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Creep Phenomena in Fiber-reinforced materials for structural rehabilitation: A literature review

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Abstract

Fiber reinforced polymer (FRP) laminates are being currently used within industrial, aerospace, and civil fields. Fiber-reinforced composites have wide applications in the building industry, the reliability of composites over time can be evaluated by characterizing their deferred behavior. However, limited information concerning the Creep behavior of Fiber-reinforced composites has been found in the literature.

Creep deformation is also known as time-dependent deformation, occurs after a period of time when composite material is under a sustained load, and deformations are increased by load, temperature, relative humidity, at a specific time. Due to the creep phenomena, material compositions lose stiffness which may affect even the strength reductions, of Fiber-reinforced materials.

The present study includes a general knowledge of different properties related to fibers and matrix, an overview of creep phenomena and presents the different research papers and comparison between those experiments.

Creep phenomena is a significant factor in determining the composites long-term strength and behavior, experimental data showed that the Fiber-reinforced composites with fibers have less creep strains than the unreinforced FRP laminates.

A creep tests program was carried out in order to model the viscous behavior of the composites and their phases. A discussion on the comparison of creep strain response by the Burgers model, resulted as the most effective for describing the long-term creep data of tested Fiber-reinforced composites.

In further studies, more attention should be at the changes in moisture content and changes in temperature. Besides, different fiber contents and fiber lengths and the effect on reinforcing structures should be more investigated.

Keywords: *Fiber-reinforced composites; Fiber reinforced polymer (FRP); Fibers; Matrix; Resins; Laminate; Creep Phenomena; Viscous behavior; Creep; Sustained load; Time-dependent deformation; Viscoelastic materials; Burgers model.*

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Introduction

Fiber-reinforced polymers are known as reinforcing elements of structure, with a wide variety of construction fields such as rehabilitation and structural upgrading of existing structures [1]. FRP have been used in structural engineering in a variety of forms: from structural profiles to internal reinforcing bars for concrete members to strips and sheets for external strengthening of concrete and other structures.

From different research studies developed at Fiber Reinforced Polymer (FRP) on concrete and masonry structures, the main problems such as adhesion, interfacial stresses, and debonding have been achieved from these studies.

Epoxy Resins as structural adhesives is one of the key components for bonding different FRP, like CFRP - Carbon fiber reinforced polymers or GFRP - Glass fiber reinforced polymer with different materials due to excellent adhesion properties, high mechanical strength, and good performance in the different environmental conditions.

Structural adhesives are categorized as load-bearing materials with good strengthening that can transmit stress without losing any structural part. Another impressive advantage of Epoxy resin as structural adhesive compared to traditional joining methods, such as bolting or welding is that structural adhesive reduces the overall weight, bonding two different materials, and distributing stress equally over a large area. [2]

Structural adhesives are exposed in nature and expose unique time-dependent behaviors, that may affect load-bearing performance, mainly because of missing some basic knowledge on how creep affects the strength of adhesive joints.

Compared to cement-based mortars they exhibit significantly faster curing times, excellent surface adhesion, increased compression, and tensile strengths as well as better corrosion and chemical resistance.

Creep phenomena have an important role because can compromise the reliability and durability of structural elements.

Creep could be a serious problem in structures, when the stresses in the adhesive joints are relatively high, typically in the strengthening of structures with FRP laminates.

1.1 Aim and Scope

The aim of this study is to investigate Creep phenomena through some experiments done by different research institutions related to creep phenomena in the long-term behavior of various FRP laminates.

Chapter 2. Includes a general knowledge of different properties related to fibers and matrix for example epoxy resins

Chapter 3. An overview of Adhesives

Chapter 4. Provides an overview of creep phenomena and explains the different creep tests that can be carried out.

Chapter 5. Presents the different research papers, and the results they got through experiments they have done.

Chapter 6. Provides a comparison between research papers and presents the conclusion of this study.

2.0 Literature Review

2.1 FIBRE REINFORCED POLYMERS

Fiber-reinforced polymer (FRP) composite materials have developed into economically and structurally viable construction materials for buildings and bridges over the last 20 years [3]. FRP composite materials used in structural engineering typically consist of glass, carbon, or aramid fibers encased in a matrix of epoxy, polyester, vinyl-ester, or phenolic thermosetting resins that have fiber concentrations greater than 30% by volume.

They have been used in structural engineering in a variety of forms: from structural profiles to internal reinforcing bars for concrete members to strips and sheets for external strengthening of concrete and other structures.

Depending on the form of the FRP product used in structural engineering, the FRP material is supplied either as a ready-to-use structural component such as a wide-flange profile or a reinforcing bar, or it is supplied in its constituent form as dry fiber and liquid polymer resin and formed and cured on site to create a structural component.

The use of fiber-reinforced polymer appeared as a promising alternative to retrofitting materials like a steel structure ..., because of the advantages of FRP such as high corrosion resistance, durability, and high strength to weight ratio.

Fiber-reinforced polymer (FRP) or advanced composite materials (ACM) are used in the construction of new buildings and bridges and for upgrading existing buildings and bridges as those materials have been proven themselves to be valuable for use. [3]

It is anticipated that FRP products in structural engineering that will be developed in the first half of the twenty-first century, will probably use more of these natural fibers as sustainability and recyclability become more important drives in the construction industry.

2.2 Materials

General Overview

To produce the FRP composite products for structural engineering, two raw materials are required, reinforcing fibers and a polymer resin matrix.

For manufacturing the FRP products for structural engineering applications two main fibers are used, glass and carbon from fibers, another important product is polymer resins are most widely used in FRP products for structural engineering, are thermosetting epoxies, polyesters, and vinyl esters resins.

Two main processes used for manufacturing FRP composite products in structural engineering are pultrusion and hand layup [1].

Pultrusion is used to manufacture FRP profiles, FRP strengthening strips, and FRP reinforcing rebars. Hand layup is used to create formed-in-place FRP strengthening sheets, fabrics, and wraps.

Fibers

In civil engineering three types of fibers dominate. These are carbon, glass, aramid fibers, and the composite are referred with name by the reinforcing fiber for example CFRP for Carbon Fiber Reinforced Polymer. They have different properties, including price, which make them more suitable than the others for different purposes. For strengthening purposes carbon fibers are the most suitable, generally, all fibers have higher stress capacity than ordinary steel and are linear elastic until failure.

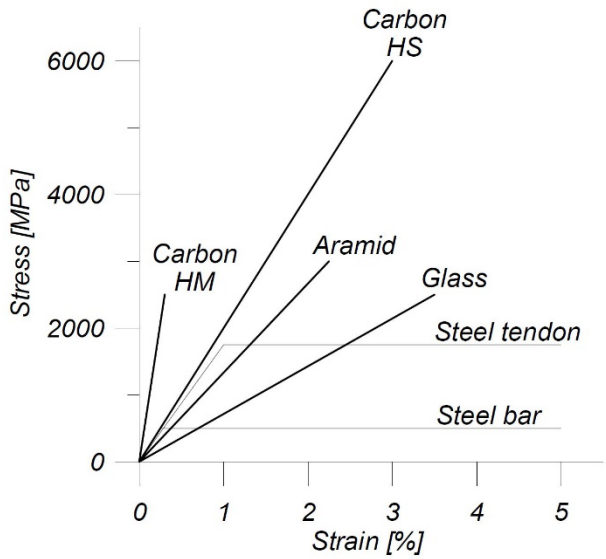


Figure 1. Properties of different fibers and typical reinforcing steel, ACI Committee 440 (1996) and Dejke (2001) [1]

Material	*Modulus of elasticity* GP_a	*Compressive strength* MP_a	*Tensile Strength* MP_a	*Density* $[^{gr}/_{cm^3}]$
Concrete	20-40	6-60	1-3	2400
Steel	200-210	240-690	240-690	7800
Carbon fiber*	200-800	NA**	2500-5000	1750-1950

Table 1. Mechanical properties of common strengthening material [1].

*Given values are for plain carbon fiber, the characteristics of the composite will vary with the amount and property of the used matrix.

**NA-Not applicable. Plain fibers buckle.

Matrix-polymer resin

The matrix should transfer forces between the fibers and protect the fibers from the environment. In civil engineering, thermosetting resins are more often used. From thermosets vinyl ester and epoxy are the most common matrices, Epoxy is mostly preferred compared to vinyl ester but is also more expensive.

Material	*Density* $[^{kg}/_{cm^3}]$	*Tensile Strength* MP_a	*Tensile modulus* MP_a	*Elongation* [%]
Vinyl ester	1000-1450	20-100	2000-4200	1.0-6.0
Epoxy	1100-1300	55-130	2500-4800	1.5-9.0

Table 2. Properties for matrix materials

2.3 Reinforcing Fibers

A higher number of continuous fibers are used to reinforce the polymer resin the volume percentage used is 20-60%, for this reason, the mechanical properties of fibers are greater than the mechanical properties of polymer resins that they reinforce, to realize their superior mechanical properties of FRP products must be synchronized both raw materials [4]. Fibers are used in reinforced cementitious materials known as glass-reinforced cement or fiber-reinforced cementitious composites FRC.

Fiber forms that are used in FRP products for structural engineering are identified as long fibers and are called continuous fibers, with lengths of 10 to 50 mm.

Reinforcing fibers are used in FRP composite products in structural engineering as a different type:

- *Glass Fibers*
- *Carbon Fibers*
- *Aramid Fibers*
- *Other Fibers*

Glass Fibers

It has a large scale of use as a different type of FRP product for structural engineering, from FRP reinforcing bars for concrete to FRP strengthening fabrics, or FRP structural profile shape. The main component in all glass formulations is Silica dioxide S_iO_2 with a large scale, constituting from 50-70% by weight of the glass.

Different types of glass fiber are written with a capital letter like E-glass because of its high electrical resistivity or C-glass known as resistant in corrosion also AR-glass alkaline resistant glass, is used to produce specific products for use in structural engineering. S-glass structural or High-strength glass is used to produce high-performance fibers.

The diameter of an individual glass fiber ranges between 3 to 24 μm micrometer, most used for FRP products for structural engineering is 17- μm diameter fiber [4]. To produce a glass fiber the process melting temperature must be around 1400 °C, glass fibers are particularly sensitive to moisture, especially in the presence of salt, and need to be well protected by the resin system used in the FRP part.

Fiber	Density ($\frac{gr}{cm^3}$)	Tensile strength MP_a	Young's modulus (GP_a)	Elongation (%)
E-glass	2.58	3445	72.3	4.8
C-glass	2.52	3310	68.9	4.8
S-glass	2.46	4890	86.9	5.7
AR-glass	2.70	3241	73.1	4.4

Table 3. Mechanical Properties of Glass fibers

Carbon Fibers

Carbon fibers are used in different applications in structural engineering products like FRP strengthening sheets and fabrics, FRP strengthening strips, and FRP prestressing tendons. Carbon fibers have been used primarily with epoxy resins, nowadays are being used more with vinyl ester and blended vinyl ester-polyester resins for FRP profiles and FRP strengthening strips, and due to the risk of thermally and electrically conductivity with carbon fibers, care must be taken when they are used in contact with metallic materials.

Carbon fibers are performing very well in warm and moist environments and when subjected to loads carbon fibers are very durable [4].

In production, carbon fiber is known in different varieties as standard modulus SM, intermediate modulus IM, high strength HS, and ultrahigh modulus UHM, carbon fiber is produced at high temperatures between 1200-1400 °C, and it has a diameter of around 5 to 10 μm.

Fiber	Density ($\frac{gr}{cm^3}$)	Tensile strength MP_a	Young's modulus (GP_a)	Elongation (%)
SM	1.55	>2500	200-280	1.3
IM	1.57	>3500	280-350	1.6
HS	1.59	>2500	350-600	1.2
UHM	1.70	>2500	>600	1.1

Table 4. Mechanical Properties of Carbon fibers

Aramid Fibers

Aramid fibers have been used to produce the first generation of FRP prestressing tendons. Nowadays aramid fibers are used as FRP reinforcing bars, and in FRP strengthening applications to wrap the columns, it has a relatively high price, difficulty in processing, and a high moisture absorption up to 6% by weight and a low melting temperature around 425°C, and poor compressive properties those issues, have made not so useful for FRP parts for structural engineering applications [4].

Fiber	Density $(^{gr}/_{cm^3})$	Tensile strength MP_a	Young's modulus (GP_a)	Elongation (%)
DuPont Kevlar 29 Aramid Fiber	1.44	2920	70.3	3.6
DuPont™ Kevlar® 49 Aramid Fiber	1.44	3000	112	3.4

Table 5. Mechanical Properties of Aramid fibers

Other Fibers some interesting fibers are in the developing phase for use in FRP products for structural engineering, like thermoplastic ultrahigh-molecular-weight UHMW or known as a short fiber are being used nowadays only in the development of ductile fiber-reinforced cement FRCs, polyvinyl alcohol PVA fibers used in FRP bars and FRP strengthening sheets in Japan.

2.4 Polymer Matrix resins

The Polymer can be described as a bunch of extremely large molecules, called macromolecules, that consist chains in which atoms are held together by covalent bonds.

The term polymer resin is referred to the primary polymer ingredient in the non-fibrous part of the FRP material that links the fibers together. The Polymer resin is also known as a matrix or binder.

Nowadays we have two groups of polymers existing today, thermosetting polymers and thermoplastic polymers, the difference between these two polymers is the way how the polymer chains are connected, when a polymer is in the solid form.

Thermosetting polymers are cross-linked, so their molecular chains are a connected as continuous three-dimensional network by strong covalently bonded atoms. Thermoplastic polymers are not cross-linked, and their molecular chains are held together by hydrogen bonds.

As a cross-linked, thermosetting structure is set when it cures during the polymerization process, and it cannot be heated and softened and then re-formed into a different shape.

The thermoplastic polymer doesn't set, but remains plastic, and the molecular chain can "flow" for example when we heat up the thermoplastic polymer can be reset into a different shape upon cooling [3].

PROPERTY	THERMOSETTING	THERMOPLASTICS
FORMULATION	COMPLEX	SIMPLE
MELT VISCOSITY	VERY LOW	HIGH
FIBER IMPREGNATION	EASY	DIFFICULT
PROCESSING TEMPERATURE/PRESSURE	LOW TO MODERATE	HIGH
FABRICATION COST	HIGH	LOW
SOLVENT RESISTANCE	EXCELLENT	POOR TO GOOD
DATABASE	VERY LARGE	SMALL
ENVIRONMENTAL DURABILITY	GOOD	UNKNOWN

Table 6. Properties for Thermosetting and Thermoplastics

Polymer resins are considered isotropic viscoelastic materials, meanwhile creep at polymer resins occurs under sustained stresses or loads and relax under constant strains or displacements.

Thermal resistance of polymers and the thermal response has a large role in their processing, properties, and behavior. A phase change from solid to liquid for a pure crystalline solid like transition temperature, called the melting point, Tm. In the case of Polymers as semicrystalline solids that contains non-crystalline amorphous regions, the thermal transitions occur at a lower temperature than Tm. The thermal transition of particular interest in structural engineering is known as the glass transition temperature T_g, which occurs in the amorphous region of the polymer at a temperature below the melting temperature, both thermosetting and thermoplastic polymers have transition temperatures.

At T_g, the physical properties like density, heat capacity, and mechanical properties like stiffness, and damping of polymers undergo a change. For example, when the temperature reached below T_g, the polymer changes from rigid (glassy) to a viscous state (rubbery).

FRP composites in structural engineering must be in rigid states with operating temperature below the glass transition temperature, however, at temperatures above the glass transition temperature the FRP part will be less durable and will have low strength.

In general, thermosetting polymer resins are not suitable to use at temperatures higher than 180°C, and thermoplastic polymers its suitable to use at high temperatures up to 450°C.

Polymer resin used in commercial and industrial products as a different type:

- *Unsaturated Polyester Resin*
- *Epoxy Resins*
- *Vinyl ester Resins*
- *Phenolic Resins*
- *Polyurethane Resins*

Unsaturated Polyester

Unsaturated polyester resins are also known as Polyester resin mostly is used to make pultruded FRP profiles and is also used to make some FRP rebars both of them are used in structural engineering. When we are facing an issue with corrosion and high corrosion resistance is required for FRP parts, higher-priced vinyl ester resins are generally recommended. Vinyl ester resins are used for demanding applications, including corrosion-resistant are often used in critical components and marine vehicles. It is called unsaturated polymer because the double-covalent bonds on polymer chains are not saturated with hydrogen atoms [5].

Polymer resins	Density at 20°C ($^{gr}/_{cm^3}$)	Tensile strength MP_a	Young's modulus (MP_a)	Elongation (%)	Max service temperature °C
Unsaturated Polyester	1.1-1.12	22-85	3200-3900	1.2-5.0	170

Table 7. Mechanical Properties of Unsaturated Polyester

Vinyl ester Resins

Vinyl ester Resins is a recently new polymer resin developed in the last 30 years, due to its good properties it became attractive as an FRP product for structural engineering, especially for resistance to corrosion and easily of processing, today most FRP rebars are made of vinyl ester resins and also a widely used to make FRP pultruded profiles, and due to their well performed on environmental durability in alkaline environments they are generally replacing other polyester resin in FRP products in structural engineering.

Vinyl ester resin is a hybrid of epoxy and unsaturated polyester resin sometimes we may find like epoxy vinyl ester resin or a modified epoxy resin, it is an unsaturated polymer that is produced from an epoxy resin [5].

Polymer resins	Density at 20°C ($^{gr}/_{cm^3}$)	Tensile strength MP_a	Young's modulus (MP_a)	Elongation (%)	Glass transition temperature °C
Vinyl ester Resins	1.03-1.15	16-95	3000-3800	2.5-9	55-145

Table 8. Mechanical Properties of Vinyl ester resins

Epoxy Resins

Epoxy Resins it has a large range of use in many FRP products for structural engineering applications, most of the carbon fiber-reinforced pre-cured FRP laminate, used for structural strengthening are made with epoxy resins. Most of the times epoxy resin adhesives are used to bond the pre-cured FRP laminate to other materials like concrete …, for a purpose of FRP strengthening process. When the epoxy resins are applied to the dry fiber sheets or fabrics are often referred to as saturants, epoxy resin is applied to the dry fiber sheet or fabric in the field and then cured on-site on this process epoxy resin is acting as the matrix for FRP composite and as an adhesive to bond the FRP composite to the substrate. Epoxy resins are not used too much to produce the large FRP profiles, due to the higher cost and the difficulties in processing large pultruded FRP parts.

An epoxy resin contains one or more epoxide groups that react with hydrogen groups [5].

Epoxy resins are particularly universal can be used in a lot of range of properties to serve as matrix materials for FRP composites or to serve as the adhesive, epoxy resin has been developed for high-temperature applications of 180 °C and higher and it is the first choice from the thermosetting resins in the aerospace industry for the last 50 years [5].

Polymer resins	Density at 20°C ($\boldsymbol{gr}/_{\boldsymbol{cm^3}}$)	Tensile strength $\boldsymbol{MP_a}$	Young's modulus ($\boldsymbol{MP_a}$)	Elongation (%)	Max service temperature °C (Duralco, adhesive)
Epoxy resins thermoplastic	1.15-1.3	27-200	850-4800	1.3-705	-260 to 350
Epoxy resins adhesives	1.15-1.3	40-65	850-4800	3-5	-260 to 350

Table 9. Mechanical Properties of Epoxy resins

Phenolic Resins

Phenolic Resins it is the oldest and most widely used thermosetting resins, they have been used for FRP products for structural engineering production of plywood and other engineered wood products [5]. They are being used in FRP products for structural engineering due to superior fire resistance.

