inductosense

WHITE PAPER

A Novel Solution for Monitoring Internal Corrosion of Pipework Under Composite Wrap Repair

Dr. Chenghuan Zhong, Inductosense Ltd
September 2017

Executive Summary

Design regulations are driving the need to seek a solution to monitor structures underneath composite wrap repairs

If the areas at risk of corrosion are known, a limited number of sensors can achieve a high detection probability

The Inductosense WAND system provides a solution to monitor structures underneath composite wrap repairs

With the accumulated measurements, a corrosion rate can be determined from the historical measurements of the WAND system. This enables the end user to plan better and operate structures more efficiently, particularly repaired components

Tested with several wrap materials and shown to be compatible with a number of materials including glass fibre, aramid and uni-directional, as well as cross-ply carbon fibre

The WAND system provides instant reliable thickness readings from the sensor underneath the composite wrap

Sequence

Composite repairs applied to structures must meet specified performance requirements. There is an increasing demand for monitoring of structures beneath these repairs.

1) Introduction

Industrial plant such as pipework in the petroleum, petrochemical and natural gas industries is often susceptible to both internal and external metal loss due to internal erosion and corrosion from the process itself or external corrosion due to environmental impact. Many of these structures have been in operation for more than 40 years and urgently require reinforcement and repair to be maintained in service [1].

Traditionally, parts of structures with severe problems are reinforced with steel sleeves or removed and replaced [2]. Recently, fibre reinforced polymer (FRP) repair. The repair systems are typically made with aramid (AFRP), carbon (CFRP), glass (GRP) or polyester fibre reinforcement in a polyester, vinyl ester, epoxy or polyurethane matrix. Compared to a steel sleeve or replacement, composite repairs have the following advantages:

a) Easier and quicker to apply, the repair can be completed when the pipe is still in operation.
b) Safer to apply, as welding is not required, consequently the risk of bursting due to welding and cutting is eliminated.
c) Cheaper to apply, an analysis reports that composite repairs are 24% cheaper than welded steel sleeve repairs and 73% cheaper than replacing the pipe [3].

With the increasing popularity of using composite repairs, standards and guidance such as IS0-24817 and ASME PCC-2 have been published to regulate their application. The objective of those standards is to ensure that composite repairs applied to structures will meet the specified performance requirements.

2) Design methodology and challenges

Both ISO-24817 and ASME PCC-2 detail design methodologies for composite repair systems applied to different defects in structures. The minimum repair laminate thickness is perhaps the most important design parameters to ensure the repaired structure can withstand specific loading. For a pipe with diameter, D, and remaining wall thickness, t_s, the required minimum laminate thickness of composite wrap, t_{min}, to achieve the design pressure, P, can be calculated using the equation below, assuming the repair is applied at zero internal pressure.

$$t_{min} = \frac{1}{\varepsilon_c E_c}\left(\frac{PD}{2} - st_s\right)$$

Where:

- ε_c is the allowable repair laminate circumferential strain
- E_c is the circumferential modulus of the repair laminate
- s is the yield stress in the ASME PCC-2 standard, and the allowable stress of the substrate in the ISO-24817 standard.

For a pipe and repair system with properties listed in Table 1, t_{min} can be plotted against the defect depth as a percentage of initial wall thickness.

Pipe	
Material	API 5L X65
Pipe size	150 ND
Modulus, [GPa]	200
Out-diameter, [mm]	168.3
Wall thickness, [mm]	7.11
Yield stress, [MPa]	448
Design factor	0.72
Allowable stress, [MPa]	322.56
Design pressure, [Mpa]	27.25
Laminate	
Modulus in hoop direction, [MPa]	23800
Allowable circumferential strain,	0.003

Table 1: Pipe and laminate properties [4]

