Composite Sleeves for Permanently Restoring the Serviceability of Pipe: A review of testing and standards
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Abstract
New technology for repair of pipes and pipelines has attracted great interest in our industry, driven by the need to minimise costs by reducing downtime and maintaining production. The adoption of such technology must be carefully controlled to ensure continued, safe operation of the systems. This paper reviews what technical data are required to support appropriate applications of mechanically applied composites.

A review of how the durability of repairs in common environments under dynamic and static loading, with various defect geometries were demonstrated using laboratory scale tests and confirmatory testing at full scale is given. The programme has been demonstrated as suitable by the 20 years successful experience with the Clock Spring repair sleeve. The requirements of current guidance documents, such as ASME PCC-2 Article 4.1 and ISO 24817, are reviewed in light of this and it is shown that they are most suitable for repair of process pipe (e.g. built according to the requirements of ASME B31.3) rather than pipelines (B31.4 and B31.8) unless long term mechanical properties have been derived by testing.

1 Introduction and Background
The repair of damaged pipe using composite sleeves such as Clock Spring has been the subject of increasing commercial interest in the last five years. Clock Spring was the first product to gain approval for use in a wide range of applications, covering low pressure process pipe to high pressure gas transmission lines. The approval was neither cheap nor easy to gain, but only granted after an extensive test programme lasting over 10 years, steered by a committee of independent industry experts coordinated through the Gas Research Institute (GRI).

With the successful track record of Clock Spring applications now extending over 15 years the guidance of the steering committee is proving to have been foresighted and reliable. It is also interesting to note that over the last five years the number of alternative products in the market place has started to increase rapidly. Suppliers’ claims that their products will perform the same as Clock Spring, but the test work which has been completed to back up these claims has, in many cases, not been completed. There is a clear need, therefore, for a common standard against which all products can be measured to ensure that the user can select a repair technique with confidence, without taking on any unforeseen risk.

The objective of this paper to is to present a brief overview of the test work originally conducted under the guidance of the GRI steering committee to demonstrate beyond doubt the suitability of Clock Spring and to compare this with the test requirements of the draft guidance documents now in preparation (ASME PPC-2 Article 4.1 and ISO TS 24817).
2  The Clock Spring Repair System

The Clock Spring Repair consists of three parts:

1. A composite sleeve manufacture from E-glass fibres and polyester resin. The fibres are all oriented to run around the hoop direction of the pipe to maximise the strength of the system in this direction. The sleeve is coloured yellow in the photograph below, Figure 1.

2. A methacrylate adhesive to secure the repair. The adhesive is coloured blue in the photograph below, Figure 1.

3. A load transfer agent (filler) to transfer load from the defect to the composite sleeve (also methacrylate based, and compatible with the adhesive). The filler is coloured light-brown in the photograph below, Figure 1.

The sleeve is manufactured in the Clock Spring production facilities under an approved, quality management system. It is a continuous coil, manufactured to specific diameters to match pipe diameters and is wound around the pipe to provide the reinforcement, Figure 1. The mechanical properties are therefore highly repeatable. It also means that the strength-member is manufactured under controlled conditions, and only the tolerant process of adhesive bonding is completed at site. The installation takes between 20 and 30 minutes, with cure of the adhesive being achieved in about two hours, at which point the repair area can be coated and backfilled (if appropriate).

The whole philosophy of the development of the Clock Spring was to make a system that was site friendly, where the installation could be undertaken by semi-skilled technicians and yet the performance of the product still be assured. With the key strength element being factory made, the only issues to control at site are the surface preparation, mixing of adhesive, application of adhesive and tightening of the coil. These are all straightforward to manage. In fact, tests have shown that only a fraction of the length of the coil needs to be bonded for the system to work (approximately 0.6m – where as the full length of the coil on a 12” pipe is 8m).

