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# "INTELLIGENT" OPTIMAL DESIGN OF MATERIALS AND STRUCTURES WHAT DOES IT MEAN ?

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## ABSTRACT

The engineers have to face very important problems in the design, the test, the survey and the maintenance of their structures. These problems did not yet get full answer even from the best people in the world. Usually in these problems (such as 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), there is no solution and the experts do not understand the problem in its whole. Moreover, the available data may be not statistically representative (i.e. are in limited number), fuzzy, qualitative and missing in part.

We propose a practical solution the « Intelligent Optimal Design of Materials and Structures » where the actual best knowledges of the researchers/experts are intelligently mixed to the results of experiments or real returns. Several examples of applications are given in this serial set of papers to explain the real meaning and power of this approach.

## INTRODUCTION

We have defined a new framework where it is needed:

i) To build a DATABASE of examples i.e. to obtain some experimental, real or simulated results where the EXPERTS indicate all variables or descriptors this may take a part. This is, at first, done with some PRIMITIVE descriptors  $x$ , which are usually in a limited number and which are often in a different number for each example. Then, the data are transformed with the introduction of some INTELLIGENT descriptors  $XX$ , with the actual whole knowledge thanks to (but often 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. But 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. Each conclusion is explained as function or set of rules of some among the input intelligent descriptors with a known reliability or accuracy.

ii) 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 that 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.

We shall give several examples of applications to explain its meaning but also to show its simplicity and its efficiency.

## THE OPTIMAL DESIGN OF STRUCTURES WITH A DIRECT LINK TO CAD

(with P. Navidi)

We consider the optimal design of a beam. To improve the safety of a car during the crash, it is needed to dissipate the maximum of energy within a limited displacement but with a limited acceleration at the level of the driver/passengers. The beam may have different complex cells linked with continuous or spot solder.

a) Building the data base

In order to obtain the basic input of the problem,

i) at first, we need to create beams with particular sections (many of these sections result from our imagination, since we need to obtain different types) and with different assemblies,

ii) then, we need to look at their behaviour during the crash. This behavior may be obtained from real dynamical experimental tests or from numerical simulations. For sake of independence from the cars companies, (although we think that experimental tests would have been much better), we have selected to use only the numerical simulations. Indeed, we used the program ALGOR from ALGOR inc to generate the meshes, the program RADIOSS from MECALOG for the dynamical crash loadings and the program NISA from EMRC for the static loadings and the description of the beam sections).

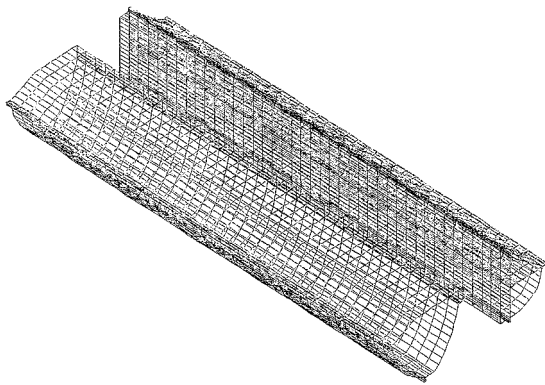


Figure 1: Examples of beams

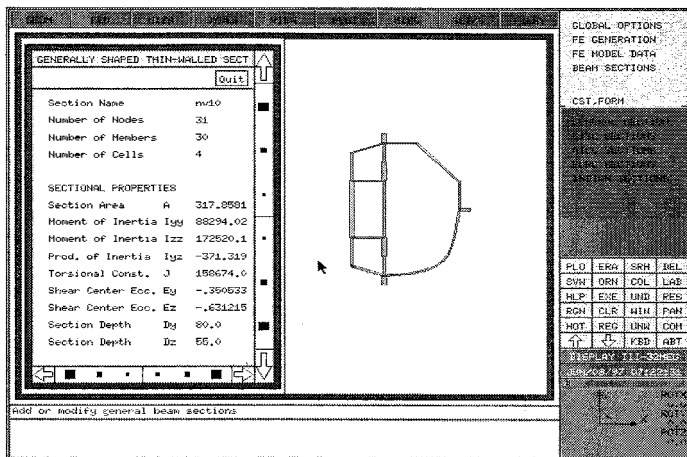


Figure 2: Definition of the section within the CAD system

Let us assume that the beam sections are already in the CAD system as shown in the figure and that they have all the same length of 400 mm.

