Tests for obtaining and investigating pre-stressed plastics

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Tensile strength tests have been carried out on composites consisting of an epoxy matrix with pre-tensioned filaments of several different materials. The results are compared with the non-reinforced matrix material and, with the exception of steel wire reinforcement, favourable results are obtained for the composites. A theoretical analysis which assumes linear elasticity gives good agreement with experimental results, but this agreement is improved by compensating for pre-load relaxation and resin contraction during the cure.

(Keywords: reinforced plastics; pre-stressed plastics; initial fibre preload; polyamide filaments; glass cord; epoxy resin)

INTRODUCTION

Results of tests on pre-stressed concrete[1,2] indicate that the introduction of initially-stressed filaments into a resin construction element should improve its mechanical properties.

Attempts have been made to alter the tensile strength of the specimen shown in *Figure 1*, and the results are compared with those from specimens containing no reinforcement.

PA (poly(ε-caproamid), Tarnamid W)[3] monofilaments of 1 mm diameter, PA cord, glass cord and steel wire were used for reinforcement.

Epoxy resin-Epidian 5 was chosen for the reinforced plastic matrix owing to its good mechanical properties[3]. A preliminary investigation of the strength characteristics of the reinforcing materials and the epoxy determined the magnitude of initial pre-stress required.

METHOD FOR OBTAINING REINFORCED SPECIMENS

An advantage of cast epoxy resins is their small contraction during hardening in comparison with other resins and also their lack of by-products[4]. It is not necessary, therefore, to carry out the hardening process under pressure, open moulds being adequate. Reinforced specimens were obtained by casting, so that an epoxy composition of low viscosity was necessary. The viscosity of epoxy compositions depends on the type of resin, the type and quantity of hardener used, and also on the presence of such additives as diluents and fillers.

The quantitative composition of the epoxy composite was established after impact tests were completed on specially cast impact specimens. The tests were carried out according to standard PN-68 C-89029[5]. Based on these results the following composition was chosen: 100 parts by weight Epidian 5, 12 parts by weight TETA (triethylenetetramine) and 7 parts by weight styrene (diluent).

To obtain a homogeneous cast, containing no air bubbles, the resin composite had to be prepared carefully.

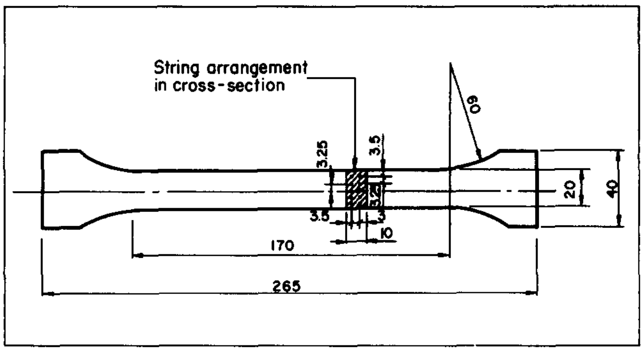

Figure 1 Shape and dimensions (mm) of samples used

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To remove volatiles, the viscosity of Epidian 5 was decreased by heating in a drier at 60°C and then deaerated for 30 min in a vacuum of 1.33×10^{-1} kPa. Hardener and diluent were added to the prepared resin and mixing was carried out carefully so as not to reintroduce air into the mixture. By cooling the upper part of the cast a temperature gradient along the sample was obtained such that the lower parts of the sample hardened first and then gradually the upper parts.

When preparing the mould for casting reinforced specimens the following scheme was adhered to: number of fibres or wires, 10; diameter of one fibre, ≈ 1 mm; in addition symmetric and uniform arrangement of the reinforcing filaments was necessary. The filaments were arranged in two parallel rows, five in each. A precisely symmetrical physical arrangement and uniformly applied stress had to be ensured because of the small cross-section of the reinforced specimen (*Figure 1*), otherwise twisting and warping occurred.

Moulds for casting specimens were made from LDPE (Politen II 003 G1)[3] and PMMA (Metapleks NL)[3]. The apparatus for introducing the initial stress in the filaments consisted of two moulds as shown in *Figure 2*. The tension was released after complete hardening of the resin, allowing 'freezing' of the stress in the samples shown in *Figure 1*.

TENSILE TEST RESULTS

Tensile strength tests were carried out 10 days after the specimens were prepared. This period was necessary for completion of curing at room temperature. The stress–strain results for reinforcement, matrix and composite are shown graphically in *Figures 3* and *4*, and in the form of arithmetic means of a series of tests in *Table 1*. Other experimental data and the results of theoretical calculations are shown in *Table 2*.

