EFFECTS OF FIBRE AND FABRIC REINFORCEMENTS ON THE RHEOLOGICAL PROPERTIES OF PLASTICS COMPOSITES

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Summary

Composites made of unsaturated polyester resin and aromatic polyamide fabrics were studied. The major advantages found were higher deformability, lower initial modulus, improved dynamic properties. With Nomex fabrics, tensile strength was substantially lower than that of composites reinforced with glass fabric. From the view of fabric structure the results indicated better properties with a higher number of light-fabric layers. The matrix diminishes the orthotropic character of the reinforcing fabric. The utilization of the strength of elementary fibres in spun yarn is decidedly better in the composite than in the unimpregnated fabric.

Introduction

Reinforced plastics, that is, two-component composite systems consisting of a resin matrix and fibre reinforcement are of increasing importance in industrial practice. Their world production makes up only 7–8% of total plastics production; however, their annual growth precedes that of all other plastics groups so that their participation in total production volume is steadily increasing. The development may be explained by the demands arising in novel applications, and — partly related to these demands — by the appearance of new reinforcing materials and matrix materials.

Rising use of composites as materials of construction is motivated by some unique properties like low density as compared to metals, resistance to corrosion, satisfactory stiffness and deformability, resp., as required by the given application (including damping capacity), simple processing of complex-shaped structural units and fair prices.

The most valuable property of fibre-reinforced plastics is high mechanical strength, which — related to density — exceeds that of steel in certain applications.

Because of the importance and future development trends of the composites we studied some questions of manufacture and properties in use; in particular, we analyzed the effect of the textile reinforcement and the expedient choice of the type of reinforcement.

Components of reinforced plastics composites

The matrix is usually a thermosetting resin such as unsaturated polyester or epoxy resin. Recently, however, thermoplastic materials are also being in use to satisfy special demands such as high dimensional stability, thermal resistance, increased thermal and electric conductivity, etc.

The fundamental requirements to reinforcing materials are:

— insolubility in the matrix and chemical passivity towards its material,

— stable, good adhesion to the matrix material,

— high strength and good elastic properties.

These requirements are best satisfied by glass, carbon, graphite and metal fibres, whiskers and certain organic polymer fibres, e.g. aromatic polyamides. The reinforcement is used in the form best suited for the given application (filament yarn, roving, mat, woven fabric etc.).

Mechanical characteristics of the main reinforcement and matrix materials are presented in Fig. 1.

Aspects of choosing components

In design with composites one calculates with an in-parallel system of the co-acting matrix and reinforcement, that is, identical deformation of both components when load is being applied. This assumption holds good in practice, if adhesive forces between the components are satisfactory. Then the failure of the composite will be controlled by the component with lower elongation to break. Since — at least for thermosetting resins — elongation to break of the matrix is lower than that of the reinforcement, failure will occur at the elongation to break of the matrix.

Consequently, if elongation to break of the matrix is low and that of the reinforcement is high (Fig. 2), the strength of the reinforcement will be utilized to a slight degree only; its participation in load-bearing will depend on the stress at which failure of the composite takes place. None the less, even if not fully utilized, it is the outstanding strength of the reinforcement that ensures the sound strength of the composite, although the value of the latter will be lower by at least one order of magnitude than that of the reinforcement by itself.

