} \quad (3)$$

where $J_n^e = \det(\boldsymbol{F}_n^e)$, $\boldsymbol{b}_n^{e*} = (J_n^e)^{-\frac{2}{3}}\boldsymbol{F}_n^e(\boldsymbol{F}_n^e)^T$ is a Cauchy-Green deformation tensor, $\bar{\lambda}_n^{e*} = \sqrt{\mathrm{tr}(\boldsymbol{b}_n^{e*})/3}$ is the effective chain stretch and $\mathcal{L}^{-1}(x)$ is the inverse Langevin function where $\mathcal{L}(x) = \coth(x) - 1/x$. The Cauchy stress acting on network C can be given by [24, 25]

$$\boldsymbol{\sigma}_C = \frac{\mu_C}{J\bar{\lambda}^*}\left[1 + \frac{\theta - \theta_o}{\hat{\theta}}\right]\frac{\mathcal{L}^{-1}\left(\frac{\bar{\lambda}^*}{\lambda_L}\right)}{\mathcal{L}^{-1}\left(\frac{1}{\lambda_L}\right)}\mathrm{dev}(\boldsymbol{b}^*) + \kappa\left(J \quad - 1\right)\boldsymbol{I} \quad (4)$$

where $J = \det(\boldsymbol{F})$, $b^* = \left(J \quad\right)^{-\frac{2}{3}}\boldsymbol{F}(\boldsymbol{F})^T$ is a Cauchy-Green deformation tensor, $\bar{\lambda}^* = \sqrt{\mathrm{tr}(\boldsymbol{b}^*)/3}$ is the effective chain stretch. Since the three networks are in parallel, they have equal deformation gradients, and thus the total stress on the systems is the sum of each network stress. For more details on the formulation of the three network model, the reader is referred to [19]. The calibrated three network parameters are shown in Table 1. All TNM parameters are calibrated based on the experimental short and long term results in Figure 4 and Figure 5, except the thermal expansion coefficient (α), the reference temperature for the thermal expansion (θ_o) and the bulk modulus. The values of θ_o and α are obtained from [1], while the bulk modulus κ is obtained from [26].

The TNM model predictions of the short term tensile and compression behavior at 23, 40, 70 and 80 °C are shown in Figure 4, showing markedly good agreement with the experimental results. Similarly, the long term compression and tensile stress relaxation predictions using the TNM constitutive model at 40 and 80 °C are presented in Figure 5 and compared to the experimental relaxation curves. In general, the predictions of the TNM model, both for short and long term mechanical behavior, agree rather well with the experiments, and can be used to represent the time and temperature dependent constitutive behavior of HDPE confidently. The TNM model will be used in a FEA model for predictions of leakage performance of a HDPE flange accounting for both time and temperature effects.

Table 1: Calibrated parameters of the three network model (TNM).

Description	Symbol	Units	Value
Shear modulus of network A	μ_A	MPa	160.91
Temperature factor	$\hat{\theta}$	K	-95.77
Locking stretch	λ_L	-	8.09
Bulk modulus	κ	MPa	2590
Flow resistance of network A	$\hat{\tau}_A$	MPa	19.74
Pressure dependence of flow	a	-	0.31
Stress exponential of network A	m_A	-	6.45
Temperature exponential	n	-	38.55
Initial shear modulus of network B	μ_{Bi}	MPa	72.71
Final shear modulus of network B	μ_{Bf}	MPa	10.46
Evolution rate of μ_{Bi}	β	-	5.21
Flow resistance of network B	$\hat{\tau}_B$	MPa	200.32
Stress exponential of network B	m_B	-	17.10
Shear modulus of network C	μ_C	MPa	0.26
Thermal expansion coefficient	α	K^{-1}	1.2×10^{-4}
Thermal expansion reference temperature	θ_o	K	296

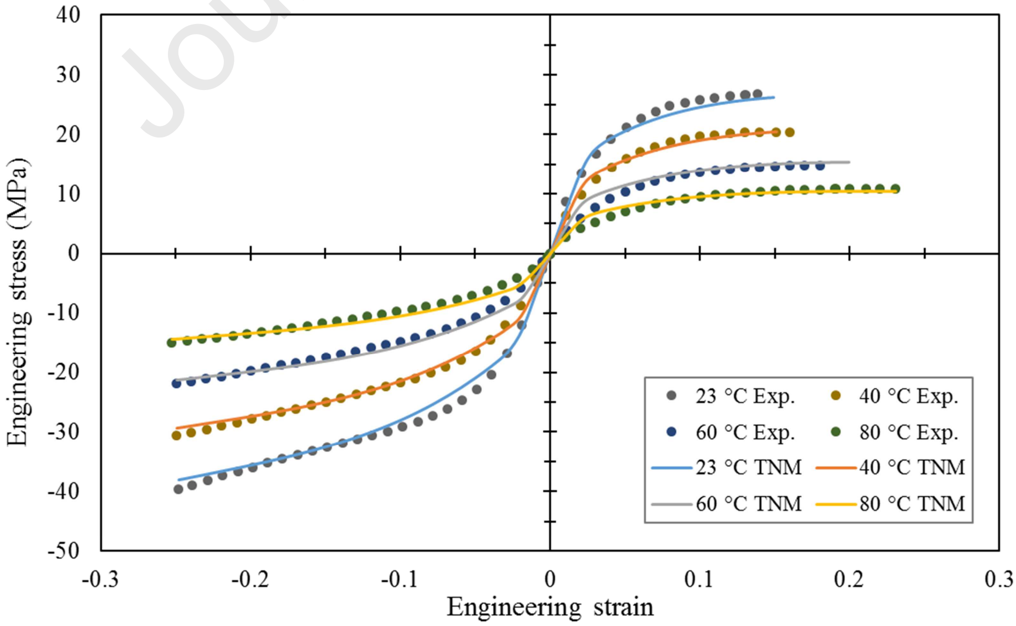


Figure 4: Short term tensile and compression engineering stress strain curves vs TNM predictions at various temperatures.

