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DESIGN OF HYBRID COMPOSITES WITH ZERO COEFFICIENT OF THERMAL EXPANSION

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Abstract

Structures used in aerospace are influenced by temperature. So coefficient of thermal expansion (CTE) is not only an important parameter of materials, but also a significant parameter of structural design of spacecrafts with high dimensional stability. In this paper, based on the analysis of the data from tests, theoretical formulae for predicting CTE and mechanical properties of hybrid composites were presented, and the calculation program was compiled. All the equations were verified by experiments. Optimization was conducted by computer. The results and methods of this paper can used both in optimal design of hybrid composites with zero CTE and in design of hybrid composites with any certain CTE values.

Ⅰ. Introduction

In order to improve the performance of aircrafts and reduce the consumption of fuel, an effevtive way is to lighten the weights of materials. Hybrid composites have more degree of freedom of design than single fiber reinforced composites, as well as their advanced comprehensive qualities, such as high specific strength and high specific modulus. Based on these facts, hybrid composites are extensively applied in aviation and space science. For structures used in aerospace, coefficient of thermal expansion is not only an important parameter of materials, but also a significant of structural design of spacecrafts. Especially, they are exposed to the variated temperature, so a low CTE value is urgently needed. And the investigation shows that well–designed hybrid composites does not only obtain ″ zero″ coefficient of thermal expansion (CTE$<$0.0 $\pm 0.4 \times 10^{-6}$ / K), but meets the requirements of mechanical properties and weight reduction. So studying of zero CTE of hybrid composites is of significance in space science.

Carbon / Glass and Carbon / Kevlar hybrid fibers are accepted to reinforce the three different kinds of resin matrixes respectively. Typical hybrid composite laminate specimens were made, and their CTE values (Rt.–150℃) were precisionly measured. The variation of CTE values of hybrid composites with structure parameters, such as fiber types, hybrid ratio, hybrid interfaces, ply order, ply angles, angle order and angle dispersion is analized. Based on the analysis of a large amount of data from tests, theoretical formulae were established, and the calculation program was complied. It is realized that after meeting the requirement of mechanics properties, the optimum disignation for hybrid composites with ″zero″ expansion or any CTE values can be made. This is especially of theoretical and practical significance for the structural design of composites in the fields of aeronauties and astronautics.

Ⅱ. Experiment

1. Raw materials

The types and properties of raw materials used in this work are listed in Table 1 and 2.

2. Form of lay–up of laminates

The parameters of laminates are listed in Table 3.

Ⅲ. Results and Discussions

1. CTE of unidirectional hybrid composites

Longitudinal CTE values of unidirectional single and hybrid fibers reinforced composites are listed in Table 4.

From Table 4, it is can be seen that the CTE values of composites are mostly decided by fibers, while matrix has some effect but not mainly factor. The larger the fiber CTE value is, the bigger the composite CTE values are: GFRP〉 CFRP〉 KFRP.[3]

Hybrid composite CTE is firstly decided by the fibers involved in hybrid: C / G〉 C / K,and secondly by the ratio of the two fibers (hybrid ratio). The results of variation is more obvious after the data in Table 4 are made into fig. 1. It shows that the CTE of hybrid composite is between that of the two kinds of single fiber reinforced composites, and is closed to that of the fiber of which the volume increases. So are the C / K and C / G hybrid composites. Therefor, zero expansion can be realized by using positive expansion fiber and negtive one at the proper ratio of them (fig 1 and 2).

Besides, expansion of the hybrid composices is also influenced by the interface number. From Table 4 and fig. 2, it is obviously seen that the more the interface number is , the greater the CTE values are. So after deciding fiber types and their hybrid ratio, reducing the number of interfaces is advantageous to obtain zero CTE value.

After deciding the above parameters, changing ply order (relative position of the two kinds of fibers) still variate the CTE of hybrid composites, as shown in Table 4. It is illustrated that in designing zero expansion of composites, ply order is also a parameter which can be adjusted.

2. CTE of multidirectional hybrid composites

From Table 5, it can be seen that CTE of multidirectional hybrid composites is greatly influenced by ply angle. 0 ° ,± 30 ° ,± 45 ° ,± 60 ° and 90 ° plies are adopted in the tests. Laminates with different angle plies have different CTE values even if the fibers are the same. And the curves of relation between CTE and ply angle are very completed, as shown in Fig.3. In the meantimes, it shows that if ply angles are properly chosen, zero expansion coefficient can be obtained.

