Master thesis within light warhead for support weapon

Investigation of defects, methods and requirement specifications in order to get a shell body shatter free

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Examensarbete inom lätt verkansdel för understödsvapen

Utredning av defekter, provningsmetoder och kravställningar för att erhålla en splitterfri granathylsa

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Abstract

At launching the shell body, especially the backplane of the shell body, will be exposed to very high stresses due to acceleration, pressure and increased temperature from the propellant combustion. Defects in the shell body could in worst case for example result in high temperature gas leakage into the warhead and thereby ignite the explosives before exiting the launcher. This kind of explosion results in serious damages and can seriously injure both the gunner and other people in the surroundings.

According to earlier study, carbon fibre reinforced epoxy with filament winding manufacturing method was the primary focus. The purpose of this master thesis was to investigate requirements and testing methods on a shell body manufactured in composite that will guarantee the safety of the gunner and surroundings in the launch phase.

The pre-study conducted in this project showed that matrix cracks and fibre breakages are most common defects in the shell body that occur during launching affected by burst pressure. Matrix crack is the less dangerous defect among the impact damage types. Discussion with composite manufacturing companies showed that fibre breakage is a very serious type of defect since more breakage of fibres leads to the shell body have reduced stresses and cannot built-up the fully potential burst pressure during launching.

Two requirement specifications were carried out, one for the shell body and another for the detection methods. These were created by own research and ideas according to found information, telephone- and e-mail contact with experts in areas and with personnel at Saab Dynamics AB.
Some requirements for the shell body were that it should be fully usable after drop tests from different heights, vibration and transportation tests yield no cyclic damage after a long transport. Furthermore, the shell body should always use a fully isolated driving band to not have hot explosive gases penetrated into critical sections which results in detonation already in the launcher barrel. The most important requirements for the detection methods were to have depth analysis, high reliability and in-field inspection.

Elimination- and decision matrices were made to find which detection methods should be the final selections in order to find the defects in a shell body. The detection methods which did not fulfil the criteria from each separate matrix were eliminated and did not proceed further as a concept. Eliminations were performed in concept generation phase (elimination matrix) and concept selection phase (decision matrix). In final selection phase a couple of methods were chosen that together found as many defects as possible.

By using both acoustic emission and shearography all the critical defects and a wide range of other defects can be detected with very high reliability and resolution at an acceptable cost. These two methods “interact” perfectly with each other. Acoustic emission is the best method to find fibre breakage and matrix cracks, which are the most commonly occurring defects during launching. But shearography does not have a good detectability of fibre breakage and matrix cracks. On the other hand, shearography has good detectability of both planar- and volumetric defects.

It is concluded that only two inspection methods, i.e. acoustic emission and shearography are needed to detect all of the possible defects in the grenade shell body. This is more economical solution requiring smaller space and fewer operators compared to one separate NDT method for detecting each type of defect.

Sammanfattning

Vid utskjutning av granathylsan utsätts framförallt bakplanet, för mycket höga påfrestningar genom acceleration, tryck och förhöjd temperatur från krutförbränningen. Vid en genombränning av granatskalet skulle sprängämnet i verkansdelen kunna tändas redan i eldröret och orsaka en vapensprängning. Den här typen av explosion resulterar i allvarliga skador både för skytten samt folk i dess omgivning.

Med hänsyn till tidigare studier har det varit fokus på kolfiberförstärkt epoxi som är tillverkad av fiberlindning. Syftet var att utreda kravställningar och metoder för provning, som garanterar skyttens och omgivningens säkerhet i utskjutningsfasen av en granat tillverkad av kompositmaterial.

Från förstudien i denna rapport visade sig att matrissprickor och fiberbrott är de vanligaste defekter som uppstår i granathylsan under utskjutningsfasen där den största påverkan är ifrån explosionstrycket. Matrissprickor är de mindre farliga defekter av de som uppstår under intryckning. Diskussion med komposittillverkande företag visade att fiberbrott är en väldigt farlig typ av defekt eftersom fibrerna står för styrkan och brott av fibrer leder till att granathylsan klarar av att utsättas för lägre påfrestningar och kan inte hjälpa till att bygga upp det önskvärda trycket som önskas under utskjutningen.

Två kravspecifikationer utfärdades, en för granathylsan och en annan för detekteringsmetoderna. Dessa två skapades genom egen studie och idéer med hänsyn till hittad information, ifrån telefon- samt email kontakt med experter inom områdena samt med hjälp av personal på Saab Dynamics AB.
Några krav som valdes för granathylsan var att den ska vara fullt användbar efter fallskärmsprovning från olika höjder, vibration- och transport tester för att inte få cykliska skador efter en lång transportering samt att alltid ha en fullt isolerad gördel så att inte de heta gaserna från explosivorna tänds redan i eldröret vilket orsakar vapensprängning.
Några krav för detekteringsmetoder var att de ska kunna göra mätningar/analyser på djupet, ha hög trovärdighet samt vara portabel.

Eliminering- och beslutsmatriser gjordes för att hitta vilka detekteringsmetoder som skulle bli de slutliga valen i jakten på att finna defekterna i granathylsan. De metoder som inte uppfyllde kriterierna från respektive matris blev eliminerade. Elimineringen utfördes i faserna för konceptgenerering och konceptval. I slutliga valet valdes ett par lämpliga metoder som tillsammans hittar så många defekter som möjligt.

Genom att använda akustisk emission samt shearografi hittades samtliga kritiska defekter plus många andra som inte anses vara kritiska med väldigt hög trovärdighet och upplösning till ett mer acceptabelt pris. Metoderna samverkar väldigt bra med varandra eftersom akustisk emission är bästa metoden att hitta fiberbrott och matrissprickor vilket är vanligt förekommande i utskjutningsfasen. Shearografi har inte samma detekterbarhet på dem två defekterna men de har å andra sidan istället väldigt god detekterbarhet på både volymetriska- och plana defekter.

Slutsatsen är att endast två metoder behövdes för att finna alla defekter vilket blir mer ekonomiskt, tar mindre plats och behöver färre certifierade operatörer jämfört med om man ska ha en detekteringsmetod för att finna respektive defekt.

Contents

Nomenclature

AC	Acoustography
AE	Acoustic emission
AO	Acousto-optic
AU	Acousto-ultrasonic
BVID	Barely visible impact damages
CCD	Charge-coupled device
CF	Carbon fibre
CFRE	Carbon fibre-reinforced epoxy
CFRP	Carbon fibre-reinforced polymers
CT	Computed tomography
CTE	Coefficient of thermal expansion
ECT	Eddy current testing
FOI	Foreign Object Inclusions
ILSS	Interlaminar shear strength
IR	Infrared
NDT	Non-destructive testing
PEXR	Penetrant enhanced X-radiography
SWF	Stress wave factor
RSV 3	Shaped charge jet
RSV 4	Projectile forming shaped charge

1. Introduction

This master thesis was performed in collaboration with Saab Dynamics AB in the course "Degree Project for Master of Science in Engineering, Mechanical Engineering", CBAEM1. This course is equivalent to 30 credits and was carried out in the spring session of year 2016. The master thesis has been performed both at Karlstad University and the taskmaster Saab Dynamics AB´s location in Karlskoga.

1.1 Background

The work for this project was performed within the area of support weapons and carried out at the department of warhead and fuse development at Saab Dynamics AB.

Warhead body, see number 2 in Figure 1, in support weapons usually have a shell body of metal (the back end marked with yellow in Figure 1) and at detonation the generated fragments from the warhead body can cause unwanted collateral effects by causing collateral damages around the target.

The warhead body can easily be explained as two chambers/parts that are isolated with a driving band from each other. One chamber/part in the front (i.e. warhead) and another in the back (where shell body works as an outer housing). In the warhead, the explosive material to get the big explosion at detonation of the warhead body is placed. In the back end chamber/part, the ignition and propellant combustion is placed where their mission is to launch the warhead body by use of a high pressure caused by the propellant combustion.

In a previous thesis [1] an investigation of the materials and manufacturing of a shell body has been made in order to get them shatter free. The results from that thesis indicated that a carbon fibre reinforced epoxy that is manufactured by filament winding technique is preferable to get a shatter free shell body.

At launching the warhead body, the shell body and specially their backplane, will be exposed to very high stresses due to acceleration, pressure and to very high temperatures from propellant combustion and their hot gases. The back plane (placed in the back end of the shell body) is then exposed for these high temperatures which can cause the back plane to "burn up" which results in leakage of the propellant combustion and their gases, and can therefore escape from their chamber. This gas leakage can also occur if there are any defects into the shell body. The leakage of gases can then penetrate the warhead chamber and ignite the explosive materials before the warhead body leaving the launcher. This kind of weapon explosion results in fatal damage to the gunner and nearby living beings as well as additional collateral damages to the surroundings.

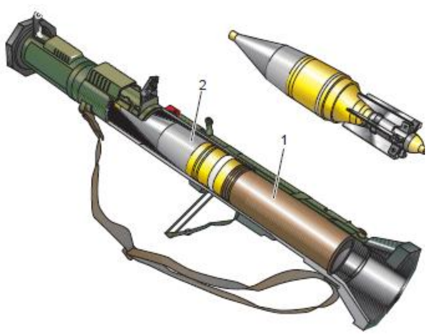

Figure 1. Basic picture over a warhead body and support weapon [2].

1.2 Purpose and problem formulation

The purpose of this master thesis was to investigate requirements and testing methods on a shell body manufactured in composite material that will guarantee the safety of the gunner and surroundings in the launch phase.

1.3 Aims of thesis work

Following are the objectives of this work:

- An understanding of the structure and function of support weapons.
- Examine which defects can arise (for example crack initiation and porosity) in a shell body with composite material and decide which of those are most critical.
- Determine requirements for the shell body in order to get them shatter free and to avoid explosion of the weapon in launching phase.
- Generate ideas of different non-destructive testing methods that can be used to detect these critical defects.
- Recommendations for further work.

The work should be completed before 31st of May 2016.

1.4 Delimitation

The most preferable composite in a shell body was derived to be carbon fibre reinforced epoxy and second best was a glass fibre reinforced polymer according to the earlier thesis [1]. The recommended manufacturing method for carbon fibre was filament winding. In this project the carbon fibre reinforced epoxy with filament winding manufacturing method was therefore the primary focus. Only non-destructive testing methods were analysed in order to detect the defects.

2. Theory

2.1 Support weapons

Support weapons often mean weapons with the aim to hold down and fight the enemy during forward motion, or to protect yourself from breakthrough of enemies. Support weapons are a category between handgun and artillery pieces, for example Carl Gustaf, see Figure 1. These types of weapons are often used in urban warfare against infantries and lighter vehicles as trucks. Both the support weapons and their warheads have many different types of products according to structure and functionality depending of their mission and type of targets.

2.2 Materials and their structure

2.2.1 Composites

Composite is “a combination of a matrix and a reinforcement, which when combined give properties superior to the properties of the individual components”. [3]

This material can be defined as a “solid material which is composed of two or more substances having different physical characteristics and in which each substance retains its identity while contributing desirable properties to the whole”. [4]

Their basic structures consist of a strong, hard and stiff reinforcement phase, often fibres, which are surrounded and held together by a more ductile matrix to increase the strength and stiffness, see Figure 2. Fibre materials can be glass, carbon or different plastics. The most commonly used material of the matrix is either thermosets or thermoplastic. Commonly used plastics in the matrix are polyester, epoxy and polyamides. The main function of the matrix is to hold the fibres in desired directions and to protect the fibres against the environment and chemical contamination. The matrix also helps to bind together the composite, transfer the load between reinforcements which make the stresses more even spread over the fibres and make the fibres more resistant to buckling. [3]

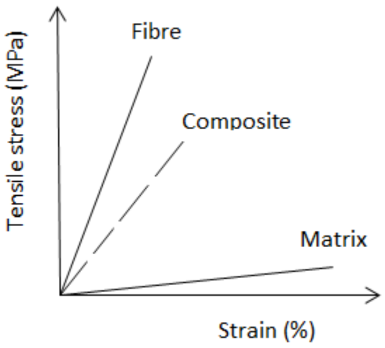

Figure 2. Comparison of tensile properties between fibre, matrix and composite [5].

The properties of the composite can also be changed depending on how the fibres are structured, i.e. aligned or with different lengths. The directions of the reinforced fibres can be changed to improve the load carrying capacity of components. [3]

The final characteristics are chosen by type of reinforcement and its fibre volume fraction (FVF), see Figure 3. To achieve high tensile modulus and strength the composite with continuous fibres is the best choice since they have a more aligned structure. FVF in finished components is often in a range of 40 – 60 % [5]. Too much FVF (over 70 %), and therefore very small amount of volume fraction for the matrix, will not be optimal due to the fact that too small amount of the matrix give less support to the fibres and make the stresses uneven spread over the fibres which leads to a reduction in strength characteristics [5], see Figure 3.

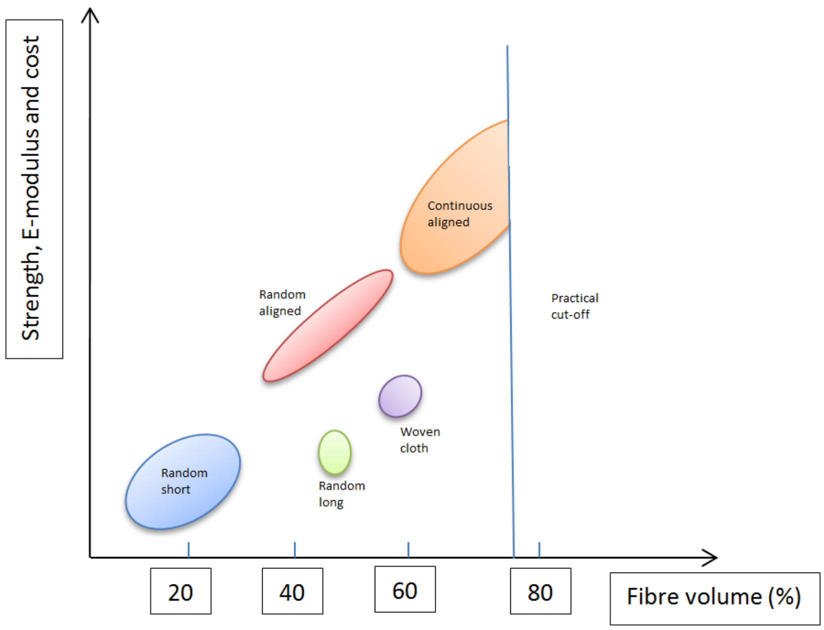

Figure 3. Effect of type of reinforcement and their volume fraction on composite capacity [5].

Composites are useful in applications where higher strength and low density are key characteristics, for example in [5]:

- Aerospace- and defence industry.
- Marine.
- Sport equipment.
- Automotive components.
- Wind turbine blades.

In different kind of vehicles the weight is of big importance where a lower weight will give lower fuel consumption and increased acceleration. In sport equipment's the weight saving leads to increased speed and better precision. In wind turbine blades a lower density gives increased power and lower energy consumption. [5]

Following are the advantages that can be gained from the use of a composite material in any particular application [5]:

- Their ability to combine the fibres and matrices to get desirable properties.
- Very high specific strength (ratio strength/weight).
- Corrosion resistant.
- High thermal conductivity.
- Low maintenance.
- Increased fatigue life.
- Reduced assembly costs due to fewer detail parts and fasteners.
- High specific modulus (ratio modulus/density).
- Very low coefficient of thermal expansion (CTE).

A good example of their ability to combine fibre and matrix can be when a part has to be immune against fire. A matrix that delay the fire uses (i.e. fire-delayed matrix) to get this desirable characteristic. Carbon fibres (CF) are chemically inert material and have thus a good fire resistance and can be used into firefighting clothes. Fire resistance depends on precursor material and a little bit on the fabrication technique that is used. Carbon fibre reinforced polymer (CFRP) can also be implemented when something has to be resistant to fire and corrosive agents. [6]

The coefficient of thermal expansion has a low value for graphite composites such as CFRP. This benefit is a property that metals cannot match. Because of the low CTE in a carbon fibre this material is preferable to use in components where very small movements are vital. Carbon fibres have generally a low CTE but they have quite big differences in CTE depending on precursor, in which direction the CTE are measured and if it is polyacrylonitrile (PAN) - or pitch based. PAN-based carbon fibres have higher strength and higher CTE whilst the pitch-based fibres have higher stiffness and lower CTE. For more information about PAN- and pitch based processes (see section 2.2.2.1 and section 2.2.2.2).

For values of some properties for CF compared to other materials, see Table 1. CFRP has a density which is only about one fifth of steel materials and their stiffness is also much higher [3]. Aluminium, whose density is one-third lower than steel, has a higher density compared to carbon fibre based composites. The strength can be as high as seven times higher for this composite and E- modulus is two times as aluminium [3]. Because the fibres are aligned parallel to each other it gives high strength properties, and due to its low density the specific strength and specific tensile modulus are extremely high, see Table 1.

Table 1. Basic properties of different composites compared to other materials [7]

Property	Carbon steel	Aluminum	E-glass	Carbon fibre
Density [g/cm3]	7.85	2.6-2.8	2.54-2.60	1.75-1.8
Tensile strength [MPa]	276-1882	230-570	3448	3530-6370
Elongation at break [%]	10-32	10-25	4.8	0.7-2.1
CTE [10-6/K]	11-16	20.4-25.0	5.4	-1.1-(-0.38)
Thermal conductivity [W/m-K]	24-65	237	1.3	10-150
Specific heat [J/g-°C]	0.45-2.10	0.90-0.96	0.81	0.71-0.75
Melting point [°C]	1500	477-660	1725	3650
Resistance [ohm-cm]	$1.74 * 10^{-5}$	$5.20 * 10^{-6}$	$4.00 * 10^{12}$	$1.3 * 10^{-3}$

2.2.2 Carbon fibre reinforced epoxy

Epoxy resin is one of the most commonly used matrix-material when high-strength and hot-curing capacities are requirements in the material. This resin makes the composite to receive good relationship between low contraction, low CTE, high strength and good adhesives. Thus, epoxy resin has a wide variety of advantages. When epoxy is applied as matrix it includes a combination of one, two or three minor epoxies uses to increase characteristics for elevated temperatures and toughness, decrease absorption of humidity and to control viscosity. One major epoxy and one to two cure agents are also included in the whole entirely matrix. Epoxy has great bonding properties. After a correct curing process it still has excellent mechanical strength, chemical resistance and electrical insulation. Epoxy resin is able to have various properties when it is combined and cured together with various curing agents. Curing agent is a substance that starts polymerization. Bisphenol A (DGEBA) is a major epoxy often used in filament winding method because it can have liquid consistency, it can be a liquid in different viscosities or it can be solid. [8]

Carbon fibres have a structure of micro graphite crystals made from organic polymer such as polyacrylonitrile. The geometry of this fibre type is a long but very thin string with a radius of only about 3 micro metres, and consists of almost only carbon atoms. There are straight crystals coordinated in the same fibre direction. The crystals consist of bonded carbon atoms, and in this case of graphite which is an allotrope of carbon atoms. The graphite layers contain a hexagonal pattern and between the layers there are strong covalent forces and weak Van der Waal (VdW) forces. An epoxy matrix is mixed with carbon fibres and then manufactured to form the carbon fibre reinforced epoxy (CFRE). [6]

Epoxy resin in the carbon fibre reinforced epoxy does not have a good resistance to sunlight and therefore not to ultraviolet (UV) exposure. This type of composite has to be protected by a UV resistance coating or likely [8]. CFRE are materials with high immunity to both heating and corrosion and are, therefore, an excellent material choice when these aspects are requirements [7].

2.2.2.1 PAN-based method

This carbon fibre process starts with a copolymerization process of the organic compound acrylonitrile with a little amount of co-monomers that form the PAN resin, see Figure 4. The PAN precursor will be spun into the acrylonitrile fibre and then to oxidation. [9]

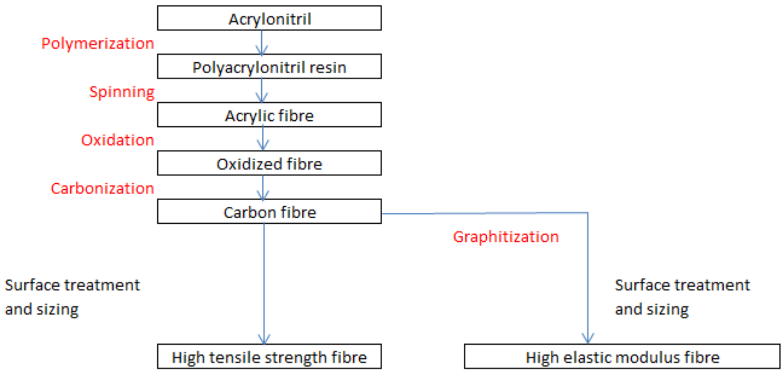

Figure 4. Description of PAN-based process [9].

In the oxidation process the fibres have to go through a high temperature furnace with a range of 200-300 °C in air atmosphere. The oxidation process is of great importance to get carbon fibres of high quality. This process can go on for several hours depending on temperature, radius and properties of the precursor. [9]

In carbonization process the already oxidized fibres pass through a carbonization furnace at a temperature of 1000 – 1500 °C to be heat treated. At this stage the fibres are treated under longitudinal tension and inert gas atmosphere (for example nitrogen or argon).

In graphitization process the carbon fibres pass through a graphitization furnace at a temperature of 2000 – 3000 °C to be heat treated. At this stage the fibres are treated under longitudinal tension and inert gas atmosphere. When the graphitization temperatures reaches 3000 °C all atoms except carbons will leave the carbon fibres and therefore fibres will have higher carbon content which in turn gives higher tensile strength to the carbon fibre.