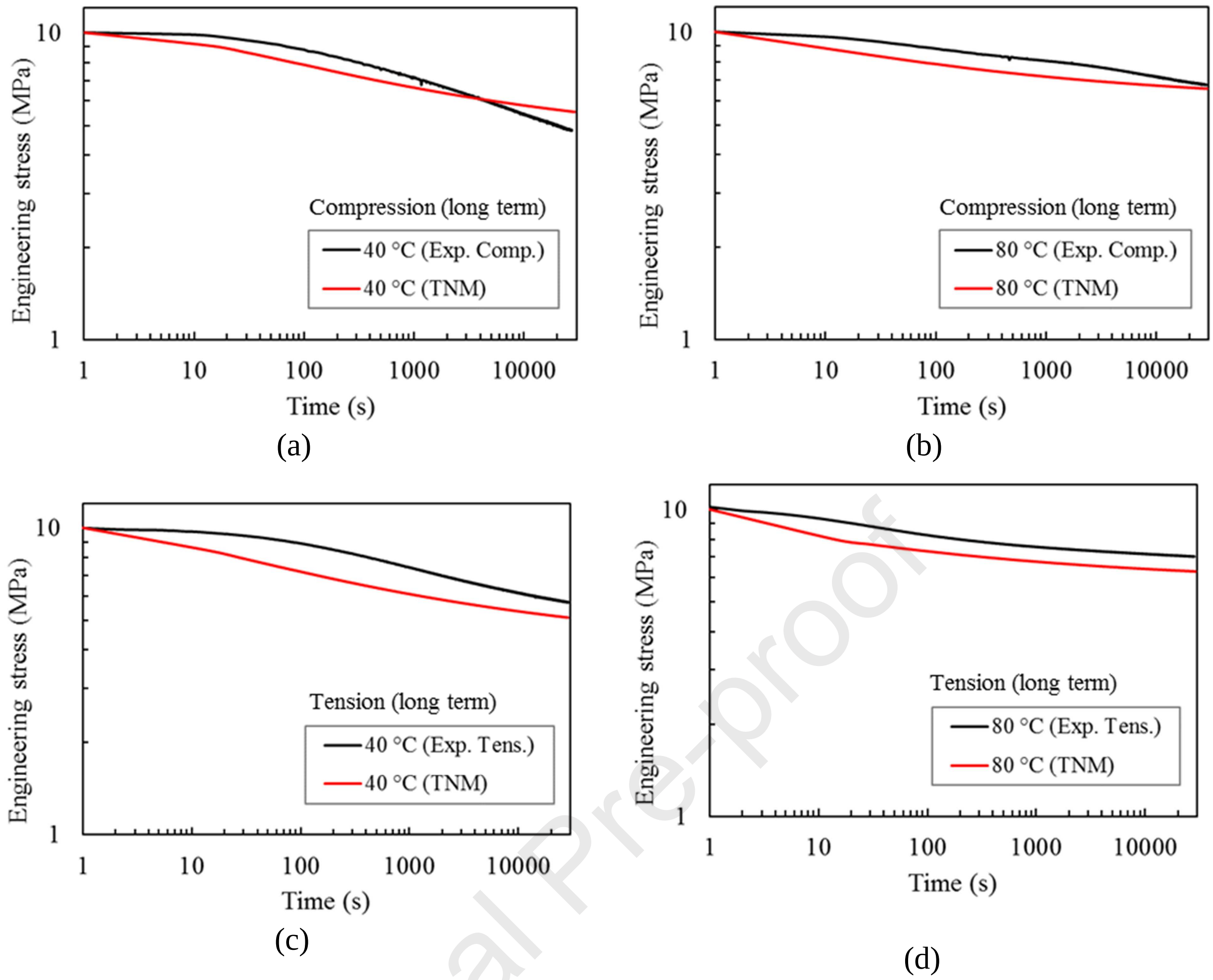


Figure 5: Comparison and tensile of long term relaxation test results with TNM predictions: (a) compression at 40 °C, (b) compression at 80 °C, (c) tensile at 40 °C and (d) tensile at 80 °C.

3. FEA model of the HDPE flange connection

The FEA model of the HDPE flange connection is developed in Abaqus/Standard [27]. A flat face HDPE PE-100 flanged connection is considered, with a pipe size of 2000 mm in outer diameter and wall thickness of 95 mm, as shown in Figure 6. The flange faces are joined with steel backing rings using a total of 64 bolts with a nominal diameter of 50.8 mm and a nut height of 50.8 mm. Cyclic symmetry boundary conditions are utilized to simulate a 1/64 segment of the entire flange connection to reduce computational cost as shown in Figure 6. The flange is meshed with 51,100 eight-node linear brick elements with hybrid formulation (C3D8H), whereas the steel backing rings and the steel bolt are meshed with eight-node linear brick elements with reduced integration and hourglass control (C3D8R).

The top and lower surfaces of the pipe section are constrained in the *z*-direction to prevent rigid body rotation. A general contact interaction is utilized with a friction coefficient of 0.2 [1]. All steel components (e.g. backing rings, bolts and nuts) are modelled as elastic solids with elastic modulus of 200 GPa, Poisson's ratio of 0.33 and thermal expansion coefficient of $11.7 \times 10^{-6}\ K^{-1}$. The HDPE material is modelled using the calibrated TNM model.

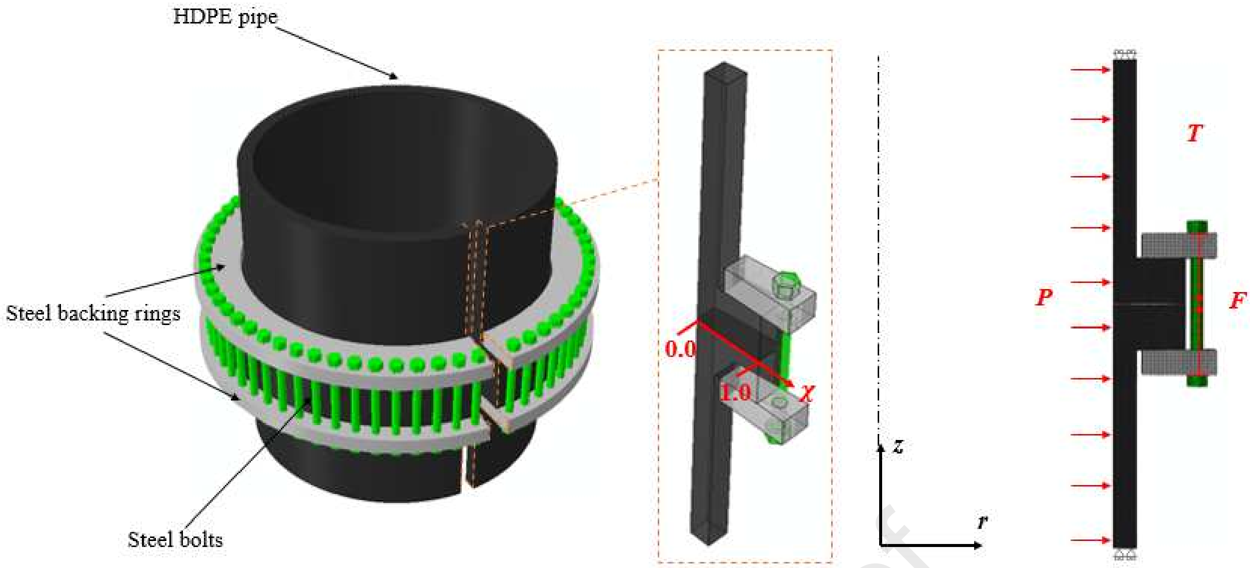


Figure 6: FEA model of the HDPE flange connection.

According to DVS 2210-1 [28], a torque of 660 Nm is required to seal a 1800 mm HDPE flanged connection with an EPDM gasket. However, since no gasket is considered in the current analysis a slightly increased reference torque of 690 Nm will be used in this study. For the purpose of this study, the relationship between torque and bolt preload will be determined using the following simplified expression

$$T = KFd \tag{5}$$

where T is the torque, K is the so called torque coefficient, F is the bolt preload, and d is bolt nominal diameter. Zinc platted bolts are assumed in this study, which has a torque coefficient of 0.25 [29]. This resulted in an initial bolt force of 54.3 kN. For the cases were re-torquing is simulated, two re-torque bolt force values are used, e.g. 54.3 kN and 108.6 kN corresponding to a torque value of 690 Nm and 1380 Nm, respectively.

The applied internal pressure (P) on the pipe internal surface is 0.6 MPa, which is used to define the leakage criteria based on the average contact stress of the flanged surface. According to [30], no leakage occurs when there is no gap between metal to metal flanges, even if the contact stresses tend to zero. Moreover, according to [29], a working pressure of 1.38 MPa would require at least 4.34 MPa of average contact stress for an HDPE gasketless flanged connection with steel backing rings to maintain tightness (at temperatures lower than 38 °C), which is about 3.14 times the working pressure. For the pressure level of 0.6 MPa used in this study, this would correspond to a contact stress requirement of 1.89 MPa, hence a minimum average contact stress over the HDPE flange surfaces of 2 MPa are chosen to represent the leakage criterion. This implies that when the average contact stress is lower than 2 MPa, tightness is not guaranteed.

