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INTELLIGENT MODELING OF WOVEN MATERIALS

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ABSTRACT

This paper shows the particular application of the general approach "Intelligent Optimal Design" to the design of a woven composite material used to make radomes and for which the mechanical and electromagnetical properties have to satisfy special properties. Although the design of such a material needs the control of almost 50 design parameters, with a very limited number of examples of materials in the data base, but with a special description of each material, it is possible to extract the rules necessary to predict the behaviour of any new material with a rather good accuracy and thereafter, to reach the optimal design (minimum cost) associated to any new requirements.

INTRODUCTION

Due to the economical and safety considerations, the engineers are forced to find the optimal design of their structures when multiphysical aspects have to be considered. Although they have sophisticated experimental set-ups, beautiful theories/models and powerful numerical tools, usually, they can not afford to realize several tests or simulations to extract the "best" case and they have to face still several lockings in their industrial world:

- no satisfactory constitutive modeling of materials, no real control of the accuracy of the numerical simulations, no real definition of the initial state and/or the effective loading of the structure
 - no insurance to have noted and measured the main signals during the tests or the returns of experiments, usually, no perfect repetability of the tests
 - the results predicted by the theories/models are often very far from the experimental ones.
- These problems have no a complete solution as the experts do not understand them in their whole.

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Moreover, the available data are often not statistically representative (limited number), fuzzy, qualitative and missing in part.

To overcross these lockings, the actual best knowledge of the researchers/experts have to be intelligently mixed with the results of experiments or real returns.

That it is why, a new approach "the intelligent optimal design of materials and structures" was elaborated, see full details in the book J. Zarka et al (2000). In this approach it is needed:

i) to build a DATA BASE of examples i.e. to obtain some experimental, real or simulated results where the EXPERTS indicate all variables or descriptors which may take a part. This is, at first, done with some PRIMITIVE descriptors x , which are often in a different number and different types for each example. Then, the data are transformed with the introduction of some INTELLIGENT descriptors xx , with the actual whole knowledge thanks to (but usually insufficient) beautiful theories and models. These descriptors may be number, boolean, strings, names of files which give access to data bases, or treatments of curves, signals and images. Now, for all examples, their number and their type are always the same which is the only one way to allow the *fusion of data*. The results or conclusions may be classes (good, not good, ...) or numbers.

ii) to generate the RULES with any Automatic Learning Tool (based on logical rules, statistics, machine learning, numerical learning, fuzzy logic, neural networks...). Each conclusion is explained as function or set of rules of some among the input intelligent descriptors with a known reliability or accuracy.

iii) to optimize at two levels (Inverse Problems):

- considering the intelligent descriptors as independent; it is possible to get the OPTIMAL SOLUTION satisfying the special required properties

and allowing the DISCOVERY OF NEW MECHANISMS,

- considering the intelligent descriptors linked to primitive descriptors for a special family; it is possible to obtain the optimal solution which is technologically possible.

So, not only a Practical Optimal Solution is obtained but also the Experts may learn the missing parts, may build models or theories based only on the retained intelligent descriptors and guided by the shapes of the rules or relationships.

Composites are more and more often used in the mechanical engineering, the civil engineering, the automotive, the aeronautical and the naval industries. It is necessary to reduce their acquisition cost while improving the life cycle and safety of the structures.

Many general contributions have been made to understand the physics and to develop models for the mechanical, electromagnetical global properties of aggregates during the modeling which is called homogenization. Simplified models, simple bounds of the properties or and even sophisticated theories ... were produced.

In the case of the woven composites, idealized geometry and even numerical finite element methods due to the complex geometry, were also done. The simulated results are sometimes near from the real experimental ones, but very often they do not give sufficient elements to be used into the real design.

This design implies a multiphysics problem: how to design the optimal woven composite (i.e. to give the composition and the process) for any special application when, only a few tests are available (due to the cost in money and time) and when the simulated predictions are not reliable.

Textile composite materials are woven fabrics with more efficient properties than layered composites. The description of the process is rather difficult: fibers are used to make bundles which are then intertwined according several types.

Here, we consider only a special hybrid woven composite where in one bundle one or two fibers are used and where one or two bundles are used for the warp and the fill in one layer. The geometrical description for the layer was given by the University of Technology of Compiègne. All the fabrics are made with 16 identical layers.

BUILDING THE DATA BASE

Eleven different fibers are available. Each fiber is fully characterized from a data base of materials. Only one resin is used and characterized.

