1 Introduction

The study carried out within the present project has the objective of demonstrating the feasibility, use and functionality of Carbon Fiber Reinforced Flexible Epoxy materials (CFRFE) for self-deployable space structures such as deployable tape-spring hinges by means of designing, simulating, manufacturing, testing and correlating a classic (100% carbon fiber reinforced plastic -rigid resin- CFRP) deployable tape-spring hinge and a CFRFE deployable tape-spring hinge and compare their mechanical and dynamic behaviours.

This project justifies the efficacy of the use of CFRFE materials in a real space case. For this purpose, a self-deployable full composite boom has been designed, manufactured, tested and validated so that in can deploy a tip payload with a relevant mass with less final impact at the final deployment than a typical CFRP hinged boom.

This study demonstrates that the use of CFRFE hinged booms can take the advantage of a simpler design with the advantage of a smoother deployment that mitigates the potential damage that the deployed payload or the platform can suffer. It includes the test at sample level of the properties of stiffness, damping, creep and thermal expansion of various materials formed from the mixture of the two resins in different proportions.

The viability of the designed structure has been justified by means of finite element models, in order to later manufacture and test hinge prototypes with the resin proportions that provide the best results for the desired purposes. Tests of these prototypes have been used to correlate the finite element models and to have a better approximation to the real properties of the structure than the one offered by coupons.

2 Requirements

A set of requirements have been provided by Airbus DS, which is a potential customer of this technology in the future. A tip mass (a reflector) of 11.1 kg will need to be deployed from the platform. The boom mass will need to be lesser than 3.3 kg. The resulting tip mass with the boom will need to have a first natural frequency higher than 1.5Hz.

Morphology of the boom and its position on the platform must conform to the scheme shown in Figure 1.

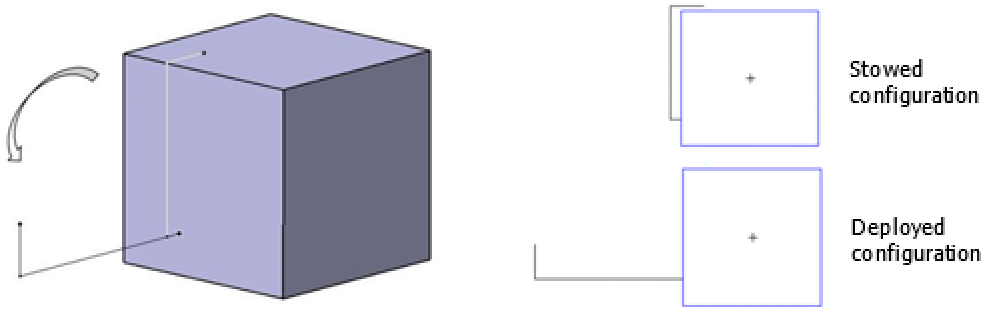

Figure 1. Global geometry of the boom

3 Test Coupon Campaign

A set of CFRFE material coupons have been tested, considering that the flexible epoxy resin can be mixed with rigid epoxy resin in different proportions, allowing a customization of stiffness and damping of the resulting composite laminate. Unidirectionally reinforced CFRFE material at various flexible epoxy resin percentages have been characterised. Additionally, multiaxial laminates have been defined and tested on terms of tensile, bending, damping and thermal expansion behaviours. Thermal cycling has also been applied to the coupons.

Four different composite materials are considered for both types of specimen, mixing the rigid and the flexible resins in proportions with 0%, 25%, 50% and 75% of the flexible one respectively.

Tensile and bending tests have been done following normalised standards. Damping tests have been done by means of acoustic measuring of the vibration produced by a cantilever laminate when played with a spike and response analysis of the oscillations decay from one bounce to the next. Creep behaviour has been measured by means of inducing in a coupon a similar bending shape to the one than it will have when the boom hinge is in folded state.

Tensile properties in the direction of the fibre have been shown to be barely dependent on the matrix, so a small deviation has been found in different epoxy resins proportions. Nevertheless, flexural behaviour of laminates with different epoxy resins proportions have shown to be considerably different: there is a very significant reduction in the flexural modulus of elasticity with respect to the tensile modulus for the more flexible mixtures. The same trend has been seen in the strength limits, being particularly noticeable the low bending strength of the laminates with high proportion of flexible epoxy resin. Damping tests have confirmed that, for the same geometry and boundary conditions, laminates with more flexible resins have a greater damping than rigid ones (1.8% compared to 0.5% of loss factor respectively). This data is not reliable when extrapolating to other geometries (damping is not only a material property), so the damping of the hinge must be calculated by testing it.

Creep tests have shown that coupons recover their initial shape after thermal cycling, providing good results and establishing an excellent starting point for validating flexible epoxy resins for space applications. Thermal expansion coefficients have also been estimated in dedicated tests.

4 Hinges Design

Two finite elements models have been built, one with a 100 % rigid resin laminate (CFRP) and the other with a mixture of rigid and flexible resins (CFRFE). The composition of this second laminate has been determined by the fulfilment of the requirements, especially the strength one. The most suitable flexible laminate that fulfil them contains a mixture of resins with 40% rigid and 60% flexible at the inner tape of the boom hinge. Both rigid and flexible designs fulfill all the established requirements for the boom, including a common first natural frequency and mode shape (1.54 Hz), as the it is driven by the in-plane behaviour of the laminate, which has been demonstrated to be common to both flexible and rigid laminates for the selected application.

Deployment of both booms with flexible and rigid epoxy resins have been simulated, taking into account the energy loss factor. The deployment simulation shows that both CFRFE and CFRP booms buckle after deployment, but the maximum deployment speed and the maximum angle developed by the hinge after buckling is lower for the CFRFE boom.

The failure theory used to extract the failure indices from the model is the Tsai-Wu criteria. The failure index of each ply of the laminate has been obtained through all the folding and deploying process. Maximum failure index in CFRP hinge is 0.734, whilst it is 0.942 in the CFRFE hinge.

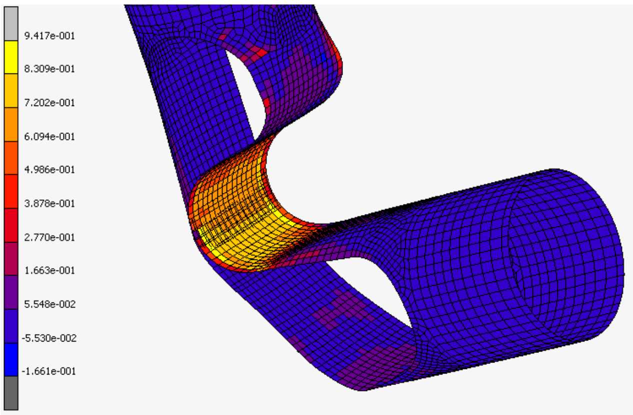

Figure 2. CFRFE Tsai-Wu failure criterion in ply 1.

5 Hinge Demonstrator Tests

Two boom breadboards, with a hinge each one, have been designed and manufactured, one of them using a standard CFRP material and the other one using CFRFE, measuring 900mm in length and 160mm in diameter. Following figure shows one of the breadboards, in the static characterization test machine in deployed position and during its folding.

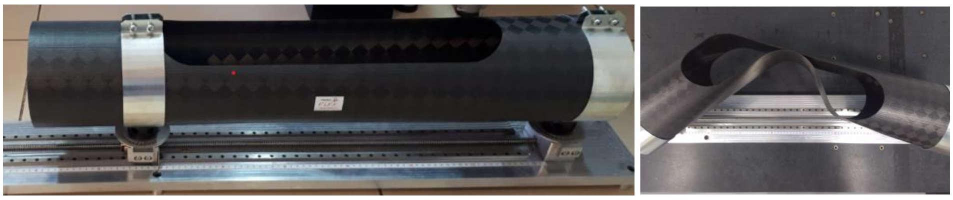

Figure 3. Demonstrator static characterization test: deployed position (L), during deployment (R).

Figure 4 shows the moment vs. hinge angle curves for both materials obtained during tests, which shows that the CFRFE hinge reduces the deployment torque to be applied to the payload with respect to the CFRP one, especially during the last stage of the deployment (from 155º to 180º).

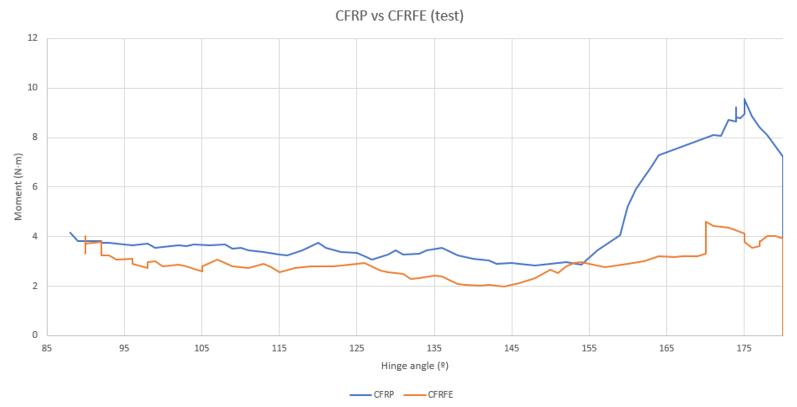

Figure 4. CFRP (blue) and CFRFE (red) static moment tests results.

Figure 5 shows the loaded deployment sequence of the boom with CFRP and CFRFE hinges. A mass of 1 kg has been included is at the free tip, inside the tube (not visible in the pictures).

Figure 5. Loaded deployment sequence of the CFRP (L) and CFRFE(R) hinges (animations from left to right and top to bottom).

The boom with the CFRP hinge can deploy carrying a mass its tip, but it buckles after fully deployed, allowing the boom to fold to the other side. This buckling affects both blades of the hinge, the intern one and the extern one. The boom with the CFRFE hinge is also able to deploy when loaded with the same mass. A slight bending beyond the fully deployed position can be observed, but the hinge does not buckle at all. A rebound is produced that causes the buckling of the intern blade, but with minor effects.

Measurements have shown that the final speed at the deployment has been reduced by a 30% (from 6.8 rad/s to 4.7 rad/s), which implies a promising result. The last test done to both breadboards has been verifying their stiffness by means of a free vibration test, and results show that the breadboard stiffness remains almost the same (less than 3% lower) for the CFRFE breadboard, which confirms the predicted behaviour during the hinge design phase. As it was expected, CFRFE hinge damping loss factor is higher than the CFRP one.

6 Conclusions

The utility of Carbon Fibre Reinforced Flexible Epoxy Resin for its use in the passive deployment of full composite structures has been demonstrated, and its stiffness, strength and damping characteristics have been tested and used for a space application: a full carbon fibre self-deployable boom with a damped behaviour with respect to simple CFRP booms. Several key-issues have been confirmed:

- The miscibility between the rigid and epoxy resins used has allowed to customize the CFRFE properties for the purpose of the selected application within some limits (basically the material strength, but also its stiffness), maximizing the damping effect of the deployment of the boom.
- The bending stiffness of CFRFE thin laminates is lower than the CFRP’s one, which allows reducing the deployment speed of the composite boom.
- The damping characteristics of CFRFE are higher than the CFRP ones. When this is combined with the lesser deployment final speed of the CFRFE boom, it drives to a smoother deployment with less impact at the end of the hinge trajectory,
- Bending strength capabilities of CFRFE thin laminates remain at remarkable levels. Its tensile strength capabilities are excellent.
- The use of CFRFE in thin laminates does not alter the membrane characteristics of the laminate with respect to CFRP thin laminates, which becomes an advantage when it is used in self-deployable booms, because the boom overall stiffness remains unchanged.
- CFRFE thin laminates do not have remarkable creep values after long storage folding.

These facts enable this material to be used in space booms and other potential applications.