I.A.C.A.D.S. - AN INTEGRATED PLATFORM FOR RESEARCH DEVELOPMENT OF COMPOSITE MATERIALS AND STRUCTURES

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ABSTRACT

The application of fibre reinforced composite materials to aircraft structure holds numerous practical advantages. These advantages are offset however by the increased complexity of stress analysis due to material anisotropy and the increased material data requirements.

This paper gives an overview of some of the work done in assimilating recent advances in computer technology to create an environment for the development of research aimed at producing tools suitable for alleviating problems specific to composite materials and structures.

Introduction

This paper does not propose to introduce any new or particularly innovative concepts. Rather it is intended to present results emanating from an attempt at reducing the complications involved in the design or analysis of composite structures by using some of the more cost effective advances in computational technology and at the same time to provide some form of platform for further research.

The concept behind the system described in this paper is not unique. Indeed, ICAN(1) and the CSM Testbed(2) are two which appear to be similar in nature and, in all probability, may be more advanced in several respects. Nevertheless the results and methodologies presented in this paper are believed to be of value.

The core computational platform IACADS (Integrated Advanced Composites Analysis and Design System) was developed on the INTEL processor based family of personal computers running under the DOS operating system. This choice was made so as to enhance access to the system for purposes of research and development at an undergraduate and post-graduate level. In order to maximise this resource the "C" programming language was chosen. This choice was made not only to maximize potential benefits of small low cost computational resources but also with an eye to possible future migration to more powerful machines running under UNIX or possibly even parallel architecture machines. In addition to this it is believed that the principles of object oriented programming may be used to good effect in the long term development of such a system.

The most immediate problem to be addressed by this software was the reduction of the material property problem so as to approach a situation as close to that experienced in design using isotropic materials as possible. This problem is directly related to the greater amount of basic material data and laminate variability as compared to an isotropic material with relatively few properties and limited variability.

In order to cope with the material data a data-base was developed. It is hierarchical in nature allowing the development of a classification procedure suitable for a particular group's needs - be this an analysis, design or development group. Test data are entered directly into the data base and a normal distribution analysis is automatically performed such that mean, 'A'-basis or 'B'-basis data is readily available. At present the data are predominantly those of the basic zero degree lamina. This data base may be quite easily re-configured to include isotropic materials or fabrics. Selection of a particular material from the data base allows its subsequent use and whereafter it is referred to purely by name. Up to thirty materials may be made available for use in computational modules in this way. A mouse driven menu selection for materials within the computational unit results in a listing of all materials selected from the data base. Clicking on the material with the mouse then makes that particular material the active one. This approach has the advantage of eliminating human error from the material data input to a computational procedure and allows isolation of the data generation process from the end-user.

The classical laminate theory based module is fully interactive allowing real time manipulation of laminates. Any change made to a laminate is immediately reflected in an update of material data shown in the data output region of the screen (Figure 1). All operations, barring load or strain input, are menu/mouse operations. For example, two layers in a laminate may be swopped by selecting 'SWOP' from the pull-down menu bar and then clicking on the two layers in the laminate graphic display.