Relative position of ply angle is defined as angle order in this paper. CTE of multidirectional hybrid composite is also infuenced by the angle order. For example, QH−14 and QH−17, in which some ply angle changes position each other only, have different CTE values. Namely, the latter is bigger than the former. Surely, this is relation with the fiber type of outer ply in 0 ° direction. It can be seen that angle order is also an adjustable factor.

CTE values of multidirectional hybrid composites have great something with to do angle dispersion shown as dispersion factor φ, which is defined as product of the number of different angles and the number of angle interfaces (interfaces between plies with different angles). Table 5 shows that for multidirectional composites, the bigger the φ value is, the smaller the CTE is .

If permitted, in designing composites with zero expansion, φ should be greater.

Ⅳ . Prediction of Composite Laminates With Zero−expansion

1. Estimation for CTE of unidirectional hybrid composites

Based on a large amount of experiment data, authors set up a formula to estimate CTE of unidirectional hybrid composites .

$$\alpha_{HY,L} = \frac{\alpha_{f1}E_{f1}V_fV_{f1}+\alpha_{f2}E_{f2}V_f(1-V_{f1})+\alpha_rE_r(1-V_f)}{E_{f1}V_fV_{f1}+E_{f2}V_f(1-V_{f1})+E_r(1-V_f)}(1+R_e) \qquad (1)$$

where

$\alpha_{HY,L}$	—longitudinal CTE of hybrid composites
$\alpha_{f1},\alpha_{f2},\alpha_r$	—CTE of fiber 1, fiber 2 and resin matrix.
E_{f1}, E_{f2},E_r	—tensile modulus of fiber 1, fiber2, and resin matrix
V_{f1},V_f	—relative volume of fiber 1 and general fiber volume
Re	—hybrid effect coefficient

The calculation results by equation (1) in which hybrid effects are neglected are listed in Table 4, and are compaired with experiment data: although they are very closed each other, some deviation still exits without consideration of hybrid effects. Whereas, hybrid effects have a relation with fiber type, hybrid ratio, hybrid interfaces and ply order , etc.

2. Prediction of unidirectcional hybrid composites with zero−expansion

The experiment results show that CTE of an unidirectional hybrid composite is depend on fiber types and their volume contents. So through variating hybrid ratio, relative volume of fibers at which CTE of the composite is zero can be obtained by equation (2):

$$V^0_{f1} = \frac{\alpha_rE_r(1-V_f)+E_{f2}\alpha_{f2}-E_{f2}\alpha_{f2}(1-V_f)}{(E_{f2}\alpha_{f2}-E_{f1}\alpha_{f1})\cdot V_f} \qquad (2)$$

Relative volume content of fiber 2 is

$V^0_{f2}=1-V^0_{f1}$.

If the hybrid effects are considered zero expansion can be realized by regulating some parameters within a rangement.

3. Estimation for CTE of multidirectional hybrid composites

Some hypotheses are assumed:

1) When temparature changes, fibers in plates maintain straight.

2) Interlaminar shear deformation are neglected.

3) Each ply of laminates is within the rangement of elastics.

4) Fiber and adhesive are no delaminated.

Based on these presumption, from single−ply plates, authors deduced an expression for CTE of symmitrical multidirectional laminates, and presented calculation program.[1]

$$\begin{Bmatrix}\alpha_x\\ \alpha_y\\ \alpha_{xy}\end{Bmatrix} = [A]^{-1}\left(\sum_{i=1}^{n} m_i[\overline{Q}^i]\begin{Bmatrix}\alpha^i_x\\ \alpha^i_y\\ \alpha^i_{xy}\end{Bmatrix}\right) \qquad (3)$$

where,

α	—CTE
[A]	—tesile stiffness matrix of plate in unit thikness
m	—thickness coefficient of laminates
n	—total number of ply
i	—No. i ply
x,y,xy	—x−direction, y−direction, xy−plane

If the single−ply plates are regarded as No. i ply of a laminates , the result is:

$$\begin{cases} \alpha_x^i = \alpha_L cos^2\theta^i + \alpha_T sin^2\theta^i \\ \alpha_y^i = \alpha_L sin^2\theta^i + \alpha_T cos^2\theta^i \\ \alpha_{xy}^i = \dfrac{2(\alpha_T - \alpha_L) sin\theta^i cos\theta^i}{1 + \alpha_L cos^2\theta^i + \alpha_T sin^2\theta^i} \end{cases} \tag{4}$$

where: θ—ply angle

L,T—fiber–orientation, transverse direction.