When the temperature increases in carbonization stage, E-modulus for CFRP also increases because of higher graphitization of carbons when the temperature increases and an ordered graphite structure has higher E-modulus than unordered carbon sheets. [9]

2.2.2.2 Pitch-based method

This carbon fibre process has two types of modes. Coal pitch is isotropic and petroleum pitch is anisotropic. There are some differences in each process, see Figure 5. Both the anisotropic- and isotropic pitch go through a molten spinning step to form pitch fibres which consists of three levels, melting the precursor, extrusion to pass through the capillary and drawing the fibres upon cooling. Next stage for both pitches are oxidation process as the pitch fibres have to pass the oxidation gas at a temperature of 200-350 °C to get oxidized fibres. [9]

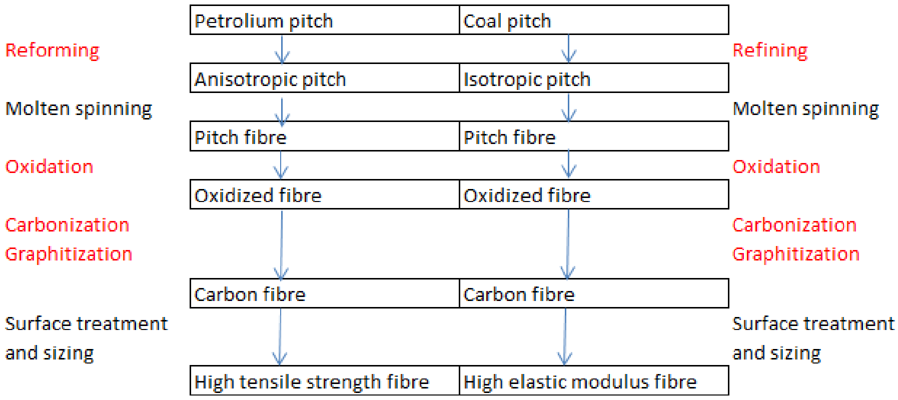

Figure 5. Description of Pitch-based process [9].

In carbonization process the already oxidized fibres pass through a carbonization furnace at a temperature of 1000 – 1500 °C to be heat treated. In this stage the fibres are treated under longitudinal tension and inert gas atmosphere. To get an orientated fibre structure the oxidization temperature has to be lower than the fibre softening limit. [9]

In the graphitization process the carbon fibres pass through a graphitization furnace at a temperature of 2000 – 3000 °C to be heat treated. In this stage the fibres are treated under longitudinal tension and inert gas atmosphere. [9]

Too low temperature during spinning leads to higher viscosity and brittle fracture during the drawing period, which not will happen if the temperature is higher. To get good quality of the carbon fibres, lower viscosity is needed. [9]

2.2.3 Surface treatment and sizing

Both pitch-based and PAN-based processes end with surface treatment and sizing of the fibres. Both surface treatments and sizing are important to enhance the mechanical characteristics for the fibres to get maximum strength capacity from the composite and thus reduce defects and increase bonding between fibre and matrix. It also makes the surface of the fibres rougher to enhance the interaction between matrix and fibre. The treatment is also of importance to increase the adhesion between matrix and fibres. [10]

When the carbonization furnace is successfully completed the fibres become surface treated. After carbonizing, the fibres have a surface that does not bond well with the epoxies and other materials used in composite materials. To give the fibres better bonding properties, their surface is slightly oxidized. The addition of oxygen atoms to the surface provides better chemical bonding properties and also etches and roughens the surface for better mechanical bonding properties. Oxidation can be achieved by immersing the fibres in various gases such as air, carbon dioxide, ozone, or in various liquids such as nitric acid.

Benefit with the treatment is to take away the outermost layer of carbon fibres there it may be disordered carbon layer that probably has reduced shear strength [11]. It can be variations in surface treatment methods depending on the fibre material but the results are the same [12].

When the adhesion is good the matrix cracks can propagate along the fibres and not break the fibres. Adhesion is dependent of how good wettability that contains. Optimizing of adhesion can happen due to following reasons [10]:

- Wettability (force balance between adhesive and cohesive forces) is enhanced.
- Take away the weakly boundary layers such as adsorption of gas molecules and contamination from surface area of the fibres.
- Add a coupling agent used to bond to matrix and fibres.

If the carbon fibres are not surface treated the manufactured parts have lower interlaminar shear stress (ILSS) and results in bad adhesion and bonds between matrix and fibres. By doing surface treatment the bonds between matrix and fibres are better which results in higher wettability of the carbon fibres and increased ILSS. [10]

The filaments are affected by sizing. Sizing is an adhesion resource that coats over the fibres to get better bonding to the matrix. The filaments keeps together to enhance the shear strength between matrix and fibre. When the surface treatment are finished the fibres becomes in a heating-mode to be able to eject volatile materials from fibre surface to avoid voids and porosity implemented in the material structure during the high-temperature process. [12]

Sizing of fibres works as a coating to avoid abrasion, fibre damage and breakage of fibres. Other aims are to protect the material from corrosion and to get a better resin bonding.

2.3 Filament winding technique

Filament winding is a method that works for every type of resin and fibre but is most effective with continuous fibre with a thermoset resin, see Figure 6.

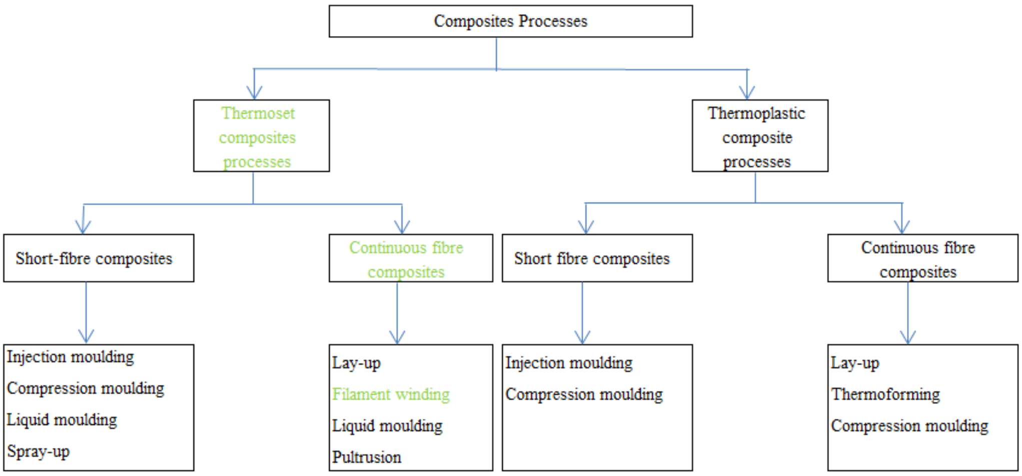

Figure 6. Manufacturing processes for different matrix composites [5].

The technique has possibility to orient the fibres to match the implemented loading. It has a high availability to control amount of resin in the finished component. It has a rapid and cheap preparation and a low-cost process. The mandrel cost can be high when producing big products, but on the other side this can produce bigger products than other methods.

The fibres are able to be highly aligned in desirable length direction but cannot be exactly aligned in favourable direction due to slippage of fibres on the mandrel. Complex geometries of the components are not suitable for this method, but shell bodies are easy enough to create. Lowest fibre angle is about 10-15 ° and depends on which type of equipment [8]. Composites are anisotropic which means they have different properties in different directions. If a low angle of the winding is determined it will be an increased E-modulus. If the angle instead is higher it leads to better hoop strength [8].There are some key parameters that the operator has to control to avoid defects which are viscosity, cure process, temperature, and winding tension and so on [13].

This is a fabrication process most commonly used for composites and useful in applications from military, aerospace and hydrospace. The method consist of a steel rotating mandrel which is stationary and a carriage arm that is moved upwards, downwards and sidewise of the mandrel at the same time. The carriage arm has a winding eye (named guide in Figure 7) that organizes the set of fibres into a roving before it rotate around the mandrel and form a layer made by composite at the surface of the mandrel, see Figure 7. Rovings is another word for a bunch of strings of the filament wound in a package. The rovings go through a resin bath before it run across the mandrel. The resin bath makes the rovings to solidify the fibres which lead to the desired composite. It is possible to choose how closely packed the rovings are to each other by changing velocity of the carriage arm and velocity of the mandrel. [8]

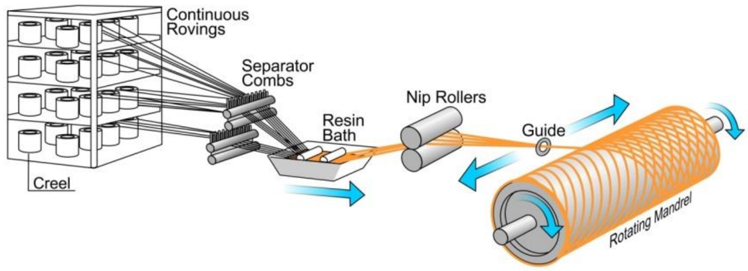

Figure 7. How filament winding technique works [14].

A CNC-machine is used to determine filament winding patterns by an engineered lay-up pattern (ELP) which then is put into the CNC. When the filament winding pattern is finished, the mandrel with finished composite layer pattern is cured to get crosslinks of the chains. The mandrel is then pulled out after the resin has been cured which allows separating the finished hollow composite from the mandrel. [8]

2.4 Defects in carbon fibre reinforced epoxy

Defects have various geometries and depending on geometry they divide into two groups, planar defects and volumetric defects. Planar defects have a bigger width-height-ratio. Cracks, delaminations and disbonds can be planar defects. Volumetric defects have a lower width-height-ratio where porosity and voids are examples of this kind of defect geometry, see Figure 8.

Figure 8. Various common defects in a composite [15].

Defects in a composite material can be developed in four main steps; in fibres, in matrix or bonds between fibre and matrix, manufacturing and in-service. [13]

It is not easy to know how much the misaligned fibres or plies reduce the mechanical properties. It is the designer's mission to construct the components to maintain the specific- and required properties of the component. A pre-determined percentage of reduced mechanical properties have to be considered due to defects always are initiated in a component during fabrication. [16]

2.4.1 Manufacturing defects

2.4.1.1 Voids/Cavity

It is common to mix up the defects voids and porosity or think they are the same damage. They are close to each other but one difference between them is pore sizes. Porosity means a series of pores and void is like one large pore. [8]

Voids are a sort of defect that includes inactive empty spaces which contain air or gas from the resin bath during filament winding which is trapped in the matrix. If the resin includes higher amount of viscosity it is easier to initiate voids in the matrix. A high viscosity resin has difficulties to cover the whole region between the adjacent fibres which lead to formation of voids nearby the fibre surface. If all fibres are not oriented in same direction during filament winding it leads to gaps between fibres or layers where voids have higher probability to be initiated. These gaps due to voids decrease the mechanical properties and the voids work as "stress raisers". Only about 3 % voids or porosity in CFRE reduces mechanical properties with up to 20 %. The vacant spots can let humidity to pass through the voids and if the voids are placed close to fibre-matrix interface the humidity reduce the adhesion and can leads to disbonds (disbonds are described in section 2.4.2.2). [17]

Studies according to [18] shows that only 1 % voids affect ILSS negative but if the voids are 5% or more the compressive strength are more affected instead. If voids initiates between fibre-matrix it lead to insufficient adhesion which results in insufficient interface and decrease in strength. If voids grow together it leads to formation of cracks. Voids affect characteristics in CFRE and results in decrease in mechanical characteristics as ILSS, tensile strength, E-modulus, fatigue resistance and compressive strength [18].

Another way that enhances the ability to initiate voids in CFRE is imperfections in the curing variables for example wrong temperature, pressure and time [19].

2.4.1.2 Porosity

Porosity is a fraction of volume voids, often occurred in the matrix. Porosity is one of the most common defect in a composite material and is initiated during manufacturing. Pores in a material are dangerous for the mechanical characteristics and occur by incorrect variables from the fabrication; these variables are viscosity, curing temperature and pressure. Pores can occur when the air and temperature is not controlled during curing which can also leads to too dry or wet areas of resin that also increase risk for matrix cracks. The relationship between mechanical characteristics and porosity-level are quite linear. These mechanical characteristics can be ILSS, E-modulus and compressive stresses in the composite. [19]

2.4.1.3 Ply misalignment

Ply-, fibre misalignment and fibre waviness cannot be totally removed from fabrication. It is very difficult to decide how much these defects lower the mechanical properties of the composite.

Ply misalignment occur if fibres in a ply not follow the aligned fibre structure from the plies nearby. This happen due to incorrect inserted parameters from filament winding technique as uneven tension of fibres. These misalignments result in a tangential gap between the layers. The rate of ply misalignment depends on how the plies are oriented to each other. Their reductions in mechanical characteristics are hard to determine since the plies can have different orientations at different plies and how many plies that are misoriented. To get the gap to disappear between plies the laminates can be stretched out in same direction as the misalignment occur. Tolerance of the misoriented layers is normally about 3-5 °. [20]

2.4.1.4 Fibre misalignment

How fibres are aligned is of great importance for the strength. If fibres do not follow the aligned structure it results in fibre misorientation and/or waviness, see Figure 9, which reduces strength characteristics of materials. The fibres in CFRE are aligned and structured in a specified way to reach desired properties. Both misoriented fibres and fibre waviness decrease strength and its stiffness and therefore the loading capacity of a CFRE get limited if the defects are outside accepted tolerances from the manufacturing method [19]. It is a big competition to determine how much fibre orientation affects the properties of a composite material. It is not easy to know how the misaligned fibres or plies are aligned and how much the other defects reduce the mechanical properties.

Figure 9. How fibre misalignment looks like [21].

The fibre misorientation can occur by ply drops. The rate of misalignment depends on variables like thickness of the plies, where the ply drops are positioned and pressure [21]. It is a defect that arises every time during manufacturing but in very small deviation that not affects the strength in a specific way since the fibres not can have exactly the desired alignment from the filament winding technique. Some percentage error has to be considered because misorientations of fibres always are developed in filament winding because of slippage of the mandrel.

2.4.1.5 Fibre waviness

In fabrication processes for composite materials, fibre waviness is caused by fibres not become placed in desired load orientation, see Figure 10. Fibre waviness occurs when the fibres are not stretched enough by the tensioner during filament winding. With loose tensioner it becomes worse steering of the fibres which lead to waviness and misalignment of the fibres. The regions with aligned fibres are stiffer and stronger compared to the wavy regions that cannot handle as much loadings as aligned fibres, this leads to earlier failure with fibre waviness. Higher amount of fibre waviness results in higher ILSS and can move stepwise to delaminations and afterwards to fibre breakage.

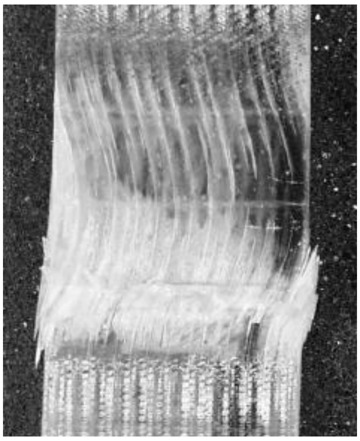

Figure 10. Laminates with fibre waviness [22].

2.4.1.6 Incorrect fibre volume fraction (FVF)

This is a manufacturing defect and is very important to get correct ratio of fibre and matrix because of large variations in ratio of fibre-matrix compared to the pre-determined before fabrication results in different mechanical characteristics compared to the desired pre-determined. FVF depends on how closely-packed the fibres are. If the tensioner makes a hard and compact fibre winding it results in more close-packed fibres and therefore more volume fraction of fibres compared to matrix at a certain volume. If the fibre windings are looser, the amount of resin instead increases at the same volume. A loose tensioner also makes variations and worsens steering of the fibres which leads to waviness and misalignment of the fibres.

2.4.1.7 Ply drops

Ply drops can occur by inclusions (gas-, air bubbles or other contaminations) between layers that make the component to an uneven structure. Ply drop can occur during manufacturing if the filament winding technique has different tensions during the process and results in different thickness at different regions at the object. The defect can lead to regions with misalignment of plies in the laminates, fibre misalignment and delaminations because uneven tension. Ply drops lead to variation in thickness and therefore gets stress concentrations [22]. The stress concentration can cause crack initiation and propagation ahead of the layers that create ply drops. Growth rate of defects are higher if ply drops are higher, i.e. more plies at the same region.

Diameter variations of each fibre layer results in changes in ply thickness and therefore non-symmetric laminates. Variations in thickness of each fibre layer depend on the cure process.

2.4.2 In-service defects

In-service defects arise during service of a component and can be buckling, impact damages or inclusions which in turn give matrix cracks, disbonds between matrix and fibre, delaminations or fibre breakage depending on energy impact. [15]

During service, components are exposed to impact-, cyclic- and/or static forces. A component has also a high probability of exposure to chemicals, heating and/or moisture there all these types of parameters reduce the mechanical characteristics in different ways.

2.4.2.1 Delamination

Delaminations can occur when there are breakages within either resin, adhesive or fibre. It can also occur due to disbonds of matrix, i.e. disbonds are a factor that can lead to delamination. They give also rise to separation of individual layers of fibres or plies which reduce amount of contact spots between the laminates and fibres and generate a higher contact resistivity of interlaminar interface. Anyhow, it must be detected at an early stage since it propagates easily once initiated.

Delaminations can occur at several stages for composites. It can happen either in manufacturing stage, assembly mode or during in-service. In-service it is enough with the impact from a dropped tool on the component to initiate delamination and therefore lower the mechanical properties.
Even if these impacts are very small or non-visual, it can propagate throughout the laminates which results in cracks in the matrix and delaminations. These defects lower the strength and increase probability of buckling. [5]

When fibre waviness occurs the ILSS increases which in turn results in delamination, afterwards when a certain load reaches a critical value the fibres breaks. [21]

2.4.2.2 Disbonds

Disbonds initiates when an adhesive material discontinues adhering to either a substrate or to the surface which an adhesive adheres, i.e. the resin does not hold to the fibres by the adhesive forces, see Figure 8. Reasons for disbonds can be when chemical-, mechanical- or physical forces that keep the bonding assembled have no the power to do that anymore, possibly because of other forces or environment worsening the bonding forces. [23]

Disbond between fibre-matrix results in uneven distribution of stresses over the fibres and therefore lower strength. Disbonds can also occur if a crack in the matrix crosses a fibre and capture moistures in the crack. The moisture loosens the adhesion between fibre-matrix. [7]

2.4.2.3 Matrix- and fibre cracks

Matrix cracks are caused by mechanical and/or thermal stresses and propagate in different ways, see Figure 11. Incorrect curing process leads to an increased risk of matrix cracks since the resin areas can be too dry or too wet depend on curing temperature and curing time. Therefore the matrix does not transfer the load between reinforcements which in turn make the fibres less resistant to buckling and binds no longer the composite together. During a fatigue process or another type of loading it is the matrix that cracks first since it has much lower strength compared to the fibres.

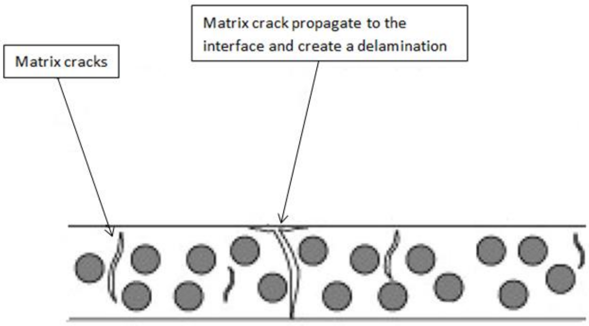

Figure 11. How matrix cracks can creates in a composite [24].

The more the cracks propagate the more fibres become broken and not can handle a built-up pressure during launching of shell body [25]. Fibre cracks eventually result in fibre breakages where the cracks are initiated by buckling and inclusions that break the fibre, or if any object strikes the fibres with a force. Fibre waviness can leads to fibre breakage when a load is applied (see section 2.4.1.5).

2.4.2.4 Crack

A crack in shell body can initiate because of the high pressure from launching. If a crack starts to propagate it leads to failure and leakage of hot gases from explosives into the pressurised region where explosives are ignited which make a weapon explosion. To avoid the leakage, a driving band is placed between shell body and gun barrel. The driving band works as a seal that does not allow propellant combustion to seep even if cracks in the matrix occur. [25]

Parametric values in the figure below, see Figure 12; ellipse angle (φ), crack length ($2c$), wall thickness (t) and crack depth (a).

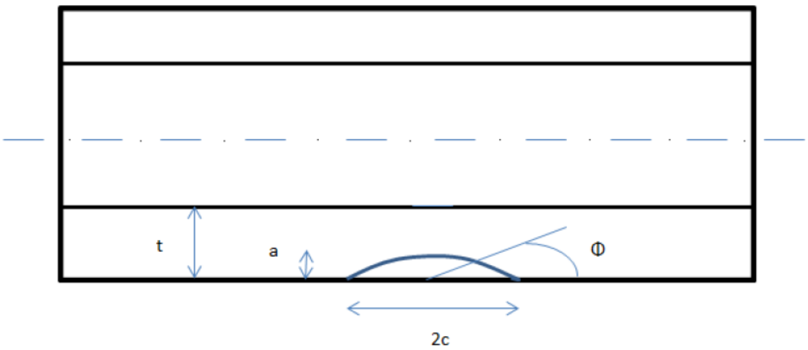

Figure 12. Layout of a surface crack in a pressure vessel [25].