STARTING POINT: DATA BASE FOR THE BASIC MATERIALS											
E_trac_F	73	55	86	85	72	14	248	35	104.3	100	4
Poisson_F	0.17	0.2	0.2	0.2	0.2	0.4	0.2	0.2	0.2	0.2	0.2
Permittiv_F	6.13	4	6	3.9	3.78	3	2.08	3.1	3.3	2.2	3.5
Spec_Mass_F	2.59	2.14	2.53	1.8	2.2	1.38	2.1	1.3	1.41	0.97	1.22
Spec_Price_F	50	450	175	250	900	35	600	1000	900	750	1000
RESIN											
E_trac_R	3.52										
Poisson_R	0.3										
eps_R	2.6										
tg_perle_R	4										
Spe_Mass_R	1.05										
Spe_Price_R	786										

Figure 1: Data for the basic elements

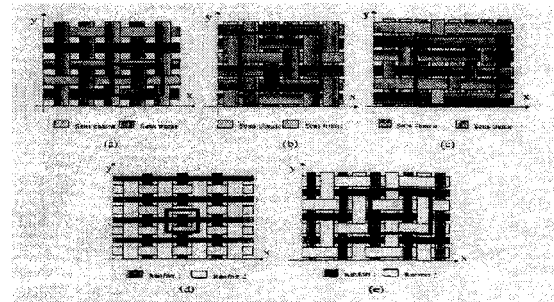


Figure 2: Position of the bundles in the fabric

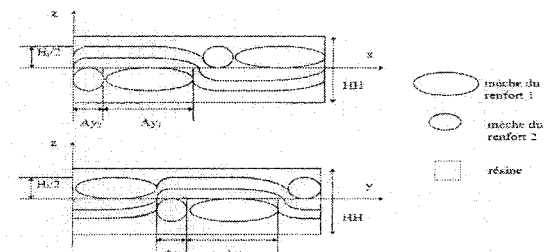


Figure 3: Definition of microscopic parameters

PRIMITIVE DESCRIPTION

The composite materials are all equilibrated fabrics with a constant step of 2: i.e. the two bundles in the warp and the fill are the same. Usually, the fabric is characterized by the macroscopic parameters:

- Porosity (x%) (rather difficult to control !)
- Nature of fibers (Glass, Peek..among the selected eleven fibers)
- Total_weight of fibers per unit surface in one layer (zzz gr)
- Hybridation_massic_ratio for the two bundles

$$Tx 1 = \frac{\text{mass (fiber 1)}}{\text{mass (fiber 1) + mass (fiber 2)}}$$

$$Tx 2 = \frac{\text{mass (fiber 2)}}{\text{mass (fiber 1) + mass (fiber 2)}}$$

- Thickness of the fabric
- Nature of the resin (here only one).

For this special problem, there are 49 active design parameters (twice {22 for each fiber: 0 or 1

selected or not, the concentration, with the number of fibers in the bundle)) + 5 for the process.

ACTIVE PARAMETERS FOR BUNDLE 1											
Glass_E	Glass_D	Glass_R	Glass_S2	Silica	Polyester	PTFE	PEEK	Vectran HS	PEHT	PEI	NUMB_FIBERS
0	0	0	0	0	0	0	0	0	1	0	0
77.93	85.85	75.95	73.74	76.66	80.08	75.02	79.00	75.93	80.48	84.25	1

ACTIVE PARAMETERS FOR BUNDLE 2											
Glass_E	Glass_D	Glass_R	Glass_S2	Silica	Polyester	PTFE	PEEK	Vectran HS	PEHT	PEI	NUMB_FIBERS
0	0	0	0	0	0	0	0	0	1	0	0
77.93	85.85	75.95	73.74	76.66	80.08	75.02	79.00	75.93	80.48	84.25	1

ACTIVE PARAMETERS FOR THE FABRIC											
Porosity	10										
Grain/mg	180										
HybridB1	65										
HybridB2	35										
Thickness	4.5										

Figure 4: Primitive active design parameters

A Design of Experiments (DOE) is impossible.

Indeed, only sixteen woven composite materials were ordered. At the AIA/CP, they were, then, mechanically characterized according the classical normalized tests: the resistance and the elastic modulus in tension, as in compression, flexion, and shearing, are defined and measured.

The fabrics were also electromagnetically characterized: the dielectric constant and the loss tangent are measured.

