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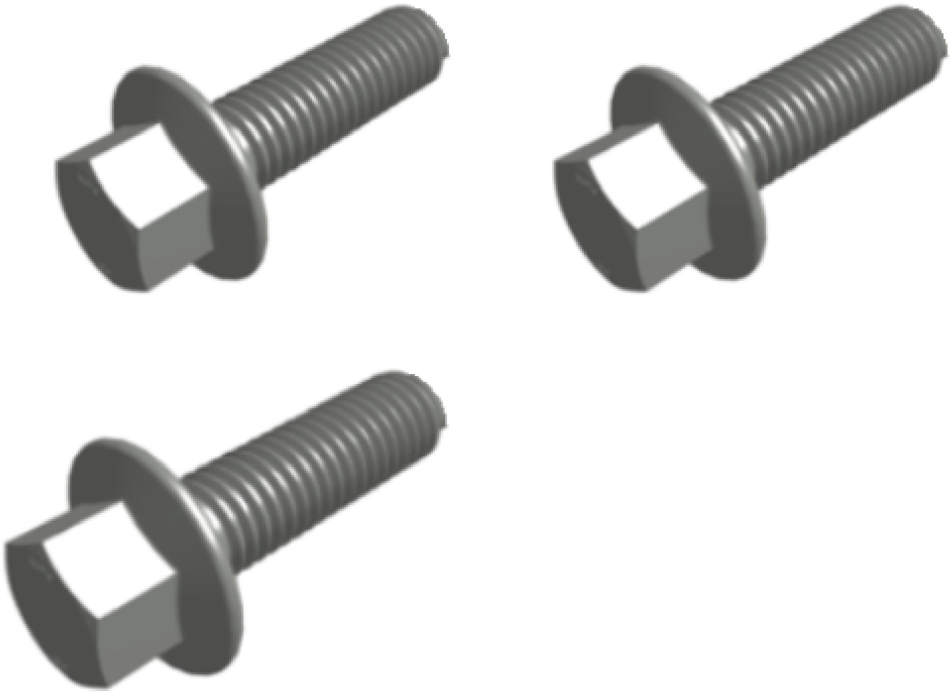

Time-Dependent Stress Behavior: A Study on Creep and Relaxation Performance for Heat Treatment-free Fasteners

Sustainable Manufacturing Solutions for the Automotive Industry

Master’s Thesis in Engineering Materials

MESFIN ASFAW ZEWGE

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
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MESFIN ASFAW ZEWGE

Supervisor: Dr. Emmy Pavlovic (CTO), Bulten Fasteners AB
Examiner: Professor Johan Ahlström, Industrial and Materials Science

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Department of Industrial and Materials Science
Division of Engineering Materials

Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Abstract

The increasing demand for sustainable manufacturing processes has driven the company Bulten to develop new fasteners (BUFOe), which are heat treatment-free, to minimize its carbon footprint. This thesis examines the time-dependent stress behavior of BUFOe fasteners (non-heat-treated) in comparison to regular heat-treated fasteners under ambient and elevated temperature conditions. It is essential to quantify the mechanical stability of the new fasteners during thermal loading to give clear recommendations regarding suitable service conditions. To achieve this goal, a testing procedure was established to measure creep strain over short periods at both ambient and elevated temperatures. The comparison between BUFOe fasteners and regular heat-treated fasteners indicates that BUFOe800X fasteners exhibit excellent performance in resisting creep deformation (0.07%), which is superior to their counterpart 8.8 fasteners and comparable to that of regular heat-treated fasteners (10.9) at room temperature. This shows that non-heat-treated fasteners may be a viable alternative in engineering applications at room temperature. However, at higher temperatures, all fasteners of BUFOe exhibited increased susceptibility to creep deformation compared with regular heat-treated fasteners within the same property classes. These findings provide valuable references for optimizing the reliability and integrity of fasteners under various industrial conditions in the continually evolving field of fastener design and manufacturing processes.

Keywords: Sustainable Manufacturing, Fasteners, Creep, Stress Relaxation, Heat Treatment-Free, BUFOe.

Preface

This thesis is not only an academic investigation but also a personal pursuit and a journey of commitment to sustainable innovation. As global manufacturing continues to evolve, reducing carbon footprints and adopting environmentally responsible practices can be achieved more effectively than ever before. It is within this context that I embarked on this study, driven by a passion to engineer solutions that balance technological advancement and environmental responsibility through a collaboration between Chalmers and Bulten Fasteners AB.

Gratitude
I extend my deepest gratitude to my advisor, Professor Johan Ahlström, whose unwavering guidance, intellectual rigor, and patience transformed this thesis from a concept into a cohesive narrative. Your insight and relentless pursuit of excellence inspired me to push boundaries even when obstacles seemed insurmountable.

To Emmy Pavlovic (PhD), I feel truly fortunate to have been guided by an expert like you. I am profoundly grateful for your generous and unwavering support. It was your amazing vision and positive energy that helped me to stretch myself beyond what felt possible when obstacles came. Your ability to bridge academia and industry has provided essential depth to this thesis, grounding it in real-world applications. I would also like to express my gratitude to Bultens entire development team for their cooperation and support, which directly contributed to the accomplishment of this thesis. Your commitment to environmentally friendly fastener technology is reshaping the future of manufacturing. Thank you for your guidance and inspiration.

I similarly thank doctoral candidates and masters students in the Materials Engineering Department at Chalmers University of Technology. Our many conversations, our mutual hardships and challenges, and our continual curiosity all created an environment where ideas could flourish.

To my precious family and friends, and in particular, my children, your unconditional love and patience steadied me when I faltered. You remind me of why this study is important in creating a better and greener world for future generations.

Why This Topic?
I'm inspired by sustainable technology because I firmly believe innovation should be about progress and conservation. The traditional manufacturing process of fasteners still assumes extensive heat-treatment processes, which have high CO_2 emissions. Heat treatment-free solutions are coming, like Bultens BUFOe fasteners, thats on the brink of a revolution, maintaining mechanical performance while significantly reducing environmental impact. This dissertation is my modest part in that revolution. By critically assessing the creep and relaxation response of these BUFOe fasteners, I was intending to offer experimental verification of the feasibility and promote the diffusion of a green engineering mindset within a variety of industries.

Trials, Triumphs, and Sleepless Nights

A thesis is not, for the most part, a straight line to the finish. This project threw things at me that I was not prepared for, and it made me have to learn way quicker than I wanted to. During testing, about halfway through the study, our primary experimental device broke, and the extensometer (necessary for real-time strain recordings) failed. The data inconsistencies threatened to derail months of work, and the original thesis focus (Stress Relaxation Performance of Heat Treatment-Free Fasteners) no longer aligned with our methodological constraints.

In the face of this crisis, we made a pivot. Relying on literature and exploratory problem-solving, we modified the evaluation logic to place an emphasis on analyzing creep deformation using displacement-derived strain calculations, a less direct but reasonable alternative. Everything had to be recalibrated, all the data had to be reanalyzed, and the thesis had to be written from scratch under intense time pressure. The last eight grueling weeks, rest was a blessing, and I labored day and night to keep up with deadlines, thinking it would be a pity to let all the hard work that had gone into this thesis and the potential that it had to offer go to waste.

I learned from this process that science is as much about flexibility as it is about accuracy. The obstacles served as a powerful reminder that setbacks can steer us toward richer insights. By characterizing the creep and relaxation performance in a materialized manner, additional insights have been included for the mechanical behavior of the fasteners. All of the many sleepless nights, hard as they were, have helped to focus me as well as deepen my gratitude for the collaboration that sustains academic endeavor.

While reading this thesis, I wish that it is not only informative but also inspiringa proof of concept that a sustainability-minded innovation can flourish despite adversity. May it play its part, however modestly, in a future where engineering excellence and environmental responsibility are inextricably linked.

Mesfin Asfaw Zewge, Gothenburg, June 2025.

Nomenclature

Below is the nomenclature of indices, parameters, and variables that have been used throughout this thesis.

Indices

c	Indices for creep and creep rate
0	Index initial strain and stress
s	Index strain in spring
d	Index strain in dashpot
y	Index yield strength

Parameters

σ_0	Initial stress
σ_y	Yield strength
E	Young's modulus
F	Preload
t	Time

Variables

η	Viscosity
ϵ_s	Strain in spring
ϵ_d	Strain in dashpot
ϵ_0	Initial stain
$\dot{\varepsilon}_c$	Creep rate

τ	Relaxation time

Symbols

Δ	Difference in creep from elevated to room temperature

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1

Introduction

Bulten is a leading manufacturer of fasteners for the automotive industry. They have developed BUFOe, which are heat treatment-free fasteners, in order to reduce their carbon footprint in the green production process, a growing trend in the market. Mechanical connections and fastening methods are the cornerstones of many structures. The creep of the fastener and the relaxation of the stress are major concerns, especially in highly loaded joints subjected to elevated service temperatures. However, consistent and repeatable evaluation of fasteners poses a challenge due to the lack of established procedures for the creep and relaxation performance of fasteners. The primary goal of this thesis is to develop a test procedure that enables the accurate assessment and comparison of the creep and relaxation behavior of heat-treatment-free fasteners with that of heat-treated fasteners.

1.1 Background and Motivation

Fasteners are critical components in the automotive sector because they ensure the stability and safety of the entire assembly. Fasteners are used to put parts together, from an engine to a chassis. The reliability and performance of fasteners are a critical aspect because the failure of a single fastener can result in severe mechanical malfunction and safety issues of entire systems. This means that the choice of fasteners and qualification testing are among the most essential tasks during all stages of a product's life cycle, ensuring compliance with requirements for strength, durability, and the influence of environmental factors.

The automotive fastener manufacturer Bulten is looking to expand their offering with more sustainable solutions. One of their most laudable initiatives is their BUFOe project, which has a goal of achieving zero carbon footprint impact on the environment from the fastener manufacturing process. The objective of this project is to exclude the use of heat-treatment for fasteners, thereby achieving a significant reduction of energy consumption, CO_2 release, and environmental load while keeping high-grade quality and performance of fasteners.

The BUFOe project started in 2020, and fasteners with compatible mechanical performance, such as 8.8 and 10.9, have been achieved. One of the final milestones yet to evaluate is the time-dependent stress behavior of the BUFOe fasteners. The time-dependent stress behavior is associated with the creep deformation and stress reduction that occur in a fastener over time. It can influence how tightly components remain assembled in the long term. Studies about time-dependent stress behavior are required to ensure the performance of the developed BUFOe fasteners. Studies of such characteristics will drive the development of reliable fasteners that can be resilient to a variety of conditions and contribute to the safety and longevity of vehicles.

1.2 Problem Statement

The lack of standardized measurement methods for fastener performance in time-dependent stress behavior has been a significant problem in the BUFOe project. This creates challenges in comparing test results across suppliers and laboratory conditions due to the lack of a universally agreed-upon test protocol. Their test conditions and methods differ between suppliers, thereby hindering the development of fasteners that are more uniform and reliable.

1.3 Objective of the Study

The thesis will evaluate the time-dependent stress behavior of five different fasteners under simulated operational conditions (e.g., temperature). Key objectives include: Developing testing methods to measure and compare the stress behavior of BUFOe fasteners and identifying fasteners with minimal creep deformation and stress relaxation.

1.4 Research Questions

The following research questions will guide the project:

RQ1: Which fastener materials exhibit the least creep deformation and stress relaxation under specific environmental conditions (e.g., elevated temperatures)?

RQ2: How does cold working influence the creep rate and stress relaxation rates?

1.5 Scope and Limitations

The thesis targets five varieties of fasteners, three of which are heat treatment-free fasteners (BUFOe) and two standard fasteners. The aim is to evaluate their stress performance under different temperature conditions. The scope is restricted to an axial load with no vibration.

One of the primary constraints encountered during the experimentation process was the limited time available for testing. Initially, several temperature settings were discussed, such as room temperatures $50°C$, $100°C$, and $150°C$. This was limited to room temperature and $150°C$. Traditional creep measurements can last for up to 10,000 hours and exhibit several phases of creep, including primary, secondary, and tertiary. Due to the limited test temperature, the fasteners are not expected to exhibit tertiary creep, and the test time was therefore limited to the time needed to reach secondary creep, meaning steady state conditions. Finally, the load level was restricted to one setting, 90% of R_{po2}, and was to be applied quickly and thereafter, be kept at a constant level. The duration of each test session restricted the ability to evaluate long-term creep deformation and preload retention behavior under prolonged exposure to mechanical and thermal stress. This limitation may have influenced the degree to which time-dependent material changes were captured, particularly in assessing characteristics over extended periods. Additionally, equipment failure posed another significant challenge, impacting the accuracy and consistency of strain measurements. A critical malfunction in the extensometer prevented real-time strain monitoring, necessitating an alternative approach for recording deformation. Instead of direct extensometer readings, strain calculations were derived using displacement measurements relative to the constant grip gap.

2

Literature Review

Designing mechanically fastened assemblies in engineering applications prioritizes critical aspects such as structural integrity, durability, and environmental sustainability of fasteners. Time-dependent stress behavior in fasteners is a key factor that influences the integrity and safety of these assemblies. Stress behavior is important for structural efficiency and functional safety of systems. Thus, time-dependent stress behavior has clearly become an important issue regarding fastener realization; a detailed understanding is required for engineering applications.

