Epoxy foam: a promising cellular material

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Project background

Composite materials are gaining more popularity in the Oil & Gas industry, thanks to their outstanding properties such as high specific stiffness, fatigue strength and corrosion resistance, in particular. Polymer foams, instead, are known to be lightweight and having a low thermal conductivity. They are not usually employed in structural applications, due to their poor mechanical performance. An exception are ***sandwich cores***, which can be manufactured using foams, adding significant bending stiffness to the structure without affecting the overall weight. At present, commodity plastic foams, such as polyurethane or polypropylene, are used as liners in commercial Oil & Gas pipelines to increase the thermal insulation.

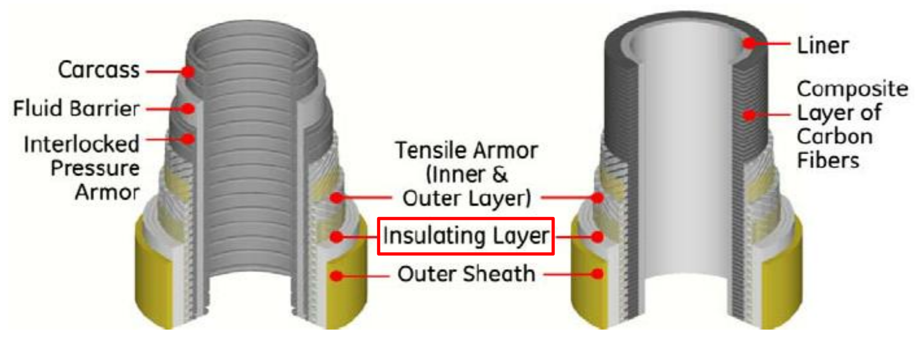


Figure 1: different hybrid designs for flexible pipelines. Source: T. A. Anderson, M. E. Vermilyea, V. Jha, N. Dodds, D. Finch, J. R. Latto, and G. E. Oil, "Qualification of Flexible Fiber-Reinforced Pipe for 10 , 000-Foot Water Depths," *Offshore Technol. Conf.*, pp. 1–9, 2013.

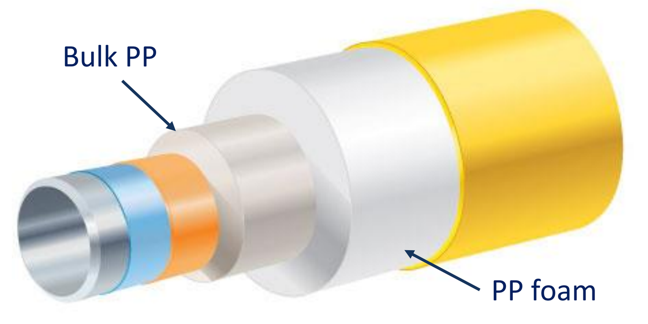


Figure 2: Multilayer PP foam applied to a commercial pipeline. Source: Bredero Shaw

In our study, we characterised the mechanical and thermal properties of an epoxy foam, synthesized from a commercial epoxy resin with the addition of a ***Chemical Foaming Agent***. The foam can add buoyancy and thermal insulation to a new generation of composite pipelines, thanks to its reduced density. Epoxies are interesting to this aim because they have good chemical stability and excellent adhesion capability.

Objectives

1. To synthesize an epoxy thermoset with controlled porosity by the addition of a Chemical Foaming Agent before curing;
2. To characterize the properties of such material: mechanical, thermal and joining strength to a GFRP substrate;
3. To apply the foam to a GFRP substrate, in order to manufacture a sandwich geometry, and evaluate the mechanical performance in flexure.

Foam preparation

Following a methodology proposed by Stefani *et al.*, the Ampreg 26 (Gurit, UK) epoxy resin undergoes a foaming reaction during the curing stage. The *Chemical Foaming Agent* is a disiloxane, which reacts with the amine curing agent, releasing gaseous H_2. The foaming reaction is positively promoted during the resin post-cure at 80 °C. A direct correlation was found between the amount of CFA added to the formulation and the final apparent density obtained.

