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COMPRESSer - DEVELOPMENT OF ECO-FRIENDLIER AND SAFER COMPOSITE PRESSURE TANKS

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ABSTRACT

The COMPRESSer project has the main aim of defining a knowledge cluster in the SUDOE region, involving a total of 3 countries: Spain, Portugal, and France. This cluster, made up by universities and other companies, will develop innovative, composite overwrapped pressure vessels by means of cutting edge experimental and numerical methods and advanced processes, supporting the future industry and commercialization of these new range of products. COMPRESSer aims to improve them with the incorporation and integration of several other advanced features such as fracture toughness, electrical conductivity or even self-structural health monitoring. On this basis, we plan to cover the entire value-chain, from design and simulation to manufacturing and experimental validation testing. These products will gradually replace traditional solutions, mostly based on metallic materials, in several application domains such as fire extinguishers or gas containers (industrial gases, oxygen) among others. This project positions as a kick-starter for future industrialization of these type of products in the SUDOE region.

Keywords: composite materials, reliability-based methods, composite overwrapped pressure vessels, finite element method, digital image correlation.

INTRODUCTION

Composite use is ever-present nowadays. However in Southwest Europe (SUDOE region – Portugal, Spain, Andorra, Gibraltar and Southwest France), most of the composite material industry is focused on the Automotive and Aerospace industry (Delogu et al. 2017). With the purpose of generating new knowledge in the SUDOE region, a cluster of Spanish, French and Portuguese companies and universities with appropriate knowledge have formed a consortium. This consortium has the aim of developing new products in the pressure storage industry, mainly in the fire extinguisher field. These products, which traditionally have been manufactured in steel and aluminium, will be replaced by a new composite solution made up of glass/carbon fiber reinforced polymers (GFRP/CFRP). The introduction of this new material will improve the performance of these liquid and gas storing elements, improving their corrosion performance or even their relative stiffness-weight (Rafiee 2016).

Each partner will contribute their expertise. On one hand, the industrial partner's input is high due to the importance of the manufacturing process and the capitalization of the results. On the other hand, the knowledge agents (mainly universities) will keep developing more environmentally-friendly COPVS, based on thermoplastic enhanced properties matrices and liners by the use of nanocomposites, and advanced manufacturing processes such as filament winding (FW) (Rosato and Grove 1964).

The main challenges of this project are the design complexity, the high price of composites and the improvement of mechanical and electrical performance. A new reliability-based method has been developed looking for a more accurate solution, estimating the failure probability through the Monte Carlo simulation method (*Tomar et al.*, 2018). For inputs to this model it has been necessary to implement innovative non-contact techniques of measurement, such as digital image correlation (DIC) (Sutton, Or Teu, and Schreier 2009), to determine the Probabilistic Distribution Functions (PDF) of the inputs. This technique provides us with more information on the composite solutions adopted than direct measurement methods such as linear variable differential transformers (LVDTs), laser transducers, extensometers or even electrical resistance strain gauges (Orell *et al.*, 2018; Sharifi *et al.*, 2018; Tekieli *et al.*, 2017). Due to the high computational cost of this simulation plan, a metamodel strategy has been adopted: the Polynomial Chaos Expansion Method (Novak and Novak 2018).

To develop the final product, more competitive, novel features have been implemented as an embedded sensor, in order to monitor the product performance in service. Finally, the improved performance was achieved thanks to the use of nanomaterial technology.

THE COMPRESSer PROJECT

Focus and objectives

COMPRESSer (lightER, eco-friendliER and safER COMPosite PRESSure tanks) is co-financed by the Sudoe Interreg Program through the European Regional Development Fund (ERDF). Funding of 474.189,00 € has been allocated to finance this three-year project, which started in February 2018 and expects to be concluded in March 2021. This project aims to enhance the capabilities of a knowledge cluster within the SUDOE region. The main output of this project is an innovative pressure vessel manufactured with composite materials able to store liquids and pressurized gases. Furthermore, the new pressure vessels will allow us to provide an innovative solution regarding the most advanced technologies on the market so that, the final product will gradually replace conventional products with economical and ecological advantages.