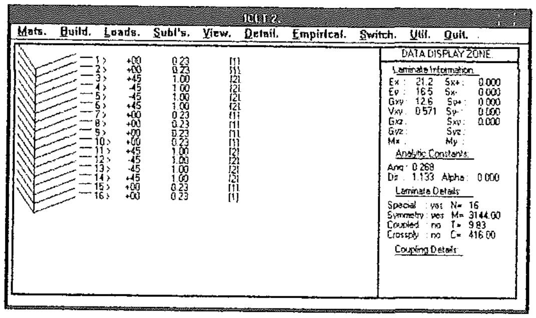

FIGURE 1 : BASIC ICLT MODULE LAYOUT

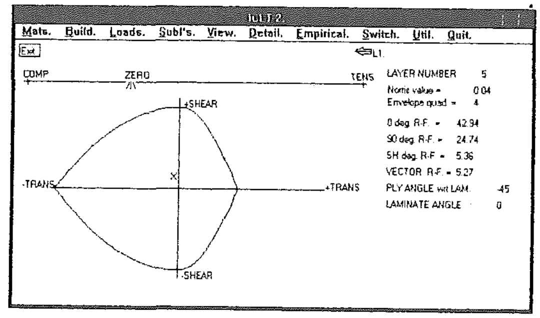

FIGURE 2 : FAILURE STATE REPRESENTATION IN THE ICLT MODULE

These layers are immediately swopped and the data output is updated to reflect this change. Six complete laminates may be worked on at any one time by exchanging them with a sub-laminate storage facility. This sub-laminate is stored on disc and therefore allows the efficient use of sub-laminates which remain available for future sessions. The module maintains a good degree of flexibility in allowing the user to recall a standard laminate and specify alternative materials. A laminate may also contain sub-laminates as single layers. The user is thus able to obtain laminate data for a wide range of laminates with the minimum amount of data input and keyboard use. Trade off studies for variations in material and layup using stiffness, strength and cost as trade-off parameters are possible. Strength values are output as first-ply failure strength values which are calculated by a modified form of the Tsai-Hill failure criterion. This failure criterion is used, not so much because of its accuracy, but because its quadratic nature allows the positioning of a lamina's stress state within the failure envelope (Figure 2). This provides the user with qualitative information regarding laminate sensitivity to variations in load. Four reserve factors are given. Three of these relate the position within the failure envelope to variations in transverse, longitudinal and shear stresses, whilst the fourth is the more commonly used total reserve factor. This information can be obtained at any time by clicking on the desired layer in the laminate stress distribution display (Figure 3). This information is useful during the design or analysis process since a degree of manual optimization may be performed to obtain a better quality laminate.

Although this is useful software on its own, its purpose is to provide a platform for research development of composite structures. To this end the software serves as a pre-processor for other computational modules requiring either material data or computed laminate data.

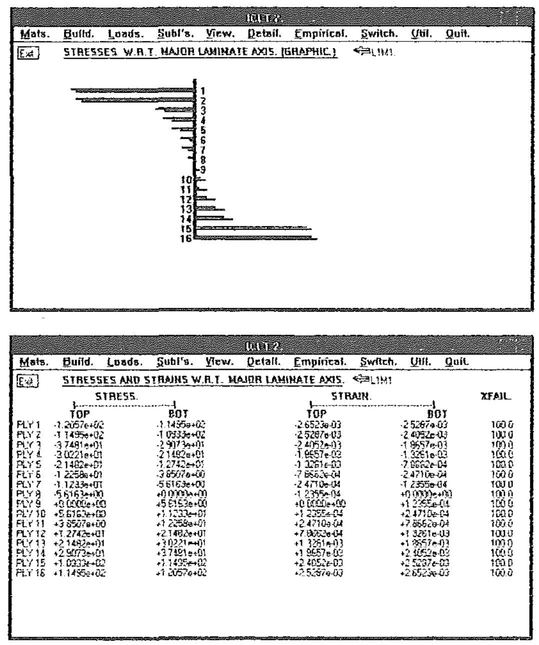

FIGURE 3 : GRAPHICAL AND NUMERICAL LAYER STRESS OUTPUT

Computational Module Development

For more detailed information on the behaviour of composite laminates numerous models have been developed by various researchers. Topics typically cover optimization, buckling and micromechanical stress distributions including failure theories. The analytic model discussed here is that presented by De Jong(3) for the determination of the stress distribution around holes in orthotropic laminates. The model is based upon the governing differential equation:

$$C_{22}\frac{\partial^4 U}{\partial x^4} - 2\,C_{26}\frac{\partial^4 U}{\partial x^3 \partial y} + (2\,C_{12} + C_{66})\frac{\partial^4 U}{\partial x^2 \partial y^2} - 2\,C_{16}\frac{\partial^4 U}{\partial x \delta y^3} + C_{11}\frac{\partial^4 U}{\partial y^4} = 0$$