In the NISA program, it is indicated how to represent the geometry of each beam section.

Of course, the number of the primitive descriptors and the nature of each of them are different for each type of section.

The following classical properties may be computed by the program:

area of cross-section, Y-coordinate of centroid, Z-coordinate of centroid, principal axes of orientation with respect to Y, Z axes, moment of inertia about Y-axis, moment of inertia about Z-axis, product of inertia about Y, Z-axes, principal moments of inertia, section modulus about centroid Y-axis, section modulus about centroid Z-axis, warping constant, torsion constant, shear center eccentricity with centroid in Y-direction, shear center eccentricity with centroid in Z-direction, depth in Y-direction, depth in Z-direction...**They represent the actual knowledge of the experts on beam sections and are the Intelligent descriptors to be introduced.**

This implies that each type of section (class) has to be treated separately as one object in a data base file. According to its type, a special treatment is made to recover the data blocks (which are primitive descriptors) from which systematically at least the properties (which are the *intelligent descriptors*) are always produced. It is obvious that these properties are univocally linked to the primitive descriptors and that the relations are not one-to-one relations i.e. that for given values of these INTELLIGENT descriptors, there might be an infinite number of PRIMITIVE descriptors.

In the same way, it is necessary to find intelligent descriptors to characterize the assembly of the beam.

Here, we have considered only weld spots which are with the steps 10, 40 and 50 mm (but any other type may be considered in the same way), different sizes and different number of spots.

Each weld spot may be assimilated to a small beam with properties (which are constant, and then no taken into account, if the same robot is used) modified according the size of the spot. The number of spots gives the number of such beams. Moreover, we have found that the *global moment of torsion* which is necessary to apply to the beam to reach a given angle of torsion, can be sufficient to characterize the assembly. The analysis was made with ALGOR and NISA.

So, we have described each beam from the INPUT PRIMITIVE DESCRIPTORS to the INPUT INTELLIGENT DESCRIPTORS.

Now, we have to complete the input data with the CONCLUSIONS DESCRIPTORS which are obtained after doing the dynamical CRASH simulation with RADIOSS. The loading is always the same : one end is clamped and on the other one one rigid mass of 100 kg is sended at the initial speed of 10m/s. We compute the resulting axial force on this extremity and the dissipated energy in function of the time. We keep only the MAXIMUM OF THE FORCE and the value of the

DISSIPATED ENERGY for a displacement of 15 mm from this analysis. On a Silicon graphics workstation (Indy R 4400), each example of beam needs about 1 to 2 hours.

We created only ~ 70 cases in the examples base. The total duration for this data base was about 4 month-man.

### b) Generating the rules with LES in its numerical version

We obtain for the dissipated energy:  

$$\begin{aligned} \text{NRJ-INT} = & -1.85e-02 * \text{IZZ} + 2.04e+03 * \text{DZ} + 4.84e-02 * \\ & \text{MOMENT-TORSION} + -6.95e-01 * \text{J} + \\ & -1.07e-04 * \text{SURF} * \text{IYY} - 1.98e-04 * \text{SURF} * \text{MOMENT-} \\ & \text{TORSION} + 1.24e-03 * \text{SURF} * \text{IZZ} + \\ & -3.34e-04 * \text{J} * \text{NB-BEAM} + 9.88e-07 * \text{IZZ} * \text{J} - 1.26e-03 \\ & * \text{J} * \text{STEP} + -1.79e-04 * \text{DZ} * \text{MOMENT-TORSION} + \\ & -7.50e-13 * \text{IZZ} **2 * \text{J} + 9.00e-07 * \text{IZZ} * \text{NB-BEAM} \\ & **2 + 5.57e-06 * \text{IZZ} * \text{STEP} **2 + \\ & 8.76e-03 * \text{DZ} **2 * \text{STEP} - 4.08e-10 * \text{SURF} * \text{IZZ} **2 \\ & + 1.95e-19 * \text{IZZ} **2 * \text{J} **2 \end{aligned}$$

A similar expression may be deduced for the **EFF-MAX**.