CTE of multidirectional composites applied in the tests were calculated by equation (3). The results are in closed with the experimental data. Whereas, due to neglecting hybrid effects, angle order and angle dispersion so on, the deviation still exists. So in order to obtain acurate estimation results, these parameters should be taken into account.

4. Prediction of multidirectional hybrid composites with zero–expansion

Because there are many variants in multidirectional compostie, some special ply patterns of single and hybrid fibers reinforced composites with zero–expansion are presented by calculation (the range of θ are presented). in Table 6 and fig.3 . It can be seen that the range of θ of which the CTE of single fiber reinforced bi–directional composites is zero is very narow, and it is hard to realize in practice. However, for composites with more than two directions, especially multidirectional hybrid compostie, the range of θ is very wide, when meeting the requirement of zero–expansion. For example, the ply angles of the specimens QL–11 and QC–13 is within the range of θ listed in Table 6, that is , in agreement with the prediction.

V. Optimal Design for Hybrid Composites with Zero Expansion

From the preceeding discussion, it is known that there are many kinds of ply patterns for multidirectional hybrid composites with zero–expansion. So it should be related with mechanical properties to decide a propriate ply form. In this paper, the optimization design for hybrid composites with zero expansion is based on the consideration of longitudinal tesile modulus and strength.[2]

1. Estimation for tensile strengh and modulus of hybrid composites

Estimation equation for the basic mechanics properties of hybrid composites were established:

1) Longitudinal tensile modulus of unidirectional composites (E_{HY}):

$$E_{HY} = [V_{f1}(E_{f1} - E_{f2}) + E_{f2}]V_f \tag{5}$$

2) Longitudinal tensile strength of unidirectional composites when fiber1 fractures (X_{HY}).

$$X_{HY}^1 = \varepsilon_{f1}[E_{f1}V_{f1}S_{f1} + E_{f2}(1 - V_{f1})S_{f1}]V_f(1 + R_e) \tag{6}$$

strength when fiber 2 fractures (X_{HY})

$$X_{HY}^2 = \varepsilon_{f2}E_{f2}(1 - v_{f1})S_{f1}V_f(1 + R_e) \tag{7}$$

where: $\varepsilon_{f1}, \varepsilon_{f2}$—fracture strains of fiber 1 and fiber2 of a composite.

S_{f1}, S_{f2}—revised coefficients of fiber 1 and fiber 2 of composite.

(3) Tensile modulus of multidirectional hybrid composites (Ex)

$$E_x = \frac{1}{a_1^*} \tag{8}$$

$$[S^*]_{HY} = \begin{bmatrix} a_{11}^* & a_{12}^* & a_{13}^* \\ a_{21}^* & a_{22}^* & a_{23}^* \\ a_{31}^* & a_{32}^* & a_{33}^* \end{bmatrix} \tag{9}$$

where: $[S^*]$— normalized in–plane compliance matrix of hybrid composite.

(4) Tensile strength of multidirectional hybrid composite.

Tesile strength of multidirectional hybrid composties are estimated by non–linear iteration. It is calculated according to fig 4.

2. Optimization design for hybrid composites with zero–expansion

For a practical strucrure which requires demensional stability, it should be not only designed into zero expansion, but also possesses excellent mechanical properties. Hybrid composites have more degrees of freedom for design than that of single fiber reinforced ones. So they meet two facts of requirements. The frame for the designing is in fig.5.

In this program, the CTE value for demand may be used instead of zero–expansion.

VI. Conclusions

1) CTE of hybrid composite is mostly infuenced by fiber type, hybrid ratio and ply angle, and is relative with hybrid interface, ply order, angle order and angle dispersion, which shouldn't be neglected. In general, conponent materials which are less affected by temperature should be chosen. And propriate hybrid ratio and ply angle should be determined. In the meantimes, reducing hybrid interface number and increasing angle dispersion coefficient are benefit to the zero expansion design.