Nowadays they are used in a limited number of FRP products like FRP strengthening strips for timber structures.

Polymer resins	Density at 20°C ($^{gr}/_{cm^3}$)	Tensile strength MP_a	Young's modulus (MP_a)	Elongation (%)	Max service temperature °C
Phenolic Resins	1.3-1.5	41-55	10000(reinforced)	0.64-0.81	152-155

Table 10. Mechanical Properties of Phenolic resins

Polyurethane Resins

Polyurethane Resins are part of thermosetting polyurethane resins, it's quite new in the market as a structural resin, recently have been used to produce high-density that can be used in resin modeling and pultrusion operations [5]. Polyurethane resins have high toughness and when combined with glass fibers produce composite products with high transverse tensile and impact strengths. And their cost is approximately the same as the high-performance vinyl ester resins.

Polymer resins	Density at 20°C ($^{gr}/_{cm^3}$)	Tensile strength MP_a	Young's modulus (MP_a)	Elongation (%)	Glass transition temperature °C
Polyurethane Resins	1.10-1.25	7.6-66	31-57.2	350-1200	80-92

Table 11. Mechanical Properties of Polyurethane resins

3.0 Adhesives

Adhesives are known as a suitable material for holding at least two surfaces in a strong and stable way [2]. One of the reasons why adhesives are used nowadays is because of their holding and bounding power, in general, adhesives are categorized as materials with high shear and tensile strength.

The main properties of adhesives are:

- Flexible material in the aspect of creating any form on surface during the attachment process.
- By improving strengthening of the joints and increasing carrying capacity.
- Distributing and transferring the load along with the components that are connecting with adhesive.

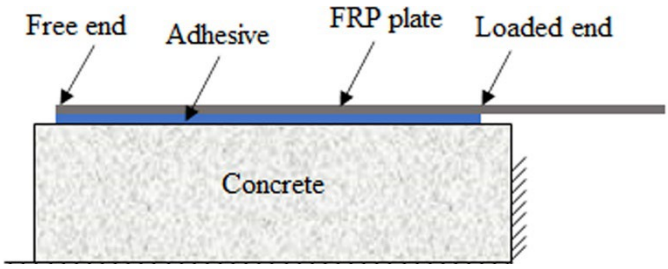


Figure 2. Components of a simple adhesive joint; Asce-library

3.1 Adhesive properties

Advantages and disadvantages of Adhesives

Adhesive components also known as glue in the commercial industry as substances to be applied to one or two surfaces separated from each other.

Like the other materials, adhesives have several advantages and disadvantages, for every adhesive, some basic conditions are required, high durability, less time for bonding, stickiness must be higher after the curing process, and the adhesive must perform high strength.

This part addresses the process of choosing a method of joining, each joining application should be considered regarding specific requirements. There are times when adhesives are the worst possible option for joining two substrates, and sometimes adhesives may be the best solution or the only alternative.

Advantages of adhesive

- Resistant against corrosion
- Easy to use for different applications
- Good insulator for electrical and thermal condition
- Can be applied to most of material surfaces
- Leak-proof of liquids at adhesive joints
- Adhesive provides excellent fatigue strength
- Bonding between surfaces easily and quickly
- Providing a large stress bearing area

Disadvantages of adhesive

- Adhesive cannot be applied while we face temperature cycles, from low to high or high to low temperature because the bond strength will decrease rapidly
- Adhesive requires a plain and clean surface to be applied
- Sensitive when is facing high humidity
- It takes time to achieve fully bonding strength
- Not so easy to inspect the finished joints
- There is no single general-purpose adhesive that can be used to join all types of surfaces

Adhesives are defined as structural adhesives and non-structural adhesives.

Non-structural adhesives are known as low strength materials, they are usually used for bonding different components with low strength requirements.

Structural adhesives are described as adhesives with high shear strength and good durability, for example, epoxy resin is categorized as a structural adhesive.

Adhesives have also been found to degrade more rapidly in a stressed environment, compare to unstressed conditions this phenomenon will be more investigated in the creep phenomenon part.

3.2 Joint Efficiency

To achieve good joint efficiency, non-uniform stress distribution should be reduced by proper joint design and selection of certain design variables affecting the stress distribution. The following variables are most important:

- Adhesive material properties
- Adhesive thickness
- Geometry of the bond area
- Adherend properties

Another important detail of adhesive is the thickness and homogeneity, it is usually best to attempt to have a constant bond-line thickness along substrates area.

Failure in the bond always begins at the maximum stress regions, therefore understanding the stress distribution in a joint is of primary importance in the design of an adhesive joint.

Sometimes joints may fail either by adhesiveness or cohesivity, adhesive failure is a defect that happens at the interfacial bond between the adhesive and the adherend, while cohesive failure is something that exists within adhesive material or adherend.

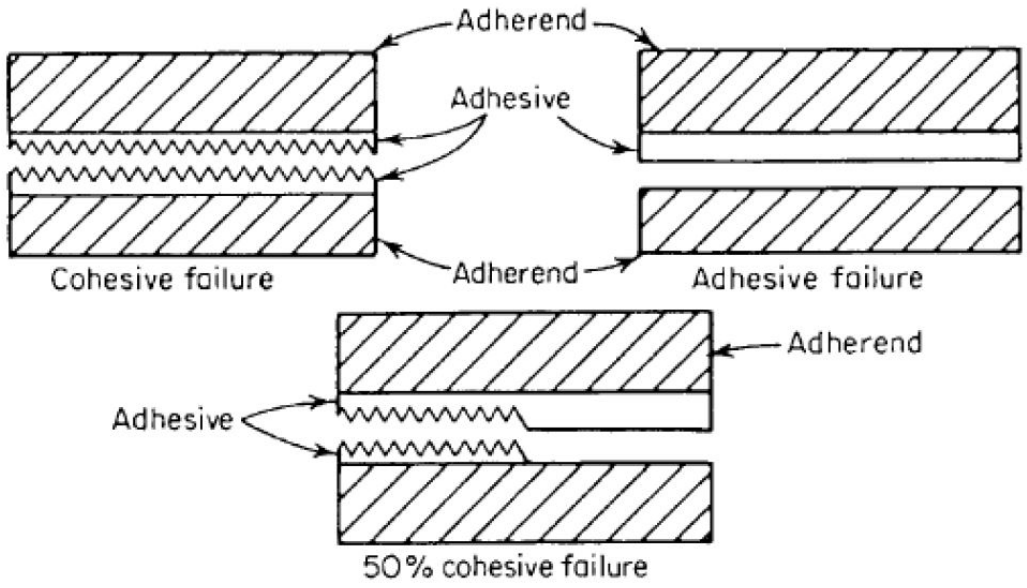


Figure 3. Two types of adhesive and cohesive failure; Edward Petrie (2000) [2]

Crack propagation sensitivity is greater with brittle adhesives because brittle adhesives are having low elongation and high modulus even the fatigue life, are generally lower with brittle adhesives [2].

3.3 Type of Stress

External loads provide local stresses that may be way higher than average stresses (average stresses are defined as the load divided by the total area), these stress concentrations are often unexpected, and they may determine the actual force that the joint can sustain, so it's so important to compensate or to minimize these effects when we are designing the joints.

Four basic types of loading stress are common to adhesive joints: tensile, shear, cleavage, and peel [2].

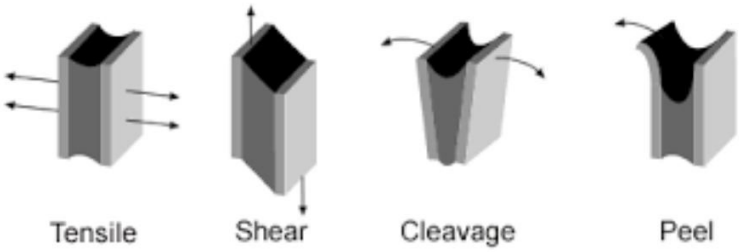


Figure 4. The four basic types of stress common to adhesives; Edward Petrie (2000) [2]

3.4 Shear Stress

Shear stress results when forces acting in the plane of the adhesive try to separate the adherends. Adhesives are strongest when is facing stresses in shear because the entire bonded area contributes to the strength of the joint. Shear stresses are measured similar to tensile forces, as force per bonding area.

The lap shear joint in Fig 5. Is the most common joint design in adhesive bonding, note that most of the stress is localized at the ends of the overlap [2].

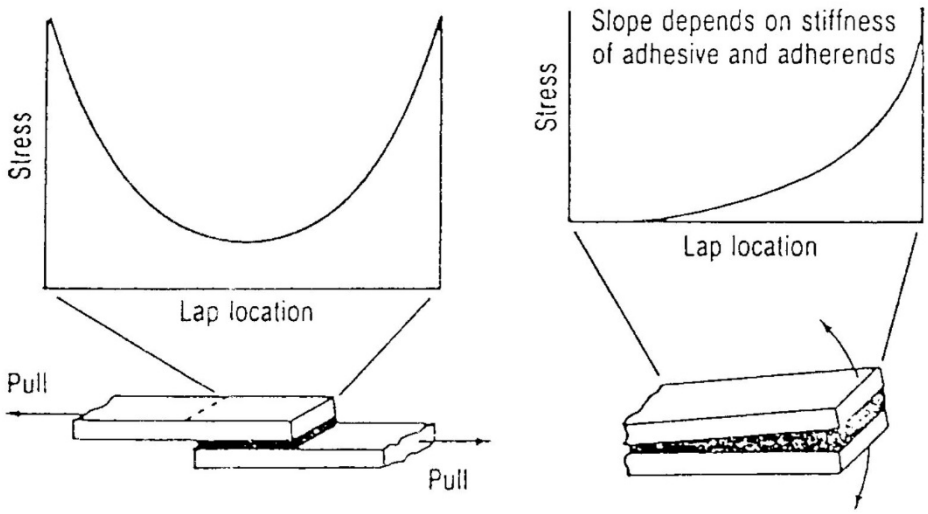


Figure 5. Stress distribution on adhesive when stressed in shear left and peel right [2]

3.5 Tensile Stress

Tensile stress occurs when forces acting perpendicular to the plane of the joint are distributed uniformly over the entire bonded area, while adhesive is in tension, develops high-stress regions at the edge of joints and those edges then support a disproportionate amount of the load [2].

At the weakest area of one of the highly stressed edges, the first small crack that occurs immediately will propagate quickly and lead to failure of the joint, but if the joint is properly designed, it will show good resistance to tensile load because the load is more easily distributed. Also, the adherend must have sufficient rigidity so the stress is distributed equally way at the entire bonded area.

In practice the stress distribution in the simple tensile joint in Fig.6, is far from uniform, it is uniform only if the adhesive and adherends do not deform laterally when the join is stressed.

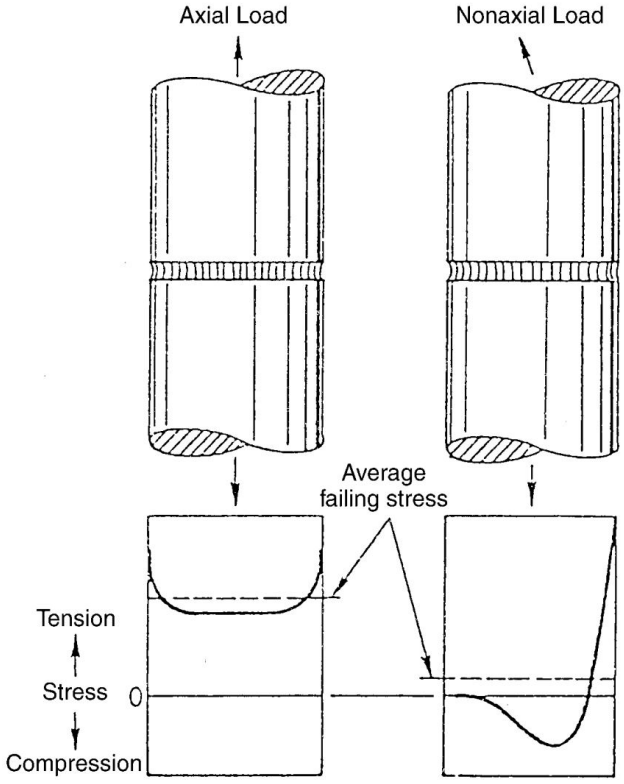


Figure 6. Stress distribution in simple tensile joint under axial and non-axial load; [2]

From Fig.7 we can see how shear strain is increased significantly, and this amount of increase is strongly related to the creep properties of the adhesive.

The peak of shear strain is localized at the ends of the joint and will be reduced with time and the strain within the central region will be increased compared to the initial time, this makes the adhesive more sensitive to creep phenomena.

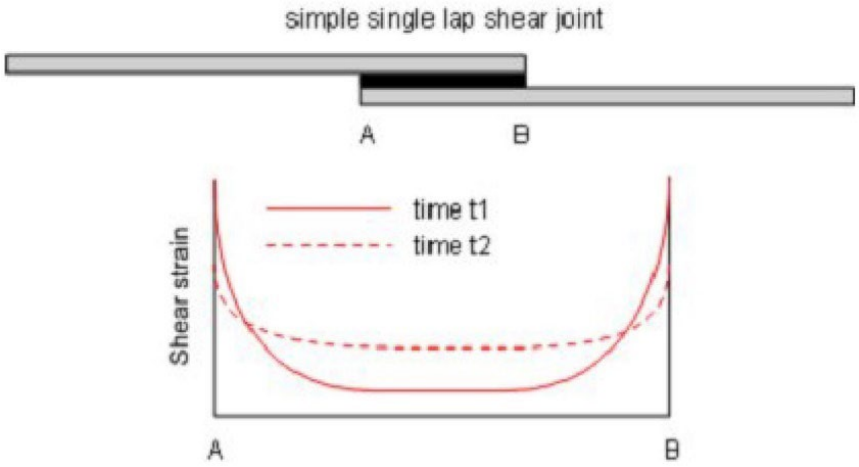


Figure 7. Shear strain at single lap joint;(www.adhesivestoolkit.com)

3.6 Effect of the Environment

For an adhesive joint to be useful, is not enough only to withstand the mechanical forces that are acting on it, but it must also resist the elements to which it is exposed during service.

Strength and durability are influenced by many common environmental elements, these include high and low temperatures, moisture or relative humidity, chemical fluids, and outdoor weathering. Mechanical stress, elevated temperatures, and high relative humidity can be a fatal combination for a certain joint if all occur at the same time. The parameters that will likely affect the durability of a joint are:

- Nature and type of environment
- Maximum stress level
- Cyclic effects of stress and environment
- Average constant stress level
- Time of exposure

4.0 Creep Phenomena

The dimensional change occurring in stressed Fiber-reinforced composites over a long time of period is called Creep [6].

All the Data for the creep test are accumulated by loading a specimen with predetermined stress and measuring the total deformation as a function of time or measuring the time necessary for a complete failure of the specimen.

A behavior of viscous materials like FRP can be investigated with creep tests, and creep behavior mainly depends on matrix type, fiber type, fiber volume, fiber orientation, load history, temperature, and humidity.

Creep deformation is also known as time-dependent deformation occurs after a period of time when a composite material or structure is under a constant load, or stress, and strain or deformations are increased by load, temperature, relative humidity, or time.

So, creep is also known as a time-dependent change in the dimensions of a plastic material when it is subjected to stress. A given loads along with gravity supplies constant stress on the plastic bone is supported at the ends. After 10 hours in this condition, there is very little deflection on plastic bone, however after 100 hours the deflection or strain has increased, and it is deflected even further after 1000 hours (Fig.8).

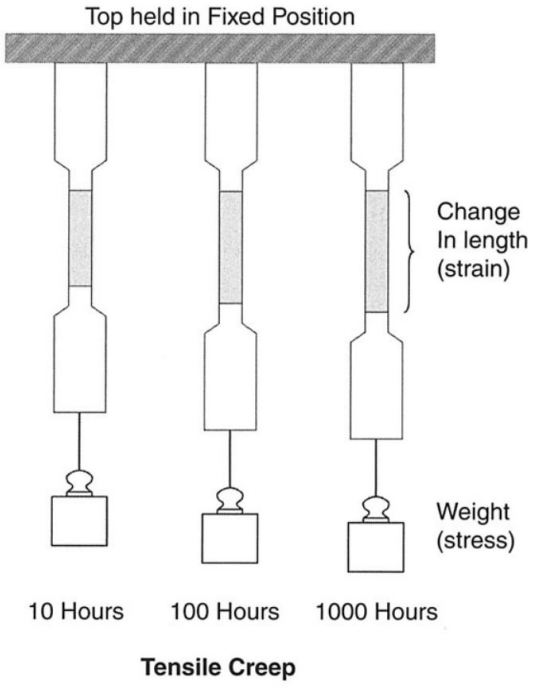


Figure 8. Illustration of Creep; Laurence W. McKeen (The Effect of Creep,2009) [6]

4.1 Creep Test

The test on creep behavior on unidirectional FRP laminate material and their phases matrix (resin) and fibers are performed at the testing laboratory of the structures department of Civil Engineering.

Preparation of specimens like Flat dog-bone samples for tensile and creep tests can be realized by cutting on a band saw machine or made as a modular molding system according to the ASTM D638 standards. The dimensional details of each type of specimens were presented in respective research papers.

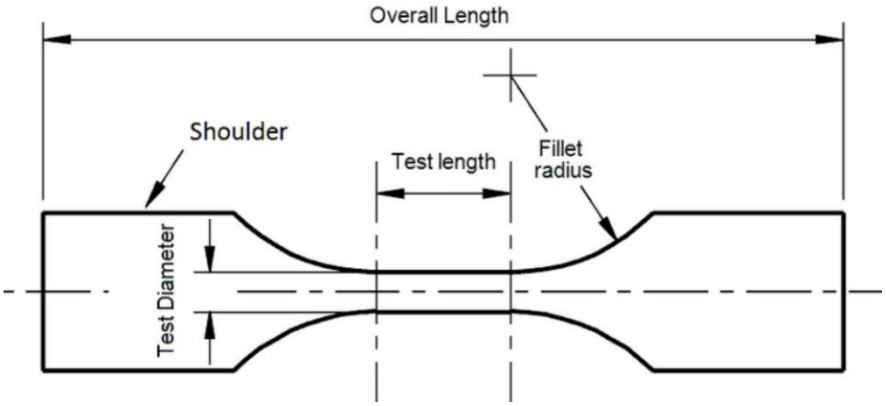


Figure 9. Flat dog-bone sample according to ASTM D638

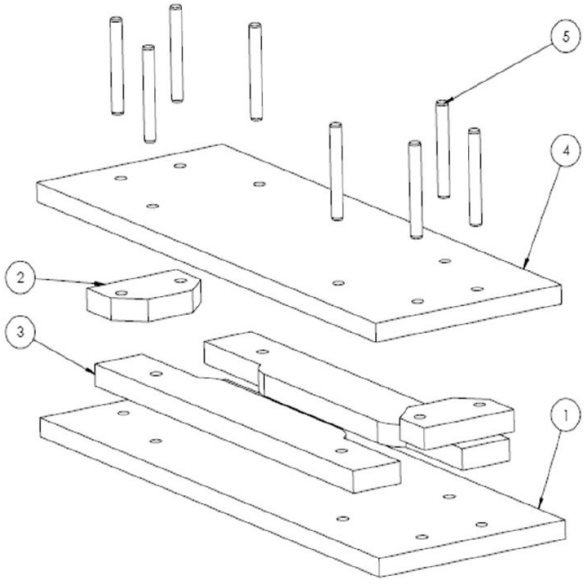


Figure 10. Schematic of mold: 1) lower plate; 2,3) mold cavity assembly; 4) upper plate; 5) alignment pins

The flat dog-bone sample first undergoes to tensile test for a short time to identify the mechanical properties of FRP materials by performing experimental tests according to ASTM D3039 standard on the different specimens for each material that we are analyzing.