(Ref 5)

This equation is reduced by assuming the x- and y-axes to be the principal material directions to:

$$\frac{E_{11}}{E_{22}} \frac{\partial^4 U}{\partial x^4} + 2 \left(\frac{E_1}{2 \, G_{12}} - \mu_{12} \right) \frac{\partial^4 U}{\partial x^2 \partial y^2} + \frac{\partial^4 U}{\partial y^4} = 0$$

By utilizing analytic functions, conformal transformations may be used in the complex plane to obtain the stress distribution around various shaped holes in orthotropic laminates. By assuming a pressure distribution at the edge of a circular hole to be a sine series with unknown coefficients, a model is developed wherein solution for these constants is possible, and subsequently estimates of the stiffness and strength of pinned connections in orthotropic laminates is possible. In this case the model is valid in regions on the hole edge as well as some distance from it. Three-dimensional plots can therefore be used to visualize changes in distribution for various laminates (Figure 4).

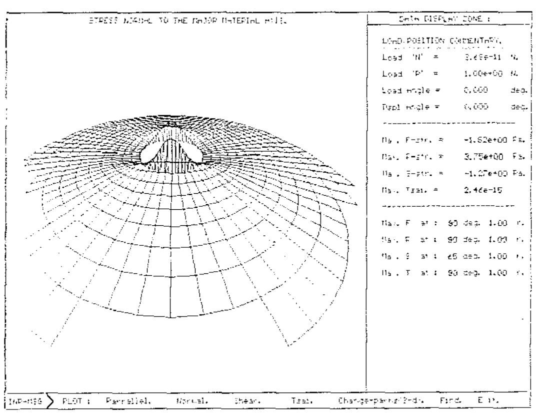

FIGURE 4 : STRESS DISTRIBUTION AROUND PIN LOADED HOLE

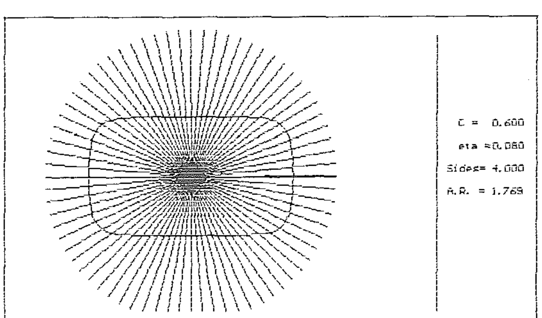

FIGURE 5 : INTERACTIVELY VARIABLE SHAPE HOLES

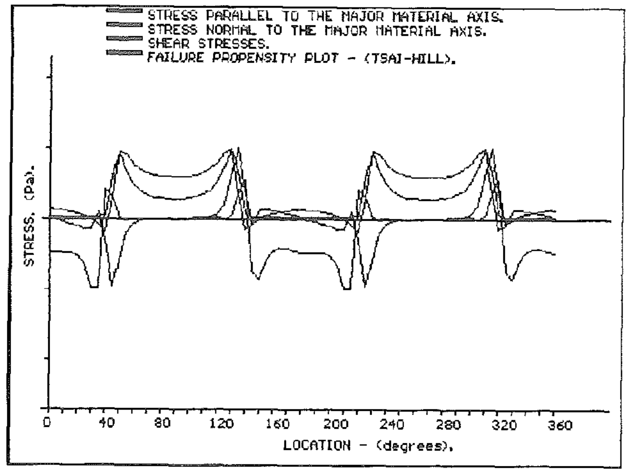

FIGURE 6 : TWO DIMENSIONAL PLOT OF STRESSES AROUND SQUARE HOLE

For other cases such as elliptical and square holes only stresses around the hole periphery are determined. Two dimensional plots of this distribution must therefore suffice.