Foaming & curing

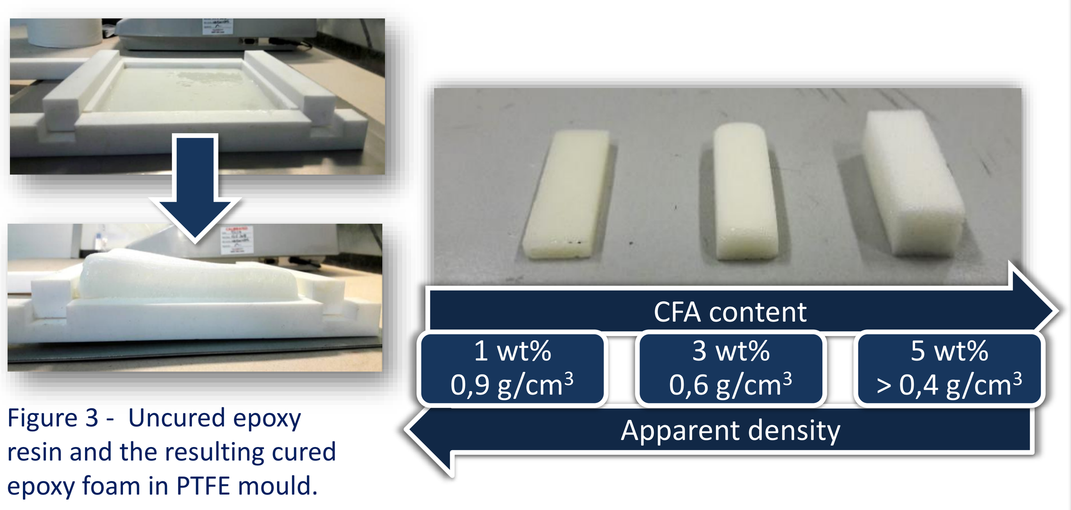


Figure 3 - Uncured epoxy resin and the resulting cured epoxy foam in PTFE mould.

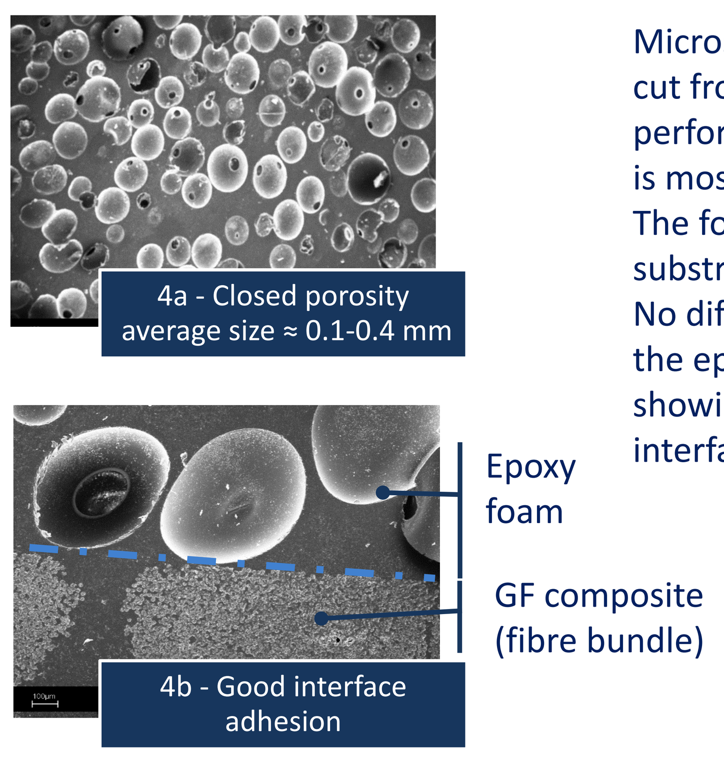
Analytical tests

To evaluate the effect of the foaming process, samples from the different formulations of epoxy foam were tested:

a) by DMA: to evaluate the possible change in Glass Transition Temperature (T_g) due to the addition of the CFA;
b) by TGA: to evaluate the thermal degradation (T(5 wt% loss)) and the char residual.

CFA content [wt%]	Tg - tanδ [°C]	T(5 wt% loss) [°C]	Char Content [wt%]
0	98± 1	300	7
1	97± 2	300	8
3	96± 3	298	9
5	97± 3	296	11

SEM micrography



Microscopy imaging of sections cut from the foam samples was performed. The resulting porosity is mostly closed.
The foam is applied on a GFRP substrate by curing directly on it. No difference or interphase in the epoxy matrix is present, showing a qualitatively good interfacial adhesion.

Figure 4a, 4b – SEM images of the epoxy foam (4a) and the interface with the GFRP as a substrate (4b).

