NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n° N5

ENVIRONMENTAL AGENTS EFFECTS ON MECHANICAL PROPERTIES OF THICK COMPOSITE STRUCTURAL ELEMENTS

by

C. CAPPELLETTI, A. RIVOLTA, G. ZAFFARONI

AGUSTA, ITALY

September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

ABSTRACT

In this work a consolidated composite structural analysis theory and a suitable treatment of the experimental data obtained from material characterization standard tests had allowed to assess the effects of the operating temperature and of the absorbed moisture on the elastic and ultimate properties of high thickness composite elements.

INTRODUCTION

It is well known that moisture uptake of fiber reinforced epoxy resin causes a decreasing mainly of matrix and interface dependent properties(1). With high thickness laminates the moisture saturation can't be reached during the supposed service life of the component and/or during industrial time scale of accelerated conditioning for testing. In the last case a different point to point moisture distribution in the laminates, called here moisture gradient, is obtained. A comparison between the moisture gradient foreseen for the service life and that obtained in accelerate laboratory ageing is then needed(2).

In addition the engineering properties data base built from standardized coupons are usually founded on mechanical tests performed only in four conditions: Room Temperature Dry, High Temperature Dry, Room Temperature moisture saturated (R.T. Wet), High Temperature moisture saturated (H.T. Wet).

For the analysis of composite laminate with a through the thickness moisture gradient none of the previous conditions is satisfied. In fact the humidity level is ply to ply different and, except at least for the first ply, is different from the saturation condition. So the use of the data obtained from the moisture saturated coupons could drive to mistaken conclusions.

In the present work we introduce a rough approach to determine the plies elastic constants and the strengths for the intermediate conditions with the final purpose to forecast the degradation of the (static) mechanical performances of composite structural elements. The general outline of the work is shown in fig.1

MATERIALS

The structural components subject of this analysis were produced starting from the following prepregs:

1) a 125°C curable glass reinforced epoxy resin;
2) a 125°C curable high modulus graphite reinforced epoxy.

To determine the mechanical properties of the materials involved standard coupons were manufactured and tested according to ASTM test methods (see table 1).

TABLE 1	
Mechanical properties	Test method
E_{11}, E_{22}, ν_{12}, X^t, Y^t	ASTM D 3039
G_{12}, S	ASTM D 3518
X^c, Y^c	ASTM D 3410

The test conditions at which the mechanical properties were experimentally determined was: T = 23°C/specimen dry, T = 23°C/moisture saturated, T = 82°C/dry, T = 70°C/moisture saturated.

The environmental ageing condition to saturate the materials was T=45°C, Relative Humidity=84%.

To investigate the hygrothermal behaviour of the composites the following physical properties were determined:

- Glass transition temperature (T_g) by T.M.A. (Thermo Mechanical Analysis);
- Moisture absorption kinetics and equilibrium parameters (i.e. the diffusion coefficient D_x and the saturation weight gain $M\infty$) by absorption tests in a controlled environment[3,4].

STRUCTURAL ELEMENTS

We have turned our interest to EH101 structural lug elements manufactured from unidirectional graphite and/or glass reinforced epoxy matrix. The structural elements have been planed to cover all the composite design requirements for two components of the EH101 helicopter rotor: outboard and inboard tension link composite plates. The typical sections of these two specimens have the same lay-up of the plates section and the lugs are representative of the blades attachment. Then all the characteristics of the plates are reproduced and tested through these structural elements. The Inboard Tension Link Structural Element is a glass reinforced epoxy plate 16 mm thick, while the Inboard Tension Link Structural Element is a glass/carbon reinforced epoxy hybrid plate 32 mm thick (see fig.2).

The structural elements have been tested applying axial loads (centrifugal force, beam and chord bending moments) representative of the flight, ground-air-ground and folding conditions.

The mechanical static tests on the structural elements were carried up at room temperature and in hot-wet environment (70°C, 84% R.H.).

In addiction the through the thickness moisture distribution obtained after artificial ageing was experimentally determined by the D.R.A. Farnborough using the "slicing" analysis[5]. This experimental step was necessary because to accellerate the moisture absorption probably we overcame the "fickian behaviour".

ANALYTICAL CODES

To simulate the behaviour of the structural elements two home made computer codes were used: LAMGEN and DIFF2D.

The first deals with the mechanical behaviour of a composite plate using the mathematical relations which constitute the basis of the structural analysis of the anisotropic laminates. Thus using as input the elastic properties of each lamina which belongs to the plate, the lay up and the strain boundary conditions we obtain the compliance of the laminate and the state of stress of each ply.

DIFF2D simulates the moisture diffusion into an hybrid composite material and it is based on the irreversible processes thermodynamic. It needs as input data: the lay up, the diffusion coefficients, the moisture saturation concentrations of the materials involved only in the test condition (T and R.H.).