Figure 1. Clock Spring® sleeve being applied to a damaged, steel pipe

Clock Spring sleeves have been used widely since the validation testing was completed (early 1990’s) typical repairs being applied to transmission pipelines (oil and gas), risers, pipe supports, process piping etc. Some examples of common applications are shown below. To date, over 300,000 successful applications have been made.
Figure 2. Repair of offshore riser

Figure 3. Repair of transmission line

Figure 4. Repair of transmission line at road crossing

Figure 5. Repair of damage / preventing degradation at supports

Figure 6. Localised repairs on a corroded steel pipe

Figure 7. Continuous repair on corroded pipe
3 Qualification Testing of the Clock Spring Repair System

Validation of the Clock Spring product was completed by an independent test body, GRI (Gas Research Institute, Chicago, USA) on behalf of the transmission pipeline industry in the US (including the US regulatory body for pipeline safety). The Clock Spring Company was not responsible for setting the test programme nor for conducting the tests. The aim of the programme was to generate sufficient data to categorically support a 50-year design life for repairs to blunt defects in ductile pipe. The investigations focussed on the following topics:

- Long-term properties of the repair system
- Confirmation that the repairs restore pipelines suffering corrosion or mechanical damage to full strength under both static and dynamic loading
- Confirmation that the repairs can be used in pipeline environments (including soil conditions and presence of cathodic protection)
- Confirmation that repairs in service perform as predicted by laboratory tests by extended field trials

3.1 Long-Term Strength of Repair System

Studies were completed on the composite sleeve and the adhesive.

Composite materials are known to show a gradual reduction in strength over time (termed a ‘creep-rupture’ behaviour). This has been reported in detail in the scientific literature, and so it was concluded that it was necessary to measure the performance for the Clock Spring materials.

The typical test method is to load mechanical test specimens to various proportions of their short term strength and then measure the times to failure. Composites typically exhibit scatter in their short-term strength, and this translates into scatter in measured time to failure. A regression curve can be fitted to the data when plotted on a log-log scale. The data can then be extrapolated to predict the long term performance.

The concept is proven (the methodology has been well documented in test standards such as ASTM 2992 for determining design levels in composite pipes) and typically uses test durations up to 10,000 hours (416 days) to predict acceptable allowable stress for a 20-year life. To justify the 50 year life required the Clock Spring tests modified the tests in three ways:

1. Test duration extended to over 20,000 hours (2.3 years)
2. Specimens saturated in water before testing and immersed in aqueous environments during tests (range of pHs from 4 to 9.5) rather than tested dry
3. Tested at temperatures of up to 60°C (140F) to give an ‘acceleration’ to any effects

This test regime was recognised as exceedingly harsh, and so accepted to give a lower bound performance. Further, the chemical composition of the resin both before and after testing were evaluated (using Fourier Transform Infrared Spectroscopy), confirming that there had been no discernible change to the polymer structure over the accelerated ageing of 2.3 year duration.
The evidence collected from over 50 long term tests and associated measurements was sufficient to support extrapolation of the results to a 50 year life. A long-term strength of 138 MPa (20ksi) was derived, and this is used in the design of Clock Spring repairs.

The adhesive used to bond the Clock Spring in place is a proprietary epoxy/methyl Methacrylate compound. It’s primary purpose is stop the Clock Spring unravelling from around the pipe when loaded. Analysis and practical testing suggested that only a short bond length is required to achieve this (75mm/3”), with a peak stress of around 1.4MPa (200psi). With short term strengths in the order of 8MPa (1200psi) it was expected that the adhesive would perform well, even more so considering a typical bond length is likely to be in the order of 4 to 20m (14 to 75’) depending on diameter.

Long-term durability tests equivalent to those completed on the sleeve were repeated on the adhesive. Bonded joints were loaded whilst immersed in aqueous solutions of varying pHs at 60°C (140F) for up to 10,000 hours (416 days). Testing showed that the peak stress quoted above was below the apparent failure threshold suggested by the tests.

The test programme completed follow best-practice guidelines and was sufficiently full to enable a long-term design stress to be derived.

### 3.2 Confirmation that Full Scale Reinforcement is Achieved

Whilst the mechanics of repairing a pipe using a composite sleeve are relatively straightforward in theory, there had been no significant work to demonstrate that the interaction between pipe and composite was as expected.

Various ‘corrosion defects’ were first replicated, by machining thin patches on test samples and then comparing repaired-strength with the strength of an undamaged pipe.