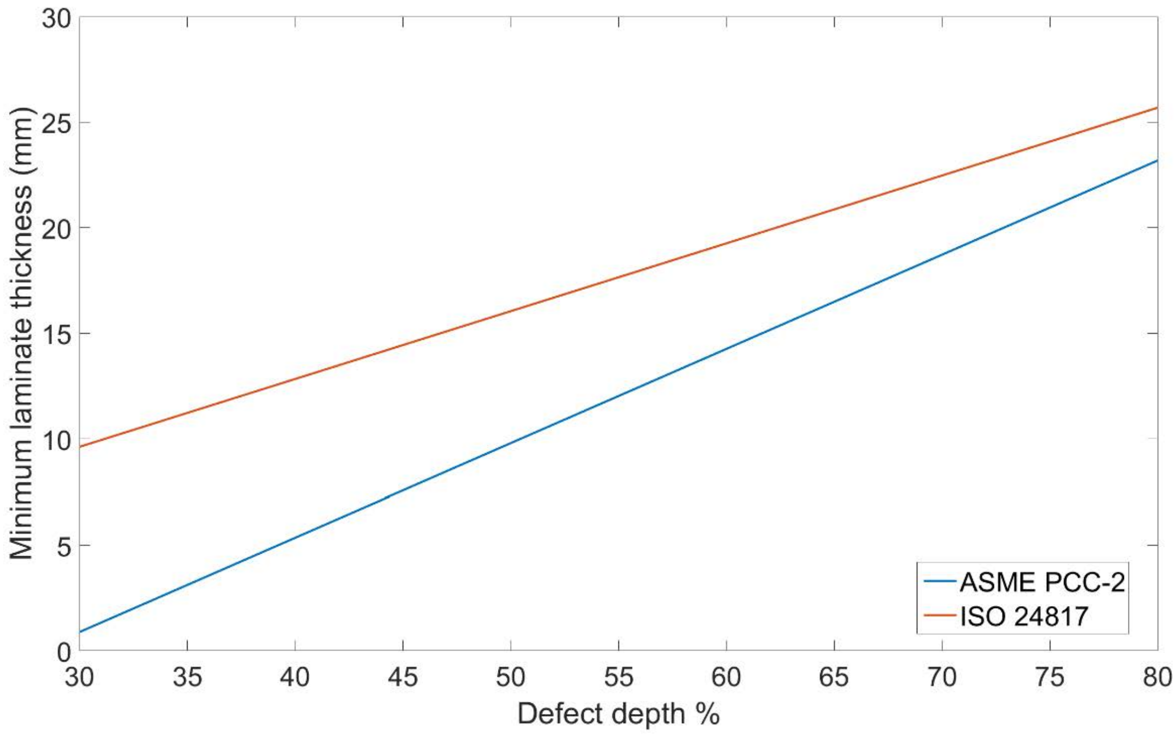

Figure 1: Minimum laminate thickness against the defect depth in percentage

Figure 1 shows that for both standards the minimum laminate thickness increases as the wall thickness drops. It can be seen that for a 10% decrease in wall thickness (i.e. from 30 to 40% defect depth), the thickness of composite wrap required increases by 4.5 mm under the ASME standard and by 3.2 mm under the ISO standard. It is worth noting that according to ISO 24817, a defect within a substrate shall be considered through-wall if the wall thickness is less than 1 mm, and the design process illustrated here is no longer valid. The calculations for the minimum laminate thickness required in the through-wall defect case are stated in

ISO 24817 section 6.5.7. In addition to specifying the minimum laminate thickness, that codes states that the repair laminate shall extend beyond the damaged region in the substrate by whichever is the bigger of 50 mm or l_{over}, which can be calculated as follows:

For slot type defects:

$$l_{over} = 2\sqrt{Dt}\ (ISO\ 24817)$$

$$l_{over} = 2.5\sqrt{Dt/2}\ (ASME\ PCC-2)$$

For circular type defects:

$$l_{over} = 4d\ where\ d < 0.5\sqrt{Dt}\ (ISO\ 24817)$$

Where:

- D is the external diameter of the substrate/pipe
- t is the thickness of the substrate
- d is the diameter of the defect

The total axial length of the repair is given as:

$$l = 2l_{over} + l_{defect} + 2l_{taper}$$

Where:

- l_{defect} is the dimension of the defect.
- l_{taper} is the tapering length of the wrap. A minimum taper of approximate 5:1 is recommended

Taking circular type defects as an example and a fixed tapering length of 20 mm, the figure below shows the length of the repair against the size of defect. Figure 2 shows that when the defect size doubles, the length of the repair also needs to be doubled.