At last, at UTC, some microscopic parameters were measured by cutting the fabric:

- A_{y1} : width of the first bundle
- A_{y2} : width of the second bundle
- H_i : height of one wave of fibers
- HH : height of one layer (the thickness of the fabric is here $16 \times HH$).

ref_CVR	Hybridation %	Total_waiv_fibers	TVF %	TMR %	porosity	Ay1	Ay2	HH	HT
2628	100%Silica(GCQ)	270.00	46.30	35.60	0.00	0.59	0.59	0.29	0.27
2529	100%Glass_E	290.00	54.80	25.40	1.06	1.90	1.90	0.31	0.31
2397	100%Glass_D	260.00	47.60	34.80	0.00	0.96	0.96	0.26	0.26
2407	52%Silica/48%Polyester	180.00	51.70	33.80	5.68	0.58	0.80	0.18	0.18
2414	54.5%Glass_E/45.5%Polyester	253.00	48.00	36.70	5.69	0.58	0.53	0.28	0.25
2412	51.5%Glass_D/48.5%Polyester	273.00	51.10	34.00	1.96	0.57	0.56	0.28	0.27
2408	64%Silica/36%PEHT	254.80	49.30	40.70	13.38	0.63	0.55	0.33	0.30
2418	75.2%Glass_S2/24.8%PEI	248.80	54.30	35.80	2.56	0.62	0.71	0.29	0.29
2419	49%Glass_S2/51%PEHT	262.00	48.90	43.50	3.02	0.63	0.61	0.38	0.33
2420	100%Vectran	270.00	47.00	43.80	6.56	0.92	0.92	0.41	0.37
2475	71.8%Silica/28.2%PEI	266.00	49.10	36.20	7.89	0.62	0.70	0.29	0.27
2470	73.4%Glass_E/26.6%PEEK	260.00	48.30	34.90	6.62	0.74	0.87	0.25	0.24
2471	59%Glass_D/41%PEEK	260.00	50.90	36.10	6.80	0.62	0.65	0.25	0.24
2474	59.7%Silica/40.3%PTFE	253.00	54.60	28.60	9.63	1.00	0.95	0.25	0.25
2478	60%Silica/40%PTFE/10%PEEK	267.00	45.30	38.30	0.00	0.63	0.66	0.26	0.23
2484	65%Glass_D/35%Vectran/24.5%PEHT	259.00	48.60	41.10	7.14	0.78	0.55	0.34	0.31

ref_CVR	EI	sigma_l	Ec	sigma_c	Ef	sigma_f	S13	eps	tg_loss
2628	15.40	347.00	1940	102.00	15.60	169.00	18.70	2.89	0.003
2529	24.70	443.00	23.40	186.00	21.10	293.00	27.60	4.39	0.011
2397	11.50	245.50	15.50	118.20	12.50	223.20	18.10	3.20	0.006
2407	13.40	324.70	16.50	82.20	11.10	162.30	11.20	3.03	0.004
2414	11.00	225.00	13.60	81.00	11.50	143.00	15.00	3.62	0.010
2412	9.90	196.00	13.80	90.90	12.40	157.00	14.90	3.22	0.005
2408	12.30	342.00	13.90	47.00	11.50	88.80	8.00	2.64	0.002
2418	10.60	283.00	13.30	83.00	12.00	150.00	16.90	3.16	0.012
2419	9.90	351.00	13.00	63.50	14.40	123.00	13.50	2.94	0.015
2420	11.80	417.00	12.50	46.00	14.10	156.00	10.70	2.85	0.003
2475	13.20	342.00	16.80	90.00	13.50	139.00	16.40	2.94	0.003
2470	15.20	260.00	15.20	88.00	13.80	149.00	17.00	3.82	0.009
2471	10.00	162.00	10.00	84.00	9.30	133.00	14.30	3.10	0.007
2474	14.30	325.00	15.10	83.00	12.80	158.00	9.80	2.82	0.005
2478	12.30	303.00	14.00	68.00	14.50	127.00	13.20	2.76	0.006
2483	15.00	305.00	14.80	63.00	13.00	128.00	13.20	3.33	0.010
2484	13.20	218.00	13.20	59.00	13.20	119.00	12.70	2.84	0.004

Figure 5: Experimental data on the woven fabrics

INTELLIGENT DESCRIPTION

It is impossible with the classical mathematical tools of data analysis to represent these results.

There is no enough tests. We need to be able to make the fusion of the different fibers in the bundles and of the different fabric parameters.

For that, we use the actual knowledges.

- For one bundle i.e. one dimensional composite, analytical approximated models for the elastic and electromagnetic properties are available.

This is also the case for layer with straight bundles.

- As a rough approximation, at first, it was assumed that the woven fabric is assimilated to a layered material with the warp in one layer and the yarn in the other layer with a 90° angle.

- Then, quasi-analytical models and finite element based models were also built. (the calculations of the elastic properties were made in one internal report of UTC based on the Ishikawa and Chou's works.

- For the electromagnetic properties, we use for one fiber, the Bruggeman's model and for two different fibers, the Kingery's model.