Accordingly, the main aim of the project is to develop a methodology to manufacture and validate the new composite overwrapped pressure vessels (COPVs) that allow us to obtain reliability-based designs and at the same time products cheaper than conventional pressure vessels. In order to deal with this main objective it is necessary to perform different research activities focused on evaluating fibers, resins, and additives, as well as developing new evaluation methods able to capture the stochastic nature of the composite material.

COMPRESSer covers the entire value-chain of these products, from design and simulation to manufacturing and experimental validation testing. The use of composite materials allows a substantial improvement in aspects such as corrosion, electrical conductivity or weight reduction (Rafiee 2016). However, the remarkable heterogeneous and directional behaviour of these new materials compared with conventional ones (Reddy 2003), means it is necessary to establish analysis techniques that allow us to predict and evaluate this behaviour.

The Consortium

The project consortium is made up of 5 beneficiary partners and 5 associates, distributed among three SUDOE countries: Spain, Portugal and France. Each partner will contribute expertise and knowledge in its corresponding field and the collaboration between all of them will be fundamental to advance the whole process of the project (Table 1).

Table 1 - Main task of the COMPRESSer partners

UNIVERSITIES			**COMPANIES**	
Bourdeaux INP	Aveiro	Salamanca	Plásticos Durex	New FireIce
➢ **NanoComposites** ➢ **Epoxy Formulations** ➢ **Tailored Properties** ➢ **Characterization**	➢ Filament Winding ➢ Process Kinematics ➢ Part Co-Design	➢ Structural Modelling; ➢ CAD + FEM; ➢ Mechanical Testing; ➢ Part Design	➢ Blow Moulding ➢ Tailored Thermoplastics	➢ Market Survey; ➢ Metallic liner ➢ Industrial Uptake

Plásticos Durex and New FireIce are the industrial partners, they will be focused on the manufacturing process, including the capitalization of the final output: a new COPV for the SUDOE space. On the other hand, universities will be focused on developing the COPV by means of extensive experimental and numerical campaigns. To this end, a total of three universities are involved: i) the University of Salamanca (Spain) as project leader; ii) the University of Aveiro (Portugal) and; iii) the University of Bordeaux INP (France). These partners will develop extensive campaigns with the aim of evaluating different types of fibres, resins and additives (mainly nanocomposites) as well as new manufacturing processes based on filament winding technology (Rosato and Grove 1964).

University of Salamanca, specifically, the Department of Mechanic Engineering is responsible for the design of industrial prototypes, simulations and numerical validation (Figure 1a). Also the TIDOP research group, at the Department of Cartographic and Land Engineering, is responsible for photogrammetric techniques (Figure 1b). Finally, the Department of Mechanics of Continuous Media and Structures Theory has the role of carrying out the testing of materials. These three departments have extensive experience in experimental testing and advanced numerical simulations (Garcia-Martin *et al.*, 2019; Garcia-Martin *et al.*, 2020; Sánchez-Aparicio *et al.*, 2015; Sánchez-Aparicio *et al.*, 2016).

a) b)

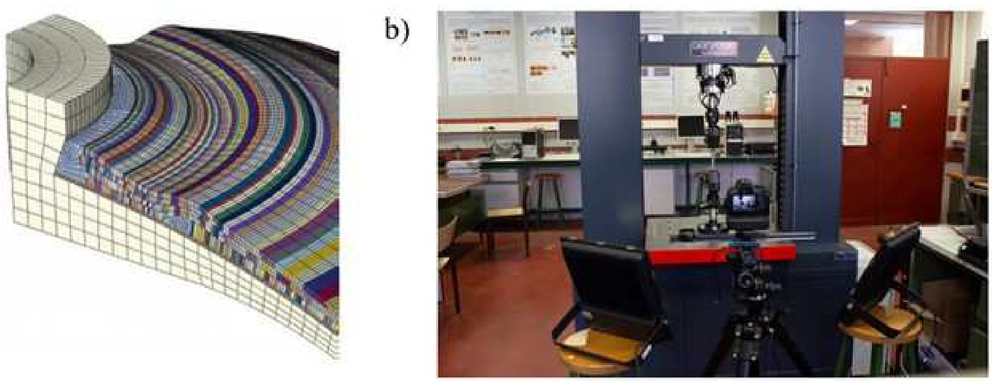

Fig. 1 - Experimental and numerical tests carried out by the University of Salamanca: a) a numerical analysis by means of the Finite Element Method; b) a digital image correlation set-up