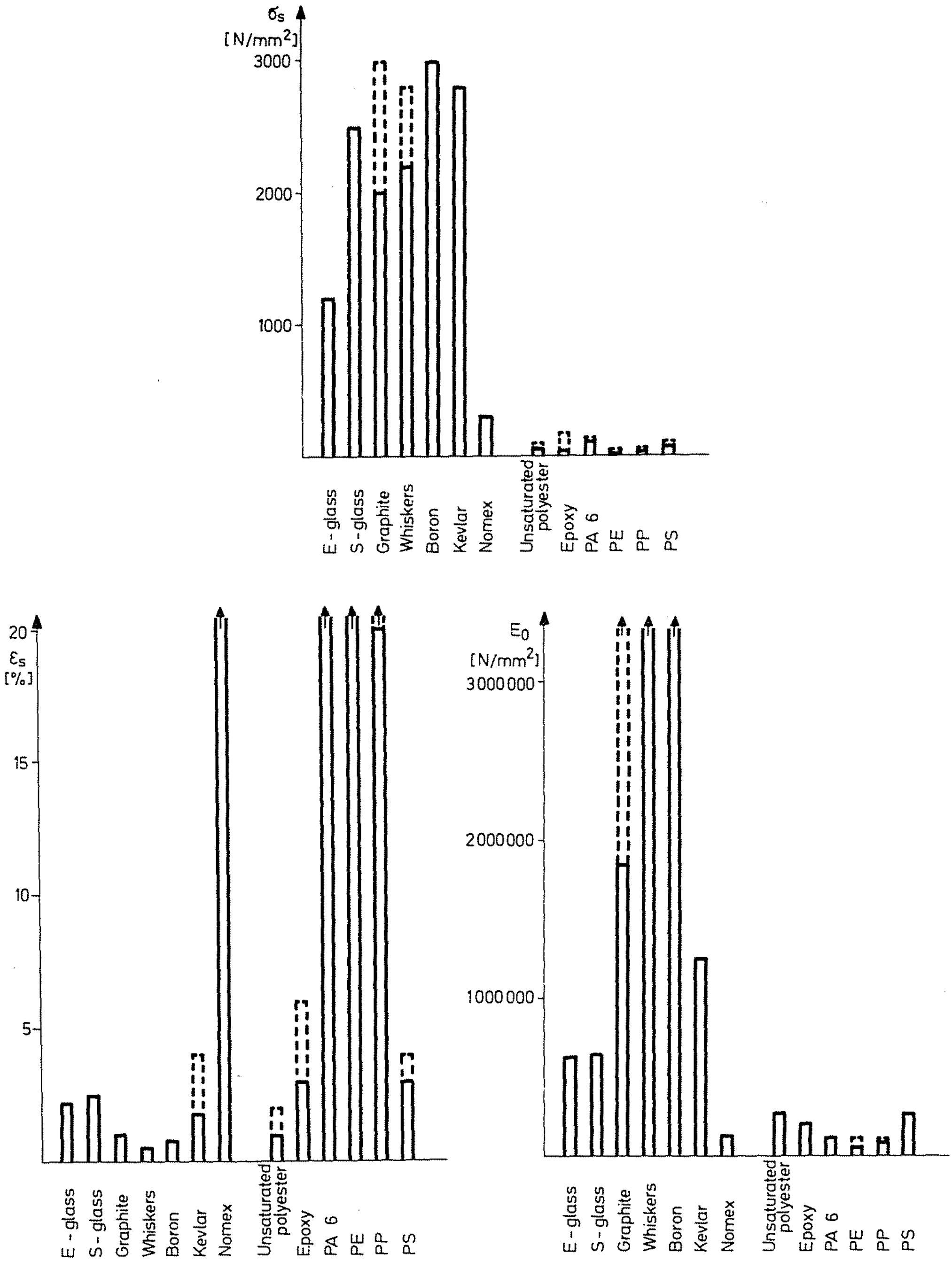

Fig. 1. Mechanical characteristics of reinforcing and matrix materials; 1/a — tensile strength; 1/b — elongation to break; 1/c — initial modulus

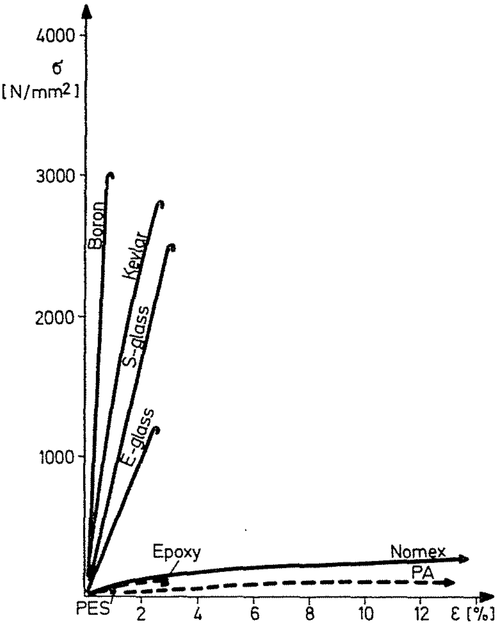

Fig. 2. Stress–strain diagrams of reinforcing and matrix materials

To utilize the strength of the reinforcement as much as possible, components of the composite should be chosen to have elongations to break as close as possible to one another.