To simulate temperature effects on tightness, it is assumed that the initial tightening of bolts and pressurization take place at room temperature (e.g. 23 °C), and thereafter heating to higher temperatures occurs linearly during the next eight hours. According to PPI guidelines [31] , the surface temperature of HDPE can increase up to 80 °C when subjected to direct sunlight in unshielded above ground piping systems. Thus, four reference cases are simulated with no re-torqueing of bolts, which correspond to relaxation from the initial tightening of bolts at four different temperatures at isothermal conditions, e.g. 23, 40, 60 and 80 °C. In order to study the effect of re-torqueing on relaxation, two cases are simulated with re-torqueing at 23 and 60 °C (8 hours heating).

In addition, to simulate a realistic scenario resembling an above ground piping system, an annual temperature profile for a selected geographic location representing the Arabian Gulf [32], shown in Figure 7, was prescribed to the model to simulate leakage over a one year period. This temperature profile will be used to simulate the performance of the HDPE flange in both leakage and yield. When the average contact stress drops below 2 MPa, re-torqueing will be initiated.

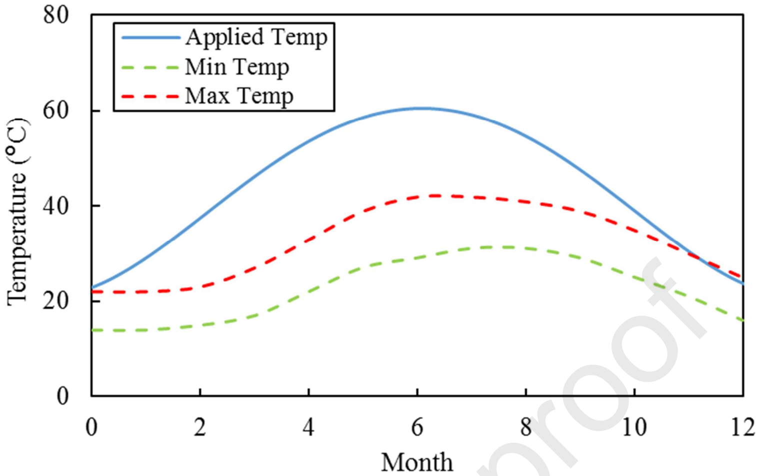


Figure 7: Annual temperature cycle [32].

4. Results: without re-torqueing

In this section, the simulation results of the relaxation behavior of the flanged connection are presented during one year of service. Moreover, the results are presented in terms of bolt load, contact stresses over the flange surfaces and deformation contours of the von-Mises stress for the cases with isothermal conditions without re-torqueing.

4.1. Bolt loads

The bolt forces relaxation with time for the four isothermal cases with 23, 40, 60 and 80 °C are shown in Figure 8, pertaining to relaxation at the various temperatures after the pressurization step. It can be noted that most of the bolt load relaxation occurs in the first 1200 hours, which agrees with the observation made by Jacobson et al [2, 3]. The thermal expansion has a significant effect on the bolt force variation vs. time as evident from Figure 8(b), pertaining to the first twelve hours of relaxation when thermal loads are active. As thermal load is applied, the bolt force increase due to the thermal expansion of the HDPE material, and this effect increases with increase in the applied isothermal load (e.g. temperature). This is attributed primarily to the thermal expansion of the HDPE, but also to the decrease in stiffness of the HDPE material at higher temperatures. However, as time elapses relaxation in the HDPE starts to dominate the mechanical response, which is manifested in a decrease in bolt force with time, e.g. after twelve hours. Subsequently, the bolt force continues to drop due to stress relaxation and reaches a plateau value, which is similar to what was observed in the stress relaxation experiments. It is also worth noting that flange rotation becomes more prominent as temperature increases as a consequence of the applied internal constant pressure and decrease in stiffness of the HDPE material. The flange rotation manifest itself in an increased bolt load at higher temperatures, as evident from Figure 9, and hence the increase in the plateau value of the bolt force (e.g. after 1 year) with increase in temperature.

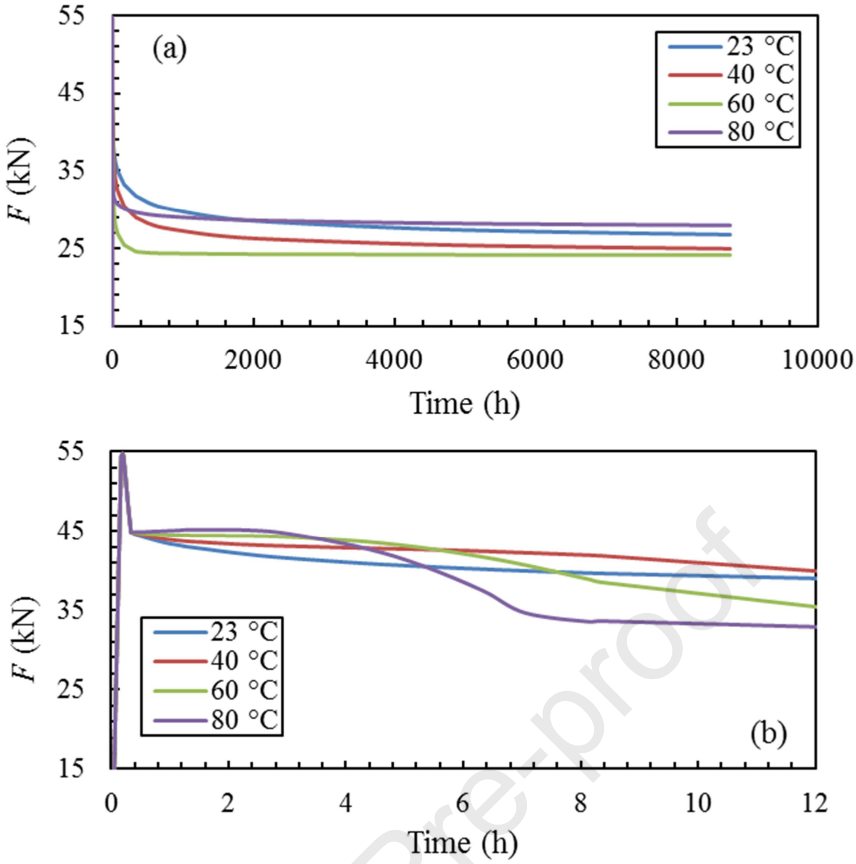


Figure 8: Bolt load (F) relaxation for 23, 40, 60, and 80 °C: (a) up to 10 000 hours and (b) during the first 12 hours.

4.2. Contour plots

In Figure 9 the von-Mises (σ_{vM}) and the contact stress (σ_c) contour plots are shown for the initial stage of bolting (e.g. F = 54 kN) and pressurization (e.g. P = 0.6 MPa), which are identical for all cases, and the subsequent relaxation stage at the isothermal temperatures 23, 60 and 80 °C.

After the bolting step, about 60% of the flange surface is compressed, whereas the remaining part of the flange is not in contact as evident from both the σ_{vM} and σ_c contours in Figure 9(a). After the pressurization step, both σ_{vM} and σ_c change and the active contact area decreases to about 30% of the total flange surface due to flange rotation. In the subsequent steps, the relaxation stage of the analysis is activated and the HDPE material is allowed to relax. As shown in Figure 9(b), the von-Mises stress σ_{vM} after 8 hours relaxation from pressurization at 23° has decreased, which is also manifested in the decrease in the contact stress σ_c. After 12 months, the effect relaxation is more pronounced and accompanied by a rotation of the flange and bulging of the pipe section as a result of creep in the HDPE material due to the active applied internal pressure. A similar trend can be observed for the 60 °C and 80 °C cases in Figure 9(c) and (d), respectively, which are also accompanied by the effect of thermal expansion. It can be noted that relaxation is accelerated during the first 8 hours as temperature increases, and the rotation of the flange and bulging of the pipe section is more pronounced due to the decrease in stiffness with increase in temperature. For the case of 80 °C in Figure 9(d), the von-Mises stress σ_{vM} has decreased considerable after 12 months and the contact stress σ_c has almost diminished potentially leading to leakage. Moreover, the excessive rotation of the flange due to creep creates a gap between the flanges which further promotes leakage.