Mechanical properties of FRP from short tensile test:

- E_f longitudinal Young modulus
- f_{fk} characteristic tensile strength
- ε_{fu} ultimate strain
- V_f the volumetric fraction of fibres
- A_f the geometrical dimensions of the samples or effective length

4.2 Creep behavior

The viscous behavior of FRP materials can be investigated by creep tests and mainly depends on:

- Matrix type
- Fiber type
- Fiber volume fraction
- Fiber orientation
- Load history
- Temperature and humidity

In a creep test, the sample is subjected to a constant tensile force and the elongation is monitored over the time, this constant tensile force is known as normalized sustained load or dead load sometimes even live constant load σ_0.

The device used for a long-term creep behavior test are mainly designed and built by the structure department of civil engineering of their institute as an example I will introduce one of the devices made by the department of Civil Engineering, University of Salerno [7]. In detail, each test device is made up of a horizontal beam, acting as the lever arm, with a set of samples and the necessary weight, required to generate the axial dead load, attached to the respective extremities (Fig. 11).

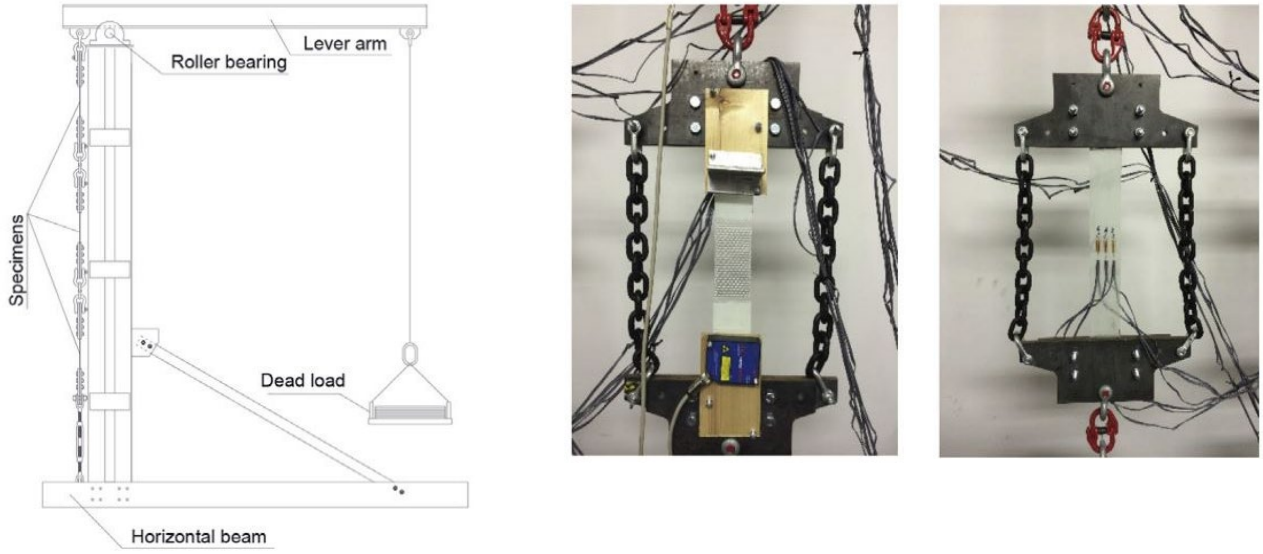


Figure 11. Device used for Creep Test Lever Arm System and set-up of FRP sample [7]

This beam is welded to a circular section tree, which is hinged at the side edge with roller bearings, connected through-bolted plates to the four columns of the equipment. The set of samples is also limited at its lower extremity, in correspondence to the base, by a horizontal beam. The devices can apply axial stresses to the test samples, through the use of a lever arm.

The data acquisition system should consist of:

- Strain gauges applied to the FRP sample
- In case of fiber samples, laser probes are used for monitoring
- Thermocouples to control the effectiveness of temperature during the test

4.3 Summary of Creep standard tests

Standard plastics tests are generally specified by two standards organizations ASTM International and ISO International organization for standardization both develop technical standards in whatever fields need them.

ASTM D2990-01 Standard test methods for Tensile, Compressive, and Flexural Creep and Creep Rupture of plastics describe the measurement of creep and creep-rupture properties of plastic under specified environmental conditions. For measurements of creep-rupture, tension is the preferred stress mode because for some ductile plastics rupture does not occur in flexure or compression.

ISO 899-1:2003 Plastics, Determination of Creep behavior-Part 1: Tensile creep specifies a method for determining the tensile creep of plastics in the form of standard test specimens under specified conditions such as that pre-treatment, temperature, and humidity.

In the first part of the creep test, a primary creep occurs when the strain rate is followed by fast growing deformations and then decreases over time.

At the secondary creep regime, the specimen is at a steady-state creep regime when the strain rate is constant over a period of time longer than the previous one.

And finally, the specimen enters into the tertiary creep stage when the stress or temperature values become very high and the creep rate increases continuously until the specimen breaks, the third part is also called creep rupture or creep fracture.

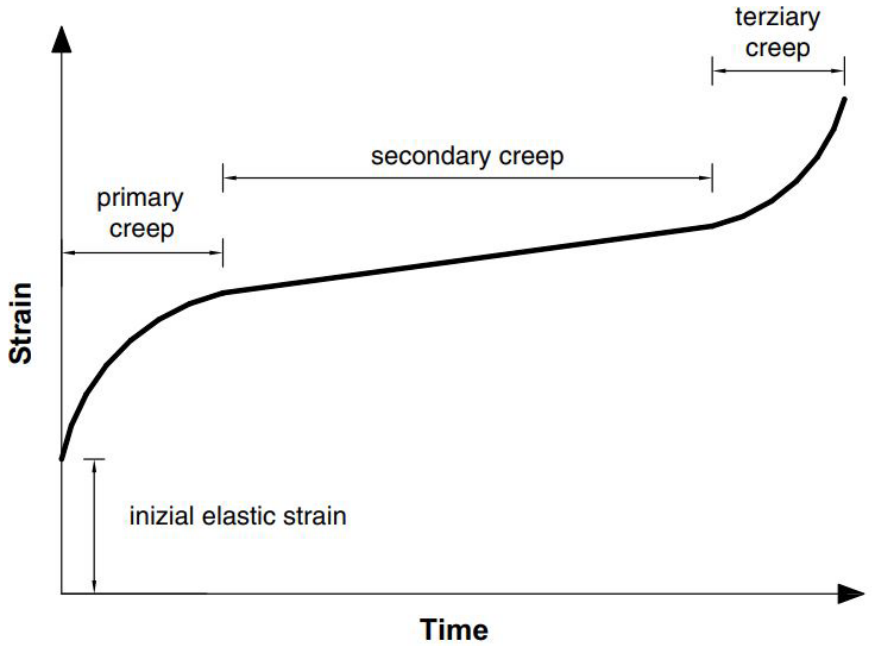


Figure 12.Creep deformations over time; Berardi, Valentino Paolo 2008 [8]

In the past ,many of the analyses about stress problems for creep have been based on an assumption that the entire creep curve could be represented by a straight line, which means creep has a constant rate.

While this may be an adequate way of treating design problems involving creep at low stresses over long periods of time, it is hardly adequate for many present-day problems, which often involve high stresses, high temperatures, and short times.

Due to the creep phenomena, material compositions lose stiffness which may affect even the strength reductions, of Fiber-reinforced materials.

It's important to understand the creep effect on stresses and strain, especially at joints considering that creep phenomena continue for a long time, and this is an important aspect of long-term performance at adhesive joints.

4.4 Modelling creep behavior

Modeling and model parameter estimation is so important for a correct prediction of the behavior of different material. The time-dependent, viscoelastic behavior of polymeric materials may be modeled by combinations of spring and viscous dashpot elements in series and parallel, the simplest model that shows both a short-term elastic as well as a long-term, limiting deformation corresponding to a fully relaxed state is shown in Figure 13.

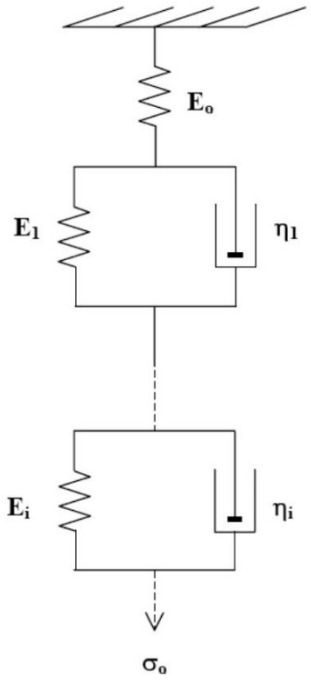


Figure 13.A spring and dashpot model for linear creep in polymers; [6]

The Elastic components can be modeled as springs of elastic constant E, given by the formula:

$$E = \frac{\sigma}{\varepsilon}$$

The viscous components can be modeled as dashpots and the viscosity of the material can be expressed as a function of the stress and the time derivative of strain:

$$\eta = \frac{\sigma}{\left(\frac{d\varepsilon}{dt}\right)}$$

Within the field of linear viscoelasticity, the Burgers rheological law can be usefully adopted for modeling the creep behavior of FRP laminates.

Through the four parameter Burger model, represents the viscoelastic behavior more realistically in comparison to other models, the use of this model for predictive purposes is not so common, probably due to the difficulty in determining the parameters. In one of the research papers, I will present in the next chapter demonstrated the efficacity of the four-parameter Burger model law in predicting the response of viscoelastic behavior, Figure 14 depicts the rheological sketch of the standard four-element viscoelastic Burger model subjected to a constant stress σ_0 for a particular time period and the corresponding stress-strain behavior with time.

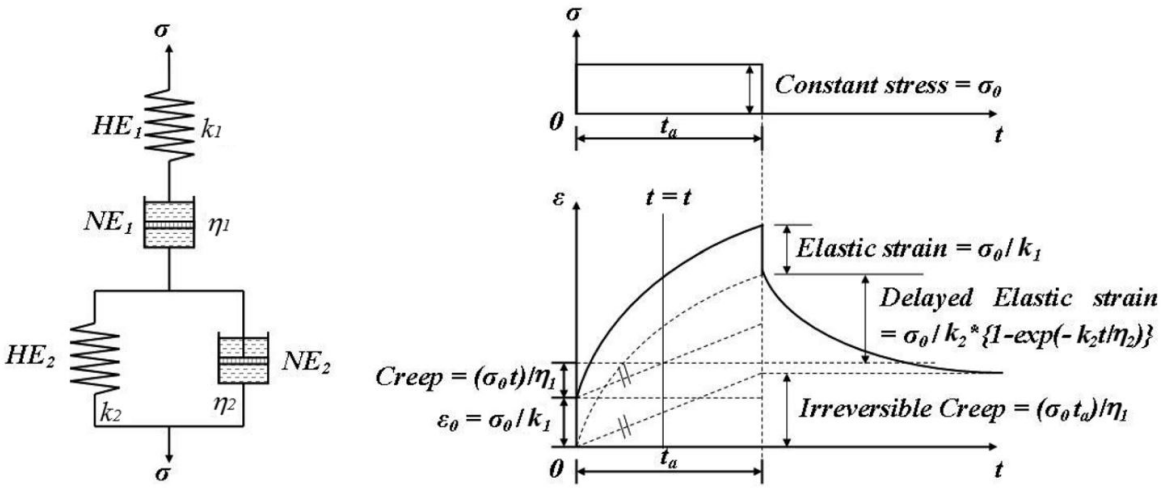


Figure 14. Rheological model and the response of a four-parameter Burger element [6]

The linear viscoelastic creep strain, as a function of time t, is related to the applied stress σ_0 and material properties:

$$\varepsilon_{(t)} = \sigma_0[\left(\frac{1}{E_1} + \frac{t}{\eta_1}\right) + \frac{1}{E_2}\left(1 - e^{-t\frac{E_2}{\eta_2}}\right)]$$

$$\varepsilon_{(t)} = \sigma_0[c_1 + c_2 * t + c_3\left(1 - e^{-t\frac{c_4}{c_3}}\right)] \quad \text{, were}$$

$$c_1 = \frac{1}{E_1}\ ;\ c_2 = \frac{1}{\eta_1};\ c_3 = \frac{1}{E_2}\ ;\ c_4 = \frac{1}{\eta_2}$$

E_1, E_2, η_1, η_2 are four-parameter Burger element models from the measured deformation-time behavior of a viscoelastic material.

In Civil Engineering applications the FRP mechanical behavior is in one dimension (along one of the natural directions) and the stresses are less than forty percent of the ultimate values. These characteristics simplify FRP long-term analysis, allowing the modeling of these innovative materials through linear viscoelastic one-dimensional models. Those models are based on either mechanical analogies or experimental data.

A different approach for modeling the creep behavior of FRP materials under constant stress over a long-time period was proposed by Findley, his empirical equation is suitable for both elastic and nonelastic viscoelasticity.

Under the linear viscoelastic hypothesis Findley law can be written in terms of time-dependent creep compliance as:

$$J_{cr}^{(t)} = \frac{\varepsilon_{cr}^{(t)}}{\sigma_0} = m_1 * (\frac{t}{t_{dim}})^n \ ;$$

- m , n are material coefficient obtained from experimental data.
- t_{dim} reference time usually set to unity

In literature, many authors adopted the power function of stress to express the strain-stress-time functions for materials with non-linear viscoelastic behavior. Among them, Nutting proposed another approach to model creep behavior of viscoelastic materials is called Nutting law:

$$\varepsilon_{\mathrm{cr}}^{(t)} = B * \sigma^P * t^q$$

B, P, q are material constants obtained from experimental data

The difference between these three different modeling laws for the viscoelastic behavior of materials I'll present in the next chapter while I will show different approaches reached from these three models at GFRP laminate specimen.

4.5 Effect of temperature

Effect of temperature has a dramatic effect on the mechanical properties of polymers by exposure to elevated temperatures, the influence of temperature on the mechanical behavior of plastics is shown in Fig.15. In this figure, we can see that by increasing temperatures, materials become more ductile with a lower modulus of elasticity and higher deformation.

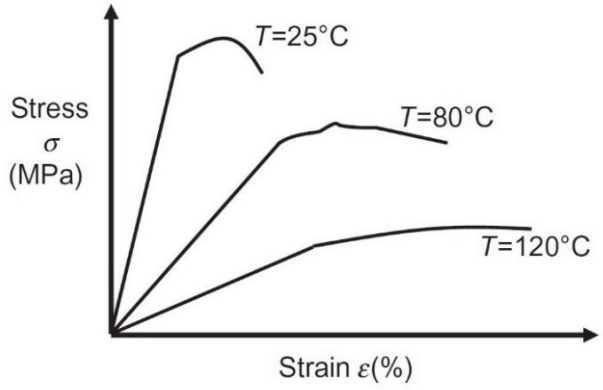


Figure 15.Effect of temperature on the stress-strain curve of a polymer; [9]

Long-term creep is generally predicted by tests are carried out at elevated temperatures, then the long-term data is predicted by using time-temperature superposition techniques. The superposition technique starts out by measuring creep rupture curves at several temperatures above the temperature for the long-term plot. Starting from the highest temperature curve, T3 shifted to the right until most of it fits over the next highest temperature, the T3+T2 curve is shifted to fit over the T1 curve and is all done, the final result is called the master curve.

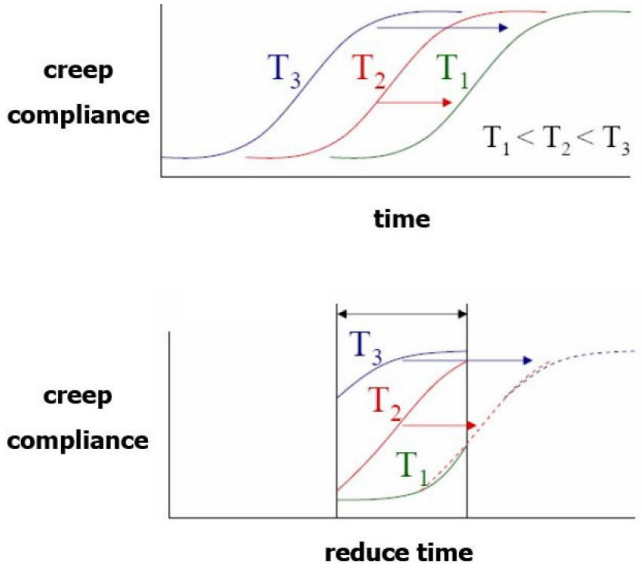


Figure 16. Time-temperature superposition; Feng 2004

5.0 Investigation of experimental approach on creep phenomena through different research papers

5.1 Evaluation of the long-term creep deformation of Epoxy Resin

Several tests were performed on short-term analyses at different temperatures with a constant load, and the corresponding results were used for creep master curve construction by means of the time-temperature superposition principle TTSP.

Tensile static and creep tests were performed on specimens made of a commercial epoxy resin, flat dog-bone samples were prepared according to ASTM D638 standard.

Mechanical properties of Epoxy resin and dimensions of dog-bone specimens are presented in Table.12 and Table.13.

Tensile strength [MPa]	Young Modulus [GPa]	Poisson's ratio [-]
28.84	10.95	0.27

Table 13.Mechanical Properties of Epoxy resin [10]

Thickness [mm]	Gage width [mm]	Gage length [mm]	Overall length [mm]	Radius of fillet [mm]	Width of grip section [mm]
5	15	70	160	12.5	35

Table 12. Dimension of dog-bone specimens [10]

Creep tests were performed by using a house designed equipment and realizing the testing system (Fig. 17).

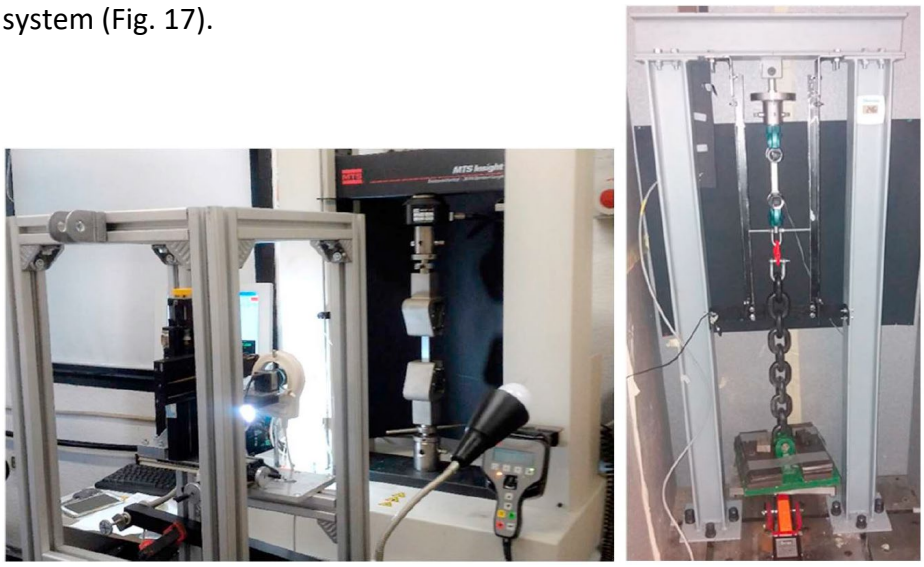


Figure 17. Experimental layout for static and creep tests [10]

The clamping system is mounted inside a steel box frame with thermal insulated chamber, and a thermostat-controlled heater is used for imposing the selected temperature field while the stress rate is applied by a sustained load.