MATERIAL DEGRADATION EXPERIMENTAL DATA AND THEIR INTERPOLATION

Absorbed moisture gives rise to a reduction of the T_g (then a reduction of the maximum operative temperature) and of the static mechanical properties (elastic constants and/or strengths). In addition also a temperature increase reduces moduli and strengths. In the following a reasonable interpolation of experimental data, determined only at extreme conditions, will be defined. For every material we have conditioned the specimens in various hygrothermal environment weighing them until saturation. Subsequently the moisture diffusion coefficient (D_x), the saturation weight gain ($M\infty$) and the T_g(wet) was determined.

The dependance of the absorption parameters on the boundary conditions is splitted in two parts: the D_x is considered to be dependent from T by an Arrhenius form and from the thickness by an empirical law:

$$D_x = D_o\, \Omega(h) \exp\left(\frac{-E_{.att}}{RT}\right)$$

while the M∞ is dependent only from the Relative Humidity:

$$M_\infty = m\,(R.H.\%)^n$$

where: T = temperature (K); h = thickness; m,n = experimental constants.

For the materials here involved the moisture absorption parameters of interest are:

TABLE 2			
Material	Outboard	Inboard	M∞ (R.H. = 84%) (% w/w)
	Dx (T = 26°C) (mm2/s)	Dx (T = 26°C) (mm2/s)	
glass/epoxy	$4.9*10^{-8}$	$8.1*10^{-8}$	0.86
carbon/epoxy	---	$2.0*10^{-7}$	1.23

Experimental data of T_g versus M∞ were fitted by a second order polynomial: $T_g = c_o + c_1 M_\infty + c_2 M_\infty^2$

This merely phenomenological approach is satisfactory for our purpose. In table 3 the empirical functions $T_g(M_\infty)$ are summarized while in fig. 2 an example of these correlations is shown.

TABLE 3			
Material	$T_g = c_o + c_1 M_\infty + c_2 M_\infty^2$		
	c_o	c_1	c_2
glass/epoxy	385.9	-16.63	-13.17
carbon/epoxy	396.1	-48.32	14.18

The mechanical properties of the materials at 23°C/DRY are summarized in table 4

TABLE 4		
Property	glass/epoxy (MPa)	carbon/epoxy (MPa)
E_{11}	45700	173000
E_{22}	13500	7750
G_{12}	5400	4400
ν_{12}	0.27	0.21
X^t	1540	1240
Y^t	46	32
X^c	1095	830
Y^c	183	173
S	78	68

To take into account the environmental effect we define a degradation factor f as:

$$f(T,M) = \frac{\textit{property at temperature } T \text{ and } \textit{moisture content } M}{\textit{property at } T=23°C \text{ and } M=0.0}$$

For each test condition the f(T,M) is reported in tab. 5 and 6.

TABLE 5 : DEGRADATION OF GLASS/EPOXY					
Test conditions	T [°C] Mt∞ (%)	23 0.0	23 0.86	82 0.00	70 0.86
	f [E_{11}]	1	1.00	1.00	0.95
	f [E_{22}]	1	1.00	0.87	0.71
	f [G_{12}]	1	0.68	0.68	0.52
	f [X^t]	1	0.82	0.86	0.71
	f [Y^t]	1	0.87	0.83	0.59
	f [X^c]	1	0.85	0.88	0.55
	f [Y^c]	1	--	0.65	0.46
	f [S]	1	1.04	0.92	0.76

TABLE 6 : DEGRADATION OF CARBON EPOXY					
Test conditions	T [°C] Mt∞ (%)	23 0.0	23 1.2	82 0.0	70 1.2
	f [E_{11}]	1	0.90	1.00	0.88
	f [E_{22}]	1	0.92	0.97	0.88
	f [G_{12}]	1	1.00	0.86	0.77
	f [X^t]	1	0.94	1.00	0.94
	f [Y^t]	1	1.00	0.56	0.56
	f [X^c]	1	0.75	0.77	0.71
	f [Y^c]	1	0.79	0.76	0.60
	f [S]	1	--	1.00	0.93

Now we show an operative approach to give a reasonable degradation factor of static properties (moduli and strengths) for $0.0 \leq M \leq M\infty$ at the temperature Top = operative temperature.

The method is based on the assumption of a power law form for the dependance of the degradation factor from the difference between the glass transition temperature and the operative temperature[7,8], i.e. at a fixed $M = M_k$ we shall consider for each mechanical property f[properties](T,M_k) represented by:

[1] $f_k = a\,(T_g\,(M_k) - Top)^b$ for $M = M_k$

where a,b = constants

$Tg(M_k)$ = glass transition temperature at the moisture level M_k.

We shall take into account the effect of the absorbed moisture on f considering in the above expression:
$a = a(M) \quad b = b(M)$

The simplest assumption which we can make is the a linear approach such as:

[2] $a = a_o + a_1 M \qquad b = b_o + b_1 M$

where a_0, a_1, b_0, b_1 are constants.

Taking the logarithm of [1] we have the linear equation:

$\ln(f_k) = \ln(a(M_k)) + b \ln(T_g(M_k)) - Top)$

and from the experimental values of f through the use of [2] it is possible to obtain f(T,M).