Studies according to [25] results from a filament wound pressure vessel show that both fracture toughness and notched strength (σ_N/σ_0, i.e. maximum load divided by the original cross-sectional area at the notch root) increases when the winding angle increase from ±45° up to ±75°. The burst strength in a carbon fibre reinforced composite with a filament winding fabrication also increases when the winding angle increase from ±45° up to ±75°.

Burst strength measure resistance to rupture during launching. Burst strength depends largely on the tensile strength and extensibility of the composite. When the a/t-ratio increases it results in a lowered notched strength value because the cracks are deeper into the material and therefore a bigger failure zone. A shorter crack length (higher a/c-ratio) means increases notched strength. When the crack length is decreased it becomes a semi-circular shape of the crack instead of a semi ellipse.

2.4.2.5 Impact damage

It is enough with the impact from a dropped tool on the component to lower the mechanical properties. Even if these impacts are very small or non-visual, it can expand throughout the laminates which results in the defect seen above. These defects make the component to get lowered strength and increased buckling. [5]

Matrix cracks and fibre breakage are most common defects in shell body that occur during launching affected by burst pressure. Matrix crack is the best defect by the impact damage types. Fibre breakage is serious since more breakage of fibres leads to the shell body have reduced stresses and cannot built-up the fully potential burst pressure during launching. [26]

Impact damages in a carbon fibre composite occur in three types of stages. In first stage the component is exposed for tensile- or shear stresses and matrix cracks start to initiates. In stage one, low energy impacts, can also cause delamination and disbonds. These occur mostly at the sub-surfaces and are often non-visible to a naked eye and are called barely visible impact damage (BVID) [15]. In stage two, growth of delaminations occur from tip of matrix cracks that are placed between layers. The last stage, fibre ends are loosened from their attachments and the fibres can result in fibre breakages.

2.4.3 Other type of defects

2.4.3.1 Temperature and moisture

Glass-transition temperature (T_g) is a significant variable for composites with low FVF because after this temperatures a decrease in mechanical characteristics occurs. It is necessary to choose a matrix that can handle the elevated temperature (epoxy resin is a good choice). If the composite is used over the resin's T_g the structure will be softer instead of its original status which changes its material- and mechanical characteristics negatively. [5]

Moisture absorption is higher at elevated temperature causing the matrix to expand. When the matrix is expanded the strains for the matrix are higher and thus decreasing the mechanical characteristics and cause buckling. If the moisture is in cold environment it results in freezing and the moisture will then bulk which in turn leads to cracks in the matrix. [5]

2.5 Non-destructive testing methods

Plenty of different non-destructive testing (NDT) methods, see Table 2 and Table 3, can be used to find defects in both thermoplastic and thermoset resins. Table 2 are methods that can find defects in CFRP and have a scale at 0-10 where 10 refer to high detectability. The NDT methods in Table 3 are methods that can find defects in composite as general and are marked with an "x" if it is limited detectability and "xx" if it is good detectability. Another very important task is to detect how small the defects can be before the properties drops too much, so called acceptance criteria. [13]

Table 2. Detectability of different methods to find defects in a CFRP [27]

Defects/Detection methods	Acoustic emission	Laser shearography	Mechanical impedance	Membrane resonance	Thermography	Ultrasonic A-scan	Ultrasonic B-scan	Ultrasonic C-scan	Ultrasonic D-scan	Radiography
Delaminations (< 10 mm)	7	9	4	4	8	5	8	9	9	7
Delaminations (> 10 mm)	7	10	6	6	10	8	10	10	10	7
Crack	7	9	0	0	4	0	0	0	0	8
Disbond	2	10	6	6	10	8	10	10	10	7
Void	0	5	1	1	5	6	6	10	6	10
Impact (BVI)	7	10	6	6	8	10	10	10	10	4
Porosity	0	8	0	0	6	5	6	9	4	10
Inclusion	0	7	4	4	7	7	7	9	6	6
Erosion	0	5	0	0	7	9	10	7	10	4
Matrix cracking	10	0	0	0	0	0	0	0	0	6
Fibre breakage	10	6	4	4	0	0	0	0	0	5
Kissing bond	0	5	1	1	2	0	0	1	0	0
Fibre waviness	0	4	0	0	2	1	8	9	0	2
Fibre- and ply misalignment	0	2	0	0	2	0	1	9	0	5
Incorrect cure	0	0	0	0	0	0	5	2	5	0
Excess resin	0	5	0	0	6	0	5	5	8	2
Excess fibre	0	5	0	0	6	0	5	5	8	2

Table 3. NDT techniques for studying composites [13]

Defects/Detection methods	Visual	Ultrasonic C-scan	Ultrasonic A-,B-, D-scan	Low frequency vibration	Radiography	Acoustic emission	Thermography	Acoustography	Acousto-ultrasonics
Fibre type									
Porosity	x	xx	x						xx
Fibre-matrix bond	x					x			
Matrix properties			x						
Fibre misalignment		x		x	x				
Volume fraction		x	xx	x	x				
Stacking sequence									xx
Foreign inclusions		x	xx		xx		xx	xx	
Translaminar cracks		x	x		x	xx	x	xx	xx
Fibre breakage						xx			
Delamination	xx	xx	xx	xx	x	xx	xx	xx	xx
Moisture initiation									
Impact damage	xx						xx	xx	

2.5.1 Ultrasonic testing methods

2.5.1.1 Ultrasonic inspection (UT)

These ultrasonic testing methods are most common for inspection of different composite materials such as carbon fibre reinforced epoxy. In other materials the max frequency is 20MHz but for composites the max is 5 MHz due to increased attenuation in a composite, this leads to detectability for small defects can be hard to find in a composite. Higher attenuation leads to lower frequency of the incident ultrasonic beam. Lower signal amplitude can affect the quality of the results negative. Attenuation in ultrasound is the decrease in frequency of the incident ultrasonic beam as a function of the distance through the object (i.e. thickness of object).

Frequencies can cause resonance which emerges between interfaces of two plies, this resonance frequency have to be avoidable [13]. Since ultrasonic inspections can detect many types of defects they can be used for quality control of components.

Ultrasonic methods are divided into the modes pulse-echo and through-transmission. A-, B- and D-scan are pulse-echo and C-scan is through-transmission. The probe works as both receiver and transducer in pulse-echo. In through-transmission mode the receiver and transducer are separate at each side of the object. The probe in pulse-echo has difficulties to find ultrasonic signals where a certain time period is equal to pulse length since the probe do not know if the signals emits or transmits from the object. The region where this happen is not analysed, also called dead zone. Shorter pulse lengths would reduce this dead zone area. In C-scan this does not occur and can therefore analyse all material without any dead zones. [13]

These methods can be performed either manual or automatic. In manual UT the probe moves by hand over the regions with contact-mode to the scanned material. Automatic UT methods on the other hand have non-contact mode where the probe moves over the surface with a determined pattern. [13]

With pulse-echo techniques the pulses have to pass through the material twice which gives decreased resolution during inspection of specimen due to higher attenuation. This can results in superimposed back wall signals. To receive better resolution in thicker materials and to eliminate the risk with superimposed back wall signals, a higher frequency from the transducer is needed. [28]

Through-transmission ultrasonic, i.e. C-scan, is the most established ultrasonic inspection method. Here the signals pass through the material once since transmitter and receiver are placed at opposite sides of the material and therefore the attenuation is lower compared to pulse-echoes in thicker materials. Inspection modes like this one are more expensive and need more space compared to pulse-echo methods and have thus more complexity for in-field inspection. Even though these negative parts the through-transmission mode are recommended. [28]

The propagation of the waves is determined by the composites microstructure. The speed of the waves is affected by weight and E-modulus. Ultrasonic attenuation is summation of scatter and absorption. The attenuation is dependent of the scatter and damping performance from the grain boundaries in the composite. The scatters that get out from the ultrasonic waves are possible to determine by control the wave attenuation when these passage through the composite. Adjustments are needed at “ultrasonic amplitude data” to get precise measures of the attenuation. The attenuations are associated with characteristics from the composite for example pore scattering. [13]

The most difficult defects to find are cracks that arises parallel to the beam and thus do not have any reflection area against the wavelength used for these products, i.e. weak signals from the beam have more difficulty to find the defects [13]. Reference standards are often needed.

2.5.1.1.1 Ultrasonic thickness measurement

Another, and shorter, name for this is ultrasonic A-scan. Ultrasonic pulses from a probe strikes the surface and travels into the specimen, see Figure 14. When the specimen has been discovered by the pulses, echoes from the ultrasonic travel back to the probe to receive the information to the probe. The probe works as both receiver and transducer. If a distortion is detected in the component the pulses starts to vibrate between front wall and back wall and the probe receive the distortion with help of the echo, otherwise it occur only vibrated signals when the pulses reach front- or back wall on the component, see Figure 13. The pulses that bounce back to the probe include information about size and placement of the defect. This determines due to amplitudes from each separate echo and time for the pulses to come back to the probe. Deepness of the defects is only known by calculations if the velocity of the ultrasound is familiar. A-scan measures single measurements in one point at the time. To get a more trustiness measurement, more analyses from other positions are needed. [27]

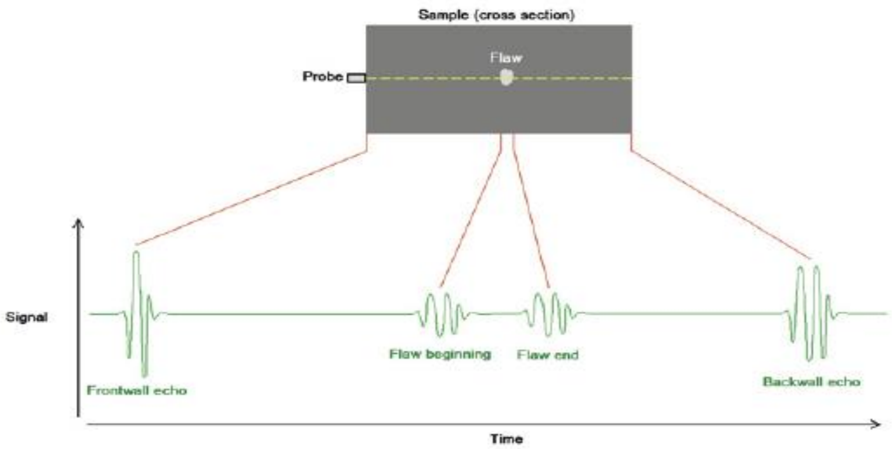

Figure 13. How A-scan works and how the defects are detected [27].

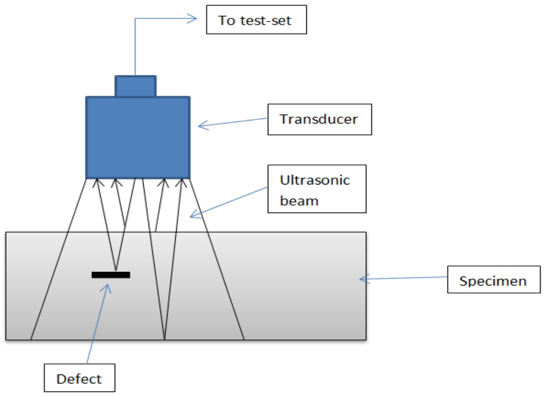

Figure 14. How the defects are found with a pulse-echo [13].

This technique have some problems when a carbon fibre reinforced polymer or any other composite is analysed due to the ultrasonic waves has grainy sound properties in the composite component. Delaminations, impacts, wrinkles, porosity and disbonds can be found by A-scan. [27]

2.5.1.1.2 Ultrasonic linear scan

This is called ultrasonic B-scan, see Figure 14. This works as A-scan but instead it measures at the same time as the probe make its movements. In B-scan the echo from separate ultrasonic pulses are discovered as lines instead of signal peaks by the probe. The lines have variations in contrasts depending on the amplitudes. Higher amplitude results in a better contrast. B-scan provides better measurements than A-scan and analyses bigger parts of the component through more measurements which results in a more trustiness method. B-scan is useful to find fibre waviness besides those that A-scan can find. A 2-D picture of a plane through the component is produced by B-scan and the probe makes measurements in each point, like A-scan, in a linear movement ahead the surface area. The values from measured amplitudes at the separate points are either coloured or a grey ratio pursuant to a pre-defined palette pattern. [27]

2.5.1.1.3 Ultrasonic through-transmission amplitude scan

This scanning technique is called ultrasonic C-scan. C-scan includes two types of transducer, i.e. a receiver and an emitter which are placed on each side of the component and has a linear movement. When the specimen has been discovered by the pulses, the echoes from the ultrasonic travels to the receiver to receive the information. The signal amplitudes become measured at the regions along the linear pattern on the component when the ultrasonic waves going through the material to the receiver. Deviated amplitudes caused by the signal may depend on defects.

The ultrasound is coupled between the emitter and receiver through a water jet coupling that strikes the surface of the component, see Figure 15. Water jet coupling or water immersion is used to reach the desirable contacts and usage of air-coupling probe or wheel probes are necessary for inspection of in-service damages. The C-scan receives a 2-D orthographic picture of the object. A depth scan can be done to see the depth of the defects, i.e. the time for the signals to bounce back. C-scan can detect impacts, inclusion, fibre waviness, fibre- and ply misalignment, voids, disbonds, delaminations and porosity. [27]

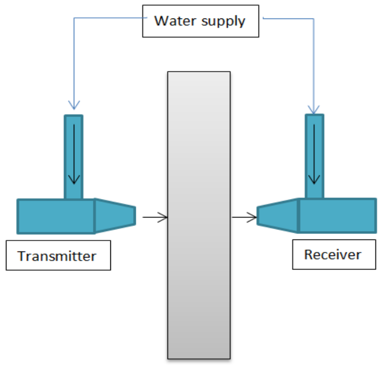

Figure 15. Basic schematic picture of a through-transmission measurement [13].

2.5.1.1.4 Ultrasonic depth scan

Another name for this one is ultrasonic D-scan. As earlier descriptions the D-scan have a probe that sends out pulses from the ultrasonic beam there the pulses bounce back to the probe when it reaches the back-wall. The probe has a linear movement and makes a 2-D orthographic picture of the object as in C-scan, but the reflected pulses from every single point determines as a A-B-scan instead of C-scan.
A D-scan makes inspection of the component from one side because it is a pulse-echo method which is widely used in reality. The 2-D map show depth and calculate how long time it takes for the echoes to come back to the probe from the interfaces. When no defects are detected the pulses from the beam hits the back wall which results in measurements of the components thickness. If defects are detected by the pulses it bounce back when the signals has hit the defect before the back wall. The values from measured amplitudes at the separate points are either coloured or a grey ratio pursuant to a pre-defined palette pattern there higher amplitude results in a better contrast. [13]

D-scan is a better choice to find planar defects measured in 2-D due to it is easier to find planar defects with pulse-echo mode compared to through-transmission mode. C-scan is able to measure a bigger amount of different defects because of the lower attenuation and therefore higher frequency and contrast. [27]

2.5.1.2 Acoustic emission and acousto-ultrasonics

Through studies according to [13] both these methods find defects by stress waves where the damages make differences in feedback from the stress waves. Differences between these methods are that in acoustic emission (AE) the stress waves becomes developed inside the material with help of an ambient loadings or external loadings. In acousto-ultrasonics (AU) the stress waves becomes developed inside the material with help of “broadband external excitation”. AU detects how much defects they are inside the material but not which type of defect it is. AE on the other hand have ability to detect which type of defects that are found [13].

2.5.1.2.1 Acoustic emission testing (AE)

Acoustic emission testing method has a major variation compared to other NDT inspection techniques; AE search and finds signals from damages inside the material while other many other NDT techniques study the structure in the component. [29]

The transducers in an AE-set up have a sensitive piezoelectric resonance sensor with very high sensitiveness, but only for a special type of frequencies. The piezoelectric sensor in the transducer applies small stress waves into the material. It the material gets a defect the material structure becomes changed which generate local acoustic waves back to the transducer. The defects have to expand and still contribute to damage if this method can find the defects and therefore the stress waves needs to be used [13]. A pre-amplifier applies after the sensor to reduce noise interference due to the acoustic signals is not powerful, see Figure 16. The filter placed after the pre-amplifier is used to transfer the noise interferences away from the signals. The amplifier enhances the signal contrast and then the signals pass through a signal conditioner to the computer for inspection. [29]

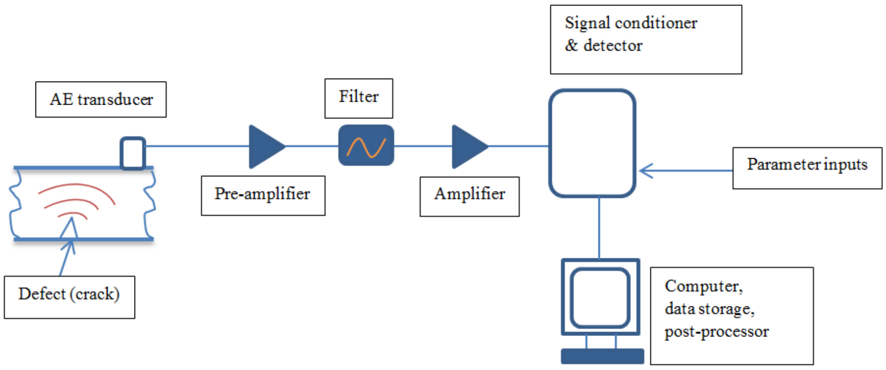

Figure 16. A basic overview of an acoustic emission set-up [29].

The acoustic signals in this method are developed by damages inside the component. The stress inside the component finds when different degrees of divergent forces from the stress waves are generated inside the sample [27]. AE method have therefore the ability to find the defects in such an early stage so they not are enough crucial for reduce mechanical properties in a serious way. The piezoelectric sensor is very sensitive to signals and can thus receive these divergent forces early in the damage initiator process. This method is effective and trustworthy with its monitoring data there the numerical process is implemented to receive the signals [13].

The numerical process has ability to find signal sources from a defect everywhere inside the component even if the whole sample not scans. Its signal sensitiveness is very high compared to other techniques which make it possible to find breakages on separate fibres. [13]

AE are able to find of defects as cracks, delaminations, fibre breakage, matrix crack and impacts. [27]

2.5.1.2.2 Acousto-ultrasonics (AU)

Acousto-ultrasonics (AU) is a NDT method and a combination of acoustic emission and ultrasonic characterization. AU is a feasible inspection method to determine material characteristics for CFRP with a filament winding.

The method consists of monitoring and analysing the ultrasonic pulses (that should simulate acoustic signals as acoustic emission testing) that is received from a controlled and complete insonification of the composite, see Figure 17. The ultrasonic pulses strike the sample with assistance of a transmitter. Receiving- and a transmitted ultrasonic transducer is established with a given length from the sample. If the sample contains defects that decrease the mechanical characteristics, the ultrasonic waves have another traveller manner. The ultrasonic waves are calculated from the received signals and the waves are reduced with higher amount of defects. To determine where in the composite the defects are, the receiver and transmitted transducer are placed so they can scan crosswise through the surface. [27]

The stress wave factor (SWF) is superposition of an amount of ultrasonic wave reflections. These waves interact with boundary surface and microstructure of the composite. AU uses digital signal process and a pattern recognition algorithm. A Fourier transform algorithm is used to get a rapid inspection of the frequency spectra. Mechanical properties such as ILSS and tensile strength has a direct relationship to SWF, if the stress wave factor decreases then the mechanical properties also decreases due to increased defects. [30]

To determine where in the composite the defects are placed, the receiver and transmitted transducer are placed horizontal so they can scan crosswise through the surface [23].

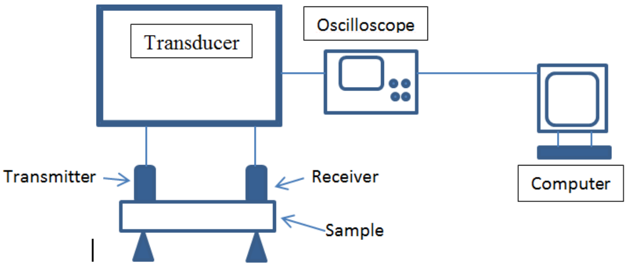

Figure 17. Basic description of acousto-ultrasonic set-up [31].

This technique is only able to find larger defects and if it is a higher amount of smaller ones. AU cannot detect smaller individual defects because the wavelength is longer compared to for example UT. AU is able to find translaminar cracks, delaminations, stacking sequence and porosity. [13]

2.5.1.3 Acoustography (AC)

Acoustography is a newer variant on ultrasonic testing that is fast, cheap and easy, see Table 4. In this technique there are two methods that can apply acoustography, either reflective shadow mode or through-transmission mode. The two different modes determine where the acousto-optic (AO) sensor is placed according to the sample. Through-transmission is used when AO-sensor and sound source are placed at each side of the sample. Reflective shadow mode has sound source and AO-sensor at same side of the sample. The sensor applies to obtain full field ultrasonic picture. The specimen becomes engulfed by acoustic couple medium in a cistern; the medium is water most often. [27]

The sensor wants an increased sensitivity to the ultrasounds and has therefore a liquid crystal molecule coating. The sensor can do analyses at regions of 150 x 150 mm at each examination which is a quite big area which results in a fast inspection method. [33]

Table 4. Inspection time for three NDT methods [33]

Parameters	Acoustography	Ultrasonic C-scan	Thermography
Scan speed	76 mm/shot	5.1 mm/s	100 mm/shot
Indexing steps	76 mm	1 mm	100 mm
Image generation time	10 sec	N/A	1 sec
Image capture time	30 ms	N/A	18 sec
Image storage time	1 sec	N/A	20 sec
Time between shots	1 sec	N/A	60 sec
Typical inspection time	3 min	3 h	10 min

These methods have difficulty in receive defect depth in the samples and the resolutions of the pictures are not as good as in C-scan. Acoustographic techniques can find delaminations, voids, impact damage, sub-surface inclusions and cracks. [27]

2.5.1.3.1 Reflective shadow acoustography

Here are both the sound source and the acousto-optic sensor placed on the same side of the component. In this mode the ultrasound pass through the component. The ultrasound spreads out after striking the component and the ultrasonic waves are make some differences such as absorbed, refracted, reflected and scattered according to the structure in the composite. The waves make a projection picture on the surface area of the sample. Acousto-optic sensor changes the projected picture to a visual picture by obtains the differences and material structure from the produced projected picture. The AO-sensor and ultrasound is interacted to the component by an acoustic couple medium. A picture of all reflected, scattered, absorbed etc. from the beam is showed on the AO-sensor where these variables are improved by defects that arises which results in a picture with shown defects. The picture show amount of signal weakened on various areas in the sample on its travel to the back of the specimen and then back to the sensor again. The sensor works as an "intensity detector" and can find damages by changes in intensity. [27]

The defect picture has higher resolution with the other acoustography mode. This is due to some causes from reflective shadow mode:

- It is an increased length between sample and sensor.
- Monochromatic waves from the source of the ultrasound which results in interference.
- If the sensor was angled compared to the sample the picture becomes twisted.