But it is possible (and recommended) to learn the **MOMENT-TORSION** as a function of the intelligent descriptors of the beam and of the primitive descriptors of the weld.

So, it is possible to give the response of ANY new type of beam and assembly.

### c) Optimization

It is useful to look at the general optimization of the beam in the space of the intelligent descriptors assuming them as independent (even if they are coming from the primitive descriptors and have links between them for each type of section and assembly).

We impose that the **EFF-MAX** has to be lower than 150,000 N and the intervals of definition of the intelligent descriptors are obtained from the limits in the data base, we looked after the solution which allows the maximum of the **NRJ-INT**. We found:

**NRJ-INT** = 6 672 127 J with **EFF-MAX** = 11 200 N for a special set of the descriptors.

This fictitious solution shows a very great improvement and is very different from the examples created in the data base. This means that, may be, some researches have to be done to try to discover if it is possible to realize such a beam associated to this special set of descriptors and to try to understand it. *But this may be a very heavy task !*

Now, we look at the optimization for one particular class of beam section in order to be sure of reaching a real technological solution. We focus, in the CAD system, to a special class of beam section, the symmetrical "double-hat" section.

Although, there are only 4 primitive descriptors to describe it, the number of intelligent descriptors are always the same and the previous learning for

**NRJ-INT** and **EFF-MAX** are always valid. The intelligent descriptors of the section have been learned as function of the 4

primitive descriptors even if they result from analytical expression.

For the double hat section and the assembly by weld, a *final tool* is given in the design office which may perform any new design for any new requirements almost instantaneously; we integrate all the learnings within Excel (from Microsoft) to obtain with **GENEHUNTER** from Wards System, the optimal solution.

For example if we assume only assemblies with welding and we force the number of weld spots to be defined by:

$$\text{NB-BEAM} = 2 * (400 / \text{STEP} + 1)$$

and we add the constraints for the primitive descriptors:

$$10 < \text{LENGTH1} < 20,$$

$$35 < \text{LENGTH2} < 60,$$

$$30 < \text{HEIGHT} < 60,$$

$$0.8 < \text{THICK} < 1.5,$$

$$10 < \text{STEP} < 50$$

and on the output/conclusion descriptor

$$\text{EFF-MAX} < 150\ 000\ \text{N}.$$

The optimal solution is defined by :

$$\text{LENGTH1} = 18.38, \text{LENGTH2} = 39.5, \text{HEIGHT} = 47.28, \text{THICK} = 1.499, \text{STEP} = 10 \text{ (then NB-BEAM} = 81)$$

for which the dissipated energy is **NRJ-INT** = 2 000 000 J and the maximum force **EFF-MAX** = 154 999 N.

To verify that these predictions are reasonable, we perform then the whole analysis with the primitive descriptors with **RADIOSS**; we find that **NRJ-INT** = 1 953 500 J and **EFF-MAX** = 155 540 N.

That means only few percents of errors and what can be considered as strictly sufficient. (less than 4 % of the values obtained by making the numerical analysis with **RADIOSS** but without any computation !!).

## INTELLIGENT MODELLING OF MATERIALS

(with T. Doux)

Composites are continuing to gain enormous uses 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.

Over several decades, many general contributions have been made to understand the physics and to develop models for the mechanical, electromagnetic global properties of aggregates during this modeling called homogenization. Several general papers on simplified models, simple bounds of the properties or and even sophisticated theories ... were produced. Books such as *Micromechanics: overall properties of heterogeneous materials*, (North-Holland) by Nemat-Nasser et al (1999), gave a general view of the state of the art in this fundamental area.

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.

The challenge is thus the following one: 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 with woven, braided or knitted fabrics have efficient properties. The description of the process is rather difficult: fibers are used to make bundles or yarns 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. We follow the geometrical description of the University of Technology of Compiègne for the layer. All the fabrics are made with 16 layers.

