

# **Uncertainty Analysis and Design with MSC/NASTRAN and PROMENVIR**

Enrique Marchante  
Department of Analysis and Studies. CASA, Space Division.  
Av. Aragón 404. 28022 Madrid, Spain

## **Abstract:**

The intensive use of Finite Element Techniques in structural analysis has been accompanied by the increase in mesh density, sometimes reaching the limits of the current computer resources. The intention is to increase the model accuracy. Nevertheless, to consider data uncertainties in the analysis has been consistently ignored in the past. As a form of compensation, conservative assumptions such as, for example, reduced values for the material strength characteristics, minimum values for dimensional tolerances or factors of safety in the loads, are being considered. This approach covers some sources of uncertainty but others are traditionally ignored, as for example: Young's modulus. Simulation techniques are the only general method to account for uncertainties, but its application to structural analysis with finite elements has been impossible in the past due to the unavailability of computational resources. Today, the resources are available and the technology exists and is implemented in the PROMENVIR system. It allows to account for uncertainties in the wide range of analysis presently available in MSC/NASTRAN. The general applicability of this methodology and the versatility of the environment is shown via three examples. The first one is oriented to show the possibilities to account for data uncertainty at analysis level. The second one focused on model updating, by definition of uncertain model parameters. The third one deals with the uncertain design, in which the design parameters are treated as uncertain variables.

## INTRODUCTION

Structural analysis today is based in the intensive use of Finite Elements codes. This fact has promoted in the past the rapid development of such method. With MSC/NASTRAN and the present computational resources, it is possible to manage Finite Element models with a high number of degrees of freedom. It is available a wide band of possibilities to choose elements that represent the physics of the problem. It is possible to solve using various mathematical models that cover from the linear static to more complex analysis such non linear problems, transient analysis, etc. Nevertheless, only pure deterministic analysis is available. To model the scatter is not allowed, despite it is a very well known fact that scatter exist, in stiffness and strength properties of the material, structure dimensions, applied loads, boundary conditions, etc. Therefore, the analyst is forced to model a stochastic reality using deterministic models.

To produce reliable structures with such a constraints is only possible if uncertainties can be covered by applying factors. The use of *conservative* values for the material strength characteristics, minimum dimensions, factors of safety for the applied loads, etc. is common practice in the analysis of space structures. But, to use conservative deterministic models based in the experience drive to heavy, non optimised structures. In some other cases, to select an appropriate conservative assumption is not so easy, for example the boundary conditions in strength analysis or the material stiffness characteristics in a modal analysis. In that cases, to produce reliable structures is very difficult, since any assumption is ever wrong and non necessarily conservative. It is possible to increase the reliability by designing high quality structures, precisely controlled, for example, using high quality materials and narrow tolerances, to minimise the scatter in the characteristics of the final manufactured structure, etc. But, it is very expensive and limited. In any case, the result is a heavy and expensive structure, but the structure's reliability is unknown.

To introduce uncertainties in the analysis is ever possible by using the simulation techniques, based on the Monte Carlo method (Sobol, 1994). It allows to take advantage of all the available and well developed analytical tools (FEM, MBS, etc.), without lose of generality. The Monte Carlo method is an old and well known technique but, despite it has been successfully applied in other fields, the application to the stochastic mechanics is quite recent. The reason is that the necessary computational time for a single deterministic analysis was quite high and the Monte Carlo method requires a high number of runs. Nevertheless, several academic applications has been published in the past and some of industrial relevance can be found in recent literature (Marchante1997, Marczyk 1995; Marczyk 1997; Marczyk et al. 1997; Pradlwarter et al. 1994).

The interest for the simulation techniques is increasing as the computers are rapidly becoming more and more performance. The natural parallelism of the simulation techniques find in the actual scenario of High Performance Computers and Networks a real opportunity. CASA, has led an international R&D consortium to develop PROMENVIR.

The uncertainty analysis is the primary use of PROMENVIR in conjunction with MSC/NASTRAN. PROMENVIR allows to convert the MSC/NASTRAN model in a stochastic model by adding probability distribution functions to the uncertain parameters. In addition, various very useful secondary applications has been developed as they are: model validation or model updating, optimisation or uncertain design, etc. They are based in moving the distribution functions of the uncertain variables in the direction to minimise the analysis results distance to a defined objective. It can be a test result measurement or a design objective. Also, these secondary applications can be used in a quasi-deterministic basis by defining very narrow amplitudes in the probability distribution functions of the uncertain variables.

This article first present the proposed methodology to account for the uncertainty in the analysis. Shows later the PROMENVIR capabilities to implement the methodology. Finally, applications of industrial relevance to uncertainty analysis, model updating and uncertain design are

presented.

## **METHODOLOGY TO ACCOUNT FOR THE UNCERTAINTIES**

The first step to account for the uncertainties is to decide which ones to consider. Then, the uncertain parameters shall be characterised by its probability distribution functions. It is standard in the space industry to characterise the materials and joints by test. But unfortunately, the number of test samples is usually small. The objective of this kind of test is to determine minimum guaranteed values. But it is difficult to use a small number of test to determine with accuracy the corresponding probability distribution functions. A method to achieve this important information has been proved and validated by CASA (Garcia, M.J., 1997) using the available test database. To determine the values of other sources of uncertainties, as for example the stiffness boundary conditions, is more difficult. In such cases, hypothesis about the scatter shall be made. To assume the scatter is more realistic that forget its existence.

In some cases, information about scatter can be found in the literature. In this sense, a wide study of scatter for space material strength characteristics and several sources of loads is done by Esnault and Klein (1996). They show, for example, a coefficient of variation of 8% for strength characteristics of metallic materials, a 10% for carbon fibre composites, a 12% for adhesive strength and up to 16% for inserts strength under axial loading. Under some conditions the scatter can be even higher. With respect to the loads, scatter can reach 30% for acoustic and 60% for transient.

