

Selection and Deployment of Non-Destructive Testing for Through-Life Integrity Assurance of Composite-Repaired Pipes

Adam Bannister, HSE Science Division, Harpur Hill, Buxton, SK17 9JN, UK
Aneta Nemcova, HSE Science Division, Harpur Hill, Buxton, SK17 9JN, UK
David Johnson, HSE Science Division, Harpur Hill, Buxton, SK17 9JN, UK
Matthew Blackburn, HSE Energy Division, Lord Cullen House, Aberdeen, AB25 3UB

Over recent years there has been an increasing trend towards the use of composite repairs on impaired containment equipment, notably piping and tanks. This has brought benefits in terms of ease of repair, improved integrity and reduced downtime. However, the risks associated with the application of such repairs have not always been well understood or correctly evaluated. Whilst the majority of repairs have been successful, there have also been failures. These have been attributable to a range of factors including poor installation practices, deficient design, inadequate specification and use in unsuitable applications.

In 2017 an industry-sponsored Shared Research Project involving operators, repair suppliers and inspection companies was established by HSE (Health and Safety Executive) to improve the collective knowledge and understanding of composite repairs. In the current paper, the outcomes of the inspection trials conducted as part of this project are summarised.

A selection of composite repaired pipes with between one and 14 years offshore service were utilised in a series of blind trials using a range of NDT (Non Destructive Testing) techniques. The pipes, of diameters between 50 mm and 450 mm, contained a range of damage and degradation features which had influenced the initial use of the composite wrap as a repair technique. These defects included external and internal wall thinning by corrosion, stress corrosion cracking, mechanical damage and cracks associated with welded connections.

Techniques evaluated included pulsed eddy current, digital/computed radiography, dynamic response spectroscopy, guided wave ultrasonics, laser shearography and microwave inspection. These have different applicability depending on the targeted region of the pipe (steel substrate, the repair laminate or the bond between the two), the pipe diameter and the extent of the repair. A total of 19 pipes were inspected in a series of blind trials and the results subsequently compared with the known pipe condition at the time of the repair installation and also with a definitive NDT inspection carried out after removal of the wrap.

Addition of a composite wrap to a pipe leads to additional difficulties in terms of inspection of the underlying substrate and the wrap itself. Based on these trials, techniques currently considered suitable for the inspection of composite wraps are pulsed eddy current for substrate screening; radiography for detection of local thinning and feature identification in the substrate and quality evaluation of the wrap, and; dynamic response spectroscopy for substrate and laminate/ bond quality indication and as a post repair installation QA tool. The other techniques evaluated in the trials may be suitable as complementary methods, although several require further demonstration of their capability to quantify defect sizes and locations. The paper concludes with a look-up table on NDT techniques that are suitable for different types of geometry and degradation mode which can be used to support an integrity-assurance plan for composite wrapped pipes

Key Words: Pipes; Composite Repairs; Non Destructive Testing; Defects

Acronyms and Abbreviations

B	Bondline
CFRP	Carbon Fibre Reinforced Plastic
CUI	Corrosion Under Insulation
CWT	Compensated Wall Thickness
DP	Dye Penetrant
DRS	Dynamic Response Spectroscopy
ECR	Engineered Composite Wrap
GFRP	Glass Fibre Reinforced Plastic
GWU	Guided Wave Ultrasonics
IR	Infrared Radiation
L	Laminate
LS	Laser Shearography
MW	Microwave
MPI	Magnetic Particle Inspection
NDT	Non-Destructive Testing
PAUT	Phased Array Ultrasonic Testing
PEC	Pulsed Eddy Current
QA	Quality Assurance
RAD	Radiography
S	Substrate
SCC	Stress Corrosion Cracking
SRP	Shared Research Project
T	Thermography

Introduction

Over recent years there has been an increasing trend towards the use of engineered composite repairs (ECRs), also known as composite wraps when applied to pipes, on impaired containment equipment such as vessels and piping. This has brought benefits in terms of improved integrity and reduced downtime. However, the risks associated with the application of such repairs have not always been correctly evaluated. Whilst the majority of repairs have been successful, there have also been failures. These have been attributable to a range of factors including poor installation practices, inadequate specification, inappropriate inspection and use in unsuitable applications.

While a number of well-established NDT techniques are used throughout industry on metallic structures, a composite wrap on a pipe or vessel renders inspection of the underlying metallic substrate significantly more complex. The presence of the composite precludes techniques which rely on direct access to the substrate surface, usually steel, while the nature of the bond and wrap quality itself can reduce the effectiveness of other methods. The composite materials which constitute the repair laminates are typically glass, carbon or aramid fibre-reinforcement within an epoxy, vinyl ester, polyurethane or polyester matrix. Repairs, which should follow the recommendations of BS EN ISO 24817 [BSI 2017], may be applied to a wide range of substrates, most commonly carbon steel and stainless steels.

The types of defects in the substrate that may lead to the installation of a composite repair are varied, Figure 1, and include general or local wall-thinning due to corrosion or erosion, pitting, cracking or through-wall penetrations. Once repaired, the extent and periodicity of any inspection will depend on a range of factors including the criticality of the application and consequences of failure. In some cases, there will be a need to inspect the substrate, repair laminate and the bond, Figure 1. The integrity of the bond is particularly important for safety critical repairs where the repair affords primary containment. The application of an engineered composite repair typically changes the potential mode of failure from rupture of the substrate to a leak, and the consequences of failure are therefore reduced. Nevertheless, the ability to monitor the evolution of flaws or changes in degradation mode in the repaired system is critical to integrity management.

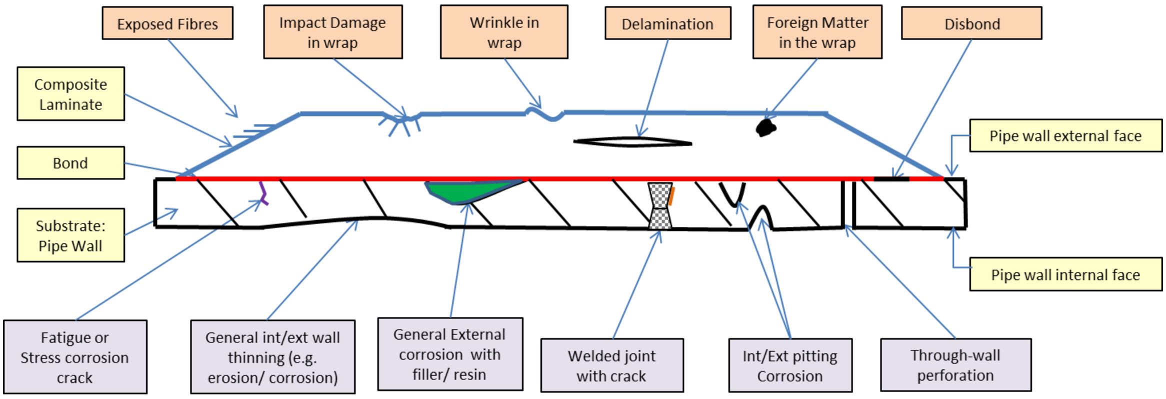


Figure 1: Types of degradation and flaws that may occur in composite wrapped pipework

A series of NDT blind trials was carried out to evaluate the capabilities of established and potential techniques and those under development to detect and size a range of degradation features in composite-wrapped pipes. The majority of the pipes were ex-service from offshore installations, while two were specifically-manufactured for the trials. The main objectives of the work were:

- To assess which techniques can be used to reliably inspect the substrate, the bond and the laminate.
- To compare results for a given pipe when using different methods and when the same method is used but by different inspection companies.
- To evaluate the capabilities of each technique to identify and quantify local degradation features such as wall thinning and pitting.
- To identify factors that may preclude the use of specific methods.
- To identify any potential improvements that could be made to improve the outcomes of inspection of composite repairs.