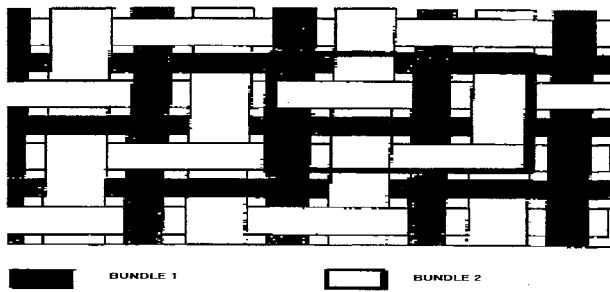


Figure 3: Relative position of the bundles in the fabric

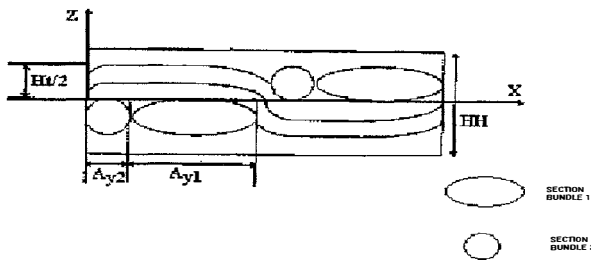


Figure 4: Definition of microscopic parameters

#### a) 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.

##### Primitive description of the data base:

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 ( $\chi^0\%$ )

Nature of fibers (Glass, Peek..among the eleven fibers)

Total\_weight of fibers per unit surface in one layer (zzz gr)

Hybridation\_massic\_ratio for the two bundles (Tx1 Glass

Tx2 Peek)

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

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

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. A Design of Experiments 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 are also electromagnetically characterized: the dielectric constant and the loss tangent are measured. Some microscopic parameters are at last measured by cutting the fabric:

$A_{y1}$ : width of the first bundle

$A_{y2}$ : width of the second bundle

$H_t$ : 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_wel_fibers | TVF%  | TMR%  | porosity | Ay1  | Ay2  | HH   | HT   |
|---------|--------------------------------------|------------------|-------|-------|----------|------|------|------|------|
| 2628    | 100% Silice (SiO2)                   | 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% Silice/48% Polyester             | 180.00           | 51.70 | 33.80 | 5.88     | 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 | 0.26 | 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% Silice/36% PEHT                  | 254.00           | 49.30 | 40.70 | 13.38    | 0.63 | 0.55 | 0.33 | 0.30 |
| 2416    | 75.2% Glass_S2/24.8 PEI              | 248.00           | 54.30 | 35.80 | 2.56     | 0.62 | 0.71 | 0.29 | 0.29 |
| 2419    | 45% Glass_S2/55 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 | 6.55     | 0.92 | 0.92 | 0.41 | 0.37 |
| 2475    | 71.8% Silice/28.2% PEI               | 266.00           | 49.10 | 36.20 | 7.89     | 0.62 | 0.70 | 0.29 | 0.27 |
| 2470    | 73.4% Glass_E/30.6% PEEK             | 260.00           | 48.30 | 34.90 | 6.62     | 0.74 | 0.59 | 0.26 | 0.24 |
| 2471    | 59% Glass_D/31% PEEK                 | 260.00           | 50.90 | 36.10 | 6.80     | 0.62 | 0.55 | 0.26 | 0.24 |
| 2474    | 59.7% Silice/40.3% PTFE              | 253.00           | 54.60 | 28.60 | 9.63     | 1.00 | 0.95 | 0.25 | 0.25 |
| 2478    | 60% Silice/25% PTFE/15% PEEK         | 267.00           | 45.30 | 38.30 | 0.00     | 0.63 | 0.66 | 0.26 | 0.23 |
| 2484    | 65% Glass_D/10.5% Vectran/24.5% PEHT | 259.00           | 48.60 | 41.10 | 7.14     | 0.78 | 0.55 | 0.34 | 0.31 |

TVF=Volume fibers

TMR=Resin content in % weight

| ref_CVR | Et    | sigma_t | Ec    | sigma_c | Ef    | sigma_f | S13   | eps  | tg_loss |
|---------|-------|---------|-------|---------|-------|---------|-------|------|---------|
| 2628    | 15.40 | 347.00  | 19.40 | 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 fabrics

*Intelligent description of the data base*

It is impossible with classical mathematical tools to represent these results. 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. It is also the case for layer with straight bundles.

