NUMERICAL & EXPERIMENTAL INVESTIGATION OF THE BEHAVIOR OF SMP STRUCTURAL JOINTS

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of the Behavior of SMP Structural Joints

by

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Vasiliki Kaymenaki,
Berlin, 2018
ABSTRACT

The main objective of the current study is the investigation of the behavior of structural joints consisting of Shape Memory Polymers. Taking into account the large environmental impact caused by the massive production of structural materials, the change of the current structural design philosophy is becoming essential. Conventional structural engineering approach involves the design of structures fulfilling first strength requirements and second serviceability limit states. The latter applies strict deformation limits mostly related to the comfort of the users and their perception of safety. Adaptive structures get inspiration by organisms present in nature, which are able to adapt their shape and properties as a response to changing surroundings. The capability of a structure to counteract an external stimulus such as earthquake event or strong winds may lead to significant material savings. In particular, adaptive structures are able to react (deform) to applied loads through controlled shape changes and redistribution of internal forces. To this end members with variable length and variable stiffness are required.

The current study focuses on the behavior of SMP joints which experience two states: locked and released. In the first state, the joint maintains its main function to transfer the loads between the connected elements whereas in the released state the joint becomes softer allowing thus a degree of movement between the elements. 3D printed Shape Memory polymers are chosen as main material due to their variable stiffness properties when exposed to external stimulus such as temperature and their ability to recover their original shape unconstrained. The thermomechanical cycle of thermally triggered SMPs constitutes of the glassy, glass transition and rubbery phase. Glass transition temperature is a threshold temperature, at which the material changes phase and a significant reduction of the young modulus occurs.

Shape Memory Polymers belong to the class of viscoelastic materials with time and temperature dependent properties. A number of experimental tests is performed for the thermomechanical characterization of the polymer. Namely, a rectangular sample is subjected to dynamic loading in a range of frequencies, while the temperature increases from 30°C to 90°C. The storage and loss modulus as well as the phase angle δ are measured as a function of temperature. The storage modulus describes the elastically stored and released energy and it is the actual modulus of the material while the loss modulus represents the dissipated energy due to friction between the molecular chains. From the storage and loss modulus, the Prony Series coefficients needed for the numerical simulation of the material, are calculated. Additionally, tensile tests are performed at various temperatures in order to define the strength and give an indication about the maximum elongation of the material. It is noted that at 25°C the strength of the material is approximately 36MPa. With the increase of the temperature the strength of the material drops while the maximum elongation increases. The shape memory effect of the polymer is also tested at different heating rates and ramp and isothermal temperature conditions. The aim of these tests is to define the factors that may influence the shape recovery phase of the polymer. It is observed that faster heating rates shift the transition phase of the polymer to higher temperatures causing delay on the onset of the recovery phase. On the other hand, slower heating rates enable the recovery process of the polymer at lower temperatures due to the intrinsic relaxation properties of the material. With respect to ramp and isothermal conditions, in both cases shape recovery occurs, with the difference that in first case the increase of the temperature triggers the recovery while in the second case the temperature is kept constant and the relaxation properties of the polymer contribute to the recovery of its original state.

The numerical simulation of the joint is based on the viscoelastic theory and makes use of the Prony Series coefficients calculated by the Dynamic Mechanical Analysis. For the validation of the numerical model, the DMA and the Shape Memory tests are numerically conducted. The numerical results are in good agreement with the experimental ones increasing thus the reliability of the results presented in the current study. Last, a truss structure is considered as a case study and the load bearing capacity of the SMP joint is assessed under permanent and variable loads. It is important to be mentioned that only the linear part of the material law is modeled numerically. Hence, the assessment of the load bearing capacity of the joint is realized until the end of the linear part of the stress – strain curve. It is concluded that at glassy state, the SMP joint is able to sustain 95% of the permanent loads and 45% of the Ultimate Limit State load combination. Upon heating, the load bearing capacity of the joint is decreased. At the temperature of 40°C, the yield stress of the material is 26MPa which drops to 15MPa after necking. At the same temperature, the maximum strain of the material increases up to 150% meaning that it is able to accommodate large shape changes.

To conclude, the current research studies the mechanical behavior of SMPs and their potential use in the field of structural engineering and especially in the design of adaptive structure where large shape changes are required. Although the strength of the material at its glassy state is comparable to other structural materials such as wood its relaxation properties need to be studied carefully. Last, it is proved that SMP can accommodate large shape changes but reinforcement of the material is needed in order to increase its load
bearing capacity. The present master thesis is part of the research program “Lighthouse Project 2017” entitled “Adaptive Joints with variable stiffness” with principal researcher Qinyu Wang from TU Eindhoven.
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1.1 Motivation

Building industry is a massive source of CO$_2$ emissions causing several undesirable environmental effects. Large amounts of building materials, such as concrete and steel, are produced every day in order to serve constructional purposes. One considerable question could be in what extend are those quantities of materials necessary for the structural design of buildings? Is there any chance to reduce them by improving the structural efficiency of our built environment?

![The Embodied Carbon of Building Materials](chart.png)

**Figure 1.1:** CO$_2$ emissions of building materials [1]

Conventional structural engineering approach involves the design of structures fulfilling first strength requirements and second serviceability limit states. The latter applies strict deformation limits mostly related to the comfort of the users and their perception of safety. In order to meet the serviceability criteria, the current method implies the increase of material ensuring thus higher stiffness. When the design is governed by unpredictable events such as strong winds or seismic excitations, the structure is overdesigned for most of its working life. The introduction of adaptation into structural engineering aims at making use of structural materials (passive systems) only for safety reasons (strength requirements) whilst active systems may control the deformation of the structure ensuring comfort and usability [2].
The theory of adaptation derives from nature. Organisms are able to adapt to an ever changing surrounding by changing their shape and properties in order either to improve their living conditions or to survive. Adaptive mechanisms have been developed by transferring knowledge from nature into engineering. The flexibility of organisms as well as their ability to recover their initial shape set the framework of adaptive structures. The capability of a structure to counteract an external stimulus such as earthquake event or strong winds may lead to significant material savings. In particular, adaptive structures are able to react (deform) to applied loads through controlled shape changes and redistribution of internal forces [3]. Although there are different methods of designing adaptive structures, the current research focuses on the combination of components with variable stiffness and length. The variable stiffness method is developed by using smart materials such as shape memory polymers. SMPs are a class of smart materials able to change their stiffness and subsequently their shape under the influence of an external stimulus such as temperature or light and return to their original state. The use of SMPs in the joints of an arch truss structure in combination with variable length members allows the structure to evolve large deformation and redirect the evolved internal forces [4].

To conclude, although adaptive systems constitute a step towards lightness and may have great potential in the field of structural engineering, the behaviour of this type of structures is a complicated and challenging task for structural engineers. My personal objective, in the current thesis, is to investigate the behaviour of joints with variable stiffness which constitute a promising tool for the design of adaptive structures.

1.2 Research Objectives

1.2.1 Lighthouse project

The current master thesis is a part of a research project funded by 4TU Concept Lighthouse 2017. The main objective of this project is the development of joints with variable stiffness. To this end, smart materials with transduction properties are selectively positioned along the structure. SMPs are considered good candidates for the realization of this project due to their large stiffness variation properties and reversible behaviour. Large deformations triggered via actuators allow the shape adaptation counteracting thus the exerted loads. A truss arch structure, able to morph in optimal shapes determined by the load path, is chosen for the implementation of the aforementioned concept (Figure 1.3). The structure consists of strategically positioned active and passive members. Actuators, which are elements with variable length, are used for the active members. The desired deformation patterns are obtained through controlled length changes of the actuators and controlled movements of the joints [5].

Initially, experimental studies were conducted in order to verify the potential use of joints with variable stiffness in the field of adaptive structures. It is concluded that large shape changes require significant joint flexibility. The combination of members with variable length and flexible joints allows the shape control with lower actuation energy and higher accuracy. The current research will contribute to the development of this concept by investigating the numerical behaviour of this type of joints.
1.2.2 Research questions

In this context, the goal of the current master thesis is to investigate the numerical and experimental behaviour of joints with variable stiffness and to get insights into the field of smart materials. To this end, a main research question and four sub questions are addressed.

Main research question: What is the behavior of structural joints with variable stiffness consisting of Shape Memory Polymers?

The main concept of the development of joints consisting of Shape Memory Polymer is based on the thermo-responsive properties of this material allowing the elongation of the actuators, when heated above its glass transition temperature \(T_g\) and becomes flexible. At the same time, an external load is applied and the shape of the joint changes. Upon cooling below its \(T_g\) the SMPs enter its glass state (solid state) and the desired locked state is achieved. When heated again the joint is able to recover its initial shape.

**Figure 1.4:** SMP joint for a truss arch structure

In order to answer the main research question, four sub-questions are formed. The sub questions aim to provide a simplified and step wise approach on this complex problem.

Sub-question 1: Which material model describes in a simplified and accurate way the behavior of Shape Memory Polymers?

Shape memory polymers belong to the class of viscoelastic materials with time and temperature dependent properties, as Figure 1.5 indicates. A decrease of modulus of elasticity is observed as the time increases whilst the influence of the temperature can be seen in the Figure 1.5(b). Some have developed different constitutive models describing the material behavior of polymers in function of time and temperature. In most of the cases combinations of spring and dash elements are used representing the elastic and viscous behavior respectively [6]. This sub-question aims at the determination of the material model that will be used for the numerical simulation of the joint.

**Figure 1.5:** Time and Temperature dependent behaviour of polymers [6]

Sub-question 2: What is the thermomechanical behavior of SMP at various temperatures?

The response of the joint to imposed temperature and external loads will be crucial for the next steps of the research. The stiffness level as well as the strength of the joint in its rubbery and glass transition state determines the magnitude of the external loads that is able to transfer to the connected elements. Taking into account the material law of SMPs, the stiffness of the polymer is reduced significantly in the rubbery phase (Table 1-1), indicating the need of adding extra stiffness. In addition, the strength and the maximum elongation of the material is strongly temperate and time dependent. To this end, a series of experimental tests is required.

**Table 1-1:** Stiffness Variability [7]

<table>
<thead>
<tr>
<th>Stiffness ratio</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_g/E_r\approx100)</td>
<td>Below and above (T_g=55) °C</td>
</tr>
</tbody>
</table>
Sub-question 4: Which factors influence the recovery phase of the polymer?

One of the main characteristics of SMPs is their ability to recover its original shape, after their exposition to external stimulus such as temperature. This sub question aims to study parameters which play significant role on the recovery behavior of the polymer and may accelerate or retard the recovery stage.

Sub-question 5: What is the load bearing capacity of the joint at different temperatures?

The current sub-question aims to define the magnitude of structural loads that this innovative type of joint is able to carry. A case study with permanent and variable loads is considered and the load bearing capacity of the joint is assessed. The answer of this sub question can also give an indication whether reinforcement of the material is needed due to the low strength at high temperatures.

1.3 Research Method

The current study focuses on the investigation of the behavior of structural joints consisting of SMPs. The development of this type of joints is realized within the framework of adaptive structures. Hence, a deep insight into this field is crucial to understand the potential of the development of joints with variable stiffness. The main principles, methods and mechanisms of adaptive structures are presented in Chapter 2. In the same section, the thermomechanical properties of SMPs as well as the molecular structure are described as recorded in literature in order to provide the reader with an overview of the material behavior.

In Chapter 3, the viscoelastic properties of the polymer and the experimental tests needed for their thermomechanical characterization are presented. This chapter consists of two parts. First, the time dependent properties such as relaxation creep and dynamic loading are analyzed. Second the effect of the temperature on the properties of the polymer is described and last the interrelation between the two properties by using the time temperature superposition principle is studied.

In order to investigate the behaviour of joints with variable stiffness and their potential application to the field of structural engineering, a case study is considered in Chapter 4. Namely, the SMP joint is part of a truss structure serving the connection between the truss elements by transferring the internal forces. The geometry of the structure as well as the load cases taken into consideration are presented in the current paragraph. In Chapter 5, the results of a series of experimental tests are presented. In particular, a rectangular SMP sample is subjected to dynamic mechanic analysis which measures the storage and the loss modulus of the polymer as the temperature increases. Tensile tests are conducted in order to measure the strength of the material at various temperatures. Last, the shape memory effect of the polymer is tested and the influence of the heating rate and isothermal conditions is studied.

Having completed the experimental tests required for the thermomechanical characterisation of the polymer, a comparison between experimental and numerical results is presented in Chapter 6. The DMA and the SME are simulated numerically and the comparison between the two studies provides the reader with a deep insight into the numerical simulation of the SMP joint while offers a good overview of the reliability of the results presented in the current research.

In Chapter 7 the response of the SMP joint to imposed permanent and variable loads is assessed. The behavior of the structural joint is studied when the material is at its glassy and glass transition phase. The assessment of the load bearing capacity is realized by comparing the linear elastic response of the joint with the stress – strain curves derived from the tensile tests and give the strength of the material at various temperatures. The aim of this research is to define the force levels that the joint can sustain under different loading conditions.

Concluding, after the results have been finalized and the research questions have been answered, the conclusions of the research project are drawn in Chapter 8. In addition, recommendations for future research are given.

