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Addicted to Manufacturing!

Joseph Zarka

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ABSTRACT

The engineers in the manufacturing, particularly among the Small and Medium Enterprises, are often thinking that the University Laboratories are too far from them: it is true that the engineers have to solve many urgent day per day problems and that they need to fight to survive among all their competitors, meanwhile the professors-researchers have in principle time to think, to define alone their actual domains, sometimes at a very fundamental and unclear level, and to "try to solve" them. The purpose of the lecture will be to show a scheme of the actual situation in France based on the experience of one researcher in mechanics and his real implication/dedication to manufacturing.

INTRODUCTION

After graduating as a mechanical/civil engineer at Ecole Polytechnique, France (1962), and holding a Dr. es-sciences degree from University of Paris (1968), the author of this lecture is currently a Directeur de Recherches of CNRS (Centre National de la Recherche Scientifique) at the Laboratoire de Mécanique des Solides de l'Ecole Polytechnique and also a part time visiting scientist at the Center of Excellence of Advanced Materials of the University of California, San Diego. During more than thirty three years, involved intensively in researches, he tried to solve important theoretical or experimental problems in very different fields: Modeling Behaviors of Inelastic Materials, Non destructive Measurement of Hardness or Residual Stresses, Numerical Inelastic Analysis of Structures, Problems of Engineers in Nuclear, Offshore, Mechanical, Civil engineering, Armament industries. He tried always to propose original and practical solutions and very often, by shaking the normal uses and customs of the previous researchers of this problem.

However, he was never satisfied by his results, as he was obliged to admit that his << class mates >> who were building the Concorde airplane, the TGV train, the Fast Breeder reactor ... did not use them.

In France, there were many institutions/offices depending of the ministry of education and researches, the ministry of industries, the ministry of defense ... which have been created to help the transfer of the results of the laborato-

ries to the industries. The general direction of the CNRS organized and supported several (often-interdisciplinary) research programs. Nowadays, however, due to the economical problems faced by the country, their budget and actions are very limited. Many << Regional Delegates >> / << Transfer Centers >> have been appointed/created in various towns in the country to help the communications between researchers and industries.

By imposing a special tax on all their sales, the French industries created their own centers to develop applied vertical actions but also to have teams able to assimilate the results of the laboratories and to provide them in a form usable by them.

In fact, during 5 years, the author was the Scientific Director of such a center for the mechanical industries. He stopped this experience because he was not yet satisfied by his results to help the industries. He wanted to do more, to show and to see that all his works could be used by any engineer involved in the design, the manufacturing, the control, the survey...

This lecture underlines how the domains of activities are built in collaboration with the engineers, how the delivering times for reports may be respected. The lecture also emphasizes the huge difficulties to introduce the results in the manufacturing; in fact, the researcher needs to be involved fully and personally if he wants them to be applied.

THE RESEARCHER

SIMPLIFIED ANALYSIS OF INELASTIC STRUCTURES – The designers of structures have often to take into account the inelastic behavior of their materials where work hardening and creep are occurring. The classical mathematical theory of plasticity has been used for many years. Great contributors have helped to spread it by giving correct formulations and useful tools to solve most of the problems. Such formulations are usually given in terms of rates or increments with unilateral constraints and involve very long and expensive computer calculations: it is necessary to define a stress field which is statically and plastically admissible i.e. all the points of the structure need to be analyzed together.

A new approach, just by introducing a change of variable, allows to give efficient bounds of the response of the structure very easily and **with only the help of quasi-static elastic analysis** even during dynamical loads as during seismic loads or contact-rolling loads as during shot peening, and dramatically decreases the amount of time required for the complex inelastic analysis. It was possible to transform the classical formulations of the two fundamental steps:

1. The constitutive modeling of materials, based on continuum mechanics
2. The numerical treatment of structures made of such materials, involving solution of the global associated boundary values problems to make them much clearer and allowing for easier and more direct solution of the problems.

Moreover, applications to time-life prediction in fatigue, in the modeling of shot-peening, rolling and in the seismic analysis which were developed, have shown the exceptional potentialities of the approach for the Mechanical Engineering, the Civil Engineering and the Aeronautical Industries.

Every step is SIMPLE, PRACTICAL and may be easily used in conjunction with the classical tools of engineers such as any elastic Finite Elements Method based code. Indeed, only simple elastic calculus are made with "cleverly" chosen loads and elastic constants which allow a drastic reduction of the time of computation by a factor from 10 to 1000! It was hoped that the resolution of the mathematical problem of the optimal design of inelastic structure was then possible but it was not sufficient.