Approach

The approach taken for the trials was that of a 'blind trial' exercise. Inspection companies were provided with the scope statement, the pipe spool, the pipe nominal diameter and information on the type of steel substrate (carbon steel or stainless steel). No prior information of the pipe spool condition, degradation mode, location of any degradation features or information on the wrap condition was provided. HSE was provided with the close-out reports by the offshore operators produced at the time of the wrap installation for each of the ex-service pipe spools, including information on the pipe history, nature of the threat (e.g. internal corrosion, external stress corrosion cracking) and the details of the wrap installation procedure used. The final definitive pipe condition was obtained after all NDT trials had been completed by removal of the composite wrap, followed by a range of inspection and physical measurements to define the benchmark pipe condition at the time of the blind trials. Comparisons were then made with the results from the NDT blind trials carried out with the composite wrap in-place.

Nineteen pipe spools were selected for the blind trials. The selection was made to cover a range of diameters, wall thicknesses, steel substrate type and degradation mode. Each pipe spool was assigned a five digit identification code which is used subsequently throughout this paper. An overview of the inspection matrix is given in Table 1. Geometrical details, such as outer diameter, nominal wall thickness and composite wrap thickness are also summarised in Table 1.Two pipe spools had been in service for over ten years, one for 5-6 years, five between 1 and 3 years and three less than 1 year. Six spools were of unknown vintage. Two samples were manufactured for the trials and had seen no service, although they had been hydrostatically pressure tested to failure to generate a leak path along the interface from the hole drilled in the substrate. All wraps were glass-fibre reinforced plastic (GFRP) with the exception of spool 17533 which comprised a carbon-fibre reinforced plastic (CFRP) wrap.

Table 1: Matrix of pipe spools used for NDT blind trials

Sample ID	**Sample type [years in service if known]**	**Base Material**	**Diameter**	**Wall Thickness**	**Composite Wrap Thickness**	**Degradation Mode/s**
16118	Ex-service [2]	Carbon Steel	8"	7 mm	23 mm	External pitting
16119	Ex-service [12]	Carbon Steel	8"	7 mm	33 mm	Internal corrosion
16124	Ex-service [0.25]	Stainless Steel	4"	3.05 mm	5 mm	External corrosion/pitting
16773	Ex-service [0.5]	Carbon Steel	2"	3.92 mm	5 mm	External corrosion
16729	Ex-service	Stainless steel	12"	4.57mm	10 mm	Impact damage
17531	Ex-service	Carbon Steel	10"	10.5 mm	5mm	Internal corrosion/erosion
16871	Ex-service	Carbon Steel	2"	3.91mm	7 mm	External/internal corrosion
16760	Ex-service	Carbon Steel	10"	9.27 mm	5.2 mm	Weld root corrosion
16766	Ex-service [14]	Carbon Steel	18"	8 mm	6 mm	External corrosion
16731	Ex-service[0.7]	Carbon Steel	~3"	11.1 mm	13 mm	Weld root internal corrosion
16743	Ex-service	Carbon Steel	2"	8.74 mm	6.6 mm	External pitting with crack
16872	Ex-service [5-6]	Carbon Steel	10"	8.1mm	21 mm	Internal corrosion
16800	Ex-service	Carbon Steel	2"	3.91 mm	6 mm	External corrosion
16772	Ex-service	Stainless Steel	¾ to 3”	3.91 mm	13.4 mm	Crack on weld toe
16768	Ex-service [2]	Stainless Steel	4"	3.6 mm	19.4 mm	External pitting
16741	Ex-service [2]	Super Duplex	10"	4.2 mm	10 mm	Stress corrosion cracking
16779	Ex-service [2-3]	Carbon Steel	8"	8.18 mm	5.7 mm	Internal corrosion/erosion
17532	Manufactured [0]	Carbon Steel	4"	6 mm	5 mm	Drilled hole + Disbond
17533	Manufactured [0]	Carbon Steel	4"	6 mm	4 mm	Drilled hole + Disbond

Examples of the types of samples used for the trials are given in Figure 2. The spools comprised a range of geometrical complexities, length, exposed surface of the pipe and surface quality of wrap.

