More than a pipe dream

Dr Jonathan Wilkins, Enoflex Ltd, UK, details the development journey for a non-metallic, cryogenic pipe technology for use in regasification terminals.

LNG is a key fuel for the energy transition and a cleaner burning alternative to oil or coal, with a lower carbon footprint. Applications to serve end-consumers continue to grow, particularly in small scale and micro scale LNG. New projects need cost-effective, rapid construction. The operator that can promise the fast, keenly priced delivery of a new facility will be in a strong place to win these opportunities.

Pipes capable of cryogenic service are an important piece of the LNG infrastructure. For instance, in a typical terminal, the pipes may run 1 km or more from the tank farm to the end of a jetty, particularly in locations with shallow water. To date, metallic pipes have been the industry norm, using cryogenic service alloys such as Stainless Steel 316. Such materials are heavy and require specialist skills for on-site welding and inspection. These activities can be costly and add to the installation management headache since expert teams need to be mobilised. Corrugated-metal hoses are well established for LNG bunkering but are best suited to shorter lengths, otherwise the corrugations can cause excessive pressure and fluid agitation that generates boil-off gas.

To solve these challenges, Enoflex has industrialised an alternative smooth-bore pipe solution using non-metallic, thermoplastic-composite materials. There are parallels with the oil and gas industry that for some years has used reeled, smooth-bore non-metallic pipes to enable rapid deployments for both on-land and subsea projects. Such oil and gas pipes are based on thermoplastic polymers and are often reinforced with carbon or glass fibres for added strength and stiffness. However, most polymeric materials become brittle at cryogenic temperatures encountered in LNG applications. To solve this fundamental issue, Shell identified and patented single-polymer-composite (SPC) materials as a good candidate that balances strength and toughness at -165˚C. Shell and Enoflex have collaborated in a joint development programme to develop, qualify, and industrialise SPC pipes into a commercial solution for LNG transfer.

The challenge

When starting the development of a new technology, it is important to define the design or economic problems that are not solved by existing products. Based on conversations with LNG operators and EPCI architects, Enoflex identified the following industry needs and mapped them to the desired pipe requirements:

1. Cost-effectiveness: Enabled by a simple product architecture and manufacturing process that minimises component-count and uses commonly available raw materials. For simplicity, it is preferable to integrate the fluid duct and the structural 'armour'.
2. Rapid installation: Enabled by 'haul off' of a continuous length of pipe from a reel and into a trench or conduit. It requires the product to have sufficient axial strength, balanced with sufficient bending flexibility.
3. Minimal generation of boil-off-gas (BOG): Enabled by a smoothbore product that reduces generation of turbulence within the fluid. It requires the product to minimise flow disturbances, such as corrugations within the fluid path.
4. Reduced on-site fabrication effort and cost: Enabled by transportation of a completed pipe reel from factory to project site, either by road transport for smaller pipes or by ship for larger diameters. It requires the product to take bending strains of the order several percent.
5. Low environmental impact: Enabled by a light-weight product that reduces energy consumption during manufacture and transportation whilst being easily recyclable at the end of life. It requires the product to be made from a single material that does not need costly separation into constituent components at the end of life.

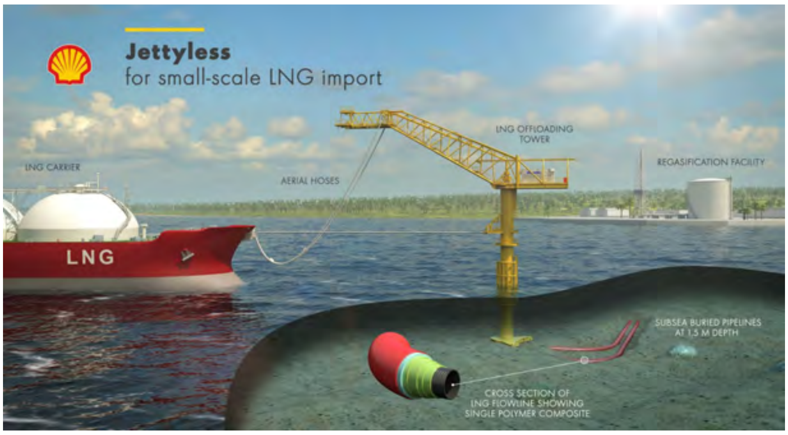

Figure 1. Jetty-less terminal concept showing the subsea pipe. Source: Shell Global Solutions.

