Ecobonding of Composite Wind Turbine Blade Structural Parts Using Eco-friendly Adhesives

Brahim Attaf

Team Europe – European Commission *39 Blvd. Charles Moretti, 13014 Marseille, France*

Email: b.attaf@wanadoo.fr

***Abstract*- Structural adhesives used to bond composite blade parts have to fulfil sustainability requirements and REACH regulation in addition to quality design requirements in terms of specific stiffness, specific strength, fatigue and weathering characteristics. To appreciate the impacts involved in the bonding process (e.g., harmful substances, amount of VOC emissions, toxic chemicals, carcinogens, odours, ...), designers and users should have more knowledge and better innovation policies on how to integrate health and environmental aspects into the bonding procedures to enable a sustainable production coupled with green manufacturing practices. With this argument as an objective, the aim of the present paper is to innovate and develop a new approach providing high performance of adhesively-bonded composite blade half-shells in terms of Quality-Health-Environment interrelated issues. Alternative solutions leading to new generation of environmentally-friendly adhesives can be achieved through the integration of a new eco-factor, λ_a, into the classical bonding formulations. Further to that, shear stress eco-ratio, Λ, *versus* adhesive lap ratio, ϕ, for different values of λ_a were plotted and some conclusions were drawn.**

Keywords*- *Ecodesign; Blades; Composite Materials; Eco-coefficients; Sustainable Development; REACH

I. INTRODUCTION

In the wind turbine industry, commonly three-bladed turbine, each glass-fibre reinforced composite blade is generally produced from two half-shells (upper and lower skins); each is moulded separately using generally the vacuum infusion process [1]. Then, the two half-shells are bonded together with a bi-component adhesive (resin and hardener). Additionally, to increase the longitudinal stiffness of the composite blade, either a spar (box beam) or stiffeners (shear web) are bonded into the half-shells, making the blade internal structure more stiff and resistant to wind loads and induced vibrations [2]. Fig. 1(a) illustrates an airfoil cross-section of a wind blade, which was derived by assembling structural components together using the chemical technique of bonding. Areas where the adhesive is applied are highlighted with red colour. At these bonded areas, the transfer of loads from one structural component to another must be performed without any adverse effect that could damage the mechanical strength of the adhesive joint.

In order to address this issue and assess the joint failure risk, the analysis is simplified by modelling the bonded areas as two flat plates bonded with a single-lap adhesive joint as shown in Fig. 1(b). The adhesive joint in question is assumed to be designed strong enough to perform safely in operating conditions and hold up the maximum load bearing capacity, fatigue resistance and climate conditions. In addition to these quality design requirements, the concept of designing adhesive joints must be environmentally-friendly and in compliance with the requirements of REACH (Regulation on Registration, Evaluation, Authorisation and Restriction on Chemicals) to ensure a high level of protection of human health and the environment from probable risks that may be posed by chemicals used for bonding. Thus, a new design strategy leading to sustainable bonding process and cleaner production have to be provided to make the new adhesively-bonded composite blades product more competitive in the worldwide wind blade market.

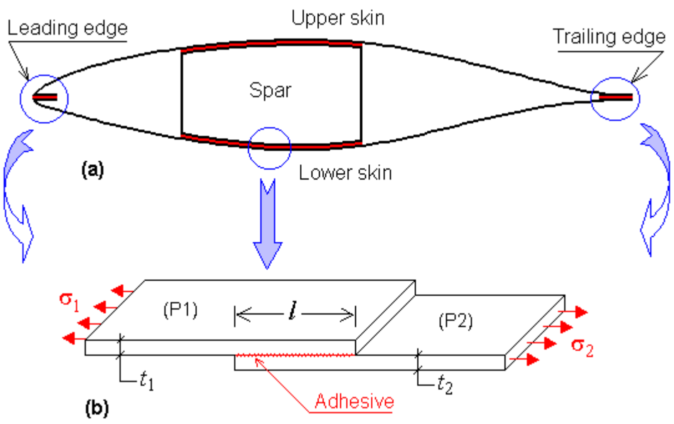


Fig. 1 Blade airfoil cross-section: (a) bonded areas, (b) simplified plate model with a single-lap adhesive joint