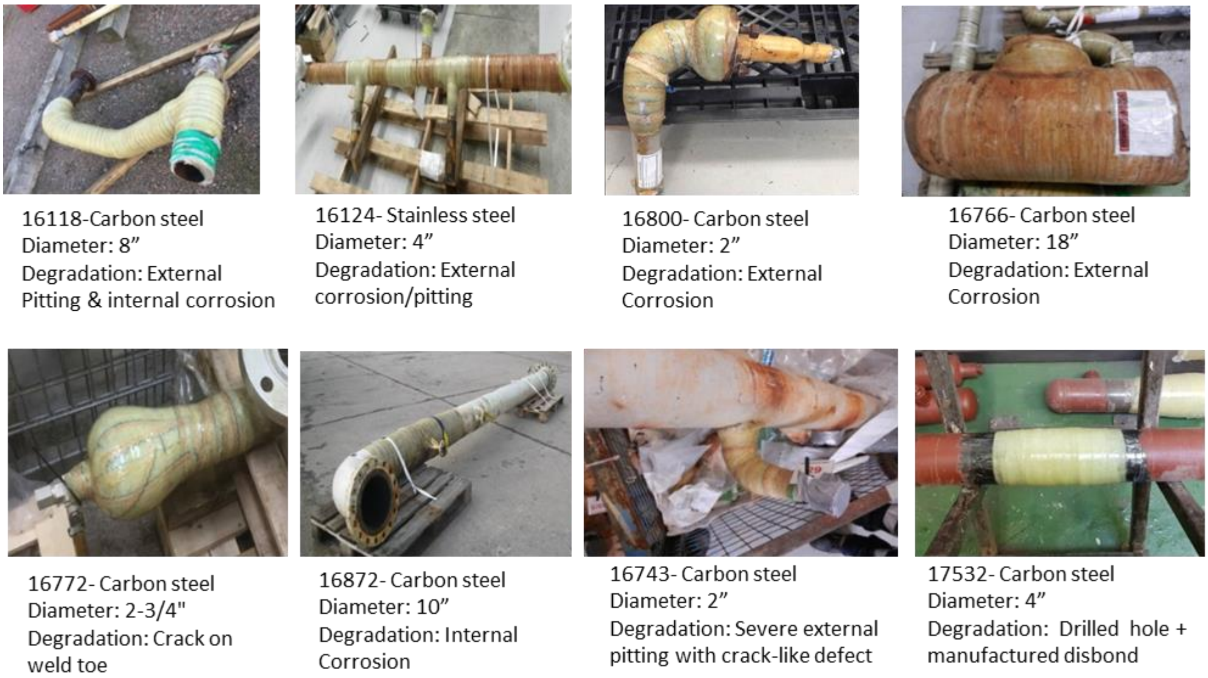


Figure 2: Examples of composite wrapped pipe spools used in blind NDT trials

Selection of NDT inspection methods

The selection of NDT methods used for each spool was left to the discretion of each participating NDT inspection company but was also informed by the output of an initial technique review carried out as part of the SRP. Discussions with NDT companies beforehand had also identified a range of techniques that could potentially be used for inspecting composite wrapped pipe spools. For some of the less mature techniques, specific geometrical limitations precluded inspection of many of the spools. The final selection of potential methods for evaluation in the trials was as follows:

- Pulsed Eddy Current (PEC)
- Radiography (RAD)
- Dynamic Response Spectroscopy (DRS)
- Guided Wave Ultrasonics (GWU)
- Laser Shearography (LS)
- Microwave (MW)
- Thermography (T)
- Phased Array Ultrasonic Testing (PAUT)

A brief summary of the underlying concept and maturity in terms of general industrial application of each of these techniques is given in Table 2. The maturity of the technique is listed in the context of general industrial applications rather than the method as applied specifically to composite wraps. In addition to these methods, visual inspection forms the first stage of an inspection plan for composite wraps.

Table 2: Overview of techniques evaluated and their industrial maturity

Inspection Method	Concept	Existing Common Applications	Industrial Maturity
Pulsed Eddy Current	Use of a pulsed magnetic field to induce eddy currents in magnetic substrates; Diffusive response of the eddy current is related to wall thickness	Inspection of corrosion under insulation (CUI) in pipes	High
Radiography	Use of high energy electromagnetic radiation in the form of X or Gamma rays, part of which are absorbed by a material, this increasing with material density or its thickness. The remaining part of the radiation is captured on a film medium to form a radiograph image of the component	Inspection of metallic components such as welds and castings	High
Dynamic Response Spectroscopy	Low frequency ultrasound is used to excite a substrate to its natural frequency. Vibration frequency response is proportional to wall thickness	Inspection of pipework through non-metallic coatings	Medium
Guided Wave Ultrasonics	Ultrasonic pulses are generated by a transducer and are transmitted along the metallic pipe. Changes in pipe wall cross section or presence of flaws change the reflected wave response which is detected by a sensor	Inspection of long metallic pipes for CUI	Medium
Laser Shearography	Measurement of relative movement of the surface of an object subjected to an additional load via e.g. heating. The movement depends on the local stiffness of the composite which in turn is affected by presence of defects. The short wavelength of visible laser light is suited to detection of such surface movements	Inspection of thin sandwich components in aerospace industry	Low/Med
Microwave	Microwaves can propagate through non-conductive materials such as GFRP. When subjected to an electric field they become polarised and store electrical energy, known as a dielectric property. Microwaves interact with this electrical property and manifest as changes in permittivity which are proportional to defect severity	Inspection of composite structures such as wind turbine blades ; concrete-coated components; Butt welds in HDPE pipes	Low
Thermography	Objects at temperature emit infrared radiation (IR); the intensity of this IR can be detected using a thermal imager. In composite wraps the flow of heat from the surface will be affected by internal flaws. Creation of temperature differential between substrate and wrap is achieved by active heating	Evaluation of wall thickness in exposed vessels and pipework	High
Phased Array Ultrasonics	A set of multiple ultrasonic probes are pulsed separately and at different times to build up an ultrasonic footprint of complex geometries	Inspection of complex welded metallic components	High

Seven inspection companies participated in the trials, covering the above range of NDT techniques across 19 pipe spools, generating 81 separate NDT reports. Due to the large number of NDT results generated, a simplified approach for comparing the capabilities of the different techniques was required. Firstly, each individual NDT report was evaluated in terms of the features identified in the substrate, their location and size. Secondly, the information on overall nominal thickness, location and value of minimum remaining wall thickness in the region was noted. This information was summarised for each pipe across all inspection techniques applied to that pipe. A comparison of observed degradation features and measured thickness at the time the wrap was installed was also made. Details from the inspection of the pipe after removal of the wrap formed the definitive pipe condition status.

Based on all of the above information, the capabilities of each inspection technique were compared across the full population of pipe spools. It was not possible to use all techniques on all pipes due to the relative maturity of each technique, logistical issues but more specifically due to technical restraints, notably:

- Pulsed eddy current cannot be used on non-magnetic materials, precluding stainless steel pipes.
- Radiography has limits in terms of maximum diameter that can be inspected, depending on wall thickness and radiographic source used; hence the largest diameter pipes were excluded.
- Guided wave ultrasonics requires access to un-wrapped substrate outside the wrapped area as well as having some specific length requirements, precluding fully wrapped or short pipes
- Microwave requires a non-conducting wrap material, precluding use on carbon-fibre wrapped pipes

Due to the varying maturity of the techniques and geometries of the pipe spools, a large number of PEC and radiographic inspections were carried out (33 and 37 respectively) while for each of the other techniques, the number of inspections made was five or less. The significance of the results should therefore be considered with these population sizes in mind.

Results from blind NDT trials

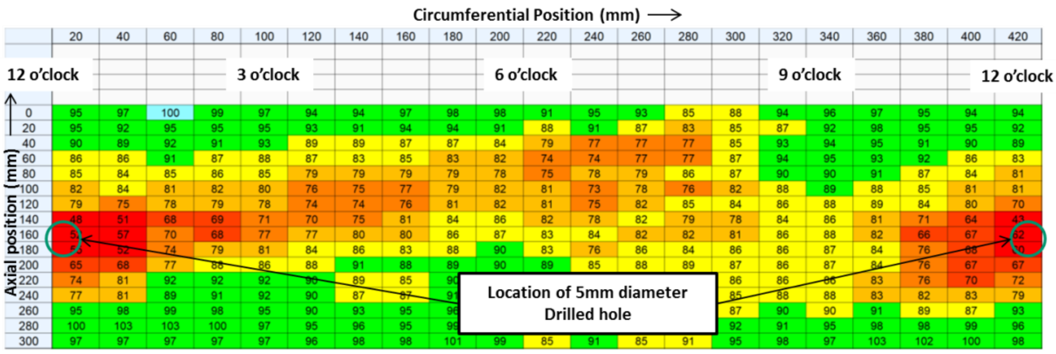
Visual Inspection

Visual inspection is the most common inspection technique currently used for engineered composite repairs. According to BS EN ISO 24817:2017, visual inspection of the repair laminate for defects is a key part of an inspection strategy. Such inspection can provide a qualitative view of evidence of exposed fibres, wrinkling and weeping in fluid-filled pipes. In the case of impact damage, delamination can result and while in glass laminates this can often be discerned as a lighter coloured region, with carbon fibre laminates the lower contrast surface yields less information.