Even if these simulated results are not very well representative of the experimental values on the fabrics, they allow to make the fusion and to help the learnings.

The set of the values predicted by these models are here our intelligent descriptors.

Successively, for each case or material, described by its active design parameters or primitive descriptors, we have analytically, the mass and the price of the fabric, and the bundles properties.

We compute these intelligent descriptors based on the models for layered composites and woven composites.

AUTOMATIC LEARNINGS

Once the data base of examples has been created within its intelligent description, it is possible to learn the various conclusions as functions of these intelligent descriptors.

More than that, we were able to learn the intelligent descriptors directly from the primitive descriptors as functions of functions.

For this special problem, we used general regression net or polynomial net in NeuroShell from Wards systems. They are both based on numerical learnings.

Then, after all these learnings, we are able to compute the other intelligent descriptors:

- for the process

A_{y1} first bundle, A_{y2} second bundle

H_i wave of fibers, HH one layer.

1. ACTIVE PARAMETERS FOR BUNDLE 1											
Class_E	Class_D	Class_S2	Class_P	Class_F	Class_P2	Class_F2	Class_P3	Class_F3	Class_P4	Class_F4	Class_P5
7153	85.93	71.74	76.66	80.08	75.82	79.90	75.93	80.46	84.25		
500	0.00	800	1.00	500	0.00	800	0.00	800	0.00		
7151	85.95	71.74	76.66	80.08	75.82	79.90	75.93	80.46	84.25		
2. ACTIVE PARAMETERS FOR BUNDLE 2											
Class_E	Class_D	Class_S2	Class_P	Class_F	Class_P2	Class_F2	Class_P3	Class_F3	Class_P4	Class_F4	Class_P5
500	0.00	800	1.00	500	0.00	800	0.00	800	0.00		
7151	85.95	71.74	76.66	80.08	75.82	79.90	75.93	80.46	84.25		
3. ACTIVE PARAMETERS FOR BUNDLE 3											
Class_E	Class_D	Class_S2	Class_P	Class_F	Class_P2	Class_F2	Class_P3	Class_F3	Class_P4	Class_F4	Class_P5
500	0.00	800	1.00	500	0.00	800	0.00	800	0.00		
7151	85.95	71.74	76.66	80.08	75.82	79.90	75.93	80.46	84.25		

Figure 6: Fusions of fibers

Porosity	1.90		
grammage	196.64		
Txyth	52.13		
Txyth2	47.87		
Thickness	4.00		
MICROSCOPIC PARAMETERS OF THE FABRIC (process)			
Widthing			
Ay1	0.80		
Ay2	0.65		
HT	0.21		
HH	0.25		
MASS AND PRICE OF THE WOVEN COMPOSITE MATERIAL			
From exact analytical expressions			
Visc	4900.00	Vib+Vres	3924.80 Vres
Mib1	3146.58	Vib1	781.11 Mres
Mib2	1648.34	Vib2	1026.15
Mass_comp	569.349	Price_comp	3889.82

Figure 7: Evaluations for microstructure and price

- for the layers with straight bundles

EXM1, EYM1, NUXYM1, NUYXM1, GXYM1
EXM2, EYM2, NUXYM2, NUYXM2, GXYM2
for the fabric

Eps_th, simulated permittivity

Exy_th, Poisson_th and Gxy_th simulated elastic coefficients.

We build these descriptors for all the 16 examples.

SIMULATED ELASTIC PROPERTIES											
FOR LAYER WITH STRAIGHT BUNDLE 1						FOR LAYER WITH STRAIGHT BUNDLE 2					
EXM1	4.1516175					EXM2	7.44831496				
EYM1	4.13247603					EYM2	4.39191131				
NUXYM1	0.22352363					NUXYM2	0.24199844				
NUYXM1	0.22249305					NUYXM2	0.14269478				
GXYM1	1.84063346					GXYM2	1.96926104				
SIMULATED ELECTROMAGNETIC PROPERTIES FOR THE FABRIC											
Volbund1	1024.16284										
Volbund2	885.35213										
Eps fib1	2.08										
Eps fib2	2.08										
Eps th	2.84912875										