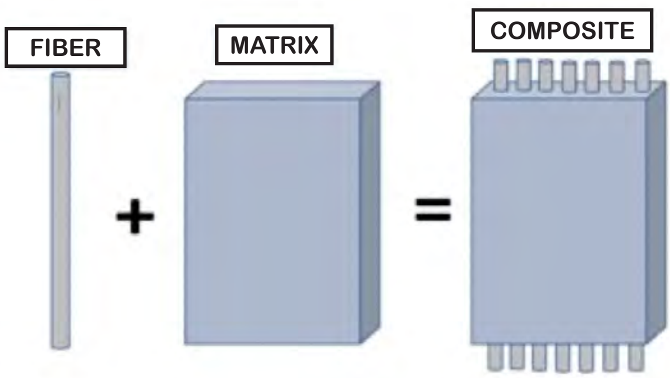

Figure 2. The fundamental building blocks of a composite material: strong fibres embedded in a supporting matrix.

Requirements 1 and 2 are aligned with an industry drive to simplify LNG terminals, for example, by moving to designs which are jetty-less, whereby subsea pipes are used to connect the vessel back to the shore, or by using floating LNG transfer infrastructure. An illustration of a jetty-less concept is shown in Figure 1, courtesy of Shell. Project construction timescales and maintenance costs can be reduced by eliminating the jetty and LNG carriers can remain in deep water without the need for regular dredging or extensive breakwaters.

Selecting the right material for the job

In any reeled pipe design, there is a trade-off between the need for bending flexibility whilst maintaining pressure resistance against the internal fluid. The pressures encountered in LNG pipes are high enough, around 20 bar, that an unreinforced plastic extrusion is unlikely to be suitable. Some form of additional reinforcement will be needed. Use of a composite material allows the designer to achieve this within a single, fully bonded component without needing to separate the product into a discrete fluid conduit and a discrete structural armour. This monolithic structure benefits the requirements 1 (cost-effectiveness) and 3 (minimal BOG).

A typical composite material consists of strong and stiff fibres dispersed in a polymer matrix that holds the fibres in place (Figure 2).

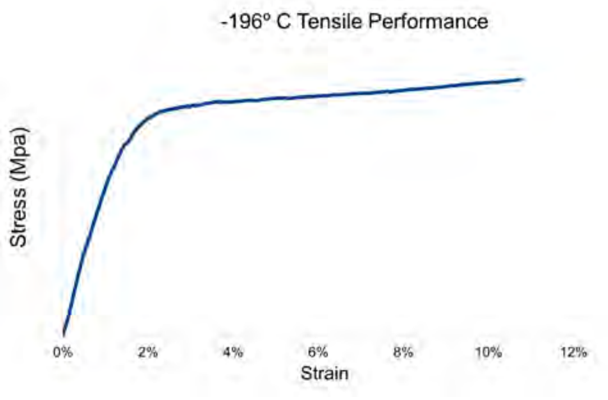

Figure 3. Typical cryogenic stress-strain performance of an SPC material showing a 'ductile tail' to the data.

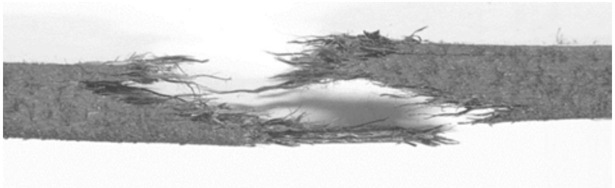

Figure 4. Corresponding cryogenic failure of an SPC material showing plenty of broken fibres, indicative of a tough, energy-absorbing failure.

Figure 5. An Enoflex laser-welding station contained within a light-proof box. Roller-tracks feed the pipe into the welding station for example from reeling carousels.

Figure 6. A view along the bore of an SPC pipe.

An analogy from the construction industry is steel re-bar inside reinforced concrete. The composite will be an order of magnitude stronger along the fibres, but more compliant in the transverse direction. Composite products, including pipes and pressure vessels, are typically built in an additive manner from individual plies of material. For example, glass-fibre or carbon-fibre reinforced composite pipes have become established in the onshore and offshore oil and gas industry. The designer can adjust the fibre angles in each ply to achieve the desired overall product behaviour. Fibres that are orientated around the pipe circumference will provide pressure resistance. A proportion of other fibres placed close to the pipe axis will provide the balance between axial strength and the bending flexibility needed for requirements 2 and 4 (haul-off and reeled transport).

