Towards a REgulatory FRamework for the usE of Structural new materials in railway passenger and freight CarbOdyshells

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WP 6

Manufacturing acceptance criteria

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- CAF
- AST
- DLR

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## Definitions

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<th>Description</th>
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<tr>
<td>US</td>
<td>UltraSonic</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fiber Reinforced Plastic</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fiber Reinforced Plastic</td>
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<td>GL</td>
<td>Germanischer Lloyd</td>
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EXECUTIVE SUMMARY

The Work Package 6.2 deals with acceptance criteria for manufacturing of structural new materials in railway passenger and freight car-bodies.

- Standards and approaches used within the composite industry for:
  - Incoming goods control
  - In-process control
  - First Article Inspection have been highlighted
- For a cost effective assessment of companies and manufacturing sites a distinguishing into three different part classes have been proposed.
- Gaps in the regulatory framework have been highlighted
- A recommendation for the use as a base of the different norms in relation to the part classes has been given.
- A recommendation for the structure of a future framework for manufacturing acceptance has been made
1 INTRODUCTION

The WP 6.2 – Manufacturing Acceptance Criteria is part of the REFRESCO WP 6 - Joint and Manufacturing. Work package WP 6 is structured into the following sub packages:

- WP 6.1 – Materials manufacturing and processes,
- WP 6.2 – Manufacturing acceptance criteria
- WP 6.3 – Joint behaviour
- WP 6.4 – Joint acceptance criteria

WP 6.1 and WP 6.2 are dealing with the material and related manufacturing. To reflect also the need to combine materials to sub-assemblies and assemblies the WP 6.3 and WP 6.4 will handle the matter of joining.

It is one of the essential topics in the use of new materials to ensure reliable and repeatable manufacturing processes in order to ensure the safe usage of the respective components in daily operation within a railway environment. Approaches from different industries like wind energy or aerospace will be highlighted. Finally the current status of standardization will be shown, which is to be seen as the essential purpose of the REFRESCO project at all.

For the definition of acceptance criteria for the manufacturing of parts and components using new structural materials it is essential to follow the entire manufacturing flow line of the potential processes identified in WP 6.1.

As shown in WP 6.1 it is in the nature of composite material that the final properties achievable are highly linked to the manufacturing parameters, a fact that is different to most of the metallic materials currently used for these kind of components. This requires that special attention is taken to the manufacturing itself and all influencing parameters. This document is therefore structured into:

- Incoming goods control
- In process control
- First part validation
- Traceability of process parameters
- Qualification needs for companies, production lines and employees
2 GENERALITIES

The framework of this document concerns structural composite parts manufacturing of structural elements.

The manufacturing technique used to manufacture a composite structure is dependent upon material performance requirements, structure configuration, and production rates. The composite design and manufacturing methods discussed in this document are primarily for structural and mechanical applications and are generally composed of a resin (matrix) and fiber reinforcement. Composites must be considered as unique materials in the design and manufacturing process because manufacturing equipment, tooling, and inspection equipment and processes have a pronounced effect on the final product. And therefore finally have a significantly influence the part/component properties and behavior.

To assure the required level of quality of structures e.g. in aerospace field, the global methodology here below exposed is considered:

- Designers have first to define the performance’s needs for the materials and the structure (including junctions),
- Tests and analysis are performed to verify the compliance between the design and the requested performance. This step is called “qualification”.
  The qualification logic is based on the complementarity between theoretical and experimental studies, and covers the different scale of the structures, from elementary scale (at material level) to full scale structure level. More details on the qualification logic considered in aerospace filed are given in the REFRESCO document D4.2
- After the qualification of the structure is achieved, quality level has to be mastered during manufacturing all along the production phase.

The main objective of this document is to focus on the last step of the here above logic. The document propose to give an overview of the most important parameters which have to be mastered and controlled during the manufacturing process of a structural composite parts (from material procurement to the structure delivery) to ensure the required performance of the structure. Finally a recommendation is given for the regulatory framework for manufacturing sites based on part classes that are describing the safety relevance of the composite parts or components.
3 INCOMING GOODS INSPECTION [1], [2]

In a composite part, the material of the part itself is realized in the same step than the shape and the design of the structure. Moreover, organic/polymer materials are usually sensitive to their own manufacturing process, and also sensitive to environmental conditions (before and after delivery).

Composites may suffer from disorders or flaws which conventional material won’t. This can be a problem, but as long as the manufacturer is aware of these composite specific problems then serious mishaps can be avoided through systematic controls in, and after, production. For raw material such as fibers, resin and core material normal demands exist concerning testing of material properties at delivery and pre-production. Some controls may be left to the material supplier but some in-house testing is nevertheless required. Generally some testing will have to be performed for every resin batch and fiber/weave roll.

As a consequence, it is very important to master the quality of the semi-product, through a document called “supplying specification”. The aim of this document is to:

- keep the memory of the material requirements
- define the tests and verifications to perform to master the compliance with the requirements
- give the material’s using requirements

The main chapters usually found in such documents are described here below, as an example:

3.1 Batch

A batch corresponds to a certain quantity of material produced in one homogeneous manufacturing step. Each material produced has to be identified with its batch number.

3.2 Handling and storage

Materials like resin, prepreg…have a limited shelf-life depending on the environment.

Epoxy resins are the most common nature of matrix material used in structural composites. Epoxies are perishable. They must be stored below freezing temperature and even then have a limited shelf life.

For example, prepreg freezing storage at -18°C condition is usually limited by the material supplier to 6 to 12 months. Over-age material could produce laminates with a higher level of porosity.
On the other hand, materials like fiber, core (foam or honeycomb) have an infinite shelf life. Nevertheless, some storage requirements can be defined, depending on the materials and its use.

For instance some materials such as foam for sandwich structures have to be protected against dust and pollution to assure a good bonding further in the manufacturing process.

In general it can be concluded, handling and storage has to be considered as a controlled process with the corresponding needs for documentation.

### 3.3 Acceptance tests

Suppliers have to certify that their materials fulfil to the required performances & properties. At the material reception, mechanical and chemical tests are requested on samples. The control frequency depends on the product maturity. A strict FIFO principle in the storage process needs to be ensured by the supplier.

#### 3.3.1 Fibres

An example of a problem that fibers may suffer from is the fiber coating, sizing which is usually added on the individual fibers. A change in the coating may change composite properties dramatically. Usually the fibers are coated to enhance the fiber–matrix bonding strength but this bonding strength is a design variable that has to be given a certain target window in which it should remain. This as the fiber-matrix interface is one of the most important factors determining impact toughness.

Too good fiber-matrix interfacial shear strength will cause the impact failure mode to shift from severe delamination, (large energy absorption), to a brittle “all or nothing” failure, (low energy absorption). A too week interface will result in lower tensile strength as the matrix ability to transfer loads to the fibers decreases. Further testing required includes tensile strength and modulus, density and fiber/bundle form and twist. A twisted fiber bundle will for example behave less stiff in the finished product than a perfectly aligned one.
For a dry fabric, an example of acceptance tests to be performed is given here below:

<table>
<thead>
<tr>
<th>Properties</th>
<th>Testing methods (as an example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>ASTM D3800IGC 0426655</td>
</tr>
<tr>
<td>Mass/unit length</td>
<td>NF ISO 1889</td>
</tr>
<tr>
<td>Tensile Modulus (GPa)</td>
<td>ASTM D4018/ ISO 527/ NFT 25101</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>ASTM D4018/ ISO 527/ NFT 25101</td>
</tr>
<tr>
<td>Sizing rate (%)</td>
<td>ASTM D4018</td>
</tr>
<tr>
<td></td>
<td>ISO 527</td>
</tr>
<tr>
<td></td>
<td>NFT 25104</td>
</tr>
<tr>
<td>Form</td>
<td>ASTM E1309</td>
</tr>
</tbody>
</table>

Table 1 Test methods for dry fabrics

The table above mentions some testing procedures and associated standards for acceptance testing of fibers and multifilament’s intended for use in aerospace applications.

Form means the roundness of individual fibers and it is of importance due to the varying material properties depending on fiber-matrix interface. Very oval fibers yields larger interface area in proportion to fiber cross sectional area and this may affect the failure behavior of the composite. Twist in concerning the alignment of individual fibers in relation to the longitudinal axis of a fiber bundle. A bundle with high degree of alignment will act stiffer when strained than a bundle consisting of poorly aligned fibers. Poorly aligned fibers might also increase the chance of micro cracking. Since no specific test method/standard is listed the manufacturer and the FAA can agree on any method that fulfils the purpose.