In this research, tensile creep tests were carried out imposing the boundary conditions reported in Table 14 over a duration of about 6 days.

Specimen	Temperature [°C]	Load [N]
PC1	40	460
PC2	40	460
PC3	35	460
PC4	35	460
PC5	30	460
PC6	30	460
PC7	25	460
PC8	25	460

Table 14.Boundary conditions of creep tests [10].

$f_{fk} = 28.84 \frac{N}{mm^2}$ characteristic tensile strength

$A_f = 75mm^2$ the geometrical dimensions of the samples or effective length

A normalized sustained load corresponding to the 20% of tensile strength:

$$\sigma = 28.84 \frac{N}{mm^2} * A = 75mm^2 => Load = 2163N * 20\% \cong 460N$$

$\sigma_0 = 6.13\ MPa$ normalized sustained load

A couple of specimens was tested for each temperature level, showing good repeatability in terms of creep strains, (Fig. 18).

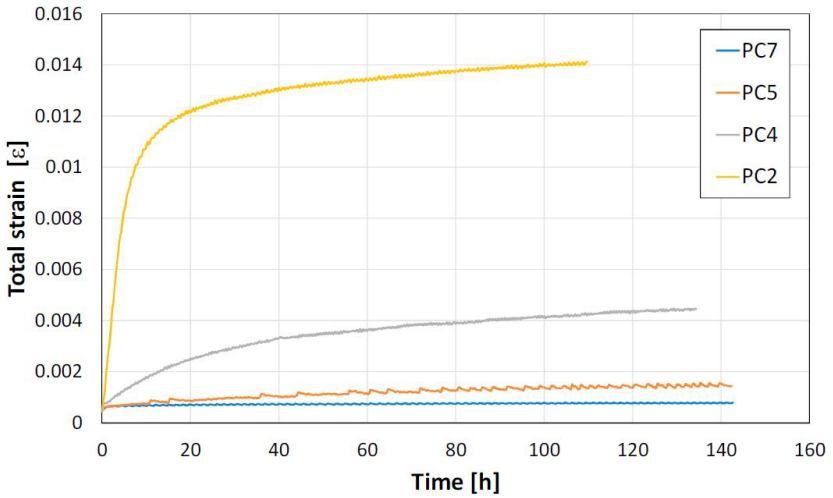


Figure 18. Total strain over time curves at various temperatures [10].

The plots of Fig. 13 show very high long-term strains at 40°C, reaching the value of about 14000 after με 5 days. The corresponding primary creep stage ends after about 1 day for the whole of the tests. Lower strain levels are recorded at 20° and 25°C without a clear transition point between primary and secondary stages.

Creep compliance (Simple Viscoelastic Model) Results

From the experimental we have $J_{(t)}$ curves the corresponding time values t_i at the temperature T_i were selected, $J_{(t)} = \frac{\varepsilon_{(t)}}{\sigma_0}$.

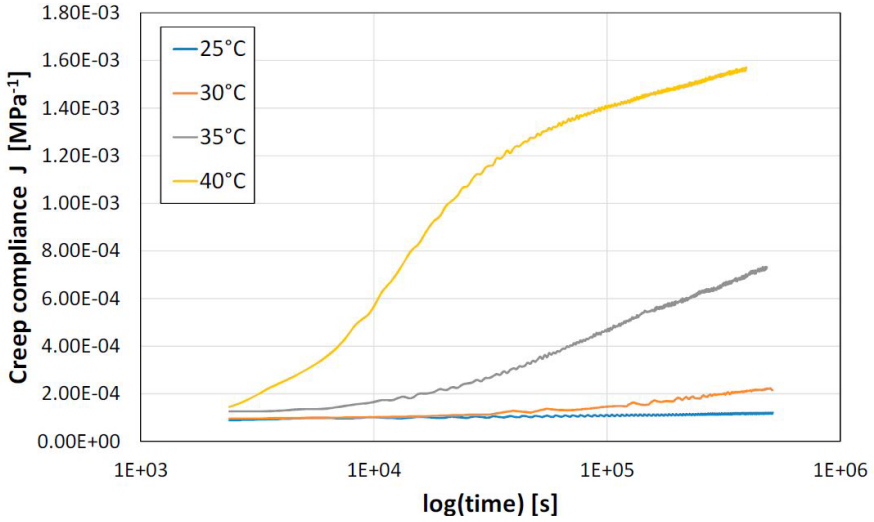


Figure 19.Creep compliance over log(time) curves at various temperatures [10].

Specifically, for the construction of the master curve at the reference temperature of 25° C, the experimental $J_{(t)}$ curves at the temperatures $T_1 = 40$ °C, $T_2 = 35$ °C, and $T_3 = 30$ °C were considered.

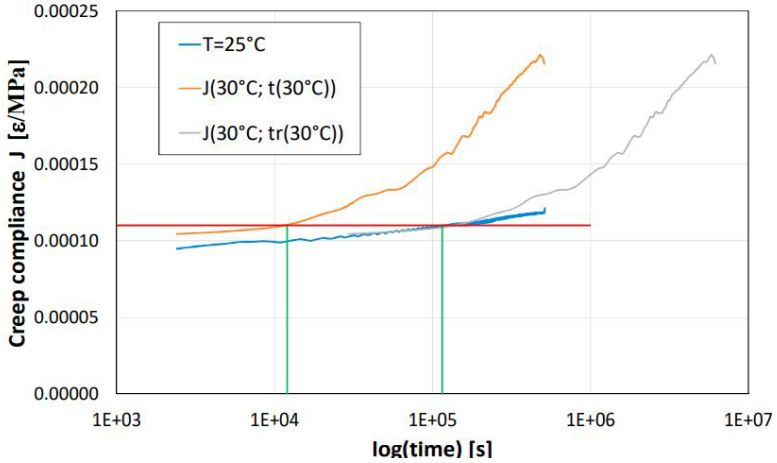


Figure 20. Shift factor evaluation at 30 °C [10]

By using TTSP time-temperature superposition principle method or known as the horizontal shift factor the long logarithmic time scale, we can predict a long-term behavior of epoxy resin from a short-term test done for example in this case for 6 days, (Fig. 20).

Shift factor was done by shifting the individual creep compliance curve at 30°C respect to temperature reference 25°C a final time of 70 days was reached, then shifting the $J_{(t)}$ curves of 35°C and 40°C a final time of about 3 and 40 years was obtained, so the creep compliance master curve for epoxy resin with reference temperature 25°C was reached, (Fig. 21).

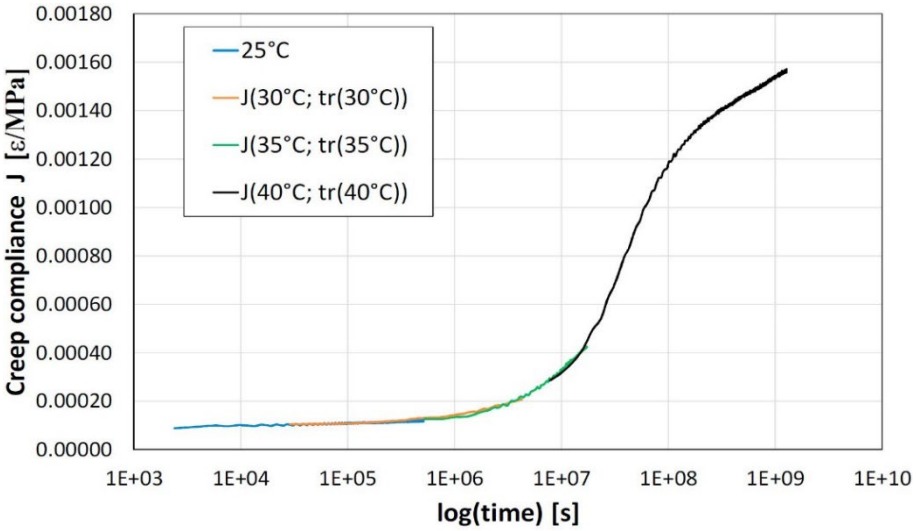


Figure 21.Creep compliance master curve at 25° C [10]

Conclusion

Creep phenomena were investigated on flat dog-bone made by commercial epoxy resin subjected to different temperatures with fixed stress corresponding to 20% of static tensile strength known as normalized sustained load 6.13 MPa was applied to obtain a stress-controlled test. By using the time-temperature superposition principle TTPS, to arrange from the short-term test result into a long-term data.

Tests at 40°C showed higher strain above 10000 με after 5 days compared to 35°C,30°C,25°C tests with 4000 με, 1400 με, 800 με this could be related to being close to the temperature of the glass transition temperature of epoxy resin 50°C.

The experimental data highlighted the strong dependence of temperature, on the long-term behavior of epoxy resin. Master curve creep increased linearly with stress, so the strain is increasing related to constant stress $\frac{\varepsilon_{(t)}}{\sigma_0}$ so normalized sustained load 6.13 MPa, from the master curve we have a value of creep compliance after 40 years $\frac{\varepsilon_{(t)}}{\sigma_0} = 0.0016$ only the strain $\varepsilon_{(t)} = 6.133 \frac{N}{mm^2} \times 0.0016$, $\varepsilon_{(t)} \cong 0.01$, it means 1%, I thought its quite small in the first view but considering that the sample it has a small cross-section, and 1% in 10 meters for example based on this master curve will be 10cm so I think it is quite a reasonable experiment.

5.2 Long-term creep behavior of resin-based polymers in the construction industry

Objective of this research paper was to develop the creep modulus master curve as a linear viscoelastic deformation for Epoxy and Vinyl ester resin applied in the construction industry. The experimental approach involves specimens at three reference material states defined as State I, State II, and State III for providing creep modulus data.

Reference State I "(fully) cured and dry state, was achieved by curing the EP at 110°C for 24h and VE at 150°C for 96h. State II standard cured as received from the commercial market and State III it was cured in the same way as a state I but they performed wet condition in this stage by leaving the EP in water with temperature 80°C for 3h and VE 30h in water with temperature 80°C, (Tab.15).

Reference state	Tempering	Moisture	Designation
ref. state I-EP	110 °C, 24 h	dry	(fully) cured & dry
ref. state I-VE	150 °C, 96 h	dry	(fully) cured & dry
ref. state II	–	as received	standard-cure – as received
ref. state III-EP	110 °C, 24h	wet	(fully) cured & wet
ref. state III-VE	150 °C, 96h	wet	(fully) cured & wet

Table 15.Overview of the reference for three specimens states [11]

The experiments were performed into a basic material characterization and material performance characterization.

- For basic material characterization they have considered differential thermal analysis DTA and dynamic mechanical analysis DMA applying these techniques, the curing behavior, and the thermomechanical behavior of those three states were examined.
- For material performance characterization include modulus measurements in tensile creep experiments were performed using a universal testing machine with a maximum force of 20 kN in a temperature chamber.

Basic material characterization DTA

Differential thermal analysis was performed at DSC 4000 by extruding the mortar of resin with weight ranging from 10 to 20 mg into a DTA pans, measurements were performed at temperatures 0°C, 23°C, and 40°C. At Epoxy resin, the main curing time decreases with increasing temperatures however the Vinyl ester resin shows significantly shorter curing time and equal influence of the curing temperature resulting in decreased main curing times for higher curing temperatures, (Fig. 22).

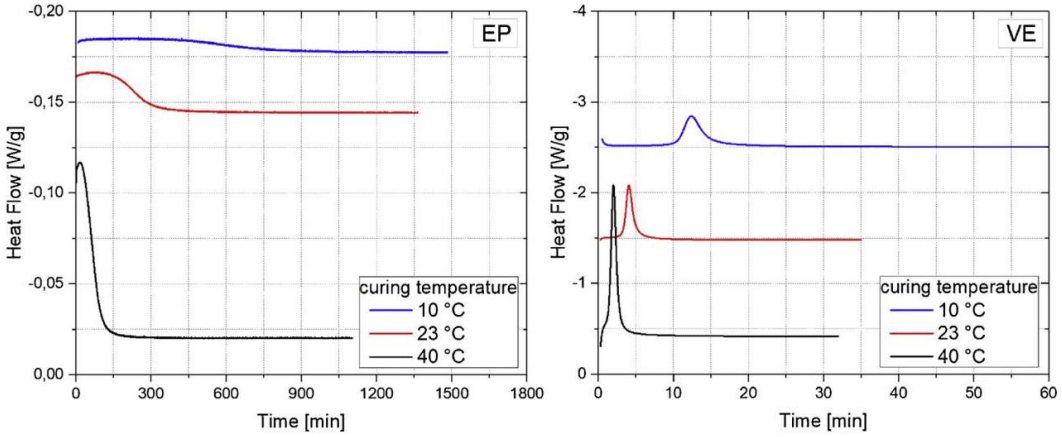


Figure 22. Heat flow over time curves for EP and VE at curing temperatures 10, 23 and 40°C [11].

The main curing times as a function of different curing temperatures are plotted in Fig.23 for EP and VE. The average main curing time of the EP resin is observed for temperatures ranging from 10 °C to 40 °C and shows a direct dependence on the temperature. VE resin shows a significantly shorter curing time compared to EP resin at a higher curing temp 40 °C decreasing the main curing time.

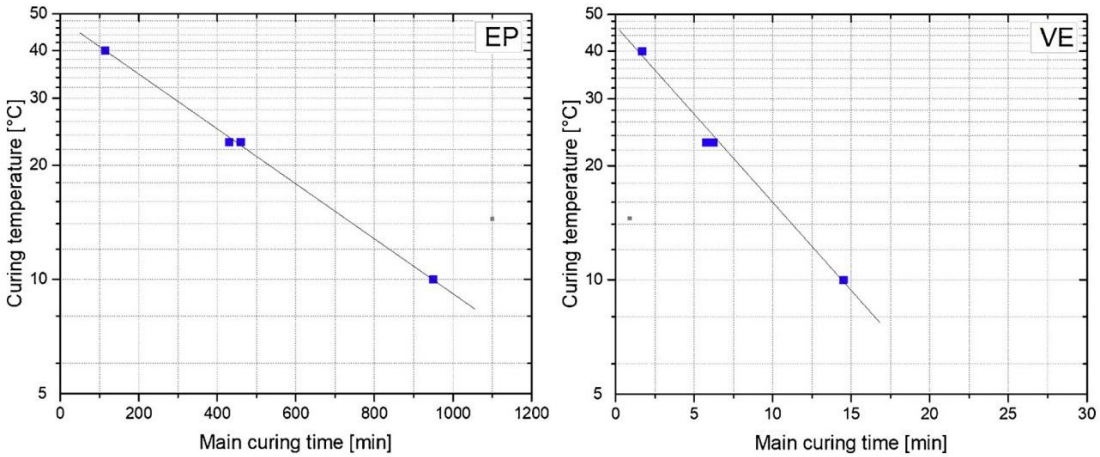


Figure 23.Main curing times at different curing temperatures for EP and VE resins [11].

Basic material characterization DMA

Dynamic mechanical analysis was performed in torsional mode with temperature ranking from 10°C to 130°C, the specimen was tested in the material reference state I and state II.

The EP resin in reference state II shows a glass transition onset temperature ($T_{g,\mathrm{onset}}$ of 55°C). By comparison, for reference state I, the $T_{g,\mathrm{onset}}$ is 82 °C.

The $T_{g,\mathrm{onset}}$ of the VE resin appears at 60 °C in reference state II, which compares to temperatures above 110 °C for reference state I.

The increase of the $T_{g,\mathrm{onset}}$ indicates a post-curing reaction taking place in both materials. For both materials, the glass transition temperatures in reference state I, are clearly above the service temperature and the testing temperatures during the creep tests, (Fig. 24).

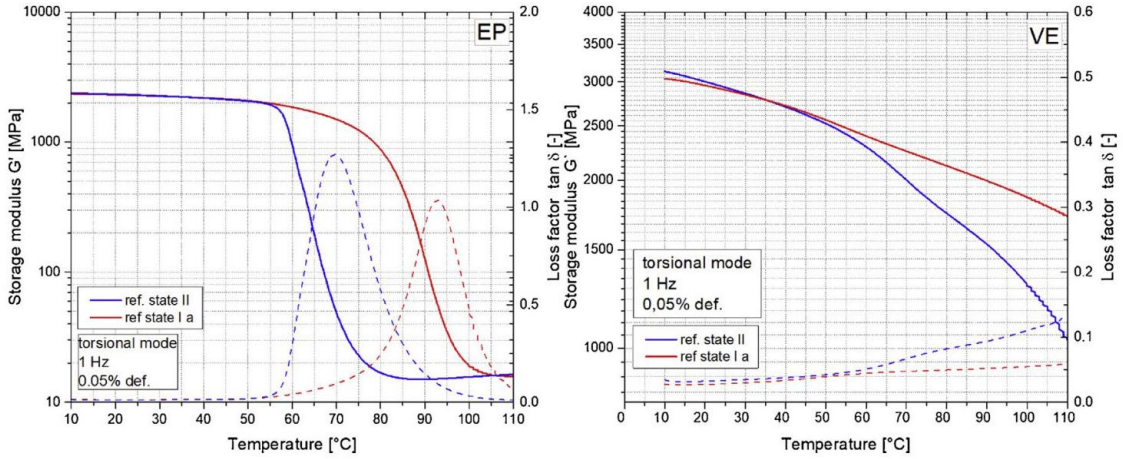


Figure 24. DMA curves measured for EP and VE resin, showing the influence of tempering on the glass transition temperature [11].

Storage modulus graph presents possible transitions archived from DMA temperature scan, most of the times we look at T_g which it shows a significant modulus drop because of gradual maintenance movement it means material is softening, (Fig. 25).

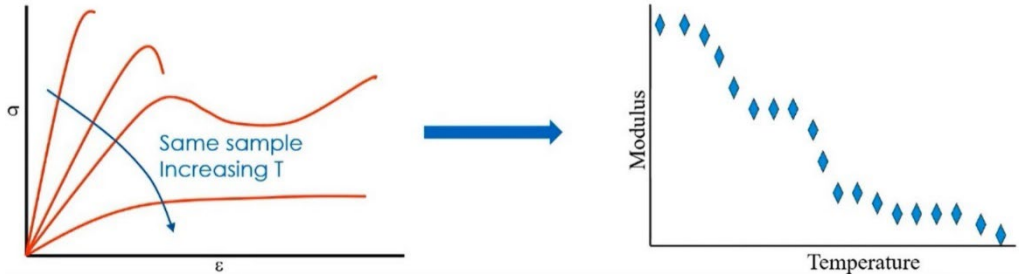


Figure 25. Polymer characterization with dynamic mechanical analysis DMA–Jun Wang Ph.D., PerkinElmer

The creep experiments were conducted with six different temperatures ranging from room temperature up to 55°C, the applied creep stress was 10MPa for EP and 7MPa for VE with test duration between 24 to 96h, the longitudinal strain was measured by extensometers and camera system, and by using DIC digital image correlation software they have evaluated the creep modulus. The creep modulus master curve of the resin system was obtained by horizontal time-temperature shifting, commonly used for the creep evaluation, (Fig. 26).