2) The expression for calculating CTE of composite can be used as basic estimation. For more precise prediction, hybrid effects can be applied to revise it.

3) Ply patterns of hybrid composites with zero expansion is much more. The optimization are made from the tensile modulus and strength, and good results are obtained. But for a practical structure, the optimization should be according to the properties which are demanded in usage. For this, it can be realized by changing the differentiation parameters instead of variating the program.

Reference

1. Zhong Weihong, ″Estimation and Tests for Hybrid Composites with Zero−expansion″. 1991.1 (Thesis).
2. Zhang Xiaohong, ″Mechanical Performance and Properties Estimation on Multidirectional Hybrid composites ″. 1992.3 (Thesis).
3. Schapery R. A., ″CTE of Composit Materials Based on Energy Prrinciples ″, J.Comp.Mater. 2(3): 380−404 (1968).

Table1. Properties of Reinforcement

Fiber type	Tensile modulus (GPa)	CTE(25∼150℃) $\alpha_L(\times 10^{-6}/K)$
Carbon (T−300)	233.0	−0.37∼−0.28
Glass (HS−2)	84.0	2.34∼3.50
Aramid (Kevlar−49)	122.0	−3.6∼−4.68

Table2. Properties of Resin Casting

Resin system type	Tensile modulus (GPa)	CTE(25∼150℃) $\alpha_L(\times 10^{-6}/K)$
Phenolic epoxy (4211)	3.60	33.57∼62.29
Bi−phenolic A (LWR−1)	3.34	39.43∼62.49 (25∼100℃)
Bimaleides (QY8911)	3.05	34.77∼57.73

Table3. Parameters of Laminates

NO. of Laminates	Form of lay−up	hybrid ratio % V_{cf}	Number of hybrid interfaces n	angle influence factor φ
4−G−1	$[O_{16G}]$	0	0	0
4−K−2	$[O_{16K}]$	0	0	0
4−C−3	$[O_{16C}]$	100	0	0
4−C/K−4	$[O_{3C}/O_{5K}]_S$	26.1	2	0
4−C/K−6	$[O_{5C}/O_{3K}]_S$	49.5	2	0
4−C/K−7	$[O_{7C}/O_{K}]_S$	80.5	2	0
4−C/G−8	$[O_{2C}/O_{6G}]_S$	15.0	2	0
4−C/G−9	$[O_{4C}/O_{4G}]_S$	39.8	2	0
4−C/G−10	$[O_{7C}/O_{G}]_S$	78.8	2	0
Q−G−12	$[O_{12G}]$	0	0	0
Q−C−13	$[O_{12C}]$	100	0	0
Q−C/G−14	$[O_{2C}/O_{4G}]_S$	34.3	2	0
Q−C/G−15	$[O_{3C}/O_{3G}]_S$	51.1	2	0
Q−C/G−16	$[O_{4C}/O_{2G}]_S$	67.6	2	0
Q−C/G−17	$[O_{C}/O_{G}]_S$	51.1	10	0
W−C/G−18	$[O_{4C}/O_{4G}]_S$	51.7	2	0
W−C/G−19	$[O_{4G}/O_{4C}]_S$	51.7	2	0
W−C/K−20	$[O_{4C}/O_{4K}]_S$	48.2	2	0
W−C/K−21	$[O_{4K}/O_{4C}]_S$	48.2	2	0
W−C/K−22	$[O_{C}/O_{K}]_S$	48.2	14	0
W−K−24	$[O_{16K}]$	0	0	0
W−C−25	$[O_{16C}]$	100	0	0