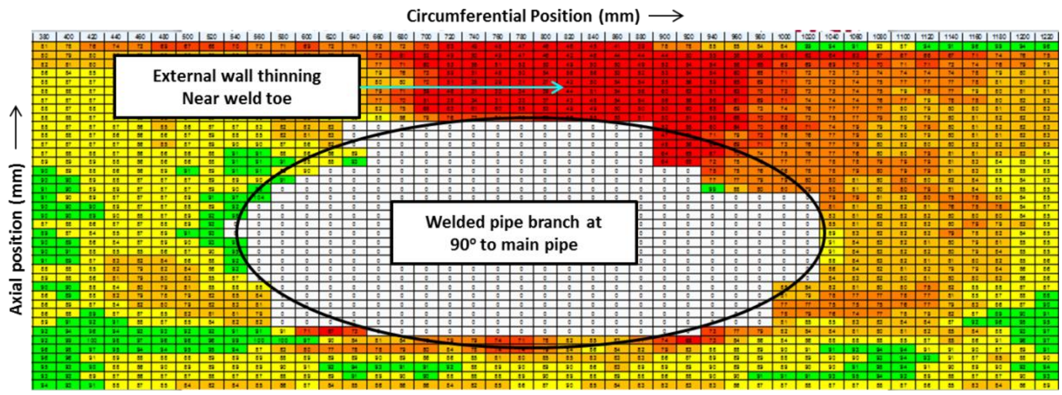
Pulsed Eddy Current Inspection (PEC)

PEC can measure the thickness of magnetic steels between ~3 and 50 mm with a non-magnetic layer over them, such as concrete or a composite wrap. A key feature of PEC is that the measured values are an average of the thickness under the probe, which has nominal diameter of typically 25 mm. The PEC footprint increases with the thickness of any layer covering the steel, known as the stand-off distance, and is 1.5 times the distance from the bottom of the probe to the bottom of the steel. The averaging effect therefore becomes more pronounced for thick composite wraps. Edge effects can also influence the accuracy of the results, typically occurring at one probe footprint distance.

In the blind trials described in the current paper, PEC inspections were carried and reported on eleven pipe spools across four inspection companies, with the final matrix giving 33 PEC inspection reports. The PEC results for two of the pipe spools, 17532 and 16766, are shown in Figure 3 to illustrate some key observations. These are presented with circumferential position as the x-axis and axial position in the wrap as the y-axis, with colour coding reflecting percentage remaining wall thickness compared to the maximum measured. Spool 17532, Figure 3a, contained a 5 mm diameter drilled hole at the 12 o'clock position, which can be seen as being represented by a region of reduced wall thickness averaged over the probe footprint. Conversely, in spool 16766 the PEC technique correctly located and sized an area of thinning, in this case, external corrosion near a weld toe.



a. Example of PEC averaging effect when measuring substrate features less than probe size (Spool 17532)



b. Example of PEC correctly capturing minimum wall thickness region larger than probe size (Spool 16766)

Figure 3: PEC results for Pipe spools 17532 and 16766

Areal averaging, based on footprint area, and increased area of averaging with stand-off distance (wrap thickness) are well known limitations of PEC. These limitations were observed in the trials, where the method showed limitations in its ability to detect localised features such as corrosion pits and through-wall perforations that were less than the size of the probe. Enhanced use of the compensated wall thickness (CWT) approach, implicit in most PEC analysis software, can limit the measurement inaccuracies in areas of localised wall thinning. The method is not able to differentiate between internal and external wall thickness loss. For the case of features of size similar to or larger than the probe footprint, the trials on PEC showed that it can be effective for general loss of thickness in the substrate.

Nevertheless, the trials identified PEC as one of the key inspection tools for composite wrapped carbon-steel pipes and it has significant benefits as a screening method. The method is able to identify locations where further inspection with other techniques may be required as well as providing a highly visual output for comparative inspections throughout the life of a composite wrapped pipe.

Radiographic Inspection

Radiographic inspection is a well-established technique that has seen extensive use across many industries for the inspection of metallic components. It can be applied as both double-wall and tangential scan techniques in composite-wrapped pipes, the former being largely used for detection of individual defects and the latter for wall thinning. The maximum diameter for reliable use of tangential radiography to inspect composite-wrapped pipes depends on wall thickness and radiography source. Typically thin walled pipes up to 14” diameter may be inspected using high energy sources, while for Schedule 40 pipes (8.2 mm wall thickness) 8” is the typical maximum diameter for which radiography can be used. General recommendations for tangential and double wall radiographic inspection are provided in BS EN ISO 2769 parts 1 and 2 [BSI 2018A, BSI 2018B].

In the blind trials, radiographic inspections were carried and reported on all 19 pipe spools, with the final matrix resulting in 37 radiographic inspection reports. For seven of the pipe spools only one radiographic inspection was made, while conversely in the case of seven other spools inspection was made by all three companies.

The radioactive sources used were Selenium 75 (dimensions 2.5 mm x 2.5 mm) by one inspection company and Iridium 192 (dimensions 1.5 mm x 1.5 mm) by two inspection companies. Of all the inspection techniques evaluated in the trials, the results for radiography represented the most varied in terms of format and detail. In particular, the range of spool sizes, geometries and wrap thicknesses was wide, such that different approaches were taken for a given spool by each inspection company. Several examples are described in further detail below, and are also shown in the wrapped condition in Figure 2.

For spool 16800, the wrap thickness varied significantly around the elbow and bolted flange region of the joint. The substrate wall thickness was measured at between 1.3 mm and 3.8 mm, with the minimum value measured after wrap removal of 2.0 mm using radiography and 1.35 mm using external laser scanning. The radiographs also clearly showed the variation in wrap thickness and the different features present in the wrap at the transition from the pipe cross section to the bolted joint, Figure 4.