1.4 Thesis Outline

- Introduction
- Literature Review
- Constitutive modelling of SMP
- Case Study
- Experimental Results
- Validation of the numerical model
- Load bearing capacity of the SMP joint
- Conclusions and Recommendations

Figure 1.6: Research method
2.1 Biomimetics in engineering

How can mechanisms present in nature influence the current design methods? Biomimetics is the science focusing on the relation between nature and engineering. The term biomimetics defines the use of biological mechanisms and functions in engineering, chemistry, electronics and so on in order to achieve an optimum design, product or analysis. This procedure entails knowledge transfer between nature, science and engineering. The aim of using biomimetics at the design process is not only to improve the performance of building components but also to evolve new features such as multi-functionality, hierarchical structuring and adaptability. According to Speck, biomimetic research is divided into two types: biology push or bottom up and technology pull or top down. The first approach encompasses the use of a biotic product as role model for the design of a structure while the second seeks for finding common features between an established design and nature. Even though the first intention of the use of biomimetics was to imitate the structure and the function of living organisms, recent studies focus on the actuation mechanisms, biomaterials and skin adaptability (Figure 2.1). The new biomimetic approach moves eventually from macrostructure to microstructure or even deeper to nanostructure scale [3], [8], [9].

![Diagram of Biomimetics: Old & New Approach](image)

2.2 Adaptability as a strategy towards lightweight structures

2.2.1 Nature

In nature, organisms are able to adjust their properties to a changing environment in order either to improve their living conditions or to survive. There are three types of adaptive strategies that are mainly used in nature. These include (a) an instantaneous reaction to external conditions such as plants bending mechanisms in case of low humidity level (Figure 2.2) or their ability to change orientation in order to capture direct sunlight (b) growth as a process of changing size and developing, the duration of this procedure ranges from minutes up to decades depending on the type of the organism (c) and evolution describing the changes needed to be made in order to enhance their chance to survive [3], [8].
2.2.2 Built environment

But how does the built environment react to a changing surrounding?

There are some cases with a certain level of adaptability which is mainly based on mechanical devices and serve functional purposes. Examples range from elements such as doors, windows, blinds, division walls to foldable bridges and roofs. However the aforementioned mechanical principle of designing adaptive structures is getting complicated or even not applicable when the geometrical complexity and scale increase. Additional to that, the overall weight of the structure and the maintenance requirements augment enormously. Therefore, in the field of structural engineering where the scale increases, in most of the cases the structures consist of rigid elements which are connected with technical hinges allowing thus slight movements. The main design method against to a seismic event (external stimulus) entails the increase of the size of the structural components and subsequently the quantity of the materials leading to an increased overall stiffness of the building [10]. The stiffness determines the resistance of the structure to an imposed deformation and its properties depend on the material, the shape and the boundary conditions of the structure. Thus, during a seismic excitation the building is either able to absorb the seismic motion or several cracks or even collapse of the structure will occur [8].

Engineers are striving for innovative methods in order to improve the efficiency of the built environment and reduce the required amount of structural materials achieving thus more lightweight structures. Any structure designed in an intelligent way aspires to be as light as possible. Its main function is to sustain live loads whilst dead loads are considered unfavourable [11]. One technique to reduce the overall weight of the structures is by allowing movements or redistribution of loads. Thus, adaptive structures can be a promising strategy towards lightness.

Firstly, it is important to mention what we consider as adaptive structures in the current study. Generally speaking, a structure is considered adaptive when it is able to detect an external change via sensors and adjust its properties in order to counteract dynamic forces such as earthquake and wind loads. In other words, adaptive structure is a machine that responds dynamically to external conditions. An adaptive structure experiences three different states, the passive state where there is no adaption and the system serves its normal function to carry the applied loads, the activated state where the actuators are enabled and last the adaptive state which is a combination of passive and activated conditions [12], [13].

Sobek and Teuffel et al introduced the potential use of adaptability as a strategy for minimizing the overall weight of the structure. To this end, members with variable stiffness and length were introduced, rendering the structure able to react to different load conditions. Their theory is based on the active control system, consisting of sensors, control unit and actuators. Even though they developed and proved, that the design of an adaptive structure based on the optimal force path and the strategic position of actuators, leads to significant material savings, the operating energy of this system was in question [13], [14]. Later, Gennaro et al conducted thorough research with regard the energy savings of active control structures. Based on his research, Figure 2.3(a) describes diagrammatically the energy savings of passive and adaptive structures. As it can be seen, the embodied energy of an active design is significantly low but several concerns are arisen with regard to operating energy which may increase during the working life of the structure. On the other hand, passive structures contain high embodied energy (large amount of structural materials) and low operational energy. Different cases such as truss structures with strategically positioned actuators, which are rarely enabled when the loads exceed a specific threshold, have been studied. It is concluded that active control systems can reach up 50% energy savings in comparison to optimised passive designs (Figure 2.3(b)) [15].
2.3 Types of adaptability

There are two main methods of designing adaptive structures:

- Passive adaptability

The first one makes use of passive systems focusing on the flexibility of the structures. Nature acts as a role model, where flexibility is often present in organisms. Figure 2.4 (a) depicts the reaction of a leaf to imposed wind loads, firstly it adjusts its surface so as to reduce the loaded area and secondly its flexibility contributes to the decrease of applied forces. Introducing this principle into engineering, less material can be used as the structures are able to avoid the governing design loads by adapting. Through the deformation of the structure, the magnitude of applied loads decreases. Decrease of the loaded areas, reduction of the form factor and the friction, redistribution of loads due to yielding, constitute methods of designing passive adaptive systems [16].

- Active adaptability

When active adaptability is used, the structure behaves in the conventional passive way up to a specific threshold of internal forces and deflections. In the rare case, that the aforementioned limits are exceeded the structure will be controlled by active systems such as actuators. In this state, actuators modify and optimize the internal load distribution (load path management) increasing thus the structural efficiency of the system. The internal stresses will be decreased due to the activity of several members towards an optimal load bearing system. Therefore, the size of the structural elements is reduced without influencing the structural capacity of the system. The use of actuators is mainly related with the live loads of the structure and their application has great potential in the field of lightweight structures where live loads are governing. They can be lead to significant material savings through redirection of internal forces [16].

Figure 2.5: Active systems [16]
2.4 Bioinspired adaptive mechanisms based on flexible and stiff components

In the current section, the framework of combing rigid and flexible components is studied. This concept is inspired by the human body where bones are the stiff components supporting the frame and muscles are the flexible members allowing the skeleton to move. The muscles are attached to the bones via tendons. When our arm rises up, the biceps contract, the tendons sense the deformation of the muscles and trigger the rotation of the human joint. Following the same principle, if the human body behaves as an adaptive structure then the muscles are the actuators, tendons are the sensors and brain is the control system. From the perspective of structures, the stiff components are the main load bearing members which sustain the imposed loads and fulfil the strength requirements (bones) while the flexible components connect the rigid bodies and allow deformations to evolve up to a certain limit (muscles). Usually, in adaptive structures the flexible components cause the actuation of the system [4].

The research of adaptive structures, in terms of components, is classified into three scales: deformation mechanisms, cooperation mechanisms and actuation mechanisms. The deformation mechanisms describe how the structure as a whole, adapts its stiffness and geometry after its exposition to an external stimulus. Characteristic examples are the compliant mechanisms, the adjustment of the prestress level of fabric structures as well as the manipulation of a degree of freedom, a technique mainly present in deployable structures. The cooperation mechanisms focus on the combination between flexible and stiff components. They are classified into three subcategories: differentiation, fusion and transformation (Figure 2.6). In the first subcategory, different materials with different stiffness properties are used for the two types of components and their behaviour is tested under several load combinations. In the fusion mechanism, the stiffness variability is achieved by combining materials with different stiffness in one member. By mixing the right percentages of each material the desired stiffness level is obtained. The last subcategory entails the transformations of stiff components into flexible and vice versa allowing thus shape adaptation. The latter triggers change of the load path and redistribution of internal forces. Special material properties are needed for the control of the transformation between the two types of components. Last, the actuation mechanisms involve materials with special properties that in this subcategory are used as actuators which sense an external stimulus and cause the deformation of the structure. Shape memory materials constitute characteristic examples due to their ability to react to external stimuli such as light and temperature. Namely, a change in temperature activates these materials and their stiffness level increases or decreases depending on their intrinsic properties [4].

Conclusively, in the current section the design of adaptive structures from perspective of stiff flexible components was studied and the existing methods were presented. The flexible and stiff components methodology sets the groundwork for the development of the framework of the transformable joints which is presented in the following paragraphs.

Table 2-1: Bioinspired Mechanisms – Overview

<table>
<thead>
<tr>
<th>Deformation Mechanisms</th>
<th>Cooperation Mechanisms</th>
<th>Actuation Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Compliant Mechanism</td>
<td>- Differentiation</td>
<td>- Special materials</td>
</tr>
<tr>
<td>- Prestress</td>
<td>- Fusion</td>
<td></td>
</tr>
<tr>
<td>- Degree of freedom</td>
<td>- Transformation</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.6: Cooperation Mechanisms (a) Differentiation, (b) Fusion, (c) Transformation
2.5 Variable stiffness concepts based on Shape Memory Materials

Even though there is a wide range of variable stiffness concepts, material engineering attracts the attention of many researchers. It does not only offer component material selection, but also allows the composite design and optimization in order to provide the optimum authority over the stiffness properties. Shape memory materials are promising candidates due to their large stiffness variety and their shape memory characteristics. Shape memory materials, such as alloys, ceramics and polymers have attracted the attention of many researchers due to their association with the shape memory effect. In particular, shape memory alloys are widely used for actuation proposes in cases of large shape adaptation. Nevertheless, according to literature, shape memory polymers are more promising candidates for variable stiffness applications as they offer high reversible strain capacity and their properties can be enhanced by adding reinforcement [7].

2.5.1 Shape memory alloys (SMAs)

Shape memory alloys belong to the class of metals with shape memory properties. The latter discovered accidentally in 1961 by a group of scientists at the Naval Ordnance Laboratory, in Maryland. Nitinol, one of the main ingredients/components of SMAs was found to possess the unique feature of shape memory [17]. SMAs have two phase transformations in the solid state. At low temperatures, the material is in its martensite, soft phase. During this phase, SMAs can be easily deformed due to the low modulus of elasticity and tensile strength. Upon heating, above its glass transition temperature, the material enters the austenite (mother) state and its stiffness increases. Through this phase, SMAs obtain their original stiff configuration and they are able to generate significant stresses under constraint support conditions. When the latter occurs, the SMAs need to evolve higher recovery forces in order to return to its original austenite phase [18], [19].

The main advantages of SMAs are the high energy density deriving from large reversible deformations and the potential high stress generation, rendering them attractive candidates for actuation applications. The actuation stress capacity of SMAs reaches up to 500MPa accompanied by reversible strain of 7%. The high fatigue rate of SMAs with a maximum of about 104 thermomechanical cycles in combination with the low stiffness modulus in room temperatures limits their use as main material in the variable stiffness context [20].

2.5.2 Shape memory polymers (SMPs)

Shape memory polymers belong to the class of smart materials with variable stiffness properties. The thermomechanical cycle of thermally triggered SMPs, constitutes of the glassy and the rubbery states. In contrast to SMAs, in the glassy phase (low temperatures) their stiffness is high enough to sustain external loads while at elevated temperatures (above glass transition) they become softer and a significant reduction of their young modulus up to 100 times occurs. Although large deformations evolve, the polymer displays some stiffness. Glass transition temperature is a threshold temperature, at which the material changes phase and a significant reduction of the young modulus takes place. Upon cooling and unloading, a temporary shape is preserved. By increasing the temperature again, SMPs return to their original state with a reversible strain capacity of 200% [21].

Some advantages of SMPs over SMAs lie in the smaller density, higher reversible deformations and the larger stiffness at room temperatures. The actuation forces of SMPs are much lower than those of SMAs. This parameter though is not considered of great importance in the variable stiffness context. Other advantages of SMPs include low cost and easy manufacturing process in combination with fabrication flexibility. One of the main disadvantages of SMPs when used alone is the low stiffness level in the rubbery phase which can be improved by adding reinforcement. However, the reversible strain capacity is decreased by an order of magnitude. Additional to that, SMPs display brittle behaviour in their glassy state and further investigation of this property is required. Other disadvantages are the danger of micro scale damage in case of uncontrollable temperatures, as well as the unknown durability and long term reliability of the this material [20].

2.5.3 Elastic memory composites (EMCs)

The term elastic memory composites is used to describe composite members based on SMPs. The aforementioned type of material is investigated in order to improve the performance of Shape Memory Polymers, with regard the low stiffness level appearing in the rubbery face and the low recovery force. Even though the reversible strain capacity is reduced by factor 10 compared to pure SMP, a sufficient stiffness variety is obtained. According to Perkins et al, complete cured thermosets, thermoplastics and partially cured resins are suitable types of SMPs for composite applications. Lan et al, studied the behaviour of SMPs reinforced with plain wave T300 carbon fibres. The main propose of the development of these
EMCs, was their use as deployable hinges. In this composite the ratio between glassy and rubbery modulus is reduced to 79 while it was equal to 100 in pure SMPs [22] - [24].

2.5.4 Shape memory composite topology concepts

Knight and Henry et al. drew inspiration from nature and developed a composite material comprising of constant and variable stiffness components. The two fractions are used for load bearing and adjustable purposes respectively. When high structural loads are applied, rigid connection between the two parts of the composite is formed. The geometry of the composite is depicted in Figure 2.7. The portion with the variable stiffness consists of shape memory polymers which when are at the rubbery phase become softer allowing thus movements between the elements with constant stiffness. The two types of material are alternated forming a laminate as it can be seen in the following figure. A number of experiments to test the behaviour laminated component consisting of spring steel and Diaplex5510 SMP were conducted. At low temperatures, the elastic modulus of the composite ranges between 8 and 12GPa while the magnitude of the reversible strains is 2-10%. The ratio between the cold and hot modulus fluctuates from 15 to 77 times [25], [26].