Previous to introduce the uncertainties, to perform a standard deterministic analysis is mandatory. Its aim is to know the problem in detail, helping in the decisions to be taken later.

The methodology to account for uncertainties in the analysis can be summarised in the following steps:

- To select the uncertainties to be considered. They will be treated as random variables.
- To characterise the stiffness and strength properties of materials and joints and to determine its probability distribution functions. Part of this information can be found in literature.
- To estimate the scatter of other parameters, such boundary conditions, etc
- To create a stochastic model. It is based in a deterministic standard model to which the distribution functions of the selected uncertain parameters are added.
- To perform the necessary Monte Carlo runs and collect the responses.
- To process statistically the results to extract conclusions.

Depending of the objective of the analysis, the number of required runs vary. In order to have a general idea of the response scatter, and its probability distribution functions, a low number of realisations is adequate (say 50). The best indicator of the precision is the confidence interval of the statistics describing the response of interest. To have high precision in the most probable response, the number of required simulations increase. In this sense, it is possible to reduce the simulation time (less realisations) via the so called *population reduction* techniques (Hurtado et al. 1996). If the intention is to assess very low probabilities, the application of *variance reduction* techniques (Schueller et al 1989; Hurtado et al 1996) is mandatory to reduce computational time.

The analysis of the simulation results gives a complete description of the response field and the corresponding probability densities. This information is very important for a deep knowledge of the structure, which can not be obtained by any other method. Also, information about the robustness of the design is obtained. The use of the correlation coefficients between input and response variables helps in the redesign, when needed. In this case, optimisation based in the stochastic response is possible

To put into practise this methodology is supported in the use of the PROMENVIR tool which capabilities are described hereafter:

- An open architecture that enables its use in combination with MSC/NASTRAN.
- Gives the necessary tools to define the stochastic model. It includes the selection of the uncertain parameters by marking the corresponding numbers in the MSC/NASTRAN input deck. To them, several standard probability distribution functions can be associated.
- Automatic generation of the Monte Carlo Simulations.
- Possibility to define multy-operational runs. It allows to combine various MSC/NASTRAN solutions in combination with user developed post processing software.
- Automatic management of parallel simulations. It includes the possibility to exploit fine grain parallelism (MSC/NASTRAN PARALLEL statement) and coarse grain parallelism in both Local Area Networks (LAN) and Wide Area Networks (WAN). PROMENVIR generates temporarily a Parallel Virtual Computer (PVC, see Figure 1).
- Automatic collection of the results which are stored in a common database.
- Statistics module to process the results and a universal format to export data to other statistical packages.
- Multiple Step Simulations. At each step, the stochastic model is updated to approximate a given objective.



Figure 1: PROMENVIR Parallel Virtual Computer

Model validation is achieved when analysis results match the test measurements. If the fact that uncertainty exist is accepted, it is necessary to compare the results from one or more test (cloud of measurements) with more than one analysis (cloud of analysis results from the simulation). If the result of one single test is inside the analysis result cloud, the model can be said to be *valid*. Otherwise, model updating becomes necessary. Defining one point (test result) as an objective, the analysis stochastic model can be updated by moving the average of the distribution function of the uncertain parameters. This PROMENVIR features is a sub-product of the ESPRIT program SCAT, oriented to stochastic model validation, actually under development. Defining very small scatter in the distribution functions, a quasi-deterministic, automatic, multi-objective model updating is achieved.

In the same manner, during design phases, design requirements can be defined as an objective and structural properties can be defined as random variables. If small range of variation is imposed, optimum solution can be search by updating the analysis model during several loops, as it was explained for model correlation. If some variables are the thickness of some structural parts, the tendency to decrease through the simulation loops means that such part is not

structurally significant and can be removed from the design (and model). A new simulation can be started with the new model to search the optimum design with the remaining parts. It can be said that the initial model is prepared for an *uncertain design*.

## XMM UPPER PLATFORM UNCERTAINTY ANALYSIS

### **Problem Definition**

XMM mission is to carry to a Earth orbit a X-ray telescope. Its structure is joined to a service module composed of a central cone, closed by two platforms and lateral panels. The cone and the platforms are made in carbon fiber skins sandwich.

Due to inserts integration requirements, sandwich skins composite shall be cured separately from the core. In such conditions, in spite of being a symmetric laminate, a warping of the skins during curing is foreseen due to previous experience. Curing temperature is 160°C. Allowed warping to enable to sandwich manufacturing is estimated in 40mm peak to peak displacement out of plane.

Panel description:

- Manufactured in G802 carbon fiber (0.2 mm thickness)
- Lay-out [45,0,-45]
- Dimensions: 2.748m x 3.038m

### **Analysis**

Working hypothesis is that warping appear due to small asymmetry in the laminate with respect to the nominal theoretical configuration. This is due to:

- Errors  $e_1$  type.* Errors in the fibers placement. This error has been estimated to have a maximum value easy to assure (+/- 2°).
- Errors  $e_2$  type.* Imperfections in the original material. Material G802 is a fabric with same number of fibers in two perpendicular directions. Therefore is supposed to have the same properties if measured in both directions. Fiber placement errors in the two perpendicular directions will invalidate this hypothesis. The angular errors has been estimated to be very small (+/- 0.2°)



Figure 2: XMM satellite

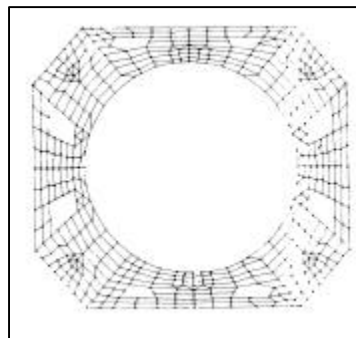


Figure 3: Platform FEM

For the analysis, a MSC/NASTRAN model is used. Each G802 lamina has been represented with four plies (PCOMP card) to consider  $e_2$  type errors (see figure 4). In addition, the panel laminate is built to enable the analysis of  $e_1$  type errors.