To avoid these causes the sensor can be oriented over the sample with no angle and with a use of acoustic coupling layer. [13]

2.5.1.3.2 Through-transmission acoustography

Through-transmission and ultrasonic C-scan works about as the same ways except from the implementation step. C-scan inspect one spot at the time with a sensor that moves over the surface and in AC the sensor often cover the desired analytic area from beginning without any movements. In the through-transmission mode the ultrasounds is developed by an AO-sensor that going through the specimen and a coupling medium before it strikes the sound source wall, see Figure 18. The wall has a "liquid crystal molecule" coating and when the ultrasounds hits the wall it receive acoustic energy and turns into other contrasts which shows on a 2-D attenuation map with use of a charge-coupled device (CCD)-camera. None of the wall or sensor is in contact with the specimen. [27]

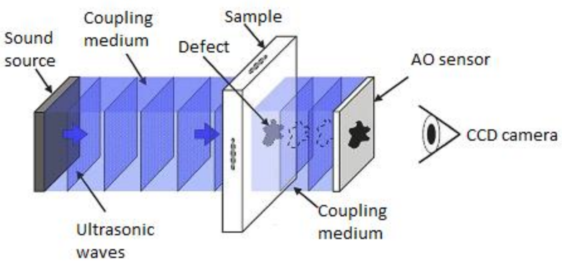

Figure 18. Overview of through-transmission acoustography [33].

2.5.2 Thermography testing methods

Thermographic inspections are methods that contain temperature increase at local areas where the material emit the heated energy. When a defect has been found it become changes in the emitted heat energy. The closer the defects are to the surface area the easier are them to detect. [13]

In composite materials that have low thermal conductivity properties, vibrothermography can be used since these types of composites let the heating's be kept a longer time at the interface. CFRE has higher thermal conductivity and should therefore not be used together with vibrothermography. CFRE should instead be used in thermal pulse thermography due to the high thermal conductivity in planar orientation. [13]

Matrix and fibres offer different thermal diffusivity and therefore other thermal characteristics. Carbon fibre have increased thermal diffusivity compared to epoxy which in turn leads to FVF is of importance for sensitivity of thermography. [34]

These methods are divided into two groups, one active method and one passive method. In active methods the "thermal gradients is produced and continuously maintained by the application of cyclic stress" [13]. In passive methods, which also are most commonly used NDT method, the "thermal gradients results from a transient change" [13]. The infrared (IR)-camera uses to collect and measure thermal response from the specimen [27]. IR-camera can detect heat differences of only 0.005 °C and can be used for tests between -50 – 100 °C [13].Vibrothermography is an active method and thermal pulse thermography is the passive one. Carbon fibre has higher thermal conductivity and should therefore not be used together with vibrothermography as seen in the text above, therefore only the thermal pulse thermography is studied.

2.5.2.1 Thermal pulse thermography

This is a non-contact mode with an implement of an extern heat source. It is a passive technique and is determined when the thermal gradients results from differences in heat rate. The flash lamp, or another used heat source, can be placed at two different ways, either at the same side of the sample as the IR-camera, see Figure 19, or at different sides. The heat sources are turned on for a short time (about 10 sec) and then turned them off. Afterwards the IR-camera receives these emitted heat energy pulses and then results in real-time images. In the defected regions, the hear energy become "stuck" which results in a higher heating at this regions and also a lower cooling rate when the heat sources are turned off.

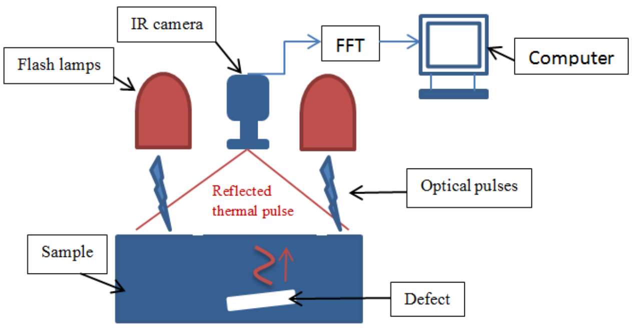

Figure 19. Schematic image over a thermal pulse thermography [35].

In tests when the IR-camera and heat source are placed at each side of the object is most used method. The heat increases at a certain speed during the heating process which is affected of the thermal characteristics of the material. This method receives both size and depth on the defect. [13]

Lengths of damages are around the same distance as the depth where the defects are placed and still keep a good resolution, i.e. if a delamination is 4 mm long it can only be detectable 4 mm into the object and still keep a good resolution. [27]

Defects found in a CFRP-material by thermal pulse thermography are fibre waviness, porosity, voids, cracks, impact damages, delaminations and disbonds. [27]

2.5.3 Radiographic testing methods

These methods can only find defects when they have their dimensions parallel to the radiation beam. Radiography is the better method for volumetric defects. This leads to a low chance to find planar defects because it strongly depends on defect orientation. Disbonds and delaminations are two types of defects that are really hard to detect since they often arise sidewise instead of parallel to the beam. When the x-ray signals scanning over these material damages the signals cannot detect any changes in material structure. It is easier to find these damages with a radio-opaque penetrant. [27]

Advantages general for the four radiographic inspection methods: Radiographic inspection has x-rays instead of ultrasonic waves, i.e. the wavelengths for x-rays are generally shorter compared to the ultrasonic waves and results in increased resolution pictures. These inspection methods are able to be used at thicker areas. It can also determine defects in closed hollow parts. [13]

X-ray computed tomography and x-ray backscatter tomography show how deep the defects are, but the other radiographic two inspection methods cannot do that due to the inspections create a "through-transmission" picture. [13]

2.5.3.1 Conventional radiographic inspection

X-ray beams from an x-ray source strikes the sample where the radiation going through the sample and then to the radio-sensitive film sheet on the other side of the sample [13], see Figure 20. The film sheet develops a 2-D shadowgraph picture of the radiations varying absorption in the sample. The shadow graphic picture contains shadows/grey-scales, when the signals going through the specimen the signals become attenuated. Attenuation of the signals occur when the material have interaction with electron energy levels that come from x-ray beam. Higher density in the component leads to lower attenuation of x-ray signals and therefore higher resolution. Different regions in the material can contain variations in density or thickness; this can be seen on the shadowgraph picture where it becomes variations in the shades in respectively regions.

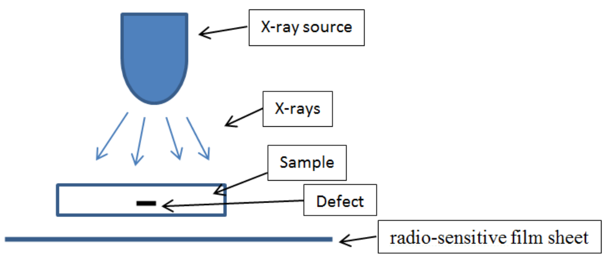

Figure 20. Description of conventional radiographic inspection [13].

CFRE has a high level transparency for x-ray signals because of its low density and therefore x-ray signals contain decreased energy. Reduction of energy level in the x-rays is due to the x-ray signals pass through the CFRE too easy and did not recognize that there was any composite in the way which in turn gives a disfigured picture. Lower energy-level gives a lower acceleration voltage, i.e. around 10-20 kV.

X-rays is used to scan other materials with higher density than composite that has higher energy level in their x-rays where the transparency is lower. [27]

The x-ray beam passed-off when the focal point has a size of max 100 micrometres. A smaller focal point, and thus higher magnification, results in more resolute pictures and smaller damages can be detected. [13]

If the deep of the defects are too small in beam orientation the defects are very hard to detect. If cracks do not lie parallel to the radiation beam they can neither be found. Defects found in a CFRP-material by thermal pulse thermography are fibre waviness, porosity, voids, cracks, impact damages, delaminations and disbonds. [27]

2.5.3.2 X-ray computed tomography

X-ray computed tomography (CT) is a radiographic NDT-method that shows the cross-section from the detected specimen instead of a shadowgraph picture. The method finds and acquires 3-D picture of volume and size of the defect. A rotating plate, there the sample is placed, is stationed between a detector and x-ray source, see Figure 21. The rotating plate rotate stepwise around its rotation axis where a lot of 2-D x-ray pictures at pre-determined interval are achieved from the object to generate these 2-D pictures into a 3-D picture by a "computer cluster" there a grey value is computed. This cross section picture corresponds to how the scanned object would look if the sample were sliced along a plane and can therefore determine the appearance inside the sample without cutting. This grey value in the "sliced" picture is measured up by a coefficient of x-ray attenuation which reflects ratio of scattered or absorbed x-rays when they overstep through each voxel (=less detectable volume in 3-D pictures. A 3-D equivalent to a pixel).

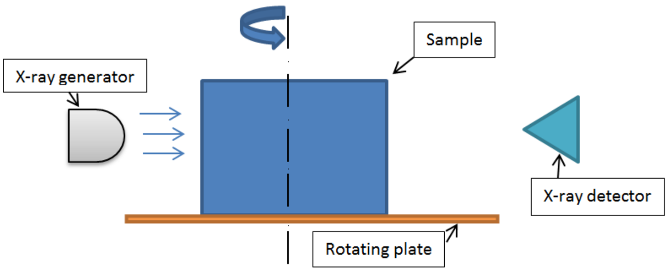

Figure 21. Basic principle of an X-ray computed tomography [36].

The attenuation of the x-rays is principal a function of energy from x-rays and composition and weight from the sample. This radiographic inspection method can find planar defects more effectively than conventional radiographic inspection due to inspection of the component is made at determined places around the component which increase the opportunity to get the radiation beam parallel to the defects and thus find the damage. [27]

Disadvantages with this technique are the need of big data files, in a range of gigabytes, which make the analysis and visualization large for saving. Some samples can include elements with too high attenuation to receive a sharp picture quality.

Advantages with this technique are that nothing or little time for preparation of the sample and to contain 3-D pictures.

2.5.3.3 Enhanced radiographic inspection (PEXR)

This method is often called penetrant enhanced x-radiography (PEXR) and works as a conventional radiographic inspection (see section 2.5.3.1) but have a better contrast due to a contrast medium, which is a substance, used to increase the contrast of fluids or material structures. This increases the contrast in the detective areas like a radio-opaque penetrant. Zinc iodide is a chemical compound with big radiation opacity. Zinc iodide is mostly used as a radio-opaque penetrant in industrial radiography to increase the contrast between the defect and undamaged composite.

Before radiography, the fluid is implemented at the surface area on the object and is then probing the areas where defects in the surface have been developed. The x-ray from the x-ray source strikes the object there the x-rays pass through the object and hit the radio-sensitive sheet at the other side of the object. On the sheet, a picture of the x-rays variety absorption inside the object is seen. During radiography the radiations that going through the defects are much more absorbed which results in earlier invisible defects from the conventional method can be detected. The defects are then compared to a reference standard. [13]

2.5.3.4 X-ray backscatter tomography

The x-ray beam from the x-ray source strikes the specimen. The photons from the beam interact with electrons from the specimen and the detector only receive the back scattered ones. Compton scattering is the most used interaction mechanism in x-ray back-scattering tomography where the photons change its path (scatters) when they come close to the charged particles (electrons in this case). When this interaction occurs in the spot where collimation orientations between detector and x-ray source intersect, the scattered photons "are approved" by the detector and thus find the defects, see Figure 22. The scattered photons have smaller energy level and thus a bigger wavelength and smaller frequency. It is only in this spot where source and detector intersects with each other the detector can register defects. [27]

Amount of backscattering from the x-ray beam depend on the compactness in the CFRE. Regions with reduced weights in the material (lower compactness) give more x-rays that not produce back-scatters and results in the detector receive worse contrast. If the detector camera receives lower back scatter values than the material should have it is a defect in this region. [13]

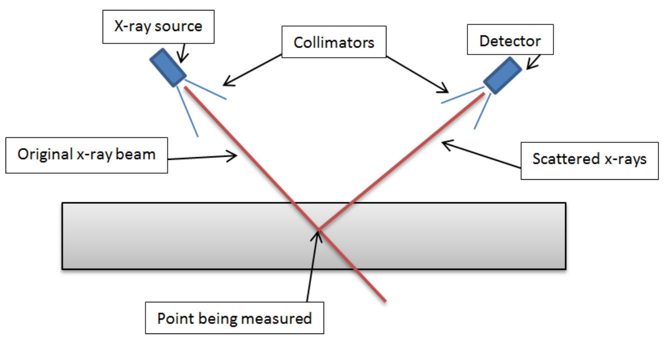

Figure 22. Description of an X-ray backscatter tomography [27].

It has only availability of inspection small regions in the material at same time which requires specimen or the inspection device to make many movements in to measure the entire volume. A 3-D tomographic image map produces. [27]

Advantages with the method are single-sided operation, suitable for large objects, high contrast and easy-to-interpret signal (scattered intensity is roughly proportional to material density).

Disadvantages are that if it is a need of detect any in-service defects the x-rays are not the best choice due to the impact damage is composed of planar defects as delaminations and disbonds. [13]

2.5.4 Laser shearography

Shearography is a highly sensitive, rapidly and con-contact method with full-field inspection. The sample becomes hit by a laser light to create an interference pattern in the sample that the shearography camera can be seen. Analogous with the interference pattern it is compared against a known reference light to get results from the interference pattern. Superposition (i.e. shear image) of these two pictures represents the sample in an unloaded condition. By applying a small external stress in the sample, the material is deformed in small magnitudes to easier see if there is any defect. A shear image of the loaded condition is then received. The unloaded and loaded pictures are compared to each other in order to find any defect. If there are any defects it results in local changes in the material structure shown as “fringe pattern” in the computer which then are converted to a 3-D strain map.

This fringe pattern contains information about the relative deformation of the component before and after applied stress, and is made up of a series of characteristic black and white fringes. Real-time monitoring leads to possibility to vary stresses and analyse if the fringes concentrations differ or change in the pattern during analysing of the material.

The black fringes have less reflection than the white fringes and therefore results in small inspection area or not good enough resolution on the resulting pictures. To increase the ability to reflection from the black fringes, a coating (for example dye penetrant developer) can make it easier. When there are no features within the sample, a regular fringe pattern is seen on the screen. This regular fringe pattern is usually a uniformly distributed fringe. [27]

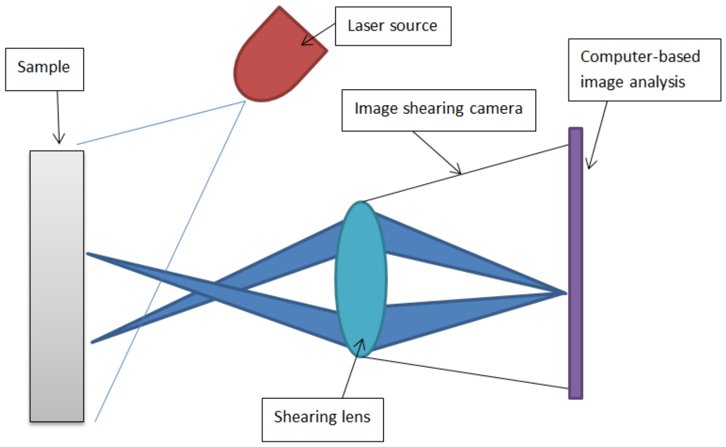

Figure 23. Description of a conventional shearography process [13].

To compare the two interface patterns there are some different ways to do that. Available methods used for this task are digital shearography, time integrated-, real-time- and sandwich technique. Digital shearography is the primary choice because of electronic recording of the fringes. [13]

With digital shearography it is possible with inspection and real-time viewing of the defects at a simpler and much cheaper way with increased resolution than the other methods. The light that becomes mirrored from the sample going through a shearing interferometer before it strikes a CCD camera. Digital shearography is a method with a computer that enables full digital recording and processing of holograms, without any photographic recording as an intermediate step which in turn make the method even faster and also have opportunity to study real-time shearography. [13]

Defects that are easiest to detect by shearography is disbonds, waviness, delaminations, impact damages, disbonds, local erosion and porosities. Impact damages in CFRE are easier to detect compared to other composites. This method can also find gas bubbles, absence of resin, voids and redundancies of adhesives. Shearography have big advantages to find differences locally in bond strength produces. [27]

2.5.5 Low frequency vibration

In methods that use ultrasonic signals there are big needs of a coupling medium. Analysis of components with honeycomb geometries are a problem since the waves from the ultrasound only spread through cell walls which are a little region of the entire area. Low frequency vibration methods have instead become an option.

Low frequency vibration is a method that subdivides into two groups, a global method and a local method. The global method measures natural frequencies in the composite by forcing vibrations of the entire structure from one single point. Characteristics that become measured from this method are frequency and damping. Local method study vibration modes and make measurements of coin tap test, mode shape, mechanical impedance and membrane resonance. [13]

Vibrations frequency range is max 20 kHz for composites. [13]

2.5.5.1 Global method

By implement a Fourier transformation to the spectrum analyser it is possible to measure damping and frequency. The low density sensor has to be placed to meet the requirements from modal anti-nodes of a vibration mode to get eminent vibrations mode. This is due to both vibration amplitudes and its sensitivity is highest at that point mode. It is quite difficult to measure the damping with a precision measurement, and because of this a better alternative is to use modal frequency. [13]

Modal frequency can determine and control the production quality of a CFRP fabricated with filament winding technique, see Figure 24. Modal frequency can detect disorientated fibres that have a difference in direction of only 1-1.5 ° and it can also find changes in FVF when fibre-matrix ratio differ with 4 % or more. [13]

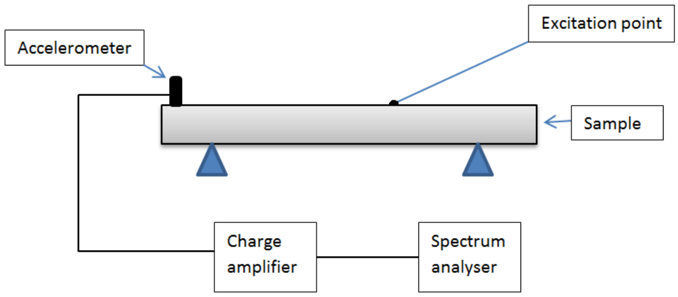

Figure 24. Basic model for modal frequencies of filament wound tubes for CFRP [13].

Advantages with global methods are: They, and many other low frequency vibration methods, can use mechanical coupling as implementation instead of fluids which make the methods very beneficial to moisture-damageable composites. [13]

Disadvantages with global methods are: Not as sensitive as the local methods due to the defects are distributed over the structure instead of in a more centred region. Have difficulties to find small defects. Signal-to-noise ratio is much lower in composite materials compared to metals due to greater matrix damping in composites. [13]

2.5.5.2 Local method

Advantages with local methods are that they are more sensitive when the frequencies are low. Due to the low frequency there is no need for a fluid mechanical coupling which is better for composites sensitive for humidity. [13]

Disadvantages are that low frequencies in local methods are not useful if the defects are deeper into the object. [13]

2.5.5.2.1 Mode shape

Mode shape associates with "local amplitude measurement". A laser is used as illumination source due to the source must be very coherent and monochromatic. [13]

The method registers phase angle and amplitude of a reflected light that comes from the inspected component. The component becomes visible as a 3-D picture when the light reflects the sample like an interferometric pattern to the film. The unloaded inspected component compares interferometric to two types of thermal/vibration/mechanical applied forces (or other types of relevant stresses). The comparisons lead to interface pattern that shows variations in deformations to find damages. [37]

Mode shape is a costly method and often use a pulse system to avoid vibrations, otherwise the sample have to be placed on a table or similar to avoid too much vibrations. If an area on the sample has damages, the mode shape process local changes which then is seen in the 3-D picture.