Standardized stress relaxation behavior evaluation of materials, as outlined in ASTM E328-21 (American Society for Testing and Materials (ASTM), 2020), has been established. Similarly, the ISO 898-1 standard has been released to specify the test methods for determining the mechanical and physical properties of fasteners (ISO, 2013). There are, however, currently no standards released that describe how stress relaxation in fasteners should be measured, or which stress relaxation value can be considered acceptable. Here, I review studies on methods to quantify the performance creep deformation and stress relaxation across materials, emphasizing the limitations of current approaches and opportunities to develop testing protocols for BUFOe fasteners.

2.1 Time-Dependent Stress Behavior of Fasteners

The relaxation of stress gradually results in decreased clamping force, which would weaken connections and parts. This deterioration is primarily due to material creep and exposure to severe environments. For the design of fasteners, it is necessary to be able to predict creep deformation and stress relaxation of the steel to guarantee a successful product under different load conditions and temperatures. Nevertheless, the complex characteristics of material behaviors (such as creep and viscoelasticity) have resulted in this issue not being addressed with the priority it deserves in engineering applications (Bergström & Boyce, 1998).

In materials science, creep refers to a material's gradual and permanent deformation under prolonged exposure to mechanical stress that is still below the material's yield strength over an extended period. This property is especially critical in metal fasteners that operate at elevated temperatures or in high-stress environments. Researchers use experimental studies and computational modeling to predict creep behavior and assess the effects of temperature. I need to understand these phenomena to quantify the impact of creep deformation and clamping force reduction.

In safety-critical applications, such as metal fasteners, creep and stress relaxation are fundamental in influencing long-term loads. This requires a thorough assessment of creep deformation and stress relaxation when designing strong fasteners capable of resisting prolonged stress and extreme environmental conditions. However, due to the diverse behavior of materials (e.g., viscoelasticity) and the varying geometry of fasteners, precisely identifying the distribution of creep and relaxation remains a challenge, despite the distinct pattern of relaxation. These complications have hindered the development of universal testing standards for fasteners.

Filling these gaps will necessitate a better method of creep and stress relaxation performance measurements for fasteners and the implementation of more advanced evaluation tools. It is hoped that this review will bring attention to the need to develop new standard testing methodologies to form a strong testing basis long-term for fastener designs to account for both creep deformation and stress relaxation successfully.

2.2 Time-Dependent Stress Mechanisms

Time-dependent stress mechanisms, such as creep deformation, can be categorized based on mechanical, thermal, or environmental factors. The mechanical stress relaxation mechanism is primarily due to the materials' viscoelastic properties, which can lead to time-dependent deformation under constant loads. When fluctuations in temperature induce changes in material properties, it can cause creep deformation.

The mathematical modeling of stress behaviour has been extensively studied. For instance, stress relaxation is predicted by the Boltzmann principle based on the material's response to a step strain input. This principle is foundational for developing constitutive models that can accurately predict the long-term behavior of materials under sustained loads (Carpenter & Knauss, 1990). The principle of the viscoelasticity model establishes the theoretical foundation of stress relaxation. Using a combination of springs and dashpots, the material response can be described as the standard linear solid model (Ferry, 1980).

Under various loading conditions, viscoelastic properties are crucial to understanding the time-dependent response of materials. Different viscoelastic models have been used to predict the behavior of materials, including the Maxwell Model, Kelvin-Voigt Model, and Generalized Maxwell Model. These models give insights into the performance of materials by forecasting stress relaxation and creep behavior. Theoretical and experimental studies have been conducted to assess the viscoelastic behavior of materials. These studies deal with steady strain or stress and describe the material's response over time. The recorded data is then utilized to fit viscoelastic models and evaluate material parameters, such as stress relaxation (Angelo, 2017).

One of the most widely used and most straightforward viscoelastic models is the classic Maxwell model, which illustrates the characteristics of viscoelastic materials using a coupling of a spring (the elastic element depicts the elastic properties of the material, distinguished by the elastic modulus E) and a dashpot (the viscous element depicts the viscous properties of the material, characterized by the viscosity η)in sequence. This model is highly beneficial for studying the stress relaxation behavior of materials. The governing equation for the Maxwell model is derived from the combination of the spring and dashpot in series. The total strain is the sum of the strains in the spring ϵ_s and the dashpotϵ_d:

The Maxwell model equations are given as follows:

$$\epsilon = \epsilon_s + \epsilon_d \tag{2.1}$$

Hooke's law gives the stress σ in the spring:

$$\sigma = E\epsilon_s \tag{2.2}$$

The strain rate in the dashpot is given by

$$\frac{d\epsilon}{dt} = \frac{\sigma}{\eta} \tag{2.3}$$

Combining these equations, we get the governing differential equation for the Maxwell model:

$$\frac{d\epsilon}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt} \tag{2.4}$$

A stress relaxation test applies a constant strain ϵ_0 to the material, and the resulting stress σ is measured over time. The solution to the governing equation for stress relaxation is:

$$\sigma(t) = \sigma_0 e^{-t/\tau} \tag{2.5}$$

where $\sigma_0 = E\epsilon_0$ is the initial stress, t is the time, and $\tau = \frac{\eta}{E}$ is the relaxation time.

The time-dependent stress mechanism is primarily due to the materials' viscoelastic properties, which can lead to creep deformation under constant loads. When fluctuations in temperature induce changes in material properties, the thermal relaxation mechanism can occur due to creep and environmental factors.

2.3 Existing Test Methods for Stress Behaviors

Many tests have been conducted to characterize the stress characteristics of materials. These methods can be broadly categorized into static and dynamic approaches, offering distinct benefits and challenges. In static testing, a material is subjected to a constant load, and the corresponding stress response is recorded as a function of time. One of the most relevant tests is the creep test, which assesses time-dependent deformation under a constant load, a feature of viscoelasticity. This approach is slow to test, making it unsuitable for time-sensitive applications.

Dynamic testing involves exposing materials to varying loads or environmental factors. For example, the fatigue test uses cyclic loading to replicate operational stresses, providing information on long-term durability. However, in fatigue testing, it is difficult to differentiate stress relaxation from other failure modes.

Since the stress relaxation in fasteners is heavily dependent on the material composition and geometry of the fastener itself, tailored testing methodologies are required and are also informed by the application. The ASTM E328-21 standard describes a testing method for materials and structures that applies constant strains and monitors stress loss over time. It highlights the need for well-defined environmental conditions (e.g., temperature, humidity) to reflect realistic conditions and ensure reproducibility (ASTM, 2020; Smith et al., 2019). ISO 898-1, intended to accompany ASTM E328-21, outlines mechanical property evaluations for fasteners (e.g., tensile strength, yield strength) at temperatures ranging from $-50°C$ to $150°C$ (ISO, 2013). While ISO 898-1 serves a wide range of scenarios, it lacks dedicated protocols for stress relaxation or environmental impact analyses, which limits its applicability to reliability studies designed for extended periods of time. This standard furnishes environmental and load-variable assessments but fails to include material-specific or long-term predictive analyses.

To conclude, the assessment of stress relaxation in materials must be approached with a detailed consideration of the testing methods and their implementation. Static methods, including creep and torque-tension tests, help to understand time-dependent deformation and initial clamping forces. However, their ability to predict long-term behavior is not as accurate, primarily because of the time-consuming nature of the tests. Dynamic methods, such as fatigue and vibration tests, replicate real-world operating stresses but cannot isolate relaxation effects from other failure modes. Although standards such as ASTM E328-21 establish defined protocols for controlled stress exposure and environmental conditions, challenges remain in considering the specific compositions of different materials and making long-range predictions. An in-depth review, such as ISO 898-1, comprehensively covers the mechanical properties of fasteners, but stress relaxation and environmental variability protocols are not explicitly defined. Such limitations underscore the need for integrated testing frameworks that incorporate material diversity and ecological interactions during testing and long-term performance evaluation.

2.4 Gaps in Current Study

Studies on approaches to assessing the performance of fasteners based on their mechanical properties have developed over the years. However, published literature finds it challenging to analyze stress relaxation in fasteners. The primary issue is the lack of uniform testing methods. Although many options exist, there is no generally accepted model available at the moment that can be used to predict the behavior of such a diverse material and application base. This variability of approach ultimately leads to conflicting results that hinder study-to-study comparisons and the generalization of knowledge.

Furthermore, current testing methodologies rarely involve protocol customization to material properties. Most of these standards were established based on classical materials, such as steel, which do not apply to modern alloys (advanced metallic materials) and composite materials, as they do not consider the particular irreversible stress-relaxation phenomena encountered in such materials. While industrial sectors are increasingly adopting this material, adequate testing procedures must be provided to characterize its behavior under service conditions.

A second under-researched area is the environment (as a factor). Modern techniques seldom examine whether the level of moisture, temperature variation, or exposure to corrosion affects the relaxation behavior. A distinction for testing fasteners under dynamic or extreme conditions is not set in standards (such as ASTM E328 and ISO 898-1), although environmental factors are considered. Empirical evidence suggests that elevated temperatures can induce relaxation and premature joint failure in specific high-heat applications. Likewise, excessive moisture exposure can result in corrosion, which may compromise structural integrity and relaxation performance. Including such factors in standardized test regimes may improve predictive models for fastener performance.

3

Development of Test Method

The time-dependent creep deformation behavior of fasteners subjected to constant axial stress simulates the behavior in actual strain distribution over time. It records strain deformation over time under controlled temperature conditions while neglecting vibration effects. This approach is used for bolts, screws, and similar threaded fasteners, with an emphasis on creep deformation or retaining clamping force. By extending findings from the lab to field application, this approach is compounded to yield holistic insights for fastener-dependent industries (automotive, aerospace, and the like).

3.1 Purpose of the Test Method

This test method is designed to provide a consistent procedure to quickly evaluate fastener creep deformation and relaxation performance under various environmental conditions and material properties. The primary purpose of this test method is to assess the stress behavior of BUFOe fasteners (non-heat-treated) and regular fasteners under various temperature conditions in order to identify which version exhibits the least creep and stress relaxation.

3.2 Test Methodology

The test procedure consists of four main stages: sample preparation, test setup, test execution, and data analysis. The stages are modified to correspondingly reduce variability and to ensure that the tests can be reproduced. The required accuracy level must enable testing laboratories to generate accurate and stable results consistently.

The test starts with applying a load. The purpose of the load is to replicate the preload that an assembled fastener typically generates; the test load is hereafter called preload. For the purpose of this thesis, the preload of 90% of $R_{p0.2}$ was selected. At this stage, the fastener is stretched to a specified level of preload to achieve sufficient clamping force and maintain axial alignment. The following methods are commonly adopted (ASTM E1012, 2019).

Direct Tension: The tool applies a specific tension to the fastener and controls the exact preload applied. F = 0.9 σ_y x A_0 - where F is the preload force, σ_y is the yield stress of the fastener, and A_0 is the nominal cross-sectional area of the fastener

(ISO 898-1).The direct tension is generally preferred, as it is accurate and applies a uniform load at the fastener centerline.

Axial Alignment: Preload application must be made with the axial alignment of the fastener. Joint misalignment negatively impacts joint performance and reliability due to uneven loading. When properly aligned, the load is transferred evenly across the fastener.

When it comes to stress monitoring in fasteners, it is crucial to ensure that the integrity and reliability of the joint are maintained over time. Fastener relaxation is tracked using the following approach: Continuous load cells are fixed in place to monitor stress relaxation during and after preload application continuously. An extensometer with strain gauges provides real-time measurement of clamping force, enabling instantaneous recognition of preload loss due to deformation of the fasteners. Constant monitoring is especially valuable in critical applications, where maintaining the clamping force is crucial for ensuring optimal performance. This information can be used to examine the relaxation characteristics of the fasteners.

These detailed procedures for proper preloading, monitoring, and realistic testing of fasteners help users ensure that fasteners are correctly applied. The direct tension method is crucial for ensuring the quality and reliability of fasteners used in various engineering applications. Proper preload application, monitoring joint stress levels, and controlling environmental conditions will help ensure the desired clamping force and joint stability.

3.2.1 Sample Preparation

The sample preparation begins with establishing the fastener details, thread type, and property class (ISO 8981, 2013). Testing fasteners for creep and relaxation performance requires conditioning the fasteners to ensure reproducible results. The following procedures are required. Fasteners are new for each test. Integrity check each fastener for wear, deformation, or damage. Any defective fasteners are scrapped. The inspection methods may be visual inspection or microscopy, which ensures the fasteners are free from defects or fatigue signs that could impact performance (ASTM E328, 2021). The sample preparation process determines the material composition, material grade (if applicable), and thread type (if applicable) of the fastener. Only use a fastener that has been consistently and reliably inspected. All these factors are critical for the performance and reliability of fasteners in engineering applications.

3.2.2 Test Setup and Procedures

The experimental testing configuration utilizes a universal testing machine equipped with an integrated, highly controlled measuring system and environmental enclosures for recording and analyzing data, as well as tracking the steps of the experimental test procedures.

3.2.2.1 Test Setup

A grip holds the fastener and resists strain variation during creep and relaxation. It is a critical component that secures the fastener during testing, allowing for slight variations in load while the fastener undergoes deformation or relaxation. This component is typically made of a strong material that can withstand preloads and high temperatures without bending or deforming. The grip is designed to facilitate axial alignment and preloading of the fastener during the tests (ASTM E8/E8M, 2024).