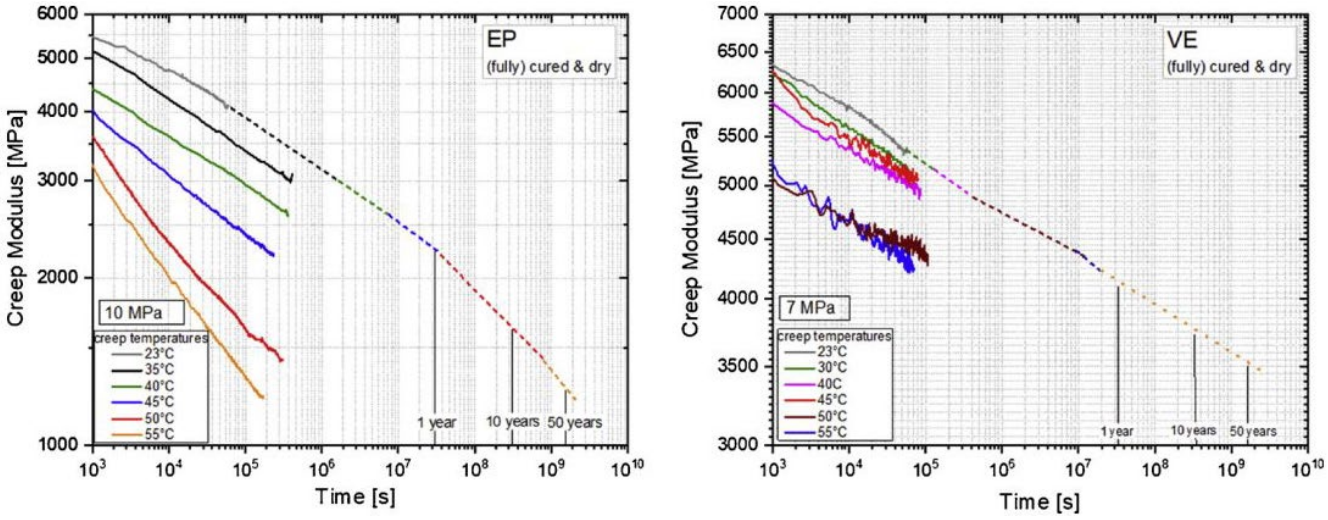


Figure 26. Logarithmic tensile creep curves for EP and VE at different temperatures in reference state I, shifted to a reference master curve at 23°C [11].

Creep modulus derived from dividing normalized sustained load known as constant load, with a longitudinal strain of the certain specimen under a specific condition (temperature) which means lower longitudinal strain higher creep modulus.

Higher temperature causes a vertical shifting of creep modulus curve to lower value, at EP resin testing temperature of 50°C and 55°C the curve shows a higher slope, based on those data of tensile creep test with temperature reference of 23°C the horizontal time-temperature shift up to 50 years were achieved and from a master curve a creep modulus of 2300 MPa for 1 year moved to 1300 MPa after 50 years.

VE specimens creep modulus 1 year moved to 4200 MPa, the modulus after 50 years was predicted by linear extrapolation of the creep modulus master curve to be 3400 MPa.

On the graph below all EP and VE, resin test results are combined into a creep modulus master curve the creep master curve for reference state I, is shifted to lower modulus values by using the reduction factors received from the short-term test. Reference state I, the secant moduli obtained with tensile test (filled red triangles) are combined with representative tensile creep test results (filled red squares) in one master curve. For EP the construction of the master curve up to 50 years was possible by time-temperature shifting, while for VE the experimental time-temperature shift master curve covered only a time up to 1 year, (Fig. 27).

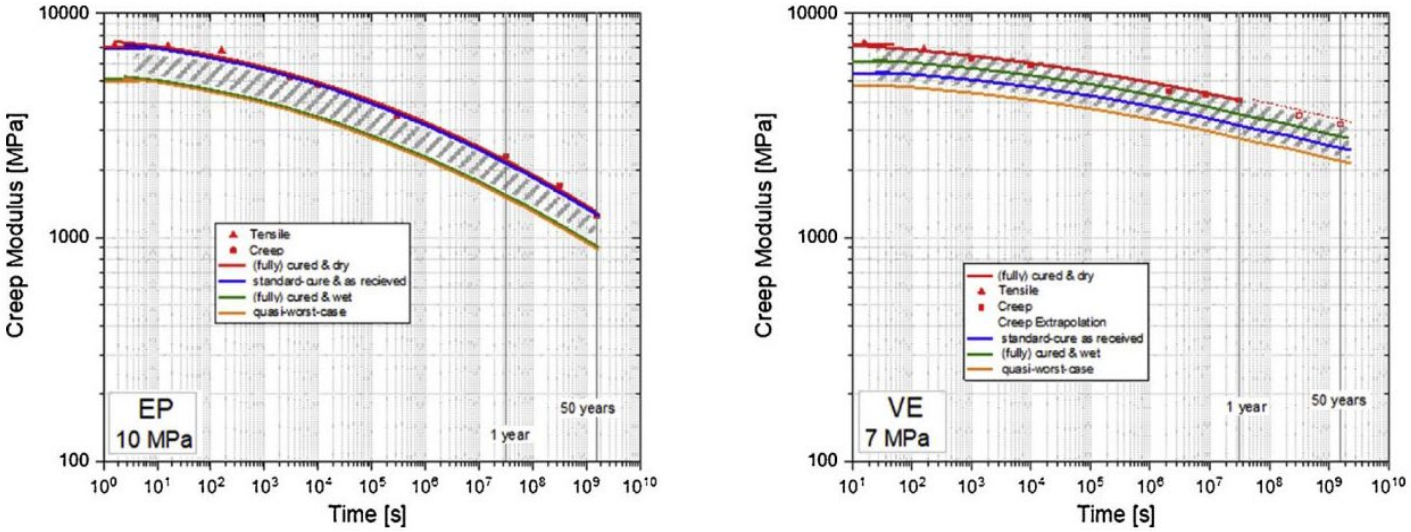


Figure 27. Creep modulus master curve for EP and VE including the reduction factor for potential creep behavior accounting for all reference states [11].

Conclusion

The creep modulus is defined by dividing the initial stress by the strain at a specific time, creep modulus value tells us something about how the material behaves if constant stress is maintained, from the final graph we can see that moving in time the creep modulus become lower it means the material is deforming more.

Based on this analysis creep modulus values for EP resin could reach a value of 1670 MPa after a year and 840 MPa at 50 years for state III and referred to state I, can achieve 2300 MPa for a year and 1200 MPa after 50 years, so we have a big difference between state I and state III. For VE resin the creep modulus values may reach 2760 MPa after a year and 2180 MPa after 50 years at state III, and at reference state I, can achieve 4200 MPa for a year and 3400 MPa after 50 years.

Two resins were tested in two different stress, creep stress was 10 MPa for EP and 7 MPa for VE this is one of the reasons why we have different results another reason I think is that VE resin is well performed on environmental durability. In alkaline environments, they are generally replacing other polyester resins on FRP products in the construction industry.

5.3 Creep behavior of GFRP laminates and their phases: Experimental investigation [7]

Long term behavior of several unidirectional glass fiber reinforced polymer (GFRP) laminates and their phases: matrix and fiber are presented in this research paper.

The short-time mechanical properties of the unidirectional GFRP, the epoxy resin specimens, and E-glass fiber samples were characterized, by performing experimental tests according to ASTM D3039 standard on four specimens for each material.

E-glass fibre mechanical properties along longitudinal direction.

E_f [GPa]	f_f [MPa]
60.00	1070

Epoxy resin mechanical properties.

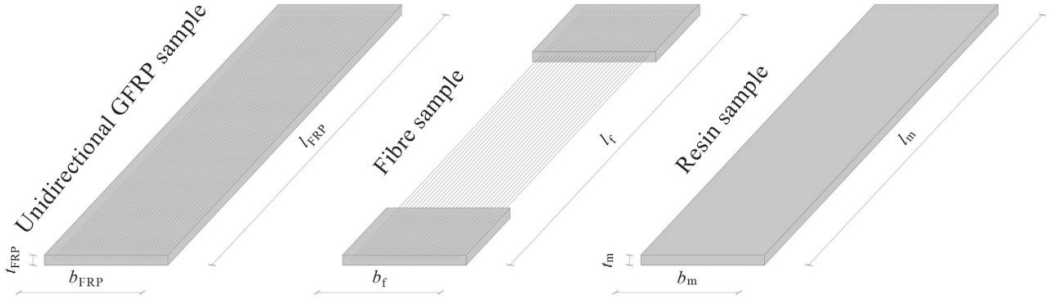
E_m [GPa]	f_m [MPa]	ν_{mu}
3.85	60	0.34

GFRP laminate mechanical properties.

E_{FRP} [GPa]	f_{FRP} [MPa]	ν_{FRP}	V_f [%]
30.50	650	0.30	50

Table 16. Mechanical Properties of E-glass fiber, Epoxy resin and GFRP specimens [7]

The geometry of the specimens used in the creep test program is depicted in Fig.28, and the dimensions of the samples, the area of the GFRP laminates, E-glass fiber samples, and the epoxy resin specimens are reported in Tab.17.



Geometrical properties of the GFRP laminate samples.

b_{FRP}	t_{FRP}	l_{FRP}	A_{FRP}
[mm]	[mm]	[mm]	[mm^2]
50.0	0.8	410.0	40.0

Geometrical and physical properties of the E-glass fibre samples.

Number of threads	Linear density of roving [tex]	b_f [mm]	t_f [mm]	l_f [mm]	A_f [mm^2]
60	300	50.0	0.42	410.0	21.0

Geometrical properties of the epoxy resin samples.

b_m	t_m	l_m	A_m
[mm]	[mm]	[mm]	[mm^2]
50.0	0.8	410.0	40.0

Figure 28. Specimens' geometry and Table 17.Geometrical properties of samples [7]

Experimental set-up and specimens in Table 18 are stress values applied to each specimen.

Experimental stress values in the GFRP specimens.

Sample ID	L1	L2	L3	L4	L5	L6
***N* [N]**	3170	3252	3302	6751	6817	6883
σ [MPa]	79.25	81.30	82.56	168.78	170.43	172.08
σ/f_{FRP} [%]	12.19	12.51	12.70	25.97	26.22	26.47

Experimental stress values in the glass fibre specimens.

Sample ID	F1	F2	F3
***N* [N]**	2772	2804	2854
σ [MPa]	132.01	133.50	135.90
σ/f_k [%]	12.34	12.48	12.70

Experimental stress values in the resin specimens.

Sample ID	M1	M2	M3	M4	M5	M6
***N* [N]**	433	499	565	651	733	783
σ [MPa]	10.83	12.48	14.13	16.27	18.32	19.58
σ/f_m [%]	18.05	20.80	23.56	27.12	30.53	32.63

Table 18.Experimental stress values at three phases of specimens [7].

Every specimen was measured by six strain gauges: $L_i - ch_j$; i= 1,2,3 laminate specimen, j-strain gauge 1,2,3...

The curve of L_i, F_i, M_i corresponds to the average value of the strain gauges at the total strain over time curves of the laminates. Experimental data was acquired for six months for almost 5000-hour, the initial stage of the test was about 700-hour for the best evolution of the primary creep.

Deformation of the E-glass fiber samples (referred to the nominal thickness of 0.42 mm, according to ISO 5084), Fig.29.

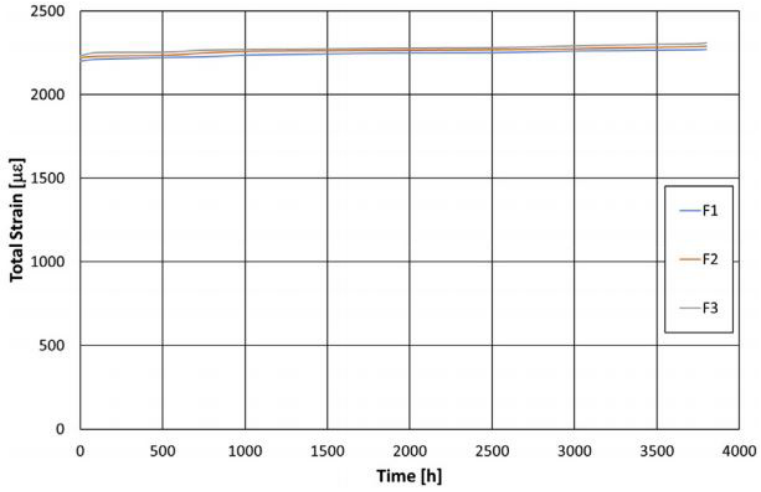


Figure 29. Deformation of the E-glass fiber samples [7].

Deformation of the Glass fiber reinforced polymer laminates, Fig.30.

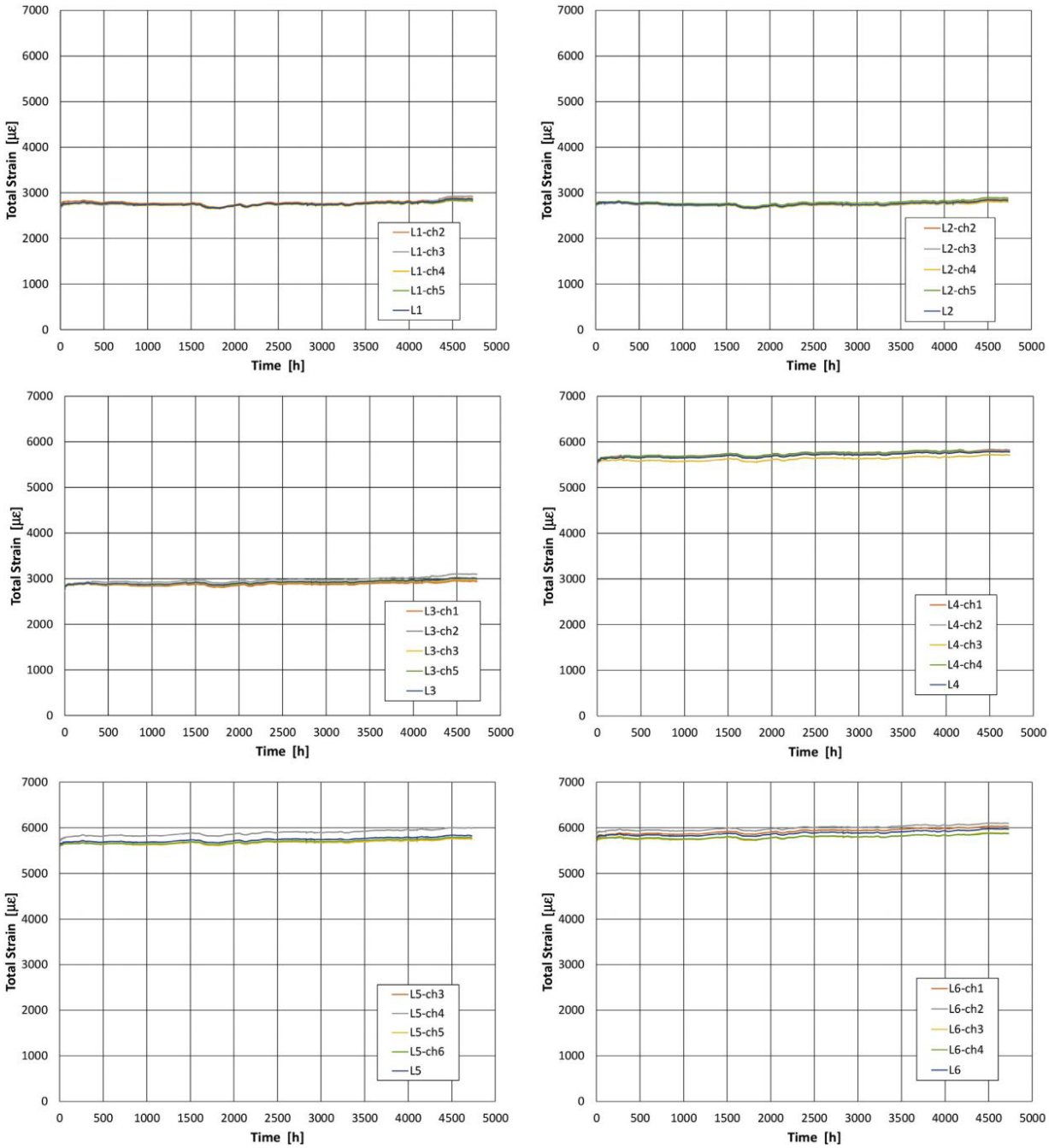


Figure 30. Deformation of the GFRP samples [7].

Deformation of the Epoxy compared to glass fiber reinforced polymer laminate and E-glass fiber sample, the Epoxy resin specimen highlighted a significant primary creep stage followed by high constant creep rate at secondary creep stage. Resin The diagrams of the M4 and M5 specimens are not presented, because they exhibited a rupture at the beginning of the creep test due to manufacturing defects, Fig.31.

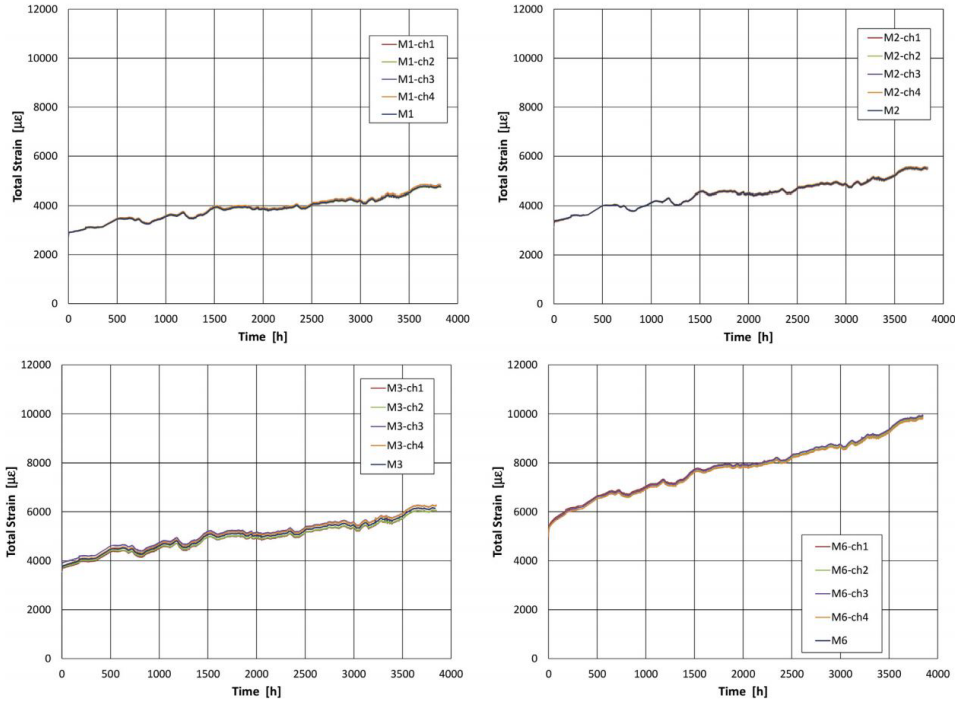


Figure 31. Deformation of the Epoxy resin specimen [7]

Increased percentage of axial deformation for Glass fiber reinforced polymer laminate, E-glass fiber sample, and Epoxy resin are reported in Table 19.