2.5.5.2.2 Coin tap test

It is an old technique of the NDT methods and is mainly used to test laminated structures. Before this technique was further developed they knocked at the structure with a coin and by ear determined if it was any defects according to the sound. If adhesive disbonds or fatigues are detected in local areas the stiffness are reduced in these areas. In the contact duration it is mostly used to measure local stiffness's and is used to plot a function of the position where the stiffness´s are detected. The function is included in a C-scan to get the results. [13]

In a newer coin tap test an instrumented hammer is knocked at different places on the sample. To receive the vibration changes, measurement of dynamic contact forces from the hammer tapings is used there a computer collect the data. Two different types of measurements can be used. The first one collects impact forces via a transducer in the knocking instrument (for example a hammer) when the structure being knocked. The second one collect sound pressures there the pressure is computed by Fourier transformation, and then a comparison is needed between the sound pressure and a sound from a reference structure. Both methods are inexpensive, fast and easy to use. [13]

2.5.5.2.3 Mechanical impedance method

This one is quite similar to the coin tap test method disregard that excitation is continuous harmonic instead of impulses. This method and coin tap test has similar physical guidelines such as the sensitivity and therefore have these more difficulty to detect defects into the deep compared with damages at the surface or near the surface. A reason for this difficulty is due to the sensitivity decreases when the depth is deeper. [13]

The analysed sample is pushed down by the contact tip of the instrument. How much the contact tip is pushed onto the sample determine how big the mechanical impedance value will be. When the tip is in contact with the sample, a voltage with an already decided frequency is implemented to the driving piezoelectric part, see Figure 25. There are correlations between output- and input voltages that are determined of amplitude and phase angle. These depends on local impedance which leads to modifications in phase angle or amplitude of the received signal which provides local changes in the impedance for the sample. [13]

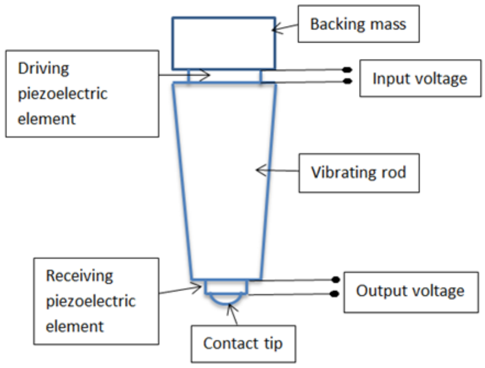

Figure 25. The instrument in a mechanical impedance method [13].

2.5.5.2.4 Membrane resonance method

The method is a simple way to determine defects. This one has a non-contact excitation source which differs from mechanical impedance technique. The scanning probe moves over the entire surface to receive membrane resonance at every place. To assure that the membrane resonance is discovered at every spot the input signal is mostly broadband. Benefit with this technique compared to ultrasonic inspection is that no coupling between the object and transducer is needed. When membrane resonance of the layer above the damages is in the same frequency range as for used excitation, the method has best possibilities to detect the defects.

A thickness measurement of uppermost membrane uses to see the quality of the specimen. If membrane and specimen have equivalent thicknesses it is a specimen without detectable defects. The regions where defects are located inside the specimen, the membrane layers at these areas increases. It is only the uppermost membranes on the specimen that measures._It is easier to detect the damages areas with this method compared to mechanical impedance technique due to it is bigger variations in dynamic impedance between good and bad regions in this method. [13]

2.5.6 Eddy current Testing (ECT)

This testing is a non-contact method and is fantastic in inspection of wires, pipes and other round components. Eddy current Testing is limited to materials that conduct electricity and thus cannot be used on plastics for example. ECT has an electric conductive coil (works as a probe), with an alternating current close to the surface area of the specimen. The alternating current is implemented in the coil and leads to an alternative magnetic field been developed inside and around the coil according to the right-hand rule. The magnetic field oscillates at same frequencies as the current going through the coil. When the alternating current have higher value the magnetic field will also increases. When this current is as little as zero the magnetic field crashes.

When the eddy current coil is nearby the sample the coil stimulates and an electromagnetic inductance helps the current to penetrate into the sample. Defects are detected with variations in amplitude, see Figure 26, and pattern of the eddy current, and in turn the magnetic field. This results in variations in coil impedance due to another movement of electrons in the coil. Amplitude and phase angles are changes which contribute to variations in the impedance. These differences show in the eddy current instrument which plot the impedance and phase angle which are associated to defects. [39]

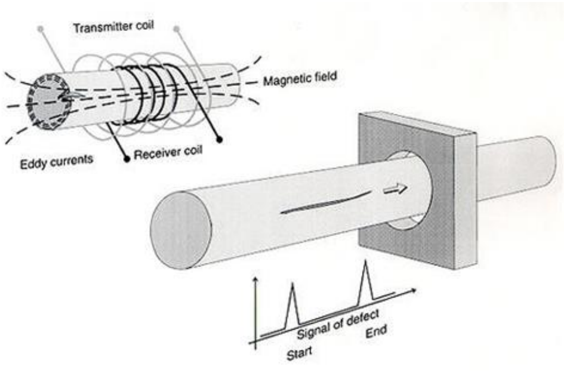

Figure 26. Usage of eddy current of a specimen [40].

The eddy current is an induced weak electric current in composites. The electric conductivity in a CFRE is much lower, around thousandth, compared to aluminium. Because of this low conductivity the current penetrate the sample much less than aluminium for example, and require a significant increased frequency to get higher signal-to-noise ratio for CFRE. [38]

Defects an ECT can detect are impact damages, delamination, heating defects, significant fibre breakage, lack of fibres and fibre waviness [27]. ECT can only find damages when the CFRE layers are about five with remained resolution. The smallest defect that can be seen is has sizes of a couple of millimetres. [38]

2.6 Pre-study

To reduce, or at least avoid, fragments from shell bodies the material was changed from aluminium 7075 – T6 to the shatter free high strength filament wound CFRE [1]. The biggest benefit with shell bodies in composite material compared to, for instance, metals is that composites do not results in uncontrolled shatter and instead results in low collateral damage (side-effects) which is favourable. Besides their high strength, low weight and good heat resistance they are also robust and has higher probability to receive increased precision. Hot curing epoxy resin and high strength carbon fibre are used to get the most desirable mechanical- and material properties. [26]

Constant vibration and regular shocks during transportation can lead to fatigue failure. The weapons should, on the other hand, be packaged and isolated to avoid fatigue. Thermal cycles can continue as long as the weapon is being transported or when it lies in storage. In both cases the temperature and humidity can have big repeated variations that occur both slow and fast.

A general specification for a shell body for reduced probability for shatter was performed (see sequences below) that includes more specific values that are required during launching, effects of the shell body during launching and important properties the material should withstand.

Launching sequence:

- Driving pressure at XX MPa during the launching without plastic deformation. This driving pressure is the dominant load on the shell body. [41]
- Acceleration at YY g during launching without plastic deformation. Use the acceleration value ZZ g for calculation of laminate analysis in order to get margins and to be suitable for other grenades in the “grenade family”. [41]
- WW kN in the back plane [41].

Effect sequence:

- Pulverized CFRE at detonation. Instead of producing shatter, as in aluminium, the CFREs leads to pulverized or burned shrapnel
- If any smaller fragments should fly away as shatter, its density is much lower and the air friction decelerate the fragments faster which results in a much lower velocity and reduce risk of hurting innocents.

Material properties:

- Water proof and not affected by water.
- Moisture absorption has to be at a minimum value.
- UV-resistance to not receive reduced properties when shell body is placed in sunlight during a hot day.
- The shell body should withstand a temperature range of -VV – QQ °C [42].
- Shell body should not be affected by fast and large temperature changes [42].
- Should withstand long transportation on rough roads.

3. Method

3.1 Implementation of work

The project was divided into three major parts: research and theory, method and result. The research phase was the biggest part. Research was both necessary and useful to get a better understanding of the fundamentals. Results have been based on an iterative process.

This mission started with a widespread planning phase in order to break down the project. Firstly a work breakdown structure (WBS) was made where the missions consisted of the main parts, i.e. documentation, presentation and processing into a tree structure. The main parts were divided into single activities in order to get a better understanding, to have it easier with logic network (also called Gantt chart) and to get a well-defined structure over the mission that was formed with 100 % of the activities in the project. After WBS the Gantt chart with an elaborated timetable was made in order to get a graphic illustration that described lengths of activities and milestones and to being able to piece together a detailed timetable to perform the work for. A pert chart was made to present the graphic illustration of the milestones in relationship to each other and to follow up the progress during the project. The lines between the milestones are activities that have to be done to reach the milestones.

A detailed literature review gained deeper understanding for further advancement of the project. The theory consisted of:

- Description of composites and then more specific about carbon fibre reinforced epoxy.
- Detection methods for manufacturing shell bodies, i.e. the filament winding technique (see Appendix 1-8 or Table 6 in section 3.4).
- Which defects that can arise and how they arise in a shell body made by CFRE.
- How the detection methods works.

Pre-study phase was performed by researching about earlier thesis, development of shatter free shell bodies. Also reports including requirements of temperatures, transport and vibration, storage conditions and parameters during launching it should withstand in order to get a shatter free shell body was analysed.

Two types of listed requirements were made, the first one is requirement specification used for detection of defects (see Appendix 9) where most important criteria were decided that should be used as criteria in decision matrices. The second requirement list was made in order to get a shatter free shell body and to avoid weapon explosion (see section 4.1). Swedish standard SS 2222 was used to get classification zones for each requirement number in the requirement list.

Then, decision matrix was made in order to eliminate the defects that not were critical and thus to find the critical defects (see section 3.3). In order to find which of the defects that was most critical in the shell body, information about defects (see section 2.4), several contacts with companies and analysis of defects were used.

The elimination phase started when all the developed concepts (i.e. NDT method) were finished. Elimination matrices were made, see Appendix 10, for every critical defect to find out which concepts that had high enough trustiness to be moved on from the concept generation phase to concept selection phase. The purpose of the elimination matrix was to systematically eliminate concepts that could not meet all the pre-determined question formulations:

- Does the concept solve the main problem? [43]
- Does the concept satisfy the requirements from Appendix 9? [43]
- Is the concept realisable? [43]
- Within margin of expenditure? [43]
- Relevant for the company? [43]
- Sufficient information? [43]

The question formulations were used as criteria in elimination matrix.

After the elimination matrices, decision matrices were made for each problem for further elimination. The decision matrices was developed in concept selection process (see Appendix 11) and sorted out those methods that do not fulfil the most important criteria developed in Appendix 9. The most reliable concept for each separate critical defect from decision matrices moved on to final selection phase.

In final selection phase there was determination of which detection methods that have best combination; In other words, the aim was to find fewest number of concepts that detect widest range of defects.

3.2 Requirement specification of shell body

The requirement list was developed with information from pre-study phase, own research and ideas, telephone- and e-mail contact with experts in NDT methods and in materials science in order to get information to get increase probability in a shatter free object. Information was also obtained about which NDT methods they recommend to find small enough defects and how many defects that can be tolerated before it reduce composites properties too much.

The listed requirements in order to get a chatter free shell body are listed as number 1-13 below.

1. The shell body should have full isolation between the chamber including propellant combustion and the explosive material in the warhead to not have leakage. The leakage make the hot propellant gases to penetrate into the warhead and results in ignite of explosive material where a detonation already occurs in the gun barrel.

2. Stricter tolerances of dimensions of shell body. Unproportioned dimensions of the shell body make it to be either a too big or too small gap between shell body and gun barrel.
Too big gap does not affect the launching in any specific way. The air between shell body and gun barrel works as a lubricant or isolation between them to avoid wobbling of the shell body. However, too small gap can results in two ways: A smaller shell body and therefore lower amount of explosives. The high pressure during launching makes the shell body to expand and pushes against the gun barrel and thus reduces initial velocity because of much higher friction.

3. A strengthen backplane in the shell body. The pressure force during launching is at a maximum at the pack plane (and the thread joints) and can therefore initiate cracks and therefore show leakage in the back plane. Also at launching the shell body, and especially the backplane of the shell body, is exposed to very high stresses due to acceleration and very high temperatures from the propellant combustion. The very high temperatures can lead to the back plane is "burned up" and therefore result in gas leakage from propellant combustion into the warhead and thereby ignite the explosives before leaving the launcher. Example of how to strengthen the back plane can be by inserting a coated tray.

4. Strengthen of thread joints. The thread joints are placed in the back end of the shell body, close to the back plane. The thread joints should withstand the loads applied on the components from the pressures during launching. The threaded joint is one of the weakest areas during launching. Cracks in the thread joint could in worst case results in parting of the sub-assemblies and exposing the explosive materials within. This crack initiator has a high probability to propagate when the launching starts. This result in breakage and an opening-up of the closed region between chamber including propellant charge and explosive materials which cause critical explosion as in requirement number 1 above.

5. Do inspection with relevant NDT method to see if there are any defects or embedded stresses in the shell body. As few embedded stresses and defects in the material during manufacturing as possible are required. However, there are always some degrees of embedded defects during fabrication process which have to be taken into consideration to have margins for the reduction of mechanical properties.

6. Control to get correct fibre volume fraction as pre-determined. Another ratio of volume fibre-matrix changes the mechanical properties. If the fibre fraction is 70% and over, and therefore a low weight percentage of epoxy resin, the resin give less support to the fibres and leads to a decrease in mechanical properties. A fibre volume fraction slightly below 70 % is a better fraction between fibre-matrix to have a high-strength composite.

7. A strict determination of a fully functional driving band is of great importance. The driving band is placed between shell body and gun barrel to have isolation and avoid propellant combustion in contact with explosive materials in the warhead. Poor manufacturing of driving band or incorrect choice of material in the driving band can make it more sensitive to the pressure and high temperature from propellant combustion and then results in leakage as in requirement number 1.

8. Avoid increased strain levels. About 1 % strain is allowed and should not exceed this value [26]. Increased strain also increases probability for matrix cracks and the shell body can expand more and lead to smaller gap between gun barrel and shell body as in requirement number 2. If the strain level increases to a higher value than tolerated it is probably because of the design of the shell body such as the CFRE not are filament wound in both radial and longitude direction in order to get a high-strength shell body in several directions.

9. Be fully functional after drop tests from 3 metres and safe for disposal from 12 metres. The shell body should be exposed to extreme weather before tests. The drops are tested in different directions. After the drops the shell body should be fully safe to be used. Inspection with NDT methods after drops to see if there are defects into the shell body is required. The drop tests from 3 metres should visualise a fall from a truck and from 12 metres it should visualise a fall from a ship or a building.

10. Maximum 4 % porosity. In aerospace industry maximum 2 % porosity is allowed. A shell body is used only one time which does not generate any remarkable number of cycles and therefore maximum 2-4 % porosity in a shell body is required. A general guideline is that 1 % porosity or void content reduces the overall strength by about 6 %. [26]

11. A safety factor of 1.5 plus an addition of extra safety factors of about 1.5 from manufacturing process where embedded defects and transportation conditions are considered.

12. Defects have to be below 4*4 mm^2. Biggest allowable defect in aerospace industry has areas of 6 * 6 mm^2 depending on how many defects and how close they are each other. If there are more defects smaller than 6 * 6 mm^2 it may not be okay anyway since they instead affect big regions on the shell body and reduce the mechanical properties a lot. [26]

13. Long-time tests should be done to visualize a transportation condition. Shell body should be fully functional after transport in uncomfortable environments.

3.2.1 Classification in damage zones

The listed requirements of the shell body were then classified in three different categories for determination of this dangerous level. Swedish standard institute have classification zones that have been developed to be applied within mechanical engineering industry. The different steps are specified according to a confirmed level of quality in aspect of technical and economic opportunities [44].

Requirements that are not satisfied result in negative consequences with varying effects. This can in worst case result in a danger of life or that the components are unworkable.

Definition of class 1 – Safety requirement: "Requirements which shall be met in order to fulfil safety regulations, e.g. requirements concerning personal safety, laws and official regulations". [44]
Definition of class 2 – Function requirement: "Requirements which mean that exceeding of the given requirements result in product non-function or render further production impossible". [44]
Definition of class 3 – Production requirement: "Requirements which mean that exceeding of the given requirements result in risk of disrupted product function or further production". [44]

3.3 Determination of critical defects

A decision matrix has been made to sort out the critical defects, see Table 5 . Each defect was compared to respective criteria and where each defect got a "+" if the criteria was true, a "-" if it was false and "0" if it was difficult to determine or if no theory confirmed the statement/criteria. Every defect with a net value of five and more are considered as critical and should therefore be further investigated in terms of finding relevant detection methods for them, see Table 5. The criteria were determined by research in order to find critical aspects and ideas from personnel at Saab Dynamics AB and composite manufacturing companies.

Table 5. Decision matrix to sort out critical defects

Criteria	**Defect**	Porosity	Voids	Ply misalignment	Fibre misalignment	Fibre waviness	Incorrect FVF	Delaminations	Disbonds	Fibre breakage	Matrix cracks	Ply drops	Temperature and moisture	Cracks	Impact damage
Propagation effect (if it expands and how easy it expands)		+	+	-	-	-	-	+	0	+	+	-	-	+	+
Affect on mechanical properties		+	+	0	0	0	0	+	+	+	0	0	0	+	+
Commonly existing defect		+	+	+	+	+	-	0	0	0	0	0	-	0	0
Can arise from several parameters		+	+	0	+	+	-	+	+	+	+	0	+	+	+
defect initiation during several stages (manufacturing etc)		0	0	-	-	-	-	+	+	+	0	-	-	+	0
How fast the defect arise		0	0	+	0	0	+	+	+	+	+	0	-	+	+
Can develop other defects		+	+	-	+	+	+	+	+	0	+	+	+	0	+
	Sum +	5	5	2	3	3	2	6	5	5	4	1	2	5	5
	Sum 0	2	2	2	2	2	1	1	2	2	3	4	1	2	2
	Sum -	0	0	3	2	2	4	0	0	0	0	2	4	0	0
	Net value	5	5	-1	1	1	-2	6	5	5	4	-1	-2	5	5
	Ranking	2	2	11	9	10	13	1	2	2	8	11	13	2	2
	Decision	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes

Voids/porosity: These are very common defects and if voids and pores are initiated close to each other they can grow together and propagate which lead to cracks. Voids cause reduction in E-modulus and much other type of strengths [18]. Voids and pores can be initiated in different ways during fabrication process of a shell body, for example during the curing process or when the fibres become placed in the resin bath with incorrect viscosity. These defects result in weakening of the shell body because only about 1 % content of pores in CFRE reduces mechanical properties with up to 6% [26].

Fibre- and ply misalignment: If only a smaller amount fibres have another direction than all the other ones, fibre misalignment will not be a critical defect since there will not be any major changes in mechanical properties. But if there is anything wrong with manufacture settings or during manufacturing it results in big content of fibres become wound in different angles, this will be a more critical defect where 20% error reduces mechanical characteristics by up to 60 % [26]. A high error in alignment results in significant decrease in strength which is very serious since the shell body cannot handle the forces it is exposed to during launching.

These defects have not the ability to propagate and only occur during manufacturing. The filament winding process has very high precision and accuracy. This results in fibre- and ply misalignment being very controlled and safe and possible problems should therefore not be seen as critical [26].

Fibre waviness: If a lower content of fibres are wavy it has a neglected influence. If the fibres not are stretched out during filament winding it is a big risk of many wavy fibres and therefore a very low compressive strength and is too weak for the pressures which make the whole shell body to collapse during launching. Waviness can occur from a weak winding.

This defect should not be critical for same reason as fibre- and ply misalignment.

Incorrect fibre volume faction: FVF depends among others on how hard the tensioner wound the fibres. Harder winding results in more compact fibres and therefore higher FVF and vice versa. Variation in FVF gives variation in mechanical properties since the fibres are major reason for determination of strength of the material.

This defect should not be critical for same reason as fibre- and ply misalignment.

Delamination: Can occur in several stages as manufacturing stage, assembly mode, by impacts and so on. Delaminations can be non-visible and have a high propagation rate and must therefore be detected in an early stage. This defect makes the component to get reduced mechanical properties. Delamination can lead to several other dangerous defects as fibre breakage and cracks.

This is an important defect that can affect the shell body in very dangerous ways, therefore it has to be further investigated. This makes it a critical defect.

Disbonds: Occur by several factors as chemical-, mechanical- and/or physical forces where it results in uneven spread stresses over the fibres which lead to decrease in stiffness [7].

Propagation process for disbonds is quite rapid but it is increased by interaction with environment and loading and can therefore be hard to see before it loses its adhesion. There are many parameters that can reduce adhesion (see section 2.2.3) which develop disbonds to a critical defect.

Fibre breakage: Increased amount of cracked fibres stepwise decrease the tensile strength. Fibre breakage can occur in many ways as by delaminations, fibre waviness, matrix cracks and during in-service. If a crack starts to grow and propagate it leads to failure and probably leakage which is serious for a shell body.

The fibres in a composite are the main parts and most important factor to hold up the loads/strength it is exposed to, therefore it has to be further investigated. This makes fibre breakage to a critical defect.

Matrix cracks: Matrix cracks are for example caused by incorrect curing, mechanical- and/or thermal stresses. Incorrect curing results in areas become too dry or too wet resin depends on curing temperature and curing time and has therefore not a good adhesion. This affects the fibres where the transfer of load between them is uneven.

Since the fibres stands for the strength and takes the loads, some matrix cracks should not affect the mechanical properties significantly and therefore not be critical.

Ply drops: Ply drops leads to variation in thickness because variation in winding hardness and therefore gets stress concentrations, but since filament winding is a very accurate method ply drops is not a critical defect.

Temperature and moisture: The matrix in a shell body is a hot curing epoxy resin. When epoxy is applied as matrix it includes one, two or three minor epoxies used to increase characteristics for elevated temperatures and toughness, decrease absorption of humidity and to control viscosity.

With correct matrix material the risk of temperature and moisture are significantly reduced and should not be critical.

Cracks: If a crack starts to propagate it rapidly leads to failure and probably leakage. Cracks occur during a high loading, during assembly or in-service when shell body get hit with forces that make a crack in the material. Cracks can propagate and be big even if the crack initiation is non-visible. The more the cracks propagate the more fibres and matrices are broken and thus have a reduced strength. This leads to a reduced built-up pressure in the shell body during launching.

This one is an important defect that can affect the shell body in very dangerous ways, therefore it has to be further investigated. This makes cracks a critical defect.