University of Aveiro carries out the processes of manufacturing the physical specimens. Additionally, they will support the simulation of the composite manufacturing process. University of Aveiro counts on technology and infrastructures which are suitable for the prototype manufacturing process. Among its equipment is a machine dedicated to the filament winding process, which will be used to manufacture the prototypes (Figure 2). Also, the researchers involved in the project have experience in composite characterization and manufacturing (Guedes, Sá, and Faria 2007; Faria and Guedes 2010).

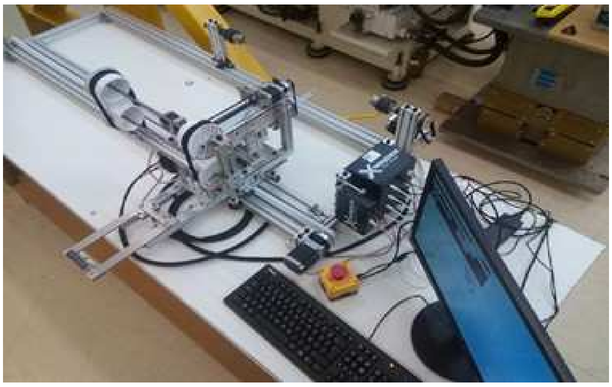

Fig. 2 - Filament Winding Equipment used by the University of Aveiro

Bordeaux INP includes 7 engineering public schools and 10 research laboratories focusing on the composite sector. This tech-centre specializes in polymers and has the aim of controlling the surface and interface of the composite solutions, developing nanocomposites and epoxy formulations (Bajpai *et al.*, 2020; Bajpai and Carlotti, 2019).

Plásticos Durex is a leading company in polymer manufacturing of thermoplastic elastomeric materials. This knowledge will form part of COMPRESSer by manufacturing the liner and providing their infrastructures for testing these materials.

New FireIce S.L.U. has 25 years of experience in the manufacturing of fire extinguishing systems, especially in metallic pressure vessels for manufacturing fire extinguishers. This experience is the principal value of the company for the project because New FireIce will contribute information about standardization, market knowledge, verification and testing. Also, the company will manufacture metallic liners and specific equipment for material improvement (Figure 3).

a) b)

Fig. 3 - New FireIce Company: (a) metallic liner manufactured; (b) image of the tube spinning facilities

The associate partners have the main aim of supporting and bringing their specific knowledge to the rest of the consortium when it is necessary. The group is made up of 5 different members: (i) Cualtis Formacion S.L. (Spain) prevention equipment expert; (ii) Hoya de la Vega S.L. (Spain) pressure equipment maintenance company; (iii) Pôle de compétitivité EMC2 (France) is an industrial cluster dedicated to advanced manufacturing technologies; (iv) Composite Solutions LDA (Portugal) supports the filament winding process and; (v) the University of Santiago de Compostela (Spain) through the Applied Financial Assessment research group, is responsible for the financial aspects related to the products of the project.

THE METHODOLOGY

The three-year COMPRESSer Project is divided into six work packages (WP) which cover the entire value-chain for the product (Figure 4). Each WP will be led by one of the main partners, but in most cases the collaboration of the other partners will be necessary for the development of the activities.