Thermal conductivity

Measurements were performed using a Fox50 Heat Flow Meter (TA, USA). A relation between the thermal conductivity and the apparent density was confirmed (Ashby M.F, 2006), following the semi-empirical equation:

$$\lambda_{foam} = \frac{1}{3}\left(\rho_r + 2\rho_r^{3/2}\right)\lambda_{epoxy} + (1-\rho_r)\lambda_{air}$$

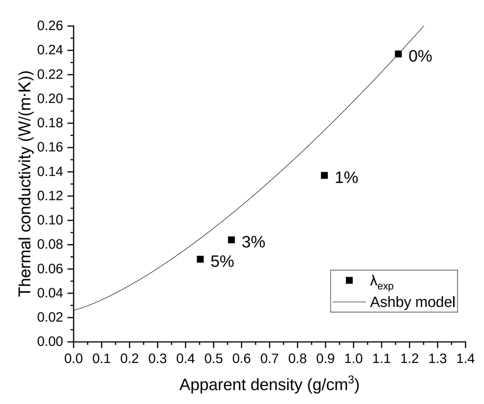
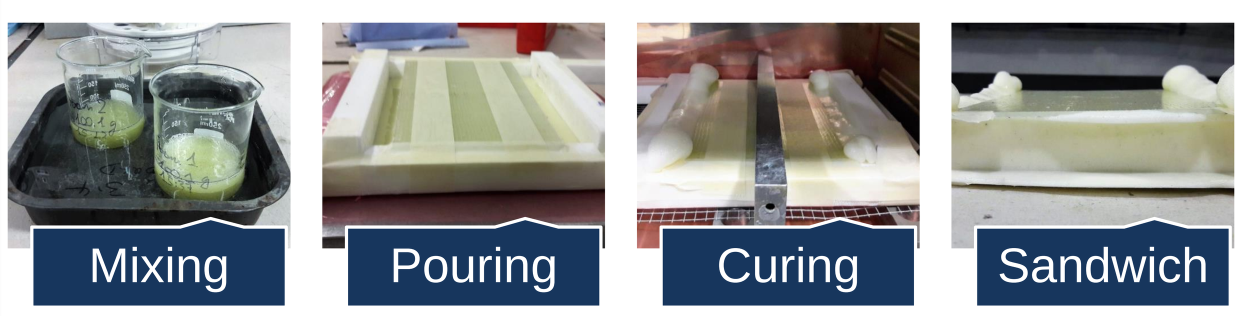


Figure 5 - Thermal conductivity in function of the apparent density.

The values found are comparable with the conductivity of common thermoplastic foams. The conductivity was also found to be steady at different temperatures, up to 70 °C. Above this temperature the glass transition is approached: the activated viscous flow causes the pores to collapse, increasing the conductivity.

Sandwich preparation

Once gained good control on the foaming process, the epoxy foam was used as core to join GFRP skins and produce a composite sandwich. The evaluation of the gel-time is critical in order to reproduce material with the same quality.



Mechanical performance

The mechanical properties of the foam with added 5 wt% of CFA were tested by unidirectional compression and 3-point bending. The properties were compared to the non-foamed bulk epoxy thermoset. Clearly the bulk thermoset has better absolute mechanical properties by far. This can be revaluated if analysing the structural performance indexes normalised for the apparent density of the material (for reference, see Ashby M.F.). In this light, the performances of the foam become competitive, in particular when the loading mode is flexural.

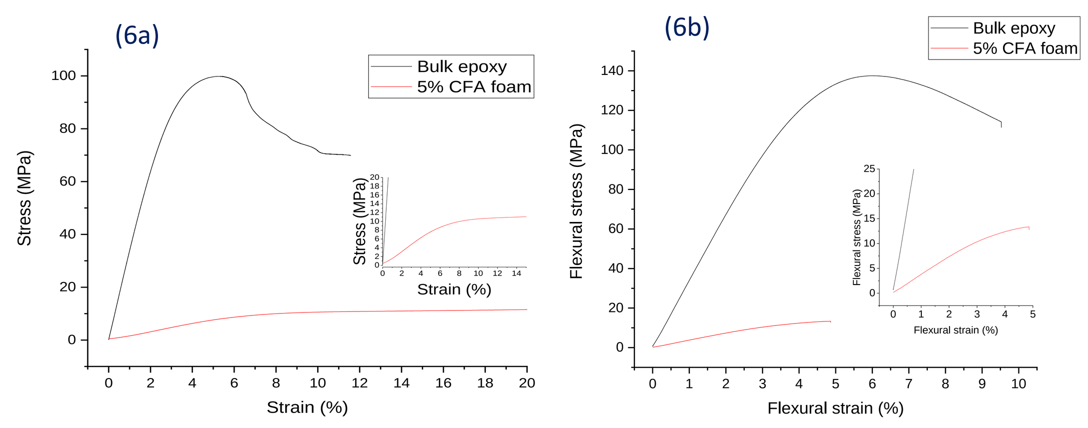


Figure 6a, b - Stress-strain curves for bulk epoxy and foam samples from the unidirectional compression (a) and 3-point bending tests (b).