In the case of elliptical and square holes parameters are available for altering the aspect ratio of the holes. In order to maintain the level of interactivity of the system these parameters can be increased or decreased using given keys. The hole shape is presented on screen together with the parameters and aspect ratio (Figure 5). In order to be able to correlate stresses in the stress output plot with the location on the hole periphery, radial lines are provided at five degree intervals (Figures 5 and 6).

Although recall of data at any point in the stress field is possible, including that given by the failure criteria as the initial failure point, it is still required to present these stress data in a format suitable for deduction of the failure process. This point is made since in real testing this initial onset of failure is very difficult to verify. It is believed that by using the first four critical points as a guide better information regarding the failure can be obtained. These four points are the maximum failure index given by the failure criteria and each of the maximum stress values for transverse, longitudinal and shear stress. Using these values a quasi failure progression graph is obtained (Figure 7). Although this does not correct for any edge effects that may be present at the hole edge or the effects of a steep stress gradient, it does give some insight into the behaviour of the pin-loaded hole at or near failure. Figures 7 and 8 show plots for the IACADS based model and a finite element model for which a cosine pressure distribution was assumed. Results from the IACADS analysis show that although transverse failure is predicted to occur below a bearing stress of 150 MPa, the presence of a bonded bush may suppress this resulting in the ultimate load occurring at a much higher value of slightly more than 300 MPa. The ultimate load under test was 303 MPa.

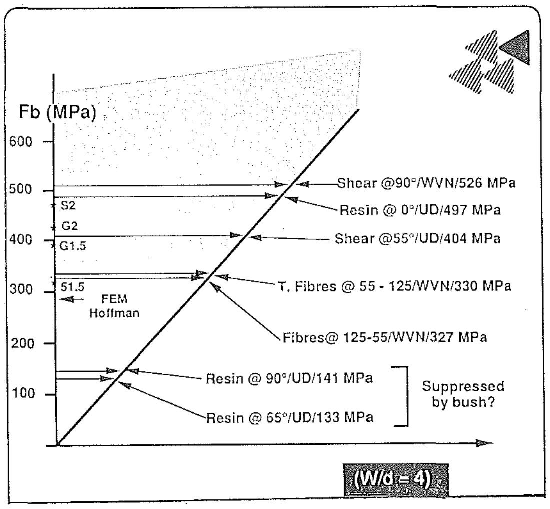

FIGURE 7 : QUASI-FAILURE PROGRESSION PREDICTED BY I.A.C.A.D.S.

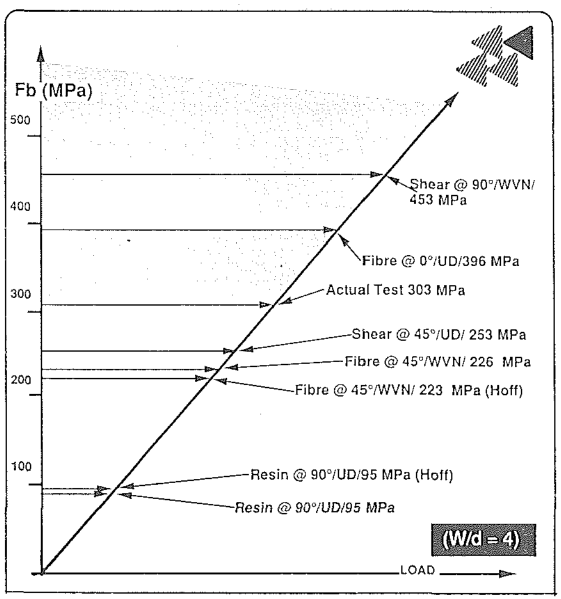

FIGURE 8 : QUASI-FAILURE PROGRESSION PREDICTED BY F.E.M.