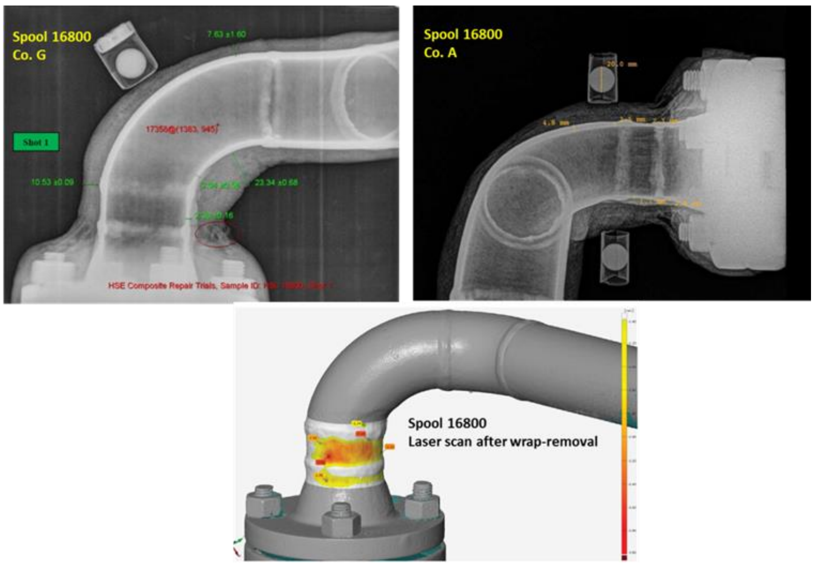


Figure 4: Comparison of two radiographic inspection results on spool 16800 with laser scan after wrap removal

Spool 16743, Figure 5, contained severe external pitting in the elbow attachment coupled with a through-wall defect located on the pipe extrados. Radiographic inspection by three companies identified the thinnest region of the pipe at the extrados and the severely pitted nature of the external surface was also discernible. Excluding the through-wall defect, the minimum substrate wall thickness was measured at 1.1 mm with the wrap on, and 0.6 mm with the wrap removed. The wall thicknesses measured with wrap on for the intrados and extrados of the spool showed good correlation with those measured by laser scanning after wrap removal. The wall breach is clearly visible in the radiograph from Company A.

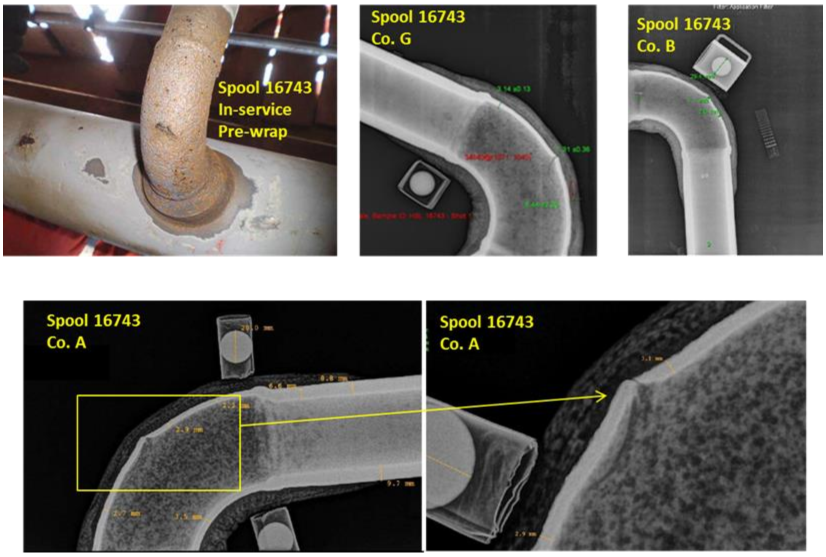


Figure 5: Comparison of radiographic inspection results on spool 16743 with wrap with condition in-service prior to wrapping

For all spools inspected by radiography, the minimum wall thicknesses measured with the wrap in place were compared with the values determined after wrap removal, Figure 6. The solid line represents 1:1 correlation, points below the 1:1 line indicate the cases where the thickness measured in the trial is less than the actual, thus representing a conservative result while points lying above the 1:1 line indicate where the minimum wall thickness has been overestimated. The dashed lines above and below the 1:1 line represent ±20% of the thickness. Where multiple data points are shown for the same spool, these represent the results from different inspection companies for that spool. It should be noted that for single-shot inspection methods such as radiography, the location of identified minimum wall thickness will not necessarily be the same between inspection companies, neither when compared with the results obtained after removal of the wrap.

The analysis shows that in general when sufficient scans are made the radiographic technique is able to detect and size minimum wall thickness zones in wrapped pipe spools. In the case of spool 16743, one set of inspections was made from one angle only and failed to locate the region of minimum remaining wall thickness. In two other cases multiple shots were taken and while the minimum wall thickness was still over-sized it was nearer to the actual value. In the case of spool 16768, localised regions of deep pitting were present on the spool substrate outer surface but this was not reported by radiography. In the case of spool 16772, the minimum wall thickness was conservatively measured by all three inspection companies at approximately 20% below the actual value.

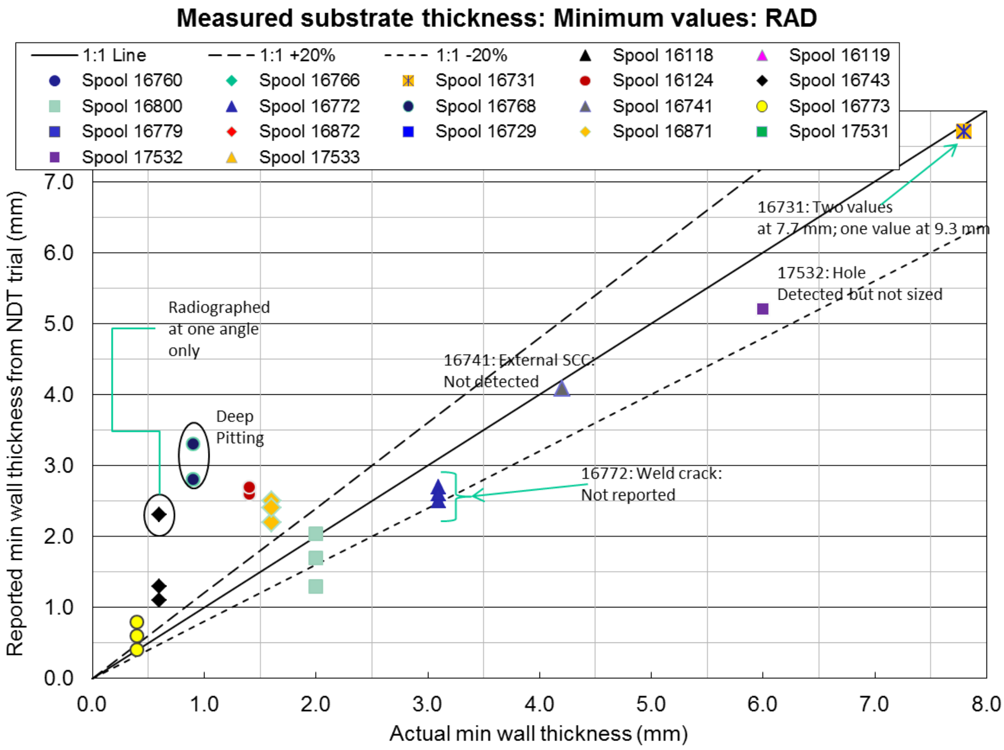


Figure 6: Comparison of minimum substrate wall thickness measured by radiography on the composite wrapped pipe spools with thickness measured directly on substrate after wrap removal

In the blind trials, the technique was able to accurately measure nominal wall thickness, regions of wall thinning, wrap thickness and wrap features, although the exact nature of the features was not established in some cases. In some of the trial results, a large number of scans were made and this provided a full quantification of the spool condition including localised substrate wall thicknesses and wrap dimensions. In other cases, a radiograph at only one angle was provided and the associated concluding view was incomplete, illustrating the need for multiple shots. Weld cracks were not consistently detected, while stress corrosion cracks were not detected by any inspection company.