It is not only the material of the reinforcement but also its form and structure that affect the mechanical behaviour of the composite to a large extent, above all, the dependence on direction of the mechanical properties. A pronounced rise in the strength of the composite in some preferred direction can be attained by using reinforcement suitable in structure. Thus, keeping in view the performance expected from the product in a certain application, optimum mechanical properties can be established by correctly choosing the structure of the reinforcement.

In certain fields of application other properties like density, resistance to corrosion, capability to damp vibrations, resistance to fatigue will also be involved in selecting matrix and reinforcement material.

Effect of reinforcement structure on the mechanical properties of the composite

As mentioned above, the strength of the reinforcement exceeds that of the matrix by at least one order of magnitude. Hence it will be the reinforcement that controls the interaction between matrix and reinforcement from the mechanical outlook. All mechanical properties of the composite, including preferential orientation of some property can be influenced by suitably choosing the reinforcement structure.

Anisotropy of composites

While thermosetting resins may be considered isotropic, thermoplastics are isotropic only approximately, since a certain extent of orientation of the molecules may occur in processing.

Reinforcements are mechanically isotropic, orthotropic or anisotropic, depending on structure (Fig. 3). The matrix being isotropic or close to isotropic, it is self-evident that mechanical isotropy of the composite will be controlled by the reinforcement.

To complement Fig. 3, let us add that reinforcements may be combined in composites and that by applying layers of anisotropic reinforcement in the so-called star arrangement, a certain extent of isotropy can be achieved.

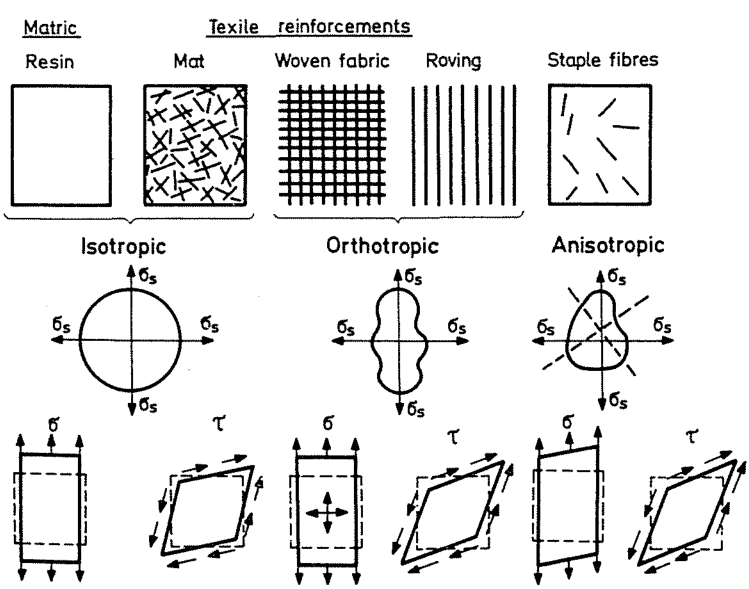

Fig. 3. Isotropic, orthotropic and anisotropic components of composites

Rheological behaviour of composites

Thermosetting matrices and inorganic reinforcement materials, by and large, follow Hooke's law in their rheological behaviour and can hence be modelled by springs. In contrast, thermoplastic matrices and organic polymer fibres are visoelastic and their rheological behaviour can be approached by a 4-parameter model only (Fig. 4).

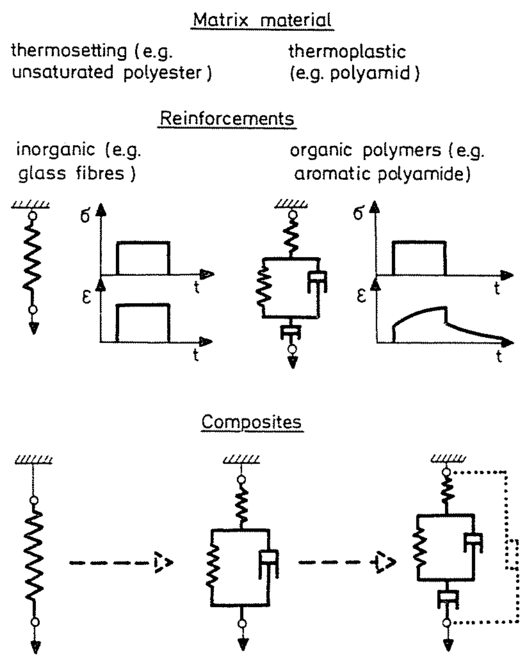

Fig. 4. Modelling of the elastic behaviour of matrix and reinforcing materials and of composites