QC−1−1	$[0_{16C}]$	100	0	0
QC−1−2	$[90_{16C}]$	100	0	0
QC−2−1	$[(\pm 60_C)_4]_S$	100	0	28
QC−2−2	$[(\pm 30_C)_4]_S$	100	0	28
QC−3−2	$[(\pm 45_C)_4]_S$	100	0	28
QK−4−1	$[0_{16K}]$	0	0	0
QK−4−2	$[90_{16K}]$	0	0	0
QK−5−1	$[(\pm 60_K)_4]_S$	0	0	28
QK−5−2	$[(\pm 30_K)_4]_S$	0	0	28
QK−6−2	$[(\pm 45_K)_4]_S$	0	0	28
QG−7−1	$[0_{16G}]$	0	0	0
QG−7−2	$[90_{16G}]$	0	0	0
QG−8−1	$[(\pm 60_G)_4]_S$	0	0	28
QG−8−2	$[(\pm 30_G)_4]_S$	0	0	28
QG−9−2	$[(\pm 45_G)_4]_S$	0	0	28
QC−10	$[0_{2C} / (\pm 30)_{2C} / 0_{2C}]_S$	100	0	18
QC−11	$[0_{2C} / (\pm 45)_{2C} / 0_{2C}]_S$	100	0	18
QC−12	$[0_C / (\pm 30)_C / 0_{2C} / (\pm 30)_C / 0_C]_S$	100	0	36
QC−13	$[0_C / (\pm 45)_C / 0_{2C} / (\pm 45)_C / 0_C]_S$	100	0	36
QH−14	$[0_{2C} / (\pm 45)_C / (\pm 45)_G / 0_{2G}]_S$	49.0	2	30
QH−15	$[0_{2C} / (\pm 60)_C / (\pm 60)_G / 0_{2G}]_S$	49.0	2	30
QH−16	$[0_{2G} / (\pm 45)_G / (\pm 45)_C / 0_{2C}]_S$	49.0	2	30
QH−17	$[(\pm 45)_C / 0_{2C} / 0_{2G} / (\pm 45)_G]_S$	49.0	2	24
QH−18	$[(\pm 45)_C / 0_{4C} / (\pm 45)_G]_S$	74.2	2	24
QH−19	$[0_{2C} / (\pm 45)_C / 0_{2C} / (\pm 45)_G]_S$	74.2	2	30
QH−21	$[0_{2C} / (\pm 60)_{2G} / 0_{2C}]_S$	49.0	4	18
QBG	$[0_G / 45_G / -45_G / 90_G / 0_G / 45_G / -45_G / 90_G]_S$	0	0	56
QBH−1	$[0_C / 45_G / -45_G / 90_G / 0_C / 45_G / -45_G / 90_G]_S$	33.68	6	56
QBH−2	$[0_G / 45_C / -45_C / 90_G / 0_G / 45_C / -45_C / 90_G]_S$	60.37	8	56
QBH−3	$[0_C / 45_C / -45_C / 90_G / 0_C / 45_C / -45_C / 90_G]_S$	82.04	6	56
QBC	$[0_C / 45_C / -45_C / 90_C / 0_C / 45_C / -45_C / 90_C]_S$	100	0	56

Table4. CTE of Unidirectional Composites

No. of laminates	α_L Estimated values $\times 16^{-6}$ / K	α_L Expremental values $\times 16^{-6}$ / K
4–C / K–4	−1.57	−1.68
4–C / K–6	−1.12	−1.44
4–C / K–7	−0.40	−0.47
4–C / G–8	2.82	3.12
4–C / G–9	1.39	1.84
4–C / G–10	0.27	0.55
Q–C / G–15	1.17	1.35
Q–C / G–16	0.64	0.74
Q–C / G–17	1.26	1.71
W–C / G–18	–	0.78
W–C / G–19	–	0.65
W–C / K–20	−1.14	−1.43
W–C / K–21	−1.14	−1.33
W–C / K–22	−1.14	−1.63
4–G–1	5.78	5.97
4–K–2	−2.7	−2.55
4–C–3	0.01	0.09
Q–G–12	4.82	5.00
Q–C–13	−0.05	−0.19
W–K–24	−3.18	−3.25
W–C–25	−0.11	−0.25

Notes: The values are all in Rt.～100℃

Table5. CTE of Multidirectional Composites by Test

(α_L, $\times 10^{-6}$ / K)(25℃～)