A load cell is used for precise applications and to measure the preload during testing. It provides trusted data during testing, as the test should run at a specified fixed preload during the entire test. The environmental chamber is added to control the testing atmosphere (temperature). The chamber provides temperature stability of $\pm 3°C$, suitable for accurate temperature-based testing (ASTM E328, 2021). The temperature range is typically RT to $150°C$, as required for testing fasteners (ISO 898-1, 2013). The reliability of the tests is determined by temperature stability to ensure reproducible results. This consists of temperature conditioning, where the fasteners are brought to the test temperature for an appropriate warming period to achieve thermal equilibrium.

The axial strain in the fasteners is measured using strain measurement techniques, such as extensometers, which provide high accuracy and reliability between two points of contact on the fasteners. The extensometers measure the strain between two points on the fastener, providing accurate readings with very low error and high precision (within ±0.000025 mm/mm) (ASTM E328, 2021). The software monitors the fastener's deformation and records the data on strain and material displacement for analysis and reporting.

The loading grip, high-accuracy load cells, controlled environmental chamber, and force control measurement techniques are essential components of the setup, providing a holistic measurement of fastener creep and relaxation performance. They help to ensure accurate measurement of fastener creep deformation and stress relaxation performance under various temperature conditions.

3.2.2.2 Procedure

The first test step is to mount and tighten the fastener onto the grip. Avoiding eccentric loading through proper axial alignment is essential to the accuracy of the test results.

The second step is to set up environmental exposure to simulate the operational environment. The fastener is warmed to a predefined temperature (e.g., $150°C$) in an environmental chamber, allowing two hours for thermal equilibrium before the specified testing time begins. The temperature is regulated with a precision of $\pm 3°C$ to provide uniform conditions for testing.

The third step is to apply preload (for example, 90% yield strength) through the load cell and record the initial stress/strain. A load cell applies the initial preload force to the fastener and maintains a constant full preload while recording strain deformation. This stage confirms that the fastener experiences the intended preload, mimicking in-service conditions, and the test begins to measure strain distribution or creep deformation for the specified time. The force of clamping and the stress in the fastener are continuously controlled and maintained at a constant level during the creep test. Every second, readable data points from the load cells are logged for real-time monitoring of the strain distribution.

The last step is termination and post-test inspection, which concludes the test upon reaching the specified time, such as four hours. The test is performed under specific conditions until all observations regarding the fastener's creep performance are measured. The test ends at specified hours, and the fasteners are removed from the grip and inspected for coating degradation (e.g., oxidation, microstructure) using microscopy.

These setups and procedures are (1) a means to mount the specimen accurately, (2) a method of exposing the specimen to the environment, (3) applying a controlled preload and a method of continuous measurements of stress, and (4) a clear termination criterion for the test, being able to measure the performance and reliability of fasteners accurately. Such a procedural approach facilitates the measurement of stress relaxation performance in fasteners for various temperature applications, thereby enabling accurate data collection and analysis.

3.2.3 Data Collection and Analysis

The test forces can be accurately and repeatedly controlled using load cells. As the preload is introduced, any deformation in the material is measured by recording the changes in displacement. This displacement data is recorded in real-time by software, and a continuous log of strain distribution changes in the material can be generated. Data points of displacement change are recorded at 1-second intervals, resulting in 14,400 data points and providing high-resolution, time-dependent documentation of deformation behavior. These precise measurements enable us to observe the material's behavior under constant loads.

To ensure repeatability and improve the accuracy of the test results, each type of fastener will undergo three separate trials. By testing three samples of the same fastener type, variations in performance can be minimized, leading to more reliable data. At each corresponding time step, the measured values from all three samples will be averaged, generating a single representative value for that specific fastener. To compute the average values for each time step across the three creep test samples, we use the formula

$$\text{Average}(i) = \frac{\text{Sample}_1(i) + \text{Sample}_2(i) + \text{Sample}_3(i)}{3}, \text{where (i) is a data point.}$$

This method ensures each averaged value measured displacement corresponds to the respective time step, improving repeatability and accuracy. To investigate the material behavior, a strain will be calculated based on the average value, and a creep strain versus time plot can be created in MATLAB. This visualization enables an in-depth study of creep deformation, which can be achieved by modeling the material's deformation under constant stress. The integration of hydraulic load cells with constrained control loading enables the simultaneous control of all axes, facilitates real-time displacement recording, provides detailed data storage, and allows for analysis in MATLAB, creating a powerful platform for materials testing.

3.3 Test Execution

This section describes the tests of stress behavior of BUFOe fasteners and regular fasteners made from varying heat-treated steel alloys according to the test methodology described in Table 3.1 The fasteners are designed for use in real-world situations. Essential features of the experiments include identifying constraints, preparing samples, establishing procedures, conducting experiments, and drawing conclusions from the results.

Five varieties of steel alloy fasteners with varying specifications are prepared for testing, including heat-treated fasteners rated at 8.8 and 10.9 and non-heat-treated fasteners with specifications BUFOe800, BUFOe800X, and BUFOe1000.

Table 3.1: Specimen specifications for testing the stress relaxation of fasteners

Fasteners Grade	**Materials Composition**	$R_{p0.2}$ **(MPa)**	**P.Class**	**Thread Type**	**Effe. Diameter (mm)**	**Treatment**
BUFOe 800	22MnB5Ti	798	8.8	M8	6.83	Cold Working
BUFOe 800X	22MnB5Ti	839	8.8	M8	6.83	Cold Working
BUFOe 1000	30MnVS6	1040	10.9	M8	6.83	Cold Working
Regular 8.8	17B2	802	8.8	M8	6.83	Heat Treated
Regular 10.9	30MnB4	996	10.9	M8	6.83	Heat Treated

The main difference between BUFOe800 and BUFOe800X is that BUFOe800X has been cold forged with a higher degree of cold working, resulting in both higher mechanical strength and a more pronounced degree of deformation in the microstructure. These fasteners are intended for practical applications. The experimental design considers two test constraints. The tests are constrained to assess short-term creep deformation and stress relaxation performance under specific temperature conditions. An indicative test was set up to establish the suitable test duration. Discussions with the development team at Bulten laid out that earlier tests performed had shown that BUFOe800 samples appeared to give the most creep and that elevated test temperatures resulted in a longer time needed to reach steady state creep behavior, but that was reached within 4 hours.

The first test was therefore for 20 hours at room temperature and $150^\circ C$. The measured result confirmed that a test period of 4 hours was sufficient to reach steady state, and the test duration was set to 4 hours for all fastener tests, see Table 3.2. The other constraint is that a two-point contact extensometer can only monitor the deformation of the fastener at the middle of the shank to the thread position due to the setup of the grip and extensometer, which cannot reach the shank. Therefore, the grip and extensometer setup should be resolved without compromising grip alignment with the fasteners by developing an extended washer on the top pointer and a threaded extension on the lower pointer of the extensometer contact. See Figure 3.1.

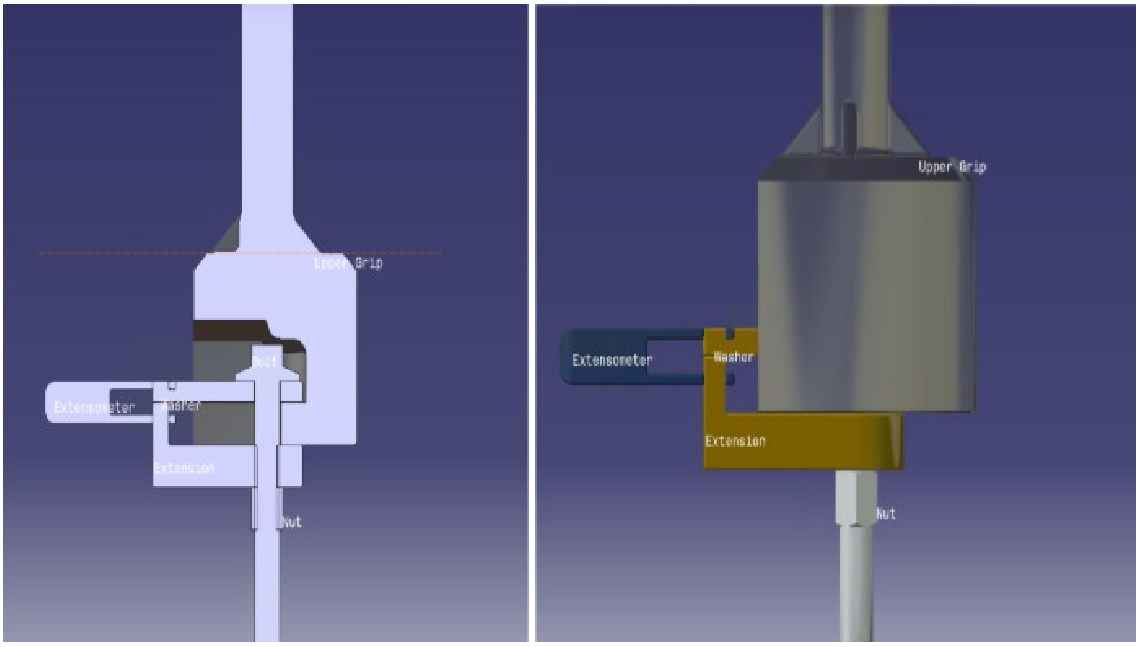


Figure 3.1: The setup of the grip and extensometer with extended washer and threaded extension.

Test environmental conditions will be set at room temperature ($25^\circ C$) and $150^\circ C$. Three separate groups will be categorized according to their test conditions. Group A for five fasteners, the evaluation will be done under constant stress at room temperature ($25^\circ C$), and Group B will be at $150^\circ C$. The fastener is heated in an environmental chamber at the set temperature, waits two hours to achieve thermal equilibrium, and then proceeds to the test at the specified time, e.g., 4 hours after heating.

The fasteners will be loaded with a preload force of 90% of their yield strength under constant strain, and stress reduction will be measured over 4 hours.

Table 3.2: Preliminary plan for testing time-dependent stress of fasteners

Fasteners Type	**No.Test Repetition**	**Preload force (KN)**	**Test duration for Group A (RT)**	**Test duration for Group B ($150°C$)**
BUFOe 800	3	26.29	20 hours (1x)	4 hours (3x)
BUFOe 800X	3	27.64	4 hours (3x)	4 hours (3x)
BUFOe 1000	3	33.20	4 hours (3x)	4 hours (3x)
Regular 8.8	3	26.42	4 hours (3x)	4 hours (3x)
Regular 10.9	3	32.81	4 hours (3x)	4 hours (3x)

Termination and post-test inspection will conclude at predetermined intervals, such as 4 hours. If the test has been carried out at an increased temperature, the fastener should be cooled to ambient temperature to help unload it from the grip. This may take 2 hours to cool down from an elevated temperature to ambient temperature. Next, microscopy will examine the tested fastener for coating failure (e.g., oxidation, microstructural changes).

The quality of data associated with the relaxed performance of fasteners is vital. The load cell controls stress (preload), while an extensometer measures the strain distribution over time. The recorded data are analyzed to evaluate the stress behavior of the fasteners under different conditions.

This approach records all the attributes used to evaluate fastener relaxation performance. This enables the users' confidence in the reliability, accuracy, and consistency of the test results by providing precise and concise methods and descriptions of the experimental design (test constraint, sample preparation, test setup, and data collection and analysis).

4

Experimental Results

The results from creep testing of five fasteners classified into two property classes at room temperature and an elevated temperature of $150°C$ are presented in this section. These fasteners were tested to evaluate and compare the creep properties of two families of fasteners under constant load and environmental conditions. Additionally, an extrapolated analysis was performed to examine the effect of the relaxations and the performance of fastened joints in maintaining the preload tension. Main conclusions are presented according to the property classes, allowing for a comparison of the creep behavior of a BUFOe fastener with that of a conventional bolt under ambient and elevated temperature environments.

The creep deformation data may be used to estimate stress relaxation behavior. The stress relaxation curves of two types of fasteners can be predicted by fitting the measured creep deformation curves and calculating the strain rates, which are used to forecast the reduction in preload tension. It can be inferred from the fitted results that the stress relaxation for both non-heat-treated and heat-treated fasteners decreases with increasing preload tension, which is beneficial for practical use.

4.1 Creep Testing Results

The results of the tests were collected as the average of the three samples of each type of fastener. For example, the BUFOe1000 fastener was tested with three samples at room temperature and three samples at elevated temperature, and then for each temperature condition, an average result of the three samples was taken. A 90% confidence interval was established for these three samples, using a standard deviation corresponding to Z = 1.96; see Appendix E.2. The calculated average creep strain is presented for each type of fastener in Table 4.1.

The strain of each fastener was calculated as the ratio of the change in displacement to the free thread length of the fasteners (distance from under the head to the first engaged thread), which was 25.5 mm and was the same for every test of each fastener (Appendix F.1). Strain distribution curves were plotted for each test. Therefore, the test results have been presented with strain curves to provide an understanding of the effect of temperature on the creep behavior of each fastener and a comparison of the strain deformation behavior among fasteners with the same property class at each temperature condition.