By adopting this strategy in the context to go green can ensure a sustainable bonding process compared to the classical adhesive bonding technique; this will offer companies alternative solutions enabling them to boost innovation, creativity and competitiveness. Some of these include (i) reduction of VOC (volatile organic compounds) emissions, (ii) use of non-toxic chemicals, (iii) use of no carcinogenic substances, (iv) generation of adhesives with low emission of odours, and so forth.

To have an order of magnitude about the adhesive mass used for a typical 50 m blade length, it is estimated that the quantity in mass of adhesive required to bond the different components is around 600 kg: a considerable volume of adhesives that can generate a significant amount of VOC emissions. To this end, and in a society aware of environmental risks, conscious designers, suppliers and users should have full intention to encourage the progress and development of environmentally-friendly practices, thereby providing new methods and processes to be applied in modern industrial and technological composite wind activities [3-4].

With this idea as a key target, the aim of this paper is to develop an innovative approach on the chemical bonding technique using eco-friendly adhesives in order to mitigate the impact of the bonding process on the environment and human health. However, it should be noted that an alternative approach can be achieved by using the process of resin transfer moulding (RTM): an ecological key solution for the production of new wind turbine blades with a total absence of bonding operations. Some researches that study on this subject area have been undertaken by the author and the output results are presented and discussed elsewhere [5].

II. RESEARCH METHODOLOGY AND APPROACH

The research methodology employed in this investigation is oriented towards the study of the mechanical strength of the adhesive joint when taking into account, during analysis, health and environmental aspects whilst maintaining quality criteria. The approach is characterized by the integration of a key eco-factor into the classical joint shear stress formulation. The difference between the sustainable and classical results can yield an estimated value. The order of scale of this value can help designers and analysts to better assess environmental and health impacts.

A. Approach of Ecobonding

Within this approach, the present eco-technique is characterized by a balanced function that simultaneously guarantees fulfilments of Quality assurance (*Q* for short), Health protection (*H* for short) and Environment preservation (*E* for short). Fig. 2 illustrates the intersection between *Q*, *H* and *E* aspects; which gives rise to new domain that fulfils the ecobonding condition, defined by the subset $\overset{\therefore}{F}$, and characterized by an assured quality, a protected health and a preserved environment [3-4]. The three dots (∴) above the character "*F*" are only a brief description of the diagram illustrated in Fig. 2, showing interaction between *Q*, *H* and *E* aspects (*i.e.*, ∴). In other terms, the three dots represent the three pillars that characterize the basic elements of the sustainable development concept.

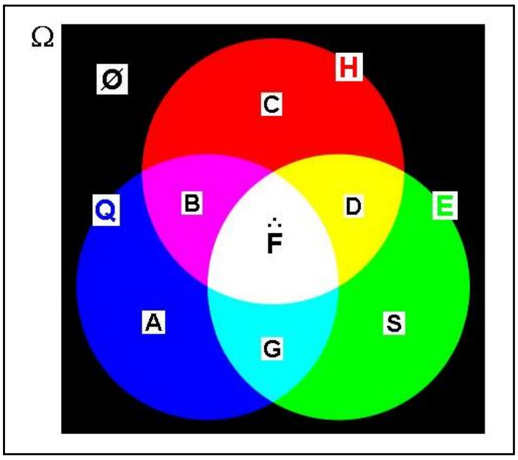


Fig. 2 Attaf's ecodesign model for ecobonding approach [3-4]

To be familiar with the state of the problem, let us consider for example an adhesively-bonded composite structure, where its components were assembled together using, in one hand, an adhesive with high amount of VOC emissions and, on the other hand, a traditional bonding process. In such situation, production operators may be exposed to manipulate physically harmful substances, while the technical quality assessment of the adhesively-bonded composite structure reveals very satisfactory compliance with quality design standards. Neither the bonding process nor the type of adhesive used is likely to fulfil the eco-standard reference conditions. Alternatively, by simply using a new type of adhesive (*e.g.*, adhesive with low amount of VOC emissions) and improving the bonding process (*e.g.*, application of adhesives by robot in a closed room) can provide a key solution that fulfils the ecobonding concept and complies with an admissible degree of tolerance to the new regulations and eco-standards.