Sizing/coating content and composition will have to be verifies by Chemical analysis and additional methods. The coating is very important to the failure behavior of the composite. In general terms it would be possible to, for some ideal fiber-matrix systems, vary the failure behavior from 100% brittle to almost “metal like” plastic just by altering the sizing type and content. Tensile modulus and Strength are natural characteristic to check. Fiber strength and stiffness has direct impact on composite properties, low fiber strength and stiffness will result in low composite strength and stiffness.

Fiber density should be checked mostly to make sure that all other properties are correct since incorrect density may indicate problems on other variables.
3.3.2 Matrices

Assuming for example the RTM production process; certain things have to be kept under control. If for example the viscosity rises for some reason, the mould filling will be more difficult and the risk for voids higher. Viscosity change may occur due to problems in raw material storing or excessive storage time. Chemical composition is another important variable. The amount of functional groups for example has a strong influence on curing behavior, achievable degree of cure and for the completed composite; load transfer abilities between fibers etc.

For a resin an example of acceptance tests to be performed is given here below:

<table>
<thead>
<tr>
<th>Mechanical &amp; chemical Properties</th>
<th>Testing methods (as an example)</th>
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<tbody>
<tr>
<td>Non polymerized material</td>
<td></td>
</tr>
<tr>
<td>Polymerization energy (J/g)</td>
<td>NFL 17-451</td>
</tr>
<tr>
<td>Viscosity (mPa.s)</td>
<td>ISO EN 3219</td>
</tr>
<tr>
<td>Gel time</td>
<td>ASTM D2471</td>
</tr>
<tr>
<td>IR</td>
<td>ASTM E1252</td>
</tr>
<tr>
<td>Cure Kinetics</td>
<td>ASTM E2041/ ASTM E2070</td>
</tr>
<tr>
<td>Rheology</td>
<td>ASTM E4473</td>
</tr>
<tr>
<td>Polymerized material</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>ASTM D792/ NFT 51 201</td>
</tr>
<tr>
<td>Glass transition (°C)</td>
<td>NFL 17-451</td>
</tr>
<tr>
<td>Maximal strength (MPa)</td>
<td>IGC 04 26 253-A</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>IGC 04 26 253-A</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>IGC 04 26 253-A</td>
</tr>
</tbody>
</table>

*Table 2 Test methods for resins*

The above table shows recommended tests and associated standards for the resin material.

Viscosity is checked to amongst others assure problem free injection when for example RTM is used to manufacture the composite. It may also indicate if the resin has been stores too long if the viscosity is higher than normal value. Viscosity and Gel time will also give a quick verification of the maxing ratio between hardener and pre-polymer which will affect the time needed in the tool for the detail to solidify. Viscosity might for example be tested according to AECMA standard prEN 6043.

Infrared Spectrophotometry and High-Pressure Liquid Chromatography are used to determine the chemical composition of the resin, such as the amount of functional...
groups and other important factors. HPLC there are no specified standards but standards for that method exists that may be modified to fit the testing of the matrix, for example ASTM D6579-00. Testing the Cure Kinetics will result in a curve describing the hardening/setting process against time. This is use to make sure that the resin will perform according to process specifications.

Rheology examination is made to determine deformation against time for the matrix material and is used again to give information about the composition of the material.

### 3.3.3 Preforms/ Prepregs

Fiber preforms should be checked according to shape, and possibility also weighed to determine its quality. Even as a distorted preform might be inserted into the mould the “bending” required to take it fit might result in the reinforcement being misaligned in the finished part. The preform weight, together with other data, may be used to estimate the fiber volume fraction and even void content if the measurement is performed accurately enough. For prepreg material a combination of the properties checked for resin and fibers will have to be verified, fiber and matrix content, chemical composition of the resin etc. No geometrical defects are allowed such as wrinkles or waviness and the adhesion to the backing tape should be perfect without bubbles to assure successful assembly of the composite.

For prepreg, testing is done at the reception before and after polymerization. An example of acceptance tests to be performed is given here below:

<table>
<thead>
<tr>
<th>Physical &amp; chemical properties</th>
<th>Testing methods (as an example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non polymerized material</td>
<td></td>
</tr>
<tr>
<td>Lineal Weight (g/m)</td>
<td>IGC 0426650</td>
</tr>
<tr>
<td>Fibre content</td>
<td>SACMA SRM23</td>
</tr>
<tr>
<td>Resin content</td>
<td>ASTM D3529</td>
</tr>
<tr>
<td></td>
<td>SACMA SRM23</td>
</tr>
<tr>
<td>Volatiles rate</td>
<td>ASTM D3530/ IGC 0426200</td>
</tr>
<tr>
<td>Flow</td>
<td>ASTM D3531/ SACMA SRM22</td>
</tr>
<tr>
<td>Gel time</td>
<td>ASTM D3532</td>
</tr>
<tr>
<td>Tack</td>
<td>IGC 0426221</td>
</tr>
<tr>
<td>Chemical definition</td>
<td>ASTM E 1252/ IGC 0426130</td>
</tr>
<tr>
<td>(Spectrophotometry IR)</td>
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Deliverable 6.2 – Manufacturing acceptance criteria

Chemical Reactivity and degree of advancement via DSC

<table>
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<th>Property</th>
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<tr>
<td>Resin density rate (%)</td>
<td>IGC 0426232</td>
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Polymerized material

<table>
<thead>
<tr>
<th>Property</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Areal weight (g/cm³)</td>
<td>IGC 0426230</td>
</tr>
<tr>
<td>Glass transition temperature dry/wet</td>
<td>/</td>
</tr>
<tr>
<td>Tensile modulus/strength</td>
<td>IGC 0426250</td>
</tr>
<tr>
<td>Shear strength</td>
<td>IGC 0426235</td>
</tr>
<tr>
<td>Compression modulus/strength</td>
<td>EN 2850</td>
</tr>
</tbody>
</table>

Table 3 Test methods for prepregs

The above listed standards are applied to ensure the quality of the prepreg material. Most of the tests are mentioned in previous sections but other require some additional description. Fiber and Resin content are measured to assure proper composite properties as for example strength and stiffness will suffer if fibre content is too low and ply to ply adhesion will be jeopardized if resin content is too low.

Differential Scanning Calorimetry; DSC, is used not only to determine the degree of cure but also water content after environmental exposure.

For dry fiber preforms this investigation has resulted in no applicable standards, but if preforms are used, it will be necessary to develop standards for the inspection of such material.

3.3.4 Foam Core

For a foam core, an example of acceptance tests to be performed is given here below:

<table>
<thead>
<tr>
<th>Mechanical &amp; chemical Properties</th>
<th>Testing methods (as an example)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core material</td>
<td></td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>ISO 845</td>
</tr>
<tr>
<td>Compression strength (MPa)</td>
<td>ISO 844</td>
</tr>
<tr>
<td>Compression modulus (MPa)</td>
<td>ISO 53421</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>ASTM C 297</td>
</tr>
<tr>
<td>Tensile modulus (MPa)</td>
<td>ASTM C 297</td>
</tr>
<tr>
<td>Shear strength (MPa)</td>
<td>ISO 1922</td>
</tr>
<tr>
<td>Shear modulus (MPa)</td>
<td>ISO 1922</td>
</tr>
</tbody>
</table>
Table 4 Test methods for Core materials

The above mentioned core related testing methods are used to verify some of the important properties of the core material.

Compressive strength is of importance as the core often is subjected to compressive stresses when the composite as a whole is subjected to bending.

Thickness is of importance as the core thickness will affect the total thickness and thus also strength and stiffness.

Control of density may be performed to determine if water or other non-desired substances has penetrated the core material.
4 IN PROCESS CONTROL [2], [1]

Composite parts are fabricated by successive placement of plies one after the other. Parts are built-up rather than machined down. Prepreg "tape" and/or "fabric" material typically comes in rolls of relatively thin strips, composed from a textile impregnated with a non-polymerized resin.

Typical composite manufacturing processes e.g. for aerospace consist of filament winding, fiber placement, pultrusion, tape laying, tape wrapping, press molding, hand layup and resin transfer molding. A summary of composite manufacturing processes is shown in Table 1 and Table 2.