The effect of both  $e_1$  and  $e_2$  errors has been analyzed using the mentioned model. Panel deformed shape for  $e_1$  type error is shown in Figure 5.

Displacement peak to peak (ptp) in the panel become:

- For  $e_1 = + 2^\circ$  ptp = 0.007mm;
- For  $e_2 = + 0.2^\circ$  ptp = 124.8 mm

Two different simulations has been performed:

- Simulation A1 consider the angle of each lamina as a random variable (3 independent random variables) with a normal probability distribution function centered at its nominal value and standard deviation one third the maximum error  $e_1$ .
- Simulation A2 consider the angle of both warp and weft lamina components for each lamina as random variables (6 random variables) with a normal probability distribution function centered at its nominal value and standard deviation one third the maximum error  $e_1$ .

Figures 6 and 7 represent the histograms of the response (ptp displacement) for both simulations after 1000 realizations.

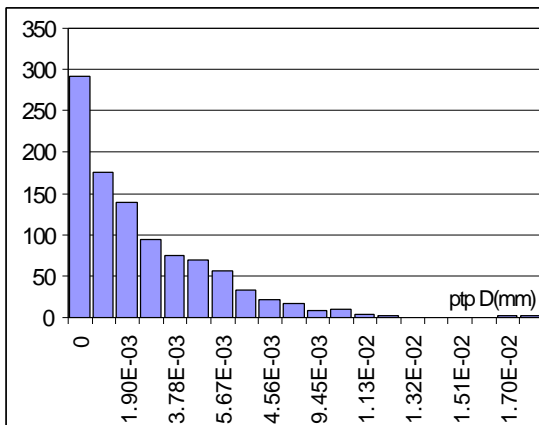


Figure 6: Panel warping due to  $e_1$

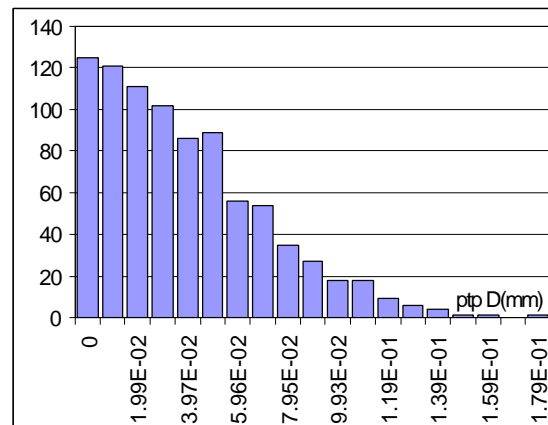


Figure 7: Panel warping due to  $e_2$

A new simulation (A3) has been performed considering both  $e_1$  and  $e_2$  errors types. Figure 8 shows the point plots of the response vs the error  $e_2$  type in each of the three lamina of the composite. Correlation coefficients of Pearson are negligible for  $e_1$  error type. For  $e_2$  error at each lamina, correlation coefficients follows:

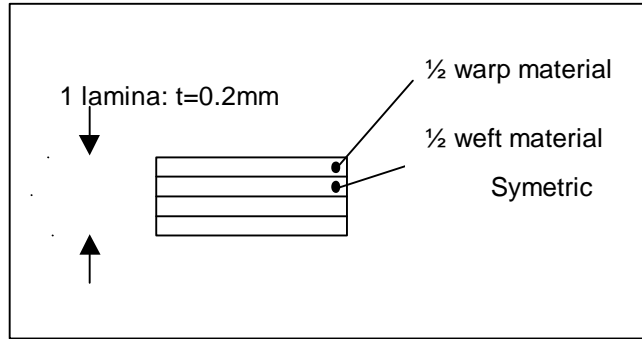


Figure 4: lamina model sketch

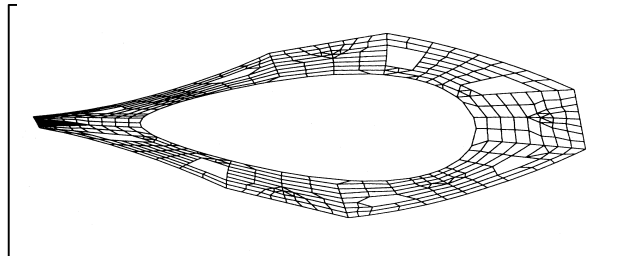


Figure 5: Panel deformed shape

- Lamina 1:  $r = 0.46$
- Lamina 2:  $r = 0.02$
- Lamina 3:  $r = 0.48$

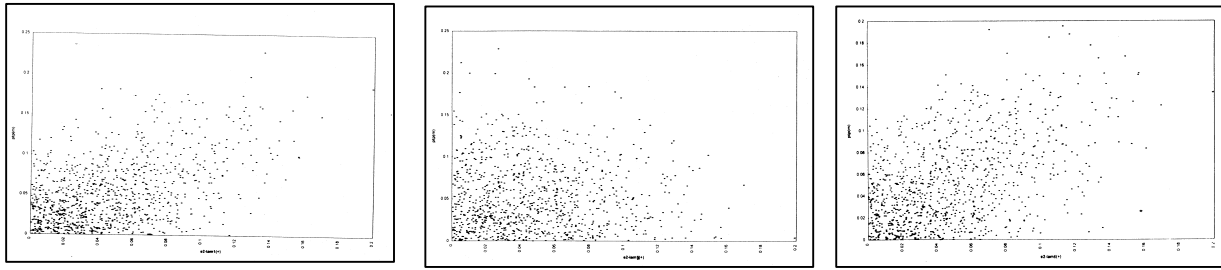


Figure 8: Response vs the error  $e_2$  type for upper lamina (left), central (center) and lower (right) lamina