Figure 8: Evaluations for straight bundle layers

SIMULATED MECHANICAL PROPERTIES FOR THE WOVEN COMPOSITE MATERIAL											
Mass_resin	2546.91	Min	1296.00	Max	4710.00						
Porosity	0.02	Min	0.00	Max	0.13						
a1	0.80	Min	0.50	Max	2.00						
a2	0.65	Min	0.50	Max	2.00						
HT	0.21	Min	0.17	Max	0.50						
HH	0.25	Min	0.18	Max	0.41						
EXM1	4.15	Min	39.69	Max	78.95						
EYM1	4.13	Min	15.94	Max	24.79						
NUXYM1	0.22	Min	0.21	Max	0.22						
NUYXM1	0.22	Min	0.06	Max	0.10						
GXYM1	1.84	Min	6.38	Max	10.11						
EXM2	7.45	Min	2.75	Max	78.95						
EYM2	4.39	Min	2.71	Max	24.79						
NUXYM2	0.24	Min	0.21	Max	0.30						
NUYXM2	0.14	Min	0.06	Max	0.25						
						Exy_th			13.39		
						Gxy_th			3.88		
						Poisson_th			0.19		

Figure 9: First evaluations for the woven fabric

Then, we can after all these learnings, give the

prediction for the real measured experimental conclusions or values of the fabric:

Ft, Fsigmat, Fc, Fsigmac, Ff, Fsigmaf, FS13, Eps and t Tg-loss.

FINAL PREDICTIONS											
Mass_resin	2546.91	Min	1000.00	Max	4710.00						
Porosity	0.02	Min	0.00	Max	0.13						
a1	0.80	Min	0.50	Max	2.00						
a2	0.65	Min	0.50	Max	2.00						
HT	0.25	Min	0.17	Max	0.50						
HT	0.21	Min	0.18	Max	0.41						
EXM1	4.15	Min	39.69	Max	78.95						
EYM1	4.13	Min	15.94	Max	24.79						
NUXYM1	0.22	Min	0.21	Max	0.22						
NUYXM1	0.22	Min	0.06	Max	0.10						
GXYM1	1.84	Min	6.38	Max	10.11						
EXM2	7.45	Min	2.75	Max	78.95						
EYM2	4.39	Min	2.71	Max	24.79						
NUXYM2	0.24	Min	0.21	Max	0.30						
NUYXM2	0.14	Min	0.06	Max	0.25						
GXYM2	1.97	Min	1.11	Max	10.11						
Exy_th	13.39	Min	10.90	Max	28.32						
Gxy_th	3.88	Min	3.15	Max	6.96						
Poisson_th	0.19	Min	0.13	Max	0.21						
eps_th	2.85	Min	2.68	Max	4.29						
PREDICTED ELECTROMAGNETIC PROPERTIES FOR THE WOVEN COMPOSITE MATERIAL											
eps	1.88					tg_loss	0.01				
PREDICTED MECHANICAL PROPERTIES FOR THE WOVEN COMPOSITE MATERIAL											
Ft	73.73					Fc	1.41				
Fsigmat	1765.37					Fsigmac	205.70				
FS13	41.49					Fsigmaf	11475.51				

Figure 10: Final predictions for the woven fabric

OPTIMAL DESIGN OF THE WOVEN FABRIC

Indeed, this approach allows to go much further and to answer to the real problem: we have to design the fabric such that its mechanical and electromagnetic properties satisfy some requirements.

We may assume that, for economical reasons, this fabric must be obtained at the lowest price but any other objective function may be taken.

This optimization problem is very difficult as, here also, there is no convexity of the functions, moreover, even if we have a reasonable representation of the functions this is not the case of their gradient. Only particular algorithms may be used. However, as all our functions are represented analytically (polynomial functions), and do not imply any new finite element analysis or test, the time to evaluate them is very short even within the program EXCEL. We use the add-on Genehunter of Wards Systems to have the total integration of this Optimal Design of the Woven Fabric.

It is elementary to introduce any new constraint on the design variables or on the conclusions or between the conclusions by referencing the particular cells.

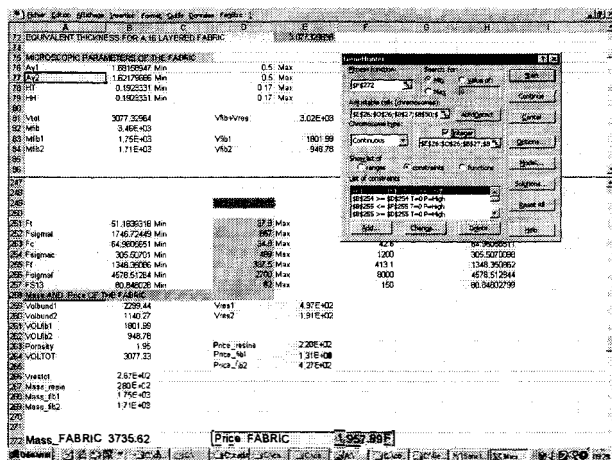


Figure 11: Intelligent optimal design tool

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