<table>
<thead>
<tr>
<th>SUPPLIED FORMS</th>
<th>PREPARATION METHODS</th>
<th>CURING METHODS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Prepreg tape of varying widths</td>
<td>• Filament winding-wet winding</td>
<td>• Autoclave/hydroclave</td>
</tr>
<tr>
<td>- unidirectional or fabric</td>
<td>or prepreg tool</td>
<td>• Oven</td>
</tr>
<tr>
<td>• Prepreg “tow” - preimpregnation fiber</td>
<td>• Hand layup</td>
<td>• Press</td>
</tr>
<tr>
<td>- blocks</td>
<td>• Tape wrapping</td>
<td>• Compression molding</td>
</tr>
<tr>
<td>• Dry fiber plus wet resin</td>
<td>• Tape laying</td>
<td></td>
</tr>
<tr>
<td>• Fiber-reinforced bulk modulus</td>
<td>• Pultrusion</td>
<td></td>
</tr>
<tr>
<td>- compound</td>
<td>• Polar winding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Braiding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Resin transfer molding</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fiber placement</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Processing technique
There are sensitive manufacturing variables that must be closely controlled during composite fabrication. The following chapter will give an overview of the main parameters which need to be mastered to assure the required quality level throughout the manufacturing process.

### 4.1 Environmental Condition - Workshop Ambiance

Most of the time, the workshop ambiance has to be controlled:

- **Temperature** (ex: 22°C ±3°C),
- **Hygrometry** (ex: <65%HR),

These both parameters are recorded all along the manufacturing phase.
• Requirement against the atmospheric pollution of the workshop (dust, grease, painting, use of silicone...)

4.2 Destocking of semi-products and maximum shelf life of materials

Fabrication of a detail part requires the material to be taken out of the freezer in a sealed bag and allowed to come to room temperature prior to any operations. Therefore a minimum resting time prior to usage needs to be respected.

Depending on the material type it could be that once the material is brought out of cool storage there is limited time it can be used to make parts (30 days is common). For very complex parts with many plies, the material's permissible out-time can be a controlling factor. If the material is not completely used, it may be returned to storage.

4.3 Tooling

The tooling required to fabricate most composite parts can be subdivided into several major categories including ply layup tools, skin or mould forms, curing aids, handling tools, drilling and trimming tools, assembly tools, moulds and mandrels.

Tools have to be checked and properly prepared and adjusted before operation begins. Any deviation, e.g. on surface quality or surface temperature could have an impact. All details for handling of the toolset before and during each manufacturing step has to be recorded.

4.4 Lay-up process

During lay-up it is necessary to include verification of the ply lay-up angle, its position in the stack, the number of plies, and the proper trim.

It is necessary to ensure although that all potential contaminates and foreign materials are not allowed to invade the material.

The most usual processes for lay-up are:

• Automated lay-up (filament winding, automated fibre placement, automated tape laying, …)
  In that case, the machine assured the suitable orientation of the fibres/tapes

• Manual lay-up
  In that case, one method consists in using a laser-ray which targeting layers from the ceiling and follows the fibber’s direction, in order to assist operator during lay-up (see pictures here after):
Overlap, thickness and clearance are locally controlled. Horizontal light is the mostly use mean for visual control.

4.5 Mould closing

For all closed mould processes like RTM-type or processes that are using any kind of vacuum bagging the proper closure and locking of the mould including a sealing
crosscheck is essential. For vacuum infusion processes the leak rate needs to be recorded prior to start of infusion.

4.6 Lamination – Infusion – Injection

For all non prepreg processes that require the application of reactive resin into the dry fibres the repeatability of the following parameters needs to be ensured and the values for each part recorded:

- Start and End
- Amount or weight of resin used
- Pressure prior and under infusion
- Any observation that indicates irregularities

4.7 Polymerization - Curing

During polymerization, if the cycle’s parameters are not fully respected, defects can appear on the final product. The table here below presents the most frequent anomalies linked to the polymerization cycle:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Too high temperature</td>
<td>Burning of the resin</td>
</tr>
<tr>
<td>Too low temperature</td>
<td>Too low final polymerization level</td>
</tr>
<tr>
<td>Non-homogeneous tempera</td>
<td>Internal stress</td>
</tr>
<tr>
<td>Too high negative pres</td>
<td>Increase the fiber fraction volume</td>
</tr>
<tr>
<td>Too low negative pres</td>
<td>Increase the porosity quantity</td>
</tr>
</tbody>
</table>

Table 7 failures during curing

To ensure proper conformance to time-temperature-pressure profiles, the curing cycle is monitored:

- Thermocouples are inserted inside the part and/or mould to ensure the control of the heating cycles (temperature & time),
- Pressure is also recorded.

These records are maintained for complete traceability of the parts.

4.8 Auto-control during manufacturing

To develop economic efficiency, keep a quality level and empower operators, operators are trained in order to perform control by themselves. Training is ensured by an internal or external authority.
Operators are monitored by the quality control office to maintain the needed quality level. They have to ensure that:

- Operations’ chronology is respected
- Manufacturing and control means are conform
- Operator’s traceability records are conform
- Failures are detected and warned
- Not conform products are kept away from workstation
- Operator’s abilities are maintained

These checks are generally performed:

- During final control
- Punctually random control
- Monitoring campaign ensured by the quality control office.

Main auto-controlled steps are presented here bellow:

- Applicable documents (technical and process documents,…) are firstly approved by the methods authority.
- Verify that previous operations are notified.
- Manufacturing and controlling means and tools conformity has to be checked.
- Control documents have to be correctly informed by the operator. (Manufacturing step process, reference, commentary…)
- Operator has to put his conformity stamp to certify the operations.
- Operator’s hierarchy have to be informed of the anomalies, in order that upgrades can be suggested
- In case of an anomaly is detected, the operator has to write a “report document”. Then, the control authority will choose to continue the operations or not.

4.9 Control and expertise on finished product

After manufacturing and before the delivery, controls and tests are systematically performed on the composite parts.

Theses controls and expertise can be made:

- On the part itself: limited to dimensional/geometrical and non-destructive test (NDT).
• For NDT topic, we propose to consider the document D7.1 (“Benchmarking of DT strategy and NDT catalogue”), chapter 6.4
• On samples manufactured in the same step than current part, or machined in scrap issued from the part itself. In that case, destructive tests such as micrographic cuts, DSC or even mechanical test on samples can be performed.

4.9.1 Curing:

The goal for the curing process is to reach 100% degree of cure. A lower degree of cure generally leads to lower tensile modulus, glass transition temperature and a decrease in thermal stability and chemical resistance for the matrix material. Factors influencing the degree of cure are amongst others resin chemical composition, curing time and temperature.

4.9.2 Delaminations:

Delaminations are cracks in the matrix between, or parallel to, reinforcement. The result is a decrease in the composites ability to carry load as the matrix primary job of distributing the load between the fibers is locally destrolled. In addition to this, a lowering in fatigue resistance might occur due to the fact that a crack is already present and the usually long time for crack initiation is vanished. Delaminations can appear as a result of fracturing and then due to interlaminar shearing. Delaminations may also occur during manufacturing usually as a result of poor wetting of the reinforcement. Another source of delamination, and an almost certain one, is machining of composites, for example drilling. It is practically impossible to cut a hole through a composite without the formation of at least a small damaged/delaminated are around the hole.

4.9.3 Voids:

These are simply bubbles of air trapped inside the composite when the curing is done. Voids can appear as single bubbles or in groups and the severity depends on size and location. A void leads to a local stress magnification/concentration in the surrounding material. As said elsewhere voids can act as the starting point for further delamination.

4.9.4 Inclusions:

Closely related to voids, inclusions are non-wanted particles, contaminations, embedded in the composite and are introduced in the manufacturing stage. The
problems related to inclusions depends on the type of inclusion, a soft weak material acts similar to a void and a hard brittle one as a source of crack initiation and delamination. The size of the inclusion is of course important, most common is ordinary dust carried by air and it should of course be kept to a minimum as a layer of dust on the preform inhibits fibre-matrix bonding ability. Larger inclusions may, if large enough, distort the reinforcement. A “perfect” inclusion, with properties suiting the matrix might not cause many problems if the inclusion bonds to the matrix and otherwise have the right properties. But all and all inclusions should be avoided and the simplest way to do that is to keep the production environment clean and airborne dust quantity to a minimum.

4.9.5 Fibre volume fraction:

Disturbances in production may result in local fibre volume fraction variations. This most often appear where the fibres are forces to make sharp turns, small radii, or around holes introduced in the moulding. The result is usually a local matrix enrichment that locally decreases the load carrying ability and thus increases damage sensibility. Another possibility is to get a local matrix shortage i.e. fibres touching each other after the matrix material has been injected and cured. Touching fibres may also be a result of pre matrix introduction bending of the reinforcement but also poor fibre wetting by the matrix. The result of touching fibres is a, however small, delaminated area.