### Discussion

It can be said that effect of the laminate fibers placement errors ( $e_1$ ) in the panel warping during curing is negligible compared with the big influence of the different material properties in perpendicular directions due to  $e_2$  errors. From this, an increment in the manufacturing tolerances could be defined. Nevertheless, a material with very high quality should be requested from the supplier.

Correlation coefficients inform about the fact that such sensitivity is more important for laminate external plies than for the ply that located at neutral line. As a consequence, manufacturing strategy in the sense to use worst material for central ply could be defined.

## TEST SAMPLE FEM UPDATING

### Problem Definition

Test samples of two different carbon fiber laminate configurations has been tested. Strength and stiffness data has been derived for both configurations. Two MSC/NASTRAN FEM are used to represent both configuration. The intention is to derive laminate properties from carbon fiber unidirectional data.

From the comparison of the analysis results and the test results, important differences are observed. A first tentative denote that to mach test results in both configurations by modifying unidirectional fiber characteristics in the FEM is not straight forward. Therefore, the use of the MSC/NASTRAN FEM and PROMENVIR to search the best FEM correlation is decided.

### Analysis

Table 1 shows the carbon fiber test data for the unidirectional lamina and the two laminates: laminate 1 is  $[0^\circ, 45^\circ, 90^\circ, -45]_s$  and laminate 2 is  $[0_2, 45, 90, -45]_s$ . Table 2 shows the material characteristics for both laminates derived by analysis using unidirectional data from test.

In the MSC/NASTRAN FEM, material characteristics are selected as random variables with PROMENVIR. A probability distribution function is associated to each variable. Small range of variation is selected in all the cases in order to approximate the solution in a quasi-deterministic basis.

Material Property	Unidirectional Lamina	Laminate 1 $[0^\circ, 45^\circ, 90^\circ, -45]_s$	Laminate 2 $[0_2, 45, 90, -45]_s$
Ex ( $N/mm^2$ )	152245	54953	75152

$E_y$ (N/mm <sup>2</sup> )	9333	55280	46586
$G_{xy}$ (N/mm <sup>2</sup> )	4224	20799	-
$\sigma_{XT}$ (N/mm <sup>2</sup> )	1849	479	805
$\sigma_{XC}$ (N/mm <sup>2</sup> )	1022	391	-
$\sigma_{YT}$ (N/mm <sup>2</sup> )	40	493	383
$\sigma_{YC}$ (N/mm <sup>2</sup> )	239	473	437
$\tau_{XY}$ (N/mm <sup>2</sup> )	91	315	-

Table 1: Material test data. Lamina and laminate

Material Property	Unidirectional lamina	Laminate 1 [0°, 45°, 90°, -45] <sub>s</sub>	Laminate 2 [0 <sub>2</sub> , 45, 90, -45] <sub>s</sub>
$E_x$ (N/mm <sup>2</sup> )	152245	57200	76200
$E_y$ (N/mm <sup>2</sup> )	9333	57200	49300
$G_{xy}$ (N/mm <sup>2</sup> )	4224	21700	18200
$\sigma_{XT}$ (N/mm <sup>2</sup> )	1849	245	323
$\sigma_{XC}$ (N/mm <sup>2</sup> )	1022	381	507
$\sigma_{YT}$ (N/mm <sup>2</sup> )	40	245	323
$\sigma_{YC}$ (N/mm <sup>2</sup> )	239	381	507
$\tau_{XY}$ (N/mm <sup>2</sup> )	91	165	139

Table 2: Laminate characteristics by analysis

Inside PROMENVIR a solver command is defined including the execution of two MSC/NASTRAN static analysis (SOL 101) and the post processing program to recover the results from the MSC/NASTRAN .F06 file to a common results file. This command is executed at each run. Laminate properties from the test samples are defined as objective with PROMENVIR. 200 loops of 15 runs each are executed. After each loop, PROMENVIR measures the distance from each realization to the objective and select the best configuration. The variable distribution functions are updated according to the better result of the previous loop and a new loop is executed.

Figure 9 shows the scatter plot for some variables. Table 3 shows the properties of the unidirectional fiber and the corresponding laminate properties for both configurations after the simulation.

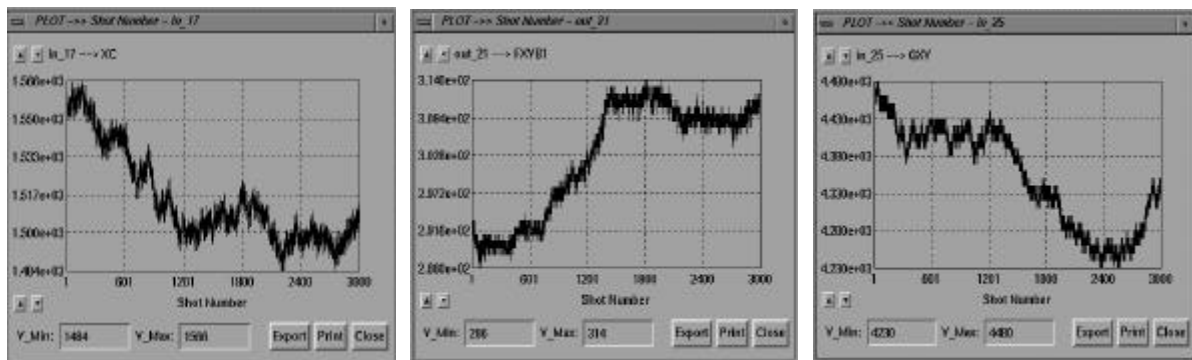


Figure 9: Scatter plot of  $\sigma_{xc}$  (a, left),  $\tau_{xc2}$  (b, center)  $G_{xy}$  (c, right)