The different behaviour of the mechanical properties, in the range of temperature and moisture explored, can be collected into these cases:

a) both temperature and moisture affect the f-value: e.g. in fig.4 (G12 of carbon/epoxy)

b) only the temperature affect the f-value (e.g. Y^t for the carbon reinforced composite);

c) only the moisture affect the f-value (e.g. E_{11} for the carbon reinforced composite).

ENVIRONMENTAL AGEING OF STRUCTURAL ELEMENTS

A level of natural environmental ageing of the structural lug elements was reproduced submitting them to the an accelerated temperature/relative humidity cycle (see table 7). The artificial environmental ageing of the structural elements was defined in such a way as to obtain in reasonable time the same moisture absorption (in terms of total uptake and internal distribution) which is typical of long term natural exposure.

TABLE 7

Step	from: (d)	to: (d)	T (°C)	Relative humidity (%)
I	0	182	50	84
II	182	245	60	84
III	245	350	50	84
(dwelling)	350	test	26	84

Following this method it is accepted that, due to the high thicknesses, the moisture absorption equilibrium cannot be reached. Then the total moisture weight gain and the through the thickness distribution obtained in the accelerated ageing needs to be compared with the "natural ageing" in the standard environment 26°C/84%R.H. to determine the equivalent number of days for which the accelerated ageing is representative. The last condition is recognized to be the average worst world wide hot/wet climatic situation[9].Because of the long time needed by the absorption in the second condition this kind of ageing shall be only simulated by the computer code DIFF2D.

The moisture concentration distributions experimentally determined (slicing analysis) of the accelerated absorption cycle of table 7 are shown in figures 5 and 6 respectively for the glass and the hybrid glass/carbon structural elements. Those profiles are used in the subsequent evaluation of the mechanical properties.

The fitting curves of the through the thickness experimental moisture gradients are shown in the figures 5 and 6.

EVALUATION OF STRUCTURAL ELEMENTS BEHAVIOUR

In every through the thickness position x we have a local moisture level M(x). Using this M(x) we compute, in every position x, $T_g(x)$ and the parameters a(x) and b(x) of the form [1] through the use of the relations [2] giving the degradation factors of the mechanical properties.

In this way we obtained the plies elastic constants in the test condition, for each structural element. These are an input of the LAMGEN code. For instance for the outboard tension link structural lug element at 23°C see fig.7

First of all it is necessary to determine the equivalent time which is the time necessary in the standard condition T=26°C, R.H.=84% to obtain the same moisture content and the same gradient measured after the accelerated ageing cycle. DIFF2D gave the following results:

- Outboard Tension Link Structural Lug Element: the accelerated cycle generated a situation comparable with a 5 years natural ageing (see fig.5).
- Inboard Tension Link Structural Lug Element: the accelerated cycle generated a situation comparable with a 6 years natural ageing (see fig.6);

A check of the mechanical properties interpolating method previously shown involves the analytical evaluation of the mechanichal behaviour of the structural elements. From the above mentioned through the thickness mechanical properties by means of the LAMGEN code we found the theoretical stiffnesses and ultimate stresses of the structural elements. The failure load was computed increasing analytically the axial load and removing from the lay up the plies everytime they reach their strenghts. The satisfactory agreement between the test and analysis results has been found as shown in table 9

TABLE 9

Conditions		Stiffness			Strength		
T (°C)	S.E.	f comp.	f exper.	% dev.	f comp.	f exper.	% dev.
outboard tension link structural element							
23	dry	1	1	13	1	1	12
23	W(n,s)	0.9	0.93	10	0.8	0.96	5
70	dry	0.9	0.77	10	0.88	0.88	11
70	W(n,s)	0.73	0.87	6	0.7	0.76	3
inboard tension link structural element							
23	dry	1	1	13	1	1	7
70	W(n,s)	0.89	0.85	6	0.78	0.75	3

S.E. = structural element (dry = not conditioned; W(n,s) = conditioned not saturated)

$$f\,comp. = \frac{computed\ property}{computed\ property\ at\ 23°C\ dry} \qquad f\,exper. = \frac{experimental\ property}{experimental\ property\ at\ 23°C\ dry}$$

$$\%\,dev. = 100\frac{|experimental - computed|}{experimental}$$

CONCLUSION

The approach here proposed is operatively satisfactory because the percent deviation of the calculated mechanical characteristics respect to the experimental determinations is less than 13%.

In addition we have estimated the "equivalent time" of natural ageing to give rise to the same conditioning of accelerated cycle.

Furthermore the method here presented could give a tool to forecast the decreasing of the static mechanical properties of a thick element in its operative life.