4.9.6 Reinforcement distortion:

Since the composites strength and stiffness is so closely related to the fibre properties, fibre alignment becomes very important. However small the misalignment might be it immediately results in some additional interlaminar shear stress when the laminated is strained.

The stresses are of course small when the misalignment is small. Ply or fibre waviness causes additional fibre-matrix interface shear stresses when the composite is strained.

4.9.7 Core shape and location:

Foam/honeycomb core shape and location and core to lamina adhesion are things that might adversely affect the strength and stiffness if there are problems with them.
4.9.8 **Micro cracking:**

Micro cracking is most common as a result of service use, but some micro cracking might appear when curing the composite as a result of thermal stressing. This often depends on the usually large difference in coefficient of thermal expansion between the matrix and the fibres. The in service micro cracking depends mainly on the matrix starting to break away from fibres not oriented in the direction of strain. As the ultimate strength of a laminate in tension is governed by the strength of the fibres, these resin micro-cracks do not immediately reduce the ultimate properties of the laminate. However, in an environment such as water or moist air, the micro-cracked laminate will absorb considerably more water than an un-cracked laminate.

4.9.9 **Chemical damage:**

This is more common in use than in manufacturing. This kind of damages includes water absorption and attack by other chemicals as fuel, oil, etc.. As long as the matrix raw material is stored under the appropriate conditions and eventual machining coolant and penetrant testing fluids are selected to suit the composite constituents the potential chemical degradation will occur during the details service life. Water absorption leads to a lowering in Tg for the matrix and the result is among others deteriorated high temperature properties, increase in weight, moisture attack on the resin and fibre sizing agents, loss of stiffness and, with time an eventual drop in ultimate properties. Other chemical may cause problems like destroyed fibre-matrix interface and surface cracking. Protective coating will help relieve these problems but the best way, when possible, is to choose materials that will not be affected by the service environment.

4.10 **FLAW DETECTION METHODS**

Finding interior defects on irregularities in composite material can be done either destructively or non destructive. Economic demands require that testing moves more and more from destructive to non destructive methods. Generally most of the techniques used for metal quality control may be used for composite control as well, adjustment to the hardware and procedures will often be necessary though. In figure 1 below most of the common testing techniques are compared to each other. The chance of flaw detection increases if several techniques are used, this since they all have their strong and weak sides, and for aerospace products it is often required that several test methods are used to ensure product quality.
<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Tap Test</th>
<th>A-Scan</th>
<th>C-Scan</th>
<th>X-Rays</th>
<th>Thermal</th>
<th>Dye Penet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Delams</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>N/A</td>
</tr>
<tr>
<td>Deep Delams</td>
<td>N/A</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>N/A</td>
</tr>
<tr>
<td>Full Dislams</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>N/A</td>
</tr>
<tr>
<td>Kissing Dislams</td>
<td>N/A</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Core Damage</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>N/A</td>
</tr>
<tr>
<td>Inclusions</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>N/A</td>
</tr>
<tr>
<td>Porosity</td>
<td>B</td>
<td>N/A</td>
<td>B</td>
<td>A</td>
<td>N/A</td>
<td>N/A</td>
<td>B</td>
</tr>
<tr>
<td>Voids</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>Backing Film</td>
<td>N/A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>N/A</td>
</tr>
<tr>
<td>Edge Damage</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>Heat Damage</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>N/A</td>
<td>B</td>
<td>N/A</td>
</tr>
<tr>
<td>Severe Impact</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>N/A</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Medium Impact</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>N/A</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>Minor Impact</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>N/A</td>
<td>C</td>
<td>N/A</td>
</tr>
<tr>
<td>Uneven Bondline</td>
<td>C</td>
<td>N/A</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>N/A</td>
</tr>
<tr>
<td>Weak Bond</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Water in Core</td>
<td>N/A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 8 Abilities of testing methods, A= Good, B=medium, C=not so good*

### 4.10.1 Visual inspection

This is the cheapest testing method to perform but have some obvious limitations. Defects detectable by vision are by nature those accessible from the parts outer surface. If visual inspection is required in the parts production governing documents inspection personnel will have to formal training and the inspection have to be performed in a certain environment with specified light conditions etc.

### 4.10.2 Tap test

Tap test is a simple test form and no more expensive than visual inspection. The idea is to listen to the sonic response that is the result of tapping the tested material with a solid hard object, a coin for example. If the response is a clear “tone” it is an OK sign, but if the response is a dull “thump” it is a sign of damage. As mentioned the simplest form of tap testing is performed using nothing other than the hand and ear of
the testing person, but several mechanized techniques for tap testing exist utilizing exact impact force/energy, computer analyzed response and of course simplified methods for recording the test results.

4.10.3 Ultrasonic inspection

Overall ultrasonic techniques are the most widely used NDT method for advanced composites. It has large potential to detect delaminations, voids, porosity, inclusions and in some cases other flaws like broken or distorted reinforcement. As mentioned earlier ultrasonics are all about studying the signal attenuation of a high frequency pulse passing through the test piece. Several types of ultrasonic techniques exists, the A-scan and C-scan listed in the figure above for example.

4.10.4 The A-scan

This technique is perhaps the simplest method of presenting ultrasonic information. The signals received by the transducer are rectified and displayed as the vertical deflection on an oscilloscope screen. An A-scan comprises a series of spikes whose position along the horizontal time axis can be calibrated in terms of depth in the sample under test so that the depth of a reflector can be measured. The amplitude of each echo gives some indication of the size and nature of the reflector, which might be a defect or a specimen boundary.

4.10.5 The C-scan technique

In this type of imaging a more complex scanning system is used such that the transducer is scanned in a plane parallel to the sample in a rectilinear raster pattern. However, modern computer controlled systems monitor the position of the transducer and store this with the ultrasonic data for that position.

The C-scan does not have the ability to determine at what depth in the material the damage is, but some c-scan computer software are able to be programmed to ignore small thickness variations that otherwise might be interpreted as interior defects.
4.10.6 X-ray or radiographic inspection;

X-ray inspection is performing by shooting a beam of radiation through the test piece and detecting the residual radiation emitted on the back side of the test piece. The difference in radiation intensity is due to that X-rays are attenuated by a mechanism involving changes in the energy states of electrons in the X-ray beam. X-radiography therefore relies on detecting changes in the electron density within the material along the length of the beam. The difference in intensity may either be used to develop suitable photographic film or by more recent techniques develop an instant computerized image. As neither delaminations nor disband affect that electron distribution significantly, these two defects are virtually invisible to X-rays.

4.10.7 Thermography:

Thermal response techniques have during recent years come more and more into use as a NDT technique for composite materials. There are several types of thermographic methods but they all have in common that the physical response to variations in temperature of the test piece is observed and measures in some way. Some thermography techniques are described shortly below.
4.10.8 Thermal Imaging:

Standard thermal imaging methods can be used passively to view structures as they heat up or cool down. The presence of water changes the local heat capacity of the structure and can be seen on the image as a cooler region.

4.10.9 Pulsed Thermography;

Pulsed thermography has been available for over 10 years and is an active method where the structures is heated by a short duration thermal pulse from flash lamp. The temperature profile of the surface is then monitored as a function of time. The principle is that the heat diffuses less well through a thermal barrier such as a delamination and the surface remains at a higher temperature above a defect of this type. Eventually the heat diffuses around the defect and the surface reaches an equilibrium state again. It is possible to use the temperature-time profile to determine the approximate depth of a defect.

4.10.10 Lock-in thermography;

This is another active method but instead of a single pulse of heat, the heat source is modulated continuously at a single frequency of modulation. Due to the periodic fluctuations of temperature it is possible to model the behavior of the structure as if the diffusion of heat obeyed the wave equation. This introduces the concept of phase. There is a phase lag between the source temperature and the surface temperature of the specimen and this will depend on the structure and its thermal properties. Hence, as well as having actual amplitude data, there is phase information that should give further insight into the condition of the structure. One immediate advantage in that the phase is unaffected by the local surface emissivity variations that cause problems with amplitude measurements.

4.10.11 Tomography:

This a non-destructive X-ray technique can be used for inspection and evaluation of composite structural components. It is also known as computerized axial tomography (CAT Scanning) and is based on the principle that radiation directed through a given volume of material will be differentially absorbed by the material according to its mass absorption and physical density. CT images produced are of cross-sectional slices through the object showing the internal distribution of the X-ray-attenuating properties of material. From these sophisticated radiation absorption measurements the material can be characterized. CAT-scan is still a young technique.
for composite control, it shows good results but is quite time consuming and requires quite expensive equipment.