Material Property	Unidirectional lamina	Laminate 1 [0°, 45°, 90°, -45] <sub>s</sub>	Laminate 2 [0 <sub>2</sub> , 45, 90, -45] <sub>s</sub>
$E_x$ (N/mm <sup>2</sup> )	148000	56000	74400
$E_y$ (N/mm <sup>2</sup> )	9390	56000	48300
$G_{xy}$ (N/mm <sup>2</sup> )	4340	21200	17800



$\sigma_{XT}$ (N/mm <sup>2</sup> )	1874	648	860
$\sigma_{XC}$ (N/mm <sup>2</sup> )	1514	574	762
$\sigma_{YT}$ (N/mm <sup>2</sup> )	107	648	564
$\sigma_{YC}$ (N/mm <sup>2</sup> )	100	574	488
$\tau_{XY}$ (N/mm <sup>2</sup> )	84	370	312

Table 3: Unidirectional lamina and laminates characteristics by analysis after simulation

The criteria to measure the distance between analysis and test is the module of the vector between analysis and test results. This is:

- Initial: D = 4289
- After simulation: D = 2327

### **Discussion**

From the analysis of the scatter plot, it can be said that some input variables *travel* and finally stabilize around a central value (see figure 9a). At that stage, the input variable does not improve the response. When a response variable stabilizes (fig. 9b), the distance between the analysis and test results has been minimized. Then, the best approximation is selected. Fig 9c shows that a variable with small influence in the response oscillates along the simulation.

It can be concluded that a better FEM is obtained after the simulation since distance between analysis model and test results reduce considerably. The updated model represents better the laminate stiffness than the strength. This is probably due to the fact that failure is computed by TSAI-WU failure envelope.

To improve the model updating, in this case, it could be consider the angular errors in the lamina placement at composite level as additional random variables.

## **OPTIMIZATION OF TEST SET-UP. UNCERTAIN DESIGN.**

### **Problem Definition**

The set-up in Figure 10 was devoted to test the Ariane 5 payload adapter 937VB. A *Universal Surflux Tool* (UST) was designed to introduce at the bottom adapter interface a flux distribution similar to that appearing during flight due to launcher configuration. The set-up consist in a 2624 mm diameter cylinder and 8 jacks to produce the required deformation at adapter lower interface. A similar set-up is going to be used for a new Ariane 5 payload adapter in development (1666V5 in Figure 11).

Overflux at upper interface is function of both input overfluxes at lower interface and the characteristics of the payload connected to its upper interface via a clamp band system. Therefore, the design of the payload dummy, to be considered as integrated part of the new test set-up shall be done with the objective to reproduce flight conditions at upper interface.

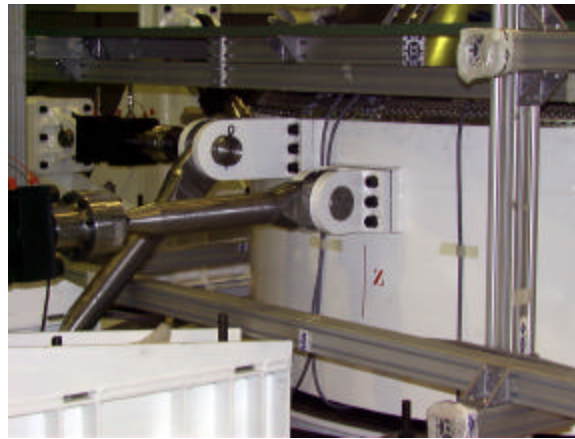
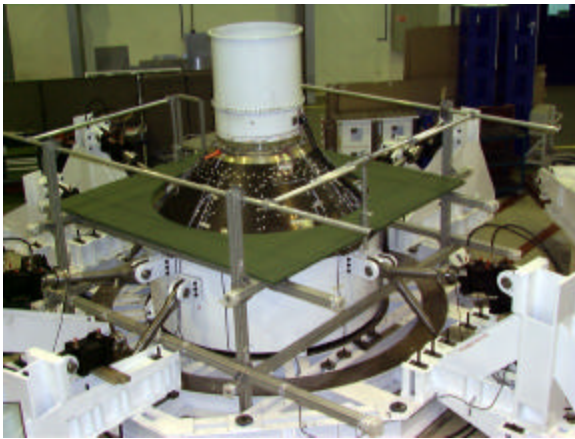
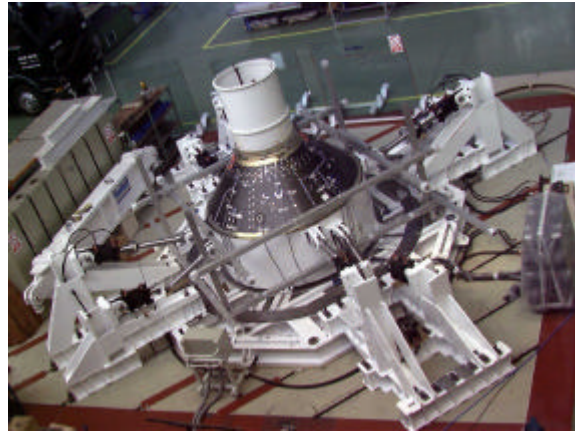
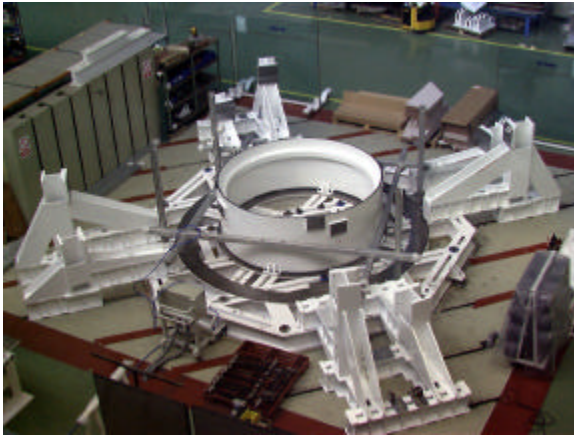