Table 4.1: The result of creep deformation of the fasteners under different conditions for four hours

Fasteners Type	**Change of D(µm) at RT (4hrs)**	**Creep Strain (%) at RT (4hrs)**	**Change of D(µm) at 150°C (4hrs)**	**Creep Strain (%) at 150°C (4hrs)**
BUFOe800	26	0.10	101	0.41
BUFOe800X	18	0.07	77	0.30
BUFOe1000	36	0.14	107	0.42
Regular 8.8	26	0.10	59	0.23
Regular 10.9	15	0.06	56	0.22

4.1.1 Influence of Temperature on Creep Tests

Figure 4.1 illustrates the strain during creep testing, comparing all fasteners at room temperature and 150°C. Both test conditions show that the initial creep rate is high, followed by a slower and more linear strain increase after approximately 4000 seconds. The heat-treated regular fasteners (8.8 and 10.9) have less strain (creep deformation) than the BUFOe fasteners, both at room temperature and 150°C. At 150°C, the creep is significantly increased for all specimens, with heat-treated samples still performing better. However, at 150°C, it is clear that the BUFOe800X performs better than BUFOe800 and BUFOE1000.

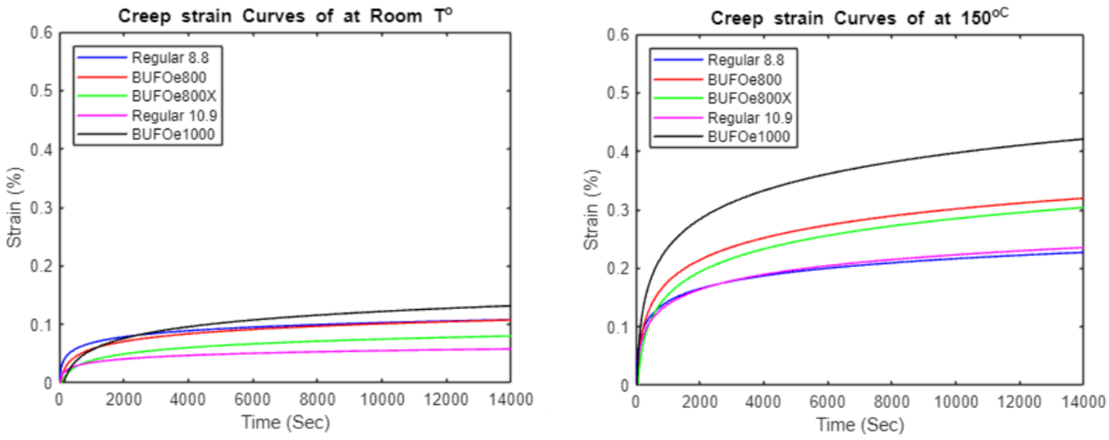


Figure 4.1: Strain curves of all classes of fasteners (left) at room temperature and (right) at 150°C

The BUFOe1000 fastener demonstrated greater susceptibility to creep deformation compared to other fasteners, exhibiting the highest strain increase due to elevated temperatures. In contrast, the standard 8.8 and 10.9 fasteners demonstrated higher resistance to deformation, maintaining their resilience at high temperatures. The BUFOe800X exhibited resistance to deformation, displaying greater stability and improved resistance to creep deformation compared to the BUFOe800 across both environmental conditions.

4.1.2 Comparative Results of Creep Behavior

Figure 4.2 shows the strain during creep testing of different strength class fasteners at room temperature (left) and 150°C (right), where the strength class 8.8 is shown in the top row and 10.9 fasteners on the bottom row.

Creep behavior of fasteners in strength class 8.8

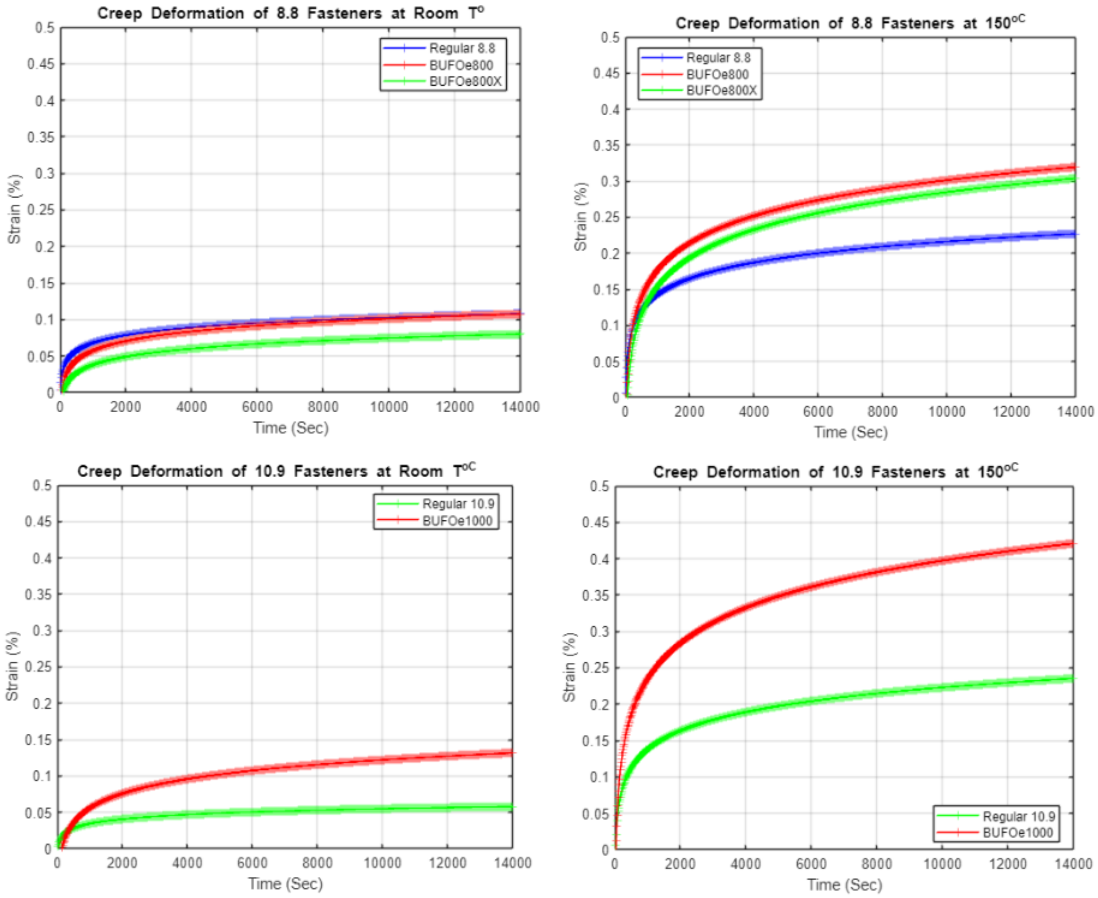


Figure 4.2: Creep strain curves of 8.8 fasteners (top) and 10.9 fasteners (bottom) at room temperature (left) and 150°C (right)

Under the 8.8 property class, BUFOe800 and standard 8.8 fasteners exhibited nearly identical strain behaviour at room temperature. The BUFOe800X exhibited lower creep, indicating its enhanced resistance to permanent elongation.

At 150°C, although creep increased for all fasteners, Regular 8.8 showed better stability and a minimal strain increase. Among the fasteners tested under elevated temperature, BUFOe800 exhibited the highest creep, and more susceptibility for creep due to elevated temperature, and BUFOe800X exhibited a moderate creep deformation due to the temperature increase, whereas Regular 8.8 demonstrated minimal deformation, confirming the effectiveness of a heat treatment microstructure in reducing creep-induced deformation.

Creep behavior of fasteners in strength class 10.9

Under the 10.9 property class, BUFOe1000 and 10.9 fasteners exhibit different strain behavior at room temperature. The 10.9 regular fastener exhibited lower creep than its heat treatment-free alternative, BUFOe1000. At 150°C, creep increased for both fastener types; regular fasteners (10.9) showed significantly better creep performance. Worth pointing out is the difference in steady-state creep condition, the slope of the linear part of the strain curve (after approximately 8000 seconds), which is higher for BUFOe1000, both at room temperature and 150°C, indicating a higher creep rate of BUFOe1000.

4.2 Discussion

The experimental results provide valuable insights into the creep characteristics of fasteners under various temperature conditions. Most likely, the same enduring creep strain was exhibited at room temperature for BUFOe800X and regular 10.9 fasteners. This indicates that under normal environmental conditions, the BUFOe800X fastener was able to maintain good mechanical properties.

However, at an elevated temperature of 150°C, a significant increase in creep deformation was observed for all BUFOe fastener types as compared to heat-treated fasteners. The BUFOe type of microstructures appears to be more sensitive to temperature increases, as they all showed higher strain than heat-treated fasteners. This demonstrates the significant effect of temperature on creep deformation and emphasizes the significance of thermal resistance under long-term elevated temperature conditions in the case of fastener applications. The higher strain deformation implies greater clamping force loss due to lower resistance to stress relaxation (K. Chawla 2009).

BUFOe1000 was found to be the most creep-sensitive of all the fasteners tested, with the most considerable change in strain observed between room and elevated temperatures. The rapid strain accumulation suggests that BUFOe1000 may not be the most suitable for applications subject to high-temperature service, as its stress relaxation increases, and its structural integrity decreases under sustained thermal loading. On the contrary, the regular fasteners had a better performance with respect to the creep deformation, and their mechanical stability and elasticity were preserved with increasing temperature. This shows the effect of heat treatment on the properties of the material as well as on the permanent elongation and temperature resistance of the material.

Further, BUFOe800X possessed more resistance to creep and better stability compared to that of BUFOe800 and regular 8.8 fasteners at room temperatures, but BUFOe800X had lower resistance to creep than the regular heat-treated fasteners at high temperatures.

Taken collectively, these results emphasize that, in material selection and heat treatment, both are necessary for improving fastener properties. The observed variations in creep behaviour further highlight the necessity for taking thermal compatibility and resistance to creep into account whenever fasteners are subjected to constant-loaded conditions at changing temperatures. Knowledge of such material behavior can assist in the creation of a more robust fastening system, leading to improved long-term structural Integrity and stability under a wide range of service conditions.

4.3 Experimental Constraints

While the technique adopted in this study provides useful information on fastener creep, some limitations have to be considered in interpreting the results. One of the key restrictions was the failure to obtain real-time measurements of strain distribution with the extensometer due to electrical grounding interference, which caused substantial signal noise and rendered the output unreliable. Instead, the crosshead position of the universal testing machine was used to measure the change in displacement and convert it to strain. This problem created a scenario where strain values might be different, and therefore make the collected data less accurate and inconsistent.

To overcome this limitation, strain values were assessed indirectly. Strain was determined as a difference in fastener elongation over distance ratio divided by a fixed grip gap. This process yielded an estimate of strain. The testing device setup was equipped with an upper grip that remained stationary during the test. The sample was loaded in two sequences: first, the load is ramped up from zero to the defined load level for the test, and second, the load is kept constant for the duration of the test. During the first sequence, the specimen should elongate elastically, since the load is below the yield point. During the second sequence, the fasteners are elongated by a displacement of the lower grip. This displacement was constantly recorded and was used as an indicator of the elongation of the material. Stress-strain curves were then calculated based on the original grip gap to fit the elastic deformation.

While this approach ensured that the constant load could be applied and elongation monitored, the absence of real-time extensometer data may lead to small deviations in strain distribution. The indirect method, such as that using displacement readings, has the potential to be an effective assessment tool due to its simplicity, although it may not fully capture the local fluctuations in material behavior.

The approach offered meaningful information with respect to the creep strains of the fasteners; the machine elasticity could be considered as a constant factor for all fasteners to correlate different responses to different combinations of thermal and mechanical exposure. Future work is suggested to involve more advanced measuring devices (digital image correlation (DIC) or laser extensometry) in order to enhance accuracy, and additional information to be learned from the strain distribution.

5

Evaluation and Analysis

The experimental characterizations were primarily performed to investigate the creep behavior, or material deformation under constant loads. The results can be correlated to determine the stress relaxation behavior, a crucial factor in fastener reliability for rail, aerospace, automotive, and machinery applications. This study identifies material heat treatment, environment, and loading as the significant influences on the time-dependent stress response in fasteners. In this chapter, creep strain test experimental data for different fastener types at various temperatures are analyzed in detail. The emphasis is on comparing BUFOe fasteners with regular heat-treated fasteners. The differences in creep strain, microstructure characteristics, and their performance with temperature are closely examined to understand their implications for mechanical applications.

5.1 Evaluation of Creep Strain

Creep strain tests were performed at room temperature and $150°C$ for 4 hours, resulting in a total of 14,400 data points for each temperature. Results indicate different levels of strain buildup in the investigated fasteners.

5.1.1 Creep Strain at Room Temperature

At ambient temperature, the creep strain of all fasteners ranged from 0.06% to 0.14%, with the Regular 10.9 fastener exhibiting the lowest initial strain (0.06%), while the BUFOe1000 had the highest (0.14%). BUFOe800X fasteners also showed superior stability in strain responses compared to the standard fasteners at room temperature.

8.8 Property Class Fasteners: BUFOe-800X exhibited the lowest creep strain (0.07%) compared to 0.10% for regular fasteners 8.8, thus demonstrating its structural stability under ambient conditions. BUFOe800 had the same creep deformation as regular fasteners 8.8 at room temperature (0.10).

10.9 Property Class Fasteners: BUFOe-1000 showed the highest strain, 0.14%, and 10.9 had the lowest, 0.06%, which was the highest creep resistance among the fasteners under room temperature conditions.

5.1.2 Creep Strain at $150°C$

At $150°C$, the creep strain values were found to be significantly larger for all fastener types. The highest strain was observed in BUFOe1000 (0.42%), followed by BUFOe800 (0.41%) and BUFOe800X (0.30%). Regular fasteners demonstrated better deformation resistance, ranging from 0.22% (Regular 10.9) to 0.23% (Regular 8.8).