No. of Laminates	80℃	100℃	120℃	140℃	150℃
QC–1–1	0.274	0.279	0.326	0.285	0.269
QC–1–2	31.38	32.55	34.50	36.91	37.48
QC–2–1	21.49	22.49	23.43	24.26	24.63
QC–2–2	−3.87	−4.16	−4.64	−5.30	−5.56
QC–3–2	3.81	3.85	3.81	3.51	3.33
QK–4–1	−2.71	−3.03	−3.36	−3.57	−3.72
QK–4–2	28.29	30.60	31.30	34.26	35.20
QK–5–1	20.22	27.39	25.51	23.82	24.22
QK–5–2	−14.66	−18.55	−19.83	−19.10	−19.23
QK–6–2	0.66	2.43	4.59	5.88	6.24
QG–7–1	4.73	4.76	4.85	5.36	5.29
QG–7–2	33.99	38.46	43.43	46.90	48.53
QG–8–1	33.88	36.33	39.82	40.61	40.83
QG–8–2	3.48	1.42	1.61	3.93	4.74
QG–9–2	15.99	15.91	15.08	13.40	12.75
QC–10	−0.759	−0.807	−0.882	−0.952	−0.968
QC–11	0.0319	0.0399	0.0399	0.0363	0.0299
QC–12	−1.284	−1.393	−1.582	−1.780	−1.824
QC–13	−0.031	−0.033	−0.034	−0.021	−0.019
QH–14	1.76	1.48	1.29	1.12	1.07
QH–15	4.00	3.99	3.71	3.26	3.15
QH–16	1.50	1.39	1.15	1.00	0.92
QH–17	1.95	1.76	1.42	1.19	1.11
QH–18	0.557	0.520	0.447	0.359	0.316
QH–19	0.35	0.28	0.19	0.079	0.046
QH–21	3.14	3.05	2.79	2.34	2.19

Table6. Several Ply Patterns of Multidirectional Composites with Zero Expansion

No.	Ply pattern	The rangement of θ when CTE is zero
1	$[(\pm\theta_C)_4]_S$	0°～7° 42.1°～42.8°
2	$[(\pm\theta_K)_4]_S$	44.2°～44.5°
3	$[O_C / (\pm\theta)_C / O_{2C} / (\pm\theta)_C / O_C]_S$	0°～11° 45°～50°
4	$[O_{2C} / (\pm\theta)_{2C} / O_{2C}]_S$	
5	$[O_{2C} / (\pm\theta)_C / (\pm\theta)_G / O_{2G}]_S$	16°～25° 35°～41°
6	$[(\pm\theta)_C / O_{2C} / O_{2G} / (\pm\theta)_G]_S$	
7	$[O_{2G} / (\pm\theta)_G / (\pm\theta)_C / O_{2C}]_S$	
8	$[O_{2C} / (\pm\theta)_C / O_{2C} / (\pm\theta)_G]_S$	7°～19° 42°～48°
9	$[(\pm\theta)_C / O_{4C} / (\pm\theta)_G]_S$	
10	$[O_{2C} / (\pm\theta)_{2G} / O_{2C}]_S$	26°～40°