Radiography remains one of the key inspection techniques for all regions of composite wrapped pipes, and provided sufficient number of shots are made, it can successfully detect most flaw types with the exception of stress corrosion cracks and has limitations when used in tangential mode with large diameter thick walled pipe.

Dynamic Response Spectroscopy (DRS)

Inspection of steels through composite repairs presents a challenge to conventional ultrasonic techniques which are based on high frequency ultrasonic signals, typically 4-15 MHz, due to the attenuation of the signal by the wrap material. DRS employs a relatively low frequency ultrasound probe, operating at typically 1 MHz or less, which is applied to the surface of the composite laminate to excite resonant modes in the substrate underneath the composite. The low frequency means that the ultrasound is largely un-attenuated by the composite laminate. The substrate resonates at natural frequencies that are related to its thickness, producing a returned signal that is processed to determine its thickness profile [Craigon 2015]. Due to the relatively large size of the transducer, DRS has an individual maximum resolution of diameter approximately 10 mm, and as such the technique will not measure features below this size. A second factor to consider is the wrap thickness, since this affects the signal attenuation. For typical glass fibre and carbon fibre wrap materials with epoxy resin, the upper wrap thickness limit for DRS is approximately 12 mm. The ability of the technique to inspect a substrate through a repair is dependent on the presence of a high quality wrap and bondline. Defects in these two zones, or filler materials used to fill external defects, prevent transmission of the signal to the substrate.

In the blind trials on four pipe spools, DRS successfully measured nominal wall thickness of manufactured pipes in the regions where the laminate and bond were defect-free, and also for the regions of an ex-service spool where the wrap was of sufficient quality. Neither localised thinning nor 10 mm diameter through-wall defects were detected, due to the diameter of the features being below the limit of resolution of the method. The DRS method was able to show evidence of potential disbonds in manufactured and pressure tested pipes, Figure 7. The regions highlighted indicate poor signal transmission to the substrate around the 0 and 350 mm circumferential locations, corresponding to the position of the 10 mm drilled hole and likely path of water tracking.

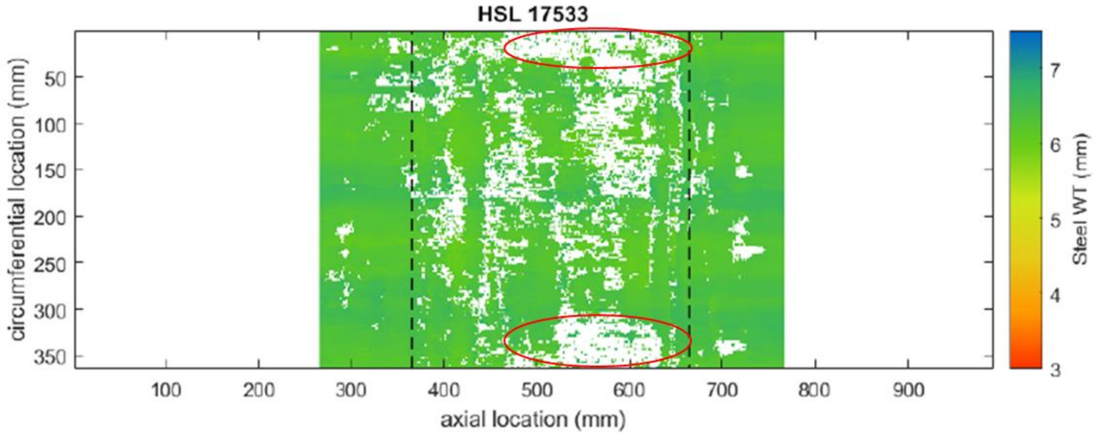


Figure 7: Dynamic Response Spectroscopy results for pipe spool 17533 after hydrostatic testing

In the ex-service spool 16741, excessive wrinkling of the wrap, a wrap thickness of 14mm and a 4mm thick substrate resulted in significant attenuation of the signal and consequently the response from the substrate was too weak to provide thickness data. In spool 16872, wrap features such as low fibre saturation and delaminations prevented the signal reaching the substrate in the majority of the wrapped area. In this case, the value of the technique was in identifying regions of poor wrap quality rather than measuring substrate thickness.

In the blind trials, DRS successfully measured nominal wall thickness of manufactured pipes in the regions where the laminate and bond were defect-free, and also for the regions of an ex-service spool where the wrap was of sufficient quality. The ability of DRS to inspect the underlying substrate through the repair is dependent on a lack of voidage in the repair and bondline. The defects which block the signal can be used to provide an indication of defects on the bond line, making DRS a useful QA tool for post-repair application and as a baseline for future screening to detect changes.

Guide Wave Ultrasonics (GWU)

GWU inspection is typically used for inspecting relatively long lengths of pipe coated with e.g. insulation, and lengths up to 50m or more can be inspected under ideal conditions. It is therefore implicitly suitable for inspection of composite wrapped pipes of relatively simple geometry. The method is covered by both BSI and ASTM standards [BSI 2011, ASTM 2016].

Due to the requirement for access to bare substrate surface beyond the wrap boundary and a length of at least 4 m, trials were carried out on only one spool, 16872. On this spool, GWU was able to detect the change in the response of the substrate under the wrap due to wall thinning. Measurements after wrap removal showed a localised minimum remaining wall thickness of 3.6 mm. The GWU method does not give absolute values of remaining thickness, however the location of the thinnest region measured after wrap removal was consistent with the location of the strongest indication shown in the GWU inspection, inferring that in the spool inspected, the technique was able to detect and locate the region of minimum wall loss, although not specifically to size the remaining wall thickness.

GWU is suited to inspection of long lengths of pipe in a relatively short time, and as a monitoring tool to detect changes in signal response over time. However, since long wavelengths are used the sensitivity to imperfections is reduced. As the method is based on detection of a percentage of cross sectional area on a given section, therefore it is not suited to detection, location and sizing of small defects. Its strength lies in the evaluation of general condition of large diameter pipes with limited numbers of features such as flanges and offtakes. In addition, it can be used for any metallic substrate, including those with fluid present in the pipe, provided bare pipe on at least one side of the wrap is accessible for the collar, or both sides of the wrap in the case of long pipe lengths.

Laser Shearography

Shearography is typically used in manufacturing industries to inspect for defects in composite materials. Its most common applications are in aerospace and marine industries for inspection of components made from thin sandwich composites or honeycomb structures with resin infusions.