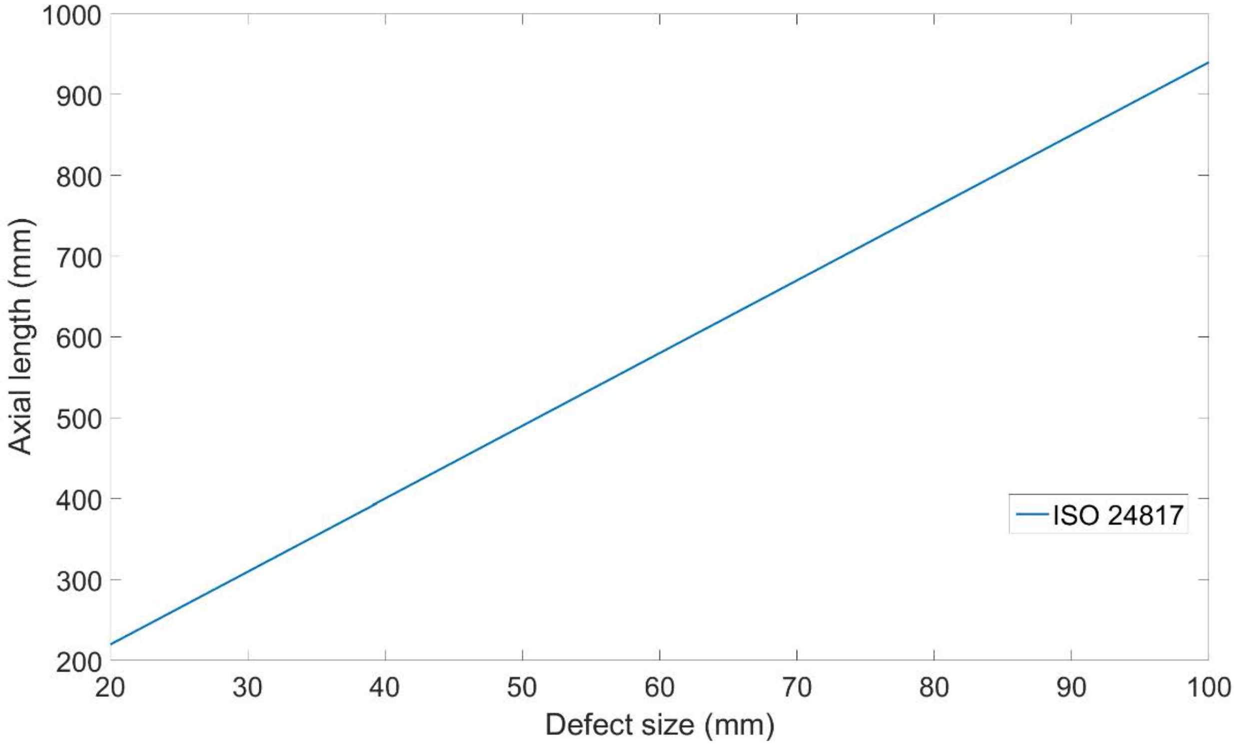

Figure 2: Axial length against the defect size

From this analysis, it can be seen that the composite repair system can only be validated when the wall thickness of the pipe and the defect size are known. Prior to applying a composite repair a non-destructive examination, such as ultrasonic testing (UT), is performed to understand the pipe thickness and the composite repair is conservatively designed based on this condition. However, once a composite repair is applied to a pipe it is no longer possible to measure the pipe thickness underneath using conventional UT. Consequently, it is not possible to establish whether the corrosion/erosion of the pipe under the repair has ceased or to further validate the fitness of the composite repair against the standards. In many cases the wrap needs to be removed after a period of time, conventional UT performed, and the wrap re-designed and applied to the damaged pipe.

3) Inductosense Solution

Inductosense offers a novel solution to monitor the wall thickness of a pipe under composite wrap repair allowing validation of the repair and potentially extending the life of the component.

Inductosense has developed the Wireless And Non-Destructive (WAND) system that uses inductive coupling to excite a wireless, battery-free sensor and make ultrasonic measurements on a structure as illustrated in Figure 3 (a). The system consists of two main parts: the sensor and the measurement probe, which are shown in Figure 3 (b). The sensors are less than 1mm thick and can be permanently fixed to a structure for fast, repeatable detection of structural changes. Inductosense has a complete system model and in-house design process which enables optimisation of the system for applications requiring different reading distances (separation between sensor and probe) and operating frequencies.