LIST OF SYMBOLS

x = spatial coordinate

t = time, t_{eq} = equivalent time

Tg = glass transition temperature

T = temperature, T_{op} = operative temperature

R.H. = percent relative humidity

M = weight percent of absorbed moisture

M_∞ = equilibrium weight percent of absorbed moisture

f = degradation factor

E_{11}, E_{22}, G_{12} = longitudinal, transversal and shear elastic modulus

ν_{12} = Poisson's ratio

X^t, Y^t = longitudinal and transversal tensile strength

S = shear strength

X^c, Y^c = longitudinal and transversal compressive strength

REFERENCES

(1) G.Springer ed., Environmental effects on composite materials;

(2) M.Raggi, U.Mariani, G.Zaffaroni, Fatigue qualification of high thickness composite rotor components, proc. of 16th ICAF symp., May 1991;

(3) R.De Iasi, J.B.Whiteside, Effect of moisture on epoxy resins and composites, ASTM-STP 658, pp.2-20;

(4) T.A.Collings, Moisture management and artificial ageing of fiber reinforced epoxy resins, Composites structures, 5, 1989;

(5) T.A.Collings, S.M.Copley, On the accelerate ageing of CFRP, Composites, July 1983 pp. 180-188;

(6) S.W.Tsai, H.T.Hahn, Introduction to composite materials;

(7) C.C.Chamis, R.F.Lark, J.H.Sinclair, Integrated theory for predicting hygrothermomechanical response of advanced composite structural components, ASTM-STP 658, pp. 160-192;

(8) S.W.Tsai ed., Composite design;

(9) T.A.Collings, The effect of observed climatic conditions on the moisture equilibrium level of fibre reinforced plastic, Composites, Jan. 1986, pp.33-41

ACKNOWLEDGMENT

The authors wish to thank Mr.T.A. Collings (formerly D.R.A.) for the slicing analysis and the precious comments, Mrs.S.M.Guerra, Mr.S.Risetti, Mr.A.Barrese to have performed much of the experimental work and Mr. G.Puricelli, Mr.F.Ghirardini for the analytical support and Mr.Zanotti for the precious comments.