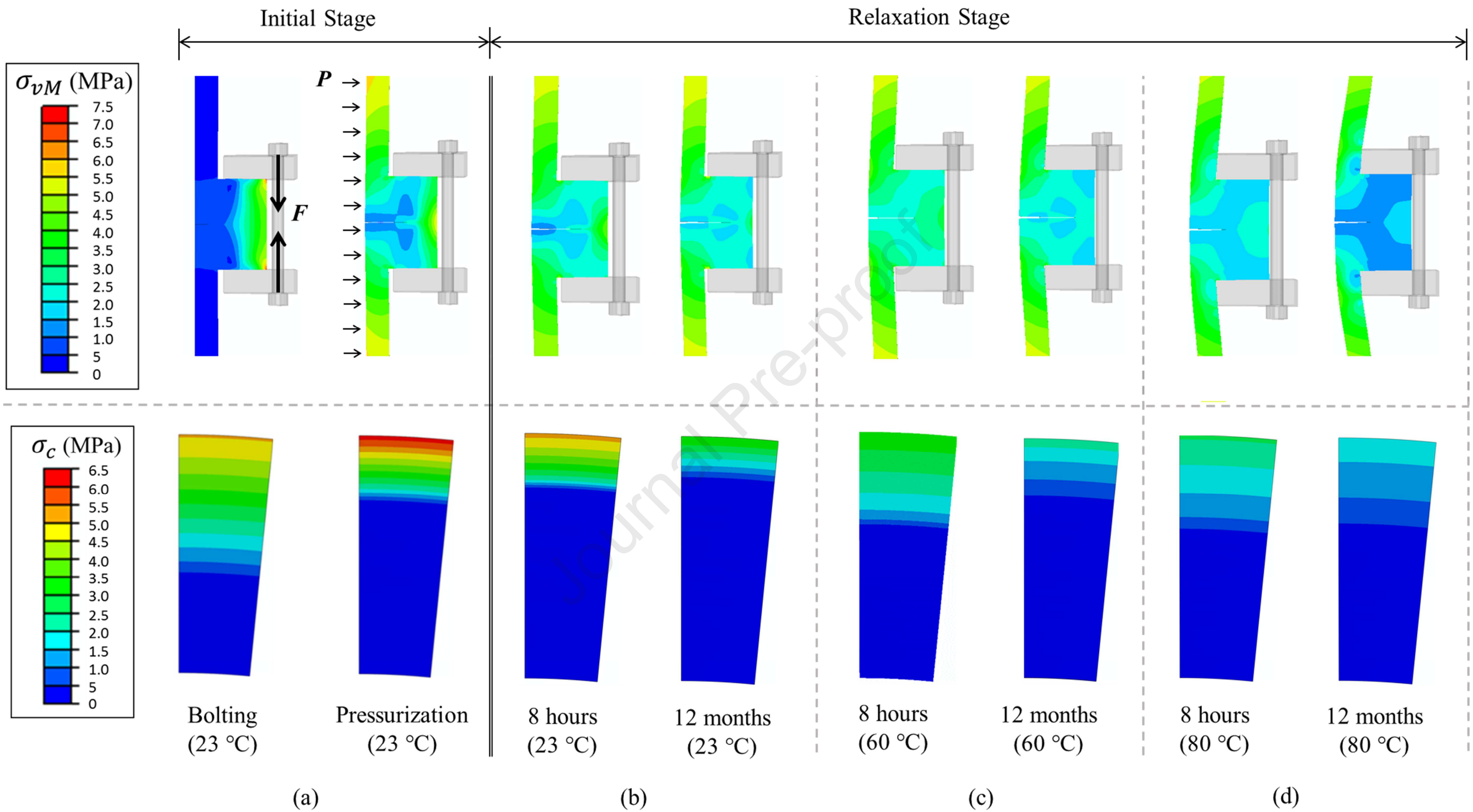


Figure 9: Contour plots of von-Mises stress σ_{vM} and average contact stress σ_c for: (a) the bolting and pressurization steps at 23 °C, and relaxation at (b) 23 °C, (c) 60 °C and (d) 80 °C after 8 hours and 12 months from pressurization.

4.3. Contact stress

The contact stress is assessed along the normalized χ-axis along the surface of the flange, where $\chi = 0$ corresponds to the inner surface of the flange and $\chi = 1$ to the outer edge of the flange as indicated in Figure 6. The variation of contact stress σ_c vs. χ is plotted for the initial stage (e.g. bolting and pressurization) and the subsequent relaxation stage for all temperatures considered (e.g. 23, 40, 60 and 80°C) at different time frames (e.g. 1, 6 and 12 months).

As can be seen from the Figure 10(a), only about 60 % of the flange surfaces (e.g. $\sigma_c > 0$) are in contact after bolting, which reduces to about 30 % after pressurization. The reduction in contact area is attributed to the flange rotation after application of the pressure. After 8 hours of relaxation, the contact surface areas (e.g. $\sigma_c > 0$) at 60 and 80 °C are larger than at 23 °C, which can be explained by the fact that the flange at 60 and 80 °C has more rotation due to lower stiffness. The drop in contact stress due to relaxation is most significant after 8 hours (c.f. Figure 10(b)) and decreases slightly after that. The change in contact stress is not as significant between 6 months (c.f. Figure 10(c)) and 12 months (c.f. Figure 10(d)).