![Figure 8. Typical test defect](image1)

![Figure 9. Defect after testing](image2)

![Figure 10. Repaired defect after testing](image3)

A range of pipe grades were tested (X42 to X60), as well as a range of diameters (6” to 36”) and toughness (Charpy upper shelf energy ranging from 40 to 68J, 30 to 50 ft-lbs). Defects ranged from 21% to 81% wall loss, and covered various shapes of corrosion profile (e.g. ‘V’ and ‘U’ shapes). All pipes would have been expected to fail at below their specified minimum yield strength (SMYS). Tests were completed on pipe removed from the field as well as on new pipe to confirm there were no unexpected changes in behaviour.
Further test iterations looked at reducing the thickness of repair applied, pre-loading the pipe prior to repair (sufficiently to cause the defect to yield), long defects to demonstrate that multiple, adjacent Clock Spring units work as expected.

These tests all focused on short-term burst strengths. However, there remained a need to look at how cyclic loading would affect the results. Composites are known to be good in low amplitude, high cycle fatigue and so performance of the sleeve was expected to be good, but there was no information concerning how the pipe and sleeve would interact (and so whether the sleeve would effectively reinforce the steel).

### 3.3 Mechanical Damage and Fatigue

Guidance documents suggest that pipe segments containing dents exceeding 7% of pipe diameter should be replaced or repaired using sleeves. Work was undertaken to investigate the benefit of applying Clock Spring in such cases. Cyclic pressure tests were conducted on 12” and 24” diameter pipes with diameter:thickness (D/t) ratios of 51, 68 and 96 (representing thick and thin walled pipe). Gouges of 15%, 30% and 50% wall thickness were introduced in addition to dents of 15% of pipe diameter. Defect lengths of 150mm (6”) and 600mm (24”) were studied. Repairs were made that looked at the affect of grinding out the gouges first and applying repairs to as-damaged pipe. The tests involved cycling from 0 to 50% maximum allowable operating pressure (MAOP) for 50,000 cycles and then to 100% MAOP until failure or cycling over 50-100% MAOP initially.

Note, the repairs were applied whilst there was no pressure in the pipe and also at 50% and 90% MAOP.

<table>
<thead>
<tr>
<th>D/t ratio</th>
<th>Gouge depths</th>
<th>Defect Lengths</th>
<th>Pressure cycles</th>
<th>Effect of dressing gouges</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>15%</td>
<td>150mm (6”)</td>
<td>0-50% MAOP for 50,000 cycles followed by 0-100% MAOP to failure</td>
<td>Undressed</td>
</tr>
<tr>
<td>68</td>
<td>30%</td>
<td>600mm (24”)</td>
<td>50-100% MAOP for 50,000 cycles followed by 0-100% MAOP to failure</td>
<td>Dressed</td>
</tr>
<tr>
<td>96</td>
<td>50%</td>
<td>600mm (24”)</td>
<td>50-100% MAOP for 50,000 cycles followed by 0-100% MAOP to failure</td>
<td>Dressed</td>
</tr>
</tbody>
</table>

The results are shown below, Figure 11.

The conclusions were that Clock Spring applied to dressed defects increased fatigue life by two orders of magnitude compared to taking no action, demonstrating the system effectively reinforced the damaged pipe.

Whilst the test programme was considered extensive, it has clearly not tested every variable, and so an element of extrapolation is required when considering repairs to mechanical damage. However, the programme is a good compromise between an achievable test programme size and a good range of results. What it does show is
that the Clock Spring repair system works well in conjunction with steel pipe to prevent fatigue damage to the steel. The range of variables tested gives an acceptable level of confidence that the repair system can be used for typical defects found in the field.

**Figure 11. Results of cyclic testing on damaged pipes**

The tests also show that the Clock Spring is effective at sharing the load with the steel pipe even at low pressures. This has been a point of particular concern as the stress-strain curve of many composites shows an initial non-linearity where some ‘shake down’ is required in the composite before it is able to effectively carry load. This has been reported in materials using a woven fabric reinforcement, where there is necessarily a level of slack due to the weave. Systems would be best tested using the 0-50% MAOP test level as a first off because of this.