Impact damages: Impact damages in a CFRE can occur in several types of stages. This is a typical in-service defect and even if these impacts are very small or non-visual, it can propagate throughout the laminates. Depending on energy impacts there are different other defects that can be initiated and propagated. These defects make the component to get reduced strength. [5]

This is an important defect that can affect the shell body in very dangerous ways, therefore it has to be further investigated. This makes impact damage to a critical defect.

3.4 Concept generation

Elimination matrix was an effective method for separating better solutions from bad solutions. The purpose of the elimination matrix was to systematically eliminate concepts that could not meet all the pre-determined question formulations:

- Does the concept solve the main problem? [43]
- Satisfy requirements? [43]
- Realisable? [43]
- Within margin of expenditure? [43]
- Relevant for the company? [43]
- Sufficient information? [43]

In the elimination matrix every brainstorming idea (i.e. the NDT methods) was analysed as concept proposals, see Table 6. Elimination matrices were made, see Appendix 10, for each critical defect to find out which concepts that had high enough trustiness to find the defects. These good concepts were moved on from the concept generation phase to concept selection phase.

Table 6. Brainstorming solution proposals for detection of defects

1	Ultrasonic A-scan
2	Ultrasonic B-scan
3	Ultrasonic C-scan
4	Ultrasonic D-scan
5	Acoustic-emission
6	Acousto-ultrasonics
7	Acoustography
8	Thermography
9	Penetrant enhanced X-radiography
10	X-ray computed tomography
11	Shearography
12	Membrane resonance
13	Eddy-current testing

In the elimination matrices the concepts was compared in a relationship against those question formulations above where each concept got a “+” if it was true, a “-“ if it was false and “?” if more information was required before a correct evaluation. These question formulations was used as criteria in each elimination matrix. The concepts from these elimination matrices with a “+” in the decision cell proceeded to concept selection phase where decision matrices were made.

For an example how an elimination matrix could looked like, see Table 7

Table 7. Elimination matrix for delamination

Solution number	Solves main problem	Satisfy remaining requirements	Realisable	Within margin of expenditure	Relevant for the company	Sufficient information	Decision
1	+	-	+	+	+	+	-
2	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+
5	-	+	+	+	?	+	-
6	+	+	+	+	+	+	+
7	+	-	+	+	+	+	-
8	+	-	+	+	+	+	+
9	-	-	+	-	+	+	-
10	-	+	+	-	+	+	-
11	+	+	+	+	+	+	+
12	+	-	+	+	+	+	-
13	+	?	+	+	-	+	+

A pre-sorting of the four methods from low frequency vibration (see section 2.5.5) that have the best possibility to detect defects has been made below.

Coin tap test is a good choice in terms of cost, speed and easiness but it requires good operator skills to recognize the defects and a consequent hitting with the hammer on the sample can reduce its mechanical properties. Coin tap was therefore not any method used in the elimination processes.
Mode shape is a costly method with complex instrument and needs a pulse system to avoid vibrations which is required for enhanced resolution.
It is easier to detect the damaged areas with membrane resonance compared to mechanical impedance technique due to it is bigger variations in dynamic impedance between good and bad regions. Membrane resonance has a non-contact excitation source which differs from mechanical impedance technique. Membrane resonance was therefore being the more preferable of these two methods.
According to this, membrane resonance is the best alternative as low frequency vibration method and was the only one of these four methods that represented low-frequency vibration during the eliminations.

A pre-sorting of x-ray radiographic inspections that have the best possibility to detect defects has been made below.

Conventional radiographic inspection does not have any depth analysis and was therefore not any method used in the elimination processes.
PEXR does not require much surface preparation and need very little time to receive resulting pictures. The earlier invisible defects from the conventional methods can be detected. PEXR has some ability compared to other radiographic inspections to find cracks, delaminations and disbonds even though they are planar defects.

X-ray backscatter CT was used for further examination instead of x-ray CT because the first one has single-side inspection which is beneficial; otherwise they work about the same way with same defect detectability.
According to this PEXR and x-ray backscatter CT were the two of these four methods that represented radiographic testing during the eliminations

3.5 Concept selection

In decision matrices, the concepts that were moved on from respective elimination matrix, was evaluated against the most important criteria developed from requirement specification for detection methods (see Appendix 9) to find which solutions that had highest trustworthiness to detect respective critical defect. All graded requirements from the requirement specification proceeded as important criteria in decision matrices (i.e. with the sign R in Appendix 9). Those wishes with grade of importance of number three and more also proceeded as important criteria in decision matrices (i.e. with the sign W in Appendix 9).

During evaluation in each decision matrix, every concept was compared against the most important criteria. If a concept got a "+" the criteria was true, a "-"if it was false and "0" if it was difficult to determine or if no theory confirmed the statement/criteria. Then these signs was summarised to a net value. Solutions with a net value of six and more were determined to have high trustworthiness and got a "Yes". These concepts with "Yes" from each separate decision matrices were compared to each other in order to find the number one concept for each critical defect.

For an example how a decision matrix looked like, see Table 8. The concepts from these decision matrices with a "Yes" in the decision cell proceeded to final selection phase.

Table 8. Decision matrix for delaminations

	Solutions							
Criteria	1 (ref)	2	3	4	6	8	11	13
Low cost		+	+	+	0	+	-	+
Easy to apply (utilisation)		0	0	0	+	+	+	-
Low running-time		-	-	-	+	+	+	+
High reliability		-	+	+	-	+	+	-
Non-contact mode		0	+	0	+	+	+	+
3-D image		0	0	0	0	0	+	0
Single-side inspection		+	-	+	0	+	+	+
Depth analysis		+	+	+	+	-	+	0
Real-time viewing		+	+	+	+	+	+	+
Inspection of asymmetric geometry		+	+	+	+	+	+	+
In-field inspection		+	+	+	+	+	+	+
Sum +		6	7	7	7	9	10	7
Sum 0		3	2	3	3	1	0	2
Sum -		2	2	1	1	1	1	2
Net value	0	4	5	6	6	8	9	5
Ranking	8	7	5	3	3	2	1	5
Decision	No	No	No	Yes	Yes	Yes	Yes	No

4. Results

NDT-methods that were concepts to detect respective defects were chosen by knowledge from the theory, personnel from Saab Dynamics AB, information from composite manufacturing companies, Table 3 and primarily from Table 2 since this one focus on CFRP. Table 3 shows detectability for composites generally and was studied very carefully.

The results of how respectively concepts were sorted out after each elimination matrix, decision matrix or if they proceed further in selection phase was determined by compare the concepts against each separate criteria in the matrices. See Appendix 10 for elimination matrices and Appendix 11 for decision matrices. Important background information that was used for rating the concepts came from section 2.5 in the theory part and from Appendix 1-8 where scaling and summaries of criteria was done for each NDT method.

4.1 Requirement specification of shell body

This requirement specification was made to avoid weapon explosion and shatter.

Overall requirements are controls of the components should be done before assembly of the warhead body. If someone suspects any damages of those, some relevant NDT method have to be used. If the shell body become dropped or otherwise damaged by impact it is important to do NDT inspection. Aspects to have in mind during determination of degrees of danger of the defects are how easy and costly it can be to repair.

The requirement specifications of shell body with their classification zones are listed, see Table 9.

Table 9. Classification of the requirements for a shell body

Number	Requirement	Classification zone
1	Fully isolation of driving band	Class 1
2	Stricter tolerances of dimensions of shell body	Class 3
3	Strengthen back plane	Class 1
4	Strengthen thread joints	Class 2
5	NDT inspection on every shell body	Class 3
6	Control of fibre volume fraction	Class 3
7	Correct fabrication and choice of material for the girdle	Class 3, but can results in Class 1
8	Max 1 % strain levels	Class 1
9	Fully safe for disposal after drop tests from 12 m	Class 2
10	Maximum 2-4 % of voids or porosity	Class 3, but too high content results in Class 1
11	Safety factor at least 2.5	Class 1
12	Cassation of shellbodies with bigger defect sizes	Class 1
13	Fully functional after transport tests	Class 2

4.2 Concept generations

Elimination of concepts started early for possibility to eliminate those concepts that were not feasible or did not satisfy the question formulation criteria in the elimination matrix [43]. Those concepts that not seemed trustworthy had to be screened out in order to find best concepts for the critical defects.

Comments in text about each concept during concept generation phase below described why respective method proceeded from the elimination matrix. The concepts that not managed the question formulations did not proceed from each elimination matrix, these are not included in the sections below.

All of the concepts for each critical defect below got the decision “Yes” from each separate elimination matrix and moved on to respective decision matrix, and the other ones did not got a “Yes”.

4.2.1 Concepts for detection of fibre breakage

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were acoustic emission, shearography and eddy current testing. For further information about the elimination, see comments about each concept below.

4.2.1.1 Acoustic emission (AE)

AE have a signal sensitivity which is very high compared to other techniques which make it possible to find breakages of separate fibres and matrix cracks. The defects, fibre breakage in this case, have to be exposed to small stresses in form of stress waves if this method should find the defects, but because these inserted stresses are very small it does not affect the mechanical properties in any way. [13]

4.2.1.2 Shearography

This method is restricted to that the fibre breakage only creates small stresses in the material structure that shearography have difficulties to find. Therefore, a smaller amount of fibre breakage would not be detected. Shearography can detect fibre breakages but not as well as AE, but better than ECT.

4.2.1.3 Eddy current testing (ECT)

ECT has only ability to detect broken fibres if there are a high percentage of total amount of fibres that are broken. ECT has not high probabilities to satisfy the remaining requirements that are initiated in the decision matrix. This method can be relevant for the company but only for studying components with high electric conductivity.

4.2.2 Concepts for detection of cracks

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were acoustic emission, acoustography, thermography, x-ray backscatter CT and shearography. For further information about the elimination, see comments about each concept below.

4.2.2.1 Acoustic emission (AE)

This method is a good method for detection of all type of cracks. AE have the ability to find the cracks in such an early stage so they are not crucial enough to reduce mechanical properties in a serious way. This is a very good method to find cracks and breakages and is quite relevant for the company.

4.2.2.2 Acoustography (AC)

It could find planar defects with orientations perpendicular to transmission path of the ultrasounds. Through-transmission mode is the mostly used AC-method but it does not have single-side inspection and did not satisfy all the most important criteria (i.e. remaining requirements) enough to proceed to decision matrix.

4.2.2.3 Thermography

Surface cracks can be detected and those works as a black body where they emit more heat energy than the material around the cracks. This leads IR-camera to analysis the crack region as warmer region compared to the surrounding. The method has limited depth in detection of defects.

4.2.2.4 X-ray radiography

X-ray backscatter CT can only find cracks when they have their dimensions parallel to the radiation beam which leads to a lower chance to find planar defects (such as cracks) because it strongly depends on defect orientation. Radiographic inspections are instead better for volumetric defects as cracks. The capital cost is much more expensive than the other NDT methods.

4.2.2.5 Shearography

Shearography could detect cracks. This method has high sensitivity to strain concentrations which make shearography able to detect cracks even if they not going through the whole specimen. Due to very good resolution and real time viewing cracks can be detected early detection procedure.

4.2.3 Concepts for detection of delamination

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were ultrasonic B-D-scan, acousto-ultrasonics, thermography, shearography and eddy current testing. For further information about the elimination, see comments about each concept below.

Delamination is one of the most common defects in filament wound composite materials. It leads to the degradation of mechanical properties and thereby eventually the failure of the overall composite component.

4.2.3.1 Ultrasonic B-scan

B-scan is a contact-mode that scans the specimen for defects at the same time as the probe makes its movements and provides 2-D picture of a plane through the component. It is easier to find planar defects with pulse-echo mode compared to through-transmission mode. All the ultrasonic inspection methods have quite low capital cost and low consumable cost.

4.2.3.2 Ultrasonic C-scan

C-scan is a non-contact mode and can be used to detect, measure and characterize a wide range of manufacturing and in-service defects. C-scan has some ability to detect planar defect but not same as pulse-echo methods. [27]

4.2.3.3 Ultrasonic D-scan

D-scan is a very good selection to find planar find defects because it is easier to find planar defects with pulse-echo mode compared to through-transmission mode.

4.2.3.4 Acousto-ultrasonics (AU)

AU is a feasible rapid inspection method to determine material characteristics for CFRP fabricated by a filament winding. Have some difficulty to find smaller defects overall since the wavelength are longer and therefore lower frequency.

4.2.3.5 Thermography

This method receives both size and depth of the defect even if the depth analysis is somewhat limited. Thermal conductivity in regions including voids, delaminations and disbonds are lower compared to the ”good” regions in the CFRE material which leads to thermal heat from the heat source getting stuck in the defect region. These defected regions have increased heating compared to the good regions and are thus easier to be detected. [13]

Thermography is an extremely cost-effective method and can analyses a big area in a very short time. With correct installed parameters it is very easy for the operator to see the defects in the IR-camera, but it require a quite skilled operator to bring out exactly which type of defect it is.

Thermography has some difficulties to find bigger delaminations because the defected area has to be heated for a longer time to emit heat energy from a bigger area. The resolution in the IR-camera is reduced if the heating time is the same for bigger delaminations compared to smaller sizes. A risk with longer time for heating is to get a more even distributed heating of the whole analysed area and therefore a decreased image quality because the emitted heat energy is about the same for the defects and the "good" regions.

Anyhow, it is possible to find parts of the bigger delaminations. By heating for a regular time it is possible to detect parts of the bigger delaminations which are fully acceptable. With use of a Fourier transformation analysis it computes image- and signal processing algorithms which make it easier to find smaller damages inside the structure.

4.2.3.6 Shearography

Experiments according to [45] showed that fringe pattern have big changes (bigger changes in fringe pattern lead to easer detection of defects) when the laser detected disbonds and delaminations and had thus easy and rapid detectability of these damages.

4.2.3.7 Eddy current testing (ECT)

ECT is cost-efficient and rapid inspection method but has limited depth analysis and can find defects in about five composite layers. ECT has to use high frequencies, 10 MHz and more, to get a better resolution because CFRE is a low electrical conductivity material which is bad for this method. The eddy-currents act parallel to the fibre layers and have a low interactive capability to find delaminations since eddy current do not create enough distortions in the current distribution so the system cannot detect the defect. [46]

4.2.4 Concepts for detection of disbonds

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were ultrasonic B-D-scan, thermography and shearography. For further information about the elimination, see comments about each concept below.

4.2.4.1 Ultrasonic B-D-scan

All of the ultrasonic methods can detect planar defects in a reliable way and therefore have good possibility to find disbonds but D-scan has best detectability of these for finding planar defects.

The pulse-echo methods can detect planar defect in a reliable way and therefore have good possibility to find disbonds. D-scan is a better choice to find planar find defects. Since C-scan is a through-transmission this one has not same high probability.

4.2.4.2 Thermography

It is important to ensure that the whole inspecting area becomes heated with same temperature because if the inspected area becomes uneven heated it can be mixed up with disbonds. The experiment according to [47] showed that disbonds can be detected with thermography and is therefore a reliable method for this defect.

Thermal conductivity for voids, delaminations and disbonds are lower compared to the "good" regions in the CFRE material which leads to thermal heat from the heat source get stuck in the defect region. These defected disbonds regions have increased heating compared to the good regions because the good regions have higher performance to keep down the heating rate. The defected regions have therefore a lower cooling rate.

4.2.4.3 Shearography

Shearography has big advantages in finding defects locally in bond strength [27]. Experiments according to [45] showed that fringe pattern had big changes when the laser detect disbonds and delaminations, and had thus easy and rapidly detectability of these damages. Satisfy remaining requirements due to real-time viewing with 3-D image etc.

4.2.5 Concepts for detection of porosity

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were ultrasonic B-D-scan, acousto-ultrasonics, thermography, PEXR, x-ray backscatter CT and shearography. For further information about the elimination, see comments about each concept below.

Ultrasonic inspection (UT) is old standard methods to find porosity in CFRP. Nowadays some newer methods as thermography, x-ray backscatter CT and shearography are options. Thermography and UT methods need skilled operators to find which type of damage it is seen on the images. The CT may be used to overcome some of the UT limitations regarding size, shape and position of all individual pores. X-ray backscatter CT and shearography receive 3-D images with micrometre resolution.
Thermography is a faster method and results in more detailed information than the ultrasonic methods.

4.2.5.1 Ultrasonic B-scan

B-scan is a pulse-echo mode which is a better choice for finding planar defects. Since porosity is a volumetric defect it is harder to find these with high resolution.

4.2.5.2 Ultrasonic C-scan

Ultrasonic C-scan is most trusty of ultrasonic scan methods. C-scan has a very good trustworthiness by the ultrasonic methods in order to find pores and other volumetric defects. If the FVF is high and therefore too small amount epoxy in the material it is hard to find porosity since they arise in the matrix, according to study of [34].

4.2.5.3 Ultrasonic D-scan

D-scan is a reflection mode which is a better choice for finding planar defects.

4.2.5.4 Acousto-ultrasonics (AU)

AU is a feasible rapid inspection method to determine material characteristics for CFRP fabricated by a filament winding. Can find both volumetric and planar defects but have longer wavelength than other ultrasonic methods and therefore lower frequency and resolution.

4.2.5.5 Thermography

Porosities are very sensitive to thermography and can be detected by measuring the thermal diffusivity from the material.

4.2.5.6 X-ray radiography

Radiographic inspections shows that these are the better methods for volumetric defects as porosity defect since the method are "specialised" to find volumetric defects.
It is possible to obtain porosity with sizes of a couple of micrometre due to the method receive a resolution of only one micrometre. X-ray backscatter CT should be the best radiographic alternatives to find porosity because its high resolution.

4.2.5.7 Shearography
The technique is a sensitive and non-contact method that can quickly inspect a structure with real-time viewing. Porosity is one of the easiest defects to detect with shearography. Shearography is a highly sensitive, rapidly and con-contact method with full-field inspection.The output from the system also show data values like defect depth, area and size of defect.

4.2.6 Concepts for detection of voids
The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were ultrasonic B-D-scan, thermography, x-ray backscatter CT and shearography. For further information about the elimination, see comments about each concept below.

For inspection with UT, the voids should be big enough to cause signal attenuation in the back-wall of the material (if it is being monitored with pulse-echo) or signal magnification in the echo of the ultrasound (if it is being looked for through-transmission) [48].

4.2.6.1 Ultrasonic B-scan
The attenuation coefficient is determined by geometry and amount of voids which can results in incorrect inspections [48] since voids can have probability to look like volumetric defects as well as planar.

4.2.6.2 Ultrasonic C-scan
The attenuation coefficient is determined by geometry and amount of voids which can results in incorrect inspections [48] since voids can have probability to look like volumetric defects as well as planar.

4.2.6.3 Ultrasonic D-scan
The attenuation coefficient is determined by geometry and amount of voids which can results in incorrect inspections [48] since voids can have probability to look like volumetric defects as well as planar.

4.2.6.4 Thermography
Thermal conductivity for voids, delaminations and disbonds are lower compared to the ”good” regions in the CFRE material which leads to thermal heat from the heat source get stuck in the defect region. These defected disbonds regions have increased heating compared to the good regions because the good regions have higher performance to keep down the heating rate. The defected regions have therefore a lower cooling rate.

4.2.6.5 X-ray radiography
Radiography methods shows that these are the better methods for volumetric defects as void defects since the method are "specialised" to find volumetric defects.
X-ray backscatter CT has depth analysis and 3-D image and should be a very good radiographic inspection alternative to find voids even if it is the more expensive radiographic method.

4.2.6.6 Shearography
Shearography is used to detect sub-surface anomalies such as voids. The technique is a sensitive and non-contact method that can quickly inspect a material structure with real-time viewing.

4.2.7 Concepts for detection of impact damage

The concepts that proceed from elimination matrix to decision matrix in the concept selection phase were ultrasonic B-D-scan, thermography, PEXR and shearography. For further information about the elimination, see comments about each concept below.

Even if the material becomes stroked by something, like a tool drop, with low energy it can cause large delaminations, non-visible defects or cracks etc. These decrease the load resistance for the CFRE and can also propagate into several serious defects. Due to this it is a big need for reliable inspection methods to find impact damages.

4.2.7.1 Ultrasonic B-D-scan

Ultrasonic testing methods have quite high possibility to detect this kind of defect but can detect only one and two of these three impact phases (see section 2.4.2.5) that can occur depend on impact energy. Otherwise these methods are very relevant for the company since it have high possibility for inspecting metals which are widely used at Saab Dynamics AB.

4.2.7.2 Thermography

Have possibility to find all three impact damage phases (see section 2.4.2.5).

4.2.7.3 X-ray radiography

If it is a need of detect any in-service defects the radiographic method can be an option, but since the impact damage can give rise to planar defects it can be difficult to find all the three impact phases.

4.2.7.4 Shearography

Impact damages in CFRE are easier to detect compared to other composites. Since shearography has good detectability in both planar- and volumetric defects, this one is the easiest method to detect impacts with.

4.3 Concept selections

Comment about each NDT method in text below during concept selection was based on concept generation process, summaries from information about the methods, same company contacts as earlier mentioned, and from theory parts of each inspection method.

4.3.1 Fibre breakage

Since ECT can only find fibre breakage when a certain amount has broken, not have 3-D analysis and generally have low resolution for CFRE it was screened out in decision matrix.

This led to acoustic emission and shearography were main alternatives for detection of fibre breakage:

Shearography is a more expensive method than the other two remaining concepts and have only some reliability to find the fibre breakages. Shearography have a wide range of other detectable defects which instead is a useful merit. Shearography cannot detect fibre breakage in micro-scale as AE since fibre breakage make small local variations in material structure where shearography have difficulties to find. But can detect those that are big enough to avoid reduction of mechanical properties [48]. This concept was therefore not the best option.