![Diagram of material tolerances]

**Figure 4 Tests for finished composites**

As shown in the above figure, composites as well as other materials may suffer from local defects and/or defects that influence the whole part. The raw materials testing mentioned earlier should reduce the risk for defects on component level but still the risk for local defects remain and is mostly depending on processing/manufacturing. This section will describe examples of test and standards useful for determining production outcome.

The following table contains material tests recommended by the FAA.
Table 9 Test methods for finished composites

All of the material properties mentioned in the table above have in common that they will weaken the material in some way if there are problems with one or more of these characteristics. Most of the methods above are destructive methods which lead to the fact that they are most suitable for testing on hang on bars, simple panels manufactured parallel to the main product. For testing on the actual product Non Destructive Testing techniques are often the only option. The testing of hang on bars might be used to verify the process outcome and as additional verification of the raw material quality.
5 FIRST ARTICLE INSPECTION [3]

5.1 FAI General

5.1.1 Definition FAI

A complete, independent, and documented physical and functional inspection process to verify that prescribed production methods have produced an acceptable item as specified by engineering drawings, planning, purchase order, engineering specifications, and/or other applicable design documents.

5.1.2 Purpose

Provides objective evidence that all engineering, design and specification requirements, including process and manufacturing validation, are correctly understood, accounted for, verified and recorded of a consistent documentation requirement for aerospace components.

5.1.3 Evaluation Activities:

The organization should conduct the following activities in support of FAI;

- Review documentation for the manufacturing process (e.g., routing sheets, manufacturing/quality plans, manufacturing work instructions, etc.) to make sure all operations are complete as planned.
- Review referenced exhibits supporting the FAI (e.g., inspection data, test data, Acceptance Test Procedures, etc.) for completeness.
- Review non-conformance documentation (if any), for completeness.
- Review material certifications for compliance, as applicable.
- Verify that approved Special Process sources are used (as applicable), and that the manufacturing planning/routing document calls out the correct specification.
- Verify that Key Characteristic requirements have been met, as applicable.
- Verify part specific gages and/or tooling are qualified and traceable, as applicable.
- Verify that every design characteristic requirement is accounted for, uniquely identified and has inspection results traceable to each unique identifier.
- Note the company FAI procedure should address all evaluation activities
- Verification of all design characteristics.
- Material and Special Process Certifications.
- Manufacturing Process Verification.
- Non-conformance resolution.

5.1.4 Full or Partial FAI

A Full or Partial FAI should be performed when:

Deliverable 6.2 – Manufacturing acceptance criteria
Full FAI:
- New part introduction
- New supplier or new location of manufacture
- Lapse in production for more than 2 years
- When required by the customer

Partial (Delta) FAI:
- Design change
- A change in the method of manufacture (e.g. Tooling, Processes, Machine, Location, Numerical Control Program, Sequence of Manufacture).

5.1.5 Current Standards

AEROSPACE:
AS/EN/SJAC9102 Revision A – Aerospace First Article Inspection Requirement.
INTERNATIONAL AEROSPACE QUALITY GROUP.

AUTOMOTIVE:
ISO/TS16949 & ISO 9001 Standards - Production part approval process (PPAP).
INTERNATIONAL AUTOMOTIVE TASK FORCE.

5.1.6 Documentation - Forms

Form 1: Part Number Accountability shall be used to identify the part that is being first article inspected (FAI part) and associated sub-assemblies or detail parts.

Form 2: Product Accountability – Raw Material, Specifications and Special Process(s), Functional Testing shall be used if any material, special processes or functional testing are defined as a design requirement.

Form 3: Characteristic Accountability, Verification and Compatibility Evaluation shall be used to record an actual measurement or inspection/verification of the FAI part for every design characteristic on the drawing, including notes.

5.2 Contribution from Task WP 6.1

According to D6.1, the composite component and sub-component considered for the car body manufacturing process definition is as follows:
<table>
<thead>
<tr>
<th>„TOP“</th>
<th>Monolithic</th>
<th>Sandwich</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CFRP</td>
<td>CFRP – Toplayer</td>
</tr>
<tr>
<td></td>
<td>Resin: Epoxy</td>
<td>Resin: Epoxy</td>
</tr>
<tr>
<td></td>
<td>UD</td>
<td>top-layers: UD or quasi-isotropic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foam: Airex T90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Honeycomb: Aramid (alternative: Aluminium*)</td>
</tr>
<tr>
<td>2</td>
<td>GFRP</td>
<td>GFRP – Toplayer</td>
</tr>
<tr>
<td></td>
<td>Resin: Epoxy</td>
<td>Resin: Epoxy</td>
</tr>
<tr>
<td></td>
<td>quasi-isotropic</td>
<td>top-layers: quasi-isotropic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Foam: Airex T90</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Honeycomb: Aluminium (alternative: Aramid)</td>
</tr>
</tbody>
</table>

*) No direct combination of carbon fibres and Aluminium due to galvanic corrosion issues. But it is possible by using at least one layer of GFRP (100g/m² dry fabric) between Aluminium HC core and CFRP. Therefore this option is still possible as "Hybrid".

Table 10 Shortlist of materials considered for process determination

5.3 GEOMETRICAL

The following chapter is devoted to identifying the design characteristic related to geometrics and physical properties of the manufactured component or sub-component that might be considered for the FAI procedure.

5.3.1 General dimensions.

First of all, general dimensions have been identified as one of the design characteristic to be checked according to the drawings. They should be in concordance with the general tolerance requirement. (ISO standard)

✓ Coordinate measuring machine (CMM)

5.3.2 Weight.

This is one of the most important physical properties, due to light-weighting requirements, especially for composite parts.

Weight can be accounted for directly by means of a weighing scale or indirectly by means of parameters like the fibre content or density.

✓ Weighing scales.
5.3.3 Thickness.

The thickness is the most important dimension for geometrical definition of shell structures, such as panels or stiffeners or stringers. Due to its influence in the structure weight, checking is considered as mandatory.

- Gage: ultrasonic or Hall effect
- Standard Calliper

5.3.4 Dimensional tolerances.

Special attention should be paid in the geometric definition of detailed areas of the part (drawings). For instance, fittings, clamps, interface plates, inserts allocation, etc. For that, tolerance limits in holes or the distance between axes should be checked.

- Coordinate measuring machine (CMM)

5.3.5 Geometrical tolerances.

Flatness or perpendicularity tolerances are also usually limited in component design and manufacturing drawings. Therefore, they should be checked in order to assure correct assembly and proper fixing with other parts of the assembly.

- Coordinate measuring machine (CMM)

5.3.6 Surface finish and hardness.

It is also common to find special specifications on surface finishing for joining or painting, gel coating, veils, etc:

- Profilemeter
- Durometer
- Barcol impressor
- EN 92
5.3.7 Appearance

It should take into account that zones with dry fibres, excess of resin, flow marks, wrinkle are critical and those defects should be identified, marked and/or reported.

5.4 PHYSICAL

5.4.1 Density.
- Archimedes’ principle (buoyancy method).
  - Buoyancy method equipment.
  - ISO1183 / ASTM D792

5.4.2 Fibre volume fraction.
- Two principal techniques:
  - Dissolving matrix phase.
  - Burning matrix phase.

- Both techniques are based in weight differences. If filled resins are used, the filler content should be considered while burning or dissolving the matrix, in order to avoid deviations

  - ISO 1172 Method B

5.4.3 Void content.
- The void content of a composite may significantly affect some of its mechanical properties. Complementary test to obtain fibre volume fraction.

  - Dissolving matrix phase.
  - Burning matrix phase.

5.4.4 Fibre orientation.
- The fibre orientation is defined by fibre placement inside de mould cavity (RTM process) or stacking sequence (VART). However, fibre orientation should be verified, as it could be subjected to changes during the resin infusion process, or deformed by mould compression.

- Same techniques as fibre volume fraction.
5.4.5 Glass transition temperatures ($T_g$) and degree of Polymerisation (%).

Achieving a glass transition temperature that is close to the values given in the TDS proves the compliance with the intended process. While the degree of polymerisation proves that the process was finally producing the requested material performance.

- DSC (Differential scanning Calorimetry)
- ASTM D7028.

5.4.6 Fibre matrix adherence

- The fibre-matrix adherence is verified and validated by performing an analysis of a broken specimen microstructure.

- REM (Entanglement Electromicroscopy)

5.5 STRUCTURAL

Next, chapter is devoted to identifying the mechanical properties related to static and dynamics performance of the manufactured component or sub-component. There is a direct relationship between structural response and process parameters.

- Curing process curve (pressure and temperature).
- Resin volume fraction reached after compression.
- Fibre orientation, wrinkling or deformation during infusion or compression process.
- Curing grade.
- Adherence fibre-matrix.