It is the cryogenic toughness and ductility that differentiates an SPC material from more widely known glass or carbon-fibre composites known in the aerospace, wind, or oil and gas industries. An SPC has fibres and matrix derived from the same thermoplastic material.[1] The fibres are drawn and elongated during production to achieve a high level of molecular orientation. This gives a strength that is many times higher than the bulk, unoriented material. Relatively low-cost polyolefin thermoplastics are well suited to this drawing process and strengths in the fibres of around 400 MPa are possible. Since the fibres and matrix polymers are similar, a good microscopic bond exists between the two. This makes an SPC particularly tough when compared to carbon-fibre/epoxy matrix composites found in other industries, for instance. In addition, an SPC product can be disposed of through common thermoplastic recycling routes which meets requirement 5 (low environmental impact). There is no need to separate the fibres and matrix from each other, which is a typical problem for other composites. The toughness and recyclability benefits were the original motivation behind the adoption of SPC by the automotive industry several decades ago.

Carbon-fibres are extremely strong; around 1000 MPa or more. Whilst such strengths are necessary in high-temperature, high-pressure deepwater oil and gas pipes, they are less relevant to LNG applications. Rather, it is the cryogenic performance that is more important. SPCs remain ductile at the temperatures encountered in LNG applications, for instance as observed by Atli-Veltin.[2] There are several reasons: the comparable coefficients of thermal contraction between chemically similar fibre and matrix, and the strong bonds between the two. Both effects reduce problems with micro-cracking at low temperatures. The molecular orientation within the SPC fibres provides ductility and movement within the material, even at cryogenic conditions. At such temperatures an extruded, unoriented polymer would be well below its glass transition temperature: the point at which the molecules in a polymer appear frozen, brittle and unsuited for structural applications.

The SPC ductility is illustrated in the stress-strain graph in Figure 3, which shows a test to destruction of an SPC material-coupon at around -190˚C, well below the temperature of LNG. Strains of above 10% are achieved and Figure 4 shows a tough, energy-absorbing failure-mode with plenty of broken fibres. By contrast, a bulk thermoplastic found in a typical extrusion would have failed at just 1 or 2%, in a brittle 'glassy' manner.

Building the finished product

Thermoplastic-based composite products can be manufactured without the need for traditional autoclaves, and SPCs are no exception. An SPC pipe can be manufactured in an additive fashion with each ply, or layer, being fused onto its predecessor. Thus, the body of the pipe grows in layers, akin to an onion skin. Enoflex uses an automated laser-welding process with accurate temperature control. This method was originally developed in the aerospace industry.[3] The thermoplastic skin of each ply of SPC is rapidly heated and melted onto its predecessor substrate. Then the two surfaces solidify together once the heat is removed. The residence time of a piece of SPC material within the welding zone is in the order of a few hundred milliseconds. This fast processing speed, SPC tape customisation, and the accurate temperature control from the laser prevents thermal damage to the SPC fibres. No permanent tooling is required, and so the length and diameter of each pipe can be adjusted for each project. Since an SPC pipe exhibits flexibility, it can be stored and hydro-tested on a reel. As shown in Figure 5, the laser-welding process is clean and requires considerably less energy or water compared to a steel mill.

For LNG applications it is important to avoid an extruded thermoplastic liner to act as a precursor 'mandrel' for the first layer of tape. An extruded liner would become brittle at cryogenic temperatures and be the 'weakest link in the chain'. Instead, the Enoflex pipe is made completely from SPC material. The welds between layers form a fluid-tight barrier. Figure 6 shows a view along the bore of an SPC pipe.

The only metallic components are in the two connectors at either end of the long length of SPC pipe body. These connectors form the interface to the rest of the LNG pipe system, for instance valves or manifolds. The end connectors are fitted to the pipe body within the factory, and can be designed to bolt or weld to the external system in whatever metallurgy choice the customer prefers.

Serving the energy transition

In addition to LNG, other liquified gases are becoming increasingly important to the energy transition: liquified carbon dioxide for non-pipeline transport via ship, the nascent liquid-hydrogen industry, and liquid-nitrogen coolant for superconducting electrification cables. Cost-effective infrastructure is vital to speed the adoption of these new energy vectors.

With such an exciting prospect of new applications and projects, now is the time for the energy industry to consider novel pipe designs. Traditional approaches may not offer the best solution to new requirements. SPC pipes are an important new technology that builds on know-how from the aerospace and oil and gas industries, but with a tailor-made balance of strength and toughness for cryogenic applications. SPC offers a step change reduction for both CAPEX and maintenance costs, and harnesses light weight and low environmental impact as key advantages relative to current stainless steel pipe technology. **LNG**

References

1. SANTOS, et al., 'Commercial self-reinforced composites: A comparative study', *Composites Part B*, Vol. 223, (2021).
2. ATLI-VELTIN, B., 'Cryogenic performance of single polymer polypropylene composites', *Cryogenics Journal*, Vol. 90, (2018).
3. 'Welding thermoplastic composites', *CompositesWorld*, (2018).