Figure 10: ARIANE 5 · ACU 937VB Test set-up view

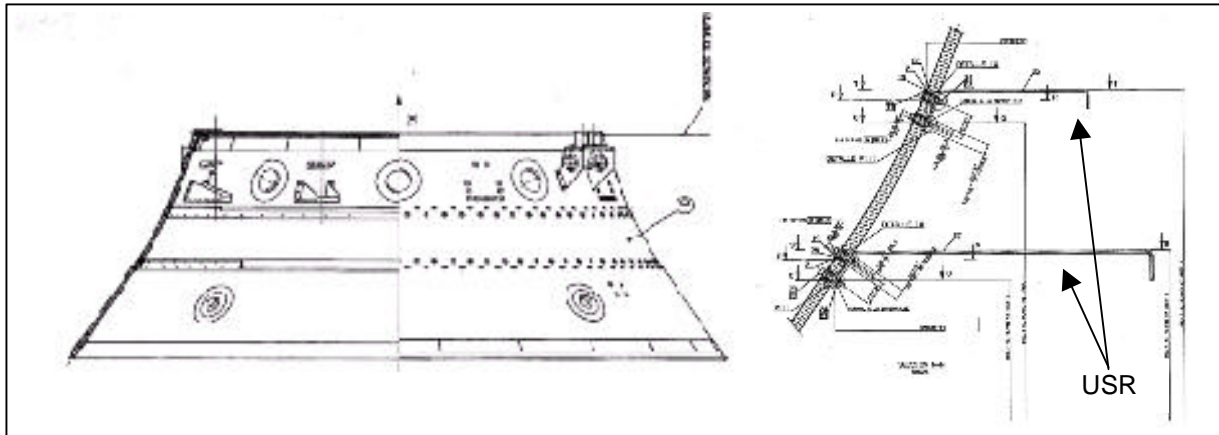


Figure 11: Adapter 1666VB5 and sketch including two USR

Two test are to be performed. The first one intends to reproduce flight conditions at the bottom interface for a clean adapter (conical shell + interface rings). Overfluxes at both interfaces are to be measured. Secondly, the same test is performed adding to the cone two *Upper Stiffening*

*Ribs* (USR in figure 11). The USR functionality is to reduce overfluxes at upper interface. Its efficiency will be stated during test. The test is designed for the adapter configuration with USR (flight configuration).

PROMENVIR is used in two separate exercises with the following objectives:

- First one is to obtain flight flux distribution at the lower interface by combination of the loads in the jacks for a given payload dummy (initial approach). Since the dummy is essential for the fluxes travelling up to upper interface, only flux distribution at bottom is expected to be obtained. Only 4 of the jacks are expected to be necessary for the flight case to be reproduced. The other 4 jacks has been designed to reproduce flux distributions corresponding to a different flight case in a different test (not used here).
- Second exercise is oriented to design the better payload dummy to achieve the fit of the test flux distribution with the flight flux distributions at the upper interface. Loads in the jacks defined in previous exercise are used.

### **Analysis**

To prepare the simulation, a model including the UST, the 1666V5 adapter, and a initial payload dummy model has been built (see Figure 12). Jacks loads have been defined as input random variables. Limits are imposed to the probability distribution functions according with the jacks maximum capacity. Solver command includes the MSC/NASTRAN static analysis and a post processing to recover *element forces* (fluxes). Some points of the flux distribution from analysis in flight conditions are defined as objective (four points close to the four peaks in the squares curve of Figure 13). This objective is associated to the corresponding response variables defined in the simulation. At this stage, simulation C1 is prepared.