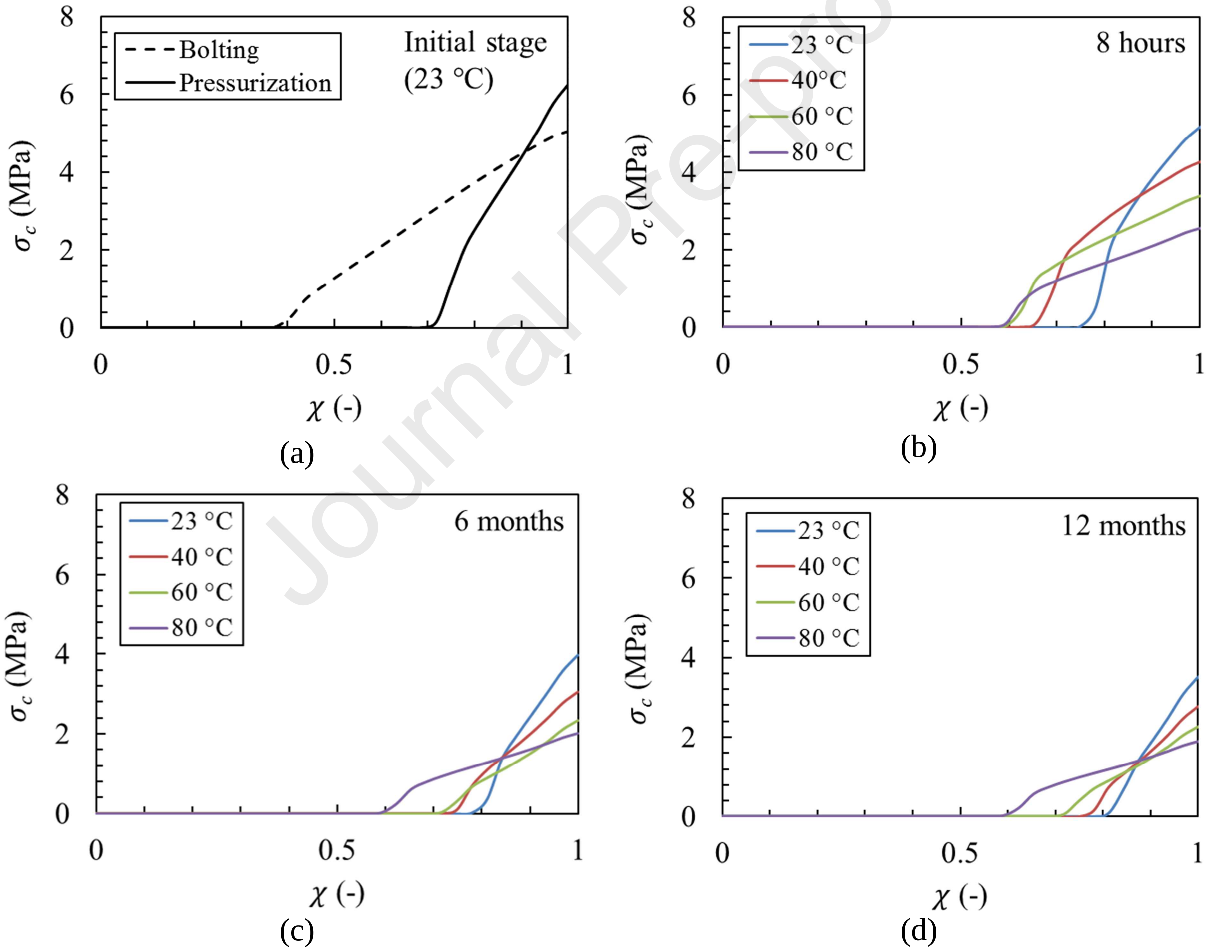


Figure 10: Contact stress σ_c variation with normalized distance χ after initial stage (a) of bolting and pressurization, and relaxation stage after: (b) 8 hours, (c) 6 month, (d) 12 months.

The maximum contact stress (σ_c^{max}) is always located at $\chi = 1$, which corresponds to the outer edge of the flange and drops rapidly with temperature as expected, which is consistent with the relaxation tests. Figure 11 σ_c^{max} vs. time is plotted, pertaining to the relaxation of maximum contact stress and showing a significant effect of temperature on relaxation.

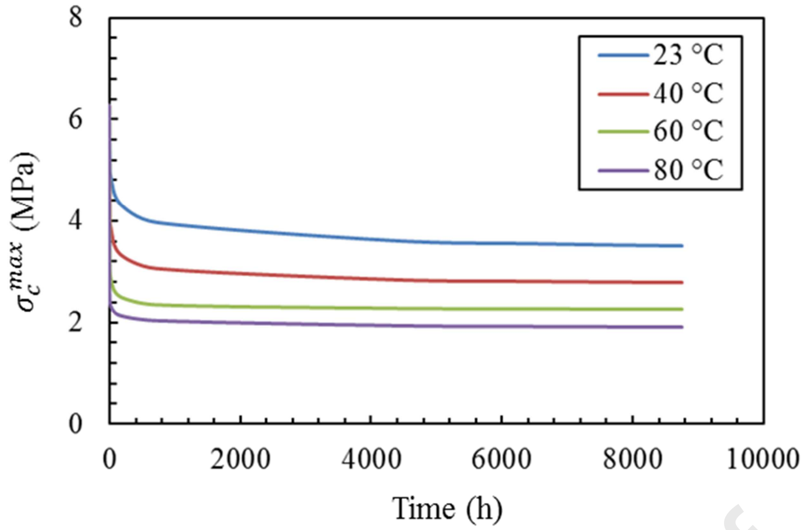


Figure 11: Maximum contact stress (σ_c^{max}) variation vs. time for all temperatures.

The maximum contact stress, which occurs along the outer edge of the flange is not an appropriate measure for assessing leakage [1], especially as the magnitude and distribution of contact stresses are highly dependent on temperature and time. In order to assess the leak tightness of the flange connection, the average compressive contact stress (σ_c^{ave}) evaluated along the surfaces in contact is here used to assess tightness and is defined as

$$\sigma_c^{ave} = \frac{1}{1-x_0}\int_{x_0}^{1} \sigma_c(\chi)\, d\chi \tag{6}$$

where $\sigma_c(\chi)$ is the contact stress as a function of normalized distance (c.f. Figure 10), and x_0 is the normalized distance of the first non-zero contact stress location. The average contact stress σ_c^{ave} is then plotted in view of the minimum required contact stress (e.g. 2 MPa) to guarantee flange tightness. In Figure 12 average contact stress σ_c^{ave} is shown versus relaxation time (logarithmic) and temperature along with the minimum required contact stress, revealing that temperature has a significant effect on σ_c^{ave}, and consequently on tightness. As the temperature increases, a large drop in σ_c^{ave} occurs, especially at longer times, and hence achieving tightness at higher temperatures is much more difficult than that at 23 °C. This shows the significance of accounting for temperature effects of flanges when exposed to elevated ambient temperatures during service.

It is clear that for the current torque level (690 Nm) and operating pressure (0.6 MPa), tightness cannot be guaranteed after one year of service (e.g. σ_c^{ave} < 2 MPa) for any of the temperature levels. Leakage occurs earlier at higher temperatures than at 23 °C, which further emphasizes the importance of the temperature effect on tightness. Hence, the requirement for re-torqueing is essential for maintaining tightness of the flange connection over its service time.

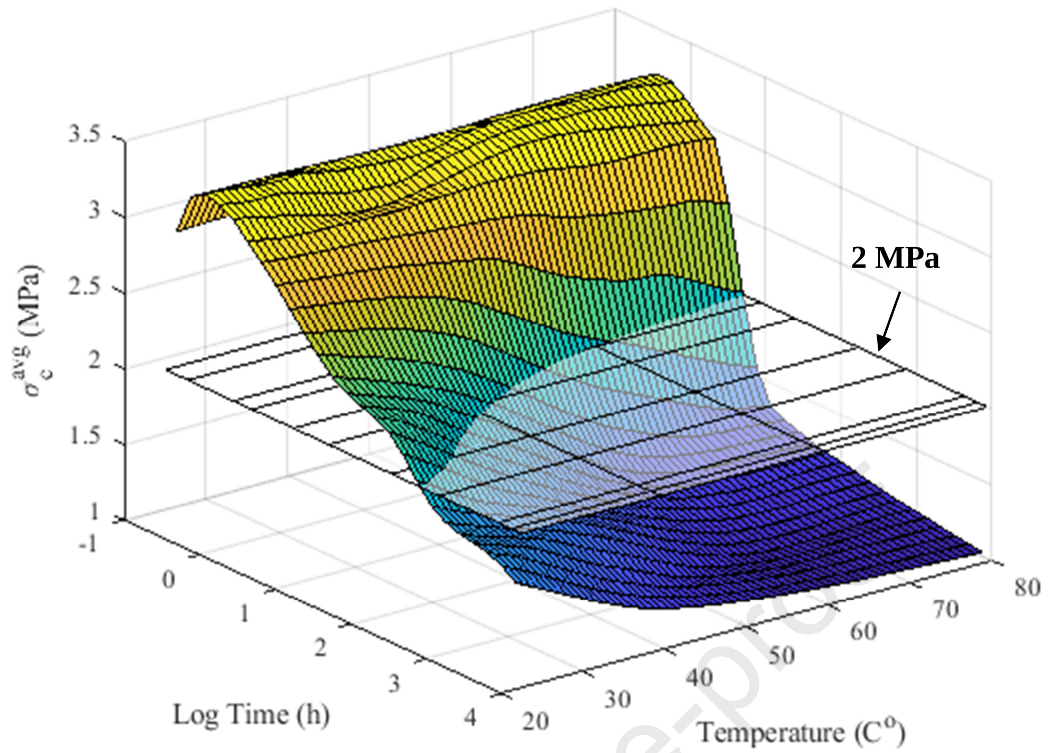


Figure 12: 3D envelope of average contact stress variation with logarithmic time with leakage plane

5. Results: with re-torqueing

As was shown in previous section, the relaxation is significant over time and is more pronounced at increased temperature levels leading to leakage. Hence, in this section the effect of re-torqueing on the tightness of the connection over time is explored using the calibrated TNM and developed FEA model.