By combining matrix materials and reinforcements, composites varying largely in rheological behaviour can be obtained. Thermosetting matrices with inorganic fibre reinforcement, e.g., will yield composites following the Hooke's law, while thermoplastic matrices with organic polymer reinforcement will result in a viscoelastic composite. When materials with opposite rheological properties are combined, the behaviour of the composite will depend above all on the component following Hooke's law, with the difference that viscoelastic behaviour is also observed to a slight extent: in addition to instantaneous elastic recovery, delayed elastic recovery also appears. Permanent deformation, however, is practically negligible if the part to be manufactured is suitably designed. Therefore the rheological behaviour of the composite can be approached satisfactorily by a three-parameter model.

Objectives of research

The only composites applied up to the present in Hungarian engineering practice are glass-reinforced thermosetting resins, mainly polyesters. The underlying concept of our work was to extend their range by novel composites which — since their properties differ from those of glass-reinforced plastics — might open new field of application and satisfy special demands in various branches of industry.

In this paper we report on the first stage of our work. We studied reinforcement of unsaturated polyester resin with aromatic polyamide fabrics, aiming at the development of materials of construction with higher deformability, lower density and superior damping capacity. We mainly used woven fabrics made of spun Nomex yarn, but used Kevlar fabrics in some experiments. The composites obtained were subjected to detailed mechanical tests, including:

— mechanical characteristics of highest significance for practical applications;

— interaction between matrix and reinforcement, particularly in order to find the most efficient structure of the reinforcing fabric.

Experimental

Materials

Unsaturated polyester Polikon P-210 manufactured by Nitrokémia Co. Fűzfő (Hungary) was used as matrix material. Cobalt naphthenate accelerator and methylethyl ketone peroxide catalyst were applied for curing the composite. The resin belongs to the group termed "flexible", that is, its deformability is relatively high for a thermosetting resin. Mechanical characteristics of test specimens prepared from the unreinforced resin were:

— tensile strength: 26 N/mm^2,

— elongation to break: 2.9%,

— initial modulus: 265.3 N/mm^2.

It should be noted that the stress-strain curve of the properly cured resin is practically linear.

In the majority of the experiments eight different fabrics woven by the Hungarian Wool Spinning Co. from Nomex spun yarn for industrial protective clothing were used. Their characteristics are listed in Table 1. In a few experiments we used Kevlar reinforcing fabric; Kevlar is an aromatic

Table 1

Characteristics of the Nomex fabrics used in the experiments

No. of fabric	Threads per 10 cm warp	Threads per 10 cm weft	Count, tex warp	Count, tex weft	Mass per unit area g	Ultimate tensile, N warp	Ultimate tensile, N weft	Elongation to break, % warp	Elongation to break, % weft
1	290	176	48	71	264	1290	913	55	31
2	200	140	68	72	240	1270	855	34	36
3	190	166	71	69	250	980	860	36	38
4	280	166	51	21	283	1350	793	49	40
5	370	180	34	52	233	1230	850	52	59
6	310	195	34	33	175	1100	590	51	30
7	280	260	74	79	423	1403	1250	37	41
8	280	176	73	80	334	1380	1000	33	24

polyamide fibre with substantially higher tensile strength and lower elongation to break than Nomex.

For comparison we prepared specimens reinforced with the usual glass fabrics.

The tensile strength and elongation to break of Fabric No. 2 is presented in a polar diagram (Fig. 5) with the remark that the polar diagrams for the other fabrics are essentially similar.