### 3.4 Cathodic Protection and Corrosion Protection

Cathodic protection (CP) is applied to pipelines to reduce corrosion losses. To be effective the current must be able to reach the any exposed surface in sufficient quantity to prevent a deleterious reaction. If coatings become disbonded from the steel and electrolytes penetrate into this crevice then the pipe surface may be shielded from the CP due to the high resistance path at this point (if no aqueous electrolyte is present then no corrosion will occur anyway).

Although the Clock Spring repair system has similar moisture absorption and electrical resistivity characteristics in aqueous environments to typical corrosion-protection coatings used on pipelines there was concern that it may lead to shielding of the CP current, and so reduce the effectiveness of the corrosion protection system. Long-term laboratory tests were therefore undertaken. 2m (6’) sections of 20” diameter pipe were placed in soil boxes and monitored for up to 36 months.
Samples of the Clock Spring were separately exposed to enable changes in electrical conductivity to be monitored.

The results demonstrated that the Clock Spring repair system allows sufficient current to pass to give the required level of protection. Inspection after one year showed no visible signs of corrosion. There was no evidence that the CP had any significant affect on the integrity of the repair sleeve.

3.5 Field Trials

With the evidence cited above providing a good engineering case for the adoption of Clock Springs there was no major barrier to their implementation. However, it was considered prudent to first implement monitored repairs to confirm the results would be transferable to the real life situations. 69 repairs across 23 separate locations were installed, and checked over periods ranging from two to seven years. In-situ monitoring via strain gauges was also implemented at selected sites and performance actively followed over four years.

At certain test sites stressed, tensile specimens and lap shear specimens were buried alongside the field repairs, and residual strength measured at the end of the trial and compared with results predicted from the laboratory testing. Finally, the chemical composition was again confirmed via FTIR.

Visual inspection was completed for all repairs. Destructive testing was conducted for others and on the small test samples. In all cases performance showed the accelerated testing completed was conservative, and supported the case for the 50 year repair life. It is now about 20 years since the first of these repairs was completed, and with successful experience this further supports the confidence placed in the technology on review of the test programme.

4 Proliferation of Technology

With Clock Spring being the first composite repair sleeve to be adopted, it has been interesting to watch the market develop. All new entrants to the market have based their products on ‘wet wrap’ technology, where fibre is applied to the pipe using resin still in its liquid form. Clock Spring also supplies this technology, known as Contour, a glass fibre reinforced epoxy resin. The key advantage this approach has is that the materials can be applied to pretty much any geometry, where as the pre-cured Clock Spring is rigid, and can only be applied to straight pipes or elbows. However, the drawbacks are more significant. The material is effectively manufactured at site, on the job. It therefore is down to the installer to control the quality of application. This requires a skilled technician and has little in-built redundancy (i.e. there is much more that can go wrong, and a higher likelihood that it will do so!). Where the pre-cured Clock Spring is simple to install and the mechanical properties are well defined, the ‘wet wrap’ is neither.

On low pressure pipe this is not such a significant issue as it sounds, as a thicker repair can be applied to account for the uncertainty. Where the repair is on a high pressure oil or gas transmission line then the performance requirements are high, and this approach is not valid, but how does an operator decide what repair system he can use and what he cannot? Until recently the tests required to demonstrate suitability have been left vague. Operators have been left to rely on suppliers.
To address this there have therefore been various initiatives to prepare documents which define both the testing requirements and design methodologies for such repairs. Initial work started in the UK in 1999, and was followed the next year by work in the US (as part of an ASME committee). Both initiatives have now resulted in documents being issued, ASME PPC-2 Article 4.1 and ISO TS 24817. The documents are based on the same principles and theory, but differ in a number of minor ways. Most notably they require significantly less test and validation work than that described above which has been proven as reliable. Work is still on-going to satisfy all interested parties that the requirements are sufficient.

5 Outline of Tests as Required by ASME and ISO Documents

The limited validation test programme was conceived for a number of reasons:

1. Initial interest from the group was on repair of process pipe (e.g. built according to ASME B31.3) rather than pipelines (B31.4 and B31.8). The pressures tend to be lower and the fluids of main interest were aqueous. However, the mechanics of assessment of the two types of pipe are very similar, so the theory applies equally to both applications but the user should bear in mind that the consequences of failure can be significantly different.