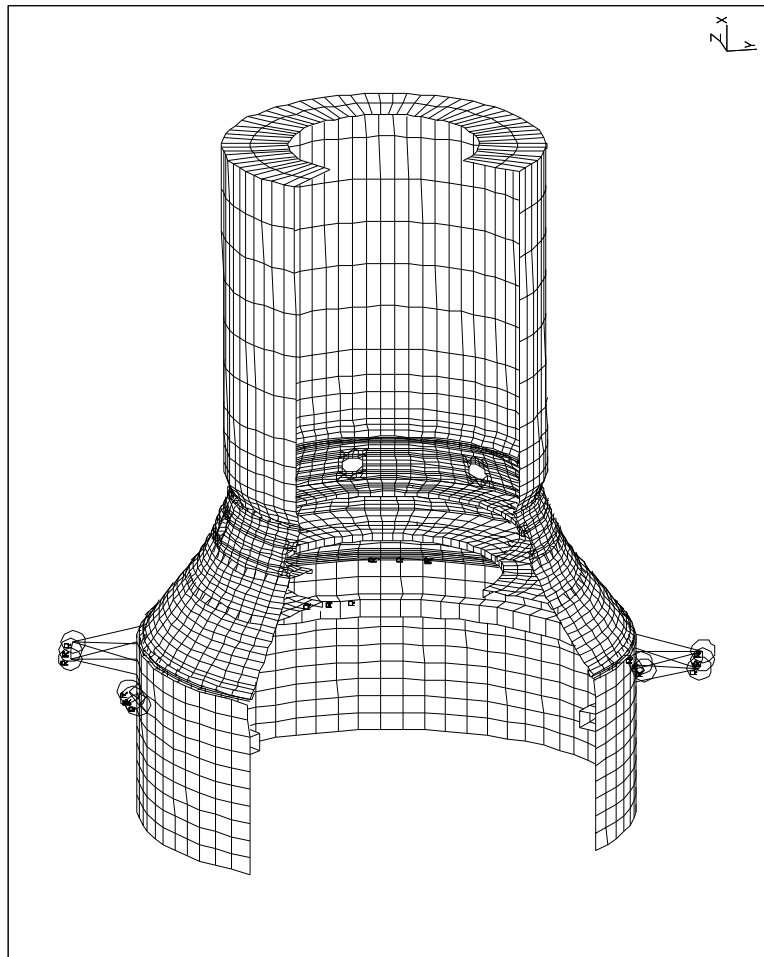


Figure 12: Adapter 1666V5 test set-up FEM

After 10 loops of 15 realizations, jacks loads stabilize. Figure 14 shows that a good fit between the test flux and flight flux at lower interface. In fact, the solution (4 jack loads) approximate, automatically, that obtained with much more effort for the 937VB5 adapter. No more details are included here since the variables behavior is very similar to the previous example.

The second objective is to improve the set-up behavior to reproduce flight flux distribution at upper interface. Figure 14 shows a bad fit at adapter upper interface after simulation C1 using the initial dummy. The jacks loads defined after simulation C1, which fit the flux at the bottom interface are fixed now.

In order to design a better payload dummy, a more complex steel cylinder is first designed and the corresponding FEM is built. Figure 15 show the parts of this dummy composed of four half-meter cylinders, four annular platforms, and four closing platforms. The thickness of all the parts are defined as random variables. Some points of the flux distribution from analysis in flight conditions at adapter upper interface are now defined as objective (four points close to the four peaks in the squares curve of Figure 14). Under this conditions simulation C2 is performed.

Table 4 shows the initial thickness for all the parts ( $t=4\text{mm}$ ) and the final thickness after 500 realizations. In table 15, it can be observed that flux distribution on test at adapter upper interface after second simulation mach better the flight peak values. After the analysis of the proposed thickness for the cylinder parts, it is decided that only structural parts 7, 8, 9, 10, 11, 12, 13 and 14 will be included in the final design. Rest of the parts are removed, some of them due to its tendency to very small thickness, some others to simplify the structure of the dummy. The lower cylinder (part 11) is maintained in spite that it thickness tend to be very small.

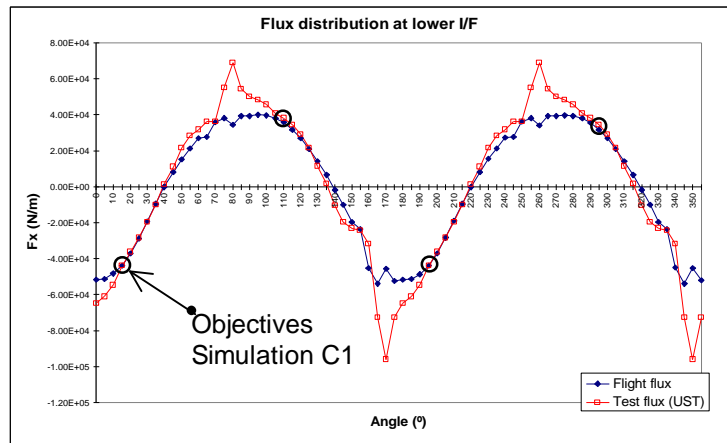


Figure 13: Flight vs. test flux distributions at adapter bottom i/f after simulation C1

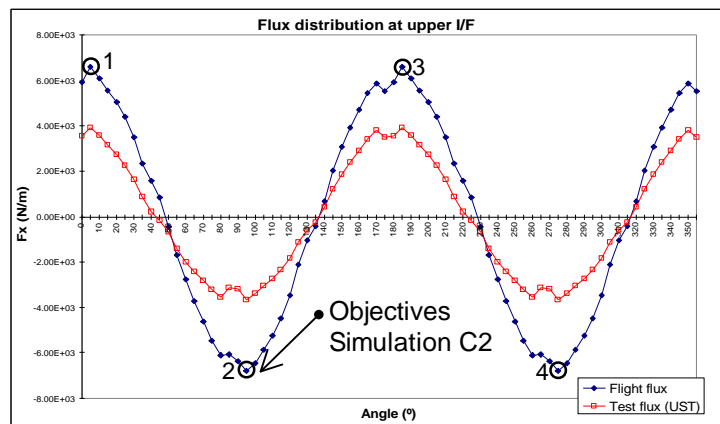


Figure 14: Flight vs. test flux distributions at adapter upper i/f after simulation C1

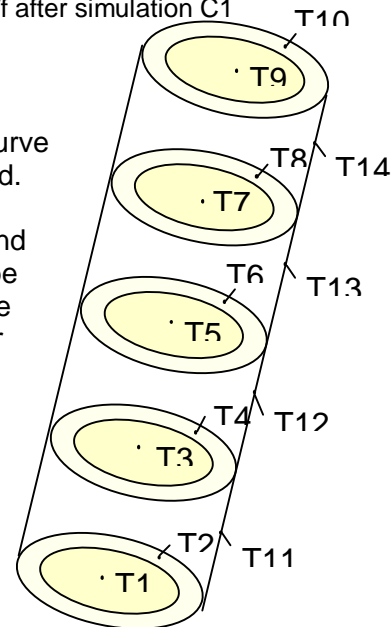


Figure 15: Cylinder dummy FEM description

A new simulation is done (C3). Now, only the selected effective parts are included in the model. The thickness of the cylinder is restrained to be above 2mm in order to avoid a very weak point on the set-up. After 3000 realizations, design variables converge to the values of table 4. Figure 16 shows the behavior of the set-up to reproduce flux at upper i/f for the new payload dummy design. Table 5 shows numerical values of flux after simulation C2 and C3 compared with the objective.