Acoustic emission is the best one to find fibre breakages since it can find breakages of single fibres. AE have not a wide range of defect detectability but is about half price of shearography in capital cost [26].

The best method for detection of fibre breakage is acoustic emission.
The cheapest method for detection of fibre breakage is acoustic emission.

4.3.2 Cracks

Acoustography has difficulty in finding defect depth and not have single-side inspection, and was therefore screened out in decision matrix.

This led to acoustic emission, thermography, x-ray backscatter CT and shearography were main alternatives for detection of cracks:

Acoustic emission is a very fast method with lower capital cost than both shearography and x-ray backscatter CT. This concept cannot detect as many defects as the other ones but is instead very useful to find different kind of cracks and breakages.

Thermography is a cheapest method of these three. It has possibility to find cracks, but only at limited depth and was not the best selection even if the price is about the half price of shearography [26].

Cracks are often a planar defect but can have a more volumetric shape. Since X-ray backscatter CT is a very expensive method and has difficulties to detect planar defect it was not the best concept.

Shearography have 3-D images, detection of a very wide range of critical- and other defects, can detect cracks with good resolution and have real time viewing which leads to early detection. With very hard competition with AE it resulted in acoustic emission was best choice for crack detection.

The best method for detection of cracks is acoustic emission.
The cheapest method for detection of cracks is shearography.

4.3.3 Delaminations

Ultrasonic B-C-scan moved on to decision matrix but did not manage the criteria and was therefore screened out in decision matrix.

Since ECT can only find fibre breakage when a certain amount has broken, not have 3-D analysis and generally have low resolution for CFRE it was screened out in decision matrix.

This led to ultrasonic D-scan, acousto-ultrasonics, thermography and shearography were the main alternative for delaminations:

D-scan has easier to detect planar defects compared to volumetric defects and is a relatively low-cost method (around half capital price of shearography) [26], with real-time viewing and depth analysis. Ultrasonic waves have on the other hand weaker analysis of the result pictures and relatively low resolution in CFRE as they have in other materials. This is because the uneven noise distribution produced by the interference of the backscattered signals. Due to this D-scan was not the best concept.

Acousto-ultrasonics is rapid but have only ability to find larger defects and if it is a higher amount of smaller ones. AU cannot detect smaller individual defects because the wavelength is longer and is therefore not one of the best concepts [13].

Thermal conductivity in regions including delaminations are lower compared to the ”good” regions in the CFRE material which leads to a good resolution of the defect. Thermography can though have some difficulties to find bigger delaminations and detect the depth of the defects, for further information see section 4.2.3.5.

Shearography have big changes in fringe pattern when delaminations are found which gives early detection with high resolution.

The best method for detection of delaminations is shearography.
The cheapest method for detection of delaminations is thermography.

4.3.4 Disbonds

B-C-scan was screened out in decision matrix since they did not manage the criteria. D-scan was the only pulse-echo method that managed the criteria.

This led to ultrasonic D-scan, thermography and shearography were main alternatives for disbonds:

D-scan has contact between probe and object which increased risk of waste at the analysis surface area. D-scan has easier to detect planar defects and is a relatively low-cost method with real-time viewing and depth analysis. Ultrasonic testing and thermography have about the same capital costs. Ultrasounds have decreased resolution in CFRE which lead to less good resolution compared to the other concepts.

In thermography, the air gap from disbonds limit the heating to pass through the composite and therefore the surface over the disbonds are hotter than region around the defect which make it to a good resolution in the IR-camera. The experiment according to [47] showed that disbonds can be detected with thermography and is therefore a reliable method for this defect. The negative with this one is their difficulty to detect defect depth.

Shearography have big changes in fringe pattern when disbonds are found which gives early detection with high resolution. This method have highest resolution of these and can find both planar- and volumetric defects and find disbonds at depth which make it to the best selection.

The best method for detection of disbonds is shearography.
The cheapest method for detection of disbonds is ultrasonic D-scan or thermography.

4.3.5 Porosity

Porosity is a volumetric defect and ultrasonic B- and D-scan was therefore screened out in decision matrix. None of them have non-contact mode.

This led to ultrasonic C-scan, acousto-ultrasonics, thermography, the two radiographic methods and shearography were main alternatives for porosity:

C-scan is a relatively low-cost method, around half capital price of shearography [26], with real-time viewing and depth analysis. Ultrasonic waves have on the other hand weaker analysis of the result pictures and relatively low resolution in CFRE as they have in other materials. This is because the uneven noise distribution produced by the interference of the backscattered signals. Due to this C-scan was not the best concept.

Acousto-ultrasonics is only able to find larger defects and if it is a higher amount of smaller ones. AU cannot detect smaller individual defects because the wavelength is longer compared to UT [13] and was not the best concept.

Thermography has some difficulties to detect higher amount of porosities. With higher amount of porosity, about 5-10 % and more in the epoxy, the sensitivity in the IR-camera becomes lower due to more pore content have higher possibility to interlock with each other and reduce the emitted heat energy. Investigation according to [34] showed that geometries of the pores have a significant impact on thermal diffusivity. Thermography is not the best concept.

Shearography is used to detect sub-surface anomalies such as porosity and have around five times lower capital cost than radiography. Shearography do also have 3-D image, real-time viewing etc.

Radiography has highest resolution of the NDT-methods explained in this project. They have also very high trustiness and can find volumetric defects at micrometre-level and every single pore. Radiography are the best methods for volumetric defects. The wavelengths for x-rays are generally shorter compared to the ultrasonic waves and results in increased resolution pictures. These inspection methods are able to be used at thicker areas. X-ray backscatter CT have single-side inspection which not PEXR has which make x-ray backscatter CT to the best concepts of these two.

The best method for detection of porosity is x-ray backscatter CT.
The cheapest method for detection of porosity is shearography.

4.3.6 Voids

For ultrasonic B-D-scan, the attenuation coefficient is determined by geometry and amount of voids which can results in incorrect inspections [48] since voids can have probability to look like volumetric defects as well as planar. B- and D-scan was screened out in decision matrix since they have lower probability to find volumetric defects.

This led to ultrasonic C-scan, thermography, x-ray backscatter CT and shearography were main alternatives for voids:

Ultrasonic C-scan has higher possibility to find wider range of defects compared to B- and D-scan. Ultrasonic methods have less good resolution in CFRE compared to radiographic methods and are thus not the best concept.

Thermography is an extremely fast method with real-time viewing. It has lowest capital cost of these three methods. Thermography did not manage to answer the criteria about inspect the defect depth.

Radiography has highest resolution and trustiness of these NDT methods and can find volumetric defects at micrometre-level. The wavelengths for x-rays are generally shorter compared to the ultrasonic waves and results in increased resolution pictures. X-ray backscatter CT also has real-time viewing, a 3-D image etc. and is best individual choice since it is specialised on volumetric defects.

Shearography is used to detect sub-surface anomalies such as void like x-ray backscatter CT, but with a faster technique and cheaper equipment.

The best method for detection of voids is x-ray backscatter CT.
The cheapest method for detection of voids is shearography.

4.3.7 Impact damage

Ultrasonic methods have quite low running-time and can only detect one and two of these three impact phases and were therefore screened out in decision matrix.

Radiography have very high capital cost. The method can detect impacts but because impact damage can give rise to planar defects the concept was therefore screened out in decision matrix.

This led to thermography and shearography were main alternatives for impact damage:

Thermography cannot find fibre breakage which is the last stage of the three impact phases (see section 2.4.2.5). Shearography has some detectability of fibre breakage and therefore thermography was not the best concept.

The impact damages must have modified the surrounding structure to be detected [48]. Shearography has good detectability in both planar- and volumetric defects which is beneficial because impact damage can cause both types of defects.

The best method for detection of impact damages is shearography.
The cheapest method for detection of impact damages is thermography.

4.4 Final selections

The best concepts, i.e. NDT-methods, to find each separate critical defect are seen in Table 10. Acoustic emission, shearography and x-ray backscatter CT were concepts that together can find all the critical defects. According to this it was not necessary to have seven different concepts for the seven critical defects. The final selections were only two of the methods, i.e. acoustic emission and shearography. In those critical defects where x-ray backscatter CT was the best concept the shearography was very close to be the best concept instead, but not vice versa.

Table 10. Summary of best concept to find respective critical defect

Critical defect	Best concept
Fibre breakage	Acoustic emission
Crack	Acoustic emission
Delamination	Shearography
Disbond	Shearography
Porosity	X-ray backscatter CT
Voids	X-ray backscatter CT
Impact damage	Shearography

With consideration of inspection methods that had ability to detect a wider range of defects with the same method it would be more economical, require less space and easier to use. This means that not the best individual method for each defect was used, but instead it was much more economical with fewer instruments, faster for the operator to learn the method etc.

X-ray backscatter CT can detect almost every critical defect and mostly of the non-critical too, but not with high accuracy every time. Volumetric defects are easiest to detect but not the planar defects which are at least as important. It has a very high resolution for detection of defects at only a few micrometres which make the costs extremely high. This detection at micrometre-level is not necessary in analysis of the shell body; this method is more beneficial in aerospace industry with longer load cycles where initiations of defects are more important to find.

Shearography can detect a very wide range of defects to a lower price of about five times than radiography [26]. Shearography can also detect both planar- and volumetric defects early in the propagation stages with a high resolution. Shearography is a non-contact method that can inspect a structure with real-time viewing with a more rapid scan speed than radiography.

AE is almost the only method to find fibre breakage and matrix cracks, and has highest detectability for finding these.

AE and radiography are a combination that can detect all desirable defects but with a higher cost and worse resolution for some defects compared to AE and shearography.

By using both acoustic emission and shearography all the critical defects and a wide range of other defects can be detected with very high reliability and resolution at an acceptable cost. These two methods combines perfectly with each other where AE is best method to find cracks as fibre breakage and matrix cracks, which are most commonly defects during launching and those shearography not have a good detectability. Shearography have instead good detectability for both planar- and volumetric defects.

Only two inspection methods were needed to detect every defect. This was found to be more economical, require less space and fewer certified operators compared to a separate NDT method for each defect.

5. Discussion

When a shell body has been exposed for stresses during launching, matrix cracks and fibre breakage are most common defects affected by propellant combustion pressure. Matrix crack is the less critical defect which occurs due to the impact damage. Fibre breakage is serious since the by propellant gas pressure reduces by breakages due to the fibres not can resist built-up pressures during launching.

Matrix cracks and fibre breakages are mostly common defects in shell body that occur during launching affected by burst pressure. Matrix crack is the less dangerous defect by the impact damage types. Fibre breakage is a very serious type of defect since the burst pressure reduces by breakages due to the fibres not can resist built-up pressures during launching.

The “manufacturing defects” initiates during manufacturing and are already initiated before launching. None of the defects imitated during manufacturing except from voids and porosity was determined as critical since the company that fabricate shell bodies to Saab Dynamics AB have a filament winding process with very high precision and accuracy resulting in very controlled and safe method and these defects should not be critical.

Delaminations and disbonds can occur if increased temperature or burst pressure changes the adhesion. Adhesion is depend of wettability (ability for a liquid to maintain contact with a solid surface) and a higher wettability needs otherwise there is a bigger risk of breakage of adhesion, and delamination can occur. Lower adhesion lead to initiating of disbonds when an adhesive material discontinues adhering to a substrate or to the surface which an adhesive adheres, i.e. one of the bodies does not hold to the other one by the adhesive forces. Both delamination and disbonds can initiates by burst pressure where the high pressure leads to cracks in adhesion. Changed temperature should not be a problem since CFRE can allow higher temperature than expected but the burst pressure during launching could results in initiating of defects or propagation of them.

Impact damages can occur when by propellant gas pressure make the shell body to expand and results in local impacts by high pressures. When there are impacts, several types of defects initiate and propagate.

Section 3.2.1 determined how the defects become affected and their level of criticalness. Since it is very difficult to determine how a certain amount of a specific defect affect stresses etcetera without do practical testing’s. Even though practical tests can be performed it is also very difficult to fabricate a shell body with specific defects. Finite element analysis (FEA) could be done but it should not anyway be same calculated numbers as practical tests since there are always some embedded stresses by a manufacturing that not are considered in FEA. With more time a FEA should be done but since this work have limited time it was not time enough to do it reliably.

UT did not become a final option as detection method even though some companies recommend it and use it for detection of defects in components used for defence industry. UT is a little cheaper than shearography and much cheaper than x-ray backscatter computed tomography but due to its reduced resolution of detect defects in CFRP compared to some other materials. It could not find defects smaller than millimetres sizes according to the equipment that manufacturing company used. UT can find size of defects that are small enough to not affect mechanical properties significantly.

It was hard to determine how the embedded stresses in the shell body affect mechanical properties because it is some deviations from a shell body to another. For safety an additional safety factor for embedded stresses beyond the regular factor at about 1.5

Price for respectively equipment was divided into three categories, low-cost, relative low/high-cost and high-cost. This was done because its high hardness to know about brand, quality, and functions and so on affects the prices.

The critical defects have been those that reduce the mechanical characteristics even at low amount of the certain defect in the shell body. Defects that propagate have also been marked as critical. A combination of these two criteria's and with a third point of view, how common they are, can make the defect really dangerous.

5.1 Future work

- Study if there is some other composite or shatter free material that can work instead of CFRE. CFRE is very expensive materials so if any other materials have similar mechanical- and material properties as CFRE but with lower price that would be even better to use.

- CFRE has not a good resistance against UV-radiation. Do investigations to find best coatings in order to have a UV-resistant shell body.

- Analysis of the effects of propellant erosion on the back plane of the shell body. Since the back plane are exposed for very high temperatures from the propellant charge, the back plane have risk of be "burned up".

- Make empirical data and mathematical models for different cases of defects.

- Make simulations of the launching sequence to get a visualisation of how the shell body reacts and how it affects by stresses.

- Study which winding angle and amount of plies that are most preferable for a high-strength shell body. Depend on winding angle, tension of rovings and amount of plies it leads to the mechanical properties are different.

- Investigate which regions in shell body those are most critically and afterwards generate ideas that can strengthen these weaker regions.

- Do practical tests with the NDT methods on different kind of defects to see that the theory match the practice.

6. Conclusion

Defects and how they initiate in CFRE and during filament winding have been found. The defects that are most easily initiated and/or propagate during launching were noted.

Fibre breakage and matrix cracks were found to be the most common defects for the shell body during launching affected by burst pressure.

Detection methods for NDT in usage of CFRE have been found. The methods have also been eliminated stepwise to find best detection method for each defect and to find combination of detection methods that can be used in order to detect both all critical defects and also other common uncritical defects.

Acoustic emission and shearography were found to the best combination in order to detect the most commonly occurring and critical defects in the shell body.

The most important requirements for the shell body were to be fully usable after drop tests from 3 metres and fully safe for disposal from 12 metres. Strengthening of the bottom/backplane where the shell body become affected by highest pressures and forces during launching phase. The shell body should always use a fully isolated driving band to not allow hot explosive gases penetrated into critical sections.

The most important requirements for the detection methods were to have depth analysis, high reliability, good inspection capability of asymmetric geometries and in-field inspection.

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References

[1] Vestlund, J. (2013). *Shatter free shell body for warhead.* Degree of Bachelor of Science in Mechanical Engineering. Karlstad: Karlstad University. Faculty of Technology and Science, section for mechanical engineering.

[2] Saab Dynamics AB. (2012). *84 mm Light Anti-Armour Weapon AT4 HEAT*. Karlskoga: Saab Dynamics AB (COMPANY RESTRICTED).

[3] Composites UK (2016). *Introduction to Composite Materials.* https://compositesuk.co.uk/composite-materials [Acc. 2016-02-16]

[4] Merriam-Webster (2015). *Definition of composite*. http://www.merriam-webster.com/dictionary/composite?utm_campaign=sd&utm_medium=serp&utm_source=jsonld [Acc. 2016-02-16]

[5] ASM International (2010). *Introduction to Composite Materials*. http://www.asminternational.org/documents/10192/1849770/05287G_Sample_Chapter.pdf [Acc. 2016-02-16]

[6] Zoltek. (2016). *Carbon fibre.* http://zoltek.com/carbonfibre/ [Acc. 2016-03-15]

[7] Unnborsson, R., Jonsson, M. & Runarsson, T. (2004). *NDT METHODS FOR EVALUATING CARBON FIBRE COMPOSITES*. https://notendur.hi.is//~runson/Project/comptest2004_paper.pdf [Acc. 2016-03-14]

[8] Campbell, F. (2010). *Structural Composite Materials.* Materials Park, Ohio: ASM International.

[9] Carbon Fibre Manufacturing Association (CMA). (2016). Manufacturing Process of carbon fibre. http://www.carbonfibre.gr.jp/english/material/manufacture.html [Acc. 2016-03-15]

[10] Tiwaria, S. & Bijweb, J. (2014). *Surface treatment of carbon fibre, a review.* New Delhi: Indian institute of technology.

[11] Park,S.J. & Meng, L.Y. (2015). Surface treatment and sizing of carbon fibres [Electronic]. Dordrecht: Springer science and business media.

[12] Lee, S.M. (1993). *Handbook of composite reinforcements*. Weinheim: Wiley-VCH publisher inc.

[13] National Composites Network (NCN) (2016). *Non-destructive testing of composite materials*. https://compositesuk.co.uk/system/files/documents/ndtofcomposites.pdf [Acc. 2016-03-11]

[14] Nuplex Industries. (2014). *Filament winding*. http://www.nuplex.com/composites/processes/filament-winding [Acc. 2016-03-16]

[15] Greene, E. (2014). *Marine Composites Non-Destructive Evaluation.* http://www.shipstructure.org/SDA_2_Greene.pdf [Acc. 2016-04-14]

[16] Davidson, P. &Waas, A.M. (2013). Effect of Fibre Waviness on the Compressive strength of unidirectional carbon fibre composites. *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. Honolulu, Hawaii, 23 - 26 April 2012. DOI: 10.2514/6.2012-1422

[17] Boey, F.Y.C. & Lye, S.W. (1992). Void reduction in autoclave processing of thermoset composites:

Part 1: High pressure effects on void reduction. *Composites*, 23 (4), page 261-265.

[18] Saidpour, S.H. & Tehranchi, H. (2001). Determination of void distribution and fibre volume fraction in filament wound composite. *Second International Convention for Filament Winding of Composite Materials*. Brussels, Belgium, *Proceeding of the Second International Convention for Filament Winding of Composite Materials*.

[19] Smith, R.A. (2015). *Composite defects and their detection*. http://www.eolss.net/sample-chapters/c05/e6-36-04-03.pdf . Farnborough: Structural Materials Centre. Qineti Ltd, Cody Technology Park

[20] Mallick, P. K. (2006). Proceedings of the American society of composites. Fairborn: DEStech Publications, Inc.

[21] Irving, P.E. & Soutis, C. (2015). *Polymer Composites in the Aerospace Industry.* Cambridge: Woodhead Publishing.

[22] Avery, D., Samborsky, D., Mandell, J. & Cairns, D. (2004). *Compression strength of carbon fibre laminates containing defects with fibre waviness*. Montana: Montana State University. http://www.montana.edu/composites/documents/AIAA_2004_0174.pdf [Acc. 2016-03-11]

[23] Corrosionpedia (2016). *Definition - What does Delamination mean?* https://www.corrosionpedia.com/definition/1371/delamination [Acc. 2013-03-14]

[24] Guedes, R. & Moura, M. (2012). *Wiley Encyclopedia of Composites* [Electronic]. New Jersey: John Wiley & Sons

[25] Tarakciogtlu, N., Akdemir, A. & Avci, A. (2001). Strength of filament wound GRP pipes with surface crack. Composites Part B: Engineering, 32 (2), 131–138. Doi: 10.1016/S1359-8368(00)00037-8

[26] Erik Olsson, Applied Composites AB, Linköping, +4613-20 97 00

[27] Vaara, P. & Leinonen, J. (2012). *Technology Survey on NDT of Carbon-fibre Composites.* Kemi: Kemi-Tornio University.

[28] Omar, M., Dongri, S. & Shen, Q. (2012). Ultrasonic NDE Techniques for Impact Damage Inspection on CFRP Laminates. *Journal of Materials Science Research*, 1 (1), 2-16.

[29] The Minerals, Metals & Materials Society (TMS). (1998). *Using Acoustic Emission in Fatigue and Fracture Materials Research*. http://www.tms.org/pubs/journals/jom/9811/huang/huang-9811.html [Acc. 2016-03-21]

[30] Kautz, H. (1986). ACOUSTO-ULTRASON1C VERIFICATION OF THE STRENGTH OF FILAMENT WOUND COMPOSITE MATERIAL. *Pressure Vessel Conference*. Chicago, Illinois, USA, July 21-24, 1986.

[31] Santos, J.B. (2000). *Dry Coupling Ultrasonic Characterisation of Flooring Tiles and Pavements.* http://www.ndt.net/article/wcndt00/papers/idn112/idn112.htm [Acc. 2016-03-14]

[32] Poudel, A., Sandhu, J., Chu, T. & Pergantis, C. (2014). Porosity Measurement in Carbon Fibre Epoxy Laminates by Using Acoustography. *ASNT 23rd Annual Research Symposium and Spring Conference*, Minneapolis, USA, 24-27 March 2014.