ANALYSIS OF THE STRENGTH PROPERTIES OF STRETCHED FIBRES IN A PLASTIC MATRIX

Assuming that all the materials used in this work are

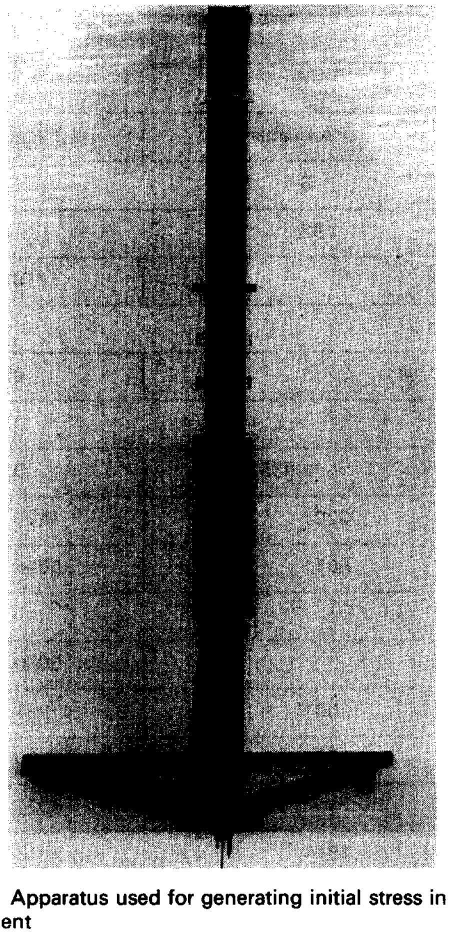

Figure 2 Apparatus used for generating initial stress in reinforcement

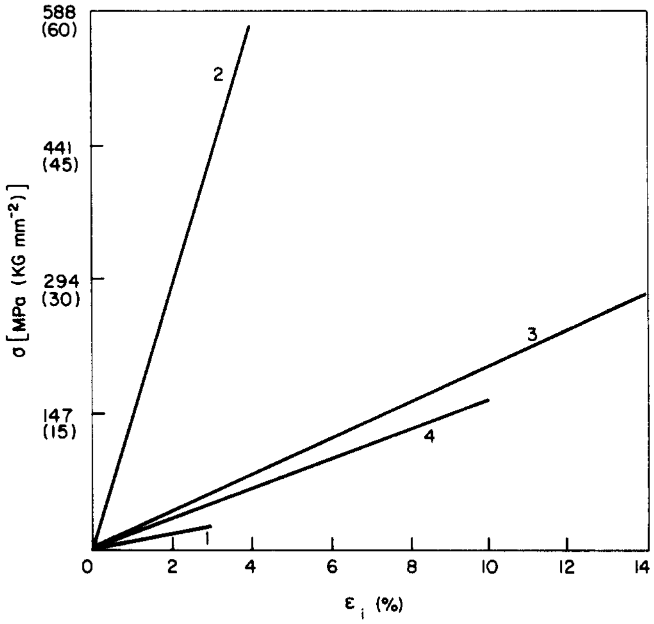

Figure 3 Dependence of stress (δ) on strain (ε): (1) unreinforced resin; (2) glass cord; (3) PA filaments; (4) PA cord