Figure 3: (a) Operation of WAND system and (b) WAND Evaluation System

Benefits:
Permanent
Fast
Embeddable

The WAND system has the following advantages:

- Permanent – the sensors can be permanently attached to structures enabling repeatable, accurate measurements from the same location not requiring precise alignment or coupling gels and significantly reducing human error. Over time corrosion rates can be accurately determined.
- Fast – an ultrasonic thickness measurement can be taken in less than a second by bringing the probe nearby and pressing a button.
- Embeddable – the sensors are battery-free, wireless and compact. They can be attached to the surface of structures underneath a layer of coating, insulation or composite repair. This alleviates the need to remove the outer layers from the structure in order to make a thickness measurement.

4) Measurements underneath composite wrap repair

The WAND sensors have been successfully bonded to structures underneath a range of materials including carbon fibre, glass and aramid composite repair wraps, coatings, insulation and non-metallic cladding. Testing shows that the material between the sensor and probe does not have an impact on the accuracy of the thickness measurement of the underlying structure. An example signal recorded from a sensor attached to a 4-inch diameter pipe before and after application of a 10 mm thick glass fibre composite repair wrap is shown in figure 4 below:

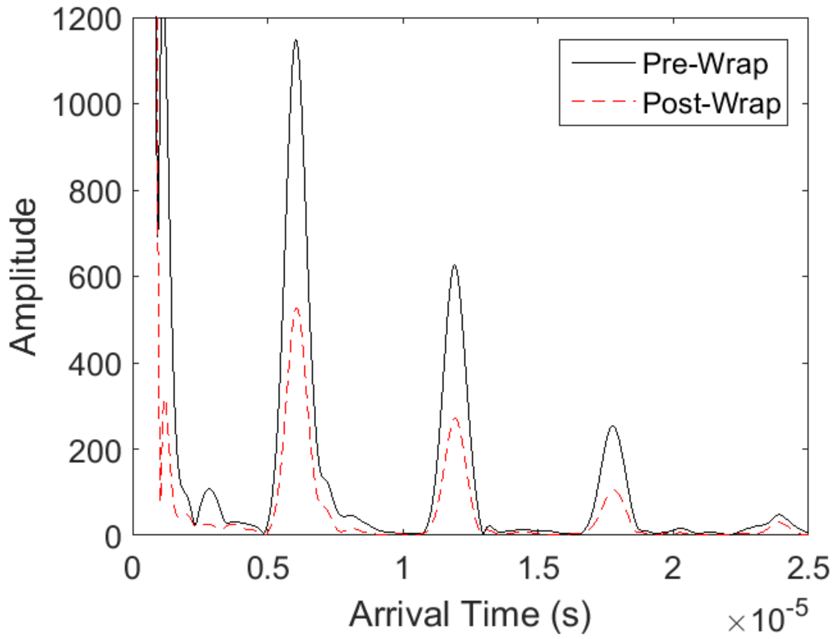

Figure 4: Enveloped ultrasonic signal from the WAND system before and after wrap application

The signal amplitude decreases with the application of the wrap, due to the increased distance between the sensor and measurement probe. However, there is no change in the arrival time, which in this case gives a consistent thickness measurement of 17.9mm. Table 2 gives a summary of composite wraps which have been tested with the WAND system. The number stated in the table does not represent the maximum thickness of wrap a measurement can be made through, but the maximum thickness of the available testing samples.

Fibre type	Lay-up	Thickness	Readability	Structure integrity
Glass	Uni-directional	25 mm	✓	
Glass	Bi-directional	10 mm	✓	✓
Glass	Quasi-isotropic	8 mm	✓	
Carbon	Bi-directional	18 mm	✓	
Carbon	Quasi-isotropic	10mm	×	
Kevlar	Cross-ply	25 mm	✓	

Table 2: List of composite wrap materials tested with the WAND system.

A limitation to the WAND system is that it is not compatible with quasi-isotropic carbon fibre repair. This is because quasi-isotropic (QI) carbon fibre acts as an electromagnetic shielding and prevents the electromagnetic signal from the probe getting through to activate the sensor.