Even though the composite offers significant increase of the elastic modulus in both low and elevated states, the integration of the heating wires into the composite as well as the time needed to reach the glass transition temperature are of primary concern. Knight et al. measured a time period of 1-2 minutes needed for the SMP to reach its glass transition temperature, denoting that the cooling of the composite will be one of the main hindering factors.

![Figure 2.7: Shape Memory Composite Topology concepts][26]

![Table 2-2: Shape Memory Materials – Comparison table][7]

<table>
<thead>
<tr>
<th>Material</th>
<th>Stiffness variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape Memory Alloys</td>
<td>$E_{hot}/E_{cold}$≈4</td>
</tr>
<tr>
<td>Shape Memory Polymers</td>
<td>$E_{cold}/E_{hot}$≈100</td>
</tr>
<tr>
<td>Elastic Memory Composites</td>
<td>$E_{cold}/E_{hot}$≈79</td>
</tr>
<tr>
<td>Shape Memory Composite topology concepts</td>
<td>$E_{cold}/E_{hot}$≈15-77</td>
</tr>
</tbody>
</table>

2.6 Joints with variable stiffness – existing concepts

The variable stiffness concept involves selectively decreasing deformation resistance in the joints during the adaptation of the structure caused by the actuators. At the same time, the overall stiffness of the structure should be high enough to sustain normally exerted loads while the structure should be able to return to its initial state. The latter implies the need of materials with reversible properties which are mainly dependent on the elastic material constants. Additional to that, a variation rather than fixed values of elastic modulus is desirable [7].
Firouzeh et al developed a type of joints with variable stiffness based on SMPs for underactuated robotic origamis. These types of structures comprise of many degrees of freedom, each one of them needed an independent actuation, increasing thus the complexity of the system. Even if the performance of the system augments, the high complexity adds extra restrictions. The use of joints with variable stiffness based on material engineering leads to a more compact and scalable design. SMPs were chosen due to the wide range of elastic modulus and the shape recovery characteristics. Except from that, the easy processing and fabrication rendered them viable candidates. In the current research, the behavior of one robotic finger comprising of three joints with variable stiffness, is investigated. Figure 2.8(a) depicts the final design of the robotic finger while in Figure 2.8(b) the different parts of the joint are presented. The composite joint consists of an embedded stretchable heater which is used for the activation of the SMP, silicone rubber a material that reduces the residual strains in the polymer and glass fibers which are used as frame for the installation of the silicone rubber. Last, a tendon is employed in order to actuate the joints (impose forces or displacements) [27].

Manzo et al proposed a new methodology for the design of active rigidity joints which is suitable for morphing applications. The aforementioned joint consists of three basic materials; SMA is used on the perimeter of the joint while the core consists of SMP with embedded heating wires for temperature control. This design aims at achieving quick transition between shape configurations via actuation and aspires to maintain sufficient bending rigidity in order to avoid extra energy consumption. SMA acts as actuator in the current design, as when heated above its glass transition temperature it shrinks and becomes stiffer imposing thus strain to the joint. The stiffness variability of shape memory polymers allows for high compliance and facilitates the contraction of SMAs at elevated temperatures while it maintains the contracted shape at low temperatures without needing energy [28].
2.7 Principal characteristics of shape memory polymers

2.7.1 General

The main mechanical characteristics of polymers are summarised and explained in the current section.

- The shear modulus of shape memory polymers depends strongly on the temperature. At low temperatures (glassy state), the shear modulus is high enough to withstand external loads while at high temperatures (rubbery state) it decreases significantly. In addition, reduction of temperature is considered equivalent to increase of the strain rate.

- At temperatures near the glass transition, the response of polymers are strongly time dependent. There are two methods of measuring the time dependent properties of polymers: (a) by applying a step load to a sample (b) by applying a sinusoidal load. The aforementioned methods are described thoroughly in section 3.1.1.

- Amorphous polymers are considered isotropic, meaning that the strain – stress response is not dependent on the material orientation.

- The behavior of shape memory polymers is reversible above the glass transition temperature. Upon heating, the polymer returns to its initial state. This represents the shape memory property of this polymers which make them viable candidates for a range of applications

- In the glassy state, SMPs are considered brittle materials

- The behavior of shape memory polymers is reversible above the glass transition temperature. Upon heating, the polymer returns to its initial state. This represents the shape memory property of this polymers which make them viable candidates for a range of applications

2.7.2 Shape Memory Effect

In the current section, the shape memory effect of polymers is described. The thermomechanical cycle of SMPs consists of six stages as illustrated in Figure 2.10. First, the polymer is fabricated at a storage temperature which in most of the cases is equal to the room temperature (1). Then, the material is heated at the deformation temperature (\( T_d > T_g \)) and becomes softer while entering the rubbery phase (2). A force or displacement is applied causing the deformation of the polymer (3). Maintaining the external force constant, the material is cooled to the storage temperature and reaches a temporary stable shape (4). Last, the external force is removed and the SMP is reheated again at \( T_r \) (recovery temperature) returning eventually to its original state (5), (6). One of the unique characteristics of SMPs is their ability to recover their original shape unconstrained. The recovery temperature of SMPs can set to any temperature by modifying their chemical structure and composition [30].

![Thermomechanical cycle of SMPs](image)

**Figure 2.10:** Thermomechanical cycle of SMPs [30]

\( T_s \) = Storage Temperature  
\( T_d \) = Deformation Temperature  
\( T_r \) = Recovery Temperature  
\( T_g \) = Glass Transition Temperature
2.7.2.1 Molecular Mechanism of SME

Netpoints and molecular switches constitute the molecular structure of shape memory polymers. Activation of shape memory effect is achieved through proper polymer network structure and morphology combined with the presence of an external stimulus. The permanent shape of the polymer is defined by the netpoints which are connected with chain segments as Figure 2.11 indicates. The chain segments are able either to elongate or shrink responding thus to an external condition such as temperature change. Solidification of the deformed chain segments ensures the stabilization of the temporary shape of the polymer. Recovery of the permanent shape is enabled, by the recoiling of the chain segments [31].

The shape memory effect is an entropy-based mechanism. When the polymer is in its original state, the chain segments adopt the configurations with the highest entropy. As the temperature increases the chain segments start moving and upon loading their configuration changes significantly. Hence, the shape of the polymer changes accompanied with a significant drop of the entropy. Upon cooling, freezing of chain segments is achieved and the temporary shape of the polymer is determined. The external load is removed and the SMP is heated again above its transition temperature causing the mobility of the chains which return to its initial configuration with the highest entropy. Thus, the recovery of the original shape is achieved [32].

![Molecular mechanism of SME](image)

**Figure 2.11:** Molecular mechanism of SME [31]

2.7.2.2 Shape Fixing and Shape recovery

Shape fixing and recovery are of significant importance as they represent the ability of the material to stabilize in a temporary shape and return to its original state after deforming, respectively. These characteristics make SMPs more attractive compared to the other polymers. Thorough investigation of shape fixing and recovery is realized through loading and unloading a SMP at a range of temperatures. The diagram of temperature versus strain (Figure 2.12) describes sufficiently the shape memory cycle including the shape fixing and recovery effects. Initially, the material is loaded when at a temperature \( T_g + 20 \) (1). A large increase of the strain is observed. The stress of the sample is held constant for a period of time in order to reveal any creep effects (2). Then the deformed sample is cooled below the transition temperature at a constant cooling rate while the applied load is held constant (3). As it can be seen the evolved strain remains constant meaning that the material is able to preserve a stable temporary shape. Following the equilibration, the sample is unloaded and strain shrinkage (if any) is observed (4). Last, the sample is heated again to \( T_g + 20 \) with a constant heating rate and the shape recovery effect is denoted (5) [33].
The classification of the shape fixing and recovery properties can also be obtained by defining shape fixing and recovery factors respectively. According to literature the aforementioned factors are given by the following formulas:

\[
R_f = \frac{(L_u - L_i)}{(L_t - L_i)} \times 100 \quad (2.1)
\]

\[
R_r = \frac{(L_u - L_f)}{(L_t - L_i)} \times 100 \quad (2.2)
\]

where, \(L_i\) is the initial length, \(L_t\) the temporary, \(L_u\) the unloaded and \(L_f\) the final recovered length.

Besides assessing the fixing and recovery performance of the material independently, the introduction of the “shape memory fill factor” allows the classification of the shape memory materials into five general categories as Figure 2.13 indicates. The shape memory fill factor is the ratio of the any shape memory material’s hatched area to the ideal shape memory polymer’s hatched area (see the hatched areas in Figure 2.13). An ideal SMP has a fill factor \(f_m\) equal to 1 while a polymer without any shape fixing ability and hence no recovery has \(f_m\) 0. A realistic case of a shape memory polymer has a fill factor of about 0.5 [34].
2.7.2.3 The effect of heating rate on Shape Recovery

SMPs belong to the class of smart materials that are able to recover their permanent shape when exposed to an external stimulus such as temperature. Shape recovery occurs due to the release of elastic strain that is applied and stored during the deformation and shape fixing phases respectively. Therefore, the viscoelastic theory describes sufficiently the Shape Memory Effect. The impact of the heating rate on the recovery performance of SMP has studied by some [35], [36]. The recovery behaviour of the material is strongly dependent on the glass transition temperature meaning that the viscoelastic characteristics are of significant importance during the recovery stage. It has been reported that faster heating rates shift the glass transition to higher temperatures causing delay on the onset of the strain recovery. On the other hand, lower heating rates enable the full shape recovery at lower temperatures in comparison with the higher heating rates. This demonstrates the important role of structural relaxation during the recovery process [35], [36], [37].

2.7.3 Modelling of SMPs

The last decades the shape memory effect of polymers has drawn substantial attention among the research community. Initially, the majority of the studies focused on experimental observations, physical understanding and emerging applications. Later, an increasing interest in the constitutive modelling of the shape memory effect of polymers was observed. Two main approaches are widely used to simulate the thermomechanical characteristics of SMPs.

The first type is purely elastic and simulates the shape memory as a two phase material comprised of the glassy and rubbery state. The material is considered frozen at low temperatures and soft at elevated temperatures. In order to describe that behaviour, a model that combines the two stiffness levels is required. This approach has been investigated and used by few Lagoudas (2008a) [40] and Wang et al (2009) [39]. Recently, Gilormini and Diani (2012) noticed that the elastic theories behind this approach consider uniform stress distribution which is not in line with corresponding experimental results. In addition, they observed that the volume fraction of each state is a function of temperature and must be provided from fitting the experimental shape memory data. Even though this approach can simulate the shape memory effect of polymers it does not predict the response of the material under various heating rates or temperatures between the glassy and rubbery state.

The second approach used for the thermomechanical modelling of SMPs is based on the theory of viscoelasticity. This method has been broadly used by many researchers and simulates various types of SMPs. The shape recovery is an intrinsic property of viscoelastic materials and thus there is no need for experimental data to describe the shape memory effect. As SMPs are strongly time and temperature dependent, a dynamic mechanical analysis is required for the determination of these properties. Various viscoelastic models have been developed; nevertheless the generalized Maxwell model is widely used for the simulation of polymers and especially from commercially available finite element software [36].

In the current research, the thermomechanical behaviour of the SMP is modelled according to the second approach (viscoelastic theory) due to the simplicity of the method and the compatibility with the available finite element software. The theory of viscoelasticity is thoroughly described in the next chapter of this study.

2.7.4 Mechanical behaviour of polymers

The mechanical properties of polymers depend on their composition, strain rate, molecular weight and temperature. By changing the distribution of molecular weight, the polymer structure, composition and cross link density the mechanical characteristics can be manipulated. However, in the current research the chemical composition of SMP is not studied and only the influence of temperature and strain rate is investigated. At low temperatures and high strain rates, polymers behave as brittle materials and failure occurs at maximum stress and low strain. Upon heating or reducing the strain rate, the behavior of polymeric materials changes from brittle to ductile (yielding). The yield point is one of the main characteristics of ductile materials, which is followed by necking (an abrupt drop in strength). Failure occurs at lower stress but quite large strain. After exceeding the yield point and entering the necking region, the cross section of the material reduces until it breaks. In some polymers, an increase in the strength after plastic deformation is observed. This effect is known as strain hardening and depends on the density of the network. It occurs due to the alignment of molecular chains in the direction of the load which increases the strength and the stiffness of the material in that direction. As the temperature increases, the strain hardening effect decreases. Beyond the glass transition temperature, the mechanical behavior of polymer changes and the elongation can reach several hundred percent before failure. The behavior of the material in this region depends on the cross link and the density. Cross linked material evolve large elastic strain...
whereas uncross linked polymers approach the viscoelastic behavior. Figure 2.14 describes the stress strain behavior of polymers under different temperature conditions [41].

![Stress-strain diagram](image)

**Figure 2.14:** (a) Stress – strain behavior of polymers [41]

Isothermal uniaxial compression or tension tests at various temperatures are performed. Figure 2.15(a) illustrates stress – strain diagrams from compression experiments at T=0, 10, 20, 30 and 60 °C at a constant rate of 0.01/s. As it can be seen, at T=10 °C, the material has a yield strength of 48MPa and the maximum elongation is less than 1%. As the temperature increases, a significant drop of the strength is observed while the material becomes softer and larger deformations are evolved. The material demonstrates distinct behaviors at temperatures below and above the glass transition temperature. At temperatures above T_g, the behavior of the polymer is hyperplastic with some viscous effects and there is no permanent deformation after unloading. When temperature is below T_g, SMPs behave as common glassy polymers with a yield stress followed by softening and then eventually hardening again. In this state, significant permanent deformations have been recorded after unloading. Figure 2.15(b) demonstrates the influence of the strain rate which is more significant at temperatures below T_g. At low strains rates, a decrease in the strength of the material is observed. In the numerical simulation of the material, the use of hyperplastic properties are suggested by the authors as it contributes to the modelling of the post-yielding behaviour of the material [42].