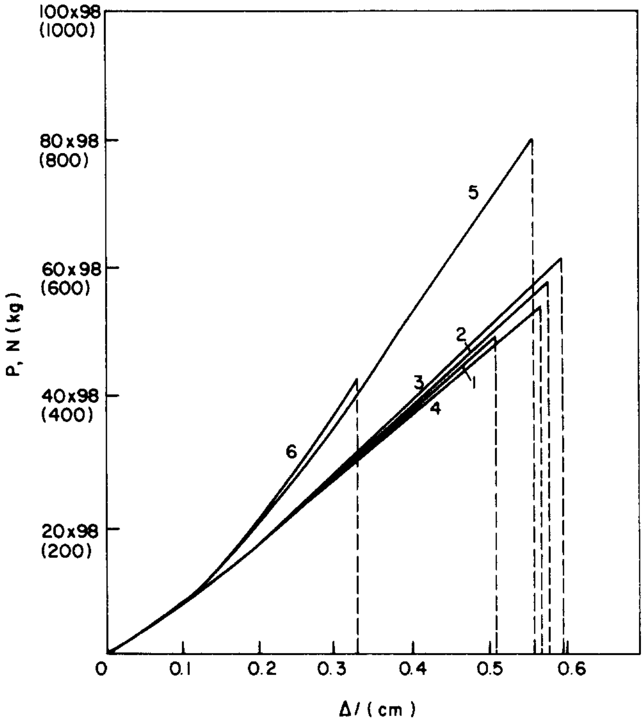

Figure 4 Dependence of force (P) on deformation (Δl) in tensile tests (for average values (P) and (Δl): (1) unreinforced resin; (2) resin reinforced by PA filaments (initial load 98.0665 N (10 kG)); (3) resin reinforced by PA filaments (initial load 220.65 N (22.5 kG)); (4) resin reinforced by PA cord (initial load 147.1 N (15 kG)); (5) resin reinforced by glass cord (initial load 98.0665 N (10 kG); (6) resin reinforced by metal wires (initial load 98.0665 N (10 kG))

linearly elastic up to the elastic limit, analytical stress–strain relations have been derived for the composites. In the following discussion subscripts s and p refer to filament and matrix, respectively, N represents force, σ, ε and E have their usual meanings of stress, strain and modulus, and A is the cross-section.

Composite specimens loaded to a longitudinal force N have stresses σ_s and σ_p in the constituent materials. The forces in the two phases are N_s and N_p and these together equal the longitudinal force N in the specimen such that: -

$$N = N_s + N_p \tag{1}$$

where:

$$N_s = A_s \times \sigma_s, \quad N_p = A_p \times \sigma_p$$

Assuming linear elasticity then:

$$\sigma_s = E_s \varepsilon_s, \quad \sigma_p = E_p \varepsilon_p \tag{2}$$

Table 1 Increase in tensile strength of the composite due to preloading various reinforcing media

	Polyamide (PA) filaments		PA cord	Glass cord	Metal wire
Initial pre-load (N_0) (N)	980.665	2206.5	1471	980.665	980.665
(kG)	100	225	150	100	100
Average percentage increase in tensile strength	17.4	24.3	11.3	62	Decrease 12.6

When the filaments are pre-loaded during the preparation of samples the initial load in the filament, N_0, becomes the external load on the sample after curing. Assuming no creep in the fibres, or matrix contraction during solidification, then prior to releasing the load on the filaments:

$$N_s = N_0 \quad \text{and} \quad N_p = 0$$

On removal of the loading device there is no external load acting and $N = 0$, the force in the filaments reduces to N_{s1} and a compressive force N_{p1} now acts on the matrix. Using equations (1) and (2), and subscripting pre-stressed composite variables with (1):

$$N_{s1} + N_{p1} = A_s E_s \varepsilon_{s1} + A_p E_p \varepsilon_{p1} = 0 \tag{3}$$

Loading initially pre-loaded specimens by a force N causes additional strain ε in both filaments and matrix such that:

$$\varepsilon_s = \varepsilon_{s1} + \varepsilon, \quad \varepsilon_p = \varepsilon_{p1} + \varepsilon \tag{4}$$

From equations (1)–(4) it is evident that:

$$\varepsilon = N/(A_s E_s + A_p E_p) \tag{5}$$

an expression independent of any initial loading.

Removal of the pre-loading in the fibres, N_0, defines the initial deformation of the plastic matrix, so that from equations (4) and (5):

Table 2

		Composite			
		Epoxy resin			
Physical dimensions		Class cord	PA filaments	PA filaments	PA cord
A_s	(mm^2)	7	8		
A_p		193	192		
E_s	(MPa)	13 730	1961		1716
E_p		807			
ϵ_{ys}		0.040	0.14		0.10
ϵ_{yp}		0.030			
ϵ_{lim}		0.031	0.0338	0.035	0.032
N_o	(N)	981		2207	1471
N_{lim}		7880	5688	6011	5394
Theoretical quantities					
$N_{lim}/N_o = 0/$		7556	5120		5060
N'_{lim}	(N)	8485	14 200	2091	264
N''_{lim}		8537	6100	7326	6530
N^*_{lim}		8517	6814		6021
N'_o		$1354 > N_0$	$1843 > N_0$	1810	1018
N''_o		319	569	892	310

$$\varepsilon_{pl} = -N_0/(A_sE_s + A_pE_p) \qquad (6)$$

and ε_{sl} may be determined subsequently by reference to equation (3).