Pressure testing was performed in collaboration with IMG Composites to quantify any possible detrimental impact of the presence of the sensor on the performance of the repair wrap. Three sensors were installed on a 4-inch diameter, 17 mm thick spool with a 10 mm diameter through thickness hole. The arrangement of sensors on the spool is shown in the figure below. It worth to note that the sensor IND_108 was directly applied over the through thickness hole, only for structural integrity testing purpose, not for ultrasonic measurements.

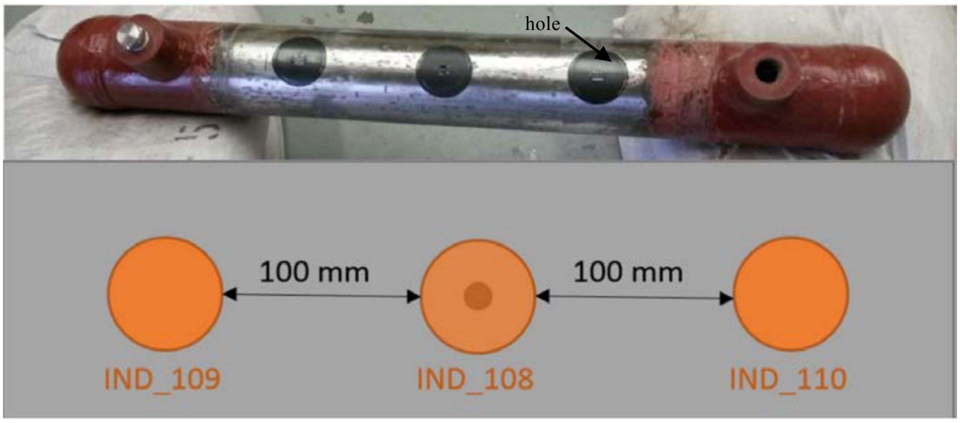

Figure 5: The arrangement of sensors on the spool for pressure tests.

Eight-ply CompoSol glass fibre repair system was applied on the spool after the installation of the sensors, and the repaired spool was filled with water and pressured in 20 bar steps up to 360 bar, the maximum safe pressure. Measurements were taken at time points: a) before wrap, b) after wrap applied but before the spool was filled with water, c) when spool pressurised to 340 bar and d) after spool de-pressurised. The measured signals are shown in the Figure 6, and their corresponded calculated thickness are summarise in the table 3.

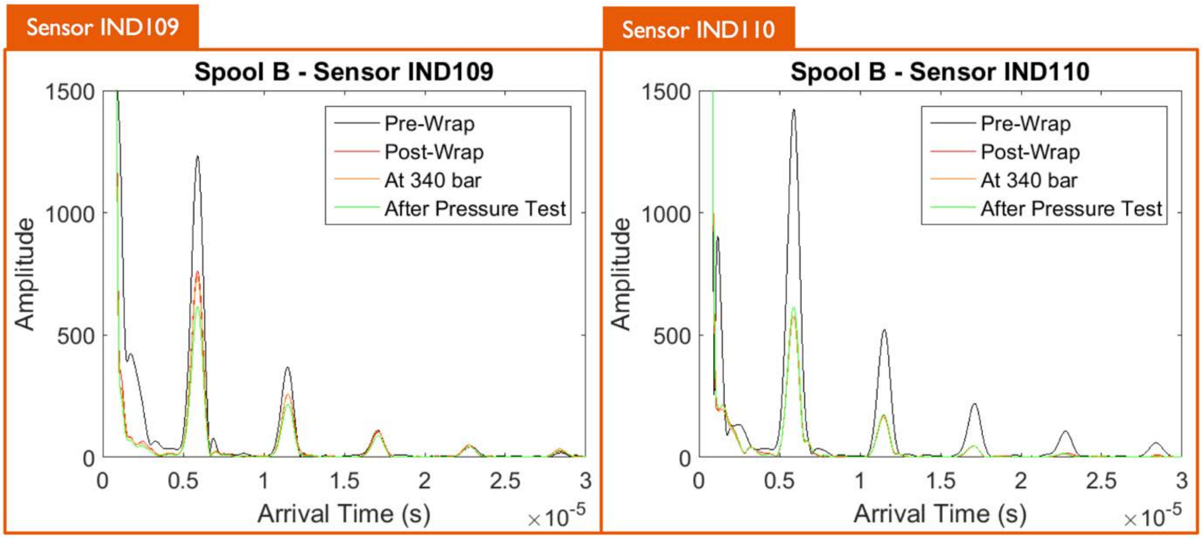

Figure 6 (Above): Enveloped ultrasonic signal from the WAND system during the pressure test