Using this technique, relative movement of the surface of an object subjected to an additional load, usually applied by heating via heat guns or high power flash lamps, is measured. The magnitude of these small surface movements depends on the local stiffness of the composite, defects such as delamination, voids or disbonding creating areas of reduced stiffness, leading to greater movement. The movement of the surface of the composite is digitally-imaged using a laser to reveal areas indicative of defects. The short wavelengths of visible laser light are well suited to detection of these small surface movements.

Free-standing laser shearography using thermal excitation was carried out on five pipe spools. Multiple shots were taken at the 12, 3, 6 and 9 o'clock positions, which together captured all the surfaces of the pipe wrap. Laser shearography results for spool 16872 are shown in Figure 8, where each of the four images is taken at one of four positions around the circumference and the pipe's longitudinal axis is in the x-direction. The areas circled in red show regions of differing isostrain, which is indicative of stronger/weaker areas within the composite wrap. A significant proportion of the wrap was reasonably well consolidated. However, a number of indications can be seen which are characteristic of disbonds and/or delaminations, with a high concentration of such features at the 6 o'clock position.

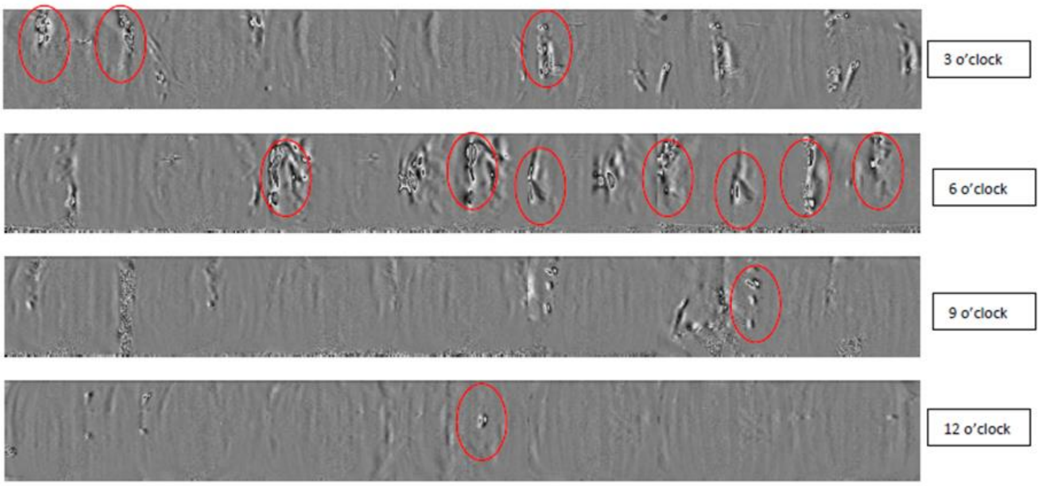


Figure 8: Laser Shearography output from inspection of pipe spool 16872

The output from these showed that the technique is able to qualitatively capture details of regions of the wrap that show different levels of delamination or consolidation, but is not able to differentiate between flaws in the laminates and disbonds at the substrate surface, nor where a where a particular feature lies in the wrap thickness. Laser shearography is currently a laboratory-based technique and has not been applied in an on-site environment.

Microwave Inspection

The use of microwave-based inspection techniques for composite materials has become increasingly more common, particularly for inspection of wind turbine blades, marine composites, and concrete structures repaired using composites. There are however few published applications of microwave inspection to engineered composite repairs, for example [Schmidt, 2009], and its application to this type of structure is still in development. The basic principle of the technique is the backscattering of microwaves as they travel between media of different dielectric constants, which in the current case would be represented by a defect in the composite wrap. The main advantages of microwave-based inspection are that it is non-invasive and non-contact and is well-suited to thick sections of GFRP as there is relatively little attenuation of microwaves at the frequencies typically employed. It is unsuitable for CFRP repairs due to their conductivity.

The method was trialled on one pipe spool, 17532, which included a drilled hole, PTFE disc and disbond from hydrostatic testing. The hole in the substrate was correctly located and sized, although the substrate is not normally the target of microwave inspection, while features at different depths within the wrap were qualitatively recorded. However, significant interpretation is required to categorise wrap features and their location within the thickness of the wrap and to quantify their dimensions. The method may prove suitable in the future but currently the results require significant subjective interpretation which limits its wider application.

Other techniques

Magnetic particle inspection (MPI) and Dye penetrant (DP) test methods are widely used on bare steel surface components to detect surface breaking cracks. Although MPI can be used on steels with thin paint coatings or galvanised layers, the thickness of composite wraps is too large for the method to work. Both MPI and DP methods are therefore unsuitable for composite wraps and were not evaluated in the current trials.

Phased array ultrasonic testing (PAUT) uses a set of multiple probes which can be pulsed separately and at different times to build up an ultrasonic footprint of complex geometries. The attenuation of the high frequency signal by the presence of the wrap limits the successful application, as does the presence of any surface irregularities in the wrap. PAUT was trialled by three Inspection Companies but the method was not successful for composite wraps. Notwithstanding this, it is the view of one Inspection Company that using a linear curved array with a low frequency might improve signal penetration through the wrap, but the contact surface would need to be smooth.

Thermography has not been demonstrated as a viable technique within the current trials, although situations in which it may give positive results were identified. Achieving the thermal differential between pipe and wrap, the reflective nature of the wrap surface and the need for high resolution infrared cameras are the current limiting factors. Active heating is considered necessary as passive heating is considered to be insufficient to generate the temperature differential between substrate and wrap. Use of such methods may have practical limitations in terms of ATEX requirements of hydrocarbon environments in plant applications.

Recommendations on suitable NDT techniques for inspection of composite wrapped pipes

Practical limitations of the identified NDT techniques

Based on the results of the blind trials using all selected techniques and feedback gained from a workshop held with the participating inspection companies, guidance on the limitations and selection of the most appropriate techniques was developed. In Table 3 below, typical geometrical and physical limitations that may preclude the use of the various techniques is summarised. Particularly notable are the pipe wall thickness, wrap thickness, magnetic properties of the substrate and presence of liquid in the pipe.