Limiting stresses for the composite may now be defined if it is assumed that failure of the fibres or matrix occurs when the stress in either one reaches the elastic limit. Assuming the fibres fail before the matrix then:

$$\sigma_s = \sigma_{ys} \quad \text{and} \quad \sigma_p < \sigma_{yp}$$

and from equations (3)–(6) the limiting load may be expressed as:

$$N'_{lim} = \varepsilon_{as}(A_sE_s + A_pE_p) - N_0A_pE_p/A_sE_s \qquad (7)$$

If, however, the matrix is assumed to fail before the filaments so that $\sigma_s < \sigma_{ys}$ and $\sigma_p = \sigma_{yp}$, then again from equations (3)–(6) the limiting load may be written as:

$$N''_{lim} = N_0 + \varepsilon_{yp}(A_sE_s + A_pE_p) \qquad (8)$$

It is possible, by manipulation of the initial stress in the fibres, to arrange for the elastic limit in both fibres and matrix to occur coincidentally under which circumstances the limiting load is written:

$$N^*_{lim} = A_s\sigma_{ys} + A_p\sigma_{yp} \qquad (9)$$

From equation (5) the corresponding strain in the composite is given by:

$$\varepsilon^*_{lim} = N^*_{lim}/(A_sE_s + A_pE_p) \qquad (10)$$

and from equation (4) the initial strains of fibre and matrix are:

$$\varepsilon^*_{sl} = \varepsilon_{ys} - \varepsilon^*_{lim}, \quad \varepsilon^*_{pl} = \varepsilon_{yp} - \varepsilon^*_{lim} \qquad (11)$$

The fibre pre-load N^0 to cause these strains is then given by equation (6) such that:

$$N^*_0 = -\varepsilon^*_{pl}(A_sE_s + A_pE_p)$$

COMPARISON OF EXPERIMENTAL DATA WITH THEORETICAL PREDICTIONS

The load–deflection diagrams for the various materials studied here, *Figure 4*, indicate almost rectilinear behaviour up to the breaking load. It is reasonable, therefore, to make one further assumption, that the ultimate strength of the materials is equivalent to the elastic limit, such that:

$$\sigma_y = \sigma_{\text{ultimate}}$$

Table 2 gives geometrical and elastic data, indicating the pre-load N_0 on the reinforcing filaments; the limiting force N_{lim} and deformation ε_{lim}, at which the specimens fail. The Table also includes values obtained from theoretical calculations for the composites used here when subjected to tensile loading. An example of these calculations is given in the following.

CALCULATIONS FOR A COMPOSITE COMPOSED OF EPOXY RESIN AND GLASS CORD

The rigidity of the composite may be expressed as:

$$\begin{aligned} A_sE_s + A_pE_p &= 7 \times 10^{-6} \times 1.373 \times 10^{10} \\ &\quad + 193 \times 10^{-6} \times 8.07 \times 10^{8} \\ &= 251.9 \times 10^{3}\ \text{N} \end{aligned}$$

From equations (7) and (8):

$$\begin{aligned} N'_{lim} &= 0.04 \times 251.9 \times 10^{3} - 981 \times 193 \times 807/7 \times 13730 \\ &= 8485\ \text{N} \\ N''_{lim} &= 981 + 0.03 \times 251.9 \times 10^{3} \\ &= 8537\ \text{N} \end{aligned}$$

For this analysis the true limiting load must be the lower of these two values, so that:

$$N'_{lim} = 8485\ \text{N}$$

which indicates failure of the fibres. For this composite the experimental value for the limiting load was $N_{lim} =$ 7880 N, being only 8% lower than the theoretically determined value. The reasons for any discrepancy are in the simplifying assumptions made in the theoretical analysis, principally: (1) ignoring any relaxation phnomenon in the initial stress; (2) disregarding curing contraction of the epoxy. Both of these factors would cause a reduction of the initial stress. An estimate of this discrepancy can be obtained by manipulation of the initial pre-load N_0 in the filaments to give agreement between failure loads. This pre-load may be obtained from equations (7) and (8) by substituting N_{lim} instead of N'_{lim} and N''_{lim}. From equation (7):

$$N'_0 = \varepsilon_{ys}(A_sE_s + A_pE_p) - M_{lim}A_sE_s/A_pE_p$$

and from equation (8):

$$N''_0 = N_{lim} - \varepsilon_{yp}(A_sE_s + A_pE_p)$$

By the substitution of geometrical and elastic data:

$$N'_0 = 1354\ \text{N}, \quad N''_0 = 324\ \text{N}$$

The larger of these results is neglected as it is greater than the applied load $N_0 = 981$ N. The second result indicates an initial stress in the specimen which is 33% of the theoretical stress. Deformations of the constituent components of the composite due to this reduced loading pattern give strains:

$$\begin{aligned} \varepsilon_{pl} &= -324/251.9 \times 10^{3} = -0.00129 \\ \varepsilon_{sl} &= -0.00129 \times 193 \times 807/7 \times 13730 \\ &= 0.00208 \end{aligned}$$