Data Screening

During the verification of the classical lamination theory module (ICLT - Interactive Classical Laminate Theory) it was found that some properties of angle-ply materials could not be satisfactorily reproduced in standard test procedures. Several properties were tested, viz. tensile modulus and tensile strength, compressive modulus and strength, shear modulus and strength and Poisson's ratio. Of these properties it was noted that the shear modulus was consistently of the order of thirty percent lower than the value predicted by ICLT.

It was noted at this stage that De Jong(4) had reported a similar discrepancy when generating values for his code. Although De Jong decided to use the lower test value in his computational work, it was still believed to be of fundamental importance to explain this discrepancy since the effectiveness of any computational procedure would be adversely affected. To this end a small literature survey was launched into the shear testing of materials (6,7,8,9). It was found that the Iosipescu test method is the most attractive for obtaining shear moduli since the specimen size is small and the test is relatively simple. In order to find the source of error a finite element model was built. At this stage it was found to be efficient to use IACADS for the formatting of material properties used in the finite element code. The material stiffness matrix data deck is directly generated and appended to the bulk data prior to a computational run. This simplifies the development of composite material finite element models significantly.

The stress contours (Figure 9) can be seen to be steep in the test region, and since the test modulus was calculated by using the average shear stress across the test section, it would almost certainly be in error. By re-running the finite element model several times for different materials it was found that the error due to the stress gradient depends upon the material being tested. Some typical differences for several test materials are given in Table 1. It should be noted that the shear strength determination using the Iosipescu shear test is difficult since crushing of the specimen at the load introduction points occurs. The use of primary material data as input to ICLT and the subsequent attempt to correlate test data and data predicted by ICLT for angle-ply laminates provides a useful method of data screening of material data. This method of data screening was applied to several materials for which sufficient test data was available. It was found that of the 10 materials tested at least two showed enough deviation so as to either disregard the validity of the basic material data or at the very least flag this data as computationally incompatible.

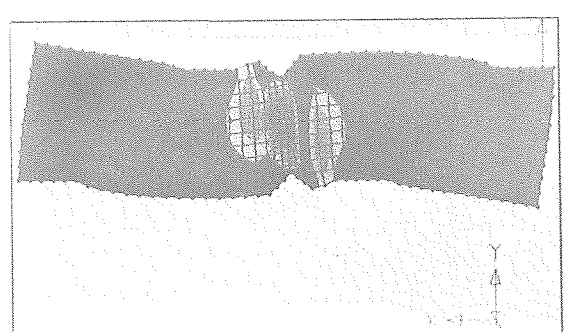

FIGURE 9 : F.E. MODEL OF IOSIPESCU SHEAR TEST

TABLE 1 : TYPICAL SHEAR MODULUS ERRORS

Material (Test Method)	Shear Modulus Test Mean (GPa)	Predicted Shear Modulus (GPa)	Percentage Difference
P_d (rail)	5,91	9,2	-35,8
P_e (rail)	6,47	9,4	-31,2
P_f (rail)	8,14	12,0	-32,2
P_g (rail)	6,51	11,0	-40,8
P_p (Iosipescu)	6,97	7,3	-4,5
P_{dj} (?)	27,74	41,0	-32,3

Although it was originally believed that good correlation of test results would reduce the load on the material testing group by eliminating the need to test for angle-ply data, it is now believed that the testing of angle-ply data is more relevant than before since it provides a quality assurance procedure.

The steep stress gradients noted in the test region led to the belief that additional errors could occur in more complex laminates due to transverse shear resulting from these gradients. In order to study the possible effects of erroneous surface strain gauge readings a "floating cube" finite element model was built.

