



## Definitions and Glossary for DURACOMP Project

The first section to this DURACOMP project is for definitions to known degradation terms. A Glossary of technical terms for composites materials is presented because it is available from another project to write a publication known as Guidance for the Design of FRP Bridges.

### 'Definitions' for known Degradation Terms

To define degradation terms it is best if we use descriptions. Ordering to introduce the degradation mechanisms is for convenience only, and is not associated with their relative importance in how FRP mechanical properties are observed to change with time due to environmental aging under either controlled laboratory or uncontrolled field conditions. It is important to recognize that mechanisms observed in a particular piece of incremental research are be specific to that investigation.

**The mechanisms of hygrothermal aging are very complex and they are interactions between molecules of water and molecules of the polymer resin based matrix.**

Molecules of water behave both as a chemical reagent in many hydrolytic and galvanic weathering reactions and as physical stressor in materials degradation. Moisture, in combination with radiation, can be a key contributor to material weathering; depends of FRP material composition and/or composite processing method.

The hydration of the surface layers can produce swelling, resulting in mechanical stress on the drier subsurface layers. In time, the equilibrium may be reached as moisture diffuses into the interior. A subsequent drying out of the surface layer results in a volume contraction; the inner hydrated layers resist this contraction, and surface stress cracking may result.

Moisture may participate in chemical degradation and may act as a solvent or carrier, e.g. in leaching away plasticizers (often referred to as Low Molecular Weight Species (LMWS)) or in carrying dissolved oxygen. Water may also participate as a reactant in hydrolysis reactions.

Absorbed water usually depresses the  $T_g$  by plasticising the polymer network.

A change in temperature and moisture content usually induces hygrothermal forces and moment resultants as well as dimensional changes. In addition, the thermal stresses produced during the cooling process after cure at elevated temperature could be so combined with those hygrothermal stresses induced by moisture absorption.



The recursive changes of internal stresses due to water absorption–desorption processes may induce fatigue damage in the inter and intralaminar region influencing long term durability performance.

The observed behaviour (Papanicolaou *et al.* 2009) can be attributed to the following mechanism (given mainly in the words of these authors): at the initial stages, a reactivation of curing reactions with the water temperature is taking place. Due to the reactivation of curing reactions, the (epoxy) polymer network initially becomes denser, so that the glass-epoxy composite shows an improved mechanical behaviour, while as time passes water plasticising effect becomes stronger leading to a subsequent lowering in the mechanical properties.

Degradation takes place because of the hydrogen bonding that is formed between the water molecules and the polar groups of the polymer chain, which disrupts the initial network. Crazes are developed within FRP due to the hygrothermal stresses causing swelling. Because the water molecule is polar, it is capable of forming hydrogen bonds with hydroxyl groups, thereby disrupting interchain hydrogen bonding with the net effect of increasing the intersegmental hydrogen bond length. Thermodynamic arguments have shown that liquid molecules can combine with polymer molecules in the glassy state and actually become part of the glassy structure, establishing an equilibrium between the liquid and glassy mixed phase.

On the other hand, it is necessary to understand that the network structure of cross-linked epoxy resins is not homogeneous, as generally assumed, but is really a mixture of highly cross-linked microgel particles (or micelles) embedded in a less highly cross-linked matrix. Because of their higher density, the micelles are not easily penetrated by the water, than is the surrounding matrix. Although they are comparatively denser, the micelles do contain a portion of the total polymer free volume.

Internal stresses maybe set-up when a penetrant diffuses into a polymer. It is to be expected that the inner, unswollen (or less swelling), part of the body will exert a compression force on the outer, swelling, part, causing swelling to be mainly along the direction of diffusion. On the other hand, the swollen region exerts, on the unattacked region, a force which tends to increase the area of the body. The distribution of these compression and expansion forces will change as diffusion proceeds, since the thickness of the unattacked region decreases.