![Stress-strain diagrams](image)

**Figure 2.15:** (a) Stress – strain behavior of SMPs under isothermal uniaxial compression for various temperatures, (b) stress – strain diagrams denoting the influence of the strain rate [42]
Furthermore, a discrepancy between the compressive and bending strength is reported in the literature. Under compression, the stiffness of the material increases due to the alignment of the polymer chains. However, the aforementioned alignment does not occur under out of plane bending making. Thus, this can be a reason why the compressive strength is greater than the bending [30].

Figure 2.16 illustrates the elastic modulus as a function of temperature. The shape memory polymer experiences four different states: solid (glassy), transition, rubbery and flow state. The Young’s modulus decreases significantly as the polymer passes from transition to rubbery phase. The glass transition temperature is positioned within the transition state and is calculated by experimental data [43]. The mechanical characteristics of shape memory polymers are summarised in the Table 2-3.

![Figure 2.16: Elastic modulus – Temperature diagram [43]](image)

<table>
<thead>
<tr>
<th>Table 2-3: SMPs mechanical properties [44]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Property</strong></td>
</tr>
<tr>
<td>Density [g/cm³]</td>
</tr>
<tr>
<td>Stress generated after recovery [MPa]</td>
</tr>
<tr>
<td>E modulus, T&lt;T_{tran} [GPa]</td>
</tr>
<tr>
<td>E modulus, T&gt;T_{tran} [GPa]</td>
</tr>
<tr>
<td>Stress needed for deformation [MPa]</td>
</tr>
<tr>
<td>Tensile strength (glassy state) [MPa]</td>
</tr>
<tr>
<td>Tensile strength (rubbery) [MPa]</td>
</tr>
<tr>
<td>Corrosion performance</td>
</tr>
</tbody>
</table>
2.8 Concluding remarks

In the current section, the conclusions from the literature review are presented:

- SMPs are viable candidates for the development of joints with variable stiffness due to high Young’s modulus at glassy state and the large reversible strains up to 200%.

- The theory of viscoelasticity can be applied for the numerical modelling of the joint. Nevertheless, the viscoelastic model can only predict the linear elastic behavior of the material. The complexity of the model increases significantly if the nonlinear behavior of the material needs to be taken into account. Thus, the current research will only consider the yield stress – strain of the material as the maximum permissible values.

- The Young’s modulus at the glassy state is around 2000MPa, taking into account that $E_g/E_r\approx100$, the Young’s modulus at the rubbery phase is 20MPa. This value is considered extremely low for structural loads. Hence, either reinforcement of the joint is needed or the temperature of the joint should always be lower than $T_g$.

- The material demonstrates distinct behaviors at temperatures below and above the glass transition temperature. This means that tensile or bending tests need to be conducted for the measurement of the yield stress at different temperatures. Additional to that, the resistance of the material against bending is different than that against tension. Hence, an assumption needs to be made. As the conduction of the tensile experiments is more feasible due to the available equipment, the design of the structural joint will be based on the tensile strength.

- At low temperatures and high strain rates, polymers behave as brittle materials and failure occurs at maximum stress and low strain. Upon heating or reducing the strain rate, the behavior of polymeric materials changes from brittle to ductile (yielding). The yield point is one of the main characteristics of ductile materials, which is followed by necking (an abrupt drop in strength). Failure occurs at lower stress but quite large strain. After exceeding the yield point and entering the necking region, the cross section of the material reduces until it breaks.

- Shape recovery occurs due to the release of elastic strain that is applied and stored during the deformation and shape fixing phases respectively. Therefore, the viscoelastic theory describes sufficiently the Shape Memory Effect. The impact of the heating rate on the recovery performance of SMP has studied. The recovery behaviour of the material is strongly dependent on the glass transition temperature meaning that the viscoelastic characteristics are of significant importance during the recovery stage. It has been reported that faster heating rates shift the glass transition to higher temperatures causing delay on the onset of the strain recovery. On the other hand, lower heating rates enable the full shape recovery at lower temperatures in comparison with the higher heating rates. This demonstrates the important role of structural relaxation during the recovery process.
Chapter 3

VISCOELASTIC BEHAVIOR OF SMPs

3.1 Material behavior - Viscoelasticity

Shape memory polymers belong to the class of viscoelastic materials with time and temperature dependent mechanical characteristics. Viscoelastic theory is used to describe both their elastic - solid and viscous - fluid behavior and it is applicable when the polymer is subjected to small strains around 1%. It is important to mention that mathematically cannot either be described by elastic or viscous laws. The main characteristic of polymers is that at low temperatures they are considered brittle glassy solid materials with high modulus and strength as the viscous part is solidified. At high temperatures, the behavior of the polymer approaches that of fluid with low viscosity and it is considered a low modulus rubbery material.

3.1.1 Time dependent properties

In order to characterize the mechanical properties of polymers, special experimental tests are required. Those include relaxation, creep and dynamic tests. A thorough description of the aforementioned experiments is presented in the current section. Even though relaxation and creep tests can be executed easily and the required equipment is simpler, dynamic tests are preferred due to their high sensitivity and the wide range of conditions that can be covered.

Relaxation

The time-dependence of polymers is attributed to their unique molecular structure and it has significant differences from the time dependence caused in other materials by fatigue moisture or other environmental conditions. Indeed, the aforementioned factors influence the behaviour of polymers but in a different way than other materials due to the viscoelastic nature of their molecular structure. Relaxation test is one of the basic methods used to specify the viscoelastic time dependent properties of polymers. During the relaxation test, a constant tensile strain is imposed to a bar at $t=0s$. The bar starts stretching while rigid boundary conditions are applied in order to ensure that the tensile strain remains constant during the relaxation test. It is observed that the stress needed to maintain the applied constant strain decreases with the time (Figure 3.1). Taking into account that the strain remains constant while the stress is decreased with the time, it is concluded the elastic modulus is a time dependent material property and (3.1) [45], [46].

![Figure 3.1: Relaxation test](image)
Chapter 3

\[ E(t) = \frac{\sigma(t)}{\varepsilon(t)} \]  (relaxation modulus) \hfill (3.1)

**Creep**

Except from the relaxation test, the study of the creep behaviour of polymers provides a deep insight into their viscoelastic properties. The sample is loaded with a constant tensile stress at \( t=0 \) as Figure 3.2(a) illustrates. The strain increases with the time under constant stress, defining a new material property called creep compliance (Figure 3.2(b)) \[45\], \[46\].

![Figure 3.2](image)

**Figure 3.2:** Creep test (a) constant applied stress (b) evolved strain \[46\]

\[ J(t) = \sigma(t)/\varepsilon(t) \] (creep compliance) \hfill (3.2)

**Dynamic loading**

Cyclic loading is another method used for the mechanical characterisation of polymers and is based on their molecular behaviour. A sample is subjected to a sinusoidal strain that varies with the time at a specific frequency according to the equation (3.3). When the material is at its elastic phase, the evolved stress is in phase with the applied strain as it can be seen in Figure 3.3(a). Once the material enters the viscous region, the resultant stress is out of phase with the imposed strain (Figure 3.3(b)), (3.4). The main cause of the delayed response is the internal viscosity between the molecular chains that intend to stretch after the imposition of the strain. The out of phase stress is given by the \(3.4\) equation.

\[ \varepsilon = \varepsilon_0 \sin(\omega t) \] \hfill (3.3)

\[ \sigma = \sigma_0 \sin(\omega t + \delta) \] \hfill (3.4)

where \( \delta = 2\pi f \Delta t \) is the phase angle in radians and \( \sigma_0 \) is the measured stress amplitude. According to the geometrical norms, the stress equation expands to the following form:

\[ \sigma = \sigma_0 \sin(\omega t) \cos(\delta) + \sigma_0 \cos(\omega t) \sin(\delta) \] \hfill (3.5)

The evolved stress consists of two components, one in phase with the strain \( \sigma_0 \sin(\omega t) \cos(\delta) \) and one which is \( \pi/2 \) out of phase with the strain \( \sigma_0 \cos(\omega t) \sin(\delta) \). Thus, two Young's moduli are defined by the equations (3.6) and (3.7). The first expression represents the storage modulus describing the elastically stored and released energy whereas the loss modulus given by (3.7) represents the lost energy due to friction and heat \[47\].

\[ E'(\omega) = \frac{\sigma_0}{\varepsilon_0} \cos(\delta) \] \hfill (3.6)

\[ E''(\omega) = \frac{\sigma_0}{\varepsilon_0} \sin(\delta) \] \hfill (3.7)
3.1.2 Temperature dependent properties

At low temperatures, polymers behave as ordinary solids, the chains are considered frozen and there is no relative movement between them and the molecules. Upon heating above the glass transition temperature, the free volume enlarges and the chains can be stretched. In the glass transition phase of polymers, a significant reduction of the Young’s modulus is observed.

The time and temperature dependent properties of polymers can be interrelated according to time temperature superposition principle. There is equivalence between temperature and time. Namely, a polymer which shows rubbery behaviour at a given temperature and testing rate (time) can have a glassy behaviour at lower temperatures or higher strain rates. Thus, curves which relate a modulus (E, G) with the time (testing rate) are measured at a range of temperatures and combined into a master curve at a reference temperature. In order to form the master curve, a time dependent shift factor \( \alpha_T \), given by the following equation (3.8), is introduced.

\[
\log(\alpha_T) = -\frac{C_1(T - T_g)}{C_2 + (T - T_g)}
\]  

(3.8)

The constants \( C_1 \) and \( C_2 \) are empirical values and are calculated by curve fitting of the experimental data. The shift is given by the equation (3.9):

\[
t_r = \frac{t_T}{\alpha_T}
\]  

(3.9)

where \( t_r \) is the time referred to reference temperature and \( t_T \) is related to the measured temperature. By using the expressions (3.13) and (3.9), a master curve at a reference temperature can be plotted including data from different temperatures [48].

3.2 Constitutive law

3.2.1 Maxwell model, spring-dashpot approach

A simple way to describe the time dependent properties of viscoelastic materials is by combining a spring and dashpot in series as it is shown in Figure 3.4. The spring represents the elastic behavior whereas the dashpot describes the viscous properties. The forces in the two components are equal while the total deformation of the element is the sum of the spring and dashpot deformations. Taking into account that stresses and strains derive from forces and deformations respectively, the following equations are formed [45]:

\[
\sigma_{tot}(t) = \sigma_s(t) = \sigma_d(t)
\]  

(3.10)

\[
\varepsilon_{tot}(t) = \varepsilon_s(t) + \varepsilon_d(t) = \frac{\dot{\varepsilon}}{E} + \frac{\sigma}{\eta}
\]  

(3.11)
By multiplying the equation (3.11) with the viscosity ($\eta$), the following constitutive equation (3.12) is defined. Since the dimensions of viscosity are Pa∙s and those of moduli of elasticity are Pa, the term ($\eta$/$E$) has dimensions of $s$ and is replaced by $\tau$ which describes the relaxation time of a Maxwell element.

$$\sigma + \frac{\eta}{E} \dot{\sigma} = \dot{\eta}$$ \hspace{1cm} (3.12)

![Figure 3.4: Maxwell element](image)

When a constant strain is applied, the relaxation modulus of a Maxwell element is reduced exponentially with the time and is given by the expression (3.13). In the case of a constant stress, the creep compliance is calculated according to the equation (3.14).

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = E \exp\left[\frac{-t}{\tau}\right]$$ \hspace{1cm} (3.13)

$$D(t) = \frac{\varepsilon(t)}{\sigma_0} = \frac{t + \tau}{\eta}$$ \hspace{1cm} (3.14)

In case a Maxwell element is subjected to a dynamic strain with radial frequency $\omega$, the storage and loss modulus are calculated by the equations (3.14) and (3.15) [45].

$$E'(\omega) = \frac{E \omega^2 \tau^2}{1 + \omega^2 \tau^2}$$ \hspace{1cm} (3.15)

$$E''(\omega) = \frac{E \omega \tau}{1 + \omega^2 \tau^2}$$ \hspace{1cm} (3.16)

### 3.2.2 Generalized Maxwell model

By adding more spring-dashpot elements, the material behavior is simulated more accurately. The Generalized Maxwell model as depicted in Figure 3.5 entails a large number of Maxwell elements in a parallel arrangement. The overall relaxation expressions are calculated by simply summing the relaxation moduli of the individual elements. The relaxation expressions consist of $N$ terms each one with different relaxation time $\tau_n$ and pre-exponential factor $E_n$ [45].

$$E(t) = \sum_{n=1}^{N} E_n \exp\left[\frac{-t}{\tau_n}\right]$$ \hspace{1cm} (3.17)

$$E'(\omega) = \sum_{n=1}^{N} E_n \frac{\omega^2 \tau^2_n}{1 + \omega^2 \tau^2_n}$$ \hspace{1cm} (3.18)

$$E''(\omega) = \sum_{n=1}^{N} E_n \frac{\omega \tau_n}{1 + \omega^2 \tau^2_n}$$ \hspace{1cm} (3.19)
If the number of terms is large enough, the aforementioned relaxation functions describe with high accuracy the behaviour of real viscoelastic materials. The expression of relaxation moduli in terms of series components is known as Prony series. Finite element software such as ANSYS requires the pairs of relaxation time $\tau_n$ and the relaxation modulus $E_n$ for the modelling of the viscoelastic behaviour. The set $(\tau_n, E_n)$ is calculated by Dynamic Mechanical Analysis test.
In order to investigate the behaviour of joints with variable stiffness and their potential application to the field of structural engineering, a case study is considered. Namely, the SMP joint is part of a truss structure serving the connection between the truss elements by transferring the internal forces. The geometry of the structure as well as the load cases taken into consideration are presented in the current paragraph. The truss structure can be a pedestrian bridge.