5.5.1 Static properties/resistance.

The following table shows the typical mechanical properties test (standards) for the materials considered in D6.1.

<table>
<thead>
<tr>
<th>MONOLITHIC</th>
<th>SANDWICH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Properties</td>
<td>Long Beam Flexure Test</td>
</tr>
</tbody>
</table>

Deliverable 6.2 – Manufacturing acceptance criteria
<table>
<thead>
<tr>
<th>Test Category</th>
<th>Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Properties</td>
<td>ASTM D3039</td>
</tr>
<tr>
<td></td>
<td>(ASTM C-393)</td>
</tr>
<tr>
<td>Short Beam Shear Test</td>
<td>ASTM D3410</td>
</tr>
<tr>
<td>In-plane Shear Response</td>
<td>ASTM D3518</td>
</tr>
<tr>
<td>Edgewise Compression Test</td>
<td>(ASTM C-364)</td>
</tr>
<tr>
<td>Flexure Properties</td>
<td>ASTM D790</td>
</tr>
<tr>
<td>Flatwise Tension Test</td>
<td>(ASTM C-297)</td>
</tr>
<tr>
<td>Interlaminar Shear Strength</td>
<td>ASTM D2344</td>
</tr>
<tr>
<td>Peel Test</td>
<td>(ASTM D-1781)</td>
</tr>
</tbody>
</table>

Table 11 Static Tests

5.5.2 Fracture mechanics or impact resistance.
- Some test and standards to characterize impact loading and resistance:
  ✓ Charpy or Izood.
  ✓ ASTM D256

- Crack propagation/evolution:
  ✓ End-Notched Flexure Testing ENF (3 point bending) and Analysis of Mode II. Interlaminar Fracture Behaviour of Glass-Cloth/Epoxy Laminates.
  ✓ Four-point end notched (4ENF) for Mode II.

5.5.3 Dynamics properties.
- Not only static response of the composite part might be checked but also dynamic response (modal analysis). Some of the parameters that might be specified are: natural frequencies, mode shapes, damping or dynamic stiffness.
  ✓ Impulse or excitation hammer.
5.5.4 **Fatigue (endurance)**
- Mechanical response of component to cyclic loading.
  ✓ S-N curves, $\varepsilon$-N curves.
  ✓ Influence of mean stress.

5.5.5 **Ageing (durability)**
- It should be required or specified to assure the evolution of mechanical properties during component service life and component strength against environmental conditions.
  ✓ Humidity.
  ✓ Temperature.
  ✓ UV-radiation.
  ✓ Wear resistance.
  ✓ EN 60068 – Environmental testing

5.6 **FIRE.**

Main objectives of design against fire is to switch off combustion process and avoid toxicity
  ✓ Development of new polymer material (fireproof).
  ✓ Modification of well-known polymer material.
  ✓ Additives.

5.6.1 **Requirements**

According to standard CEN-TS_45545, Fire protection railway vehicles, the requirements related to fire performance of materials and components depend on their intrinsic nature but also:
  ✓ on the location of the materials or components within the design;
  ✓ on the shape and the layout of the materials;
  ✓ on surface directly exposed and the relative mass and the thickness of the materials.

It is on this basis that listed products have been classified and further differentiated into subgroups as follows:
  ✓ their general location (interiors or exteriors);
✓ their specific use (furniture, electro technical equipment, mechanical equipment)

### Table 4: Requirements of listed products (continue)

<table>
<thead>
<tr>
<th>Product No</th>
<th>Name</th>
<th>Description</th>
<th>Requirement</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>EX</td>
<td>Exterior located</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EX 1a</td>
<td>External body shell, walls</td>
<td>Vertical parts of external structure of body shell and door leaves (including paint/coating systems, films)</td>
<td>R6</td>
<td></td>
</tr>
<tr>
<td>EX 1b</td>
<td>External cab housing</td>
<td>Front of the train until Cab partition (including paint/coating systems, films)</td>
<td>R16</td>
<td></td>
</tr>
<tr>
<td>EX 2</td>
<td>External body shell, roof</td>
<td>External roof structure of the car body (including paint/coating systems, films)</td>
<td>R7</td>
<td>Respect of R6 is considered complying R7</td>
</tr>
<tr>
<td>EX 3</td>
<td>External body shell, underframe</td>
<td>External surfaces of underframe structure of the body shell (floor) including paint and coating systems (thermal, design and acoustic coating) and protective floor paneling</td>
<td>R6</td>
<td></td>
</tr>
</tbody>
</table>

**Table 12 Example of requirements - external body car structure**

#### 5.6.2 Validation tests and hazardous levels.

According to design and operation categories of the train, hazardous levels are defined:

### Table 7 Set of material requirements (continue)

<table>
<thead>
<tr>
<th>Short name of requirement set (used for)</th>
<th>Test method Reference</th>
<th>Parameter Unit</th>
<th>Requirement Definition</th>
<th>HL1</th>
<th>HL2</th>
<th>HL3</th>
</tr>
</thead>
<tbody>
<tr>
<td>R6 (IN6: EX 1a EX3: EX4; EX5; EX6; EX7; EX8; E2B clause 6.3.4; E4C clause 5.4.1)</td>
<td>T02 ISO 5659-2</td>
<td>CFE kWhm²</td>
<td>Minimum</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>T03:01 ISO 5660-1:50kWhm²</td>
<td>MARRE kWhm²</td>
<td>Maximum</td>
<td>90</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>T10:01 EN ISO 5659-2: 50kWhm²</td>
<td>Uₘₜ max dimensionless</td>
<td>Maximum</td>
<td>-</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>T11:01 EN ISO 5659-2: 50kWhm²</td>
<td>CITₕ dimensionless</td>
<td>Minimum</td>
<td>-</td>
<td>1.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

**Table 13 Hazardous levels – R6 class requirement**
### 5.6.3 Test method (list extracted from CEN-TS_45545)

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Standard</th>
<th>Short description</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>T01</td>
<td>EN ISO 4589-2</td>
<td>Determination of burning behaviour by oxygen index</td>
<td>OI</td>
</tr>
<tr>
<td>T02</td>
<td>ISO 5656-2</td>
<td>Lateral Flame Spread</td>
<td>CFE</td>
</tr>
<tr>
<td>T03.1</td>
<td>ISO 5660-1</td>
<td>Fire test – Reaction to fire: Part 1 Rate of heat release (Cone calorimeter Method)</td>
<td>MARHE</td>
</tr>
<tr>
<td>T03.2</td>
<td>ISO 5660-1</td>
<td>Fire test – Reaction to fire: Part 1 Rate of heat release (Cone calorimeter Method)</td>
<td>MARHE</td>
</tr>
<tr>
<td>T04</td>
<td>EN ISO 9239-1</td>
<td>Radiant panel test for horizontal flame spread of floorings</td>
<td>CFR</td>
</tr>
<tr>
<td>T05</td>
<td>EN ISO 11925-2</td>
<td>Ignition when subjected to direct impingement of flame</td>
<td>ISO x Flame application</td>
</tr>
<tr>
<td>T06</td>
<td>ISO 9706-2</td>
<td>Furniture Calorimeter retracted seat;</td>
<td>MARHE</td>
</tr>
<tr>
<td>T07</td>
<td>EN ISO 12952 –3/4</td>
<td>Burning behaviour of bedding products Part 3/4: Ignitability by a small open flame</td>
<td>After burning time</td>
</tr>
<tr>
<td>T08</td>
<td>IEC 60385-1-40</td>
<td>Guidance for assessing the fire hazard of electrotechnical products – Insulating liquid</td>
<td>Class K</td>
</tr>
<tr>
<td>T09.1</td>
<td>EN 60332-1-2</td>
<td>Tests on electric and optical fibre cables under fire conditions – Part 1:2 Test for vertical flame propagation for a single insulated wire or cable – Procedure for 1 kW pre-mixed flame</td>
<td>Height of burned zone and height of unburned zone</td>
</tr>
<tr>
<td>T09.2</td>
<td>EN 50266-2-4</td>
<td>Common test methods for cables under fire conditions – Test for vertical flame spread of vertically-mounted bunches of wire or cables, Part 2-4: Procedures – Category C</td>
<td>Height of burned zone front side and backside</td>
</tr>
<tr>
<td>T09.3</td>
<td>EN 50305 § 9.1.1</td>
<td>Railway applications – Railway rolling stock cables having special fire performance – Test methods</td>
<td>Height of burned zone front side and backside</td>
</tr>
<tr>
<td>T09.4</td>
<td>EN 50305 § 9.1.2</td>
<td>Railway applications – Railway rolling stock cables having special fire performance – Test methods</td>
<td>Height of burned zone front side and backside</td>
</tr>
<tr>
<td>T10.01</td>
<td>EN ISO 5659-2</td>
<td>Plastics – Smoke generation Part 2 determination of optical density by a single-chamber test</td>
<td>Ds (4) see # 3.1.2</td>
</tr>
<tr>
<td>T10.02</td>
<td>EN ISO 5659-2</td>
<td>Plastics – Smoke generation Part 2 determination of optical density by a single-chamber test</td>
<td>VOI (4) see # 3.1.3</td>
</tr>
<tr>
<td>T10.03</td>
<td>EN ISO 5659-2</td>
<td>Plastics – Smoke generation Part 2 determination of optical density by a single-chamber test</td>
<td>Ds (max) see # 3.1.2</td>
</tr>
<tr>
<td>T10.04</td>
<td>EN ISO 5659-2</td>
<td>Plastics – Smoke generation Part 2 determination of optical density by a single-chamber test</td>
<td>Ds (max) see # 3.1.2</td>
</tr>
<tr>
<td>T11.01</td>
<td>CEN/TS 45545-2 Annex C</td>
<td>Gas analysis in the smoke box EN ISO 5659-2, using FTIR technique</td>
<td>CTF_E at 4 and 8 min</td>
</tr>
<tr>
<td>T11.02</td>
<td>CEN/TS 45545-2 Annex C</td>
<td>Gas analysis in the smoke box EN ISO 5659-2, using FTIR technique</td>
<td>CTF_E at 4 and 8 min</td>
</tr>
<tr>
<td>T12</td>
<td>NF X 70-100-1 NF X 70-100-2</td>
<td>Gas analysis for the 8 gases described on # 3.1.5 C1; C1H; C1H2; C1H3; C1H4; C1H5; C1H6; C1H7</td>
<td>CTF_E at 4 and 8 min</td>
</tr>
<tr>
<td>T13</td>
<td>EN 61554-2</td>
<td>Measurement of smoke density of cables burning under defined conditions Part 2: Test procedure and requirements</td>
<td>Transmission</td>
</tr>
<tr>
<td>T14</td>
<td>EN 13501-1</td>
<td>Fire classification of construction products and building elements Part 1 Classification using test data from reaction to fire tests</td>
<td>Table 1</td>
</tr>
</tbody>
</table>