Longitudinal deformations of the GFRP samples.

Sample ID	$\varepsilon\ (t=0)$ [%]	$\varepsilon\ (t=100\ h)$ [%]	$\varepsilon\ (t=1000\ h)$ [%]	$\varepsilon\ (t=2500\ h)$ [%]	$\varepsilon\ (t=4700\ h)$ [%]	$\Delta\varepsilon/\varepsilon\ (t=0)$ [%]
L1	0.268	0.272	0.274	0.275	0.281	4.82
L2	0.270	0.276	0.277	0.278	0.284	4.88
L3	0.284	0.289	0.291	0.292	0.298	4.96
L4	0.551	0.560	0.565	0.573	0.577	4.74
L5	0.557	0.567	0.569	0.575	0.584	4.75
L6	0.573	0.582	0.582	0.590	0.599	4.57

Longitudinal deformations of the E-glass fibre samples.

Sample ID	$\varepsilon\ (t=0)$ [%]	$\varepsilon\ (t=100\ h)$ [%]	$\varepsilon\ (t=1000\ h)$ [%]	$\varepsilon\ (t=2500\ h)$ [%]	$\varepsilon\ (t=3800\ h)$ [%]	$\Delta\varepsilon/\varepsilon\ (t=0)$ [%]
F1	0.220	0.221	0.224	0.225	0.228	3.64
F2	0.222	0.223	0.226	0.227	0.231	4.05
F3	0.223	0.225	0.227	0.228	0.232	4.04

Longitudinal deformations of the resin samples.

Sample ID	$\varepsilon\ (t=0)$ [%]	$\varepsilon\ (t=100\ h)$ [%]	$\varepsilon\ (t=1000\ h)$ [%]	$\varepsilon\ (t=2500\ h)$ [%]	$\varepsilon\ (t=3800\ h)$ [%]	$\Delta\varepsilon/\varepsilon\ (t=0)$ [%]
M1	0.282	0.299	0.359	0.397	0.480	70.30
M2	0.323	0.346	0.415	0.460	0.552	70.92
M3	0.366	0.391	0.464	0.515	0.623	70.12
M6	0.507	0.576	0.699	0.815	0.996	96.52

Table 19. Longitudinal deformations of GFRP, E-glass fiber and Epoxy resin [7]

The creep compliance curves of GFRP, fibers and epoxy resins, Figs. 32-33-34

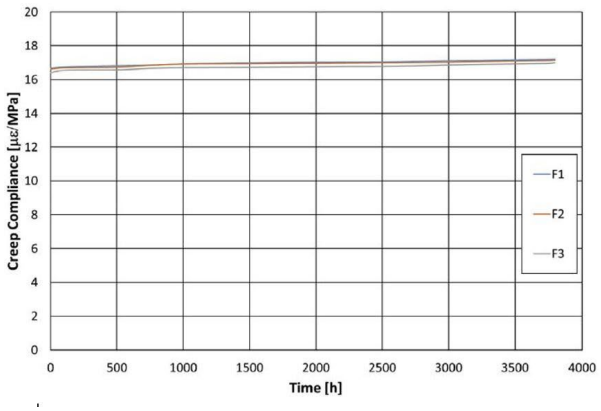


Figure 34.Creep compliance of the fibers

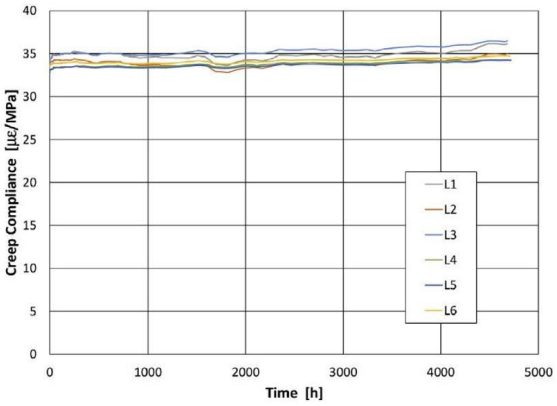


Figure 32.Creep compliance of the laminates

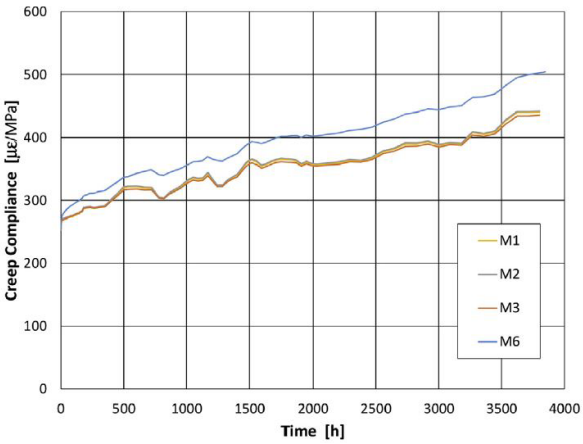


Figure 33. Creep compliance of the Epoxy resin

Conclusion

The laminates and fibers specimens have shown very small significant changes of the creep compliance curves between samples, because of applied stress level, the specimen M6 is not similar to M1, M2, and M3.

From a mechanical point of view, the GFRP laminates and the fiber samples have exhibited a linear viscoelastic behavior, while a non-linear creep behavior has been observed for the resin specimens.

The experimental results have highlighted a significant increase of longitudinal strains in the Epoxy resin specimen after more than five months and a limited strain deformation for Glass fiber reinforced polymer laminate and E-glass fiber.

The percentage strain increase of the resins after 3800 h varies from 70% to about 100%, whilst the corresponding percentage variation of the laminates and fibers is less than 5%. reported in Table 19.

5.4 Creep phenomena in FRP materials

In this research are presented results of a creep test on several Glass fiber reinforced polymers GFRP laminates and their phases matrix and fiber, subjected to different stress values under constant environmental conditions.

The mechanical properties of the GFRP laminates, polyester resin specimens, and glass fiber samples are summarized, in Table 20.

GFRP laminate mechanical properties reported in technical sheet.

E_{FRP} [GPa]	f_{FRPk} [MPa]	ε_{FRPu} [%]	V_f [%]
48.972	994.28	2.03	65.00

Polyester resin mechanical properties reported in technical sheet.

E_m [GPa]	f_{mk} [MPa]	ε_{mu} [%]
3.00	67.00	2.03

Glass fibre mechanical properties reported in technical sheet.

E_f [GPa]	f_{fk} [MPa]	ε_{fu} [%]
72.50	2500.00	6.57

Table 20.Mechanical Properties of GFRP specimens, Polyester resin, and E-glass fiber [12].

- E_{FRP}, E_M, E_f the longitudinal Young modulus
- f_{FRPk}, f_{mk}, f_{fk} *the* characteristic tensile strength
- V_f the volumetric fraction of fibres and $\varepsilon_{FRPu}, \varepsilon_{mu}, \varepsilon_{fu}$ ultimate strain

The geometrical properties of the GFRP laminates, polyester resin specimens, and glass fiber samples are reported, in Table 21.

Geometrical properties of the GFRP laminate samples.

Sample ID	b_{FRP} [mm]	t_{FRP} [mm]	A_{FRP} [mm^2]
1G	15.00	1.60	24.00
2G	20.00	1.60	32.00
3G	25.00	1.60	40.00

Geometrical properties of the polyester resin samples.

Sample ID	l_m [mm]	d_m [mm]	A_m [mm^2]
1P_i	40.0	10.0	78.54
2P_i	40.0	7.8	47.78

Geometrical properties of the glass fibre samples.

Sample ID	Number of rovings	A_f [mm^2]
1F	4.00	7.52
2F	6.00	11.28
3F	10.00	18.80

Table 21. Geometrical properties of GFRP specimens, Polyester resin, and E-glass fiber [12]

- A_{FRP}, A_m, A_f the geometrical dimensions of the samples or effective length.

Two metallic devices were used for the tests on glass fibers and GFRP laminates, each test device is made up of a horizontal beam, acting as the lever arm, with a set of samples and the necessary weight, required to generate the axial dead load. The Creep tests were carried out for different stress values at constant room temperatures of 20°C, (Tab.22).

Experimental stress values in fibre and GFRP specimens.

Sample ID	1F	2F	3F	1G	2G	3G
N (N)	3000	3000	3000	3000	3000	3000
σ (MPa)	159.57	265.96	398.94	75.00	93.75	125.00
σ/f_k (%)	6.38	10.64	15.96	7.55	9.42	12.58

Experimental stress values in resin specimens.

Sample ID	1P_1	1P_2	2P_1	2P_2
N (N)	430	430	430	430
σ (MPa)	5.56	5.56	9.14	9.14
σ/f_{mk} (%)	8.30	8.30	13.64	13.64

Table 22. Experimental stress values at three phases of specimens [12]

The values of the axial deformation recorded over time for E-fiber samples and Glass fiber reinforced polymers GFRP laminates are plotted in Figure 35.

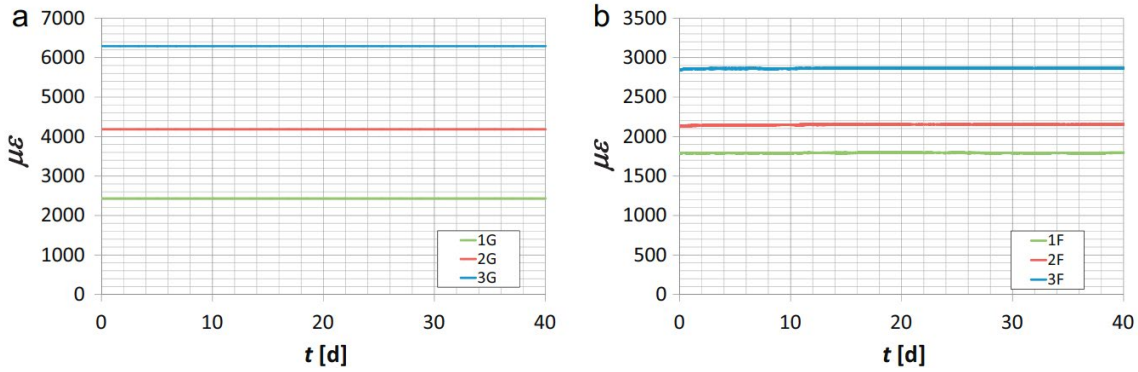


Figure 35. Deformation of the glass fibers and deformations of the GFRP samples [12]

Longitudinal deformation for glass fibers over time almost negligible and a limited deferred deformation in GFRP specimens, more specifically the increase percentage of the axial deformation for E glass and GFRP are reported in Table 23.

Longitudinal deformations of the fibre samples (Device 1).

Sample ID	σ [MPa]	σ/f_{fk} [%]	$\varepsilon(t=0)$ [%]	$\varepsilon(t=40\,\mathrm{d})$ [%]	$\Delta\varepsilon/\varepsilon(t=0)$ [%]
1F	159.57	6.38	0.24	0.24	–
2F	265.96	10.64	0.42	0.42	–
3F	398.94	15.96	0.63	0.63	–

Longitudinal deformations of the GFRP samples (Device 2).

Sample ID	σ [MPa]	σ/f_{FRPk} [%]	$\varepsilon(t=0)$ [%]	$\varepsilon\,(t=45\,\mathrm{d})$ [%]	$\Delta\varepsilon/\varepsilon\,(t=0)$ [%]
1G	75.00	7.55	0.179	0.180	0.616
2G	93.75	9.42	0.213	0.216	1.599
3G	125.00	12.58	0.284	0.287	1.234

Table 23. Longitudinal deformation of fiber and GFRP [12]

The values of the axial deformation recorded over time in Polyester resin is plotted are Figure 36.

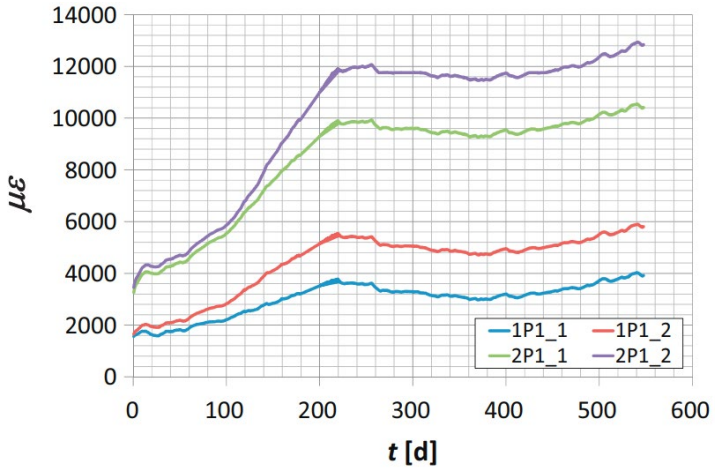


Figure 36. Deformation of the Polyester resin [12]

The experimental results have shown an increase in the longitudinal deformation exhibited by polyester resin samples over time from the early hours of observation reported in Table 24.

Longitudinal deformations of the resin samples (Device 3).

Column	Sample ID	σ[MPa]	σ/f_{mk} [%]	ε ($t=0$) [%]	ε ($t=547$ d)	$\Delta\varepsilon/\varepsilon$ ($t=0$) [%]
1	1P_1	5.56	8.30	0.149	0.3919	150
	1P_2	5.56	8.30	0.150	0.5805	251
2	2P_1	9.14	13.64	0.271	1.041	219
	2P_2	9.14	13.64	0.287	1.284	271

Table 24. Longitudinal deformation of Polyester resin [12]

Conclusion

Several creep tests have been performed for different stress values at a constant temperature so the experimental results of creep phenomena in GFRP pultruded laminates and their phases are presented. The experimental results have shown a significant increase in the longitudinal deformation at polyester resin samples over the time from the early hours of observation, negligible strains in glass fibers, and limited deferred deformation for GFRP specimens less than 2%.

From research papers 5.3 and 5.4 about creep phenomena of GFRP and phases matrix and fiber, in 5.3 we have Epoxy resin as a matrix and at 5.4 we have Polyester resin as a matrix, both of the specimens are loaded approximately with the same load and comparing M1,M2 epoxy resins and 1P_2, 2P_2 polyester resins we can see that polyester resins reach almost 10000 micro strains over the time of 200 days however Epoxy resins reach almost 6000 micro strains over the time of 150 days so we can see that Epoxy resin is performing better than Polyester resin on experimental testes about creep phenomena.

5.5 Experimental investigation and numerical modeling of creep response of glass fiber reinforced polymer composites

In field of civil engineering, FRP composites are mainly used for strengthening existing reinforced concrete and masonry elements, as well as in new structures in different shapes.

Durability and reliability of composite structures are strongly affected by material viscosity, and rheological properties of FRP-s can influence the long-term performance of structural components.

In this experimental investigation, the tests were continued for about 42 months, from the previous research paper they have done, presented in 5.3.

Experimental creep tests

Six GFRP specimens, made of unidirectional E-glass fibers and epoxy matrix, were tested at room temperature under different stress levels. The unidirectional E-glass fiber has a single orientation 0^o, produced with technology warp-weft.

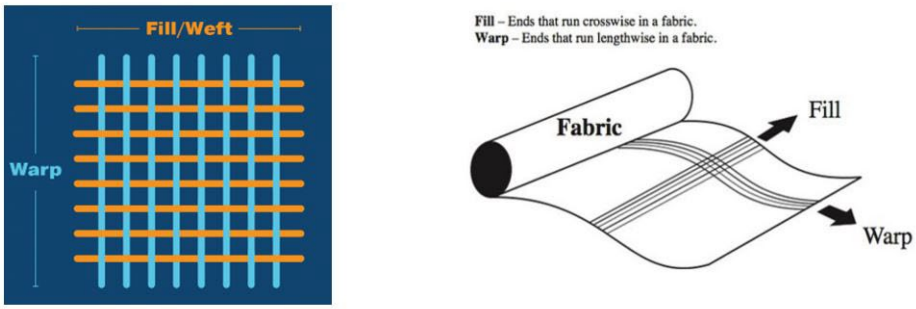


Figure 37. Technology used to produce GFRP, warp-weft [13]

A constant load was applied to the specimens over time by leverage systems, equipped with multichannel strain gage data, the effectiveness of temperature control over the whole test duration was monitored by means of thermocouples located close to the specimens, Fig.38.

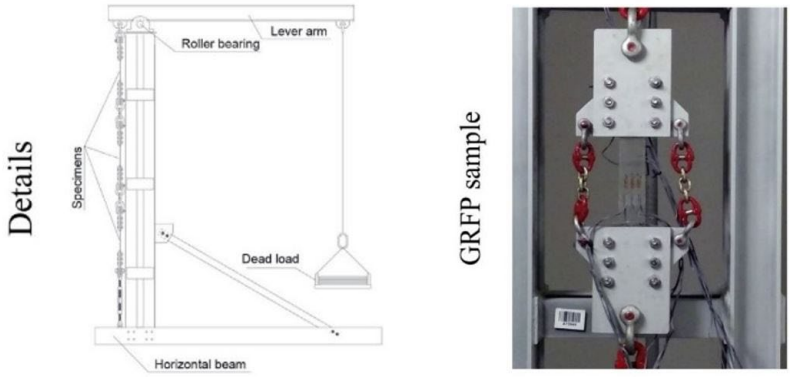
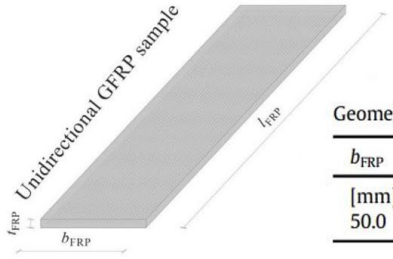


Figure 38. Constant load applied by Leverage systems [13]

Different properties of GFRP specimens

- Geometrical properties of the GFRP laminate samples



Geometrical properties of the GFRP laminate samples.

b_{FRP}	t_{FRP}	l_{FRP}	A_{FRP}
[mm]	[mm]	[mm]	[mm^2]
50.0	0.8	410.0	40.0

Figure 39. Geometrical properties of the GFRP laminate samples

- GFRP laminate mechanical properties

First by performing short-time tests of GFRP laminates they have obtained mechanical properties like Young modulus, Tensile strength, and Fiber volume ratio.

GFRP laminate mechanical properties.

E_{FRP} [GPa]	f_{FRP} [MPa]	ν_{FRP}	V_f [%]
30.50	650	0.30	50

Figure 40. GFRP laminate mechanical properties

The stress level σ_0 applied to each sample and the respective percentage of the tensile strength, σ/f_{FRP}, are reported in Table 26.

TABLE 1 Stress levels applied to GFRP specimens

Sample ID	L1	L2	L3	L4	L5	L6
σ_0 ($\pm$1 MPa)	79	81	83	169	170	172
σ_0/f_{FRP} (%)	12.2	12.5	12.7	26.0	26.2	26.5

Table 25. Stress levels applied to GFRP specimens

The plots of total strain versus time of laminate specimens are shown in Figure 41. The nomenclature $L_i - ch_j$; $i = 1,2,3$ laminate specimen , j $= 1,2,3$ strain gauge.