### 4.1 Truss structure

#### 4.1.1 Geometry

The geometrical characteristics of the structure are presented in Figure 4.1 and Figure 4.2. The total length is 11.40m, the overall height is 0.90m and the width is equal to 2.0m. Each truss element has a length of 2.40m. All the structural elements are assumed to be made of steel S355 and the structure is considered simply supported.

![Figure 4.1: Front view](image1)

![Figure 4.2: Plan view](image2)

#### 4.1.2 Load Cases

Three load cases are taken into account including the self-weight of the steel structure (LC1), permanent (LC2) and last variable loads (LC3). The dead load is set to 3.0kN/m² including the weight of the bridge deck and the finishing layers. Taking into account that each truss bay supports a 1.0m wide area, the Uniformly Distributed Load (UDL) is 3.00kN/m. A live load of 1.5kN/m² is taken into consideration accounting for snow load. The UDL derived from the live load is set to 1.50kN/m. Only these three load cases are considered for the assessment of the load bearing capacity of the joint at different temperature
levels. This assumption serves the simplicity needed for the current level of research. Figure 4.3 and Figure 4.4 illustrate the dead and live loads applied to the truss structure.

In the case of an extreme scenario, such as strong wind or a seismic excitation the truss structure should be able to change shape as a reaction to the external stimulus. Therefore the SMP joint needs to accommodate shape changes due to the elongation of the actuators and then recover its initial shape. This case is investigated by taking into account the permanent loads as well as axial forces due to the elongation of the actuators.

![Figure 4.3](image1.png)

**Figure 4.3:** LC2 – Permanent Loads

![Figure 4.4](image2.png)

**Figure 4.4:** LC3 – Variable Loads

4.1.3 Static Analysis

A linear static analysis is performed in SCIA engineer in order to evaluate the response of the truss structure under the imposed dead and live loads [49]. Ultimate Linear State is taken into account with the factors of 1.35 and 1.50 for the permanent and variable loads, respectively. The magnitude of the internal forces is presented in the Figure 4.5 and the dimensions of the cross sections are determined (Table 4-1).

![Figure 4.5](image3.png)

**Figure 4.5:** Internal forces ULS

![Figure 4.6](image4.png)

**Figure 4.6:** Steel check - ULS

<table>
<thead>
<tr>
<th>Table 4-1: Cross section properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>CHS</td>
</tr>
</tbody>
</table>
4.2 SMP Joint

4.2.1 Geometry – 3D printed samples

The dimensions of the Shape Memory Polymer joint are illustrated in the Figure 4.7. Bolt connection is proposed for the connection between the actuator and the SMP joint. The length of the joint is 960mm and the height is 238mm. The diameter of each element is 80mm.

![Figure 4.7: Geometrical characteristics of SMP joint](image)

![Figure 4.8: 3D printed SMP joint, scale 1:6](image)

![Figure 4.9: 3D printed SMP joint with heating wires, scale 1:6](image)

4.2.2 Load Cases

The maximum internal forces of each load case, mentioned above are summarised in the following tables. As it can be seen in Figure 4.5 tensile and compressive forces are imposed to the joint and the load configuration is presented in Figure 4.10.

![Figure 4.10: Applied forces to the joint](image)
Table 4-2: Internal forces LC1+LC2

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>61.22</td>
</tr>
<tr>
<td>F₂</td>
<td>45.92</td>
</tr>
<tr>
<td>F₃</td>
<td>8.77</td>
</tr>
<tr>
<td>F₄</td>
<td>8.77</td>
</tr>
</tbody>
</table>

Table 4-3: Internal forces LC3

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>22.96</td>
</tr>
<tr>
<td>F₂</td>
<td>13.16</td>
</tr>
<tr>
<td>F₃</td>
<td>4.39</td>
</tr>
<tr>
<td>F₄</td>
<td>-4.39</td>
</tr>
</tbody>
</table>

Table 4-4: Internal forces ULS

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>128.57</td>
</tr>
<tr>
<td>F₂</td>
<td>96.43</td>
</tr>
<tr>
<td>F₃</td>
<td>18.42</td>
</tr>
<tr>
<td>F₄</td>
<td>-18.42</td>
</tr>
</tbody>
</table>
Chapter 5

EXPERIMENTAL RESULTS

5.1 3D Printed Samples

Additive manufacturing is employed for the creation of the SMP specimens. This method offers considerable design freedom and convenience with regard the production of the samples needed for testing [50]. The SMP material that we used is MM-5520 filament from SMP Technologies [51]. It belongs to the thermoplastic polyurethane elastomer family which is semi-crystalline. For the 3D printing of the samples, fused deposition modelling (FDM) is used. Namely, the thermoplastic filament is melt at a hot nozzle and extruded to construct the 3D specimens. Leapfrog Creator 3D Printer is used and the specimens are printed in high quality mode. The infill pattern of the first samples was rectilinear with angle of 45° (Figure 5.1(a)), but due to the lack of testing equipment, the rectilinear pattern with fill angle 90° illustrated in Figure 5.1(b) is finally used. The main reason of the selection of this pattern was the extremely low thickness and width of the samples needed for the tensile tests. All the experiments were carried out in the DMA machine in which the maximum applied force is 18N meaning that the area of the samples needs to be extremely small in order to reach stresses of around 40MPa in ambient temperature. The infill pattern of the 3D printed samples influences the mechanical properties of the material as the infill angle of 45° gives higher strength and stiffness. The role of the infill pattern on the material behavior is not investigated in the current research but few experiments were conducted in the early stage of the research and the results are included in the appendix A.

![Infill pattern of the 3D printed specimens](image)

Figure 5.1: Infill pattern of the 3D printed specimens (a) rectilinear 45° (b) rectilinear 90°

![3D printed sample](image)

Figure 5.2: 3D printed sample, infill pattern rectilinear 45°

![3D printed sample](image)

Figure 5.3: 3D printed sample, infill pattern rectilinear 90°
5.2 Dynamic Mechanical Analysis

5.2.1 Description

For the thermomechanical characterization of the SMP, a Dynamic Mechanical Analysis test is conducted (Figure 5.4(a)). This experiment provides information about the time and temperature dependent properties of viscoelastic materials such as SMPs. In particular, the dynamic storage modulus, dynamic loss modulus and a mechanical damping factor δ are measured. Using this data, the Prony series coefficients, needed for the numerical simulation of the material, are calculated. During the experiment, an oscillatory strain which corresponds to a displacement of 10um is applied to a SMP sample with dimensions of 6.7mmx2mmx0.17mm (Figure 5.4(b)) at a range of frequencies from 0.30 Hz to 60Hz. The temperature increases from 40ºC to 90ºC with a rate of 1ºC/min. When a sinusoidal strain is applied, the evolved stress has also a sinusoidal form with a phase of angle δ, due to the viscous properties of the material as it can be seen in Figure 3.3. The phase angle δ is equal to the ratio of storage to loss modulus.

![DMA test](image1)

![Q800 analyzer](image2)

Figure 5.4: DMA test (a) Q800 analyzer (b) geometrical properties of the SMP sample

5.2.2 Measured data

The results of the DMA test, at different levels of frequency are presented in the following diagrams. As it was expected, the storage modulus is decreased with the increase of the temperature as the material becomes softer and less force is needed for deformation. The polymer experiences the glass transition phase between ≈50ºC and ≈75  ºC. Low frequency corresponds to a low strain rate and due to the relaxation properties of polymers; the storage modulus is smaller at lower frequencies (Figure 5.5). The loss modulus which describes the energy dissipation of the material is plotted against temperature in Figure 5.6. Before entering the glass transition phase an increase of the loss modulus is denoted meaning that energy is dissipated in the ambient environment. Upon heating, the mobility of the molecular chains increases, however molecular friction restricts the motion, causing thus energy dissipation. Therefore, even if the material is less stiff, more force is dissipated in the form of energy leading to the increase of loss modulus. Above the glass transition temperature, the material experiences the viscous behaviour, the molecular friction reduces significantly and the loss modulus decreases. The relative changes between loss and storage modulus are emphasized by their ratio which is given in Figure 5.7. The maximum value of the tanδ diagram represents the glass transition temperature of the material.
Glass transition temperature

The glass transition temperature is determined by the tanδ curve of 1Hz frequency. The temperature, at which the damping factor reaches its maximum, is the glass transition temperature of the polymer. Although, the point with the maximum tanδ is not completely clear from the graph, the temperature of 65.6 °C is set as the glass transition temperature.

<table>
<thead>
<tr>
<th>Glass Transition Temperature</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tg</td>
<td>65.6</td>
</tr>
</tbody>
</table>

Figure 5.5: Storage modulus – Temperature

Figure 5.6: Loss modulus – Temperature

Figure 5.7: Tanδ – Temperature
5.2.4 Prony Series Coefficients

For the calculation of the Prony series coefficients, the time temperature superimposition principle is applied. Storage modulus vs frequency diagrams are plotted at various temperatures as Figure 5.8 illustrates. The aforementioned diagrams represent the measured properties of the polymer in a specific time period. In order to predict the behaviour of the material at longer and shorter time ranges, a reference temperature of 50 °C is chosen and the curves above and below this temperature are shifted so as to form a master curve. Namely, each curve for temperatures below 50 °C is shifted to the left representing the behaviour of the material in shorter times whereas each curve for temperatures above 50 °C is shifted to the right providing continuation to longer times. The curves shifted to the right describe the longer time required at 50 °C to achieve the same level of storage modulus. Likewise, the curves shifted to the left represent the shorter time needed at 50 °C in order to obtain the same magnitude of storage modulus. The master curve for T<sub>r</sub>=50 °C is depicted in Figure 5.9 and we consider that τ=1/ω and ω=2πf. The values of the shift factors a<sub>T</sub> at various temperatures are given in Figure 5.10. The shift factor a<sub>T</sub> is equal to 1 at reference temperature. In the current study, a<sub>T</sub> is considered a multiplication factor.

![Figure 5.8: Storage modulus – frequency curves at a range of temperatures](image)

![Figure 5.9: Master curve (at T=50°C) obtained by shifting along the frequency axis](image)
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Having extrapolated the time scale of the measured data, the calculation of the Prony series coefficients is following. The relaxation and loss moduli are given by the equations (5.1) and (5.2).

\[ G'(\omega) = G_0 \left[ 1 - \sum_{i=1}^{N} g_i \right] + G_0 \sum_{i=1}^{N} \frac{g_i \tau_i^2 \omega^2}{1 + \tau_i^2 \omega^2} \]  \hspace{1cm} (5.1)

\[ G''(\omega) = G_0 \sum_{i=1}^{N} \frac{g_i \tau_i \omega_i}{1 + \tau_i^2 \omega^2} \]  \hspace{1cm} (5.2)

where,

- \( G_0 \) : relaxation modulus at \( t=0 \)
- \( g_i \) : dimensionless relaxation modulus
- \( \tau_i \) : relaxation time

In this case we are interested in the reverse relationship, considering as known factors the \( G'(\omega) \) and \( G''(\omega) \) the values of \( N \), \( g_i \) and \( \tau_i \) need to be calculated. To this end, the following a repeated method is implemented:

1. A value of \( N \) is chosen
2. Values of \( g_i \) and \( \tau_i \) are assumed
3. \( G'(\omega) \) and \( G''(\omega) \) are calculated
4. The residual between the calculated and experimental dynamic data is specified
5. The parameters \( g_i \) and \( \tau_i \) are optimized by using a minimization algorithm and step 3 is repeated

Having completed the repeated method presented above the final pairs of \( g_i \) and \( \tau_i \) are presented in the Table 5-2.

**Table 5-2:** Relaxation times and relative moduli

<table>
<thead>
<tr>
<th>N [Maxwell elements]</th>
<th>( \tau_i ) [s]</th>
<th>( g_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00E-06</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1.00E-05</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.00E-04</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.00E-03</td>
<td>0.0331</td>
</tr>
<tr>
<td>5</td>
<td>1.00E-02</td>
<td>0.1158</td>
</tr>
<tr>
<td>6</td>
<td>1.00E-01</td>
<td>0.1241</td>
</tr>
<tr>
<td>7</td>
<td>1.00E+00</td>
<td>0.1669</td>
</tr>
</tbody>
</table>
5.2.5 WLF constants

Except for the Prony series coefficients calculated to the previous paragraph, ANSYS requires the $C_1$ and $C_2$ constants for the numerical simulation of the material behaviour. These coefficients are calculated by curve fitting the WLF equation to the shift factors given in Figure 5.10. The final values are given in Table 5-3.