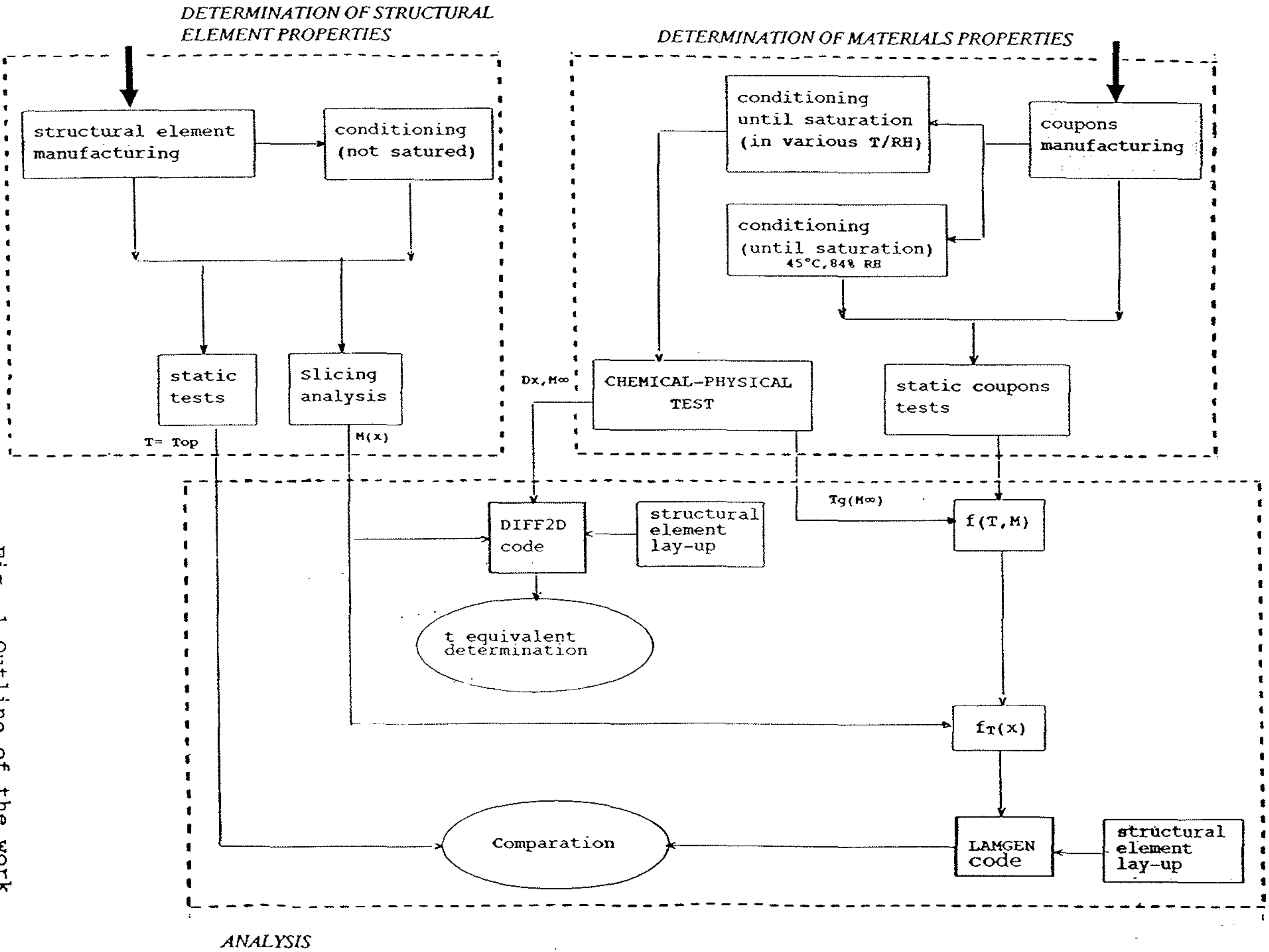
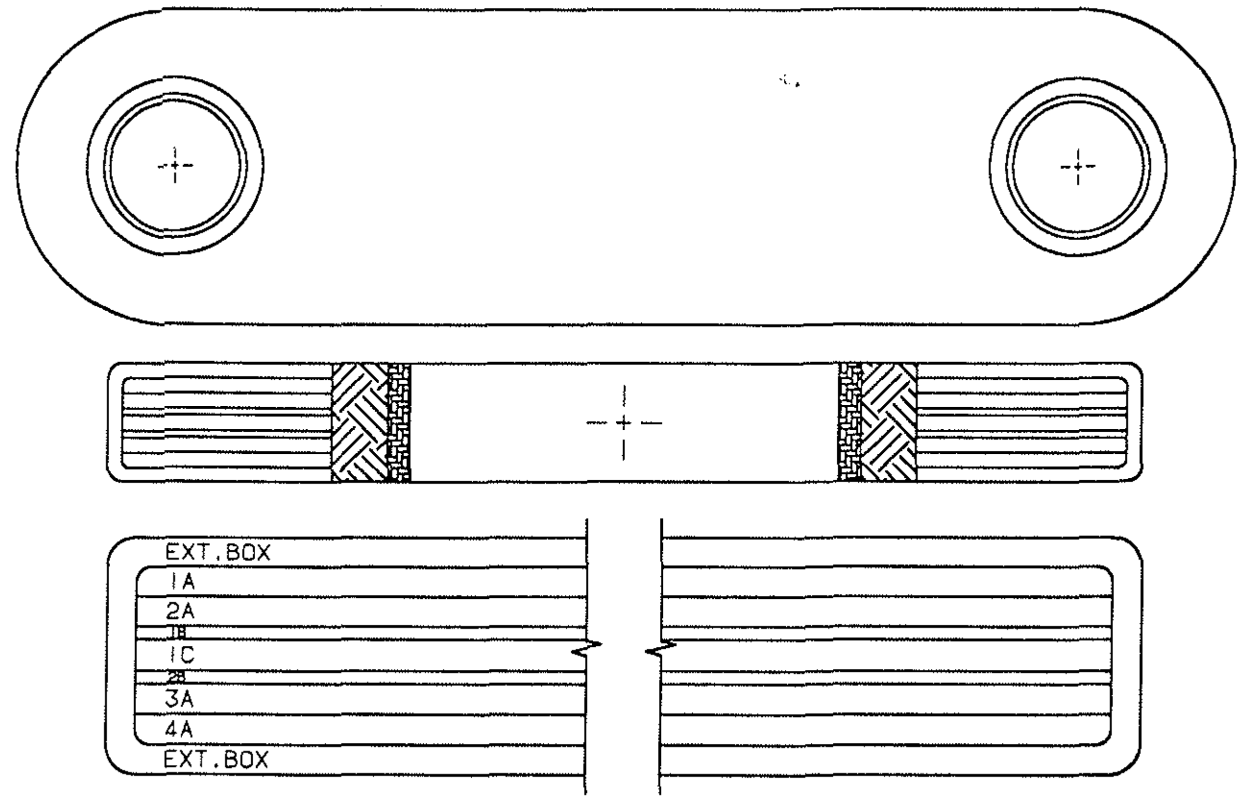