Table 3 (Right): Thickness measured fr the sensors installed on spool during t pressure test

Measurement Point	Measured Thickness (mm) IND109	IND110
Before wrap	17.1	17.0
After wrap	17.1	17.0
At 340 bar pressure	17.1	17.0
After pressure released	17.1	17.0

From the results, it can be seen that both sensors are shown to be functioning correctly during and after pressure testing, giving consistent thickness measurements. Also, it has been found that the repair wrap is remained intact at the maximum test pressure of 360 bar, the conclusion was that the incorporation of Inductosense sensors beneath the CompoSol repair wrap does not cause premature failure of the wrap.

5) Comparison with conventional UT

The WAND system enables a fast UT thickness measurement of a structure underneath a composite wrap without requiring complex instrumentation, coupling gels or skilled operation. The WAND probe is just brought near to the sensor and a measurement taken with the push of a button. It reduces human error from the measurement process.

A number of measurements were made from a test block, with the probe randomly positioned over the sensor each time, and misalignment between sensor and probe of between 6 and 16 mm. The thickness recorded from each measurement is plotted against signal amplitude in Figure 7. The variation in echo amplitude shown here is caused by changes in reading distance and the degree of alignment between the probe and sensor. While the change in amplitude is significant it is important to note that this does not have an affect the measured thickness.