Material	ρ [kg/m³]	Comp E [MPa]	Comp E/ρ [MPa·m³/kg]	Comp σ [MPa]	Comp σ/ρ [kPa·m³/kg]
Bulk epoxy	1150 ± 10	3330 ± 84	2.895	100.5 ± 1.1	87.4
5% CFA foam	400 ± 20	155 ± 3	0.386	10.4 ± 0.2	26.0

Material	ρ [kg/cm³]	Flex E [MPa]	Flex E/ρ [MPa·m³/kg]	Flex $E^{1/2}/\rho$ (beam)	Flex $E^{1/3}/\rho$ (plate)
Bulk epoxy	1150 ± 10	3404 ± 55	2.948	1.561	1.283
5% CFA foam	400 ± 20	378 ± 7	0.941	1.529	1.799

Material	ρ [kg/cm³]	Flex σ [MPa]	Flex σ/ρ [kPa·m³/kg]	Flex $\sigma^{2/3}/\rho$ (beam)	Flex $\sigma^{1/2}/\rho$ (plate)
Bulk epoxy	1150 ± 10	132.3 ± 1.1	114.6	22.49	9.96
5% CFA foam	400 ± 20	12.6 ± 0.6	31.3	13.46	8.82

To evaluate the mechanical properties of the epoxy foam sandwich, the 3-point bending test was used again. The results show a dependence of the mechanical strength and the type of failure on the morphology of the foam. Even a relatively slight change in the porosity distribution can result in transition from a brittle to a pseudo-ductile fracture of the material.
When the porosity is optimal, up to 2/3 of the flexural strength can be retained by the material after the failure of the composite skin, increasing notably the crashworthiness of the sandwich geometry.

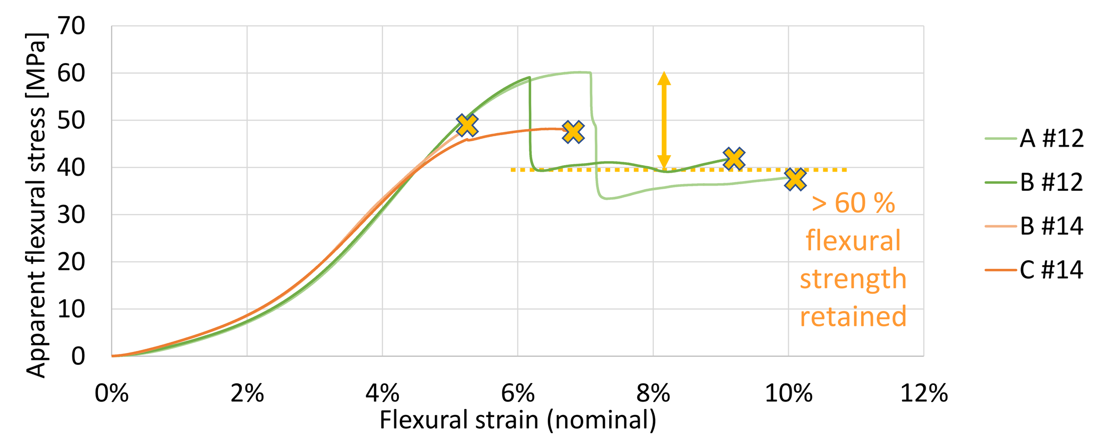


Figure 7 – 3-point bending runs on epoxy sandwich specimens obtained from different batches.`

Conclusions

A chemical foaming method has been proven successful to obtain a foam with controlled porosity from a commercial grade epoxy resin. The foaming process is influenced by many operative conditions (temperature and uncured resin viscosity, in first) and needs to be carefully controlled to produce a consistent quality product.

The material showed a range of properties that have the potential to be tailored in function of the end application. The foam has good flexibility and specific strength. The thermal conductivity is close or even lower compared to commercial insulating polymers. If manufactured to the geometry of composite sandwich, it can offer superior mechanical performance, particularly interesting for applications which need high specific flexural stiffness.

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Acknowledgements

The authors gratefully acknowledge that the research leading to these results has received funding from the European Union's Horizon 2020 Research and Innovation programme under the Marie Sklodowska-Curie Action ITN grant agreement No 642557 – CoACH ETN.
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3rd-4th October 2018
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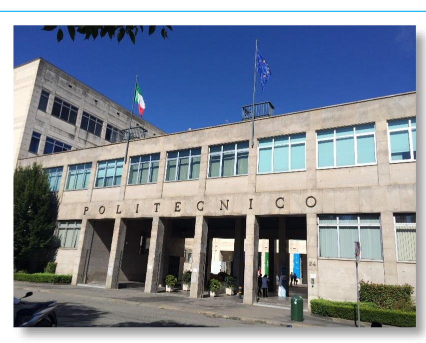

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