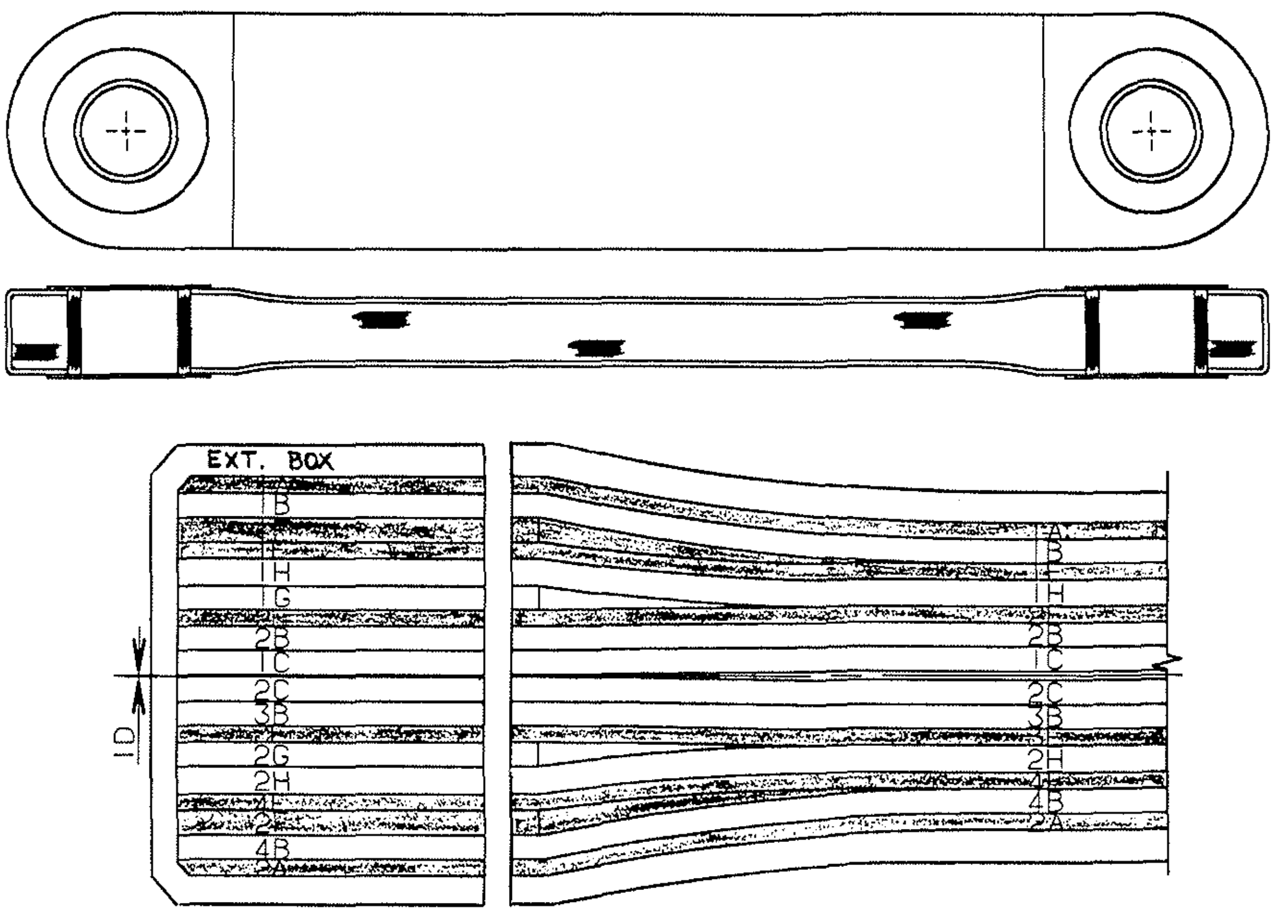