Finite Element Modelling

The finite element method of analysis has become an invaluable research and structural analysis tool. This is even more true in analysis of structures made from composite laminates where deformation and natural frequencies may be altered by variations in material and layup. To this end IACADS can be used to generate material data in several formats acceptable to finite element codes. This aid assisted in the development of a finite element model of a carbon fibre aircraft. The wing was first geometrically defined on a personal computer based CAD system (Figure 10) enabling the definition of individual components of the wing structure. This aspect is relevant since it enabled the total wing model to consist of individually defined components.

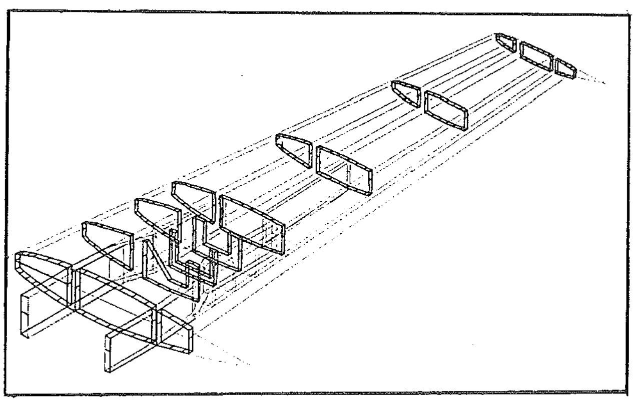

FIGURE 10: P.C. BASED CAD WING DEFINITION

Element meshing was performed such that each component exists in its entirety as a separable item. Interfaces between components, for example between a rib and the skin, may consist of several elements on top of one another with each element belonging to is own component. This approach offers two distinct advantages. Firstly, components may be optimized or modified individually, the loading on each component coming from the surrounding complete structure. Secondly, regions of complex layup such as zones where two or more components are bonded together using flanges, are no longer gross approximations. Figure 11 shows the stress distribution in the bottom wing skin. The effect of the flanged bond lines along the spars and ribs can be clearly seen. This effect is due to both the thickened laminate along the bond line as well as the load transfer to the underlying component. This added detail can be used to obtain more comprehensive information regarding the integrity of the bonded joint.

Table 2 gives correlation of deflections along the wing with test data. Results of local strains are affected by the fact that spar-cap gauges could not be placed as well as desired. Also, pairs of strain gauges were used to determine the shear strain at various points. This led to some problems since the direction of maximum shear could not be determined. It is suggested that in future full strain gauge rosettes be used in regions of complex stress. This gauge data can then be fully examined using IACADS.

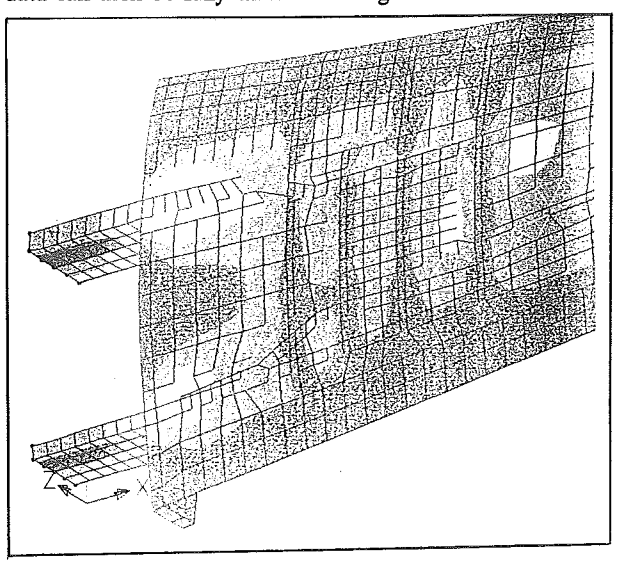

FIGURE 11 : STRESS CONTOURS ON LOWER AIRCRAFT WING SKIN

The concept of being able to extract components from a complete structure leads naturally to the concept of macro/micro modelling whereby successive models cover smaller zones in more detail using input data obtained from the larger model. This process as applied to the wing model is depicted in Figure 12. This can be naturally

TABLE 2 : DEFLECTION CORRELATIONS ALONG WING SPAN

Position	Test Av (mm)	F.E. Model (mm)
1 (Tip)	101,67	105,00
2	106,25	106,30
3	57,25	57,62
4	57,25	63,02
5	13,68	10,16
6	12,03	15,65
7	0,85	0,17
8 (Root)	0,98	1,27

extended to include pre-defined micromechanical models which could possibly be used to obtain detailed information suitable for fatigue life estimation.