B. Application of Probability Theory

By considering the universal sample space $\Omega=\{Q, H, E, A, B, C, D, S, G, \overset{\therefore}{F}, \varnothing\}$ as shown in Fig. 2, the evaluation of the number of chances providing the realization of the event $\overset{\therefore}{F}$ can be obtained using the theory of conditional probability. For such needs, the event $\overset{\therefore}{F}$ and the associated probability can be written, respectively, as follows [4, 6]:

$$\overset{\therefore}{F} = Q \cap H \cap E \tag{1a}$$

$$P(\overset{\therefore}{F}) = P(Q \cap H \cap E) \tag{1b}$$

where, $\cap$ denotes intersection symbol.

According to the dependency of sets *Q*, *H* and *E* and the rules of multiplication in the probability theory, Eq. (1b) can be written as follows:

$$P(\overset{\therefore}{F}) = P(Q) \times P(H|Q) \times P(E|Q \cap H) \tag{2}$$

in which,

$$P(E|Q \cap H) = P(Q \cap H \cap E)/P(Q \cap H)$$

and

$$P(H|Q) = P(Q \cap H)/P(Q)$$

To achieve the condition of ecobonding, it is convenient to assign to each of *Q*, *H* and *E* aspects a specific coefficient representing the probability of approval. It may therefore be considered that [3-4]:

- α = P(Q) is an eco-coefficient defining the criterion that assess adhesive performance in terms of quality assurance considerations;
- β = P(H |Q) is an eco-coefficient defining the criterion that assess the adhesive performance with regard to health protection, knowing that quality assurance is achieved; and
- γ = P(E |Q $\cap$ H) is an eco-coefficient defining the criterion that assess adhesive performance with regard to environmental preservation, knowing that health protection and quality assurance are achieved.

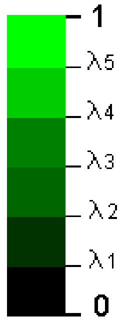
C. Key Performance Indicator (KPI) for Ecobonding

In considering the mathematical product of the above-mentioned eco-coefficients, the condition of ecobonding is performed and the resultant quantity obtained by multiplication rules is represented by a single factor called "eco-factor" and denoted by the character λ_a. Consequently, Eq. (2) can be written as follows:

$$\lambda_a = \alpha \times \beta \times \gamma \tag{3}$$

This eco-factor is regarded as a key performance indicator (KPI), made for the purpose of discussion and analysis and will be used to provide better assessment of *Q-H-E* performance in relation to the bonding process and associated substances. For instance, if the eco-factor λ_a approaches unity (*i.e.*, 100%), the process and the adhesives used for bonding are fully compliant with the green bonding requirements, which ensures the sustainability conditions. However, if the eco-factor λ_a is not close to the target value required by sustainability standards, it is recommended to search for possible new alternatives that provide new eco-coefficients and then new resultant eco-factor. Table I recapitulates the assessment method for different intervals of the eco-factor and shows a rating satisfaction measure in the form of colour gauges.