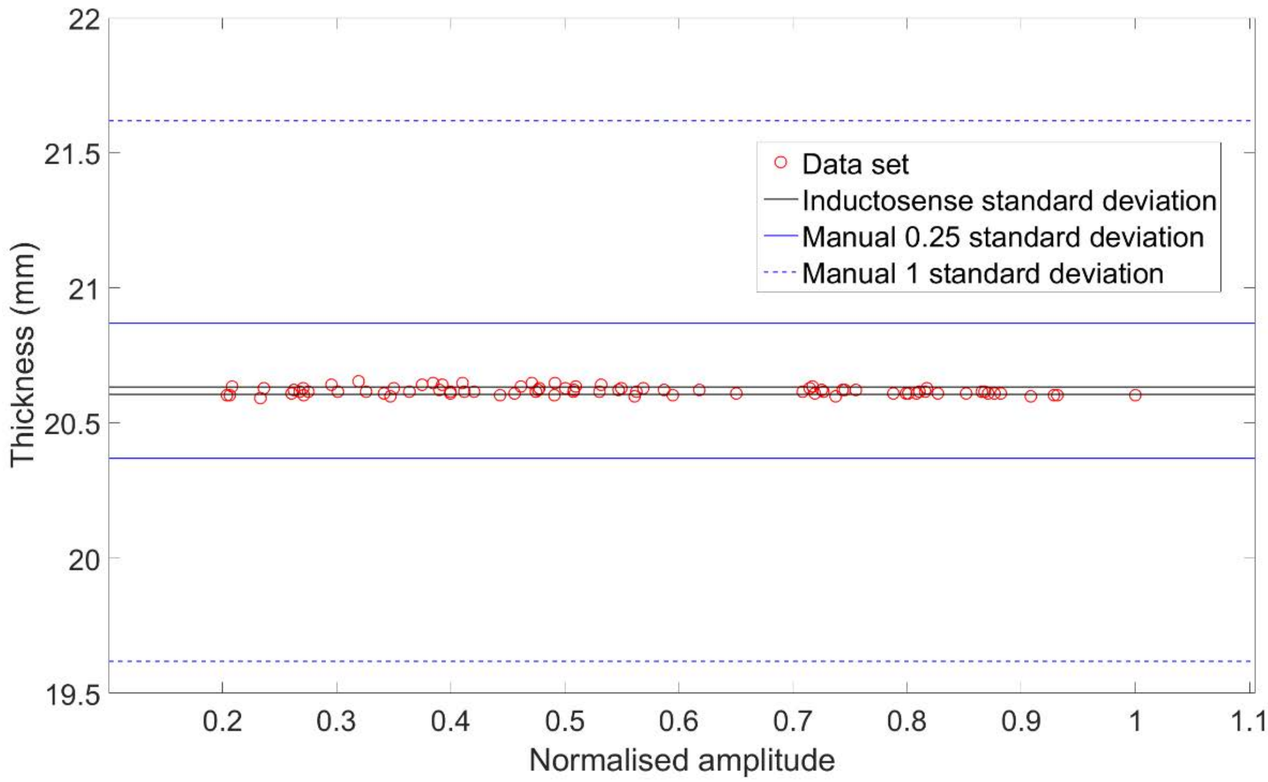

Figure 7: Standard deviation of 80 measurements from a 20.6mm thick Al test block using the WAND system

The standard deviation was calculated for this data set and is shown in the following table against estimates of standard deviation for manual UT measurements cited in Yi. et al [5] and Wilson et al.[6]. These values are also plotted in figure 7 for comparison. With the WAND system the scatter in measured thicknesses is reduced to a very low level.

Technique	Standard deviation (mm)
Inductosense WAND	0.021
Manual (Yi.et al)	~0.25
Manual (Wilson et al)	~1

Table 4: Standard deviation of different techniques.

6) Corrosion Monitoring

The WAND system enables the user to save and export the ultrasonic signal as well as the thickness measurement. Over a period of time, the true corrosion rate of the structure can be calculated. This can be useful for a composite repair as the operator could then optimise the scheduling of the component repair and ensure that the integrity of the structure is within the design limit of the wrap until the next shutdown.

A WAND sensor was applied to pipework on a corrosion test rig under a composite wrap (shown in Figure 8 (a)). The pipework was subjected to internal corrosion over a period of time and was also monitored using an electrical resistance (ER) probe. Figure 8 (b) shows the results from the WAND sensor and ER probe and the corrosion rate from both methods is shown in Table 5.

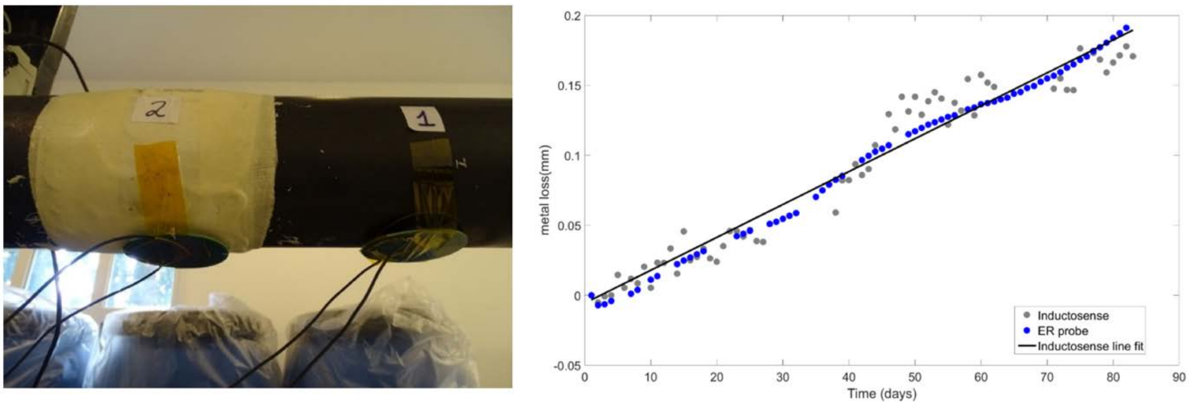

Figure 8: (a) Erosion rig set-up, (b) Measurements from WAND sensor and ER probe

Technique	Corrosion Rate (mm/year)
Inductosense WAND	0.86
ER probe	0.89

Table 5: Corrosion rate predicted by the Inductosense WAND and ER probe

7) Local measurements and area coverage

The standard WAND bulk wave sensor has an active area of 5 mm x 15 mm, which is similar to a manual UT probe. The internal surface of pipework does not corrode uniformly and local defects are more likely to occur due to changes in internal flow or chemical concentration. As the WAND sensor is permanently bonded to the structure it provides only a point measurement underneath the sensor. Therefore the probability of detecting a localised defect from a single sensor is low. However, with composite repair applications, the area exhibiting internal corrosion/erosion is usually well known as it is assessed prior to applying the repair. With this knowledge, only a few sensors are required to achieve a good probability of detection. Figure 9 shows the relationship between the number of sensors installed around a defect and the probability of detection.