Fig. 1 Outline of the work



OUTBOARD TENSION LINK STRUCTURAL ELEMENT



INBOARD TENSION LINK STRUCTURAL ELEMENT

Glass / Epoxy

Carbon / Epoxy

FIGURE 2: Structural elements Lay up

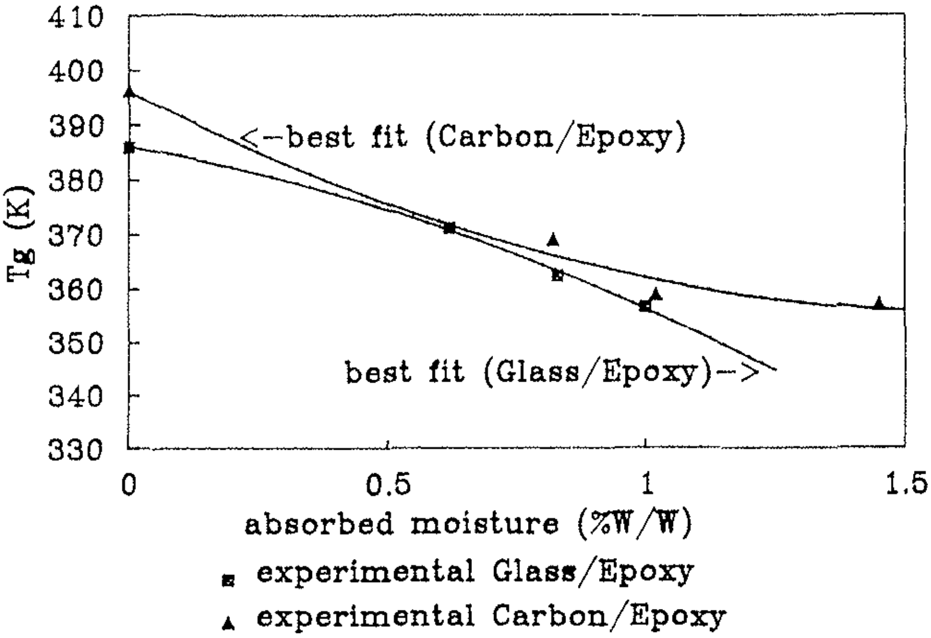


FIGURE 3: Glass transition temperature depression

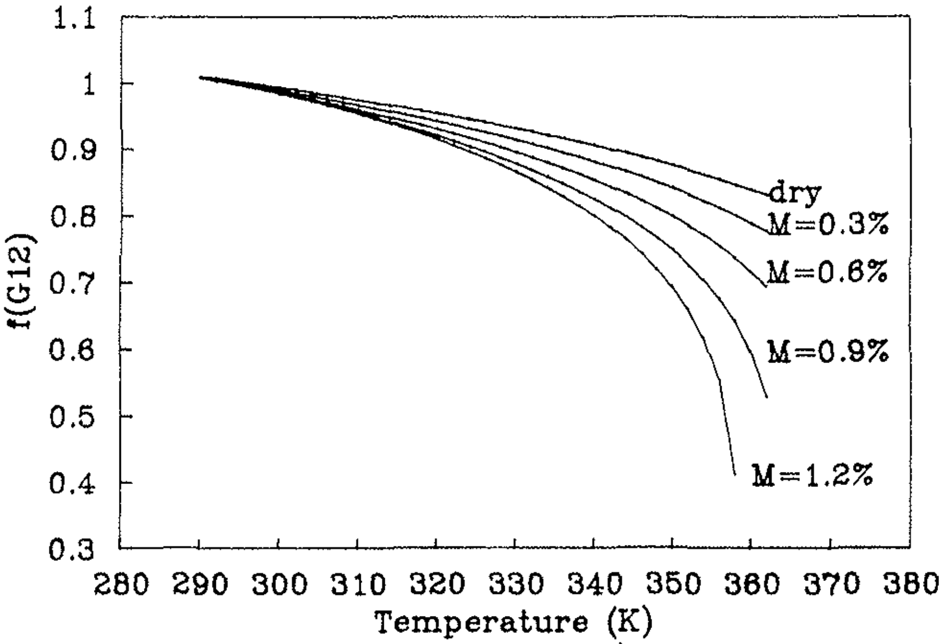


FIGURE 4: f factor for G12 Carbon/Epoxy

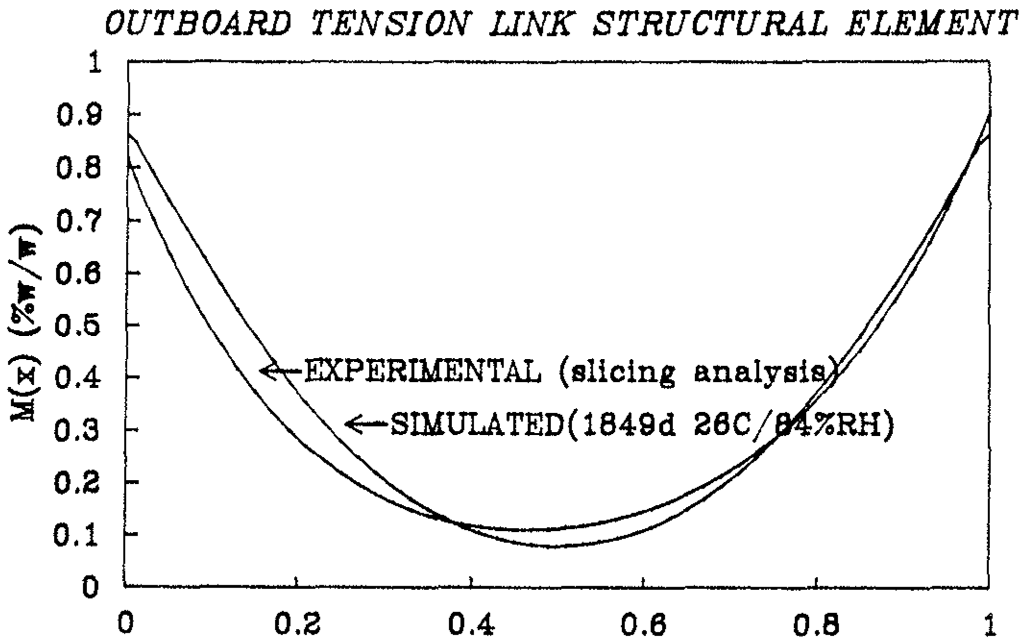


FIGURE 5: comparison of the moisture internal distribution after the hygrothermal cycle (tab.7) and simulated at 26C/84%RH