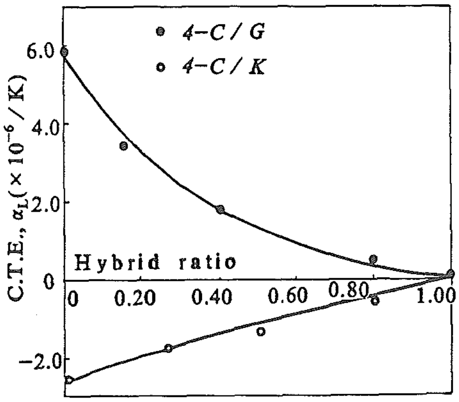


Fig.1 Relation Between Hybrid Ratio and Hybrid composite

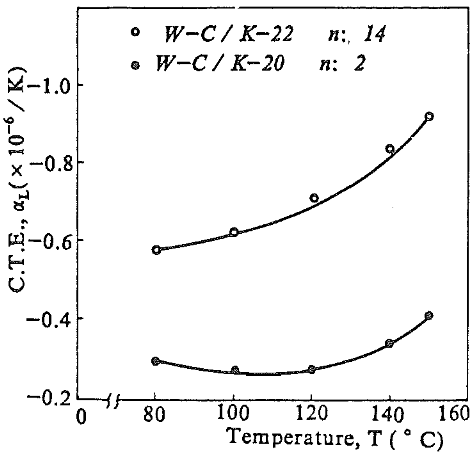
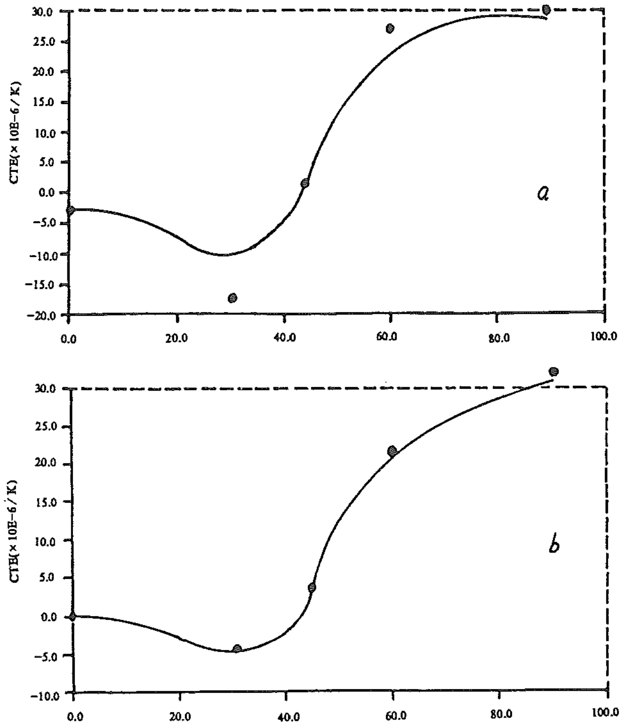


fig.2 Relation between number of hybrid interfaces and CTE of hybrid composites.



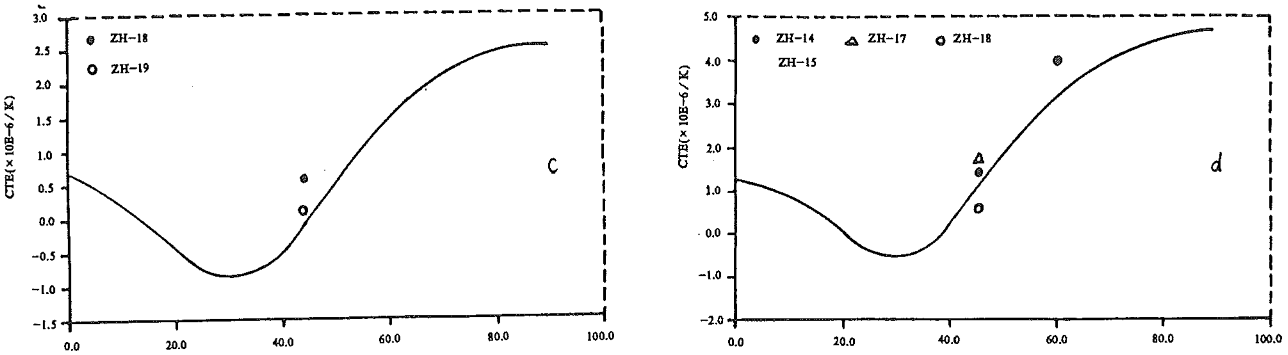


fig.3 CTE of sevral laminates with different ply patterns. Comparison of theoretical curves with experimental points.