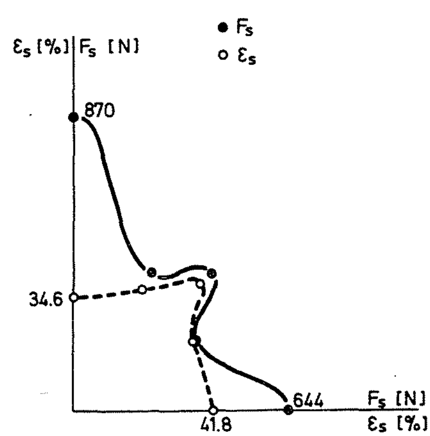

Fig. 5. Polar diagram of tensile load and elongation to break for fabric No. 2

Behaviour of the composites in quasi-static tensile tests

Tensile tests have the advantage that they are simple to perform and yield much valuable information regarding the behaviour of composites in quasi-static load conditions. From the load *vs.* extension diagrams recorded the following mechanical properties were evaluated:

— ultimate tensile load F_S,
— elongation to break ε_S,
— initial modulus E_0,
— tensile strength (ultimate tensile stress σ_S),
— yield point σ_f,
— elongation to yield point ε_f,
— breaking work W_s.

Some typical results are shown in Figures 6–12. Fig. 6 presents tensile load to break for the specimens prepared from fabrics No. 3, 4 and 6 in warp

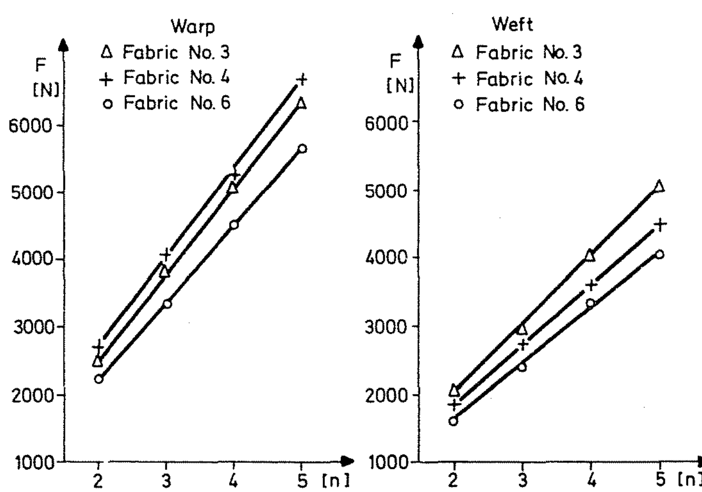

Fig. 6. Ultimate tensile load of composites *vs.* number of reinforcing layers

and weft direction *versus* number of reinforcing layers. The figure indicates that the load to break is close to proportional to the number of reinforcing layers. Figure 7 presents load to break of a composite and that of the reinforcement *versus* number of layers. The figure indicates that the composite is stronger than the reinforcement by itself. This is explained, on the one hand, by the surplus strength added by the resin, and on the other hand, by virtue of adhesive forces

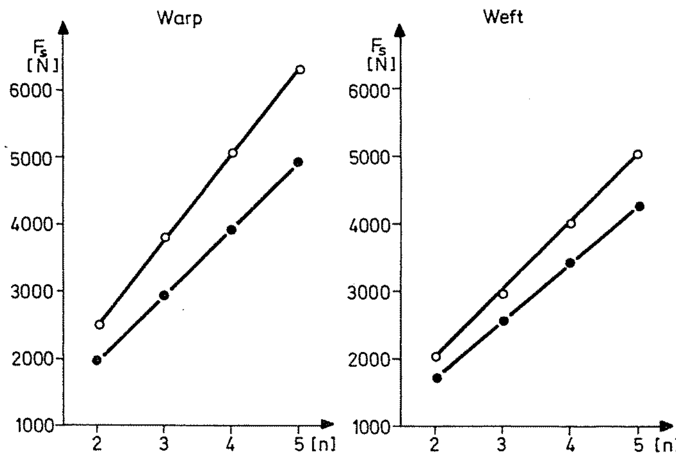

Fig. 7. Ultimate tensile load of the composite (○) and the reinforcement (●) *vs.* number of layers

between fibres within the yarn (and yarns within the fabric) replace friction forces in the unimpregnated fabric, adhesive forces being more effective.

Figure 8 shows tensile strength of the composite *versus* number of reinforcing layers. The figure clearly demonstrates the increase of tensile strength with the number of reinforcing layers, that is, the relationship between tensile load to break and number of layers (cf. Fig. 6) is only close to linear. Increase in tensile strength is explained by the levelling effect of "doubling" the fabric layers.