8.8 Property Class Fasteners: The regular 8.8 fasteners had the least creep strain difference, ΔCreep (0.13%). BUFOe800 and BUFOe800X showed moderate ΔCreep (0.31% and 0.23%, respectively) while heat-treated fasteners revealed a significantly lower ΔCreep (Regular 8.8: 0.13%), indicating the improved thermal stability.

10.9 Property Class Fasteners: BUFOe1000 had the highest ΔCreep(0.28%), and Regular 10.9 ΔCreep(0.06%) had the lowest. The fasteners BUFO1000 demonstrated the maximum increase in strain (0.28%). The temperature-creep-induced difference in the strain gap between room temperature and $150°C$, ΔCreep, reveals important temperature-sensitive features. The thermally induced strain changes reveal the inconsistency in the material's behavior under thermal load.

5.2 Comparison Between BUFOe and Regular Fasteners

General characterizations of microstructure were done to compare fasteners based on their property class, specifically BUFOe fasteners (Non-heat-treated), with those of the standard fasteners (heat-treated).

5.2.1 Effect of Microstructural Characteristics

Creep in material can originate from a number of mechanisms in the microstructure. The more common mechanisms are i) dislocation movements, including climb, ii) grain boundary sliding, iii) diffusion, and iv) recrystallization. From these mechanisms, only dislocation movements and grain boundary sliding are expected to be larger contributors at modest temperatures such as those used for steel fasteners in this thesis. Regarding dislocation movement, there are a number of microstructure features that can act as obstacles, preventing dislocations from moving. Those are solid solutes, precipitates, grain boundaries, and other dislocations. Hence, for this study, the focus of the microstructure investigation is to compare the main dominating features that could explain the big difference in creep performance observed when comparing BUFOe fasteners with regular heat-treated fasteners.

The steel used for the five fasteners does not contain solid solutes of the size and amount that are expected to cause a difference in creep behavior. Furthermore, for precipitates, the BUFOe materials are not prepared in such a way that small, dislocation-pinning precipitates (such as VC or TiC) exist in the microstructure, and the cementite in the heat-treated structures is expected to be too coarse to be efficient pinning points. This leaves us with grain boundaries and other dislocations (a high dislocation density) as possible obstacles for dislocation movements, thereby reducing the tendency to creep. Note that grain boundaries can cause creep via grain boundary sliding at higher temperatures and loads. Microstructures were examined after traditional grinding and polishing, followed by etching in 5% Nital.

8.8 Property Class Fasteners: - Non heat-treated (BUFOe800 and BUFOe800X) have deformed and elongated ferrite/pearlite grain structures. This structure appears to result in further creep deformation under stress and provides lesser resistance to creep at high temperatures. Regular fasteners have a compact and dense martensitic microstructure, which seems to improve their creep resistance. This tight grain packing is believed to at least partly explain the lower creep strain results compared to the BUFOe fasteners (Figure 5.1).

10.9 Property Class Fasteners: The BUFOe1000 has a deformed, elongated ferrite/-pearlite grain structure, similar to BUFOe800 and BUFOe800X. As BUFOe1000 had the highest creep, this microstructure grain indicates that ferrite/pearlite has less resistance to creep. The elongated ferrite/pearlite morphology may be conducive to grain boundary sliding and dislocation slip under the effect of stress, both known creep mechanisms (Figure 5.2).

At $150^\circ C$, the increased energy will create a weaker resistance to dislocation movement in all microstructures of steel. The lower grain boundary density in the heat

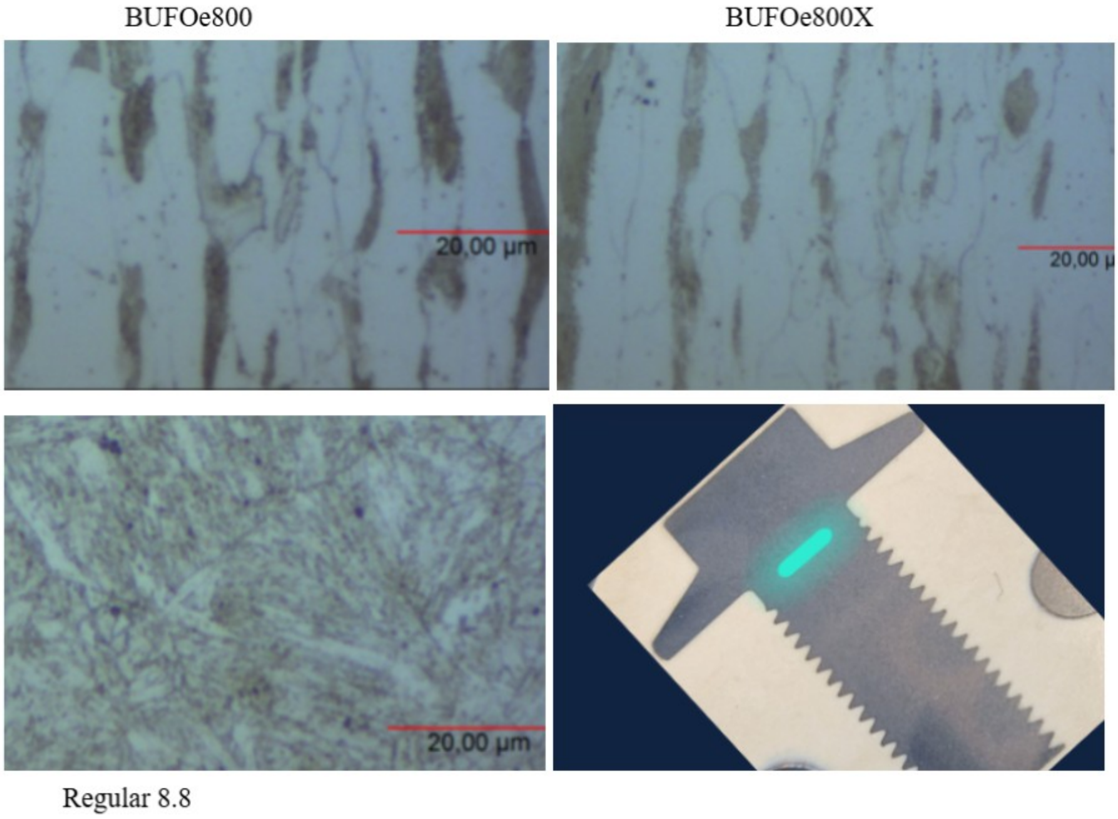


Figure 5.1: Microstructure of property class 8.8 fasteners.

treatment-free steels may offer fewer obstacles to dislocation movements in comparison to the dense microstructure of martensite in heat-treated fasteners. The fine-grained martensite may, in fact, provide enough obstacles to impede movements of dislocations up to 150°C, thereby outperforming heat treatment-free BUFOe. The better creep performance of BUFOe800X as compared to BUFOe800 could be an effect of the increased work hardening (dislocation density) caused by the higher amount of deformation used to cold forge BUFOe800X as compared to BUFOe800. Regular fasteners have a 10.9 grade designation and feature a fine, dense microstructure that has been hardened through quenching and tempering. The high boundary density will impede the movement of dislocations in fine-grained materials.

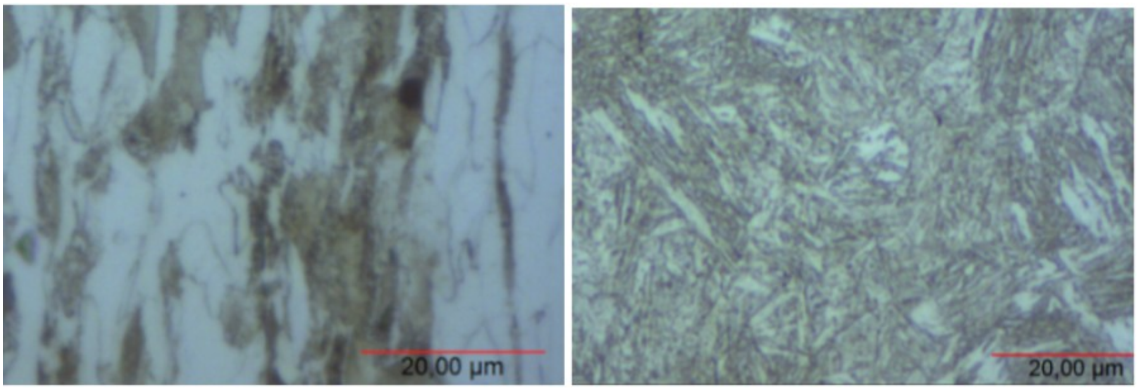


Figure 5.2: Microstructure of BUFOe1000 (left) and regular fastener 10.9 (right).

5.2.2 Creep Test and Temperature Effect

As creep strain was observed at room temperature, and the elongated grain structure was observed, the value of creep strain in BUFOe fasteners at an elevated temperature was expected to be higher than that at a low temperature. Comparing regular fasteners with non heat-treated fasteners revealed higher stability and lower creep strain at 150°C, possibly attributed to the refined microstructure achieved through heat treatment. The creep deformation difference due to temperature change was the greatest in BUFOe800 ΔCreep0.31% and the smallest in Regular 8.8, at ΔCreep0.13%.

The low density of boundaries in BUFOe appears to be the cause of extensive creep; thus, the peak strain of BUFOe1000 (0.42%) is understandable. This barrier effect, due to the tight boundaries of the regular fasteners, reduces creep compared to BUFOe800 at 150°C. A more general comparison between BUFOe and regular fasteners can be found in Table 5.1.

Table 5.1: General comparison of BUFOe vs Regular fasteners on creep performance and temperature sensitivity

Parameter	BUFOe Fasteners	Regular Fasteners
Microstructure	Ferritic/pearlite, large, elongated grains; low boundary density	Martensitic, compact, fine grains; high boundary density
RT Creep Resistance	Moderate (0.14%)	Better (0.10%)
150°C Creep Resistance	Moderate (0.42%)	Better (0.23%)
ΔCreep (RT 150°C)	High (0.31%)	Low (0.16%)

6

Stress Relaxation Performance

6.1 From Empirical Creep Test Results

This chapter describes the approach to extrapolate stress relaxation from findings and data obtained from empirical creep tests and investigates the stress relaxation response of different fastener types. Predicted stress relaxation over 4 hours (14,400 seconds) at room temperature and 150°C based on the Maxwell viscoelastic relaxation model are used to study the loss of preload between non heat-treated fasteners (i.e.,(BUFOe800X, BUFOe800, and BUFOe1000) and heat-treated fasteners (ie Regular 8.8 and Regular 10.9) at a 36 mm^2 nominal stress-based area. The significant parameters found are creep strain rate: $\dot{\varepsilon}_c$, viscosity: η, relaxation time: τ, residual stress: $\sigma(4h)$ and stress relaxation percentage: % stress relaxation.

6.2 Methodology

Stress relaxation of regular fasteners and non heat treated fasteners was computed at both at room temperature and 150°C, based on a few assumptions, including the reduction of Young's modulus by 3% at 150°C (Kan K. 2019), a nominal stress area equal to that of the fastener (36 mm^2), and the application of the Maxwell-type viscoelastic model (creep rate, viscosity, relaxation time) to predict the results of the creep test. Models: Maxwell and Voigt-Kelvin viscoelastic models were used. Key Assumptions:

- Constant nominal stress area for all types of fasteners is identical: 36 mm^2.
- Young's modulus decreases by 3% at 150°C compared to that at RT.
- Parameter estimation: the creep strain rates measured for 4 hours were used to derive.
- Viscosity: η, calculated from the basic Maxwell definition:

$$\eta = \frac{\sigma_0}{\dot{\varepsilon}_c} \tag{6.1}$$

  where (σ_0) is the initial stress.

- Relaxation time: τ, this is obtained from:

$$\tau = \frac{\eta}{E} \tag{6.2}$$

  Where E is Young's modulus.

Stress Relaxation Modeling: The Maxwell model equation for stress relaxation:

$$\sigma(t) = \sigma_0 e^{-t/\tau} \tag{6.3}$$

was applied to the remaining stress prediction,

$$\sigma(4h)$$

and the percentage stress relaxation after 4 hours:

$$\text{Relaxation (\%)} = \left(\frac{\sigma_0 - \sigma(4h)}{\sigma_0} \right) \times 100 \tag{6.4}$$

6.3 Results at Room Temperature and $150°C$

6.3.1 Analysis at Room Temperature

Table 6.1: Stress Relaxation Performance of 8.8 Property Class Fasteners at Room Temperature (4 hrs)

Fastener Type	σ_0 (MPa)	$\dot{\varepsilon}_c$ (s^{-1})	η (MPas)	τ (s)	$\sigma(4h)$ (MPa)	Relaxation (%)
BUFOe800	730.3	9.38e^{-8}	7.79e^{9}	38,447	507.1	30.7
BUFOe800X	767.8	5.55e^{-8}	1.37e^{10}	69,260	628.2	18.2
Regular 8.8	733.9	9.38e^{-8}	8.00e^{9}	40,002	517.2	29.5

Table 6.2: Stress Relaxation Performance of 10.9 Property Class Fasteners at Room Temperature (4 hrs)

Fastener Type	σ_0 (MPa)	$\dot{\varepsilon}_c$ (s^{-1})	η (MPas)	τ (s)	$\sigma(4h)$ (MPa)	Relaxation (%)
BUFOe1000	922.2	1.02e^{-7}	8.97e^{9}	44,731	667.2	27.6
Regular 10.9	911.4	4.42e^{-8}	1.96e^{10}	98,442	786.4	13.7

BUFOe800X exhibited the lowest RT relaxation (18.2%) among Class 8.8 fasteners, significantly better than BUFOe800 (30.7%) and Regular 8.8 (29.5%). This correlates with its much lower creep rate and higher viscosity/relaxation time. The regular 10.9 fasteners demonstrated the best overall RT performance, characterized by the lowest relaxation (13.7%), driven by the lowest creep rate and the highest viscosity/relaxation time among all fasteners tested.