Table 5-3: WLF constants

<table>
<thead>
<tr>
<th>$T_R\degree C$</th>
<th>$C_1$</th>
<th>$C_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>16.61</td>
<td>32.78</td>
</tr>
</tbody>
</table>

5.3 Tensile tests

5.3.1 Description

Tensile tests are performed at a range of temperatures to define the level of yield stress and strain as well as to give an indication about the maximum elongation of the material. Special tensile tester with controlled climate is needed for the conduction of tensile tests at high temperatures. Nevertheless, this type of equipment was not available in TU Delft during the execution of the current master thesis. For this reason, the Dynamic Mechanical Analyzer Q800 is used and some special restrictions are applied due to maximum range of elongation and force that this machine can obtain. Namely, at high temperatures when the material enters the transition phase, the distance between the two clamps was not large enough to accommodate the large evolved deflections. Thus, this study provides only an indication about the elongation of the material and the repetition of the experiments at a tensile tester with temperature chamber, is highly recommended in the future research. Additional to that, the maximum tensile force of the DMA is 18N, a value that determines the short dimensions of the samples and subsequently influences the 3D printing infill pattern as it has been mentioned in §5.1. Normally, dog bone shaped specimens are used for tensile testing but in this study rectangular shaped samples are tested as the machine can only support this shape. Except for the aforementioned restrictions, the DMA machine offers high accuracy with regard the maximum strength and the temperature and time dependent properties of Shape Memory Polymer. Hence, in some cases only one sample is tested and the results are considered reliable.

Three samples are tested in each temperature, and the stress – strain graphs are presented in the following section. All the specimens were tested under a strain ramp of 10%/min. The modulus of elasticity is calculated at $\varepsilon=1\%$ and the yield stress and strain values are summarised in the tables below.

5.3.2 Stress - strain curves at various temperatures

- $T=25\degree C$
  
  Figure 5.11 illustrates the stress - strain diagram of the three samples at 25$\degree$C. The behaviour of specimens 1 and 2 is quite similar whilst sample 3 has higher maximum stress and lower maximum elongation. The linear region of the three graphs is almost identical and they all show brittle behaviour. The mechanical properties of the three samples at 25$\degree$C are summarised in Table 5-4.
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Figure 5.11: Stress - strain curve at T=25°C

Table 5-4: Material properties at T=25°C

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_y$ [MPa]</th>
<th>$\varepsilon_y$ [%]</th>
<th>$\varepsilon_u$ [%]</th>
<th>E [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31.33</td>
<td>3.01</td>
<td>16</td>
<td>1588</td>
</tr>
<tr>
<td>2</td>
<td>32.23</td>
<td>3.73</td>
<td>14.6</td>
<td>1515</td>
</tr>
<tr>
<td>3</td>
<td>36.44</td>
<td>3.85</td>
<td>8</td>
<td>1522</td>
</tr>
</tbody>
</table>

- **T=36°C**
  Tensile tests are performed at T=36°C which is the minimum temperature that the DMA furnace can accommodate when it is closed. As it can be seen, the elongation of the material increases whilst the necking effect starts to evolve. The maximum stress is lower compared to the experiments presented above and a drop in the elastic modulus is noted. An overview of the material properties is given in Table 5-5. Figure 5.13 illustrates the failure mode of samples 1 and 2.

Figure 5.12: Stress - strain curve at T=36°C
Table 5-5: Material properties at T=36°C

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_y$ [MPa]</th>
<th>$\varepsilon_y$ [%]</th>
<th>$\varepsilon_u$ [%]</th>
<th>E [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30.32</td>
<td>3.85</td>
<td>30</td>
<td>1474</td>
</tr>
<tr>
<td>2</td>
<td>32.71</td>
<td>4.26</td>
<td>23</td>
<td>1360</td>
</tr>
<tr>
<td>3</td>
<td>26.62</td>
<td>3.36</td>
<td>27</td>
<td>1200</td>
</tr>
</tbody>
</table>

Figure 5.13: Failure of the samples at T=36°C

- **T=40°C**

The results of the tensile tests at T=40°C are presented in Figure 5.14. The three specimens show similar behaviour and the yield stress is equal to 26MPa. Beyond the yield point, an abrupt drop of the stress is observed and the material enters the necking region where the cross section area of the sample in the stretching direction is reduced. Table 5-6 provides an overview of the material properties at T=40°C, while Figure 5.15 depicts the elongation of the sample.

Figure 5.14: Stress - strain curve at T=40°C
**EXPERIMENTAL RESULTS**

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**Table 5-6:** Material properties at T=40°C

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_y$ [MPa]</th>
<th>$\varepsilon_y$ [%]</th>
<th>$\varepsilon_u$ [%]</th>
<th>$E$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26.86</td>
<td>3.46</td>
<td>137</td>
<td>1291</td>
</tr>
<tr>
<td>2</td>
<td>26.80</td>
<td>4.00</td>
<td>175</td>
<td>1288</td>
</tr>
<tr>
<td>3</td>
<td>26.47</td>
<td>7.30</td>
<td>143</td>
<td>1198</td>
</tr>
</tbody>
</table>

**Figure 5.15:** Sample before (a) and after (b) the tensile test T=40°C (maximum elongation reached)

- **T=50°C**
  
The stress strain behaviour of the 3D printed SMP at T=50°C is illustrated in Figure 5.16. The maximum stress has an average value of 4.6MPa which significantly lower than the maximum stress evolved at T=40°C. This means that the material is at its glass transition phase and the less force is needed for deformation. The modulus of elasticity shows also a significant drop as it was expected.

**Table 5-7:** Material properties at T=50°C

**Figure 5.16:** Stress - strain curve at T=50°C
Several samples are tested at $T=55^\circ C$ but only the results of two samples are considered valid and presented in Figure 5.17. The first sample shows strain hardening after necking. Since the material enters the glass transition region (Figure 5.5) mobility of polymer chains is observed. Alignment of chains in the stretching direction increases the strength and stiffness of the material. Hence, increase of the stress is noted as the strain increases. The ultimate strain of the sample 2 is considered quite low nevertheless the maximum stress gives a good indication about the strength of the material. The maximum elongation is considered greater than the one presented in the following diagram. The measured properties of the material at $T=55^\circ C$ are summarised in Table 5-8.

![Stress-strain curve at T=55°C](image.png)

**Figure 5.17:** Stress - strain curve at $T=55^\circ C$

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_y$ [MPa]</th>
<th>$\varepsilon_y$ [%]</th>
<th>$\varepsilon_u$ [%]</th>
<th>$E$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.58</td>
<td>1.99</td>
<td>200</td>
<td>464</td>
</tr>
<tr>
<td>2</td>
<td>3.58</td>
<td>2.29</td>
<td>200</td>
<td>379</td>
</tr>
<tr>
<td>3</td>
<td>4.60</td>
<td>2.00</td>
<td>200</td>
<td>380</td>
</tr>
</tbody>
</table>

**T=65^\circ C**

Figure 5.18 illustrates the tensile behavior of the material at $T=65^\circ C$ where the maximum stress is close to zero and there is no yield point. The material, at this temperature shows rubbery behaviour. The elongation is considered much larger than the one presented in the following figure but due to technical limitation the measurement of the maximum elongation was not possible.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma_y$ [MPa]</th>
<th>$\varepsilon_y$ [%]</th>
<th>$\varepsilon_u$ [%]</th>
<th>$E$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.01</td>
<td>2.54</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>2.52</td>
<td>2.29</td>
<td>-</td>
<td>145</td>
</tr>
</tbody>
</table>
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5.3.3 Comparison

Figure 5.19 depicts the stress - strain diagrams of the material at various temperatures. At low temperatures, the material shows brittle characteristics whereas as the temperature increases, yielding and the necking are observed (ductile behaviour). The maximum stress reduces significantly with the increase of the temperature and the material approaches the rubbery behaviour. A comparison between Figure 5.19 and Figure 2.14 proves that stress strain behaviour of the 3D printed SMP is in good agreement with that described in literature review. In order to provide a better overview about the level of stress at various temperatures, the maximum stress of each temperature is plotted in Figure 5.20. Upon heating, the maximum stress is reduced as less force is required for deformation.
5.4 Shape Memory Effect

In the present paragraph, the Shape Memory Effect of the SMP is tested. First the specimens are heated up to 65°C and an instant static force corresponding to a tensile strain of 50% is applied. Cooling of the samples is following, while the deformation remains constant until the end of this process. Then, the load is removed, stresses are released and the material is heated again while the recovered strain is monitored. The influence of two different parameters is studied in order to assess the response of the SMP and specify factors that may affect the recovery phase. The first parameter includes the heating ramps; a slower and faster heating rate of 1°C/min and 5°C/min are examined. Except for the heating rate, the effect of isothermal conditions is also studied (second parameter). The sample is heated up to certain temperature and then it is kept constant while the recovery strain, caused mainly by the intrinsic relaxation properties of polymers, is recorded. The investigation of those two parameters aims at suggesting ways of accelerating the recovery stage of the material without reaching high temperatures which reduce significantly the strength and consequently the load bearing capacity of the material as Table 5-4 denotes. Four experiments are conducted in total in the DMA Q800 machine. In the first two, the heating rate was 1°C/min and the effect of isothermal and heating ramp is tested. Following the same principle, in the last two experiments the faster heating ramp (5°C/min) was used and both isothermal and ramp conditions are studied. The dimensions of the four samples are given in the following table.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimensions LxWxT [mm]</th>
<th>Recovery Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.43x2.02x0.21</td>
<td>1°C/min - ramp</td>
</tr>
<tr>
<td>2</td>
<td>7.9x2.08x0.133</td>
<td>1°C/min - isothermal</td>
</tr>
<tr>
<td>3</td>
<td>8.29x2.13x0.138</td>
<td>5°C/min - ramp</td>
</tr>
<tr>
<td>4</td>
<td>7.37x2.10x0.195</td>
<td>5°C/min - isothermal</td>
</tr>
</tbody>
</table>

5.4.1 Loading Conditions

First the specimen is heated up to 65°C (0-t₁) and while the temperature is held constant an instant external force is imposed causing deformation (t₁-t₂). Then the sample is cooled down while the applied force is...
kept constant \( (t_2-t_3) \). The external load is removed and the sample is heated again \((t_3-t_4)\). Schematic representation of the loading conditions is given in Figure 5.21 and Figure 5.22. Namely, the first figure depicts the temperature conditions applied to the four different cases in order to investigate the shape recovery response of the material. In Figure 5.21(a) and (b) a heating ramp of 1°C/min is applied, the difference lies on the fact that in case (a) the temperature increase from 35 °C to 80 °C while in case (b) temperature rises from 35 °C to 65 °C and it is kept constant for a period of time. In Figure 5.21(c) and (d) a faster heating rate of 5°C/min is applied and both ramp and isothermal conditions are considered.

Figure 5.21: Loading Conditions (a) Temperature – heating ramp 1°C/min, (b) Temperature – Isothermal 1°C/min until 65 °C, (c) Temperature – heating ramp 5°C/min, (d) Isothermal 5°C/min until 65 °C

5.4.2 Results

Figure 5.23 demonstrates the applied temperature and force as well as the evolved strain as a function of time for the heating ramp of 5°C/min (case (c) Figure 5.21). The time periods \( t_1, t_2, t_3 \) and \( t_4 \), mentioned above, are defined as being monitored during the experiment. In particular, from \( t=0 \) to \( t=3\text{min} \) the sample is heated to 65 °C. While keeping the temperature constant, an external force is applied in a period of 1min \((t_2=4\text{min})\). Then the sample is cooled down and the applied force is kept constant between
$t_2=3\text{min}$ and $t_3=8.6\text{min}$ It is observed that through the cooling process and the onset of reheating, the evolved strain remains constant meaning that a temporary shape is preserved. Hence, the shape fixing ability of SMP is denoted. In the last time step ($t_3-t_4=20\text{min}$), the polymer is heated again and the evolved strain is reduced, demonstrating the shape recovery of the polymer after its exposition to an external stimulus such as temperature. The duration of the recovery stage in the current experiment is $11.4\text{min}$ while the whole experiment lasts $20\text{min}$. The other three experiments give similar results with regard the evolution of strain as function of time and temperature. The recovery phase of all specimens is presented and analysed to the next paragraph.

![Graph showing temperature and strain evolution](chart.png)

**Figure 5.23:** Applied temperature and force, evolved strain as a function of time
• Heating rate
The effect of the heating rate on the recovery response of SMP is illustrated in Figure 5.24. The evolved strain is plotted against temperature for two levels of heating ramps, 1°C/min and 5°C/min. It is denoted that faster heating rates shift the glass transition region to the right, meaning that higher temperatures are required for the same level of recovery strain compared to slower heating rates. At lower heating rates, the relaxation characteristics of polymers derived from their viscoelastic intrinsic characteristics accelerate the recovery process, thus larger recovery is achieved at lower temperatures. The influence of the heating rate on the recovery behaviour of SMP, as described in the current study is in good agreement with the expected behaviour reported in literature §2.7.2.3. Another important factor needs to be mentioned is the duration of the recovery phase in the two different cases. As it was expected, the recovery phase of the 1°C/min heating rate is around 30min larger than that of 5°C/min (Figure 5.25). Hence, even if slower heating rates reduce significantly the temperature needed for the same level of recovery strain, the duration of the whole process is a factor that should be taken into consideration.