INTELLIGENT OPTIMAL DESIGN – In 1986, after noticing the needs of the industries: a practical solution and even now, an optimal solution, and also the actual loads in the real 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, it was considered as necessary to start a new research program on "Intelligent Optimal Design of Materials and Structures" where the actual best knowledge of the researchers/experts are intelligently mixed to the results of experiments or real returns.

With the support of some "big" French industries (CEA, CNES, DRET, EDF, Peugeot, Renault, Sagem), in the laboratory, a special research group was created with the strict objective to build a system able to recover knowledge from raw data. It was imposed a limited time of three years to perform the works. At that time, we were guided by an extraordinary American tool, ALN 4060, to test adhesive joints, based on adaptive learning network.

We are interested by problems when there is no solution and when 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.

The approach that we proposed may help to improve the knowledge of the experts themselves by bringing them the rules explicitly and giving them the degree of confidence of these rules.

But chiefly, the solution of any new problem may be obtained and moreover an optimal solution may be reached too.

A new framework was created; it is needed:

1. 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 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. 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.
2. 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.
3. 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.

APPLICATIONS – This framework was applied to several different problems:

- Intelligent optimal design of elastic aggregates
- Intelligent optimal mesh for FEM simulation in 2-D structures
- Intelligent optimal use of explosives in civil engineering
- Intelligent optimal design of reliable structures

Since, this is a SAE conference; the application to *intelligent optimal design of a structure within the CAD system* will be reviewed here.

Automatic Learning Expert Systems – We recall briefly the principles of any AUTOMATIC LEARNING EXPERT SYSTEMS Generator i.e. where the rules base is automatically extracted from the raw examples base given by the expert. They are important in technical domains where experts know they do not know the full solution but they are able to build an examples base, for which the solution is known experimentally or numerically with sometimes some *fuzzy or missing* information.

The main problem is to provide a good description of such an examples base. (By analogy, we can say that the database is the program, the learning tool is the compiler, and the execution gives the knowledge).

Such a learning system includes five main functions:

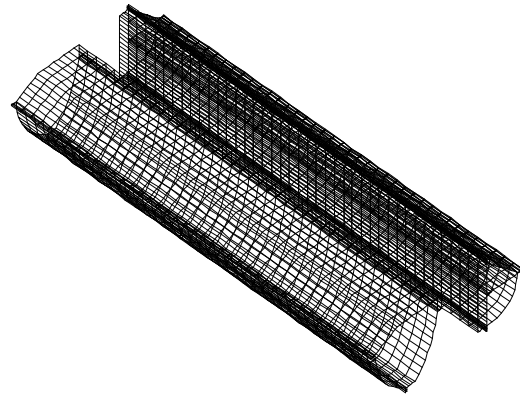
- **PREPARE:** to transform the example files from user format (ASCII, dBase, Excel...) into the own format of the system and to handle the separation of the descriptors and the splitting of the initial data base into a training set and a test set.
- **LEARN:** to automatically extract a rules base from the training set according to the quality of available information (noise, sparseness of the training set...).
- **TEST:** to experimentally evaluate the quality of the extracted rule on the test set.
- **INCLEAR:** to allow the expert to visualize IN CLEAR the extracted rules with the initial user format and to say what descriptors are kept.
- **CONCLUDE:** from the description of a new case, to deliver a conclusion based on the extracted rules. In all problems, it is necessary to consider one conclusion that may be a class or any continuous real number. Moreover, often, several conclusions may be considered together. The rules have to be automatically generated for each one of them.

Then an optional but fundamental sixth function, OPTIMIZE, based on genetic algorithms and other special optimization techniques, may be used to solve the inverse problem i.e. when some conclusions and some descriptors have to belong to some given sets (or constraints), what are the possible solutions and in some particular cases what is the best solution if an objective function is given (cost, weight...)?

Several automatic learning systems are now available; they are based on logical rules, statistics, machine learning, numerical learning, fuzzy logic, and neural networks.

Example of One Problem of Optimal Design with a Direct Link to CAD – It concerns the improvement of the safety of a car particularly during the crash where 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.

In a special office, they have to design a beam. The beam may have different complex cells linked with continuous or spot solder. It is necessary to find its optimal design. In Germany, in United Kingdom, and among all the automotive industries, centers to test each case were created.