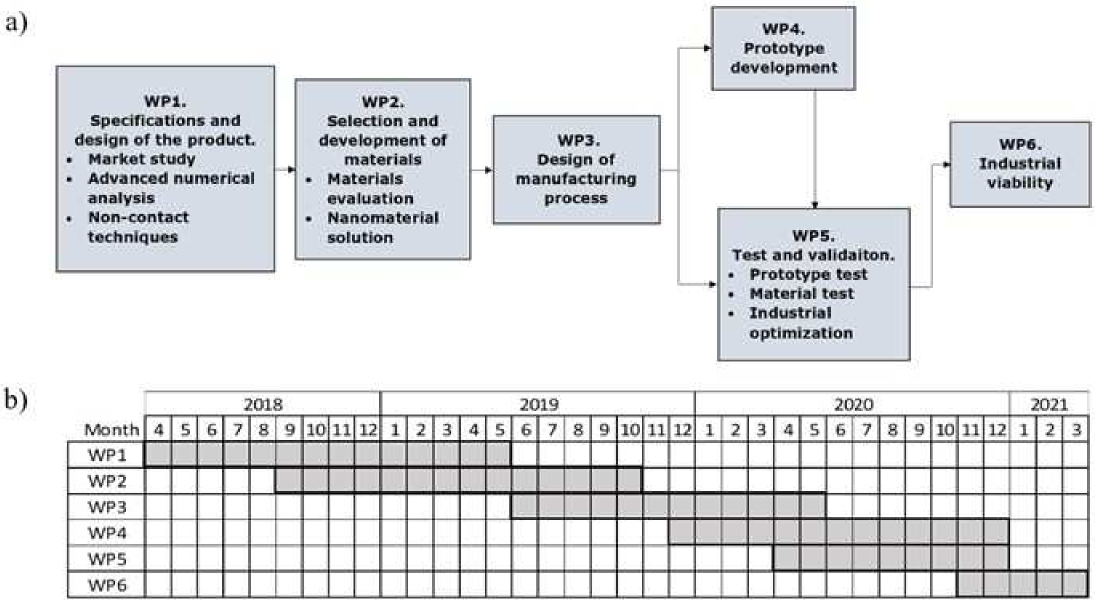

Fig. 4 - (a) COMPRESSer Workflow; (b) COMPRESSer - Gantt chart

WP 1: Specifications and design of the product (14 months).

The first work package is led by the University of Salamanca but all the consortium is implicated in the activities. On the one hand this WP has the aim of evaluating the current demands, limitations and trends in the SUDOE region in relation to manufacturing processes. In order to achieve this aim a market survey will be performed with the help of industrial partners and associates. These partners will contribute their know-how and expertise. In parallel to this activity a state of the art process is required with the aim of verifying the available materials and strategies to develop the final product.

WP 2: Selection and development of materials (14 months).

The second WP consist of selecting and developing materials, led by INP Bordeaux. Firstly, a technical analysis of fibres and resins will be carried out in order to identify the new formulations and additives that allow us to improve the mechanical and electrical behaviour of the material, as well as to reduce its weight.

Secondly, a technical analysis of nanomaterials will allow us to study the feasibility of using nanomaterial-based solutions for the manufacture of COPVs.

WP 3: Design of manufacturing process (12 months)

The third WP has the aim of designing the manufacturing process and will be led by Universidad de Aveiro and Plásticos Durex, who will contribute their knowledge and experience in manufacturing processes of composite materials.

At this stage of the project, the activities consist mainly of designing the manufacturing process of a development liner with the filament winding technique. Conventional liners will also be manufactured in order to compare them with the new thermoplastic liner, which will have an innovative configuration with a smaller mass.

WP 4: Prototype development (13 months)

This work package has the aim of manufacturing both virtual and physical final prototypes and will be led by the University of Salamanca. Firstly, different specimens will be tested in order to determine the mechanical properties of composite materials, in order to create the numerical models of the prototype. Then, the physical prototypes will be manufactured and evaluated in WP 5. Therefore, WP5 and WP6 will be performed simultaneously.

From the numerical results obtained during the first stage of this WP, the companies FireIce and Plásticos Durex will manufacture different metallic and polymer liners. These liners will be used by the University of Aveiro to manufacture different prototypes by means of the filament winding method. These prototypes will be used to verify the experimental results. Finally, the University of Bordeaux will provide the modified composite material configurations that will improve the final product.