Automated micromechanical models

The concept of using very fine finite element models to model a laminate's layers in detail has been used to examine the validity of the classical laminate theory program (ICLT). It has also been used to examine edge stresses in angle-ply laminates as a natural progression of the finite element model used to find the source of errors in shear tests. It is interesting to note that a ± 45° (balanced weave) angle-ply does not display any edge effects in tension. The possibility of creating an automated three-dimensional finite element model within IACADS has been investigated. The obtaining of free-edge stresses in an arbitrary laminate alone does not warrant the creation of such a facility. However, the results presented in Table 3 show that for unidirectional laminates the bearing stress at failure is reasonably well predicted. However, for laminates that are more complex there is considerable deviation. This deviation could be attributed either to inaccurate determination of the onset of failure during the test procedure, or the presence of through-the-thickness stresses which are present at the free hole edge and may be present some distance from the hole edge due to the steep stress gradients that exist in the vicinity of the hole. In order to quickly and effectively examine such regions of steep stress gradient a three-dimensional finite element probe may be of benefit.

The benefits of such a probe could be measured firstly in accessibility to a simple interactive three-dimensional model for research and analysis purposes and secondly by the savings in computer resources required to perform such analysis. Unless the standard finite element code used to model such a detailed section of a laminate possesses enough intelligence to reduce the number of stiffness matrices as required, a model of a ten layer laminate with forty elements per side would typically require sixteen thousand stiffness matrices for brick elements. However, a tailored automated and self contained finite element model

TABLE 3 : CORRELATION OF BEARING STRENGTH DATA WITH I.A.C.A.D.S. ON FIBREDUX 920G-R

Laminate	Test Load	Predicted Load	% Diff.
[0°]	~ 1500	1504	-0.3
[20°]	~ 1300	1295	+0.4
[40°]	~1300	1209	+7.5
[60°]	~1250	1196	+4.52
[90°]	~1200	811	-48
	266	287.5	8%
a	3560	2661	34
b	3500	3067	14
d	3800	3195	19
e	3400	2674	27
f	4300	2561	68
g	2500	2070	21
h	2790	2369	18
j	3760	3108	21
l	4350	2556	70
m	3200	2430	31
o	1300	1329	-2
p	3457	2578	34
q	4100	2910	27
r	3650	3580	-3
s	2263	1654	36
t	1260	1135	11
u	4890	3596	36

would only require ten such stiffness matrices - one for each layer. In addition these matrices would be automatically available through IACADS. The solution of the resulting set of equations could possibly also be optimized, since the model is square and of known connectivity.

Conclusion

Much work remains in the development of this system. However, although I.A.C.A.D.S. is not as advanced as other existing systems, this can be seen as an advantage because newer technology can be assimilated during its development. For example the use of largely parallel systems may be used conveniently in the solution of stress fields in situations such as that for pin-loaded holes. Since the solution requires only the location of the point at which the stress is to be calculated, (plus of course basic material and loading data), all points can be calculated simultaneously resulting in an almost real-time analysis. The use of object orientated programming methodologies makes progression towards automated optimisation procedures more easily attainable.

Although I.A.C.A.D.S. has been shown to be valuable in practical applications, its value lies most probably in its role as a research development platform.