For each specimen, the data from strain gauges that failed before the end of the test, due to the embrittlement of bonding with an edge, were excluded from the calculus of the average strain value, and therefore, they have been removed from Figure 41.

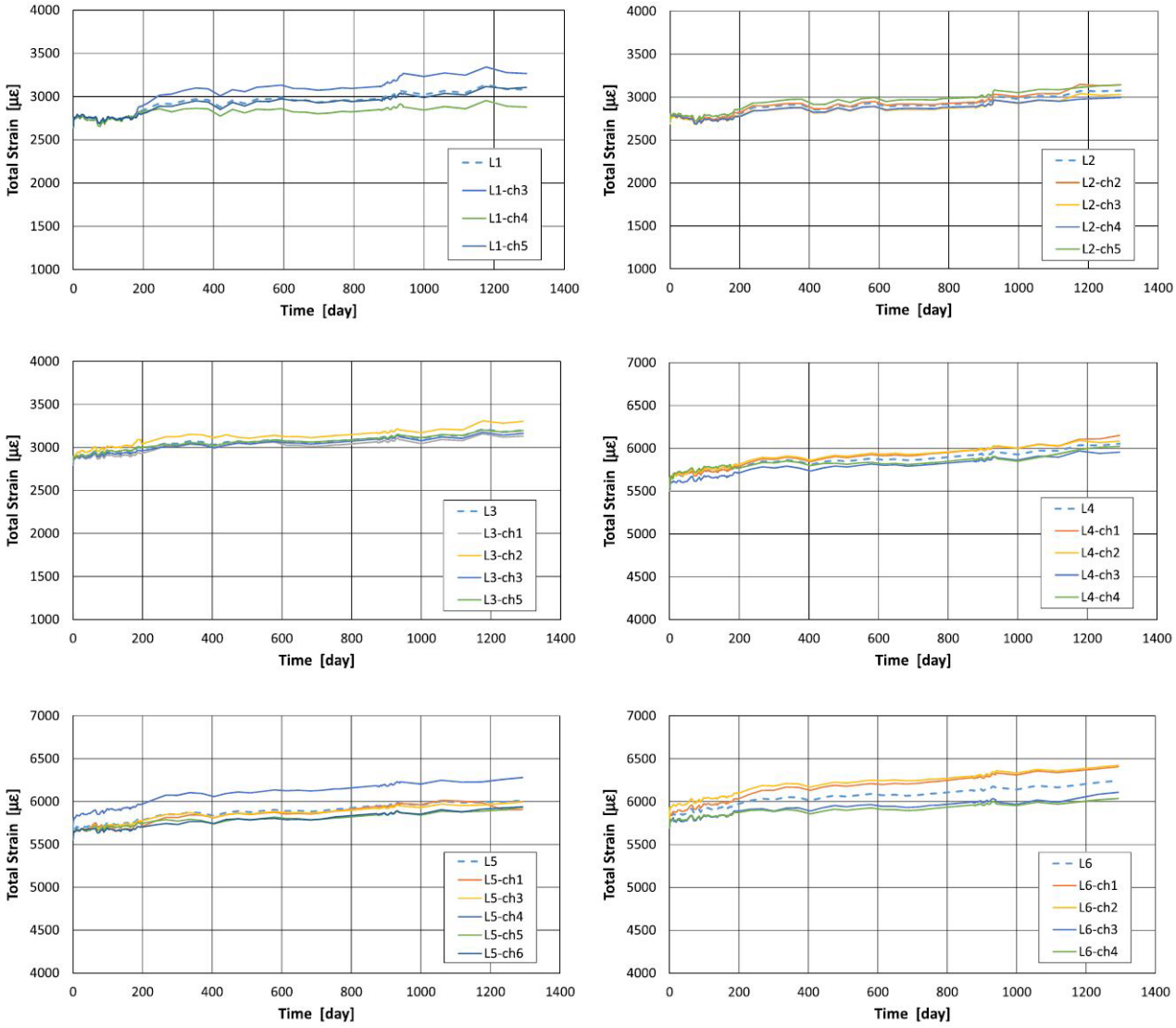


Figure 41. Total strains of the GFRP laminates [13]

The plots showed a short primary creep stage, more easily highlighted by the data at higher stress. The tertiary phase was not reached. The percentage variations of average longitudinal strains at different times for each GFRP specimen are displayed in Table 26.

- The plots of total strain

Sample ID	ε ($t = 0$) ($\pm 5\ \mu\varepsilon$)	ε ($t = 12\ m.$) ($\pm 5\ \mu\varepsilon$)	ε ($t = 24\ m.$) ($\pm 5\ \mu\varepsilon$)	ε ($t = 36\ m.$) ($\pm 5\ \mu\varepsilon$)	ε ($t = 42\ m.$) ($\pm 5\ \mu\varepsilon$)	$\Delta\varepsilon/\varepsilon$ ($t = 0$) (%)
L1	2677	2896	2934	3042	3066	14.6
L2	2704	2911	2901	3016	3078	13.8
L3	2839	3064	3065	3143	3198	12.7
L4	5509	5845	5868	5973	6053	9.9
L5	5571	5865	5893	6005	6072	9.0
L6	5726	6049	6075	6186	6244	9.1

Table 26. Axial deformations of the GFRP specimens [13]

The experimental creep outcomes showed that after about 42 months of loading, the difference between a longitudinal final strain and elastic strain Δε of the GFRP composite samples ranges from 9% to nearly 14%.

Although the creep strain rates of laminates are quite lower than those of the matrix phase from the previous research paper, it was clear that the deformations in GFRP composite laminate are not negligible especially for strengthening applications over a long time.

The trends of resulting creep compliance values are plotted in Figure 42. The maximum variation of creep compliances with reference to the corresponding mean value is smaller than 5%.

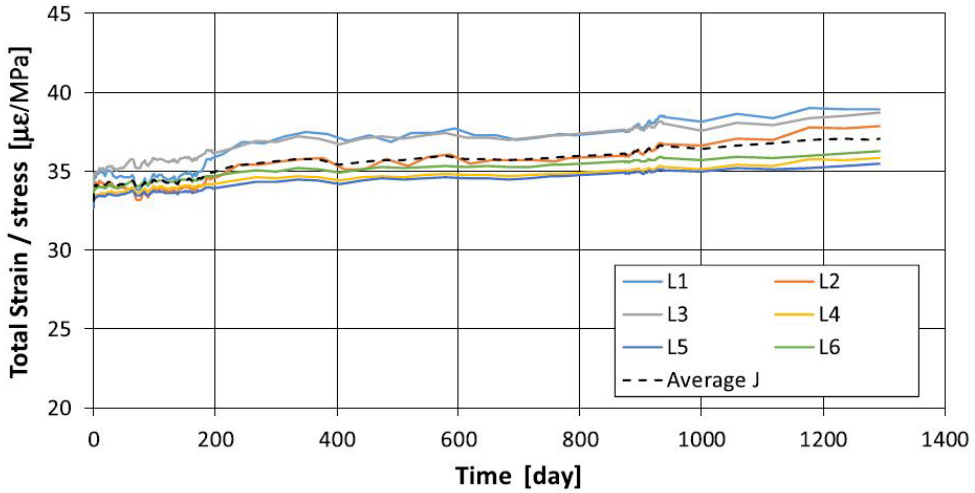


Figure 42. Creep compliance curves of the GFRP laminates [13]

The experiment pointed out an almost linear viscoelastic behavior of the GFRP specimens.

Within the field of linear viscoelasticity, the Burgers rheological law can be usefully adopted for modeling the creep behavior of GFRP laminates.

The linear viscoelastic creep strain, as a function of time t, is related to the applied stress σ_0 and material properties:

$$\varepsilon_{(t)} = \sigma_0[\left(\frac{1}{E_1} + \frac{t}{\eta_1}\right) + \frac{1}{E_2}\left(1 - e^{-t\frac{E_2}{\eta_2}}\right)]$$

$$\varepsilon_{(t)} = \sigma_0[c_1 + c_2 * t + c_3\left(1 - e^{-t\frac{c_4}{c_3}}\right)] \quad \text{, were}$$

$$c_1 = \frac{1}{E_1}\ ;\ c_2 = \frac{1}{\eta_1};\ c_3 = \frac{1}{E_2}\ ;\ c_4 = \frac{1}{\eta_2}$$

E_1, E_2, η_1, η_2 are four-parameter Burger element model from the measured deformation-time behavior of a viscoelastic material.

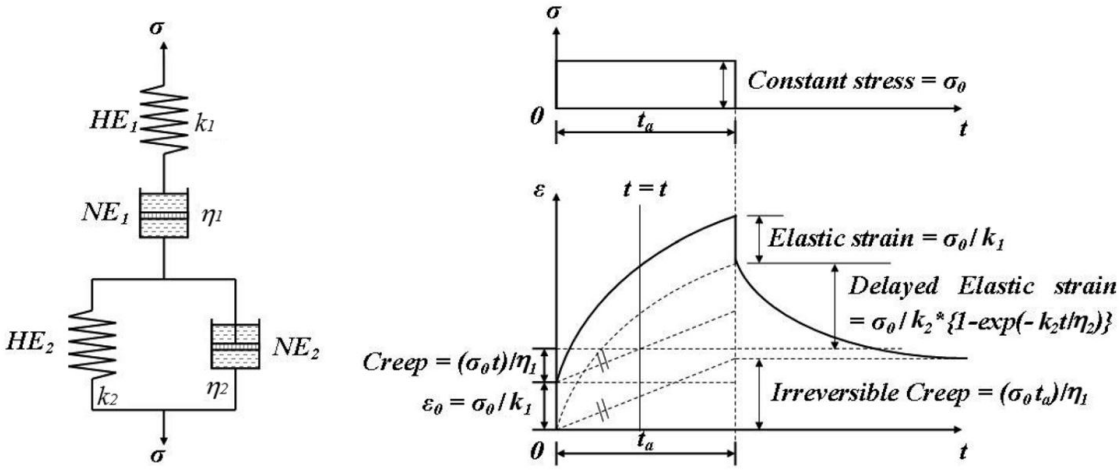


Figure 43. Rheological model and the response of a four-parameter Burger element.

- Value of c_1, c_2, c_3, c_4 are reported in Table 27.

c_1 (MPa^{-1})	c_2 (MPa^{-1} day^{-1})	c_3 (MPa^{-1})	c_4 (MPa^{-1} day^{-1})
$3.33 \cdot 10^{-5}$	$2.47 \cdot 10^{-9}$	$8.01 \cdot 10^{-7}$	$1.39 \cdot 10^{-6}$

Table 27. Burger's coefficients for the laminates

A different approach for modeling the creep behavior of FRP materials under constant stress over a long-time period was proposed by Findley, his empirical equation is suitable for both elastic and nonelastic viscoelasticity. Under the linear viscoelastic hypothesis, Findlay law can be written in terms of time-dependent creep compliance as: $J_{cr}^{(t)} = \frac{\varepsilon_{cr}^{(t)}}{\sigma_0} = m_1 * (\frac{t}{t_{dim}})^n$;

- m , n are material coefficient obtained from experimental data
- t_{dim} reference time usually set to unity

m_1	n
$7.65 \cdot 10^{-7}$	$2.06 \cdot 10^{-1}$

Table 28. Parameters of Findley's creep law, time is in days

Another approach was done by Nutting: $\varepsilon_{cr}^{(t)} = B * \sigma^P * t^q$

B, P, q are material constants obtained from experimental data, are reported, Tab.29.

B	p	q
$6.59 \cdot 10^{-6}$	$4.18 \cdot 10^{-1}$	$2.84 \cdot 10^{-1}$

Table 29. Coefficients of Nutting model, time is in days

Comparison of total strains from predictive models and experimental samples results for L2 and L6 are plotted in Figure 44.

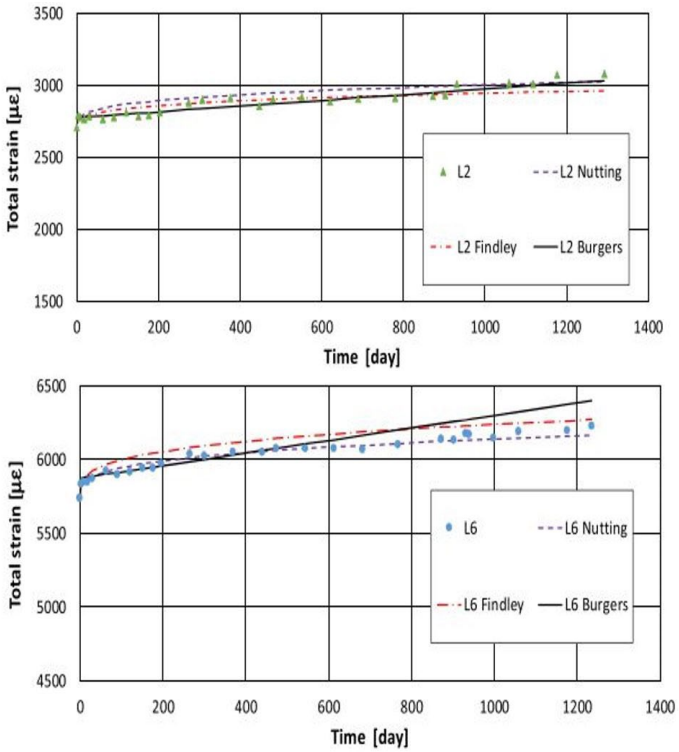


Figure 44. Comparison of predicted total strains for L2 and L6 specimens, respectively.

Conclusion

Despite experimental data dispersion results from low stress level exposure, the Burgers model described the whole creep phenomena quite well.

From Findley empirical law gave a satisfactory prediction until 900 days, then an underestimation of around 3.5% was pointed out.

The nonlinear viscoelastic model by nutting resulted less suitable respect to the other investigated relationship at the sample L6 with a higher stress level of GFRP laminate ultimate strength, the predictions represented by Burger's equation were satisfactory for about 500 days.

The difference in total strain after 1300 days is about 3% for specimen L6. At the same time, we can see that the linear viscoelastic Findley model overestimated all the data points, showing less accuracy for short-term creep stage for L6 the nutting law was instead suitable for the whole test duration, but strain prediction where underestimated by about 1% at the finale period at the range from 900 to 1300 days, at the same range of data the final result from Findlay law was overestimated for around 1%.

In Figure 45, it is shown a comparison between the predicted strains for GFRP laminated obtained by the Burgers model considering a test duration of 6 and 42 months respectively.

For this comparison, we can see a difference in the percentage of 6% after 1300 days and even smaller at sample L6 at Burgers model prediction for 42 months.

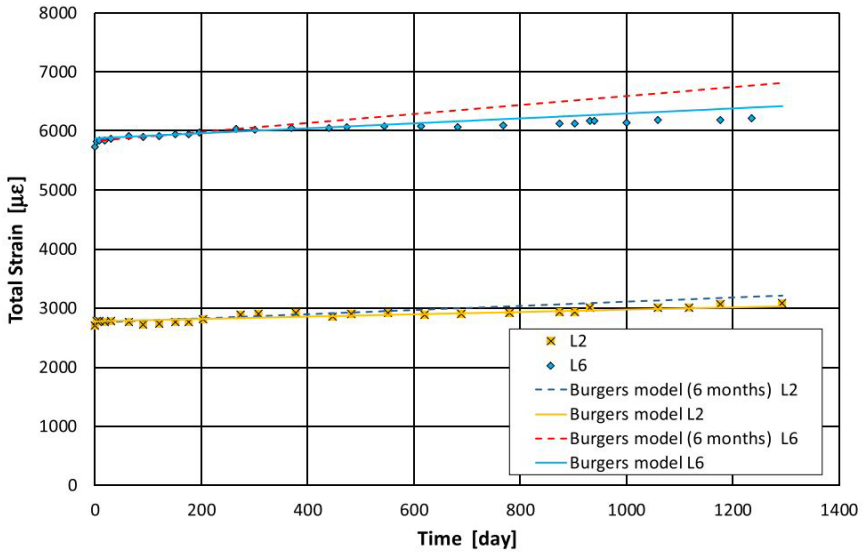


Figure 45. Comparison between models by interpolating data set of 6 and 42-month test duration [13].

Long-term creep behavior of unidirectional GFRP laminates was experimentally investigated under different uniaxial loading conditions for a time of 42 months at controlled room temperature.

Creep strain increments ranging from 9% to 14% were recorded. The mechanical Burgers model was found to be better suited for describing the long-term creep behavior than Findley and Nutting equations.

In conclusion, from the previous considerations, the Burgers model resulted as the most effective for the description of the long-term creep data of tested GFRP laminate.

6.0 Crossing data from different research papers and Conclusion

6.1 Difference between Epoxy and Polyester resins under different normalized sustained load

At the production industry both Epoxy and Polyester resins are the most popular resins used for a wide range of applications, in this case, both of them are used as a matrix of Glass fiber reinforced polymer composites GFRP.

From Research papers 5.3 and 5.4 about creep phenomena at Glass fiber reinforced polymers GFRP laminates and their phases: matrix and fiber, difference between Epoxy and Polyester resins for 150 days or 3600 hours under different normalized sustained load is presented.

Both experimental data investigation has highlighted significant deferred deformation in the Epoxy resin and Polyester resin over the time, and a limited strain deformation on E-fiber glass and GFRP laminate almost negligible, (Fig. 46).

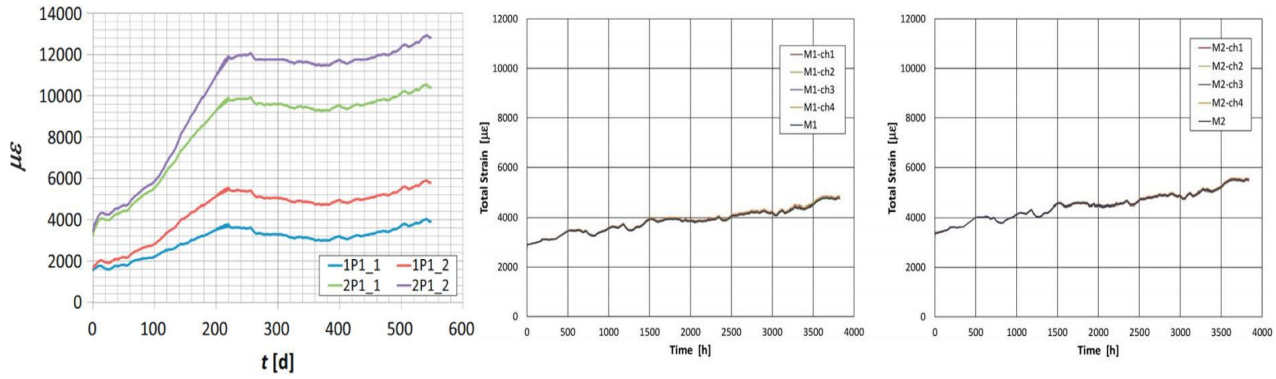


Figure 46. Comparison of total strain over time between Polyester resin and Epoxy resin

PL1 and PL2 are the sample ID for Polyester resin and EP1 and EP2 for Epoxy resin both of them are having a similar dimension of the specimen.

This comparison, two resins Epoxy and Polyester are in a range of normalized sustained load between $5\ to\ 20\%\ (\sigma_0/f_m)$, and from the testes, we have a result of diagram of strain over the time for 0 hours, 1000 hours, 2500 hours, and 3600 hours that is approximately 150 days, Tab.30.