For the woven fabric, there are quasi-analytical models and finite element based models. (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.

**b) Automatic learnings**

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. For this special problem, we use general regression net or polynomial net in Neuro-shell from Wards systems. They are both based on numerical learnings

Then, after learning, we are able to compute the other intelligent descriptors:

- for the process
- $A_{y1}$  first bundle ,  $A_{y2}$  second bundle
- $H_t$  wave of fibers, HH one layer
- for the layers with straight bundles
- EXM1, EYM1, NUXYM1, NUXXM1, GXYM1
- EXM2, EYM2, NUXYM2, NUXXM2, 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.

Then, we can after learning, give the real measured experimental conclusions or values of the fabric:

$F_t$ ,  $F_{\text{sigmat}}$ ,  $F_c$ ,  $F_{\text{sigmac}}$ ,  $F_f$ ,  $F_{\text{sigmaf}}$ ,  $FS13$ ,  $E_{\text{ps}}$  and  $t_{\text{Tg-loss}}$ .

**c) 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 end 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-inn Genehunter of Wards Systems to have the total integration of the 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.

| ACTIVE PARAMETERS FOR BUNDLE 1 |         |         |          |        |           |       |       |            |       |                 |
|--------------------------------|---------|---------|----------|--------|-----------|-------|-------|------------|-------|-----------------|
| Glass_E                        | Glass_D | Glass_R | Glass_S2 | Silice | Polyester | PTFE  | PEEK  | Vectran_HS | PEHT  | PEI NUMB_FIBERS |
| 0                              | 0       | 0       | 0        | 0      | 0         | 0     | 0     | 0          | 1     | 0               |
| 77.93                          | 85.95   | 75.95   | 73.74    | 76.66  | 80.08     | 75.02 | 79.00 | 75.93      | 80.46 | 84.25           |

| ACTIVE PARAMETERS FOR BUNDLE 2 |         |         |          |        |           |       |       |            |       |                 |
|--------------------------------|---------|---------|----------|--------|-----------|-------|-------|------------|-------|-----------------|
| Glass_E                        | Glass_D | Glass_R | Glass_S2 | Silice | Polyester | PTFE  | PEEK  | Vectran_HS | PEHT  | PEI NUMB_FIBERS |
| 0                              | 0       | 0       | 0        | 0      | 0         | 0     | 0     | 0          | 1     | 0               |
| 77.93                          | 85.95   | 75.95   | 73.74    | 76.66  | 80.08     | 75.02 | 79.00 | 75.93      | 80.46 | 84.25           |

| ACTIVE PARAMETERS FOR THE FABRIC |     |
|----------------------------------|-----|
| Porosity                         | 10  |
| Grammage                         | 180 |
| HybridB1                         | 65  |
| HybridB2                         | 35  |
| Thickness                        | 4.5 |

Figure 6: Primitive active design parameters

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

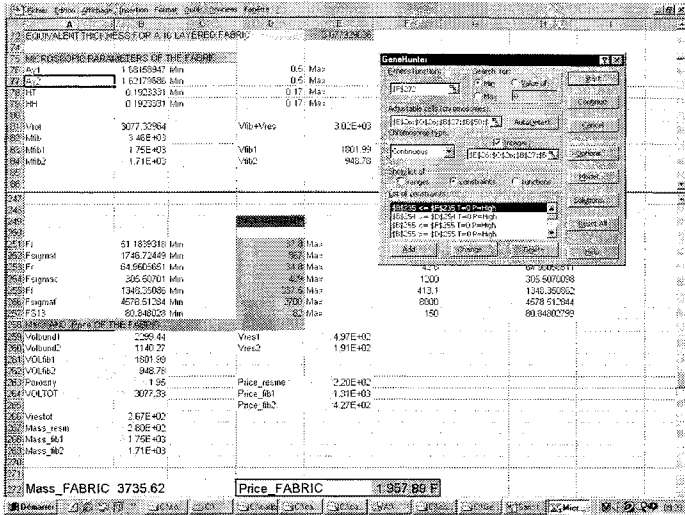


Figure 7: Example of an intelligent optimal design tool

## INTELLIGENT ADAPTATIVE MESH FOR 2D INELASTIC ANALYSIS OF STRUCTURES

(with J.M. Hablot)

During inelastic analysis, actually, only *estimations of the error* are made what is insufficient. Very often, even if these estimators are very small, this does not imply that the *errors* i.e. the difference between the exact solution of any field (stress, strain, energy ..) and the approximated solution of the field obtained with the numerical simulation, is small !