Also, using equation (4) the limiting value of strain may be obtained:

$$\varepsilon_{lim} = \varepsilon_{yp} - \varepsilon_{pl} = 0.03 - (-0.00129) = 0.0313$$

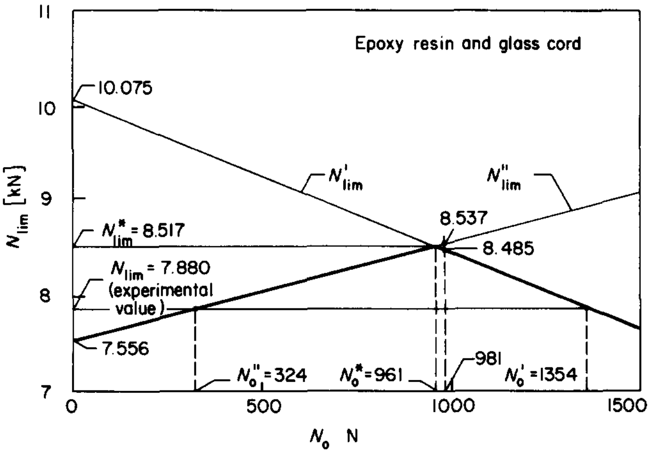

Figure 5 Limiting load as a function of pre-load

and the fibre strain just prior to failure is given by:

$$\varepsilon_s = \varepsilon_{sl} + \varepsilon_{lim} = 0.00208 + 0.0313 = 0.0334 < \varepsilon_{ys}$$

The value of $\varepsilon_{lim} = 0.0313$ here is very close to that found experimentally (0.031), and tends to confirm the assumption that the discrepancy between the theory and experimental results is due to a reduction of the initial preloading. If the optimum initial pre-load were used, then from equation (9) the limiting load would be:

$$N^*_{lim} = 8517 \text{ N}$$

which is not much greater than N'_{lim}(8485 N). This analysis is shown in *Figure 5*, where N_{lim} is plotted as a function of N_0. Similarly, the other composites tested here displayed limit loadings which differed from the theoretical predictions. In each case the effective value of pre-load N_0, to which the experimental value N_{lim} corresponds, is always much smaller than the preload actually applied. For composites based on epoxy resin and PA filaments, where the initial pre-load $N_0 = 981$ N, the true initial stress was only 57% of that predicted theoretically. In the other cases, where a far greater pre-load N_0 was applied, the effective value is less easily defined. For example, in the case of PA filaments with pre-load $N_0 = 2207$ N, the same limit value N_{lim} is obtained at the effective pre-load $N'_0 = 1810 \text{ N} < N_0$ and $N''_0 = 892 \text{ N} < N_0$, representing, respectively, 82% and 40% of the applied value.

CONCLUSIONS

(1) Reinforced plastics (*Table 1*) demonstrate significant increases in tensile strength compared with the unreinforced epoxy matrix. The only exception is the attempt to reinforce with steel filaments, in this case the strength of the composite decreases.

(2) Comparison of experimental data with theoretical analysis confirms the influence of initial fibre pre-load on the strength increase of cast composites. However, the increase in strength does not correspond exactly to that predicted from the assumption of linear elasticity. The initial stress in the composite being lower than that predicted for a given pre-loading. It is suggested that this reduction in initial stress is due to stress relaxation and resin contraction during the cure.

(3) It is suggested that the reduction in strength of the steel reinforced composite may be due to the low deformation of these filaments during pre-loading, coupled with poor adhesion between the steel wire and the epoxy matrix.

(4) This work demonstrates some of the advantages to be gained from the incorporation of pre-tensioned reinforcing materials in cast matrices. However, further work is required both to improve the technology and to compensate for loss of these improved properties with time.

REFERENCES

1 Kozak, R. 'Strunobeton i strunożelbeton' (Pre-tensioned pre-stressed concrete and reinforced concrete), Poznań Politechnic, 1960
2 Suwalski, L. 'Zelbet' (Reinforced concrete), Arkady, Warsaw, 1963
3 Saechtling, H. and Zebrowski, W. 'Tworzywa sztuczne', Kunststoff-Taschenbuch, WNT, Warsaw, 1978
4 Brojer, Z., Hertz, Z. and Penczek, P. 'Zywice epoksydowe' (Epoxy resins), WNT, Warsaw, 1972
5 PN-68-C-89029