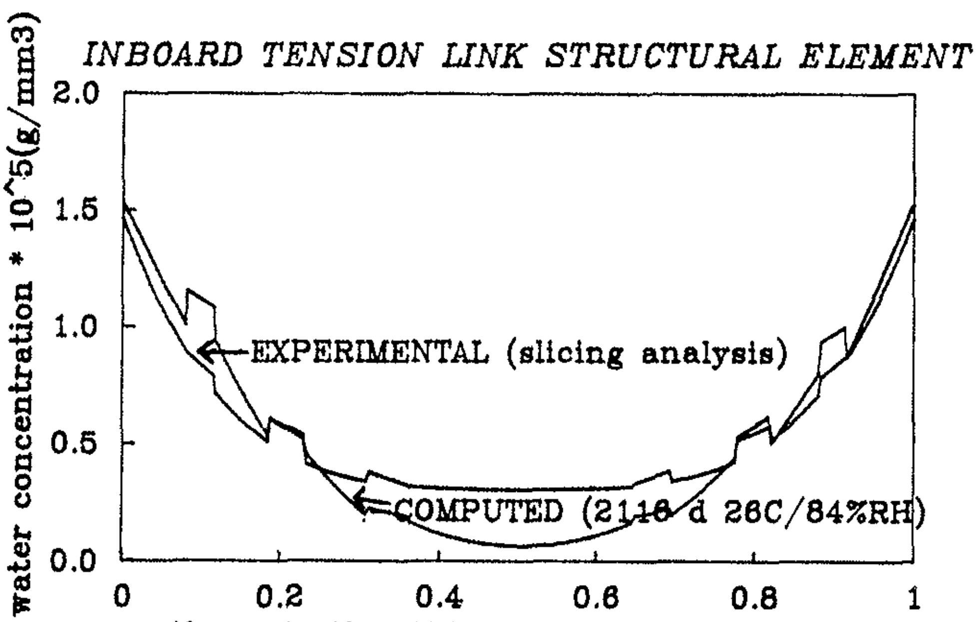


FIGURE 6: comparison of the moisture internal distribution after the hygrothermal cycle (tab.7) and simulated at 26C/84%

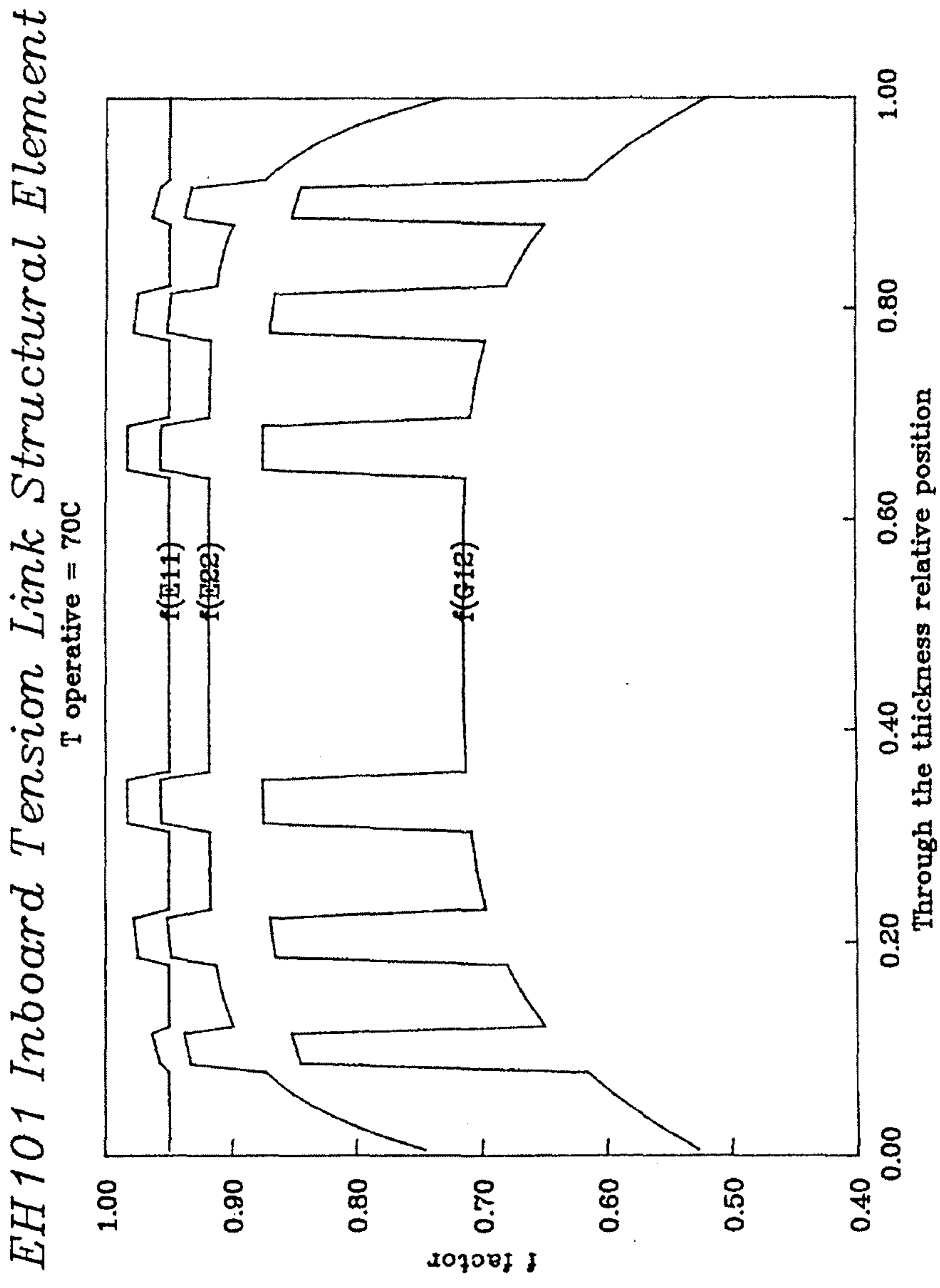


Fig.7 Inboard tension link f factor internal distribution