![Figure 5.24: Strain – Temperature diagram for two levels of heating rates](image)

Figure 5.24: Strain – Temperature diagram for two levels of heating rates

![Figure 5.25: Strain – Time diagram for two levels of heating rates](image)

Figure 5.25: Strain – Time diagram for two levels of heating rates

• Isothermal Conditions
In the present case, the heating rate is kept constant at 5°C/min and the influence of isothermal and ramp conditions on the behaviour of the polymer, is investigated. The evolution of temperature during the two experiments is described by the Figure 5.21(a) and (b). In the first case, during the shape recovery the sample is heated up to 80 °C whereas in the second case the specimen is heated to 65 °C and the temperature is held constant for a period of time. The
comparison of the behaviour of the material under the two different conditions is illustrated in Figure 5.26. It is observed that at isothermal conditions the evolved strain is also reduced due to the relaxation properties of the polymer. Figure 5.27 gives an insight about the time needed for the shape recovery in the two cases. Under isothermal conditions, an additional time period of 15 minutes is required to obtain the same strain level as the one with increases temperature.

Figure 5.26: Strain – Temperature diagram for heating ramp and isothermal conditions

Figure 5.27: Strain – Time diagram for a heating ramp and isothermal
VALIDATION OF THE NUMERICAL MODEL

In the current paragraph, a comparison between numerical and experimental results is presented in order to prove that the numerical model simulates accurately the linear behavior of SMP. To this end, the DMA test as well as the shape memory effect (SME) is simulated in ANSYS [52] and a comparison between numerical and experimental results is made. The aforementioned comparison provides the reader with a deep insight into the numerical simulation of the SMP joint while offers a good overview of the reliability of the results presented in the current research.

6.1 Material Model

The viscoelastic theory is used for the simulation of the material behaviour in ANSYS. The Prony Series coefficients calculated in §5.2.4 (Table 5-2) as well as the WLF constants and the reference temperature given in §5.2.5 (Table 5-3) are imported into the material model. Except for the viscoelastic characteristics, some additional properties such as Poisson ratio and modulus of elasticity are required. Table 6-1 provides information about the material properties used in the numerical simulation. Only the linear part of the stress – strain curves is simulated as Figure 6.1 illustrates.

![Material model](image)

**Figure 6.1:** Material model

**Table 6-1:** Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ [GPa]</td>
<td>1.588</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.38</td>
</tr>
</tbody>
</table>

6.1.1 DMA

The numerical response of the viscoelastic material to imposed dynamic displacement is presented in the current paragraph. The geometry of the sample is identical with the one used for the actual DMA test (Figure 5.4(b)). A dynamic displacement of $d_0 = 0.00001\sin2\pi t$ is applied to the free short edge of the sample while the other short edge is considered fixed. The numerical model, consisting of 2D elements with thickness of 1mm is illustrated in Figure 6.2(a). Schematic representation of the applied displacement is given in Figure 6.2(b). The sample is tested under sinusoidal displacement with frequency of 1Hz at a
range of temperatures. The stress-strain response of the material is recorded, and the decrease of storage modulus as a function of temperature is calculated by dividing the maximum stress with the maximum strain at each level of temperature. Additional to that, the damping factor $\delta$ is calculated by taking into account the phase angle between the applied strain and the resultant stress.

![Figure 6.2](image)

**Figure 6.2:** (a) Numerical model (b) Applied displacement

### 6.1.2 Results

The applied strain and resultant stress are plotted against time at various temperatures in order to assess the temperature dependent properties of SMPs. At temperatures below the glass transition (Figure 6.3(a)), the stress is in phase with the strain as the molecular chains are frozen and there is no relative motion among them. Upon heating, the polymer enters the glass transition phase (Figure 6.3 (b), (c), (d)), and a relative movement of the polymer chains starts evolving. A phase lag between stress and strain is noted which takes its maximum at 69.7°C. The phase angle represents the ratio between loss and storage modulus. As it has been mentioned above, the loss modulus describes the dissipated energy and increases due to the friction among the molecular chains. The storage modulus decreases with the increase of the temperature as the polymer becomes softer. Therefore, the phase angle $\delta$ increases in the transition region. When the temperature exceeds the glass transition (Figure 6.3(e), (f)), the phase lag decreases due to significant reduction of friction between the polymer chains. The polymer is positioned at the viscous regime and less energy is dissipated to the surrounding environment. To conclude, the stress - strain vs time diagrams prove that ANSYS simulates sufficiently the viscoelastic behaviour of the polymer. A comparison between experimental and numerical results is following.
6.1.3 Comparison between numerical and experimental results

Figure 6.4 and Figure 6.5 illustrate the tanδ and the storage modulus of the polymer as a function of temperature including experimental and numerical results. With regard the numerical results, dynamic analyses were conducted at nine different temperatures. The tanδ is calculated by the time difference between the maximum stress and strain whereas the equation (3.6) is used for the calculation of the storage modulus. The numerical results are in good agreement with the experimental and it is concluded that the current numerical approach simulates accurately the behaviour of the SMP.
6.2 Shape Memory Effect

6.2.1 Description

The numerical simulation of the shape memory effect of the rectangular samples presented in §5.4 is described in the present section. The geometrical characteristics and the material properties employed for the simulation of the specimens are given in §6.1. The model is discretised by 3D solid finite elements with mesh density of 0.1mm. The one short edge is considered fixed and a tensile displacement equivalent to 50% strain is applied to the other edge according to load – time diagram given in Figure 5.22. The four different temperature load cases are applied as described in Figure 5.21. Identical geometrical properties and loading conditions with the experimental tests are used in order to increase the accuracy of the comparison between experimental and numerical data. The calculation time required for each analysis ranges between 15 to 20 minutes in a laptop computer.

6.2.2 Results

Schematic representation of the shape effect of the rectangular sample 1 is illustrated in Figure 6.6. Initially the specimen is heated up to 65°C and a tensile displacement is applied causing deformation. The sample is cooled down to 35°C and the prescribed displacement is removed while the sample maintains a temporary shape. Through the recovery phase, the specimen temperature is increased from 35°C to 70°C with heating rate of 1°C/min. Upon heating (T=57°C, T=60°C), the deformation reduces gradually and the sample recovers its original shape at T=65°C.
6.2.3 Comparison between experimental and numerical results

In order to verify that the numerical model simulates accurately the shape recovery of the material, a comparison between experimental and numerical results is presented in the current paragraph. The evolved strain is plotted against temperature for the two levels of heating rates. Figure 6.7 depicts the strain distribution when the temperature increases from 35°C to 75°C with a heating ramp of 1°C/min. It is observed that the numerical response is in good agreement with the experimental until the temperature of 62°C. Beyond this temperature, small but not significant divergences are shown. Figure 6.8 illustrates the evolved strain as a function of temperature for 5°C/min heating rate. The response of the two cases is identical until 62°C. For higher temperatures, difference in the strain level is noted. Due to the fast heating rate, it is possible that there are discrepancies between the temperature of the sample and the oven of the DMA machine. In the experimental results, the temperature of the DMA furnace is monitored as there was no the proper technical equipment to measure the temperature of the sample directly.

Figure 6.6: Shape recovery evolution at different temperatures (1°C/min)

Figure 6.7: Strain– Temperature diagram, 1°C/min
Figure 6.8: Strain–Temperature diagram, 5°C/min

Figure 6.9 demonstrates the strain as a function of time when the sample is heated up to 65°C and the temperature is kept constant for a period of time. The intrinsic relaxation properties of the SMP are shown in both experimental and numerical studies while the comparison between the two graphs is in good agreement ensuring that the numerical model simulates the time relaxation effect.

Figure 6.9: Strain – time diagram, isothermal conditions
Having completed the experimental tests and the steps needed for the validation of the numerical model, the response of the SMP joint, described in §4.2, under imposed axial forces is investigated. First this innovative type of structural joint is tested under normally imposed vertical loads in order to assess the potential use of this joint as structural component. The behavior of the structural joint is studied when the material is at its glassy and glass transition phase. The assessment of the load bearing capacity is realized by comparing the linear response of the joint with the stress – strain curves derived from the tensile tests and give the strength of the material at various temperatures. The aim of this research is to define the force levels that the joint can sustain under the loading conditions demonstrated in §4.1.3.

7.1 Numerical model

Schematic representation of the numerical model is given in Figure 7.1. Quadratic 3D solid elements are employed for the mesh refinement. Longitudinal springs simulate the support conditions, while their edge is considered fixed as the motion caused by the elongation of the actuators is not taken into account in the present study. The stiffness of the springs is considered low in order to allow the deformation of the joint. Axial loads are applied on the four edges of the joint in one time step with duration of 100s. The step is divided into 50 sub steps in order to define the maximum level of the force that the joint is able to carry. Tensile forces are imposed on the three members of the joint while a compressive force is applied on the fourth member as Figure 7.2 illustrates. The loading conditions are determined according to the static analysis of the truss structure presented in chapter 4.

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1$</td>
<td>128.57</td>
</tr>
<tr>
<td>$F_2$</td>
<td>96.43</td>
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<tr>
<td>$F_3$</td>
<td>18.42</td>
</tr>
<tr>
<td>$F_4$</td>
<td>-18.42</td>
</tr>
</tbody>
</table>

Figure 7.1: Numerical model of the SMP joint

Figure 7.2: Applied loads
## 7.2 Glassy State

### 7.2.1.1 Results

Figure 7.3 depicts the deformed state of the joint at ambient temperature (25°C). It is observed that the maximum deformation is evolved to the member with the highest tensile force. The magnitude of the maximum deformation is 6mm and is considered quite low. The distribution of stresses among the joint is given in Figure 7.4, where the mode of failure around the hole is demonstrated. High local stresses are evolved in the inner part of the hole nevertheless; these stresses are not considered determined for the failure of the joint. The distribution of strains is demonstrated in Figure 7.5. The maximum and the minimum values given in this figure are quite high and concern the inner part of the hole where high local stresses and strains are evolved. More information about the numerical singularities is given in §7.3.3. Apart from the area where the failure appears, the stresses and strains evolved at the other parts of the joint are below the yield stress.

![Deformed state](image1)

**Figure 7.3:** Deformed state [m]

![Distribution of stresses](image2)

**Figure 7.4:** Distribution of stresses [Pa]

![Distribution of strains](image3)

**Figure 7.5:** Distribution of strains

The stress – strain diagram illustrating the response of the joint is plotted in Figure 7.6. The evolved stress and strain are compared to the material law defined by the tensile tests and the maximum level of stress and strain that the joint can sustain is determined. Table 7-1 summarizes the magnitude of the maximum acceptable forces. It is concluded that the joint is able to carry the 95% of the permanent loads and 45% of the ULS combination which includes the safety factors for permanent and variable loads.
7.3 Glass Transition phase

The response of the joint to imposed axial forces, at elevated temperatures, is described in the present paragraph. The load bearing capacity of the joint is assessed at the temperatures of 36ºC, 40ºC and 50ºC. Higher temperatures are taken into account, since the strength of the material is extremely low, at higher temperatures and the joint is unable to carry any structural loads.

7.3.1 T=36ºC

Figure 7.7 illustrates the deformed state of the joint after the imposition of axial loads when it is heated up to 36ºC. The maximum deformation (≈5 mm) is evolved in the member with the highest tensile force. Figure 7.8 illustrates the distribution of stresses and it can be seen that the failure of the joint occurs in the adjacent area of the right hole. The strength of the material at T=36 ºC is 30-32MPa. The stresses evolved in the other parts of the joint range from 11.5MPa to 20MPa, values that are significantly lower than its strength. Figure 7.9 illustrates the strain distribution of the joint and again the maximum strain is evolved in the adjacent area of the holes.

Table 7-1: Maximum force at T=25ºC

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
<th>LCI</th>
<th>ULS CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>58.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>43.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>8.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F4</td>
<td>-8.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 7.7:** Deformed state [m]
Figure 7.8: Distribution of stresses [Pa]

Figure 7.9: Distribution of strains

The maximum evolved stress – strain is plotted in the same graph with the curve which demonstrates the strength of the material at 36ºC. It is observed that the onset of the non – linear behaviour of the material is located in the middle of the linear region. The magnitude of the axial forces that the joint can sustain is given in Table 7-2.

Table 7-2: Maximum force at T=36ºC

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
<th>LC1</th>
<th>ULS CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>52.02</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₂</td>
<td>39.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₃</td>
<td>7.45</td>
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<td></td>
</tr>
<tr>
<td>F₄</td>
<td>-7.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.3.2 T=40ºC

The deformed state of the joint when heated at 40ºC and axial loads are applied to its four edges is depicted in Figure 7.11. The maximum evolved deformation is positioned in the same area as the temperatures studied above. The distribution of stresses and strains are given in Figure 7.12 and Figure 7.13 respectively. Failure occurs in the adjacent area of the right hole where the highest tensile force is applied. The yield stress of the material at this temperature is 26MPa and it is noted that the level of the evolved stresses among the joint varies from 9 to 17MPa well below the limit.
Figure 7.11: Distribution of total deformation [m]

Figure 7.12: Distribution of stresses [Pa]

Figure 7.13: Distribution of strains

The stress – strain diagram is plotted and compared to the material law at the specific temperature. It is noted that the material shows ductile behaviour and is able to accommodate large deflections while the stress remains constant at 16 MPa. The level of the permissible forces as well as the percentage of the permanent and ULS loads that the joint can sustain is given in Table 7-3.

Figure 7.14: Stress – strain curve at T=40ºC
### Table 7-3: Maximum force at T=40°C

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
<th>LC1</th>
<th>ULS CO</th>
</tr>
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<tbody>
<tr>
<td>F₁</td>
<td>41.33</td>
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<td>67.5%</td>
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<tr>
<td>F₂</td>
<td>31.00</td>
<td></td>
<td>32%</td>
</tr>
<tr>
<td>F₃</td>
<td>5.92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₄</td>
<td>-5.92</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 7.3.3 T=50°C

The load bearing capacity of the joint is also assessed at T=50 °C and the distribution of deformations is given in Figure 7.15.