2. The materials in use at the time were based on typical epoxy resin chemistry reinforced with glass or carbon fibres. The generic, mechanical performance characteristics of these classes of materials are well understood. Universal allowable design strains were proposed based on the experience with these classes of materials pipe and pressure vessel applications. This meant that no long term testing was required to satisfy the document, but was balanced by the conservative allowable specified. Measurement of standard mechanical properties (in tension) is therefore required. The documents also give methods for using allowables measured by long-term testing. Given the reduction in uncertainty associated with actual measurements the document employs a lower factor of safety – so leading to a thinner repair. The approach is to encourage testing by rewarding with more competitive designs.

Given the main applications were to process pipe the work also looked at how to design the repairs to stop leaks through holes in the pipes. A method based on measuring a fracture toughness parameter between the pipe and composite was derived. The property measured is unique to each combination of substrate type (steel, stainless steel etc.), method of surface preparation (grit blasting combined with surface roughness) and repair material. This gave rise to the concept of a 'repair system' which is used to describe a specific combination of these three elements and any filler materials. Changing one element means the fracture toughness property changes and so should be re-measured. The practicality is that results measured on carbon steel cannot be applied to stainless steel or any other pipe. All tests were short-term (based on measuring a failure pressure) and the long-term performance was assumed to match that known to govern the behaviour of glass fibre reinforced epoxy pipe (as the two were considered to have similar failure modes). Tests of medium term duration were then completed to confirm the assumption was valid.

Lap shear data to give an indication of bond strength are also required. The tests must be completed on as-made specimens and then again on specimens which have
been subject to immersion in water at 40 ºC for six weeks. The immersion test was again required to demonstrate that the performance was in line with that assumed in setting factors of safety.

Both guidance documents now require one burst test on a pipe spool with simulated corrosion damage to demonstrate restoration of the burst strength of a pristine pipe. This gives limited information on the ability of the system to repair such damage and the concept of the test was more to demonstrate the mechanical properties of the repair system (as noted in the preface to the test in the documents) rather than prove the systems are suitable for repairing pipelines.

In summary, the guidance documents propose a limited test programme, but one which is being increasingly used for the qualification of repair systems. The underlying theory is based on known performance of traditional thermoset resin systems (such as polyesters, vinyl ester and epoxies) and the initial experience has been that the guidance is very reliable. The design allowables are conservative, which is considered appropriate given the limited nature of the test programme.

The main area of weakness of the testing (and of design guidance) is how the repair systems work on pipelines. The specific topics of relevance are:

1. Repair of mechanical damage. This topic is under discussion by the two committees at the time of writing. The validation testing at present does not consider how the steel pipe, filler and composite work together to reinforce the steel over time. This will require a range of tests looking at different defect depths in the pipes and different thicknesses of repair. The ability of the filler to support the steel and so prevent it failing by fatigue will be considered. Clearly the information already measured on the Clock Spring products demonstrates the suitability of this specific product, but it cannot be extrapolated to other systems.
2. Long term durability. This should be measured for the repair of pipelines.
3. Cathodic protection. The relevant ASTM standard is referenced for investigating this in the documents and should be completed.

6 Typical Repair Thickneses

One of the main problems with the use of composite repairs is that end-users are generally unfamiliar with the polymeric materials, and have no real idea about how thick a sensible repair should be. A few examples are therefore outlined below to give the reader an idea of the typical repair thickness that should be expected.

The calculation methods in the guidance documents require use of a spreadsheet or similar tool. There is nothing a graduate-qualified engineer should not cope with, but the some of the equations are not intuitive and have to be solved by iteration rather than direct calculation. It is because of this that it is considered helpful to present a few examples below.