Sometime, Engineers will perform the numerical simulation, then they will reduce the mesh according some rules, and if the new solution is not too far from the previous one, they will take it as a good one. This is a very expensive and this is not efficient. Indeed, a lot of expertise is needed during the numerical simulations with also experimental correlations.

It is practically important to have a method where, when the range of the error (that will never be known) is required, it is possible to indicate **a priori** the minimum cost (or Number of Degrees of Freedom or number of nodes) and to draw the optimal mesh (i.e. with this minimal number) to reach this error.

We have thought that may be, with automatic learning, it would be possible to extract some useful rules. The main difficulty is that only a few examples of EXACT INELASTIC SOLUTIONS are known (cylinder, sphere with symmetrical loadings !) and such a learning means a data base of representative examples which contains several elastoplastic structures, their discretizations and for each of them the known errors !!

### a) Building the data base

To build the data base of examples, it is necessary to have exact solutions of different elastoplastic problems.

We obtain them by an inverse method as indicated in J.M Hablot's thesis:

#### i) Exact fields for an indefinite 2-D body

We start by taking any displacement field

- $u_j = f_u(x_j, t)$  chosen with regular analytical functions  $f_u$
- the strains  $\epsilon$  are then analytically computed from this displacement
- the stresses  $\sigma$  are computed from the strains using the material constitutive laws
- at last the body forces  $X$  are computed after introducing the stresses in the equilibrium (or dynamic) equations.

In the case of the Mises criterion and the associated plastic strain rates with the normality rule, the stresses are exactly computed from the strains.

#### ii) Particular solution for one given finite 2-D structure

We can choose any domain  $V$  with arbitrary shape with the boundary  $\partial V$ . This boundary is split into  $\partial_u V$  where the imposed components of the displacement are taken from the displacement field and  $\partial_F V$  where the imposed components of the surface force are computed from the stress field. In  $V$ , the body force are taken as in the previous i).

So at any time, we have defined a classical initial boundary value problem with the loading path on the structure but for which we know the exact solution.

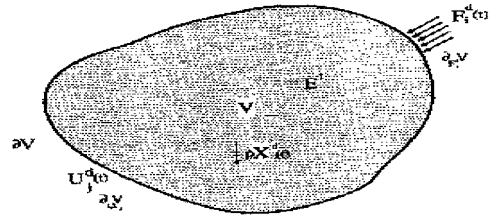


Figure 8: Geometry and loading on the structure

Associated to the indefinite solution i), an infinite number of particular solutions may be built only by changing the shape of  $V$ .

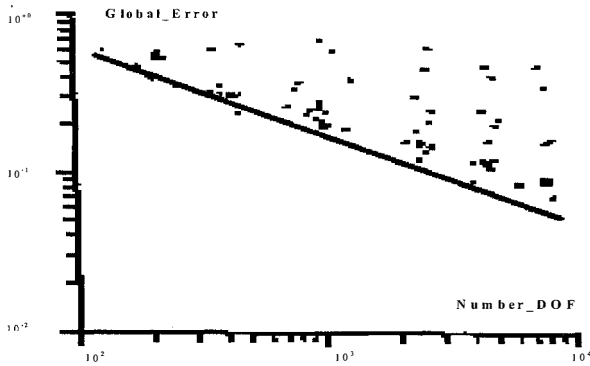
#### iii) Numerical solution for the given finite 2-D structure

We choose a mesh and a time discretization, and with any finite element numerical program, we compute the numerical solution. All the errors (local in one node or element global for the structure) on all the fields (stress, strain, displacement, energy..) may thus be evaluated.

This was done for ~ 26 different geometries (during more than 2 years of intensive works).

### b) Optimal meshing rule

*Empirically, it was noted that, when using various meshes for a given number of degrees of freedom, it was impossible to obtain an error lower than a special value.* This corresponds to what we called the **OPTIMAL CURVE**. This curve is different for each problem.