BUFOe1000 showed relaxation (27.6%) comparable to the BUFOe-800 and Regular 8.8, but significantly higher than Regular 10.9.

6.3.2 Analysis at 150°C

Table 6.3: Stress Relaxation Performance 8.8 Property Class fasteners at 150°C (4 hrs)

Fastener Type	σ_0 (MPa)	$\dot{\varepsilon}_c$ (s^{-1})	η (MPas)	τ (s)	$\sigma(4h)$ (MPa)	Relaxation (%)
BUFOe800	730.3	$2.16e^{-7}$	$3.88e^9$	16,970	319.3	56.3
BUFOe800X	769.5	$2.07e^{-7}$	$3.74e^9$	18,788	364.0	52.7
Regular 8.8	733.9	$1.45e^{-7}$	$5.08e^9$	25,500	424.2	42.2

Elevated temperature drastically increases stress relaxation for all fasteners. Among Class 8.8 fasteners, Regular 8.8 showed the best performance at 150°C (42.2% relaxation), followed by BUFOe800X (52.7%), and then BUFOe800 (56.3%).

Table 6.4: Stress Relaxation Performance of 10.9 Property Class fasteners at 150°C (4 hrs)

Fastener Type	σ_0 (MPa)	$\dot{\varepsilon}_c$ (s^{-1})	η (MPas)	τ (s)	$\sigma(4h)$ (MPa)	Relaxation (%)
BUFOe1000	922.2	$2.88e^{-7}$	$3.21e^9$	15,970	384.3	58.3
Regular 10.9	911.4	$1.55e^{-7}$	$5.87e^9$	29,393	566.6	37.8

At 150°C, regular 10.9 fasteners still had better performance with the lowest relaxation (37.8%), while the highest remaining stress (566.6 MPa) was shown. This is due to their much lower creep rate and higher viscosity and relaxation time than all others. The stress relaxation performance of BUFOe1000 was significantly degraded at high temperatures (58.3% relaxation), just like that of BUFOe800.

6.3.3 Maxwell Model-Based Extrapolation

With the Maxwell model, the extrapolated stress relaxation curves were plotted, allowing the stress relaxation feature of fasteners in different strength classes under various temperatures to be visually displayed. Figure 6.1 shows the stress relaxation of different strength class fasteners at room temperature (left) and 150°C (right), where the strength class 8.8 is shown in the top row and 10.9 fasteners on the bottom row.

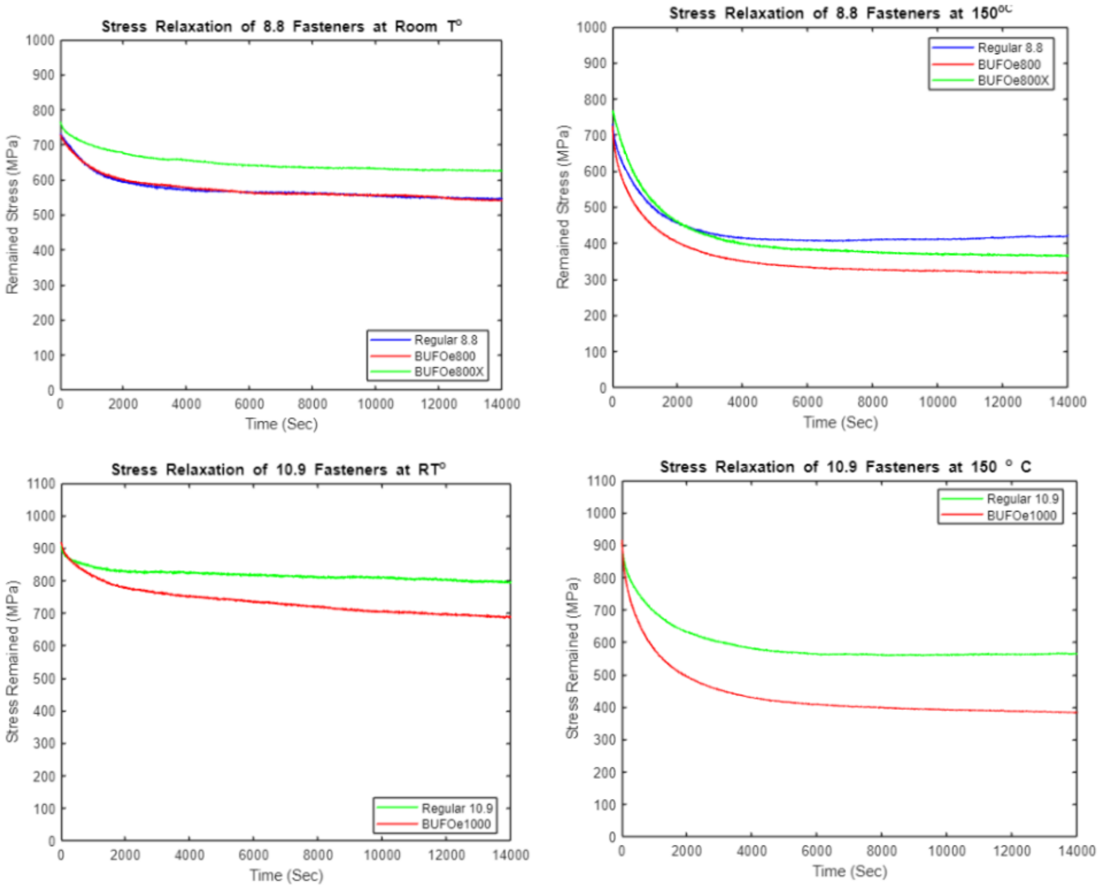


Figure 6.1: Stress relaxation curves of the strength class 8.8 (top) and strength class 10.9 (bottom) at room temperature (left) and 150°C (right) of different fasteners.

6.3.4 Temperature Impact Comparison

The negative influence of increased temperature on the ability of stress relaxation illustrated by BUFOe fasteners is considerable, with increments of 25%-34 % points. Regular heat-treated fasteners exhibited considerably better resistance to temperature-influenced stress relaxation. Regular 10.9 was raised by 24.1% points, while Regular 8.8 showed the smallest rise, with only 12.7% points, see table 6.5.

6.4 Discussion

The evaluation of creep strain in various fastener types demonstrates the importance of determining mechanical performance at different temperatures. The application's temperature and mechanical stress requirements are used to determine the best fastening method, either BUFOe or regular fasteners. BUFOe800X is excellent for room-temperature applications, offering a trade-off between cost and performance; however, thermal isolation is required if the ambient temperature is not constant. The experiment highlights the superiority of heat-treated fasteners in creep control at 150°C. The results emphasize the significance of material screening for specific

Table 6.5: Increase in Stress Relaxation from RT to 150°C

Fastener Type	Stress Relaxation at RT (%)	Stress Relaxation at150°C (%)	Increase (%)
BUFOe800	30.7	56.3	25.6
BUFOe800X	18.2	52.7	34.5
Regular 8.8	29.5	42.2	12.7
BUFOe1000	27.6	58.3	30.7
Regular 10.9	13.7	37.8	24.1

applications. BUFOe is sustainable, but its operational scope must exclude sustained thermal exposure.

The prediction of the stress relaxation from the empirical creep test result by the Maxwell model gives an overview of the stress relaxation behavior of different fastener types at different temperatures. Non-heat-treated BUFOe800X has lower relaxation than its counterpart of regular fastener under room temperature, but at 150°C, all BUFOe relax more than heat-treated fasteners. As a consequence, higher than half of their preload loss over time can be observed (e.g., 52-58% for BUFOe8 at 150°C versus 37-42% for Regular grades). The BUFOe800X fasteners had enhanced RT performance relative to the other BUFOe types, yet were still strongly temperature sensitive.

Considering the sustainability versus performance trade-off, BUFOe fasteners can offer an environmental advantage over regular fasteners due to the elimination of high-energy consumption heat treatment and CO_2; however, this is not without a trade-offin particular, higher stress relaxation is observed, especially at elevated temperatures. Their applications shall be critically examined against the performance expectations of the joint.

7
Conclusion

This chapter presents a summary of the results from an experimental study on the time-dependent stress response of five fastener types as a function of time and thermal operating conditions. The paper achieves its research objectives by assessing creep deformation and stress relaxation behavior based on empirical data, offering practical recommendations, acknowledging any limitations, and proposing future research work.

7.1 Summary of Findings

The creep tests of fasteners measured strain accumulation at room temperature (RT) and 150°C for 4 hrs.

Table 7.1: Creep Test Results Summary

Fastener Type	Strain at RT (%)	Strain at 150°C (%)	ΔCreep Strain (%)
BUFOe800	0.10	0.41	0.31
BUFOe800X	0.07	0.30	0.23
Regular 8.8	0.10	0.23	0.13
BUFOe1000	0.14	0.42	0.28
Regular 10.9	0.06	0.22	0.16

Particular observations, at 150°C, revealed that all fasteners exhibited more creep deformation from the range (0.22% to 0.42%), regular fastener 10.9 exhibited the least creep deformation (0.22%), and BUFOe1000 showed the highest strain (0.45%). Regarding temperature sensitivity, Regular 8.8 and exhibited the smallest creep strain increase from room temperature to 150°C, ΔCreep Strain (0.13%), whereas BUFOe800 showed the largest ΔCreep Strain (0.31%). Regarding the cold work effect, the BUFOe800X (modified version) exhibited better strain resistance at 150°C compared to that of BUFOe800, revealing the effect of material processing.

The extrapolation of stress relaxation from empirical creep test data using the

Maxwell viscoelastic model provides insights into the stress relaxation performance of different fastener types under varying temperature conditions. Regarding temperature impact, elevated temperature drastically accelerates stress relaxation in all fasteners. However, the degree of acceleration is moderately higher for BUFOe fasteners (a 25%-34% percent increase in relaxation) compared to Regular fasteners (12%-24% percents increase).

7.2 Analysis of Research Questions

- RQ1: What fasteners exhibit low creep deformation and stress relaxation at high temperatures? Low creep deformation can be correlated to lower stress relaxation. In this domain (0.22% strain), the standard 10.9 grade exhibited the best creep resistance during exposure at 150°C compared to BUFOe fasteners. Meanwhile, its small ΔCreep Strain (0.22%) also demonstrates stable stress retention during thermal stress loading. Regarding stress relaxation speculation, BUFOe800X is suited for high temperature conditions with the need for load retention. BUFOe1000 is not a candidate for elevated temperature due to higher creep deformation (0.42%).

- RQ2: What is the effect of cold working on the creep and stress relaxation behavior? BUFOe800X (extra cold worked) demonstrates excellent creep resistance at room temperature and decreases the creeo strain by 26.8% and and 28.6% at 150°C compared to BUFOe800 and BUFOe1000 respectively, validating the fact that the processing condition is optimized for improved creep properties.

7.3 Limitations

The lack of the possibility to obtain real-time strain measurements (the extensometer failure) was a source of possible data variation. Manual strain gauge measurements could also have contributed to inaccuracy, especially for small differences in strain values (e.g., Regular 8.8 vs. BUFOe800 at RT). This problem can be eliminated by using accurate and trustworthy sensors at elevated temperatures in future work.

7.4 Future Works

1 Stress relaxation testing: Directly test stress relaxation under constant strain as a complement to the creep data.

2 Longer-time effects: Test at moderate temperatures (50°C - 250°C) and durations, further down to 100 hours.

3 Microstructural investigation: Relate the creep rates to the grain boundaries/-precipitates evolutions (by using SEM/TEM).

4 Real-time monitoring: Use DIC digital image correlation (DIC) for spatially resolved strain mapping, for 2-D strain mapping.

7.5 Final Remarks

This work contributes to understanding temperature and time-dependent stressed performance of fasteners. In terms of material performance, the BUFOe fasteners performed as the same as regular fasteners at room temperature. At elevated temperatures, $150°C$ the BUFOe fasteners showed considerably lower creep resistance. As the role of processing cold work (e.g., BUFO800X) at room temperature suppresses creep deformation remarkably, this must be carefully balanced to minimize thermal susceptibility. Regarding sensitivity to temperature, the deformation behavior of all BUFOe fasteners was rapid at $150°C$ (e.g., BUFOe1000), illustrating the necessity of temperature-specific fastener choice.

This study identifies that BUFOe800X is the most suitable fastener at room temperatures but it needs improvement when compared with its regular counterpart (8.8 fastener) as the best performing (ΔCreep Strain: 0.13%), Their resistance to stress relaxation at $150°C$ is also moderately lower than regular fasteners.