Matrix 1	Sample ID	σ_0/f_m (%)	ε, 0h (PL)	ε, 100h (PL)	ε, 1000h (PL)	ε, 2500h (PL)	ε, 3600h (PL)
Polyester Resin (1)	PL1	8.3	0.15	0.1532	0.1967	0.2439	0.278
Polyester Resin (2)	PL2	13.64	0.287	0.2945	0.3779	0.4868	0.5654
Matrix 2	Sample ID	σ_0/f_m (%)	ε, 0h (EP)	ε, 100h (EP)	ε, 1000h (EP)	ε, 2500h (EP)	ε, 3600h (EP)
Epoxy Resin (1)	EP1	18.05	0.282	0.303	0.359	0.397	0.48
Epoxy Resin (2)	EP2	20.8	0.323	0.346	0.415	0.46	0.552

Table 30. Axial deformations of Polyester and Epoxy resin over a specific time

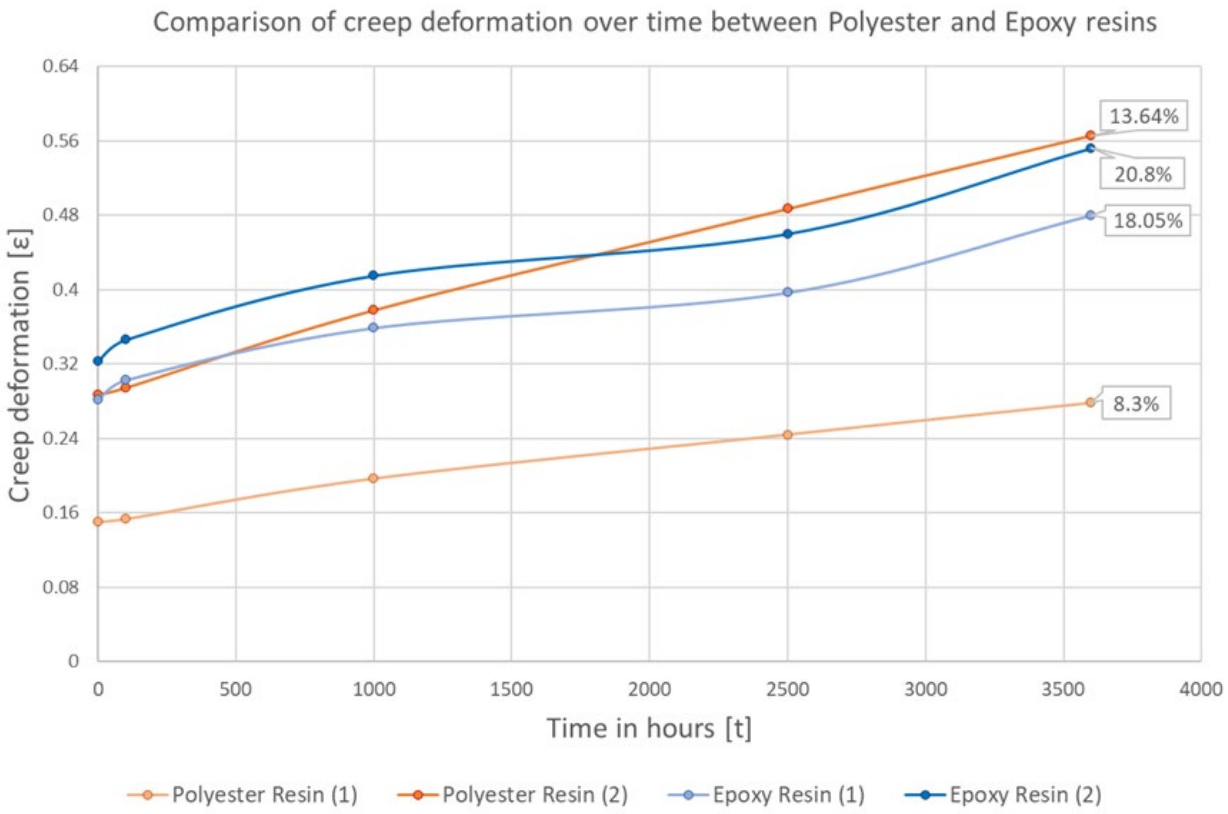


Figure 47. Difference between Epoxy and Polyester resins after 3600 hours

The nomenclatures:

- Polyester Resin (1) referred to the results of Polyester Resin, under 8.30% sustained load on long-term analyses of creep phenomena
- Polyester Resin (2) referred to the results of Polyester Resin, under 13.64% sustained load on long-term analyses of creep phenomena
- Epoxy Resin (1) referred to the results of Epoxy resin, under 18.05% sustained load on long-term analyses of creep phenomena
- Epoxy Resin (2) referred to the results of Epoxy resin, under 20.8% sustained load on long-term analyses of creep phenomena

From early hours observation, the experimental results have highlighted a significant increase of the axial creep deformation for both resins.

A high difference in creep deformation over the time is highlighted between Polyester resin (1) under a sustained load 8.3% (σ_0/f_m) and Polyester resin (2) under a sustained load 13.6% (σ_0/f_m), creep deformation at Polyester resin (2) are almost double compared to Polyester resin (1). While low differences in creep deformation are shown between Epoxy resin (1) and Epoxy resin (2).

Crossing those data, we can see that creep deformation in Polyester resin (2) under a sustained load of 13.6%, after 600 hours of testing is overlapping the Epoxy resin (1) with sustained load 18.05% and after 2000 hours of testing the Polyester (1) is overlapping even the Epoxy resin (2) with higher sustained 20.8%.

From these analyses between these two resins can be noticed that Epoxy resin is performing better than Polyester resin. Considering that matrix is the component where creep deformations are higher rather than deformations at Fibers, or the FRP laminated, this comparison takes an important part in a design point of view of FRP laminates in the construction industry.

6.2 Creep deformation on Epoxy resin affected by different temperatures from short-term creep analyses

Exposure to elevated temperatures has a huge impact on the mechanical properties of polymers, especially at higher temperature, As temperature increases, a significant amount of the flexural and compressive strength of epoxy decreases. When the temperature increases to a higher degree °C, epoxy reaches the glass transition temperature, and it begins to deform. The glass transition T_g varieties from 50-80°C.

From Research paper 5.1 about creep phenomena, several tests were performed on short-term analyses for approximately 6 days with a constant load $\sigma_0 = 6.13$ MPa. Elevating the temperature begin from 25 degrees up to 40 degrees, the thermostat-controlled heater was used for imposing the selected temperature field, whilst the constant load was applied, Tab.31.

Sample ID	σ0/fm (%)	Temp °C	ε,20h	ε,60h	ε,80h	ε,120h
EP1	20 (%)	25	0.0005	0.0005	0.0005	0.0005
EP2	20 (%)	30	0.001	0.0016	0.0018	0.0018
EP3	20 (%)	35	0.0028	0.0039	0.004	0.0043
EP4	20 (%)	40	0.0112	0.0137	0.0139	0.0141

Table 31. Axial deformations of Epoxy resin under different temperatures

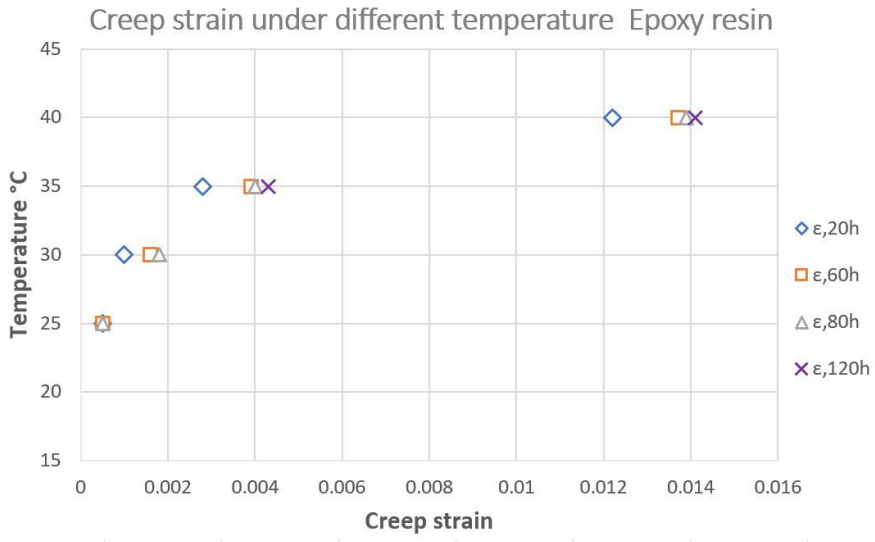


Figure 48.Creep strain under different temperature at Epoxy resin

So, from these short-term analyses about creep on epoxy, it seems very clear that the EP4 under a higher temperature shows very high long-term strains at 40°C, reaching the value of about 14000 after με (micro-strain) for 5 days and much lower strain levels are recorded at 35° and almost negligible for 25° and 30°C this could be related to being close temperature of the glass transition temperature of epoxy resin 50°C.

I can conclude that one of the most important features is choosing the right matrix according to the glass transition temperature, which must take into consideration the environmental condition what will be used.

6.3 Conclusion about Modelling Creep behavior

From the research paper related to experimental investigation and numerical modeling of creep response at GFRP, the experimental investigation tests have been performed for a period of 42 months and numerical modeling of creep behavior has been done by three different equations Burger law, Findley, and Nutting.

The experimental creep outcomes for L2 and L6 GFRP under different constant load after about 42 months resulting in total strain versus time of laminate specimens are plotted in Figure 49. The nomenclature $L_i - ch_j$; $i = 1,2,3$ laminate specimen , j $= 1,2,3$ strain gauge.

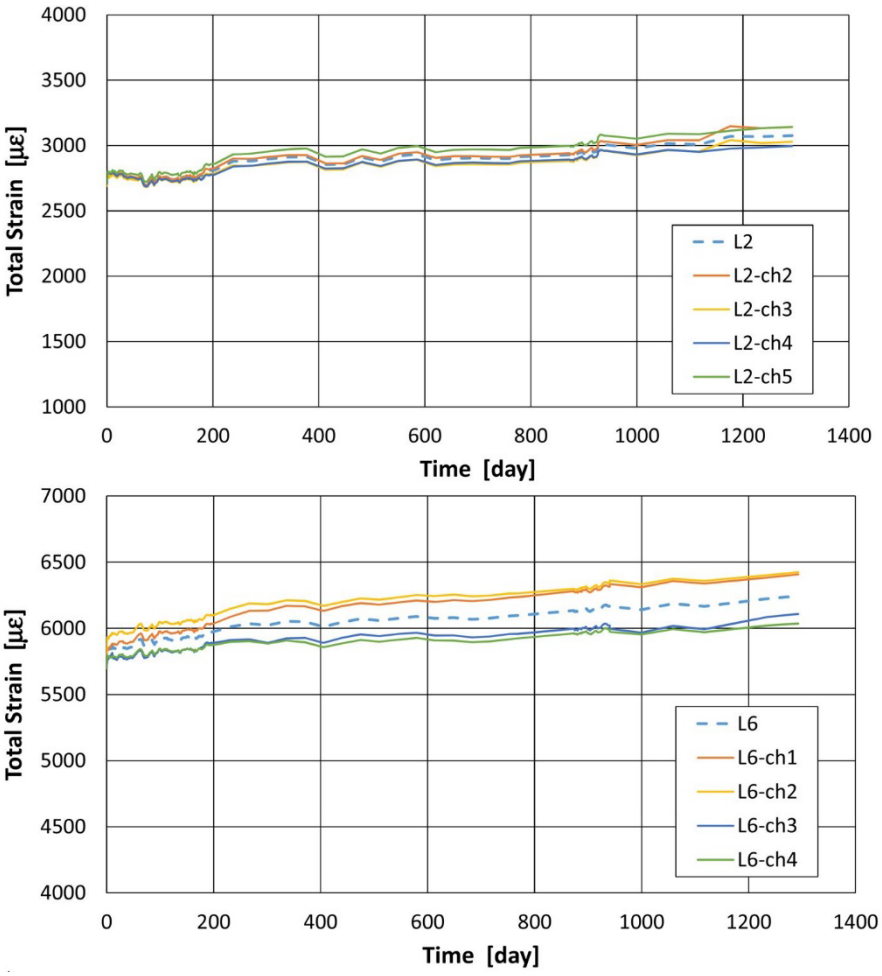


Figure 49. The experimental creep strains of the GFRP laminates [13]

A comparison of total strains from predictive numerical modeling of creep behavior for GFRP composites and total strains with experimental investigation tests for 42 months are plotted in Figure 50.

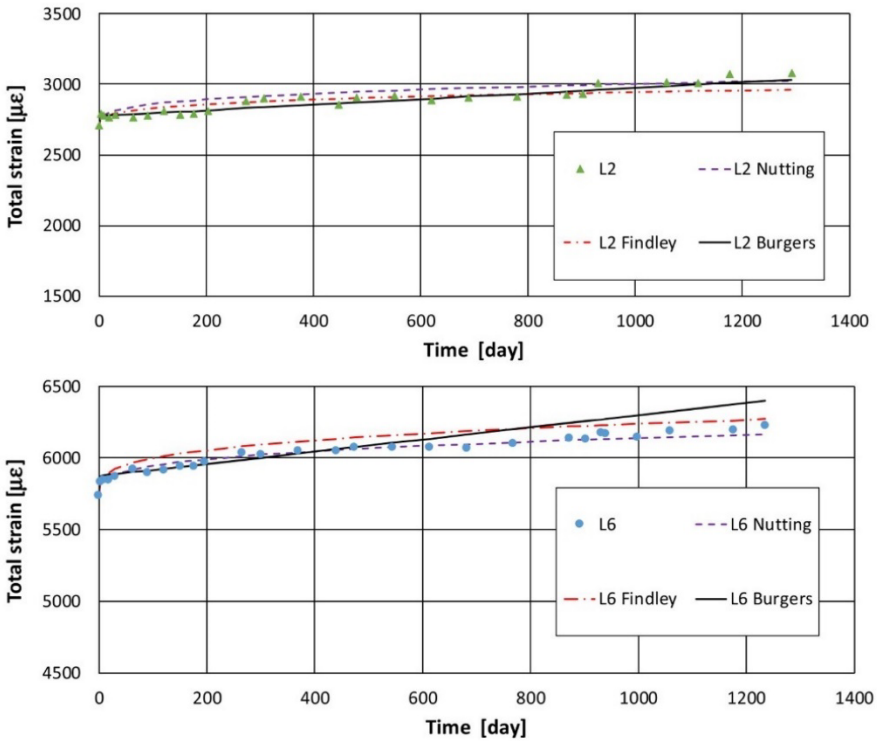


Figure 50. Comparison of predicted total strains for L2 and L6 laminates [13]

The experimental creep outcomes of GFRP laminate L2 marked with a green triangle, have been compared with three different numerical modeling of creep behavior Findley, Nutting, and Burger models.

Findley and Nutting's predictive modeling gave a satisfactory prediction until 900 days, then an underestimation of around 3.5% was pointed out from 900 to 1300 days however the Burger model described the whole creep phenomena quite well for L2 GFRP laminate.

At GFRP laminate L6 the experimental creep outcomes were marked with a blue circle, The viscoelastic model by Findley overestimated all the data points, showing less accuracy for the creep stage of L6. The Nutting model was instead suitable for the whole test duration, but strain prediction were underestimated by about 1% in the final period at the range from 900 to 1300 days. The predictions represented by

Burger's equation were satisfactory for about 500 days, and the difference in total strain after 1300 days is about 3% for specimen L6.

The mechanical Burgers model was found to be better suited for describing the long-term creep behavior than Findley and Nutting equations.

In conclusion, the Burgers model resulted as the more effective for the description of the long-term creep data of tested GFRP laminate.

Conclusion

Creep deformations are also known as time-dependent deformation that occur after a period of time when composite material is under a sustained load, and deformations are increased by load, temperature, and relative humidity, for a specific time. Due to the creep phenomena, material compositions lose stiffness which may affect even the strength reductions, of Fiber-reinforced materials.

To produce fiber-reinforced composites, two raw materials are required, reinforcing fibers and polymer resin matrix.

The behavior of FRP materials mainly depends on:

- Matrix type
- Fiber type
- Fiber volume fraction
- Fiber orientation
- Load history
- Temperature and humidity

In this thesis, some experimental studies on the creep behavior of Fiber-reinforced materials for structural rehabilitation, have been presented. In particular, several creep tests has been performed by different research institute considering different conditions that may enhance the creep phenomena at fiber-reinforced materials.

The influence of temperature on the mechanical behavior of plastics has a dramatic effect, on the mechanical properties of polymers by exposure to elevated temperatures, the material becomes more ductile with a lower modulus of elasticity and higher deformation.

The experimental data investigation in chapter 6.2 Creep deformation in Epoxy resin affected by different temperatures from short-term creep analyses, has highlighted significant creep deformation in Epoxy resin due to elevated temperatures, at 40°C the creep deformation reached a value of about 14000 after με (micro-strain) for 5 days, so axial creep deformations are higher because the glass transition temperature of epoxy resin is 50°C. At T_g, glass transition temperature the physical properties like density, heat capacity, and mechanical properties like stiffness, of polymers undergo changes. One of the most important features is choosing the right matrix according to the glass transition temperature, taking into consideration the environmental condition that will be used.

Considering that matrix is the component when creep deformations are higher while deformations at Fibers, or at Fiber-reinforced composites are almost negligible.

In chapter 6.1 a difference between Epoxy and Polyester matrix under a sustained load is presented, from Research papers 5.3 and 5.4 about creep phenomena at Glass fiber reinforced polymers GFRP laminates and their phases: matrix and fiber, both experimental data investigation has highlighted significant deferred deformation in the Epoxy resins and Polyester resins over time, and a limited strain deformation on E-fiber glass and GFRP laminate almost negligible.

Crossing those data highlighted that creep deformations in Polyester resin under lower sustained load are overlapping the deformations in Epoxy resin under higher sustained load after 3600 hours of creep evaluation, from these analyses can be noticed that Epoxy resin is performing better than Polyester resin.

Considering that matrix is the component where creep deformations are higher, this comparison takes an important part in a design point of view of FRP laminates in the construction industry.

Another important aspect in design point of view at Fiber-reinforced composites is numerical modeling of creep behavior, In chapter 6.3 a comparison between three different equations used for numerical modeling of creep behavior is presented.

The experimental creep outcomes of GFRP laminate after 42 months have been compared with three different numerical modeling of creep behavior. The Burgers model resulted as the most effective for the description of the long-term creep data of tested GFRP laminate, Fig.50.

The creep behavior of Fiber-reinforced composites can be compensated for by using accurate and well-established design procedures or by modification of the matrix composition with reinforcing fillers.

In general, creep phenomena at Fiber-reinforced composites are not investigated that much, the short-term mechanical behavior of FRPs and strengthening FRP systems was investigated by several researches, only limited studies were performed on the long-term mechanical behavior of these materials and reinforcement systems. The viscosity of materials has an important role in design/verification processes, because it can compromise the reliability and durability of these elements.

In further studies, more attention should be at the change in moisture content and changes in temperature, which are inevitable in exposed structures. Besides, different fiber contents and fiber lengths and the effect on reinforcing structures should be more investigated.

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