TABLE I PROBABILITY COLOUR GAUGES FOR DIFFERENT ECO-FACTOR VALUES OF λ_A

Interval	**Assessment**	**Gauge**
$\lambda_5 \leq \lambda \leq 1$	Excellent	
$\lambda_4 \leq \lambda < \lambda_5$	Very good	
$\lambda_3 \leq \lambda < \lambda_4$	Good	
$\lambda_2 \leq \lambda < \lambda_3$	Fair	
$\lambda_1 \leq \lambda < \lambda_2$	Poor	
$0 \leq \lambda < \lambda_1$	Very poor	

The resultant eco-factor will be inserted into the standard mechanical characterization formulae of adhesive materials and into the joint design approach. Hence, the shear modulus of adhesive G_a determined from experimental results must be adapted to the actual situation by integrating health and environmental considerations into characterization tests. Consequently, the new shear eco-modulus of adhesive will become $\overset{\therefore}{G}_a$.

In relation to this orientation, the elastic shear eco-factor can be evaluated by the following ratio [7]:

$$\frac{\overset{\therefore}{G}_a}{G_a} = \lambda_a \tag{4}$$

where: G_a , $\overset{\therefore}{G}_a$ are classical and sustainable shear moduli of adhesive joint, respectively.

III. ADHESIVE BONDING ANALYSIS OF SINGLE-LAP JOINTS

The present analysis will concentrate only on the joint behaviour when this latter is subjected to in-plane forces.

A. *Classical Formulations*

In the case of one-dimensional analysis, the differential equation governing a bonded single-lab joint (Fig. 1(b)) can be written as follows [8]:

$$\frac{d^2Y}{dx^2} - \omega^2 Y = 0 \tag{5}$$

in which: $Y = \frac{\sigma_1}{E_1} - \frac{\sigma_2}{E_2}$ and $\omega^2 = \frac{G_a}{t_a}\left(\frac{1}{E_1\ t_1} + \frac{1}{E_2 t_2}\right)$

The general solution of Eq. (5) can be expressed in the following form:

$$Y = A_1\ ch\,\omega x + A_2\ sh\,\omega x \tag{6}$$

where, $A_1 = \frac{\sigma_{10}}{E_1}$ and $A_2 = -\left(\frac{\sigma_{20}}{E_2\ sh\omega l} + \frac{\sigma_{10}}{E_1\ th\,\omega l}\right)$

Whereas, the classical adhesive shear stress formulation can be derived in the following form [8]:

$$\tau_a = \frac{G_a}{t_a\omega}\left[\left(\frac{\sigma_{10}}{E_1}\frac{1}{th\omega l} + \frac{\sigma_{20}}{E_2}\frac{1}{sh\omega l}\right)ch\omega x - \frac{\sigma_{10}}{E_1}sh\omega x\right] \tag{7}$$

B. *Sustainable Formulations (Eco-formulations)*

In order to assess the adhesive impacts on human health and the environment, the elastic shear eco-factor expressed by Eq. (4) is integrated into Eq. (7) to take into account the *Q-H-E* interrelated issues. To this end, the new formulation of the eco-adhesive shear stress can be written as follows:

$$\overset{\therefore}{\tau}_a = \frac{\lambda_a G_a}{t_a\overline{\omega}}\left[\left(\frac{\sigma_{10}}{E_1}\frac{1}{th\overline{\omega}l} + \frac{\sigma_{20}}{E_2}\frac{1}{sh\overline{\omega}l}\right)ch\overline{\omega}x - \frac{\sigma_{10}}{E_1}sh\overline{\omega}x\right] \tag{8}$$

where: $\overline{\omega}^2 = \frac{\lambda_a G_a}{t_a}\left(\frac{1}{E_1\ t_1} + \frac{1}{E_2 t_2}\right)$

It should be pointed out that the elastic characteristics E_1, E_2, σ_{10} and σ_{20} are assumed to be sustainable values; and they have already been considered satisfying the sustainability requirements in former design stages as discussed in other works [9-10].

IV. RESULTS AND DISCUSSION

For a wide dissemination of research results to other industrial sectors involved in the process of bonding, a general case study was considered to investigate the effect of the eco-factor λ_a on the shear moduli of adhesive joint. To this end, two bonded flat plates were considered as illustrated in Fig. 1(b). The mechanical and geometrical data were derived from previous work [8].