6.1 Common Sense Check

The first point is to give a ball park feel for what thickness of repair should be required. The design guides both specify allowable properties in terms of strain. The allowable stress is determined by multiplying this given allowable by the measured stiffness. A typical stiffness for a multi-axis glass fibre reinforced material would be in
the order of 10 to 20GPa (this has fibres aligned in more than one axis, such as the system used in the Clock Spring Contour product). A unidirectional material (such as the Clock Spring) will have a higher stiffness in the hoop direction of the pipe, but lower in the axial direction. The actual allowable strain is dependent on temperature of service vs. the measured temperature limits of the resin, the life-time of the repair and any thermal strains that need to be accounted for. Values in the range of 0.15% to 0.25% would be reasonable for a 20 year design life. The table below shows the relevant allowable stresses, and also the thickness of repair required to strengthen a pipe showing 50% wall loss due to corrosion. The calculations are based on a 20” diameter line at 120 barg pressure.

Table 1. Allowable stresses in pipeline and typical repair materials. Thickness of repair on a 20” diameter steel pipe at 120 barg with 50% wall loss.

<table>
<thead>
<tr>
<th>Basis of allowable</th>
<th>Typical Pipeline Steel</th>
<th>Clock Spring</th>
<th>Repair in accordance with ISO TS 24817</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Stress</td>
<td>ASME B31</td>
<td>Long Term Testing</td>
<td>Default value based on allowable strain</td>
</tr>
<tr>
<td>Original wall thickness</td>
<td>172MPa</td>
<td>138MPa</td>
<td>36MPa</td>
</tr>
<tr>
<td>Repair thickness for 50% wall loss</td>
<td>10.3mm</td>
<td>9mm*</td>
<td>35mm</td>
</tr>
</tbody>
</table>

The effect of the higher factor of safety built into the documents for products not backed by long-term testing is immediately apparent in the greater repair thickness required. This demonstrates the encouragement to complete long-term testing, and also highlights that the documents give a practical barrier to repair of large diameter lines operating at high pressures if that testing has not been completed. For a repair to a tee connection operating at 20 bar a different story unfolds.

Table 2. Allowable stresses in tee and typical repair materials. Thickness of repair to ¾” branch at 20 barg showing full wall loss.

<table>
<thead>
<tr>
<th>Basis of allowable</th>
<th>Typical Pipeline Steel</th>
<th>Clock Spring</th>
<th>Repair in accordance with ISO TS 24817</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allowable Stress</td>
<td>ASME B31</td>
<td>Long Term Testing</td>
<td>Default value based on allowable strain</td>
</tr>
<tr>
<td>Original wall thickness</td>
<td>138MPa</td>
<td>138MPa</td>
<td>36MPa</td>
</tr>
<tr>
<td>Repair thickness for 100% wall loss</td>
<td>3.7mm</td>
<td>1.3mm</td>
<td>5mm</td>
</tr>
</tbody>
</table>

In this case the repair thickness based on the generic repair is very feasible. The repair was undertaken using the Clock Spring Contour System, and is shown below.

* Clock Spring units are supplied in standard thicknesses of 12.5mm (½”) and so the calculation demonstrates the standard unit is acceptable. Experience has demonstrated that this standard thickness is suitable for almost all repair scenarios encountered. Whilst good practice would still expect a design justification for all repairs, it is a fair assumption that Clock Spring will be a suitable repair option if the relevant construction code allows repair of that particular defect.
The pre-cured Clock Spring system could not be used because it cannot be applied to this kind of geometry.

**Figure 12. Tee subject to extensive wall thinning, before and after repair**

### 7 Summary

This paper has outlined the testing completed to validate the Clock Spring composite pipeline repair sleeve. The testing has been proven to be satisfactory after over 15 years of successful service. Recent guidance documents requiring significantly less testing are shown to be based on reasonable assumptions, but necessarily include large factors of safety to off-set the fact that only short term testing is required. This limits their useful range of application to lower pressure or smaller diameter pipe unless the long-term testing is completed. The guidance documents have yet to consider typical pipeline damage, but this is a topic under consideration currently.

The guidance documents make reference to long term testing and addressing of specific pipeline issues (such as cathodic protection), but the user will need to satisfy themselves that these tests have indeed been completed. The existence of the guidance is helpful, but the value is in their application and compliance to their requirements.

### 8 References

4. ISO TS 24817 ‘Composite Repairs for pipework – qualification, design, installation, testing and inspection’ Dec 2006.
5. Add reference to ISO prEN 13121, ‘GRP tanks and vessels for use above ground’.