In addition to the tightness requirement, here the safety factor against yielding the HDPE material is defined as

$$SF_y = S_y \, / \, \sigma_{vM}^{max} \quad (7)$$

where σ_{vM}^{max} is the maximum von-Mises stress in the flange and pipe section, and S_y is the tensile yield strength as a function of temperature obtained from the experimental results [33] and is given by

$$S_y = \ 30.689 \ - 0.2539 \, T \quad (8)$$

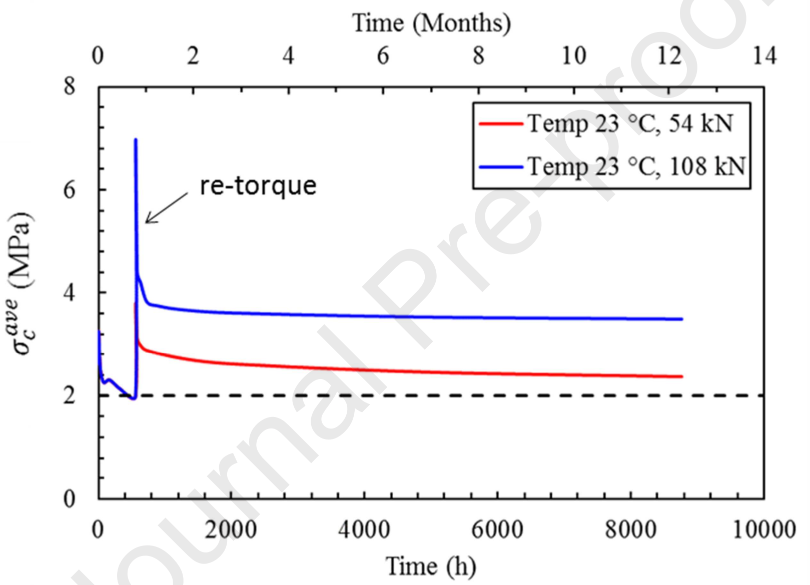
To ensure tightness the average contact stress is required to be larger than 2 MPa (e.g. $\sigma_c^{ave} \geq 2$) and to ensure protection against yielding the safety factor against yielding is required to be larger than 2 (e.g. $SF_y \geq 2$). When both criteria are met, safe operation and performance of the flange connection is guaranteed.

5.1. Constant temperature

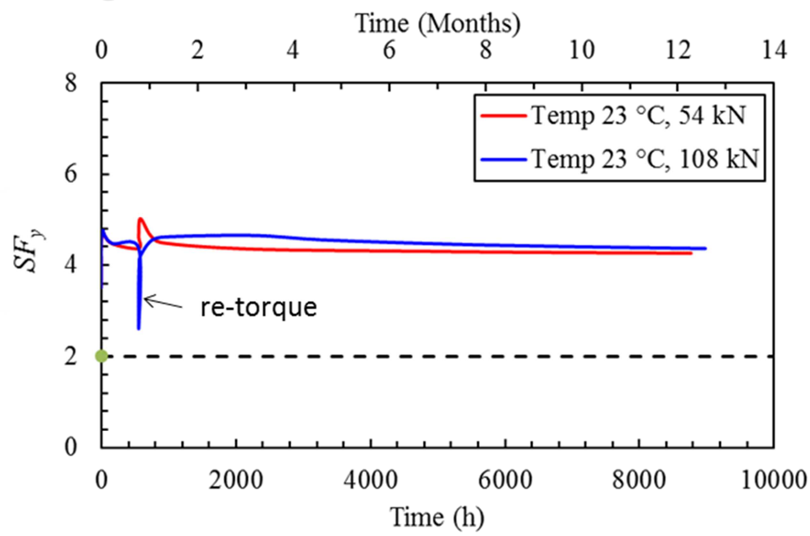
Here the results for simulations with a constant temperature load over time are presented, pertaining to the cases with 23 and 60 °C.

Two re-torqueing forces are considered, 54 kN corresponding to the initial bolt force and 108 kN corresponding to twice the initial bolt force. Re-torqueing is applied once the average contact stress is below 2 MPa, e.g. $\sigma_c^{ave} < 2$.

The average contact stress plot and the safety factor against yielding over time for the 23 °C case are shown in Figure 13, respectively. It can be seen in Figure 13(a) that the contact stress relaxes to 2 MPa after about one month, and one retightening with 54 kN is sufficient to ensure tightness ($\sigma_c^{ave} > 2$ MPa) for one year of service. Hence, there is no need to re-torque with the higher value of 108 kN. The safety factor in Figure 13(b) decreases at the instance of re-torqueing with 108 kN, but stays rather unchanged throughout the time.



(a)



(b)

Figure 13: (a) average contact stress σ_c^{ave} and (b) safety factor against yielding SF_y for 23 °C with 54 kN and 108 kN re-torqueing.

In Figure 14, σ_c^{ave} and SF_y over time is shown for the case with 60 °C revealing a rather different behavior. As can be seen in Figure 14(a), the first re-torque with 54 kN takes place after 8 hours, with subsequent re-torques after 65 hours, 1 month and 8 months. Hence, a total of four re-torques are required at different time intervals to maintain tightness at 60 °C. Evidently, when temperature increases the need for several re-torques is necessary to maintain tightness due to the accelerated relaxation in the HDPE material with increasing temperature. When re-torqueing with 108 kN at 60 °C, only one re-torque is required after 8 hours. Figure 14(b) shows SF_y over time indicating that yielding criterion is met at all times.

In both scenarios re-torqueing with the higher value 108 kN proves much more efficient since only one re-torque is needed after one month at 23 °C and after 8 hours at 60 °C, and is thus a better re-torque plan.