Finally, since the fibre–matrix interphase area is characterised by voids, microcracks, and other defects, which create preferential diffusion path, it is obvious that, at the initial time interval of immersion, absorbed water molecules occupy the empty spaces available into



the fibre–matrix interphase region (a non-constant sized region of nanometre thickness surrounding the glass fibres where the coupling agent and polymer interact for matrix having different mechanical properties to bulk matrix (Gao and Mäder 2002)), leading to a plasticisation of the interphase material and a decrease in the interphase thickness. Next, as immersion time increases, and absorbed water plasticises the bulk matrix, the interphase is expanded leading to a weaker bonding of the two main phases. The observed behaviour (Papanicolaou *et al.* 2009) is the result of all phenomena already presented which may coexist. **Degradation and/or improvement in the mechanical and viscoelastic performance of the polymeric composite can equally be expected.**

Other mechanisms mentioned in Mouzakis *et al.* (2008) are as follows, they are given supporting references too:

- Absorbed water has been found to disrupt the interfacial bonds.
- An irreversible effect is the creation of a secondary cross-linking in the matrix, due to a specific kind of hydrogen bond that forms between resin (matrix) and water molecules. This phenomenon depends on the chemical structure of the resin, the temperature and the total period of exposure to water.
- Temperature and UV radiation can either impose scission of the chemical bonds of the matrix (i.e. main C–C chain scission), leading to photo/thermal oxidation and crazing of the material, or lead to polymer post-curing.
- Dynamic mechanical analysis work with a glass-polyester FRP found that above 100°C trends are reversed; the values of storage modulus become lower and the values of  $\tan\delta$  higher for the aged FRP, especially the saturated material, in comparison with the pristine sample. This finding is possibly due to the presence of a mechanism creating an expanded interphase region of increased ductility around the glass fibers, as confirmed by a previous experimental study by Hodzic *et al.* (1994).

Chemical composition of the resin appears to affect the equilibrium content of water. Iso- and ortho-phthalic polyesters are different in this sense.

Mouzakis *et al.* (2008) highlights the underlying fact that changes in the (polymer) resin matrix can be either reversible (plasticization and swelling) or irreversible (dissolution, hydrolysis and microcracking).

Important **reference sources** for understanding mechanisms are:

Prian, L. and Barkatt, A. (1999). 'Degradation mechanism of fiber-reinforced plastics and its implications to prediction of long-term behavior,' *Journal of Materials Science*, **34**, 16, 3977-3989.



Weitsman, Y.J. and Elhahi, M. (2000). 'Effects of fluids on the deformation, strength and durability of polymeric composites - An overview,' *Mechanics of Time Dependent Materials*, **4** 2, 107-126

Mouzakis, D.E., Zog, H. and Galiotis, C. (2008). 'Accelerated environmental ageing study of polyester/glass fiber reinforced composites (GFRPCs),' *Composites Part B: Engineering*, **39** 3, 467–475.

Papanicolaou, G.C., Xepapadaki, A.G. and Zaroucha, D.S. (2009). 'Effect of water uptake on creep behaviour of glass–epoxy composites,' *Plastics, Rubber and Composites*, **38** 2/3/4, 72-79.

Key references for introducing the interphase region:

Hodzic, A., Kim, J.K., Lowe, A.E. and Stachurski, Z.H. (2004). 'The effects of water aging on the interphase region and interlaminar fracture toughness in polymer–glass composites,' *Composites Science and Technology*, **64** 13-14, 2185–2195.

Gao, S. L. and Mäder, E. (2002). 'Characterization of interphase nanoscale property variations in glass fiber reinforced polypropylene and epoxy resin matrix,' *Composites Part A: Applied Sciences and Manufacturing*, **33**, 559-576.

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### **Glossary** (in preparation)

Accelerator:	Substance that accelerates the chemical reaction between the polymer resin system and curing agent.
Additives:	Term used for a large number of specialist chemicals that are added to resins to impart specific matrix properties, such as removal from processing mould, flame retardancy and UV protection.
Adherend:	Component in an adhesively bonded connection.
Adhesion:	State in which two surfaces are connected together at the interface by mechanical or chemical forces or interlocking actions.
Adhesive:	A substance, can be a polymer based material, which when applied on mating surfaces is capable of bonding the two adherends together. An adhesive can be in liquid, film or paste form. There are structural or non-structural types of products.