Table 14 Test method (list extracted from CEN-TS_45545)

Deliverable 6.2 – Manufacturing acceptance criteria
6 TRACEABILITY OF PROCESS PARAMETER – IN PROCESS DOCUMENTATION

6.1 General requirements

Each manufacturing step has to be monitored and recorded. For this the usage of a Process Control Sheets (PCS) is state of the art, where all important manufacturing process parameters of each part can easily be traced. Because of the high number of process parameters to be recorded the use of digital systems is recommended.

6.2 PCS - Content

As a minimum, the following data shall be recorded and archived on the PCS:

- PART INFORMATION
  - material number
  - drawing number & revision level
  - Supplier identification (and/or serial) number
  - Mould identification number

- GEL COATING, if applicable
  - Raw material batch number(s)
  - Catalyst and accelerator ratios
  - Quantity of raw materials consumed
  - Gel coat spraying room, gel coat and mould temperatures
  - Wet film thickness at a minimum of three (3) locations (per sketch)
  - Operator ID, start and end time and date

- MIXING, if applicable
  - Raw material batch numbers (resin, catalyst, filler, etc.)
  - Mixing room temperature
  - Operator ID, start and end time and date

- LAMINATING
  - Raw material batch numbers (fibre reinforcements)
  - Quantity of resin and filler consumed
  - Acknowledgement for each reinforcement layer applied, Ply book
  - Operator ID, start and end time and date

- POLYMERISATION - CURING
  - Hardness level (Barcol) measured in at least three (3) different locations on the part
  - Operator ID, start and end time and date
• DE-MOULDING
  o Operator ID, date

• POST CURING, if applicable
  o Temperature curve
  o Final hardness level (Barcol), nine (9) readings per square meter (1 per square foot)
  o Operator ID, start and end time and date

• TRIMMING
  o Operator ID, date

• FRP THICKNESS
  o At controlled & conformed areas
  o Operator ID, date

• MASS
  o FRP Mass
  o Operator ID, date

• SURFACE PREPARATION
  o Operator ID, date

• ASSEMBLY
  o Functionality assessment
  o Operator ID, date

• INTERMEDIATE QUALITY GATE(S)
  o PASS or FAIL
  o Operator ID, date

Storage of the records and access to all parameters collected should be possible during the entire time of operation.
7 QUALIFICATION NEEDS FOR COMPANIES, PRODUCTION LINES AND EMPLOYEES

As of today none of the companies and neither their workforce, currently producing FRP parts for railway applications, have to undergo any kind of certification in order to prove their level of specific experience with the FRP material. This is mostly driven by the facts that such regulations are nearly not existing for railway parts, but also by the nature of the majority of today’s railway FRP parts, as being mainly non-structural. Nevertheless the number of semi-structural application used at safety relevant locations of modern trains is raising. Today most of the FRP exterior parts for trains have to prove their performance using FEA calculation and subsequently need to show how the conformity of the FEA assumptions with the results of the manufacturing line is achieved and guaranteed under serial conditions. For this the certification of the companies, the assessment of the related infrastructure and internal processes as well as the independent education and certification of the related workforce is essential. Examples from wind industry and bonding for railway vehicles or part need to be considered to define a potential way forward to a regulatory approach for manufacturing lines.

7.1 Qualification for Companies

Germanischer Loyd (GL) is one of the certifying bodies within the wind industry. In one of its publication: “Rules for Classification and Construction part II - Materials and Welding - section 1 Fibre Reinforced Plastics and Bonding; Chapter D 1.1 it is required that "Manufacture of FRP-components shall only be performed by workshops which are approved by GL for the manufacture of components made from fibre-reinforced thermosetting resins". Further GL provides in its publication a detailed list of requirements that needs to be fulfilled to get certified by them.


Finally there is also a railway related standard that deals with the qualification needs for FRP manufacturer. The NF F 01-281- Railway rolling stock — Parts in fibre-reinforced thermosetting composites — Specifications, test methods, manufacturing, qualification and assessment of conformity; is giving detailed requirements on the infrastructural and process limitations for the manufacturing
7.2 **Technical equipment**

All technical equipment used for the related processes needs to be validated and verified to prove the ability to ensure the manufacturing of parts of repeatable quality and performance.

7.3 **Qualification for workforce**

In order to ensure stable quality of the manufacturing line the manufacture of FRP-components shall only be carried out by persons with sufficient professional knowledge and skills with respect to FRP. This professional knowledge and the skill level should be provided in training courses followed by an examination that proves the effectiveness of the course. Finally the success should be verified by certificates that can be used for the work force part of qualification of the company.

7.4 **Manufacturing surveillance**

For the manufacturing of FRP parts or components a manufacturing surveillance is essential and should cover the control of the material used for manufacturing, the surveillance of the real production line, including intermediate quality gates, and the inspection of the finished parts or components prior to further activities like e.g. assembly, shipment or installation. Also performing of structural tests at randomly chosen samples could be considered.

Manufacturing surveillance can be carried out internally, using company internal processes and qualified internal personnel, or by third –party surveillance. The level of surveillance needs to be aligned with the part class (level of safety relevance, refer to chapter 2 of this document) and the level of certification of the manufacturing company.

7.5 **Documentation**

All records of the manufacturing steps have to be documented per part in a traceable manner as described in chapter 7 of this document. This and all reports of the manufacturing surveillance have to be filed. The time frame for the storage of these documents should depend on the part class. This means, that for parts with a high safety relevance the storage time should be the whole lifetime of the component. The same approach should be used for the storage of physical samples out of the serial production of the parts. Both, the storage of the related documents and the physical samples of the manufacturing could later provide evidence for failure analysis if necessary.
8 REGULATIVE FRAMEWORK PROPOSAL/ APPROACH

To reach a common regulatory framework for the European rail industry it is necessary to have a system of norms and standards which covers a whole range of manufacturing processes versus the different level of structural performance of the considered components or parts.

8.1 Processes

As a result of WP 6.1 a comprehensive list of potential processes used for structural applications, their advantages and disadvantages was provided. These processes were grouped into 5 main categories:

- Contact moulding processes
- Vacuum assisted processes
- RTM-type processes
- Prepreg type processes
- Continuous processes

Any potential regulatory framework has to cover the specific conditions and requirements that are linked to these processes.