Several thousand of beams have been evaluated experimentally or by numerical simulations. For each type of beam, expensive design of experiments allow by interpolation to predict new cases in this type but are not able to say anything for a new type. We have applied our framework:

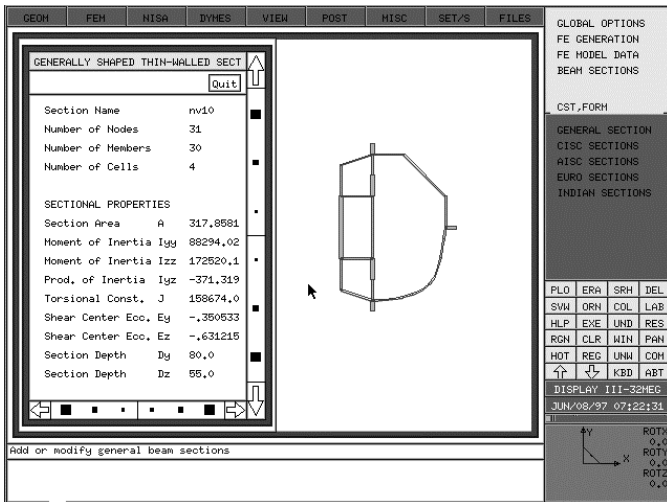
Building the data base – In order to obtain the basic input of the problem,

1. 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,
2. Then, we need to look at their behavior 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 loads and the program NISA from EMRC for the static loads and the description of the beam sections).

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.



- 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.

Only the following nine properties are used in the static analysis of a beam:

1. A = cross-sectional area (or SURF-TOLE)
2. I_{YY} = moment of inertia about Y-axis
3. I_{ZZ} = moment of inertia about Z-axis
4. I_{YZ} = product of inertia
5. J = torsional constant
6. EY = shear center eccentricity with centroid in Y-direction
7. EZ = shear center eccentricity with centroid in Z-direction
8. DY = depth in Y-direction
9. DZ = depth in Z-direction.

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 three data blocks (which are primitive descriptors) from which systematically at least the nine 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 are considering 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 (but any other global prop-

We need to create three blocks of data:

1. The first one provides the data about member connectivity and member thickness, then for each member of the section,
 - a. member ID number,
 - b. its near end node number,
 - c. its far end node number, and
 - d. its thickness
2. The second block gives information about member location with respect to the exterior or interior cells, then for each member of the section
 - a. member ID number,
 - b. exterior cell number to the left of the member,
 - c. exterior cell number to the right of the member,
 - d. interior cell number to the left of the member and
3. interior cell number to the left of the member.
The third block gives the nodal coordinates, for each node:
 - a. node number
 - b. Z coordinate, and
 - c. Y coordinate in the global reference triad XYZ where Z is horizontal and Y is vertical.

Of course, the number of 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 resp. to Y,
- Z axes, moment of inertia about Y-axis,
- moment of inertia about Z-axis,
- product of inertia about Y,

erty such as during the elastic wave propagation within the beam, may be used). One end section of the beam is clamped and on the other end, we apply the resulting displacement of a rotation around the X-axis. The analysis was made with ALGOR and NISA.

It is also necessary to describe the material properties except if, as here, we consider that only one material is used.

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 that 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 rigid mass of 100 kg is sent 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:

- 20 minutes for the introduction of the geometry and the automatic mesh into plate and beam elements
- 20 minutes for the elastic static analysis to obtain the intelligent descriptors and the moment of torsion
- 20 to 40 minutes for the dynamical crash limited to a displacement of 15 mm.

We created only ~ 70 cases in the examples base. In order to reduce the times of treatment and post-treatment, we were obliged to develop several procedures. The total duration for this database was about four man-months.

Generating the rules with LES in its numerical version – We obtain for the dissipated energy:

$$\begin{aligned}
 \text{NRJ-INT} = & -1.8500\text{e-}02 * \text{IZZ} \\
 & +2.04336\text{e+}03 * \text{DZ} +4.84872\text{e-}02 * \text{MOMENT} \\
 & \text{-TORSION} + (-6.975\text{e-}01) * \text{J} \\
 & + (-1.0778\text{e-}04) * \text{SURF} * \text{IYY} \\
 & + (-1.981167\text{e-}04) * \text{SURF} * \text{MOMENT} \\
 & \text{-TORSION} +1.24552\text{e-}03 * \text{SURF} * \text{IZZ} \\
 & + (-3.34226\text{e-}04) * \text{J} * \text{NB-BEAM} \\
 & +9.8804\text{e-}07 * \text{IZZ} * \text{J} \\
 & + (-1.2599\text{e-}03) * \text{J} * \text{STEP} \\
 & + (-1.7946146\text{e-}04) * \text{DZ} * \text{MOMENT} \\
 & \text{-TORSION} + (-7.5096\text{e-}13) * \text{IZZ} **2 * \text{J} \\
 & +9.0022\text{e-}07 * \text{IZZ} * \text{NB-BEAM} **2 \\
 & + 5.5738\text{e-}06 * \text{IZZ} * \text{STEP} **2 \\
 & +8.7610\text{e-}03 * \text{DZ} **2 * \text{STEP} \\
 & + (-4.08879\text{e-}10) * \text{SURF} * \text{IZZ} **2 \\
 & +1.954515\text{e-}19 * \text{IZZ} **2 * \text{J} **2
 \end{aligned}$$

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.