Anisotropic:	A material having mechanical properties being directionally dependent.
Aramid fibre:	High strength, long-chain, aromatic polyamide synthetic fibre.
Autoclave:	Closed vessel with an environment of pressure, with or without heating to an enclosed object which is undergoing a chemical reaction or other operation.
Autoclave moulding:	Manufacturing process for FRP materials and components similar to the vacuum bag technique.
Balanced laminate:	FRP where the individual layers (or plies) are stacked so that there is a balance maintained of $+\theta$ oriented layers and $-\theta$ oriented layers at the same height from the laminate's mid-plane.
Bond:	Adhesion of one material surface to another using an adhesive or other bonding agent.
Bonded connection:	Connection between two components (adherends) where surfaces are held together by means of an adhesive or another polymer material.
Brittle material:	When subjected to stress the material breaks without significant deformation (strain). The material fractures on rupture.
Carbon fibre:	Fibre type with low density and high strength and/or high modulus of elasticity. High strength and/or high modulus fibres are produced from organic materials such as polyacrylonitrile (PAN).
Catalyst:	Chemical compound (usually an organic peroxide) which initiates polymerisation, for the cure of a resin matrix.
Chopped Strand Mat (CSM):	Non-woven mat with short strands cut (approximately 50 mm long) from continuous fibre (or filament) strands and fairly evenly distributed and randomly oriented within the plane of the mat. The mat is held together by a binder.
Closed mould:	Two-piece mould that encloses the uncured FRP component and will apply pressure, and heat.
Component:	Any element or member made of one or more FRP materials, with or without a core material. The FRP component can have metallic features, say, for a moulded joint.
Composite:	Alternative term for FRP. In this publication composite is a material comprising a polymer resin matrix reinforced by fibres or filaments (often of glass, carbon or aramid).



Connection:	For design purposes it is the assembly of the basic components required to represent the behaviour during the transfer of the relevant internal forces and moments at the connection.
Contact moulding:	Manufacturing process for FRP materials and components without application of external pressure and heat.
Continuous Filament Mat (CFM):	Non-woven mat with yarns or strands (of individual continuous fibres (or filaments)) fairly evenly distributed and randomly oriented within the plane of the mat. The mat is held together by a binder.
Core:	In sandwich construction the core is the central part to which top and bottom FRP face sheets are attached. Foams, honeycombs, woods (balsa) and cork are core materials.
Corrosion resistance:	Ability of FRP material not to have degraded mechanical properties immediately, or over time, on contact with environmental conditions.
Crazing:	Fine cracks at or under the surface of a matrix in the finished FRP component.
Creep:	Time dependent part of strain resulting from stress.
Cure:	Process of hardening of a thermosetting polymer resin (by cross-linking of the molecular structure), often under the influence of heat energy.
Curing agent:	Chemical compound(s) used to cure a thermoset polymer resin.
Curing cycle:	Schedule of time periods at specified conditions to which a reacting thermosetting material is subjected in order to reach a specified property level.
Delamination:	The separation of the layers of material in a laminate. This may be local or may cover a significant area of the component. It may occur at any time in the cure or subsequent life of the laminate and may arise from a wide variety of causes. This mode of failure is linked to a relatively low through-thickness tensile strength.
Epoxy resins:	Thermoset polymer resins that can be of widely different formulations, but, which are characterised by the reaction of the epoxy group to form a cross-linked hard resin.
Fabric, Non-woven:	Textile structure produced by bonding or interlocking of fibres (or filaments), or both, accomplished by mechanical, chemical, thermal or solvent means, and combinations thereof.



Fabric, Woven:	Generic reinforcement construction consisting of interlaced yarns or fibres, usually a planar structure. The warp direction of the woven fabric is taken to be the longitudinal (or 0°) direction, which is the direction of the principal load action.
Ferrule	A metallic insert with an outer diameter close to the hole diameter size through which a mechanical fastener passes through to strengthen a FRP bolted connection.
Fibre:	General term for a material in a filamentary form. Often, 'fibre' is used synonymously with 'filament', and it is the more common of the two terms used.
Fibre content:	Quantity of fibre in the FRP material. Usually expressed as the percentage volume or weight fraction in the FRP.
FRP:	Abbreviation for any Fibre Reinforced Polymer material or Fibre Reinforced Polymer composite .
FRP designer:	Experienced professional engineer with specialist knowledge of FRP materials and structural design.
FRP properties:	Properties of an FRP lamina, laminate, section or component.
Filament:	Single element of reinforcing material having small diameter and very long length; length can be considered as continuous.
Fill (Filling):	In a woven fabric, the yarn running from the long, outer, finished side edges at right angles to the warp.
Filler:	Relatively inert substance added to a polymer resin to alter its physical, mechanical, thermal, electrical or other properties or to lower cost. The term is often used specifically to mean particulate additives.
Finishing:	Application of a coupling agent to fibres to improve the bond between the filament surface and the resin matrix. Finishes can contain ingredients that provide lubrication to the fibre surface, thereby preventing abrasion damage during handling or a binder that promotes strand integrity and facilitates packing of the fibres. Finishing is also known as sizing.
Gel:	State of a polymer resin, which has set to a jelly-like consistency.
Gel coat:	Thin layer of unreinforced quick-setting resin on the outer surface of an FRP component. Used in moulding processes to provide an improved surface to the FRP product.