**Figure 9: Definition of the optimal curve**

It is known that the finite element meshes have to be refined where the gradients are high.

So, empirally, we saw that,

by taking a mesh size of element,  $h$ , in any point as:

$$h = r_r * k / (r_r \parallel \text{grad}(\phi^\beta) \parallel)^\alpha$$

where  $r_r$  is a characteristic length of the structure,  $k$  is one unknown constant,  $\alpha = 0.5$  and  $\beta = 1$  and  $\phi$  is the equivalent stress, this rule is very efficient and gives the best results.

### c) Automatic learnings

The objective is to be able to predict the error associated to any discretization, before making the inelastic analysis of any new structure. This implies the creation of a data base of examples.

#### i) Intelligent description of one example

Each example must contain the intelligent description of the geometry of the structure, its loading, its materials properties, its spatial and temporal discretizations and as the conclusions, the errors between the numerical results and the correspondings exact values.

We have selected, (after several trials) to describe each example, by taking

- the representation of the elastic stress field i.e. the response of the structure assumed to be only elastic and with a rather rough mesh. So, the cost of this computation is reasonable and the effects of both geometry and the loading are taken into account. This elastic stress field may be characterized by the equivalent Mises stress field and its gradient and from these two scalar fields, descriptors are deduced

- other descriptors to define the element size field for the mesh, the material properties,
- the mean and extreme values of the leastic stress increments for the time discretization
- the conclusions are the maximal or global error at the end of the loading.

#### ii) Error associated to any mesh in one particular structure

Here, only the description of the mesh has to be kept in each example. We use 39 descriptors for that. This allows to

define another approach of "adaptive mesh" during inelastic analysis. But this was not considered as an important problem.

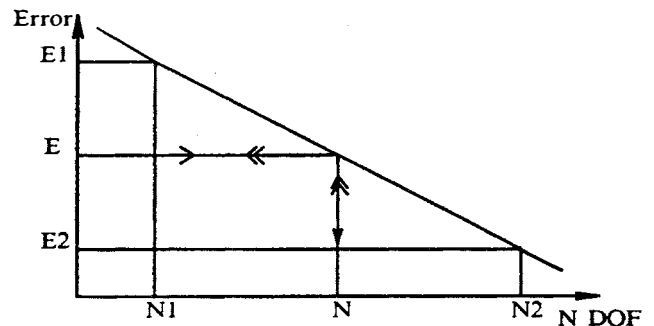
#### iii) Optimal curve

As it is possible to introduce an optimal curve for each problem (i.e. for a given number of degrees of freedom, there is no mesh which will give an error lower than a special value), we prefer to predict it.

We characterize this curve by two couples of points (number of degrees of freedom, minimal error,  $(E1, N1)$ ,  $(E2, N2)$ ) which are taken as the conclusions of the example. Once again, here only 2-D examples are put in the data base, but the same treatment could have been applied to any general 3-D structure.

### d) Practical procedure

When a new problem is defined by its geometry, its materials and its loading, we generate the intelligent descriptors for it (it is necessary to perform the linear elastic analysis with a rather crude mesh) and we build its optimal curve (with the previous rules). We noted that the cost of this operation represents roughly twice the time of the elastic analysis.



**Figure 10: Construction and uses of the optimal curve**

This allows to answer to the fundamental questions:

- the number of degrees of freedom is set by the analyst due to the fact, he can not afford to spend more time (or money) for his analysis. Then, the system tells him what the minimal error will be no matter the distribution of his mesh. and after the full incremental analysis.

- he wants to each an a priori error, the system tells him what the minimal number of degrees of freedom is needed. If this is compatible with his time of analysis, the optimal mesh based on the empirical meshing rule is then built.

## CONCLUSIONS

Other examples of applications on the optimal fatigue and stress corrosion design, the optimal design of explosive, the optimal process control of a factory ... will be presented during this special session.

Intelligent Optimal Design means that a lot of works is needed to recover the available data and expertise into an



intelligent data management (synthesis). Each example will have an intelligent description for each particular problem. The results allow not only to give the answer for any new case but also the optimal solution.

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