WP 5: Tests and validation (9 months)

The fifth work package consists of testing and validating physical prototypes and optimizing the industrial solutions. This WP is led by the company New FireIce, thanks to its experience in the sector. In order to validate the prototype it is programmed to carry out additional experimentation. This has the aim of verifying the numerical results obtained by the previous WP. To this end, several safety tests will be carried out on the physical prototypes. These tests will be performed under the European regulations referring to pressurized vessels. Complementary to this, we aim to verify the requirements in terms of electrical conductivity, thermal capacities, corrosion resistance and ergonomics, among others.

WP 6: Industrial viability (5 months)

Finally, the sixth work package has the aim of studying the industrial viability of the project and this final stage is led by New FireIce. A new market survey will be carried out in order to know the potential sectors for the final product. In addition, technology transfer campaigns will try to bring the product to market. The University of Salamanca, University of Aveiro and Bordeaux INP University will be responsible for holding meetings with the industrial sector in their respective countries.

ONGOING PROJECT ACTIVITIES

The initial steps of the project were focused on evaluating the state-of-art processes in terms of feasible solutions as well as experimental and numerical methods for pressure vessels. After that, the company New FireIce carried out a market survey, which brought information about the status of pressure vessels within the SUDOE region (COMPRESSer 2018a). At the same time, University of Salamanca carried out different studies on the methodology for the design and optimization works (COMPRESSer 2018b, 2019a). These studies concluded that the Digital Image Correlation method is the most powerful measurement tool as well as the Finite Element Method for the numerical simulation of prototypes.

The second stage is already finished too. In these WPs the principal work took place in INP Bordeaux University. During this WP different fibres, resins and additives were studied by means of different laboratory tests such as scanning electronic microscopy (SEM) (COMPRESSer 2019b), Figure 5, including an evaluation of its electrical and thermal properties which have a great influence on the correct design of the final prototype.

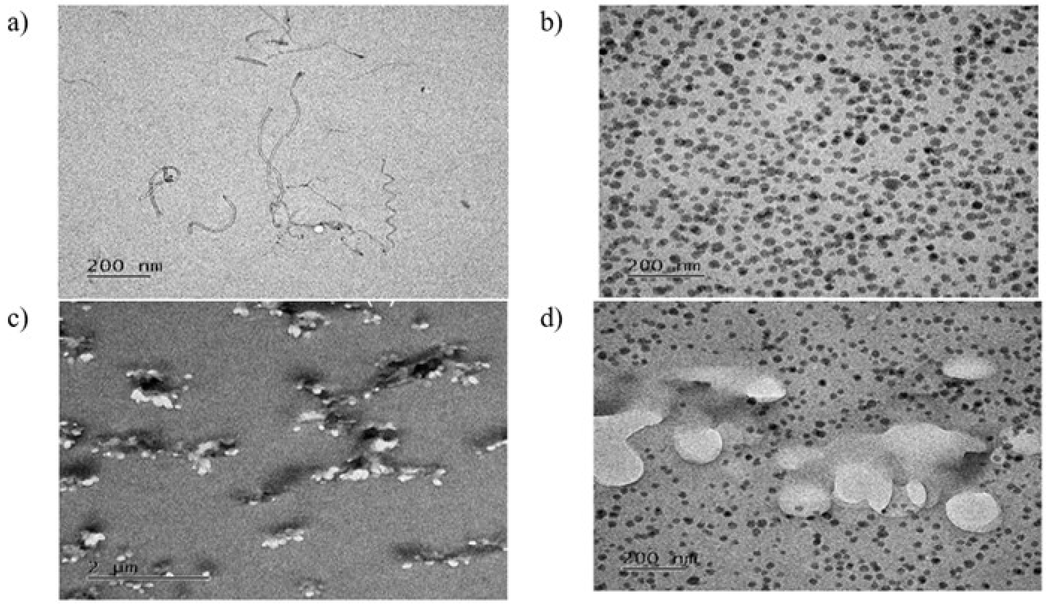

Fig. 5 - SEM images acquired during the material evaluation: a) Carbon nanotubes (0.1 CNT); b) SiO_2 nanoparticles (20 SiO_2); c) core–shell 28 rubber (10 CSR) nanoparticles and; d) Hybrid SiO2 nanoparticles and soft CSR nanoparticles system (5CSR_10 SiO_2)

The materials used are diglycidyl ether of bisphenol (CA144); anhydride based cured agent (CH141) and; anhydride cured, low viscosity epoxy resin system (CR144). The modifiers used are carbon nanotube (CNT); Silicon dioxide (SiO2) and core shell rubber (CSR) (Table 2). According to the results obtained, Epoxy based hybrid nanocomposites solution appears to be the most appropriate material (Bajpai *et al.*, 2020).