Glass fibre:	Reinforcing fibre made by drawing molten glass through bushings. There are different types of glass fibres. E-glass is the dominant type of glass fibre.
Glass Transition Temperature ( $T_g$ ):	Approximate midpoint of the temperature range over which the glass transition takes place, below $T_g$ the polymer resin is a brittle material and above $T_g$ it is a rubbery material.
Hand lay-up:	FRP manufacturing process in which a thermoset polymer resin and the fibre reinforcement layers are applied manually either to an open mould or to a working surface in a number of successive layers.
Honeycomb:	Lightweight cellular core material made from either metallic sheets or non-metallic materials and formed into hexagonal-shaped cells.
Hybrid:	Resin system or fibre reinforcement system made from two or more different polymers or fibre reinforcement types.
Hybrid connection:	Connection between two components where the surfaces are held together by combination of adhesive bonding and mechanical fastening. Hybrid connection is also known as a combined connection.
Impregnation:	Process of combining the fibre reinforcement with liquid polymer resin.
Insert:	Integral part of the FRP component consisting of metal or other material that may be moulded or bonded into position or pressed into the component after completion.
Interlaminar:	Descriptive term pertaining to some feature (e.g. void), event (e.g. fracture) or shear stress that exists or occurs between two adjacent FRP layers.
Intralaminar:	Within the laminae of a laminate.
Joint:	Zone where two or more members are joined using connections of mechanical fasteners, adhesive bonding or a combination of both methods.
Junction	Interface region between individual panels in a thin-walled FRP component or structure having different mechanical properties to the intersecting panels.
Lamina:	A single layer or ply in a laminate of a number of individual layers of fibre reinforcement.
Laminate:	FRP material formed from curing and consolidating one or more layers or plies of one or more fibre reinforced polymer materials.





Layer:	Synonymous with terms 'ply' or 'lamina' with the FRP material.
Lay-up:	Fabrication involving the stacking of successive laminae or layers or plies.
Mat:	Fibrous material comprising randomly oriented chopped or swirled continuous fibres loosely held together with a binder.
Matrix:	Can be a polymer resin system alone or in combination with additives.
Moulding:	Forming of an FRP material in a solid form or prescribed shape and size within a closed or open mould, can be accomplished under pressure and heat. Term can be used to denote the finished component.
NDE:	Non-Destructive Evaluation. Broadly considered synonymous with NDI.
NDI:	Non-Destructive Inspection. A process or procedure for determining the quality or characteristics of a material, part, or assembly without permanently altering the subject or its properties.
NDT:	Non-Destructive Testing. Broadly considered synonymous with NDI.
Open Mould:	A single-piece unenclosed mould.
Orthotropic:	Having three mutually perpendicular planes of elastic symmetry, which are coincident with the geometric planes of symmetry.
Peel ply:	Exterior (sacrificial) layer that is removed to create an improved bond to additional material or another component. Also acts as a proactive layer to ensure that the surface remains undamaged and uncontaminated prior to bonding.
Ply:	Synonymous with terms 'lamina' or 'layer'.
Polyester:	Usual term for an unsaturated polyester thermoset resin, which is capable of being cured from a liquid or solid state when subject to the right conditions.
Polymer:	An organic material composed of molecules characterized by the repetition of one or more types of monomeric units.
Porosity:	Volume fraction of the FRP material that is of air or other gases trapped within the total volume.
Postcure:	Additional application of external heat energy, usually without additional pressure, to complete the cure or improve mechanical properties or both.