![Distribution of total deformation [m]](image)

**Figure 7.15:** Distribution of total deformation [m]

The strength of the material is around 4MPa and the joint can sustain extremely low loads. The comparison between the response of the material and the constitutive law is presented in Figure 7.16 and the magnitude of the axial forces that the joint can carry is given in Table 7-4.

![Stress – strain curve at T=40°C](image)

**Figure 7.16:** Stress – strain curve at T=40°C

### Table 7-4: Maximum force at T=50°C

<table>
<thead>
<tr>
<th>Force</th>
<th>Value [kN]</th>
<th>LC1</th>
<th>ULS CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>F₁</td>
<td>5.14</td>
<td>8%</td>
<td>4%</td>
</tr>
<tr>
<td>F₂</td>
<td>3.86</td>
<td></td>
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</tr>
<tr>
<td>F₃</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F₄</td>
<td>0.74</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.4 Numerical Singularities

Due to the use of 3D solid elements for the mesh refinement, numerical singularities appear which increasing the value of the maximum stress. It is interesting to mention that if beam elements were used for the simulation, numerical singularities will not be induced. Because of the complexity of the material model, 3D solid elements are required in the current research. Sharp corners, constrained edges as well as areas where geometrical changes occur, are possible regions of numerical singularities. While the magnitude of stresses sounds alarming, it is considered very local phenomenon and cannot affect the load bearing capacity of a structure. In case of a brittle material it may crack or a ductile material it may yield. This will lead to local redistribution of stresses without causing major failure. Many design standards allow high local stresses as long as the imposed loads are static. Under cyclic load high local stresses may be a true problem because of fatigue. In the present study, the behaviour of the joint is only studied under static loads so numerical singularities are neglected.
This Chapter summarizes the results obtained from the present research and gives recommendations for further research in order to investigate the full potential of the application of this smart material to field of structural engineering and particularly for the design of adaptive structures. In the first section an overview of the conclusions of the study is given while the second part includes recommendations for future research.

8.1 Conclusions

With the conduction of the current MSc thesis the main research question is successfully answered and a deep insight into the thermomechanical behavior of SMPs is obtained. The study consists of both numerical and experimental results as well as a comparison between them which increases significantly the reliability of the results. Additive manufacturing was used for the production of the SMP samples. 3D printing is a new and promising technology in the field of architecture and structural engineering. The main conclusions of the research are summarized below:

After thorough research in the literature, it is concluded that the behavior of SMP has been studied by some and finds mainly applications to the fields of aerospace engineering and biomedicine. It is a new and promising material for structural applications, especially for adaptive structures due its stiffness variability. Having completed a number of experimental tests, it is interesting to be mentioned that the strength of 3D printed SMPs at ambient temperatures is approximately 36MPa, a value that is comparable to the strength of other materials, such as wood, used for structural applications nowadays. Nevertheless, the mechanical behavior of the material is strongly temperature dependent and decreases with the increase of the temperature. At the temperature of 40°C, the yield stress of the material is 26MPa which drops to 15MPa after necking. The material shows ductile behavior and is able to accommodate strains up to 150%. The strength of the material at this temperature is relatively high while the permissible strain level shows that the material can serve large shape changes needed for the design of adaptive structures. When is heated up to 50°C, the strength of the material reduces to 4MPa which is extremely low for structural applications.

The Shape Memory Effect of the polymer is also tested, both numerically and experimentally and some interesting conclusions are drawn. The influence of two different parameters, heating rate and isothermal conditions, on the shape recovery behavior of the polymer was studied. It is proved that faster heating rates shift the transition phase of the polymer to higher temperatures whereas at slower heating ramps, lower temperatures are required for the shape recovery of the polymer. Nevertheless, in last case the duration of the recovery phase is longer. The second parameter includes, heating of the polymer up to a certain temperature and then isothermal conditions are maintained while the shape recovery occurs due to the relaxation properties of the polymer. A comparison between the duration of the recovery stage in the three cases, faster heating rate, slower heating rate and isothermal conditions showed that the latter requires longer time period. The SME was simulated numerically, taking into account the parameters mentioned above and the comparison between experimental and numerical results is in good agreement meaning that the numerical model simulates accurately the behavior of the polymer.

The viscoelastic theory was used for the numerical simulation of the material model and Prony series coefficients, calculated by the Dynamic Mechanical Analysis are imported into ANSYS. It is concluded that this material model based on that theory simulates accurately the linear behavior of the polymer and obtains reliable results with regard to Shape Memory Effect. Therefore, even if SMP is a new material in the field of structural engineering, in the present study apart from the experimental tests, a numerical simulation approach is suggested and proved that provides reliable results.

A case study was considered in order to assess the load bearing capacity of the joint under normally imposed permanent and variable loads. It is concluded that at glassy state, the SMP joint can sustain 95% of
the permanent loads and 45% of the Ultimate Limit State load combination. The failure occurs in the
adjacent area of the hole needed for the connection between the actuators and the SMP joint. Upon
heating, the load bearing capacity of the joint is decreased. Nevertheless, the temperature at which the joint
can bear a significant percent of applied loads is specified and it can be taken into account for future
research. This study gives an indication about the response of the joint in a real case scenario and sets the
groundwork for future study.

Last, some additional experimental results, presented in the appendix, emphasize the influence of the infill
angle of the infill pattern on the mechanical behavior of the polymer. It is concluded that the vertical infill
pattern of the 3D printed samples shifts the transition phase of the polymer to higher temperatures
compared to the diagonal infill pattern.

8.2 Recommendations

Having analyzed the conclusions of the present study, additional directions to follow are suggested and
presented in the current section.

1. **Nonlinear behavior of the SMP**

   The numerical model, employed in the present study, describes the linear region of the material
behavior. In order to investigate more thoroughly the behavior of the SMP joint in ANSYS, the
nonlinear part needs to be simulated. This can be realized by coding the constitutive law in
FORTRAN and importing into ANSYS. Although the material will be modelled more accurately
the whole process is time consuming due to compatibility difficulties between the software.

2. **Flexural Strength of the Polymer**

   In literature it is reported that the bending strength of the polymer differs from the tensile
strength measure in this study. Therefore, additional experimental tests are suggested in order to
specify the flexural strength of the material.

3. **Strain rate**

   The level of strain rate influences the load bearing capacity of the polymer. A number of
experiments at different strain rates are suggested in order to investigate the impact of this
parameter on the behavior of the joint.

4. **Infill pattern of the 3D printed SMP polymer**

   Some additional experimental results are presented, in the Appendix and emphasize the influence
of the angle of the infill pattern on the mechanical properties of the polymer. It has been proved
that the infill pattern with angle of 90 degrees shifts the transition phase of the polymer to higher
temperatures and in general influences the transition stage of the material. Hence, it is highly
recommended to study the influence of the infill pattern on the thermomechanical properties of
the polymer.

5. **Chemical composition of SMP**

   As reported in literature, the mechanical properties of polymers depend on their composition,
strain rate, molecular weight and temperature. By changing the distribution of molecular weight,
the polymer structure, composition and cross link density the mechanical characteristics can be
manipulated. In the current research, the effect of the temperature is studied thus the investigation
of other factors, such as the chemical composition, that may influence the behavior of the material
is suggested.

6. **SMP Composite**

   Due to the low strength of the polymer at high temperatures, it is suggested to investigate the
behavior of reinforced SMP. This of course will increase the strength of the material but attention
needs to be drawn on the shape recovery phase and the percentage of possible permanent
deformations that can evolve on the SMP joint. The type of the new material as well as the
connection between them will influence the behavior of the joint. Some initial thoughts entails
the reinforcement of the joint with fibers. It is expected that the position and the orientation of the
fibers will play significant role in the formulation of the composite joint.

7. **Shape of the Structural Joint**

   The shape of the joint can play significant role in its structural behavior. Different shape
configurations can be studied and eventually an optimal shape can be obtained.
Chapter 9

REFERENCES


REFERENCES


Numerical and Experimental Investigation of the behavior of SMP Structural Joints
In the current section some additional experimental results, denoting the influence of the infill angle of the samples on the thermomechanical behaviour of the polymer, are presented. As it has been mentioned in §5.1 two different infill angles are used for the 3D printing of the samples. Due to lack of technical equipment for the tensile tests, the results of the research are based on the infill angle of 90°. Nevertheless, samples with infill angle of 45° are subjected to dynamic loading for the thermomechanical characterization of the polymer and the measured data are given in the hereby paragraph. Apart from the DMA test, some tensile tests are also performed.

### 10.1 3D printed Samples

Several samples were printed by using Leapfrog Creatr 3D printer at high quality as Figure 10.1 illustrates. Initially, the infill pattern of the samples was rectilinear with 45° infill angle. Dynamic Mechanical Analysis test was carried out and the measured data are presented hereby. The mechanical properties of the SMP filament provided by the supplier are summarised in Table 10-1.

![Leapfrog Creatr 3D Printer, 3D printing of the samples](image)

**Figure 10.1:** Leapfrog Creatr 3D Printer, 3D printing of the samples

<table>
<thead>
<tr>
<th>Property</th>
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<th>Rubbery</th>
</tr>
</thead>
<tbody>
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<td>100% Modulus (MPa)</td>
<td>-</td>
<td>2.1</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>48</td>
<td>13</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>30 - 50</td>
<td>&gt;600</td>
</tr>
<tr>
<td>Bending Modulus (MPa)</td>
<td>2150</td>
<td>-</td>
</tr>
<tr>
<td>Bending Strength (MPa)</td>
<td>80</td>
<td>-</td>
</tr>
<tr>
<td>Specific gravity</td>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>Glass Transition Temperature (°C)</td>
<td></td>
<td>55</td>
</tr>
</tbody>
</table>
10.2 DMA – results

The 3D printed sample presented in Figure 10.2 was subjected to dynamic analysis. A sinusoidal displacement is applied to the sample at a range of frequencies between 60 and 1 Hz. The temperature increases from 25 °C to 90 °C while the storage and the loss modulus as well as the factor tanδ are measured.

![Infill pattern and dimensions](image)

**Figure 10.2:** Geometrical characteristics of the 3D printed sample (a) infill pattern 45° (b) dimensions

Figure 10.3 illustrates the storage modulus as a function of temperature. As it was expected the storage modulus decreases with the increase of the temperature as the polymer becomes softer. It is observed that the glass transition phase of the sample with the 45° infill angle is between 40 °C and 65 °C. Figure 10.4 demonstrates the tanδ – temperature diagram. It can be seen that the ration between loss and storage modulus increases initially as energy is dissipated to the ambient environment due to the friction between the molecular chains of the polymer. The glass transition temperature is calculated when the loss modulus is equal to storage modulus and given in the Table 10-2. The glass transition temperature measured by the DMA test is 56.5°C while the value provided by the supplier is 55 °C (Table 10-1). Therefore, it is concluded that the mechanical properties given by the supplier are in good agreement with the results of the DMA test for the sample with the 45° rectilinear pattern.

![Storage modulus diagram](image)

**Figure 10.3:** Storage modulus – temperature diagram
Numerical and Experimental Investigation of the behavior of SMP Structural Joints

10.3 Comparison between numerical and experimental results

Following the same method as in chapter 6, the Prony series coefficients were calculated and imported into ANSYS in order to simulate the behaviour of the material. A rectangular sample with the same dimensions as the one illustrated in Figure 10.2 was subjected to a sinusoidal displacement with a frequency of 1Hz while the applied strain and the resultant stress are recorded at various temperatures. It can be seen that the phase angle increases with the temperature and takes its maximum at glass transition temperature. For temperatures greater than the glass transition, the phase angle reduces as there is no friction between the molecular chains of the polymer.
The storage modulus as calculated by the numerical model is plotted against temperature and compared to experimental data (Figure 10.1). It is noted that the numerical results are in good agreement with the experimental ensuring thus the reliability of the numerical results. Additional to that, the tanδ is calculated numerically and a comparison between numerical and experimental results is illustrated in Figure 10.2. Significant difference is observed between numerical and experimental results for temperatures below the glass transition. This occurs due to the fact the WLF equation that is used in ANSYS gives better results for temperatures $T < T_g$.

Figure 10.5: $\sigma - t$, $\varepsilon - t$ curves at different temperatures

Figure 10.6: $\sigma - t$, $\varepsilon - t$ curves at different temperatures
10.4 Influence of the infill pattern on the thermomechanical behaviour of the 3D printed samples

In order to study the influence of the angle of the infill pattern on the behaviour of the polymer, a comparison between the thermomechanical properties of the two types of samples is presented in the current paragraph. The storage modulus is plotted against temperature for the two different type of infill pattern in Figure 10.8. It is observed that the transition phase of the sample with the linear pattern is shifted to higher temperature in comparison to the 45° 3D printed pattern. Additionally, the glass transition temperature of the first sample (linear pattern) is 10°C higher as Table 10-3 and Figure 10.9 demonstrate. The infill pattern of the 3D printed samples is a property that needs to be study as it can influence significantly the thermomechanical behaviour of the polymer.

Figure 10.8: Storage modulus – Temperature of the two types of 3D printed patterns at f=1Hz
Figure 10.9: $\tan \delta$ – Temperature of the two types of 3D printed patterns at $f=1\text{Hz}$

<table>
<thead>
<tr>
<th>Infill pattern</th>
<th>$T_g \degree \text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$45^\circ$</td>
<td>56.5</td>
</tr>
<tr>
<td>$90^\circ$</td>
<td>65.6</td>
</tr>
</tbody>
</table>