It is assumed that Plate 1 is made of isotropic material (titanium alloy), whereas Plate 2 is made of carbon-epoxy composites with 10 unidirectional layers and 60% fibre volume fraction, and defined by the stacking sequence configuration [07/90/+45/-45]. Table II summarizes the main mechanical and geometrical characteristics of the adhesive-joint and plates.

TABLE II MATERIAL AND GEOMETRIC CHARACTERISTICS OF ADHESIVE JOINT AND PLATES

Characteristics (unit)	**Adhesive (araldite)**	**Plate 1: titanium**	**Plate 2: carbon/epoxy**
Modulus of elasticity (MPa)	NA(*)	E_1=105000	E_2=100590
Shear modulus (MPa)	G_a=1700	NA(*)	NA(*)
Thickness (mm)	t_a=0.2	t_1=1.5	t_2=1.25
Length (mm)	l=40	NA(*)	NA(*)
Tensile force (Nmm^{-1})	NA(*)	N_1=200	N_2=200
Stress at free end (MPa)	NA(*)	σ_{10}=67	σ_{20}=80
Shear stress failure (MPa)	τ_{fa}=15	NA(*)	NA(*)

(*) Not Applicable in this analysis

To determine the eco-adhesive shear stress, $\overset{\therefore}{\tau}_a$, the analysis was carried out using Eq. (8) pursued by a small computer program. The lap length of the adhesive joint, *x*, was varied from 0 mm to 40 mm with an increment of Δx =2 mm. The relationships between $\overset{\therefore}{\tau}_a$ and *x* for different values of λ_a are presented in Fig. 3.

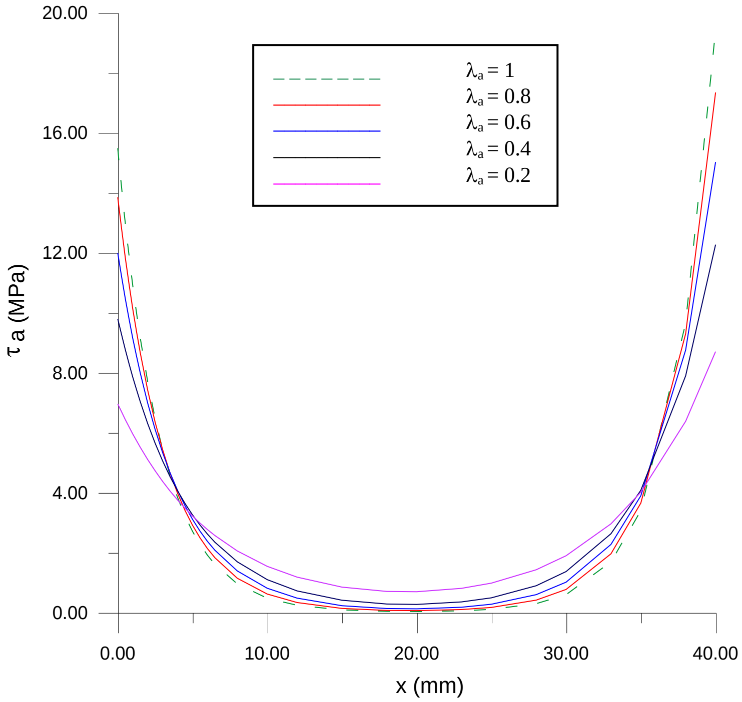


Fig. 3 Shear stress distribution $\overset{\therefore}{\tau}_a$ *versus* adhesive joint lap length *x* for different values of λ_a