Preform:	Pre-shaped (dry) fibre reinforcement for a moulded FRP component.
Prepolymer	The term pre-polymer refers to a monomer or system of monomers that have been reacted to an intermediate molecular weight state. This material is capable of further polymerization by reactive groups to a fully cured high molecular weight state.
Prepreg:	Factory-made lamina (layer or ply) of a reactive polymer resin matrix and reinforcing fibres (unidirectional, fabrics or mats).
Pultrusion:	Continuous closed mould manufacturing process for thin-walled open and closed FRP shapes (or profiles or sections), having constant cross-sectional area in the direction of pultrusion.
Quasi-isotropic laminate:	Laminate that approaches having isotropic properties in its plane by having a number of layers with specific orientations and lay-up arrangements. As an example, unidirectional laminae are often grouped using the four orientations of $0^\circ$ , $90^\circ$ and $\pm 45^\circ$ .
Mould release facilitate agent:	or Mould release agent. A lubricant applied to the mould surfaces to release of the moulded component or unit. It can be a chemical compound or a solid material such as a cellulose or plastic film.
Reinforcement:	Fibres that are added to a polymer matrix to form an FRP material with the required mechanical properties. Reinforcement types range from short fibres to continuous fibres, through to complex woven fabrics and stitched fabrics.
Resin:	Polymer material with indefinite and often high molecular weight and a softening or melting range that exhibits a tendency to flow when subjected to stress. It can exist in solid, semi-solid or liquid state.
Resin system:	An organic polymer or prepolymer used as a matrix to contain the fibrous reinforcement in an FRP material or as an adhesive. This organic matrix may be a thermoset or a thermoplastic, and may contain a wide variety of components or additives to influence handleability, processing behaviour and ultimate properties. In FRP materials the resin based matrix is used to impregnate the fibres and bind fibres and layers of fibre together.
Resin Transfer Moulding (RTM):	FRP manufacturing process in which a catalysed polymer resin is injected into a closed mould already containing the preform for the component.
Roving:	Strands or bundles of continuous fibres with little or no twist along their length.



Sandwich construction:	FRP structural form comprising lightweight core material to which two high strength FRP faces are adhesively bonded.
Sizing:	Coating applied to fibres (or filaments) during their manufacture to improve handling and protect from abrasion.
Stacking sequence:	Orientations and lay-up arrangements of the laminae (or layers or plies) in the FRP laminate.
Stitched fabrics:	A textile fabric that also has fibre reinforcement in the out-of-plane direction.
Strand:	Assembly of parallel fibres (or filaments), normally an untwisted bundle or assembly of continuous filaments used as a unit.
Stress relaxation:	Time dependent decrease in stress in a solid under given constraint conditions.
Stress rupture:	Failure (by rupture) of an FRP material at a sustained tensile stress level that is considerably lower than the short-term ultimate tensile strength. Can be referred to as creep rupture.
Swelling	Volumetric changes due to moisture content alone, independent of thermal expansion.
Symmetric laminate:	Laminate in which each lamina type, angles and composition is exactly mirrored about the mid-plane of the FRP material.
Thermoplastic:	Polymer resin that softens each time it is heated and hardens when cooled.
Thermoset:	Class of polymers that, when cured using heat, chemical, or other means, changes into a substantially infusible and insoluble material.
Tow:	An untwisted bundle of continuous filaments. Commonly used in referring to man-made fibers, particularly carbon and graphite fibers, in the FRP industry.
Unidirectional laminate:	FRP material with all the continuous fibres aligned in a single orientation.
Vacuum bag moulding:	FRP manufacturing process in which the lay-up is cured under pressure generated by drawing a vacuum in the space between the lay-up and a flexible sheet placed over it and sealed at the edges.
Veil:	Thin layer of mat similar to a surface mat, often of organic fibres.
Vinylester:	Thermosetting resin that is chemically similar to both unsaturated polyesters and epoxy resins.



Voids:	Pockets of gas or near-vacuum air trapped within an FRP component.
Warp:	Longitudinally oriented yarn in a woven fabric (see Fill or Weft); a group of yarns in long lengths and approximately parallel.
Weft or fill:	Transversely oriented yeans in woven fabric.
Wet-out:	Complete wetting or saturation of the fibre reinforcement by the resin matrix.
Wet lay-up:	FRP manufacturing process for making an FRP laminate by applying a liquid resin system whilst or after the reinforcement is put in place.
Yarn:	Generic term for strands or bundles of continuous fibres (or filaments), usually twisted for producing fabric reinforcements.
0°	Orientation of fibres, laminae or component that is aligned to the principal direction of loading.
±45°	Orientation that is 45° from the 0° and 90° orientation.
90°	Orientation(s) that is/are perpendicular to the 0° orientation.

### Abbreviations

ACM:	Advanced Composite Material
AFRP:	Aramid Fibre Reinforced Polymer
ASTM:	American Society of Testing and Materials
ATH:	Aluminium trihydrate (flame retardant additive)
BSI:	British Standard Institute
CEN:	Comité Européen de Normalisation
CFM:	Continuous Filament Mat
CFRP:	Carbon fibre reinforced polymer
GFRP:	Glass fibre reinforced polymer
HDT:	Heat Deflection Temperature
HM fibre:	High Modulus version of a fibre
HS fibre;	High Strength version of a fibre
ILSS	Inter-Laminar Shear Stress (or strength)
PFRP:	Pultruded Fibre Reinforced Polymer
VRTM	Vacuum Resin Transfer Moulding