With regular heat-treated fasteners, especially 10.9, long-term stability is far greater. They hold preload much better without stress relaxation, at both room temperature (13.7%, as an example) and especially at high temperature (37% for Regular 10.9 vs. >56% for BUFOe types). Furthermore, Regular 8.8 exhibits also the smallest thermal dependence of creep rate with respect to Class 8.8 BUFOe fasteners. With an increase in temperature, the rate of decline of stress relaxation is enormously increased in all fasteners. The acceleration is considerably higher for BUFOe fasteners (a 25%-34% point increase in relaxation) than for Regular (12%-24% point increase) at $150°C$.

Such findings provide a valuable reference for the design and production of fasteners in the continually evolving field of fastener design and manufacturing, as well as for the optimization of the mechanical reliability of fasteners under different industrial conditions.

Bibliography

[1] M. Meyers, K. Chawla, (2009) Mechanical Behavior of Materials. Cambridge University Press, Second Edition, 71155, 653688.

[2] ASTM (2020). ASTM E328 - Standard Test Methods for Stress Relaxation in Materials and Structures. ASTM International.

[3] ASTM E8/E8M-16a: Standard Test Methods for Tension Testing of Metallic Materials. ASTM International.

[4] ISO 898-1:2016: Mechanical Properties of FastenersPart 1: Bolts, Screws, and Nuts.

[5] ASTM F2096-16: Standard Test Method for Measuring the Relaxation Properties of Bolted Joints. ASTM International.

[6] N.V. Nguyen (2020). An experimental study on stress relaxation behavior of high-strength steel wire: Microstructural evolution and degradation of mechanical properties. Construction and Building Materials 261 (2020) 119926.

[7] M. Yang, Z. Wang, and P. Li (2021). Stress relaxation behaviors of graphene fibers. MOE Key Laboratory of Macromolecular Synthesis and Functionalization, Department of Polymer Science and Engineering.

[8] S. Jeong and C. Baig (2020). Molecular process of stress relaxation for sheared polymer meltsSchool of Energy and Chemical Engineering, Ulsan National Institute of Science and Technology.

[9] X. Wang. (2018) Experimental study on stress relaxation properties of structural cables. Construction and Building Materials 175 (2018): 777789.

[10] Bergström & Boyce (1998). Constitutive Modeling of the Large-Strain Time-Dependent Behavior of Elastomers. Journal of the Mechanics and Physics of Solids, 46(5), 931-954.

[11] ISO. (2013). ISO 898-1Mechanical Properties of Fasteners Made of Carbon Steel and Alloy SteelPart 1: Bolts, Screws, and Studs. International Organization for Standardization.

[12] Ferry (1980), Viscoelastic Properties of Polymers. New York, Wiley Interscience.

[13] V. Caccese, K. Berube (2009), Influence of stress relaxation on clamp-up force in hybrid composite-to-metal bolted joints. Composite Structures 89 (2009) 285-293.

[14] Y. Zhang, Y. Ni, and Z. Wang (2023), Stress-Strain Monitoring Technology for Bolted Fasteners Based on the 3D Digital Image Correlation Method. Research Square.

[15] A. Guliev, V. Sharifova, and F. Yusubov (2023), Relaxation Resistance of Austenitic Steels After Various Heat Treatments. Metal Science and Heat Treatment. Vol. 65, No. 1, pp. 812.

[16] Kathoey, F., Elias, A., & Elias, A. (2021). A Simplified Stress Analysis of Functionally Graded Beams and Influence of Material Function on Deflection. Applied Sciences, 11(24), 11747.

[17] Kan, K. (2019), Assessment of creep damage models in the prediction of high-temperature creep behavior of Alloy 617. Australian Nuclear Science and Technology Organisation (ANSTO), Sydney, NSW 2232, Australia.

[18] A. Marro (2017), Modeling of viscoelastic materials and creep behavior. Meccanica (2017) 52: 3015-3021.

[19] TR 048. (2016), Details of Tests for Post-Installed Fasteners in Concrete. European Organisation for Technical Assessment. www.EOTA.EU

[20] Neeraj, M. (2023), LongTerm Prediction of Creep and StressRelaxation Behavior in Synthetic Fabrics Using the TimeTemperature Superposition Principle. Fibers and Polymers (2023) 24:2195-2207.

[21] Zhang, T. (2023), Experimental study on mechanical properties and tightening method of stainless steel high-strength bolts. Engineering Structures 290 (2023) 116176.

[22] J. Huang, J. Liu, H. Gong, and X. Deng (2022), A comprehensive review of loosening detection methods for threaded fasteners. Mechanical Systems and Signal Processing 168 (2022) 108652.

[23] Y. Chen, J. Zhou (2024), Stress relaxation behavior and its effect on the mechanical performance of a wire cable. Mechanics of Time-Dependent Materials (2024) 28:595-615.

[24] X.. Lu1 (2020), Stress Relaxation Behavior of GH4169 Alloy. Materials Science Forum Submitted: (2020) ISSN: 1662-9752, Vol. 1013, pp. 52-58.

[25] D. Roylance (2024) Engineering Viscoelasticity. Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge.

[26] Che. Lin, Y. Chen, Ch. Lin and Ke. Chang (2022), Constitutive Equations for Analyzing Stress Relaxation and Creep of Viscoelastic Materials Based on Standard Linear Solid Model Derived with Finite Loading Rate. Polymers 2022, 14, 2124. https://doi.org/10.3390/polym1410212.

[27] Gustaver, M. (2020) A Chalmers University of Technology master's thesis template for LaTeX. Unpublished.

A

Appendix 1

A.1 Chemical Composition of BUFOe and Regular Fasteners

Fasteners	Steel	C	Si	Mn
8.8	17B2	0.15-0.17	0.10max	0.70-0.90
10.9	30MnB4	0.28-0.32	0.20max	0.80-1.00
BUFOe 800	22MnB5Ti	0.20-0.25	0.26-0.60	1.10-1.50
BUFOe 1000	30MnVS6	0.27-0.33	0.30-0.60	1.20-1.60

Table A.1: The Ratio of Chemical Composition of C, Si, and Mn for Various Fasteners

Fasteners	Steel	P	S	Cr
8.8	17B2	0.020max	0.020max	0.15max
10.9	30MnB4	0.020max	0.020max	0.10-0.25
BUFOe 800	22MnB5Ti	0.025max	0.025max	0.20-0.40
BUFOe 1000	30MnVS6	0.025max	0.025max	0.10-0.30

Table A.2: The Ratio of Chemical Composition of P, S, and Cr for Fasteners

Fasteners	Steel	Ni	Mo	Cu
8.8	17B2	0.15max	0.05max	0.02-0.05
10.9	30MnB4	0.20max	0.06max	0.015-0.05
BUFOe 800	22MnB5Ti	0.15max	-	0.15max
BUFOe 1000	30MnVS6	0.15max	-	0.15max

Table A.3: The Ratio of Chemical Composition of Ni, Mo, and Cu for Fasteners

Fasteners	Al	V	Ti	B
8.8	-	0.01-0.09	0.002-0.005	-
10.9	-	0.01-0.09	0.001-0.005	-
BUFOe 800	0.020-0.060	-	0.020-0.050	0.002-0.005
BUFOe 1000	0.020-0.060	0.07-0.20	-	-

Table A.4: The Ratio of Chemical Composition of Al, V, Ti, and B for Fasteners

B

Appendix 2

B.1 Displacement Curves to Strain Curves

The displacement change of each sample was continuously recorded, and the average of the three samples of each type of fastener was calculated as creep deformation and subsequently converted into strain, as illustrated in the accompanying figure. Initially, the displacement curves of all five fasteners were plotted, after which they were transformed into strain by normalizing the values concerning the initial grip separation (25.5 mm). Subsequently, the creep strain behavior of the five fasteners was analyzed and represented graphically, see Figure B.1.

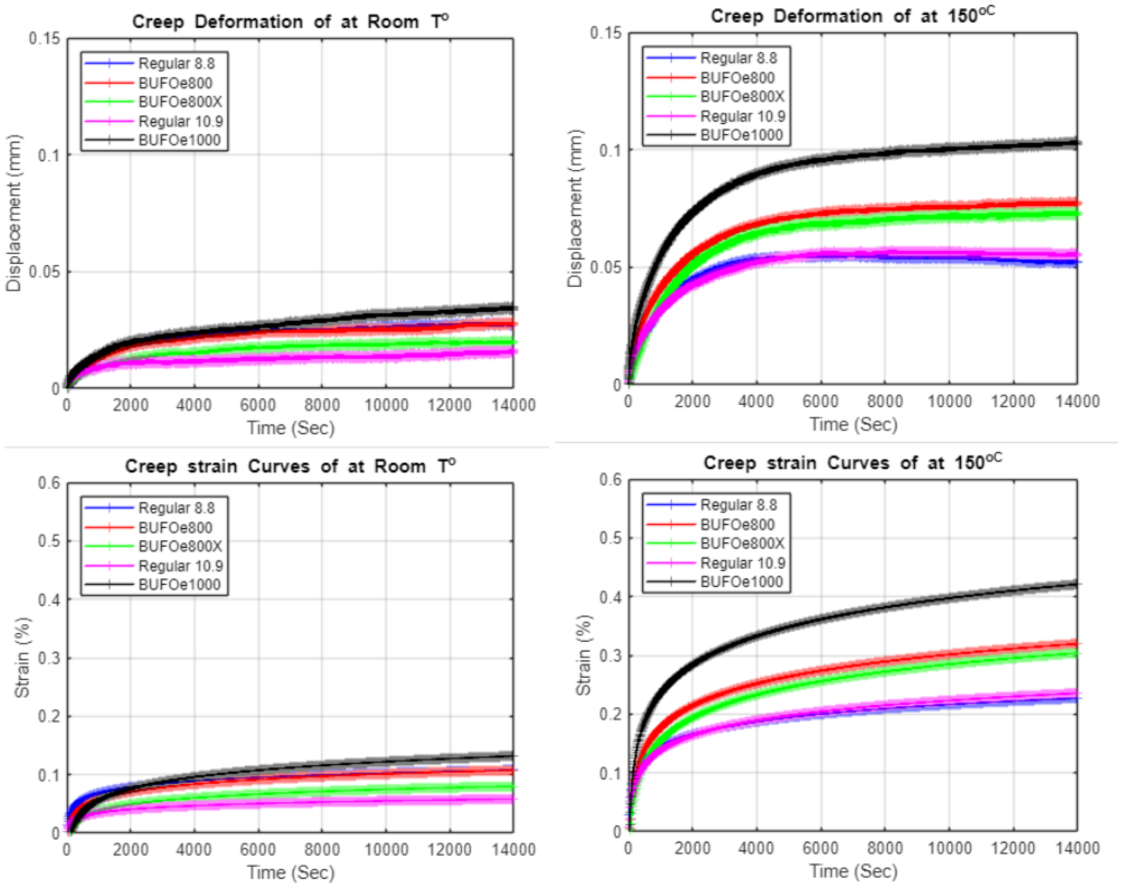


Figure B.1: Displacement curves (top) and strain curves (bottom) at room temperature (left) and 150°C (right) of all fasteners.

C

Appendix 3

C.1 Stress Relaxation Curves for Fasteners by Using Maxwell Models and Creep Test Results

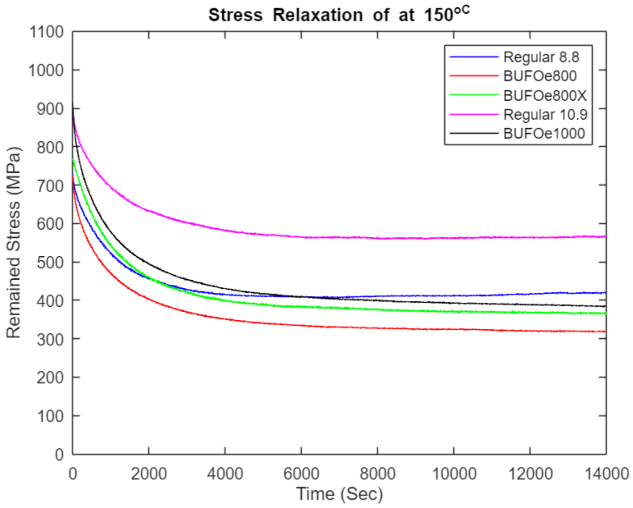


Figure C.1: Stress relaxation curves based on the Maxwell model at 150°C of all fasteners.

D

Appendix 4

D.1 Microstructure of the Different Fasteners

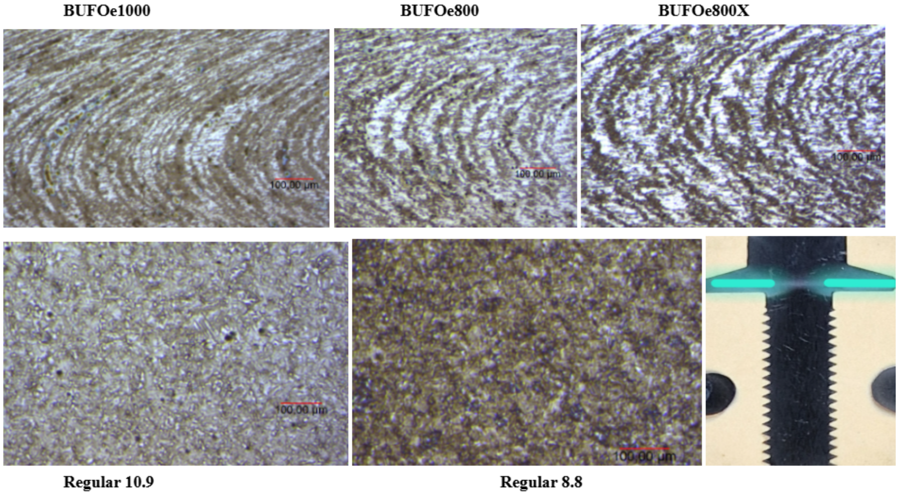


Figure D.1: Microstructure of fasteners' longitudinal direction at flange.