The analysis of results shows that for all values of λ_a, the distribution of shear stress developed through the adhesive joint length behaves globally in the same manner within two specific limits of *x*-length: (i) high stress concentrations occur around the adhesive free ends (near the two corners) and (ii) low stress distributions occur in a large region in the middle of the adhesive layer. Points of intersection between different sets of curves occur at values of $x \approx 5$ mm and $x \approx 35$ mm for the same value of $\overset{\therefore}{\tau}_a$. Moreover, for values of $x \in [0; 5] \cup [35; 40]$ mm, the eco-adhesive shear stress values decreases when λ_a decreases. This decrease is observed to be very important around the adhesive free ends. For instance, if *x*=0 mm and λ_a = 1.0; 0.2, the shear stress $\overset{\therefore}{\tau}_a$ reaches the values of 16 MPa; 7 MPa, respectively. However, if *x*=40 mm and λ_a = 1.0; 0.2, the shear stress $\overset{\therefore}{\tau}_a$ reaches its maximum values at 20 MPa; 8 MPa, respectively. Within the middle region of the adhesive joint, when $x \in [5; 35]$ mm, the observed relationship is reversed!

For better interpretation of the obtained results, the relationships are produced in the form of graphs with normalized axes for which the resulting system of units is dimensionless quantities for both axes. It is therefore assumed that there is a given ratio between the partial and total length of the adhesive joint, $\phi = x/l$, called "adhesive joint ratio". Similarly, a given ratio between the sustainable shear stress and the classical shear stress is defined as $\Lambda = \ddot{\tau}_a / \tau_a$ and called "shear stress eco-ratio"

The relationships between Λ and ϕ for different values of λ_a are presented in Fig. 4. The shear stress distributions are normalized by τ_a (*i.e.*, classical shear stress that corresponds to $\lambda_a=1$). It can be seen from Fig. 4 that points of intersection between normalized curves occur when ϕ is equal to 0.11 and 0.88 and all maximums occur at the same value of $\phi=0.5$. The effect of varying λ_a is seen to be significant when $0.11<\phi<0.88$, mainly for $\lambda_a=0.2$.

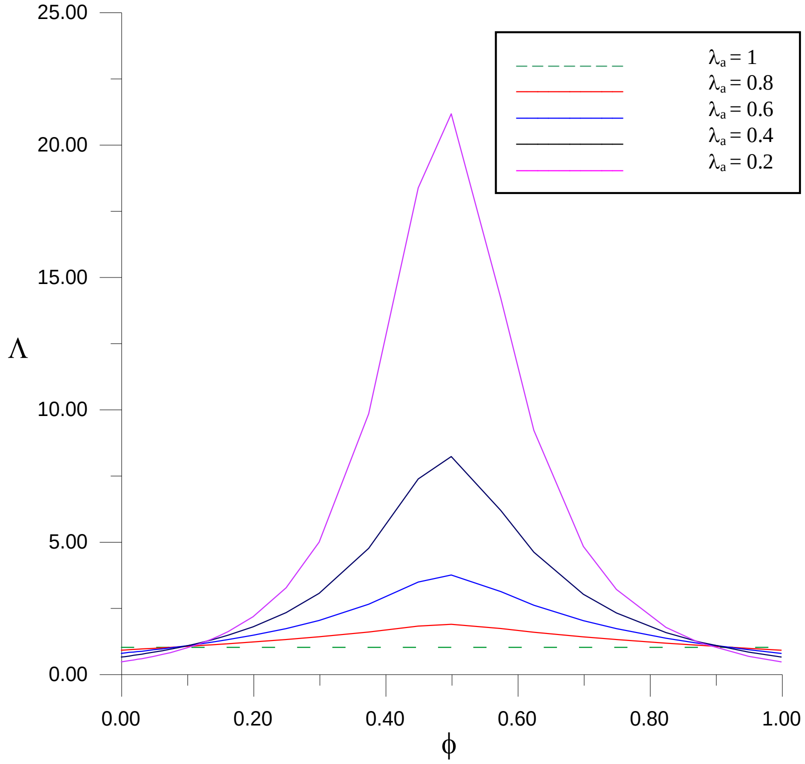


Fig. 4 Normalized relationships between Λ and ϕ for different values of λ_a

V. CONCLUSION

To meet the requirements of REACH through the concept of ecobonding, a key factor named "elastic shear eco-factor" and denoted by the character λ_a was integrated into the classical formulation of adhesively-bonded blade composite parts. This eco-factor takes into account a combination of the three related and complementary dimensions of sustainability, which are characterized by Quality assurance, Health protection and Environment preservation aspects.