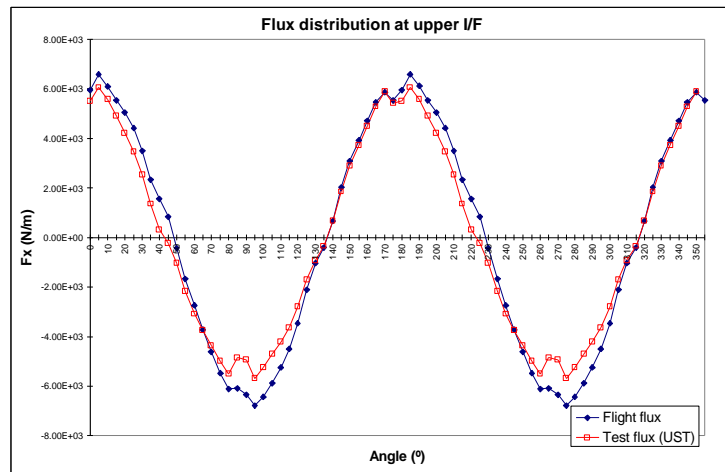


Figure 16: Flight vs. test flux distributions at adapter upper i/f after simulation C3

Design phase	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
Initial thickness	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
After simulation C2	4.1	0.1	0.6	0.1	2.1	0.1	1.4	2.0	1.0	2.0	0.1	3.5	1.5	4.2
Decision (NO -> removed)	NO	NO	NO	NO	NO	NO	1.4	2.0	1.0	2.0	2.0	3.5	2.0	4.2
After simulation C3	-	-	-	-	-	-	0.5	0.8	1.0	1.8	2.3	3.7	2.0	8.0

Table 4: Payload dummy cylinder thickness (mm) evolution

	Flux 1 (N/mm)	Flux 2 (N/mm)	Flux 3 (N/mm)	Flux 4 (N/mm)
Objective	6500	-6500	6500	-6500
Initial. After simulation C1	3950	-3740	3950	-3740
After simulation C2	4430	-4120	4430	-4120
After simulation C3	6050	-5690	6050	-5690

Table 5: Flux objective vs. simulation results.

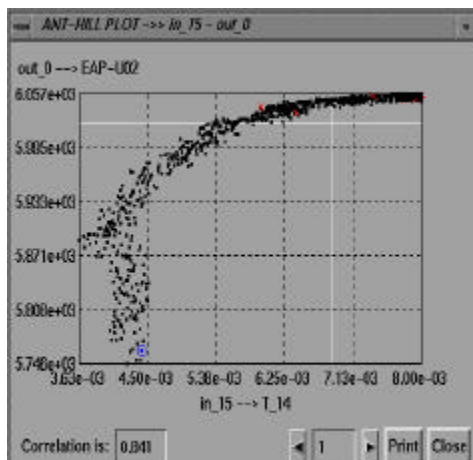


Figure 17: input output variables point plots

### Discussion

Input variables scatter and number of realizations depend of the objective. To start, a small number of realizations with a big scatter helps to approximate quickly the optimum. Then, important variables shall be identified. This helps, for example, to decide which parts to be maintained in the design. For the final design definition, a greater number of realizations and a smaller scatter drive to stabilize as close as possible to the objective. This approach presents an important advantage with respect to the optimization by gradients, since big scatter avoid the process to be conducted to local minimum.

In Figure 17, it can be seen that the objective is approximated when upper cylinder thickness increase.

With the available stochastic model (FEM + design random variables) to obtain a better result

is difficult, but the approximation has been quite better than the best result to be obtained without optimization

The multi-step optimization has been demonstrated to be valid for both objectives.

## CONCLUSIONS

The methodology here explained allows to account for the uncertainties in the analysis using MSC/NASTRAN and PROMENVIR. This fact takes advantage of the high degree of development and sophistication of MSC/NASTRAN. Also, this approach facilitates its use, since does not imply a drastic change, to a completely new product.

An important benefit of the proposed methodology is a better knowledge of the structure that is obtained by examining the response field and the correlation with the uncertain parameters. The application from the initial phases of the development allows robust design. Tolerances can be narrowed or relaxed for a defined response scatter objective.

Space structures can be further developed in a stochastic-based optimisation, resulting in lighter structures, by deletion of the safety factors. Safer structures are obtained at the time. Since the entire response scenario is scanned and none *a priori* hypothesis is needed to select the *worst* case, the risk of non conservative assumptions is deleted.

It is important to remark that the methods are well probed and the technology is available. Some application are possible today, some other will be possible in a few years with faster computers. To apply this methodology today can give important benefits in a short time, as well as produce the required know how to face other problems in the coming future.

To apply MSC/NASTRAN and PROMENVIR in a quasi-deterministic basis offers to the user a very versatile environment for optimisation, uncertain design, model validation or model updating.

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