Optimization – We have thought that it was 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 imposed 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:

$$\begin{aligned}
 \text{NRJ-INT} &= 6\ 672\ 127\ \text{J} \\
 \text{EFF-MAX} &= 11\ 200\ \text{N}
 \end{aligned}$$

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 database. 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!

We looked after 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 four primitive descriptors to describe it, the number of intelligent descriptors is always the same and the previous learning for NRJ-INT and EFF-MAX are always valid. The intelligent descriptors of the section have to be learned as function of the four 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 performed any new design for any new requirements almost instantaneously; we integrated all the data 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:

$$\begin{aligned}
 10 &< \text{LENGTH1} < 20, \\
 35 &< \text{LENGTH2} < 60,
 \end{aligned}$$

30 < HEIGHT < 60,
 0.8 < THICK < 1.5,
 10 < STEP < 50

and on the output/conclusion descriptor

EFF-MAX < 150 000 N.

The optimal solution is defined by:

LENGTH1 = 18.38,
 LENGTH2 = 39.5,
 HEIGHT = 47.28,
 THICK = 1.499,
 STEP = 10 (then NB-BEAM = 81)

for which the dissipated energy is:

NRJ-INT = 2 000 000 J

and the maximum force:

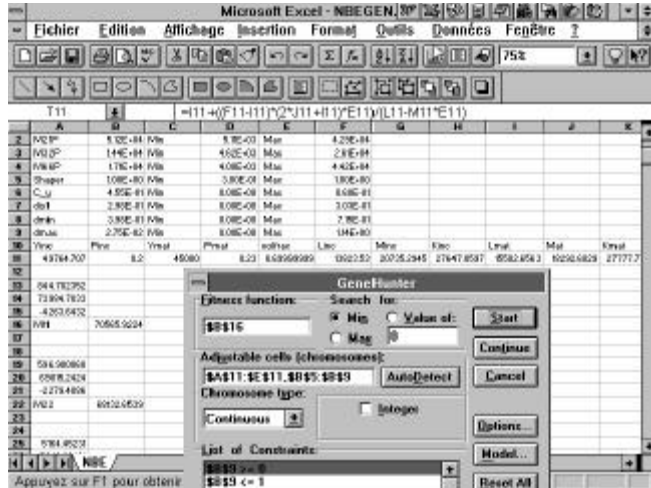
EFF-MAX = 154 999 N.

To verify that these predictions are reasonable, we performed then the whole analysis with the primitive descriptors with RADIOSS; we found that

NRJ-INT = 1 953 500 J

EFF-MAX = 155 540 N.

That means only few percent of error 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!)



CEAM OF UCSD – With the support of ONR, the author is now a part time visitor to CEAM. The objective of this US-French collaboration is to develop a system to optimize the design of welded structures. But another objective for the author is that, if the American laboratories and industries are using his tool, the French researchers and industries will be more receptive to his proposals too.

THE PROFESSOR – The author is organizing, regularly and several times during the year, intensive workshops to train engineers and researchers to the use of his frameworks in France and now in USA too.

He is invited to give courses to various countries.

Most of the time, he gives the books and the programs written by himself or with his collaborators.

He is convinced that if the industries use his tools that they will be more powerful and competitive and that as in just return of being paid to make such a wonderful job, the country will take profit of his work.

THE INDUSTRIAL

In parallel, to insure the transfer to industries of the results, the author supported some of the expenses of his patents and created some industries such as MECALOG which has developed the RADIOSS software worldwide used in the car industries but also, particularly, CADLM which is devoted to help the Small and Medium Industries (even if to have more credits, most of the large French industries are also its customers).

Each month, at CADLM, free Open Houses are organized to demonstrate the several tools that are available and **to sensitize the industries to these modern tools for the design of the future.**

CADLM is proposing systems among the best ones and at the lowest prices in the French market and training the users to these systems. CADLM is able to take in charge sometimes the entire problem of one particular customer until even the optimization step.

CONCLUSION

The author is hoping that he will be more and more helpful to the manufacturing even if he considers that his two last books are his testaments.

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