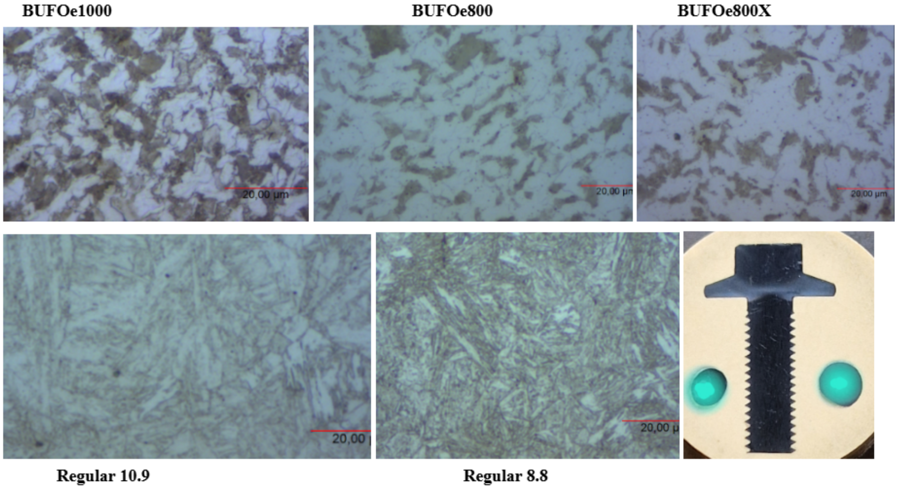
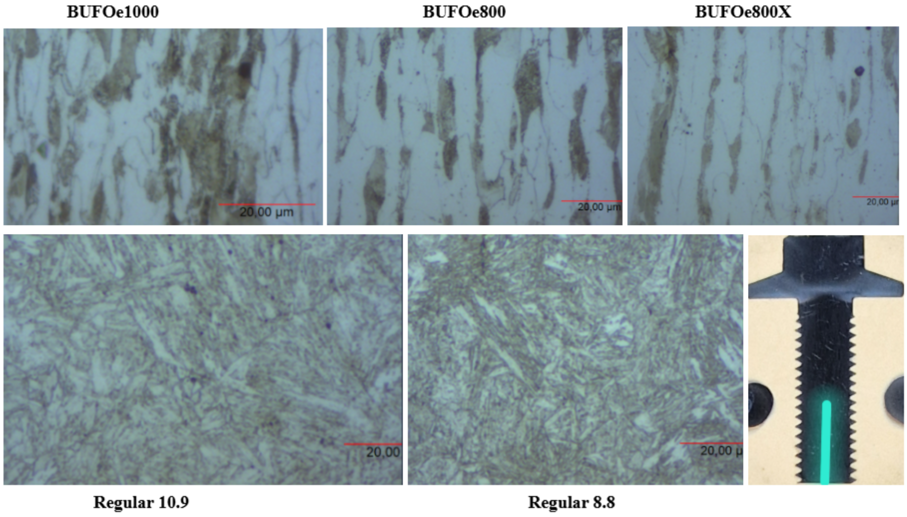


Figure D.2: Microstructure of fasteners' cross-section view.



BUFOe1000 BUFOe800 BUFOe800X

Regular 10.9 Regular 8.8

Figure D.3: Microstructure of fasteners' longitudinal direction at threads.

E

Appendix 6

E.1 The Average Result from three samples of a Fastener Type

E.1.1 Extract relevant columns

```
xRT3 = data_RT3(:, 3);   Time
FRT3 = data_RT3(:, 1);   Force
DRT3 = data_RT3(:, 2);   Displacement
eRT3 = DRT3 ./ 25.5;     Strain

xRT2 = data_RT2(:, 3);
FRT2 = data_RT2(:, 1);
DRT2 = data_RT2(:, 2);
eRT2 = DRT2 ./ 25.5;

xRT1 = data_RT1(:, 3);
FRT1 = data_RT1(:, 1);
DRT1 = data_RT1(:, 2);
eRT1 = DRT1 ./ 25.5;
```

E.1.2 Create a common time vector for interpolation

```
x_common = linspace(min([xRT1; xRT2; xRT3]), ...
                    max([xRT1; xRT2; xRT3]), ...
                    max([length(xRT1), length(xRT2), length(xRT3)]));
```

E.1.3 Interpolate data to align on common time

```
FRT1_interp = interp1(xRT1, FRT1, x_common);
FRT2_interp = interp1(xRT2, FRT2, x_common);
FRT3_interp = interp1(xRT3, FRT3, x_common);

eRT1_interp = interp1(xRT1, eRT1, x_common);
eRT2_interp = interp1(xRT2, eRT2, x_common);
```

```
eRT3_interp = interp1(xRT3, eRT3, x_common);

DRT1_interp = interp1(xRT1, DRT1, x_common);
DRT2_interp = interp1(xRT2, DRT2, x_common);
DRT3_interp = interp1(xRT3, DRT3, x_common);
```

E.1.4 Compute averages

```
F_avg = (FRT1_interp + FRT2_interp + FRT3_interp) / 3;
e_avg = (eRT1_interp + eRT2_interp + eRT3_interp) / 3;
D_avg = (DRT1_interp + DRT2_interp + DRT3_interp) / 3;
```

E.1.5 Define confidence level (90%)

```
confidence_level = 90;
z_score = 1.645;  Z-score for 90% confidence
```

E.1.6 Compute standard error and confidence intervals

```
SE_F = std([FRT1_interp; FRT2_interp; FRT3_interp]) / sqrt(3);
SE_e = std([eRT1_interp; eRT2_interp; eRT3_interp]) / sqrt(3);
SE_D = std([DRT1_interp; DRT2_interp; DRT3_interp]) / sqrt(3);

CI_F = z_score * SE_F;  Confidence Interval for Force
CI_e = z_score * SE_e;  Confidence Interval for Strain
CI_D = z_score * SE_D;  Confidence Interval for Displacement
```

The results of the tests were collected as the average of the three samples of each type of fastener. For example, the BUFOe1000 fastener was tested with three samples at room temperature and three samples at elevated temperature, and then for each temperature condition, an average result of the three samples was taken. A 90% of confidence interval was established for these three samples, using standard deviation corresponding to Z = 1.96. Figure E.1

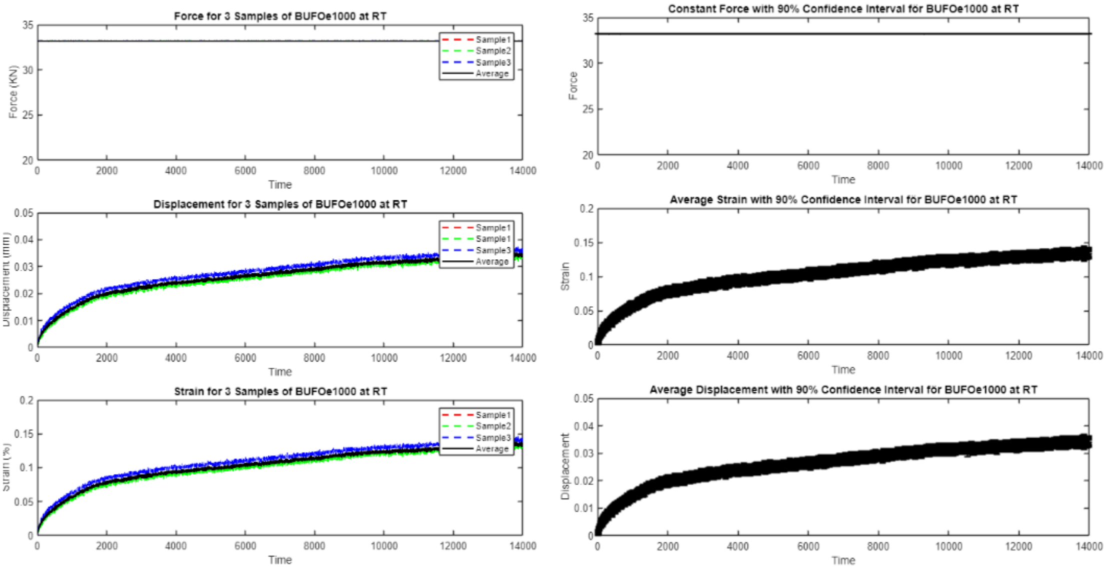


Figure E.1: The average of the three samples and their confidence interval at RT.

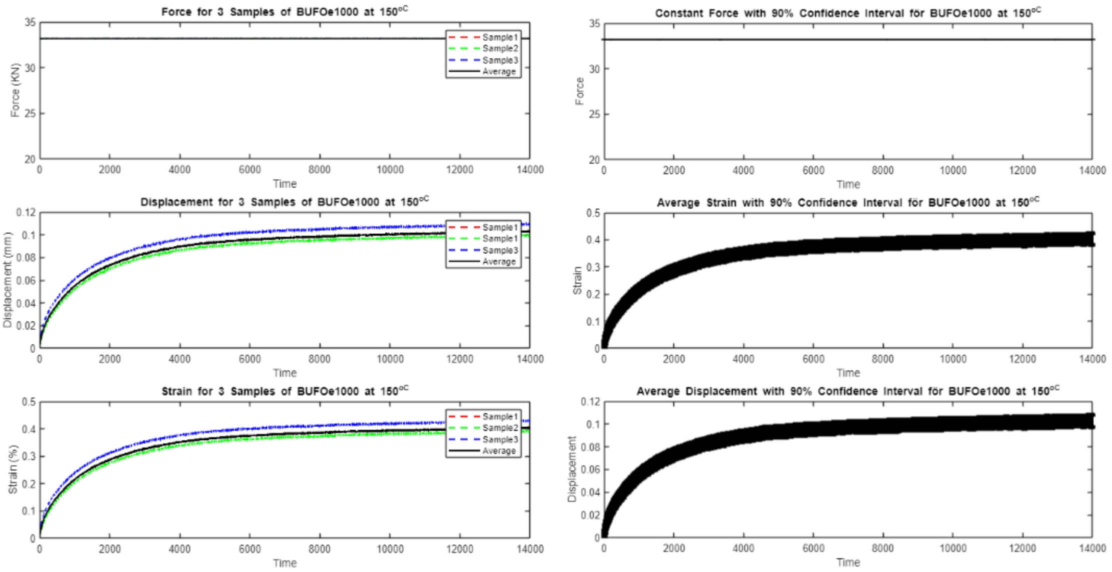


Figure E.2: The average of the three samples and their confidence interval at $150°C$.

F

Appendix 5

F.1 Initial Length

To accurately calculate strain, the initial length was defined as the gap between the grip at the region where the fastener exhibited the most significant creep deformation. This gap was measured at 25 mm, ensuring that strain assessments reflect the fasteners true elongation behavior, see Figure F.1. To account for specimen safety, an additional 0.5 mm was incorporated, resulting in a total grip gap of 25.5 mm for all testing setup and testing fasteners.

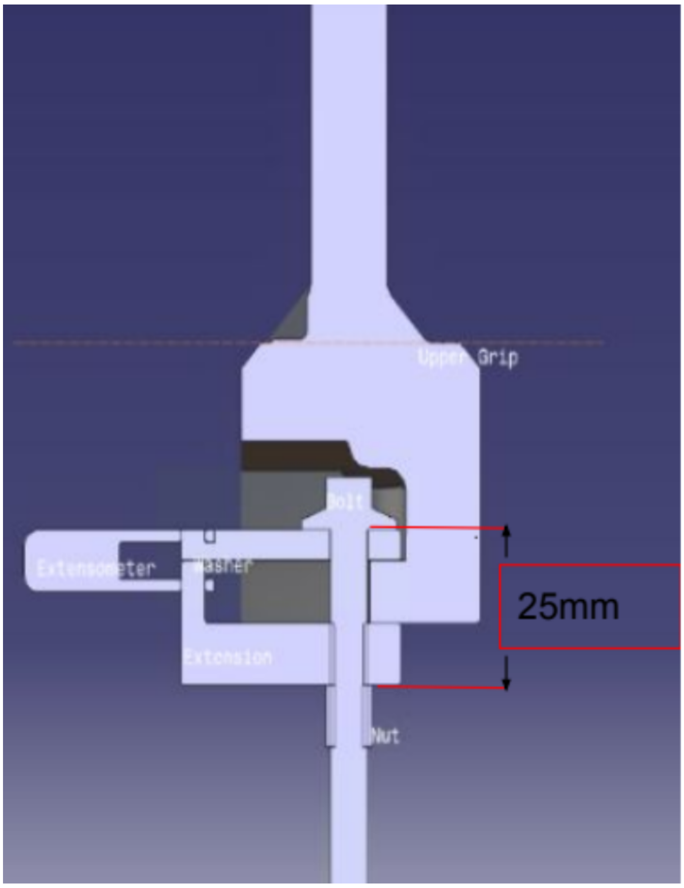


Figure F.1: The initial length was defined as the gap between the grip, specifically at the region where the fastener could exhibit creep deformation.

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