[33] Poudel, A.,Shrestha, S., Sandhu, J., Chu, T. & Pergantis, C. (2014). Comparison and analysis of Acoustography with other NDE techniques for foreign object inclusion detection in graphite epoxy composites. *Composites Part B*. 1 September 2015, volume 78, page 86-94.
DOI: 10.1016/j.compositesb.2015.03.048

[34] Meola, C. & Toscano, C. (2014). Flash Thermography to Evaluate Porosity in Carbon Fiber Reinforced Polymer (CFRPs). Materials, 7, ss. 1484-1501.doi:10.3390/ma7031483

[35] Edevis (2016). *Pulse Thermography*. https://www.edevis.com/content/en/pulse_thermography.php [Acc. 2016-03-14]

[36] Shimadzu (2016). *Micro Focus X-Ray CT System*.
http://www.shimadzu.com/an/ndi/ct/smx100ct.html [Acc. 2016-03-14]

[37] NDT Turkey (2007). *Introduction to Optical Holographic NDT.*
http://www.turkndt.org/sub/makale/ornek/Introduction%20to%20Optical%20Holographic%20NDT.pdf [Acc. 2016-03-18]

[38] Heuer, H. & Schulze, M. (2011). Eddy current Testing of Carbon Fibre Materials by High Resolution Directional Sensors. *SMART MATERIALS, STRUCTURES & NDT in AEROSPACE*. Montreal, Quebec, Canada, 2 - 4 November 2011

[39] The merrick group inc. (2015). *What is Eddy current Testing?*
http://www.merrickgroupinc.com/2015/08/what-is-eddy-current-testing/ [Acc. 2016-03-15]

[40] Total Materia (2007). *Eddy current Testing*.
http://www.totalmateria.com/page.aspx?ID=CheckArticle&site=kts&NM=197 [Acc. 2016-03-15]

[41] Lindh, S. (2010). *Hållfasthet för verkanshöljen med graderad verkan (GRG/CG).* Karlskoga: Saab Dynamics AB (COMPANY RESTRICTED).

[42] Arnell, E. (2008). General Life Cycle Environmental Profile for portable Ground Combat Systems. Karlskoga: Saab Dynamics AB (COMPANY RESTRICTED).

[43] Johannesson, H., Persson, J & Pettersson, D. (2004). *Produktutveckling – effektiva metoder för konstruktion och design*. Stockholm: Liber.

[44] Swedish standard institute (1986). Technical documentation – Classification of requirements on manufacturing documentation. Stockholm: SIS Förlag AB.

[45] Maji, A. K. & Satpathi, D. (1997). Electronic Shearography for Detecting Disbonds in Lattice/Skin Structures. Research in Non-destructive Evaluation. March 1997, 9 (1), ss 1-11.

[46] Cheng, L. & Tian, Y.G. (2012). Comparison of Non-destructive Testing Methods on Detection of Delaminations in Composites. *Journal of Sensors*, 2012 (3), 7 pages. doi:10.1155/2012/408437

[47] Quinn, M.T., Hribar, J.R., Ruiz, R.L. & Hawkins, G.F. (1988). THERMOGRAPHIC DETECTION OF BURIED DE BONDS. *Review of Progress in Quantitative Non-destructive Evaluation*. Williamsburg, USA, June 22–26 1987. DOI: 10.1007/978-1-4613-0979-6_29

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Appendix 1. Detection methods for ultrasonic inspection

Ultrasonic A-scan	scale	comment
Cost	4	Relatively low capital cost and very low consumable cost.
Utilisation	3	Amplitude or the actual waveform of the signal plotted against time so the operator can draw the conclusions.
Running-time	2	A-scan measures single measurements in one point at the time.
Reliability	2	Ultrasound has weaker noise characteristics in composites which reduces the reliability of a single measurement. To get a better trustiness more analyses from other positions at the object needs.
Mode	-	Contact
Image	-	2-D
Detectable defects	4	Can detect a wider range of defects, but cannot find cracks. Best detectability for planar defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	No
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Ultrasonic B-scan	scale	comment
Cost	4	Relatively low capital cost and very low consumable cost.
Utilisation	4	Success depends on operator skills and experience. B-scan scanning the specimen thoroughly and the graph help to visualize inside of the specimen.
Running-time	3	Measures at the same time as the probe make its movements but are anyway a relatively time-consuming process.
Reliability	3	Ultrasonic waves have weaker analysis pictures and relatively low resolution in CFRE.
Mode	-	Contact
Image	-	2-D
Detectable defects	4	B-scan is useful to find fibre waviness besides those that A-scan can find.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Ultrasonic C-scan	scale	comment
Cost	4	Relatively low capital cost and very low consumable cost.
Utilisation	5	C-scan presentations are produced with an automated data acquisition system, such as a computer controlled immersion scanning system. Probe moves over surface.
Running-time	3	A slower NDT process that take hours if the inspected region at the sample are bigger. About 17 hours to inspect 9 m^2.
Reliability	4	Ultrasonic waves have weaker analysis pictures and relatively low resolution in CFRE. Through-transmission mode make it easier to get higher resolution
Mode	-	Non-contact
Image	-	2-D
Detectable defects	4	Can detect a very wide range of defects, but cannot find cracks. Best detectability for planar defects.
Single-side inspection	-	No
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Ultrasonic D-scan	scale	comment
Cost	4	Relatively low capital cost and very low consumable cost.
Utilisation	5	D-scan scanning the specimen thoroughly and the graph help to visualize inside of the specimen.
Running-time	3	It measures at the same time as the probe makes its movements but is anyway a time-consuming process.
Reliability	4	Ultrasonic waves have weaker analysis pictures and relatively low resolution in CFRE. Pulse-echo make it easier to find planar defects
Mode	-	Contact
Image	-	2-D
Detectable defects	4	Can detect a very wide range of defects, but cannot find cracks. Best detectability for planar defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 2. Detection methods for acoustic emission and acousto-ultrasonics

Acoustic emission (AE)	scale	comment
Cost	3	There are some instruments needed to reduce background noise and computer processor.
Utilisation	5	Easy to use
Running-time	5	Rapid and complete inspection.
Reliability	5	Find signal sources from a defect everywhere inside the component even if the whole sample not scans. Its signal sensitiveness is very high compared to other techniques which make it possible to find breakages on separate fibres.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	5	Cracks and breakages as matrix cracking, fibre breakage and some other defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Acousto-ultrasonics (AU)	scale	comment
Cost	4	About the same as ultrasonic inspection.
Utilisation	5	Easy to use.
Running-time	4	Fourier transform algorithm is used to get a rapid inspection of the frequency spectra.
Reliability	2	This technique is only able to find larger defects and if it is a higher amount of smaller ones. AU cannot detect smaller individual defects because the wavelength is longer compared to UT.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	3	Translaminar cracks, delaminations, stacking sequence and porosity.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 3. Detection methods for acoustography

Acoustography (AC)	scale	comment
Cost	4	Low-cost method. Usage of a conventional probe that focuses through lenses that gives a good resolution instead of use an expensive high-performance probe.
Utilisation	5	Implementation is as C-scan but there is no need of move the sensor. The AO sensor can be stationed at same place and analyse the desire area.
Running-time	5	Full-field inspection. The sensor can do analyses at regions of 150 x 150 mm^2 at each examination which is a quite big area which results in a fast inspection method.
Reliability	5	This method had really good performance to find and measure amount of porosity in the sample. Can find delaminations, voids, impact damage, sub-surface inclusions and cracks.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	3	Translaminar cracks, impact damages, delaminations and planar defects.
Single-side inspection	-	Not for through-transmission but for reflective shadow.
Depth analysis	-	No
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	No

Appendix 4. Detection methods for thermography

Thermography		
	scale	comment
Cost	5	Cost-effective with simple and practical equipment's. Major savings in time, people, work and machinery.
Utilisation	4	Easy operability since it basically only is to place the heat sources against the specimen and align the IR camera. Environmental conditions also play an important role outdoor due to cloud cover, solar radiation, and wind speed.
Running-time	5	It enables large-area measurements that are performed contact free and fast. The heat sources turns on for about 10 seconds and then the IR camera analyse the emitted heat energy.
Reliability	5	Easy analysis of the inspection results independent of the experience of the inspector.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	4	Wide range of defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes, but limited depth.
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 5. Detection methods for radiographic inspection

X-ray backscatter computed tomography	scale	comment
Cost	1	Radiography has highest capital cost of the NDT methods and high consumable cost.
Utilisation	3	Have real-time viewing but has a need of higher operator skills. The results can be hard to interpret even if it gives a visual picture. Are able to be used at thicker areas.
Running-time	4	Little preparation and with medium scanning speed. A faster than ultrasonic but slower than shearography.
Reliability	3	Best NDT method for volumetric defects. This one can find volumetric defects more effectively than other radiographic inspection.
Mode	-	Non-contact
Image	-	3-D
Detectable defects	4	Radiography methods are best for finding volumetric defects. Have some detectability for planar- and crack like defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Penetrant enhanced X-ray radiography (PEXR)	scale	comment
Cost	2	High capital cost and high consumable cost.
Utilisation	3	Have real-time viewing but has a need of higher operator skills. The results can be hard to interpret even if it gives a visual picture. Are able to be used at thicker areas.
Running-time	5	Not much surface preparation is required. Have a fast time to receive resulting pictures.
Reliability	5	Earlier invisible defects from the conventional radiographic methods can be detected. Translaminar cracks are much easier to detect with this method compared to other ones. X-rays instead of ultrasonic waves, i.e. the wavelengths for X-rays are generally shorter compared to the ultrasonic waves and results in increased resolution pictures.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	3	Best method to find volumetric defects.Have difficulties to find planar defects.
Single-side inspection	-	No
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 6. Detection methods for shearography

	Shearography	
	scale	comment
Cost	3	Relatively high capital cost.
Utilisation	5	Shearography offer "real-time viewing" and is a highly sensitive method with full-field inspection. 3-D strain map for easy detection of defects.
Running-time	5	Shearography provides very rapid inspection allowing immediate feedback for process controls. Up to 100 times faster than ultrasonic inspection.
Reliability	5	Fringe pattern have big changes in laser light when the laser detect defects and had thus easy and rapidly detectability of these damages. Real time video image for easier and faster inspections.
Mode	-	Non-contact
Image	-	3-D.
Detectable defects	5	Very wide range of defects. Have good resolution in detection of both planar- and volumetric defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 7. Detection methods for membrane resonance

Membrane resonance	scale	comment
Cost	5	Low-cost method
Utilisation	5	easy to use
Running-time	3	The scanning probe moves over the entire surface to receive membrane resonance everywhere
Reliability	3	The accuracy depends on the operator. Can only find near-surface defects and have thus dissiculties to find defects into the depth.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	3	Bigger delaminations, disbonds, impacts (BVI)
Single-side inspection	-	Yes
Depth analysis	-	No
Real-time viewing	-	No
Inspection of asymetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 8. Detection methods for eddy current testing

Eddy current testing	scale	comment
Cost	5	Quite low capital cost and low consumable cost.
Utilisation	3	The operator observes the response from the reference standards and then compares with reference pattern from tested sample to categorize parts. Quite skilled operator needed.
Running-time	4	About 0.5 m^2 / min in scan speed depend on eddy current probe.
Reliability	1	The electric conductivity in a carbon fibre is much lower, around thousandth, compared to aluminium. Because of this low conductivity the current penetrate the sample much less than aluminium for example. This requires a significant increased frequency to get higher signal-to-noise ratio for the CFRE.
Mode	-	Non-contact
Image	-	2-D
Detectable defects	5	Wide range of defects except for matrix cracks. Detect mostly external defects.
Single-side inspection	-	Yes
Depth analysis	-	Yes, but about five layers.
Real-time viewing	-	Yes
Inspection of asymmetric geometry	-	Yes
In-field / Portable	-	Yes

Appendix 9. Requirement specification for detection methods

Aspect / Life-cycle	Process	Environment	Human	Economy
Create (development, design)	1.1	1.2	1.3	1.4
Production (manufacrure, assemblage inspect, store-keeping)	2.1	2.2	2.3	2.4
Usage (Installation, use, maintain)	3.1	3.2	3.3	3.4

Criterion nr	Cell	Criterion	Req. (R) Wish (W)	Limit (L) Func. (F)	Importance (1-5)
1	1.1	Small dimensions of instrument	W	L	2
2	1.2	Method with no usage of current	W	F	1
3	1.3	Few components in the instrument	W	L	1
4	1.3	Low weight method	W	L	2
5	1.4	Low cost method	W	F	3
6	2.1	3-D image	W	F	3
7	2.1	Single-side inspection	W	F	3
8	2.1	Depth analysis	R	F	5
9	2.2	Water resistant method	W	L	2
10	2.3	Real-time viewing	W	F	4
11	2.4	Cheap cost for assamblage of components	W	L	2
12	3.1	High reliability	R	F	5
13	3.1	Non-contact mode	W	F	4
14	3.1	Old and experienced detection methods	W	L	2
15	3.1	Easy to apply (utilisation)	W	F	4
16	3.2				
17	3.3	Low running-time	W	F	4
18	3.3	Inspection of asymmetric geometry	R	F	5
19	3.3	In-field inspection	R	F	4
20	3.4	Cheap to maintain	W	L	2

Appendix 10. Elimination matrices for critical manufacturing defects

1	Ultrasonic A-scan
2	Ultrasonic B-scan
3	Ultrasonic C-scan
4	Ultrasonic D-scan
5	Acoustic-emission
6	Acousto-ultrasonics
7	Acoustography
8	Thermography
9	Penetrant enhanced X-radiography
10	X-ray back scatter computed tomography
11	Shearography
12	Membrane resonance
13	Eddy-current testing

Fibre breakage

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	+	-	+	+	+	+	-
2	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	-	+	+	+	+	+	-
7	-	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	+	-	+	-	?	+	+
10	-	+	+	-	+	+	-
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Cracks

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	-	-	+	+	+	+	-
2	-	+	+	+	+	+	-
3	-	+	+	+	+	+	-
4	-	+	+	+	+	+	-
5	+	+	+	+	+	+	+
6	-	+	+	+	+	+	-
7	+	?	+	+	+	+	+
8	+	+	+	+	+	+	+
9	-	-	+	-	?	+	-
10	+	+	+	-	+	+	+
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Delamination

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	+	-	+	+	+	+	-
2	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	+	+	+	+	+	+	+
7	+	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	-	-	+	-	?	+	-
10	-	+	+	-	+	+	-
11	+	+	+	+	+	+	+
12	+	-	+	+	?	+	-
13	+	-	+	+	?	+	+

Disbonds

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	+	-	+	+	+	+	-
2	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	-	+	+	+	+	+	-
7	-	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	-	-	+	-	?	+	-
10	-	+	+	-	+	+	-
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Porosity

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	?	-	+	+	+	+	-
2	?	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	?	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	+	+	+	+	+	+	+
7	+	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	+	-	+	-	?	+	+
10	+	+	+	-	+	+	+
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Voids

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	?	-	+	+	+	+	-
2	?	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	?	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	-	+	+	+	+	+	-
7	+	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	-	-	+	-	?	+	-
10	+	+	+	-	+	+	+
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Impact damage

Solution number	Solves main problem?	Satisfy remaining requirements?	Realisable?	Within margin of expenditure?	Relevant for the company?	Sufficient information?	Decision
1	+	-	+	+	+	+	-
2	+	+	+	+	+	+	+
3	+	+	+	+	+	+	+
4	+	+	+	+	+	+	+
5	-	+	+	+	+	+	-
6	-	+	+	+	+	+	-
7	-	?	+	+	+	+	-
8	+	+	+	+	+	+	+
9	+	-	+	-	?	+	+
10	-	+	+	-	+	+	-
11	+	+	+	+	+	+	+
12	-	-	+	+	?	+	-
13	-	-	+	+	?	+	-

Appendix 11. Decision matrices for critical manufacturing defects

1	Ultrasonic A-scan
2	Ultrasonic B-scan
3	Ultrasonic C-scan
4	Ultrasonic D-scan
5	Acoustic-emission
6	Acousto-ultrasonics
7	Acoustography
8	Thermography
9	Penetrant enhanced X-radiography
10	X-ray back scatter computed tomography
11	Shearography
12	Membrane resonance
13	Eddy-current testing

Fibre breakage

	Solutions			
Criteria	1 (ref)	5	11	13
Low cost		0	-	+
Easy to apply (utilisation)		+	+	-
Low running-time		+	+	+
High reliability		+	-	-
Non-contact mode		+	+	+
3-D image		-	+	-
Single-side inspection		+	+	+
Depth analysis		+	+	0
Real-time viewing		+	+	+
Inspection of asymetric geometry		+	+	+
In-field inspection		+	+	+
Sum +		9	9	7
Sum 0		1	0	1
Sum -		1	2	3
Net value	0	8	7	4
Ranking	4	1	2	3
Decision	No	Yes	Yes	No

Cracks

Criteria	Solutions 1 (ref)	5	7	8	10	11
Low cost		0	+	+	-	-
Easy to apply (utilisation)		+	+	+	-	+
Low running-time		+	+	+	+	+
High reliability		+	0	+	0	+
Non-contact mode		+	+	+	+	+
3-D image		0	0	0	+	+
Single-side inspection		+	0	+	+	+
Depth analysis		+	-	-	+	+
Real-time viewing		+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+
In-field inspection		+	-	+	+	+
Sum +		9	6	9	8	10
Sum 0		2	3	1	1	0
Sum -		0	2	1	2	1
Net value	0	9	4	8	6	9
Ranking	6	1	5	3	4	1
Decision	No	Yes	No	Yes	Yes	Yes

Delaminations

Criteria	Solutions 1 (ref)	2	3	4	6	8	11	13
Low cost		+	+	+	0	+	-	+
Easy to apply (utilisation)		0	0	0	+	+	+	-
Low running-time		-	-	-	+	+	+	+
High reliability		+	0	+	-	+	+	-
Non-contact mode		-	+	-	+	+	+	+
3-D image		-	0	0	0	0	+	-
Single-side inspection		+	-	+	0	+	+	+
Depth analysis		+	+	+	+	-	+	0
Real-time viewing		+	+	+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+	+	+
In-field inspection		+	+	+	+	+	+	+
Sum +		7	6	7	7	9	10	7
Sum 0		1	3	2	3	1	0	1
Sum -		3	2	2	1	1	1	3
Net value	0	4	4	5	6	8	9	4
Ranking	8	5	5	4	3	2	1	5
Decision	No	No	No	Yes	Yes	Yes	Yes	No

Disbonds

Criteria	Solutions 1 (ref)	2	3	4	8	11
Low cost		+	+	+	+	-
Easy to apply (utilisation)		0	0	0	+	+
Low running-time		-	-	-	+	+
High reliability		+	0	+	+	+
Non-contact mode		-	+	-	+	+
3-D image		-	0	0	0	+
Single-side inspection		+	-	+	+	+
Depth analysis		+	+	+	-	+
Real-time viewing		+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+
In-field inspection		+	+	+	+	+
Sum +		7	6	7	9	10
Sum 0		1	3	2	1	0
Sum -		3	2	2	1	1
Net value	0	4	4	5	8	9
Ranking	6	4	4	3	2	1
Decision	No	No	No	Yes	Yes	Yes

Porosity

Criteria	Solutions 1 (ref)	2	3	4	6	8	9	10	11
Low cost		+	+	+	0	+	-	-	-
Easy to apply (utilisation)		0	0	0	+	+	0	-	+
Low running-time		-	-	-	+	+	+	+	+
High reliability		0	+	0	-	0	+	+	0
Non-contact mode		-	+	-	+	+	+	+	+
3-D image		-	0	0	0	0	0	+	+
Single-side inspection		+	-	+	0	+	-	+	+
Depth analysis		+	+	+	+	-	+	+	+
Real-time viewing		+	+	+	+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+	+	+	+
In-field inspection		+	+	+	+	+	+	+	+
Sum +		6	7	6	7	8	7	9	9
Sum 0		2	2	3	3	2	2	0	1
Sum -		3	2	2	1	1	2	2	1
Net value	0	3	5	4	6	7	5	7	8
Ranking	9	8	5	7	4	2	5	2	1
Decision	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes

Voids

	Solutions					
Criteria	1 (ref)	2	3	4	8	10	11
Low cost		+	+	+	+	-	+
Easy to apply (utilisation)		0	0	0	+	-	+
Low running-time		-	-	-	+	+	+
High reliability		-	+	-	+	+	0
Non-contact mode		-	+	-	+	+	+
3-D image		0	0	0	0	+	+
Single-side inspection		+	-	+	+	+	+
Depth analysis		+	+	+	-	+	+
Real-time viewing		+	+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+	+
In-field inspection		+	+	+	+	+	+
Sum +		6	7	6	9	9	10
Sum 0		2	2	2	1	0	1
Sum -		3	2	3	1	2	0
Net value	0	3	5	3	8	7	10
Ranking	7	5	4	5	2	3	1
Decision	No	No	Yes	No	Yes	Yes	Yes

Impact damage

	Solutions						
Criteria	1 (ref)	2	3	4	8	9	11
Low cost		+	+	+	+	-	+
Easy to apply (utilisation)		0	0	0	+	0	+
Low running-time		-	-	-	+	+	+
High reliability		-	0	0	0	-	+
Non-contact mode		-	+	-	+	+	+
3-D image		0	0	0	0	0	+
Single-side inspection		+	-	+	+	-	+
Depth analysis		+	+	+	-	+	+
Real-time viewing		+	+	+	+	+	+
Inspection of asymetric geometry		+	+	+	+	+	+
In-field inspection		+	+	+	+	+	+
Sum +		6	6	6	8	6	11
Sum 0		2	3	3	2	3	0
Sum -		3	2	2	1	2	0
Net value	0	3	4	4	7	4	11
Ranking	7	6	3	3	2	3	1
Decision	No	No	No	No	Yes	No	Yes