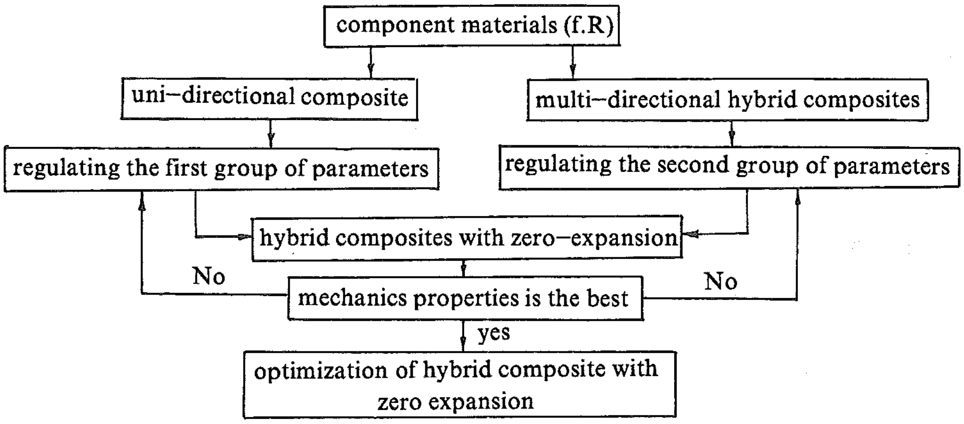


Fig 5 Frame of optimization design

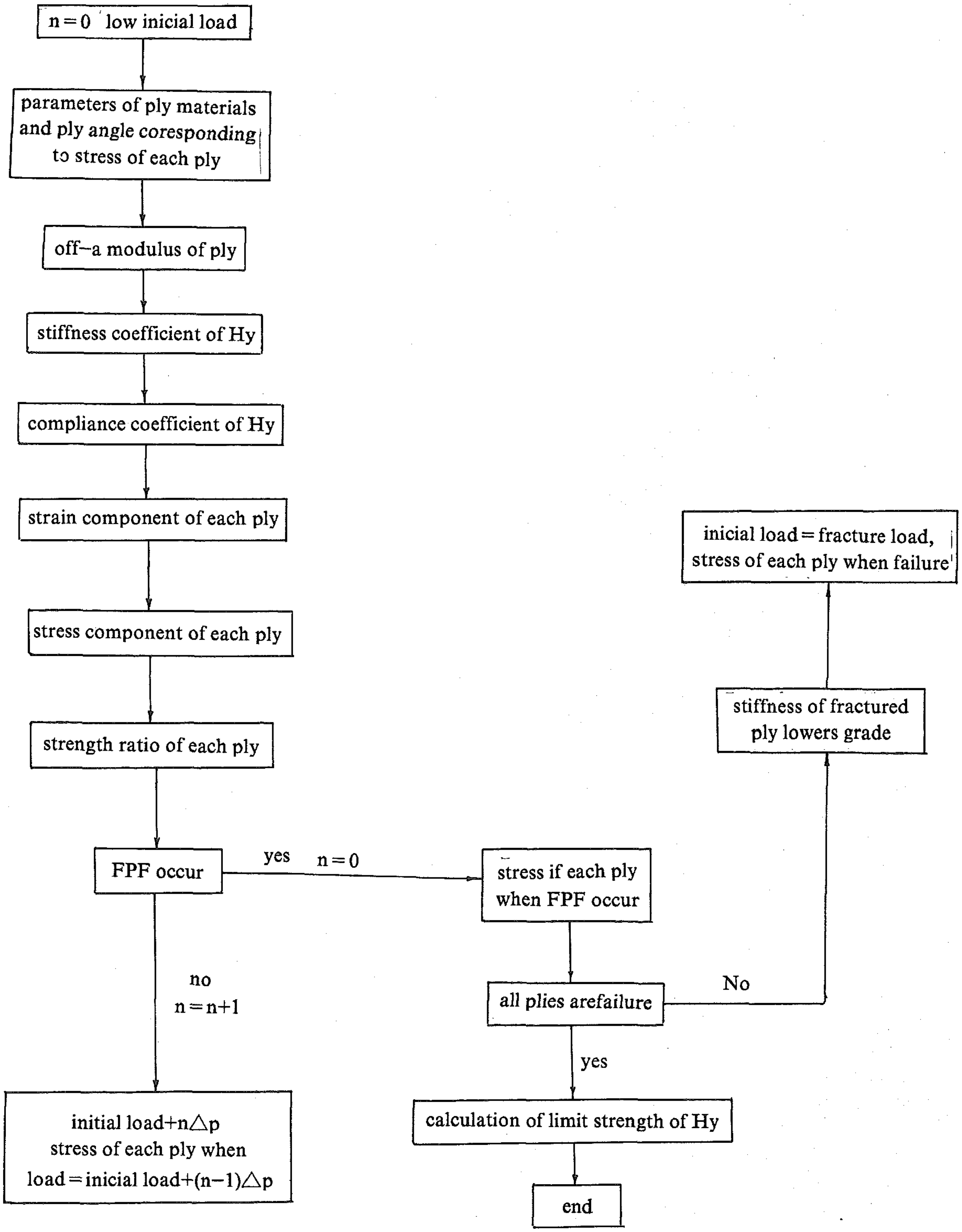


Fig 4. Frame of non–linear iteration estimating for strength of Hy