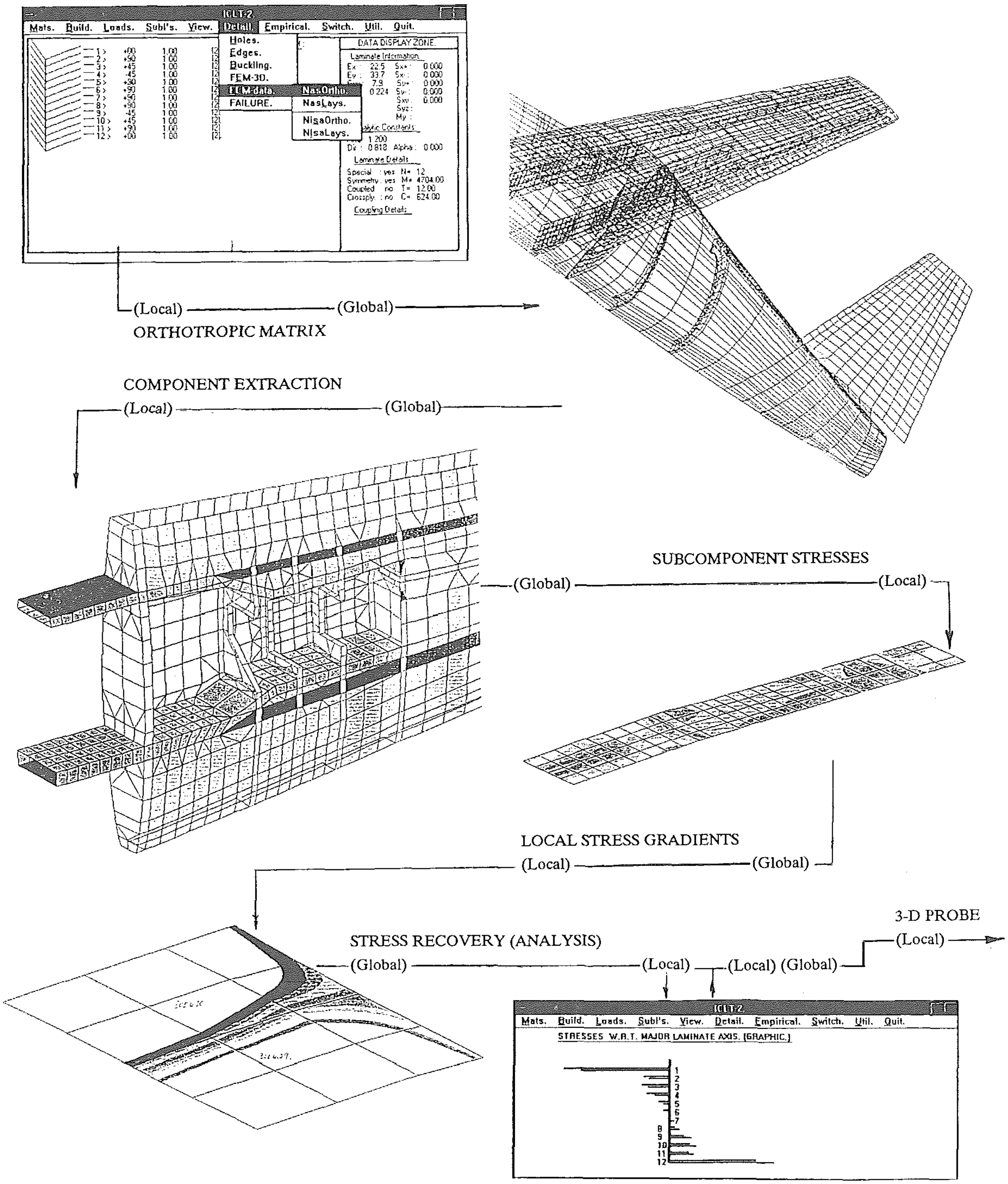

FIGURE 12 : TYPICAL GLOBAL/LOCAL PROCESS IN COMPOSITE STRESS ANALYSIS

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