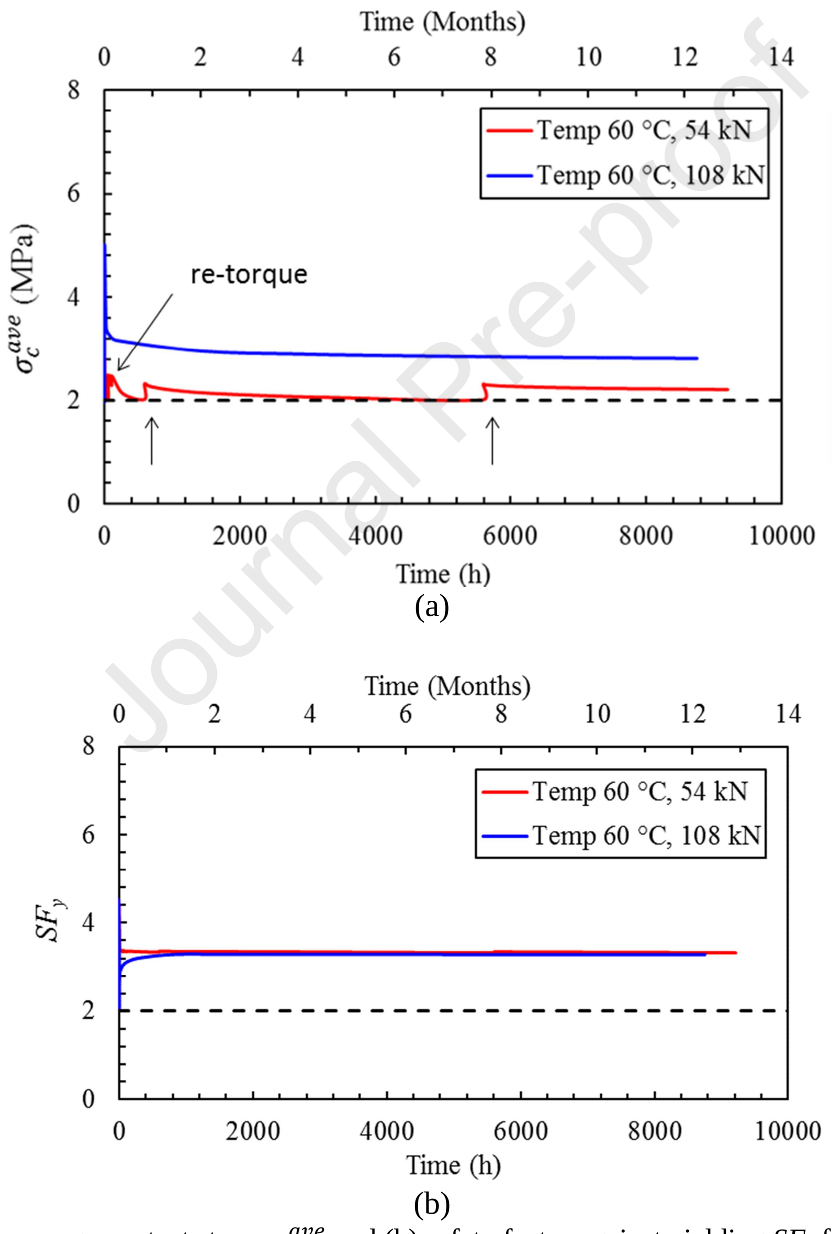


Figure 14: (a) average contact stress σ_c^{ave} and (b) safety factor against yielding SF_y for 60 °C with 54 kN and 108 kN re-torqueing.

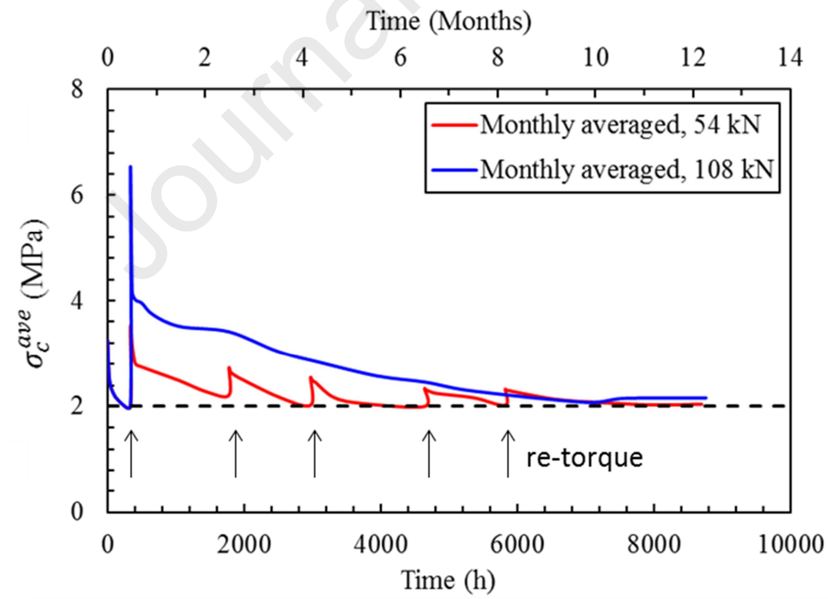
5.2. Annual variation in temperature profile

To simulate a realistic scenario resembling an above ground piping system exposed to sunlight the annual temperature profile shown in Figure 6 is applied to the model, resembling one year temperature cycle [32], with a minimum of 23 °C and a maximum of 60 °C. Two re-torque values are considered, 54 kN and 108 kN and the corresponding average contact stress over time is shown in Figure 15(a). As can be seen, one 108 kN re-torque is sufficient to keep the flange tight for the full service duration of one year, whereas five re-torques with 54 kN are required.

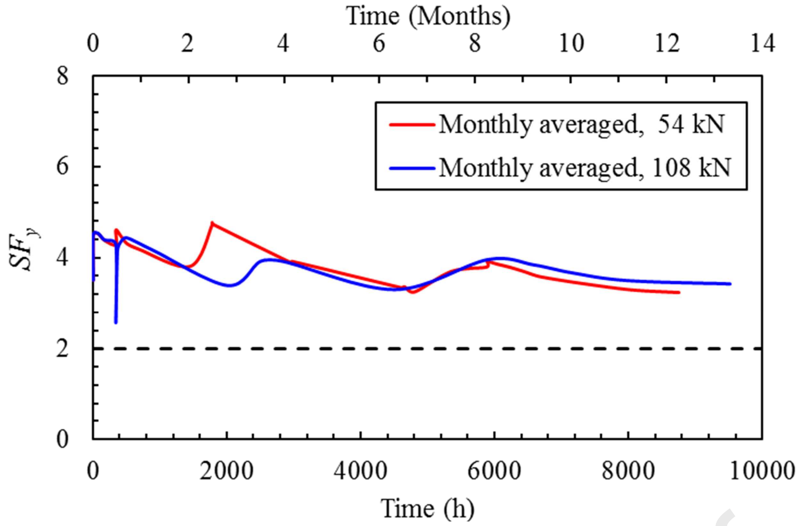
Moreover, the effect of temperature increases, following the temperature profile in Figure 6, is manifested in the first 6 months in Figure 15(a) as a decrease of σ_c^{ave} after re-torque with 54 kN. Towards the end of the year, the average contact stress slightly increases, which can be explained by the diminishing stress relaxation effect in addition to the decrease of contact area due to thermal contraction.

The safety factor against yield over time is shown in Figure 15(b), indicating some fluctuation in the value due to the effect of temperature variation over time. The change of temperature results in yield strength as per Eqn. (8) and change in von-Mises stress due to change in stiffness with temperature, which is the reason to the fluctuationsin SF_y. However, the yielding criterion is met throughout the year since $SF_y > 2$.

It can also be concluded here that for the case with annual variation in temperature profile, the 108 kN re-torque plan is the preferred one, since only one re-torque is required over the year.



(a)



(b)

Figure 15: (a) average contact stress σ_c^{ave} and (b) safety factor against yielding SF_y for annual variation in temperature profile with 54 kN and 108 kN re-torqueing

6. Conclusion

In the current study, the effect of temperature on tightness of a HDPE flange connection with steel backing ring was investigated using finite element analysis (FEA) over a period of one year. To accurately account for the mechanical behavior of HDPE, the temperature and time independent mechanical properties of HDPE were experimentally obtained using both short and long term tensile, compression, and relaxation tests.

The experimental test results were used to calibrate a visco-elastic plastic constitutive three network model (TNM), which predicts both the short and long term behavior of HDPE markedly well. The calibrated TNM model was used in an FEA model to investigate the tightness in a HDPE flange at various constant temperatures (23, 40, 60 and 80 °C) over one year of service. Through the FEA results, leakage was assessed by examining relaxation in the bolt forces and average contact stress variation with time and temperature. It was found that the tightness of the flanged connection is heavily dependent on temperature, where leakage occurs earlier with the increase in temperature. To simulate a realistic scenario resembling an above ground piping system exposed to sunlight, an annual temperature profile was applied to the FEA model. It was found that due the significant relaxation in the HDPE material re-torqueing of the bolts is necessary to guarantee tightness of the flange connection. Based on the FEA results, re-torquing intervals over the service period could be derived, showing that a re-torque value of 108 kN is more efficient since only one re-torque is required.