Table 3: Geometrical and related limitations to use of the different NDT inspection techniques for composite wraps

Aspect	Principal effects on inspection techniques
Large pipe diameters	• Radiography: May limit application, typical limit is 8” for Schedule 40 pipes, increasing to 14” for thinnest walls; exact limit depends on pipe wall thickness and radiographic source being used.
Small pipe diameters	• PEC and DRS: May limit application due to probe size and contact requirement: Typical lower limit 2” for PEC and 4” for DRS
Maximum wall thickness	• Radiography: May limit application depending on radiographic source being used.
Minimum wall thickness	• PEC and DRS: Typically 3mm lower thickness limit; limit for DRS increases with wrap thickness
Substrate magnetic properties	• PEC: Requires magnetic material such as C-steel; cannot be used on austenitic, duplex or super-duplex steels
Wrap material	• Microwave: Cannot be used on carbon fibre wraps (Material must be non-conducting) • Visual: Less effective on CFRP due to lack of contrast
Wrap thickness	• PEC: Wrap thickness increases lift-off and therefore exacerbates wall thickness averaging effect • DRS: Limited to 12 mm wrap thickness in most cases, up to 19 mm by exception • Radiography: Thick wraps can decrease image resolution • Laser Shearography: Limited to ~10 mm thickness
Wrap surface quality	• Laser Shearography: Surface scratches or gouges can affect image quality • DRS: Poor surface quality such as wrinkles limits applicability of method
Liquid within pipe	• Radiography: Presence of oil or water reduces image resolution and increases required exposure time. • GWU: Length range of inspection is reduced by presence of high viscosity fluids.
Presence of welded features, attachments or component edges	• PEC: Edge effects occur at < one probe footprint diameter • GWU: Welded attachments and flanges can affect results
Extent of wrap coverage	• GWU: Requires access to bare pipe surface on at least one side of the wrap

Technique capability and selection

A summary of suitability of the techniques evaluated in the blind trials is given in Table 4. The three columns S, B and L refer to the technique suitability for inspecting the substrate, the bondline and the laminate respectively, where:

- Green indicates where a method is highly suitable for that particular region of the wrapped pipe, provided that other geometrical and material type requirements are satisfied
- Amber indicates where a method may be suitable for that particular region of the wrapped pipe but with restrictions or with further validation
- Red indicates where a method is unsuitable under any circumstances for that particular region of the wrapped pipe

The optimum use and major limitations/considerations for each technique are given in the final column of Table 4. It should be noted that the detail is necessarily brief and each technique would require further consideration for a specific application before a definitive decision on its suitability was made.

Table 4: Summary of capabilities, optimum use and limitations of the trialled NDT techniques

Method	Generic View and Capabilities	S	B	L	Optimum Use	Limitations
VIS	•Impact damage •Gross disbonds at edges of repairs •Edge lift-off; wrinkling; exposed fibres •Weeping in Fluid-filled pipes				•Overview of indicative surface condition of wrap •Wrap surface only	•Subjective unless photographed •Wrap opacity limits
MPI **DP**	•Access to substrate surface •Methods impractical				•Technique not suitable	•No access to substrate surface: unsuitable
PAUT	•Conventional high frequency ultrasonics unsuitable for composite wraps due to signal attenuation by wrap layers				•None pending further validation	•Signal attenuation
THERM	•Requires high quality wrap to enable substrate flaws to be detected •Requires active heating				•Detection of significant wall thinning in pipes with high quality wrap	•Demonstration of technique is limited •High resolution IR camera and active heating required
PEC	•Substrate must be magnetic •Measured wall thickness is mean of thicknesses under probe (volume averaging effect) and increases with stand-off distance •Effective for measurement of general wall thickness loss, less so for localised				•General wall thickness loss/ thinning •Screening and tracking	•Flaw or feature of size less than probe footprint cannot be distinguished •Will not identify pitting or cracks
RAD	•Multiple shots needed to detect and measure minimum ligament and ensure maximum coverage •Spatial access from multiple angles •Finds most gross features when carried out with sufficient coverage				•General and localised wall thinning •Detection of pitting	•Not suitable for Diameter ≥8" for tangential on schedule 40 pipes: Chord thickness and radiation source dependent •Image quality affected by internal fluids
DRS	•Substrate thickness can be measured when laminate and bond are high quality •Areas of poor quality of bond or laminate show visually in scans: substrate thickness not measurable in these regions as signal does not reach substrate •Can detect local substrate features of diameter >~10 mm				•Substrate wall thickness features ≥10 mm •Qualitative mapping of wrap •Mapping of bondline and laminate flaws as baseline	•Typical 12 mm maximum wrap thickness •Feature detection limit is 10 mm due to size of probe •Defect nearest to wrap surface may mask detection of defects deeper in wrap, on bondline and in substrate
LS	•Requires scans from 12/3/6/9 o'clock •Highlights qualitative level of consolidation in the wrap •Difficult to determine depth of indications: Small surface flaws and large deep flaws give similar response				•Qualitative imaging of presence of delamination in the wrap on repairs	•Currently lab-based only •Defect sizing/depth capability not yet developed for composite wraps
MW	•Suited to thick sections of GFRP wraps •Provides images of wrap at different depths into the layers •Visual representation of features at different depths into the wrap				•Qualitative delamination detection in the wrap	•Cannot be used on carbon fibre wraps •High degree of results interpretation
GWU	•Suitable for general wall-thinning measurement and its location •Suitable for tracking changes to damage condition by continuous monitoring				•Tracking changes in wall thickness under short wraps •Works for all metals	•Needs access to bare pipe substrate •Sizing and precise location of flaws/thinning difficult •Based on cross-sectional losses, ineffective for pits

Conclusions

Adherence to existing standards is the cornerstone of high quality installations for composite wrap repairs. Throughout subsequent defined-life, the ability to inspect for known degradation modes and new threats is required, for which the capabilities and limitations of inspection techniques must be clearly understood. Installation of a composite wrap repair increases the inspection complexity. In order to evaluate the suitability of a range of NDT techniques, a series of inspection blind trials was carried out. Based on these trials, the suitability of the various techniques has been assessed as below:

Techniques currently considered suitable for the inspection of composite wraps:

- Pulsed Eddy Current: Substrate screening, magnetic materials only
- Radiography: Local thinning and feature identification in substrate and quality evaluation of wrap
- Dynamic Response Spectroscopy: Substrate and wrap/ bond quality indication, and as a post repair installation QA tool
- Several of the above techniques may need to be used in combination depending on pipe material, geometry, degradation modes, defect locations and wrap quality

Techniques considered suitable as complementary methods to those above, or which may be suitable as stand-alone techniques pending demonstration of ability to provide quantitative results:

- Guided Wave Ultrasonics: Substrate condition thickness monitoring
- Laser Shearography: Wrap qualitative condition indication

Techniques which require further development/validation before they are considered suitable:

- Microwave: Wrap qualitative condition monitoring; further work required on results interpretation
- Thermography: Substrate condition monitoring; Further demonstration in actual in-service conditions required

The inspection strategy for composite wrapped pipes should be defined at the repair/replace decision making stage, and an inspection viability step helps reduce the risk of basing this decision on an unsuitable inspection technique. The quality of the repair installation can improve the performance of some inspection techniques, but needs to be balanced against excessive wrap thickness which may reduce the resolution of PEC, DRS and some radiographic techniques. A baseline inspection prior to, and immediately after, repair application provides a key benchmark.

Potential improvements for each inspection technique have been identified. These include consistent formats for results presentation, calibration of less-developed methods against samples containing known flaws, development of signal processing methods to improve the defect resolution of existing techniques and implementation of continuous monitoring.

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