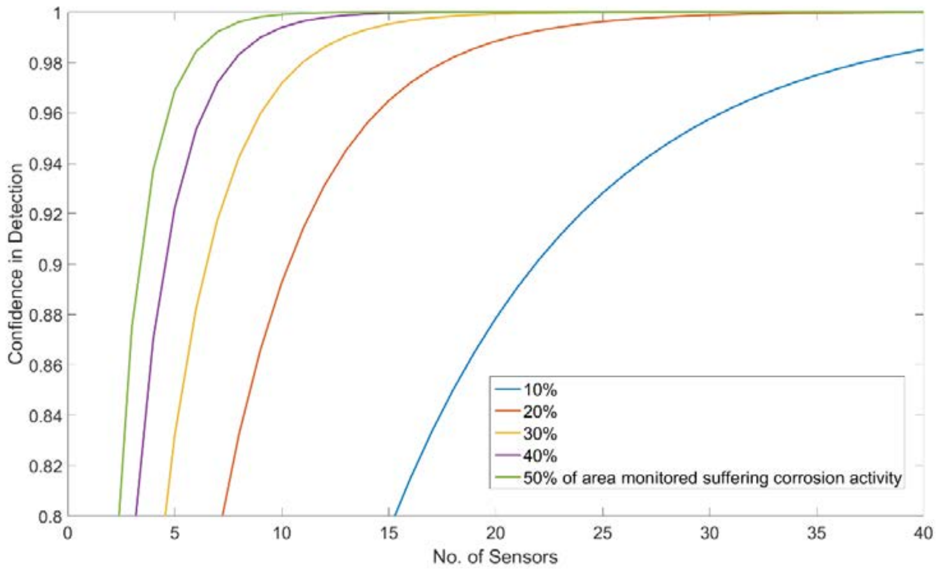

Figure 9: Variation of the probability of detection with the number of sensors

8) Conclusion

- Design regulations are driving the need to seek a solution to monitor structures underneath composite wrap repairs.
- The Inductosense WAND system provides a solution to monitor structures underneath composite wrap repairs. The system has been tested with several wrap materials and shown to be compatible with a number of materials including glass fibre, aramid and uni-directional, as well as cross-ply carbon fibre.
- The WAND system provides instant reliable thickness readings from the sensor underneath the composite wrap.
- With the accumulated measurements, a corrosion rate can be determined from the historical measurements of the WAND system. This enables the end user to plan better and operate structures more efficiently, particularly repaired components.
- If the areas at risk of corrosion are known, a limited number of sensors can achieve a high detection probability.

9) References

[1] Pipelines International. Evaluating different rehabilitation approaches 2009

[2] Mohitpour M, Golshan H, Murray A. Pipeline design and construction: a practical approach. 2nd ed. New York, NY: ASME Press; 2003, p. 499-518.

[3] Koch GH, Brongers MP, Tompson NG, Virmani YP, Payer JH. Corrosion cost and preventative strategies in the United States. Federal Highway Administration, Office of Infrastructure Research and Development; 2001. p. 260–311.

[4] Nariman S, Hamid R, Amandeep V. Composite repair of pipelines, considering the effect of live pressure-analytical and numerical models with respect to ISO/TS 24817 and ASME PCC-2.

[5] Yi, W.G., M-R. Lee, J-H. Lee and S-H. Lee, A study on the ultrasonic thickness measurement of wall thinned pipe in nuclear power plants. in 12th Asia-Pacific Conference on NDT. 2006. Auckland, New Zealand. 2

[6] Wilson, P.T., Krouse D.P., Statistical Analysis of UT Wall thickness data from corroded plant, Nondestructive Testing Australia, Vol 41, No.3, 2004.