8.2 Performance level/ definition of part classes

In order to keep the cost impact caused by the additional measures for certification, process validation and verification and the related documentation within an acceptable level, while at the same time cover all necessary aspects, the definition of different usage and performance levels or classes for the parts or components is recommended.

8.2.1 Part Class C – Non-structural components

Parts or components that have only to carry their own weight with no major additional loads and parts that are not belonging to part class A or B.

Examples are e.g. interior parts or small exterior covers for antennas or cameras

8.2.2 Part Class B – Structural components

Parts or components with no major safety relevance and/or that are loaded with additional extra loadings like passenger loads, pressure pulses; that normally require additionally FEA calculation.

Examples are e.g. exterior covers, cab covers, interior stairs
8.2.3 Part Class A – Fully structural components

Parts or components with direct safety relevant functions and/or that are a direct member of the load bearing path of the primary structure.

Examples are e.g.: Load bearing cab structures, bolster structures, sidewall elements

8.3 COMPETITIVE CONTENT

Information like

- Processes for FAI’s
- Detailed QA measures during manufacturing
- Details of incoming/ outgoing goods control processes

are to be seen as competitive processes which not need to be part of a European framework. The intended framework should only cover the minimum set of requirements on these processes, in order to guarantee traceability and repeatability

8.4 SPECIFIC REQUIREMENTS

Norms which are defining specific requirements for rail vehicles like the EN 45545 for Fire and Smoke or the EN 12663 for Structural requirements are not recommended to be part of the framework.

They represent requirements which have to be fulfilled for each rail vehicle, independent from the material of the body shell but it need to be discussed if they need to be adopted to fit for composites.

8.5 EXISTING NORMS/ FRAMEWORKS

8.5.1 EN 15085

In front of the above mentioned background the existing EN 15085 gives an excellent example for a regulatory framework for welded connections in metallic structures. The idea of the framework is to cover all requirements for design, layout, assessment and quality assurance approach based on the same philosophy.

This gives a clear guideline which enables supplier and customer to reach a stable quality. It makes results and requirements transparent and secures the comparability of welding manufacturers. It leads to the possibility of objective cost evaluations and clear responsibilities.

The EN 15085 consists of different parts which are dealing with different topics.

They are:

- Part 1 – General
Defines Terms and gives general comments

- **Part 2 – Quality requirements and certification of welding manufacturers**
  Defines certification levels for the product and relates them to Qualification needs to the manufacturers

- **Part 3 – Design requirements**
  Creates a relation of safety categories (LOW/ MEDIUM/ HIGH) and stress category (Fatigue utilisation). This is related to performance classes (CP A to CP D) for the welding seam which are related to inspection classes (T 1 to 4).
  The inspection class defines the necessary effort for testing. Gives advises for the design engineer regarding the arrangement of welding seams.

- **Part 4 – Production requirements**
  Defines steps for the manufacturing of a welded connection.
  Mentions documents for planning and exceptions for testing.
  Defines rules for repairs.

- **Part 5 – Inspection, testing and documentation**
  It defines rules for planning and documentation of QA measures in the manufacturing.

The EN 15085 explicitly excludes methodologies, boundaries and values for static and fatigue analysis.

**8.5.2 GL Rules for Classification and Construction part II – Materials and Welding; section 1 Fibre Reinforced Plastics and Bonding**

This comprehensive standard for design and construction of wind turbines is describing detailed requirements for FRP materials, because this material is vastly used in structural applications for these structures.

- **Chapter A – Definitions**
- **Chapter B – Materials**
  - Thermosetting resins
  - Reinforcing materials
  - Core materials for sandwich construction
  - Prepregs
  - Adhesives
- **Chapter C – Approval of materials**
- **Chapter D – Requirements for manufacturers**
• Approval by GL required for workshop
• Laminating workshop requirements
• Storage rooms requirements

• Chapter E – Guidelines for processing
  • General requirements
  • Requirements for moulds
  • Building up the laminate
  • Glass-fibre spraying
  • Curing and tempering
  • Adhesive bonding

• Chapter F – Manufacturing surveillance
  • General
  • Incoming inspection
  • Production surveillance
  • Structural tests

Under all existing standards considered in this chapter this seems to be closest to the needs of structural FRP parts for railway applications.

8.5.3 DIN 6701 – Adhesive bonding of railway vehicles and parts

The DIN 6701 represents a national framework for bonded structures in the rail industry and it follows the same approach as the EN 15085.

This Regulation consists of the following parts:

• Part 1 – Basic terms
  Defines Terms and gives general comments

• Part 2 – Qualification of manufacturer of adhesive bonded materials
  Classifies bonded connections in relation to the qualification of the manufacturers. Defines qualification needs for manufacturers.

• Part 3 – Guideline for construction design and verification
  Classifies bonded connections in relation to safety needs. Gives advises for the design. Specifies testing and supports dimensioning.

• Part 4 – Manufacturing controls and quality assurance
  Defines steps for the manufacturing of a welded connection. Mentions documents for planning and exceptions for testing. Defines rules for repairs.
Additional parts are in preparation for manufacturing planning and quality assurance.

8.5.4 NF F 01 281 – Railway rolling stock — Parts in fibre-reinforced thermo-setting composites

Originally this is a very old, but very useful standard, with the actual revision of 2014 to cover the latest developments. It was mainly used in the part for non-structural or semi-structural parts and covers the following main points

- **Part classes**
  Classification of the parts with respect to their usage

- **Requirements on materials**
  Material selection, matrix, reinforcement, cores and metal parts

- **Requirements on finished parts**
  Definition of failure and defects, visual aspects, dimensional and weight tolerances, minimal values for mechanical properties, degree of polymerization and BARCOL hardness, Fire performance

- **Test methods**
  Definition of the tests required to determine compliance with the above mentioned requirements

- **Marking requirements**
  Definition of minimum requirements on marking of parts

- **Packaging and labeling**
  Definition of minimum requirements on packaging and related labeling

- **Manufacturing**
  Requirements on process control sheet and process parameters

- **FAI**

8.6 CONCLUSION

As pointed out in the report of WP 6.1 and in the above chapters of this document, there are quite a lot of manufacturing parameters influencing the final performance of a composite part, not all of them are testable in a non-destructive way. These vast number of parameters are nearly impossible to include in a separate regulatory framework. At the same time a strong focus on today’s set of parameters would limit the ability of a future regulatory framework to cope with future new developments. Therefore an approach is recommended to handle the production line within a manufacturing company as a process itself, that has to fulfil specific requirements, and that needs to be certified by a third-party assessor. Naturally, Companies that

Deliverable 6.2 – Manufacturing acceptance criteria
manufacture parts that are highly structural loaded and parts with a higher safety relevance require a different level of requirements compared to those delivering non-structural parts only. It is recommended to use the structure of the in the following chapters of this document mentioned regulations, to adopt and development them as mentioned towards to the rail requirements and once approved to give them the status of a European Norm.

8.6.1 Part Class C – Non-structural components

For this kind of parts the regulation of NF F 01-281 delivers a good starting point for further standardisation work. All necessary steps of composite manufacturing are covered, and the only missing package is the lacking certification of the manufacturing site internal working structure, processes and workforce. For this the approach of DIN 6701 part 2 and 4 should be adapted into a new certification standard.

8.6.2 Part Class B – Structural components

For this group of parts the more stringent requirements stipulated in GL Rules for Classification and Construction part II – Materials and Welding; section 1 Fibre Reinforced Plastics and Bonding; and the classification approach of DIN 6701 should be used as the base to develop the manufacturing acceptance for structural composite components.

8.6.3 Part Class A – Fully structural components

For the manufacturing of part class A parts the approach of chapter 9.6.2 – Part Class B – Structural components - above should be implemented in combination with a mandatory third-party inspection of the related production and the additional requirement of small reference samples that could be used for witnessing compliance of production with performance achieved during FAI.
9 SUMMARY

In this subtask an overview about the major steps of the manufacturing of a composite part or component is given, based on existing norms and standards used in aircraft and automotive industry. These steps cover incoming goods control, in-process control up to the First Article Inspection.

Most of the standards are general applicable for all kinds of composites and therefore also can be used for structural parts in railway applications.

According to the agreements from the beginning of this projects tests have not been performed.

In the last chapter a recommendation for the structure of a regulatory framework is given, referring to existing regulations form wind industry and from railway bonding. For further activities in regard to such a framework, the introduction of the related regulation boards is strongly recommended.
### Norms and standards cited

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11 REFERENCES

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