The modeling approach presented herein can be utilized to simulate tightness conditions for similar HDPE assemblies of various dimensions and at different loadings to derive re-torqueing plans to counteract the effect of temperature on relaxation in the HDPE material. Especially as leakage due to temperature and relaxation is prominent in the HDPE pipe flange industry.

References

[1] I. Barsoum, Z. Barsoum and M. Islam, "Thermomechanical Evaluation of the Performance and Integrity of a HDPE Stub-End Bolted Flange Connection," *Journal of Pressure Vessel Technology,* vol. 141, 2019.

[2] L. Jacobsson, H. Andersson and D. Venneti, "Tightness of flange joints for large polyethylene pipes – Part 1 Numerical simulations," *SP Technical Research Institute of Sweden, Building Technology and Mechanics,* no. 49, 2011.

[3] L. Jacobsson, H. Andersson and D. Vennetti, "Tightness of flange joints for large polyethylene pipes – Part 2 Full scale experimental investigation," *SP Technical Research Institute of Sweden, Building Technology and Mechanics,* no. 50, 2011.

[4] J. Sällström, J. Sandström and S. Sällberg, "Water Tightness of Flange Joints at Valves – Full scale experiments and finite element analysis," in *Proceedings of the 18th Plastic Pipes Conference*, Berlin, 2016 .

[5] J. Sällström, J. Sandström and S. Sällberg, "Täthet hos flänsförband mellan stora polyetenrör och ventiler – experimentell och numerisk studie," Svenskt Vatten Utveckling, 2017.

[6] G. Bibel and R. Ezell, "An Improved Flange Bolt-Up Procedure Using Experimentally Determined Elastic Interaction Coefficients," *Journal of Pressure Vessel Technology,* vol. 114, pp. 439-443, 1992.

[7] N. Sayed, Z. Wu and X. Yang, "Achieving Uniform Clamp Load in Gasketed Bolted Joints Using a Nonlinear Finite Element Model," *Journal of Pressure Vessel Technology,* vol. 132, no. 3, 2010.

[8] J. Bickford, An Introduction to the Design and Behaviour of Bolted Joints, Newyork: CRC Press, 1995.

[9] H. Estrada, "Analysis of Leakage in Bolted-Flanged Joints Using Contact Finite Element Analysis," *Journal of Mechanics Engineering and Automation* , vol. 5, pp. 135-142, 2015.

[10] T. Sawa, K. Tenma, T. Kobayashi and R. Kurosawa, "Finite Element Method Stress Analysis and Evaluation of the Sealing Performance in Box-Shape Flange Gasketed Connections Subjected to Internal Pressure," *Journal of Pressure Vessel Technology,* vol. 139, 2017.

[11] N. Bu, N. Ueno and O. Fukuda, "Finite Element Analysis of Contact Stress in a Full-metallic Pipe Joint for Hydrogen Pipelines," in *Proceedings of the 5th IASME/WSEAS international conference on Energy & environment,* 2010.

[12] T. Sawa, N. Ogata and T. Nishida, "Stress Analysis and Determination of Bolt Preload in Pipe Flange Connections With Gaskets Under Internal Pressure," *Journal of Pressure Vessel Technology,* vol. 124, pp. 385-396, 2002.

[13] P. Luyt, N. Theron and F. Pietra, "Non-linear finite element modelling and analysis of the effect of gasket creep-relaxation on circular bolted flange connections," *International*

Journal of Pressure Vessels and Piping, vol. 150, pp. 52-61, 2017.

[14] Bouroge, " HE3490-LS Tensile Data Apr-09 ACS016-2011".

[15] ISO, "ISO 527 :Plastics Determination of Tensile Properties—Part 1: General Principles," International Organization for Standardization, Geneva, 2012.

[16] ISO, "ISO 527 :Plastics Determination of Tensile Properties—Part 2: Test conditions for moulding and extrusion plastics," International Organization for Standardization, Geneva, 2012.

[17] ASTM , "ASTM D695: Standard Test Method for Compressive Properties of Rigid Plastics," American Society for Testing and Materials, West Conshohocken, 2002.

[18] J. Bergstrom and J. Bischoff, "An Advanced Thermomechanical Constitutive Model for UHMWPE," *International Journal of Structural Changes in Solids-Mechanics and applications,* vol. 2, no. 1, pp. 31-39, 2010.

[19] J. Bergström, Mechanics of Solid Polymers Theory and Computational Modeling, Elsevier Inc., 2015.

[20] T. S. Hansen and B. U. Kristiansen, "Achieving a more Accurate Prediction of a Polymer Snap Deformation Pattern," in *SIMULIA Customer Conference,* 2011 .

[21] P. M. Frontini, F. Rueda and J. P. Torres, "Constitutive modeling and Computational Simulations of the external pressure induced buckling collapse of High Density Polyethylene (HDPE) liners," in *13th International Conference on Fracture* , Beijing, 2013.

[22] J. Bergstrom, C. Rimnac and S. Kurtz, "An augmented hybrid constitutive model for simulation of unloading and cyclic loading behavior of conventional and highly crosslinked UHMWPE," *Biomaterials,* vol. 25, p. 2171–2178, 2004.

[23] J. Bergström, S. Kurtz, C. Rimnac and A. Edidin, "Constitutive modeling of ultra-high molecular weight polyethylene under large-deformation and cyclic loading conditions," *Biomaterials,* vol. 23, no. 11, pp. 2329-2343, 2002.

[24] E. M. Arruda and M. C. Boyce, "A three-dimensional constitutive model for the large stretch behavior of rubber elastic materials," *Journal of the Mechanics and Physics of Solids,* vol. 41, no. 2, pp. 389-412, 1993.

[25] J. Bergström, Mechanics of Solid Polymers Theory and Computational Modeling, Elsevier Inc., 2015.

[26] R. W. Warfield, J. Cuevas and F. R. Barnet, ""Single Specimen Determination of Young's and Bulk Moduli of Polymers,," Naval Ordnance Laboratory, White Oak, Maryland , 1969.

[27] SIMULIA Dassault Syste`mes, *Abaqus/Standard, 6.14 ed.,* Velizy-Villacoublay, France: SIMULIA Dassault Syste`mes, 2014.

[28] DVS – DEUTSCHER VERBAND FÜR SCHWEISSEN UND VERWANDTE VERFAHREN E.V., "Industrial piping made of thermoplastics Design and execution Above-ground pipe systems Flanged joints: Description, requirements and assembly," DVS,

Düsseldorf, 2006.

[29] P. P. I. (PPI), "Bolt Torque for Polyethylene Flanged Joints TN38," Plastics Pipe Institute (PPI), Irving, TX, 2011.

[30] M. Abid and D. H. Nash, "Leakage criteria through a non-gasketed flange pipe joint," Research gate, 2004.

[31] P. P. I. (PPI), "Handbook of Polyethylene Pipe," Plastics Pipe Institute , Irving, TX, 2008.

[32] Weather and Climate, "weather-and-climate.com," [Online]. Available: https://weather-and-climate.com/average-monthly-Rainfall-Temperature-Sunshine,abu-dhabi-ae,United-Arab-Emirates. [Accessed 4 February 2019].

[33] A. Shahin, I. Barsoum and M. Islam, "Constitutive model calibration of the time and temperature-dependent behavior of high density polyethylene," *Polymer Testing*, vol. 91, 2020.

Highlights

- The temperature effect on the short and long term response in tension and compression of HDPE is investigated experimentally
- Experiments are used to calibrate the three network viscoelastic-plastic constitutive model (TNM)
- The calibrated TNM model is used to simulate the time and temperature dependent behavior of a bolted HDPE flange
- The numerical results show that temperature and time has a significant effect on leakage in the HDPE flange, and the need for bolt re-torqueing can be necessary.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: