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The effect of a thermo-oxidative environment on the behaviour of multistable [0/90] unsymmetric composite plates

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ABSTRACT

The present paper focuses on the effect of a thermo-oxidative environment (150 °C under atmospheric air) on the deformation behaviour of multistable IM7-977-2 [0/90] unsymmetric carbon–epoxy composite plates. Sample curvatures are measured at high temperature as a function of the ageing time by an optical method, by following the displacement of marker points situated on the external side of the plate and by fitting them with an interpolation algorithm. The predictions of a composite plate model taking into account thermo-oxidative affected mechanical properties of the elementary ply and the residual strains produced by thermo-oxidation allow interpreting and understanding the experimental results.

1. Introduction

The multistable behaviour of composite plates and shells has been the object of several research studies [1–11], focusing mainly on the prediction of the deformed shapes and their intrinsic stability. These predictions have shown a number of interesting features which can be conveniently explored for parametric actuation, morphing applications and so on.

While the behaviour of *virgin structures* is quite well understood and characterised, there is poor understanding about the response of structures which are *degraded* under the effect, for instance, of *environmental loads*.

It is well known that multistability of composite plates can be promoted by internal stresses such as manufacturing stress due to curing, mechanically induced pre-stress, mismatch stress [12–16]: these stresses are susceptible to evolve with time, due to ageing and degradation mechanisms.

Therefore, when exposed to aggressive environments (high temperature, high relative humidity, UV rays, etc.), multistable structures can change their features and lose their functionality. *Not much research is available about the ageing behaviour of multistable structures.*

[0/90] unsymmetric composite plates are the simplest example of multistable structures: they can be conveniently employed as "sample" structures to explore – numerically and experimentally – the elementary issues related to multistability: moreover, these plates can be used to monitor the evolution of the internal stresses (which promote multistability) with time [12–17].

The first systematic study about the mechanical behaviour of [0/90] unsymmetric plates under thermal solicitations has been carried out by Hyer [12] in the early 1980s. Hyer studied the *cured shapes* of [0/90] unsymmetric plates proposing a Rayleigh–Ritz based model for the prediction of the plate distortion [18]. This work has been fundamental for understanding the basic multistability issues related to unsymmetric laminates.

In short, Hyer's observations can be summarised as follows:

- Depending on their geometrical dimensions and on the magnitude of the temperature differential between cure temperature and room temperature, cured square and rectangular initially flat plates have the tendency to show at room temperature either unique saddle-like deformed shapes, either cylindrical shapes.
- The two cylindrical shapes observed at room temperature – when observed – are separated by a "snap-through" event. The saddle-like deformed shapes – when observed – are unique.

It has to be noted that the existence of multiple cured shapes is affected by the geometrical arrangement of the plate but also by the temperature differential experienced by the structure from cure to room temperature. This means that multistability in fact depends on the level of *internal stress* (and total potential energy)

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within the plate. If for some reason (ageing, degradation, damage, fracture) part of this stress (or energy) is released, multistability may be lost.

Some recent papers by Gigliotti et al. [19,20] have shown – experimentally and theoretically – that:

- The aspect ratio (AR, length-to-width ratio) of rectangular plates *may affect consistently the multistability behaviour* [19,20]. This is a purely geometric effect which can however usefully exploited to design tests.
- Humid ageing (water absorption) may have a consistent effect on the multistability behaviour [17]: due to humid ageing, initially cylindrically deformed plates – exhibiting snap-through phenomena – may show a unique saddle-like shape. In many cases water absorption promotes uniquely physical ageing (which is reversible), therefore the plates regain their initial deformed shape (and their multistability features) upon re-drying.

It has to be noted that – when the effect of the environment is reversible – it can be virtually eliminated at some state: for instance, purely thermoelastic stress (like that studied by Hyer [12,18]) can be eliminated at a value of temperature which is called stress free temperature: the effect of reversible water absorption is eliminated in the dry state.

Temperature changes and water absorption are not the only form of ageing occurring in composite materials. Chemical ageing – characterised mainly by the occurrence of chemical reactions – can also take place: in this case the degradation is irreversible.

The present paper focuses on the effects of a thermo-oxidative environment on the deformation behaviour of multistable [0/90] unsymmetric carbon–epoxy composite plates.

The aim of the research is twofold: from one side, it wants to establish the direct effect of thermo-oxidation on the deformation behaviour of [0/90] unsymmetric plates, taken as the prototype of multistable structures. From another side, [0/90] unsymmetric plates are seen as smart specimens which can be employed to monitor the response of the composite material upon thermo-oxidative ageing.

Thermo-oxidation is a degradation phenomenon (chemical ageing) occurring in organic resins at temperatures higher than around 100 °C, thus, in some cases, depending on the material, well below the glass transition temperature. Reinforcing fibres (carbon fibres, for instance) may also be affected by thermo-oxidative phenomena; however their thermal degradation starts from around 300 °C. In fact, carbon fibres appear to have a stabilizing effect on ageing polymer matrices, whereas the fibre/matrix interphase seems to be a privileged path for the oxygen diffusion by accelerating its penetration along the fibre direction [21].

Oxygen diffusion from the surfaces exposed to the environment to the heart of the matter engenders chemical reactions with some active sites of the macromolecular network. A detailed chemical/mechanistic model [22], tracing the evolution of oxygen concentration (and other species involved in the thermo-oxidative chemical reaction), has been developed in order to explain on physico-chemical grounds the mechanical phenomena occurring during thermal degradation.

At the macromolecular level the change of atomic structure in the oxidised layer (splitting of chemical bonds) may lead to local decrease of apparent elastic modulus and embrittlement ("antiplasticization" phenomenon [21–24]). On the other hand thermal oxidation promotes local density and mass changes, leading to the development of shrinkage strains [23–25]. Depending on its size, the oxidised sample may exhibit sharp property gradients, starting from the surface – directly exposed to the environment – to the heart, less affected by oxygen reaction-diffusion. Usually this gradient is condensed in a thickness of a few tens of microns, this underlines the clearly local nature of the phenomenon.

The idea behind employing [0/90] unsymmetric plates for the monitoring of thermo-oxidative phenomena in composite materials, schematically illustrated in Fig. 1, has been already presented in a preceding paper [27] and can be summarised as follows:

- The development of a thermo-oxidative thin layer close to the external surfaces exposed to the environment has the tendency to *modify* the deformation field of the plate, which is initially distorted by the manufacturing curing stresses. This change is related to the fact that both mechanical properties modifications and development of chemical shrinkage strains take place during thermo-oxidation within the oxidised layer. In other words thermo-oxidative ageing leads to the establishment of a *multilayer structural configuration* in which material properties and anelastic strains are distributed (essentially along the thickness) according to the gradients imposed by the thermo-oxidative process.
- It should be kept in mind that thermo-oxidation promotes also embrittlement of the exposed surfaces. The development of fracture and damage phenomena during thermo-oxidative ageing cannot be excluded a priori; this is particularly true in [0/90] unsymmetric structural arrangements in which a consistent residual stress state has the tendency to settle down.

The issue explored in the present paper has been theoretically addressed in a precedent paper by the same authors [27]; some preliminary experimental results have also been presented in [28].

With respect to the past research [27,28], two main differences can be singled out:

- From the modelling point of view the initial formulation presented in [27], which was purely elastic, has been enriched by taking into account the viscoelastic behaviour of the polymer matrix, at high temperature: since the development of residual distortion due to thermo-oxidation takes place at high temperature, when viscoelastic effect are unavoidable, taking into account viscoelasticity is essential. Moreover the kinematic field employed for the simulation of the plate distortion has been enriched in the light of Ref. [20].
- From the experimental point of view, the test campaign presented in [28] was carried out essentially at room temperature, by means of *interrupted tests*. Samples were aged at 150 °C and their curvature measured at room temperature, at different ageing times, by a mechanical comparator. Performing interrupted tests on 0/90 plates may have some important drawback: in fact, removing samples for the oven

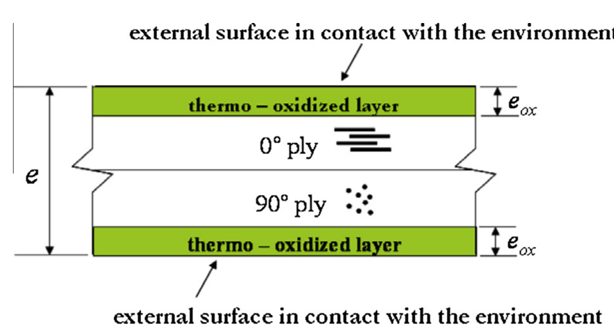

Fig. 1. Schematics of the effect of a thermo-oxidative environment on the curvature of 0/90 unsymmetric plates.