Table 2 - Composition and nomenclature of bulk epoxy-based composites. EP denotes the reference epoxy / hardener system and x represent the water percentage used, and Y represents the modifier

System	CA144(g)	CH141 (g)	Modifier (g)	CR144(g)
EP_0.1 CNT	84	82.8	8.75	2.5
EP_20SiO_2	18.2	62.6	75	2.5
EP_10CSR	54	77	49	2.5
EP_5CSR_10 SiO_2	35	73	24/43.7	2.5

The third and fourth WPs are under development. Hence an extensive experimental campaign was carried out using the DIC approach for evaluating the mechanical properties of the composite material (Young Modulus, Poisson ratio and strength) suggested in the previous WP. The results of this campaign allowed us to extract the probability density functions of these variables. With this information different numerical simulations, by means of stochastic finite element simulations, are performed (Figure 6). In order to reduce the computational costs of these simulations the Polynomial Chaos Expansion was adopted (Novak and Novak 2018). This metamodel allows us to simulate with great accuracy and low-cost the mechanical behaviour of the numerical designs, as well as to perform sensitivity analysis by means of the Sobol indices (Garcia-Martin *et al.*, 2019; Garcia-Martin *et al.*, 2020). This workflow will be used to obtain the final prototype.

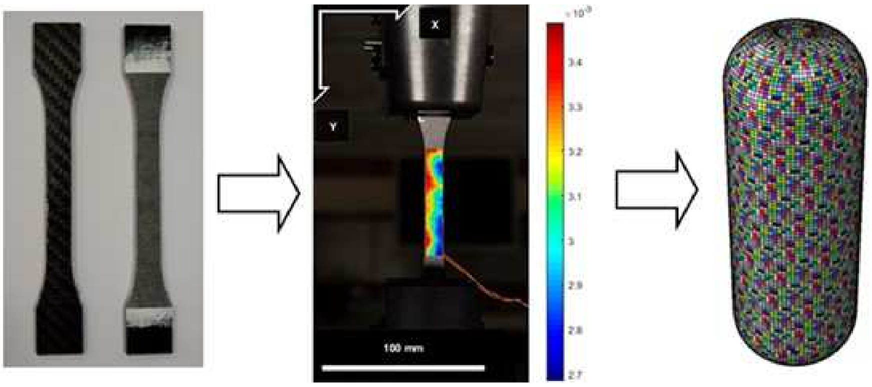

Fig. 4 - Process for design and optimization of composite solutions: 1-specimen manufacturing; 2-characterization test by means of the digital image correlation and; 3-numerical evaluating, integrating optimization methods and reliability approaches

For the manufacturing of this final product, University of Salamanca and University of Aveiro are in contact to carry out prototypes and specimens in order to verify the designs carried out by the University of Salamanca.

RESULTS AND CONCLUSIONS

The project development is in the third and fourth stage and we are expecting the development of the final prototype. However, the finished WPs and the achievements obtained during previous stages have shown successful results.

During this stage of the project, the following conclusions can be drawn:

- The market survey showed that within the SUDOE region the COVs are not highly developed yet. However, in this case, it has many commercial advantages.
- Filament winding is a technique that will allow us to optimize production resources.
- Digital image correlation is a non-contact and full-field photogrammetric technique able to obtain the mechanical properties of composite solutions.
- The combination of digital image correlation approaches and reliability-based methods, based on the use of finite element simulations, allows us to evaluate these advance solutions from a stochastic point of view.
- Thanks to the use of metamodeling strategies it is possible to perform Monte Carlo simulations with a reasonable computational cost.

In the next months we expect to develop a strong alternative to the traditional fire extinguishers based on an improved COPV with electrical properties, matrixes and liners lighter, eco-friendlier and safer than the conventional ones.

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