Normalized curves illustrating the shear stress distributions through the adhesive joint length for different values of λ_a were presented; and by simply undertaking a comparison between ecological and classical results, structural designers and engineers involved in adhesive bonding applications can improve the performance of the ecobonding process through an explicit assessment of the *Q-H-E* interrelated issues.

Specific recommendations on bonding processes are to give particular attention to (i) chemical substances used in the bonding process, (ii) the amount of VOC emissions, (iii) the performance improvement level of *Q-H-E* interrelated issues, (iv) the amount of expired adhesives and possible ways of recycling, (v) research and innovation activities aiming to put in place new regulations and eco-standards, and so forth.

ACKNOWLEDGMENTS

The author would like to thank Dr. R. Tiberkak and Dr. M. Bachene for their assistance during this study.

REFERENCES

[1] P. Schubel, "Technical cost modelling for a generic 45-m wind turbine blade produced by vacuum infusion," Renewable energy 35, N°1. 2010, p. 183-18.

[2] B. Attaf and L. Hollaway, "Vibrational analyses of glass reinforced polyester composite plates reinforced by a minimum mass central stiffener," Composites Vol.21, N°5, 1990, p. 425-430.

[3] B. Attaf, "Towards the optimisation of the ecodesign function for composites," JEC Composites 34, 2007, p. 58-60.

[4] B. Attaf, "Generation of new eco-friendly composite materials via the integration of ecodesign coefficients," In Brahim Attaf (ed.), Advances in composite materials-Ecodesign and analysis. Intech Open Access Publisher, 2011, p.1-20.

[5] B. Attaf, "Ecomoulding of Composite Wind Turbine Blades Using Green Manufacturing RTM Process," ISRN Materials Science, vol. 2012, Article ID 734328, 9 pages.

[6] B. Attaf, "Probability approach in ecodesign of fibre-reinforced composite structures," Congrès Algérien de Mécanique, 2009, Algeria.

[7] B. Attaf, "Eco-characterisation of composite materials," JEC Composites 42, 2008, p. 58-60.

[8] D. Gay, Matériaux composites. 2ème édition. Paris: Hermes, 1989, p. 497-508.

[9] B. Attaf, "Structural ecodesign of onshore and offshore composite wind turbine blades," 1ère Conférence Franco-Syrienne sur les énergies renouvelables, 2010, Damascus, Syria.

[10] B. Attaf, "Eco-conception et développement des pales d'éoliennes en matériaux composites," 1er Séminaire Méditerranéen sur l'Energie Eolienne, 2010, Algeria.

Brahim Attaf works as an independent Expert/Researcher in the field of composite materials and structures. He obtained his Engineering degree from the Ecole Nationale Polytechnique of Algiers (ENPA), Algiers, Algeria, in 1985, and then his Ph.D. degree from the University of Surrey, Guildford, UK, in 1990.

He has previously worked as a Lecturer/Researcher (Maitre de Conferences) within the Departments of Aeronautics, Mechanics and Civil Engineering at the University of Blida in Algeria (1990–2000), and he was responsible for design office and quality assurance with composite firms in France (2000–2003). Since 2003 he has been independently involved in sustainability research actions leading to ecodesign of composite materials and structures through the integration of environmental and health aspects into product lifecycle. His main research and teaching interests focus on vibration and stability analyses of composite structures subjected to hygrothermomechanical loading using finite-element approach and experimental investigations.

Dr. Attaf has published many scientific papers, edited two books, and successfully trained/supervised many engineers and postgraduate students (Master's and Ph.D.'s).