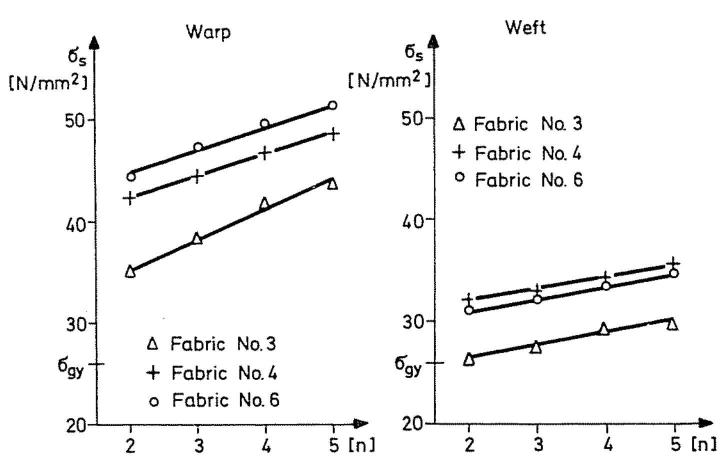

Fig. 8. Tensile strength of composites *vs.* number of layers

Elongation values corresponding to the yield point, that is, to the end of the linear section in the load-extension curve *versus* number of reinforcing layers are presented in Fig. 9. It is of interest to note that deformability of the

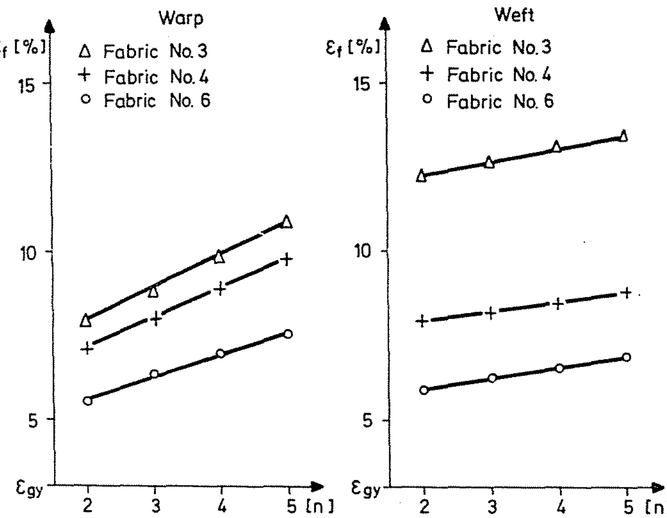

Fig. 9. Elongation to yield point of composites *vs.* number of reinforcing layers

composite, i.e. the value of ε_f increases significantly with the number of layers. The relationship between initial modulus and number of layers presented in Fig. 10 indicates a similar trend: E_0 increases with the number of layers.

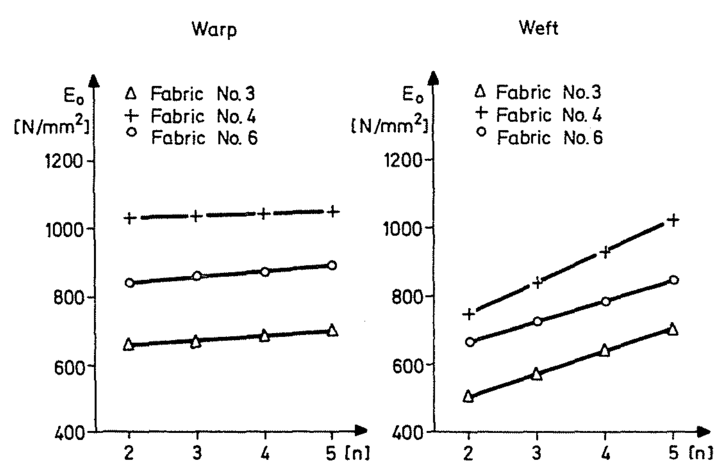

Fig. 10. Initial modulus of composites *vs.* number of layers

In the previous figures 6 to 10 the mechanical properties of the composites — being orthotropic structures — are presented as measured in the two main symmetry axes (warp and weft directions of the reinforcing fabric). The mechanical properties of the composite prepared with fabric No. 2 were also represented in a polar diagram (Fig. 11). It is of interest to compare the figure with Fig. 5, the polar diagram for the same fabric. The effect of the resin matrix lowering orthotropy can readily be observed, the polar diagram shown in Fig. 11 is much closer to that of an isotropic material.

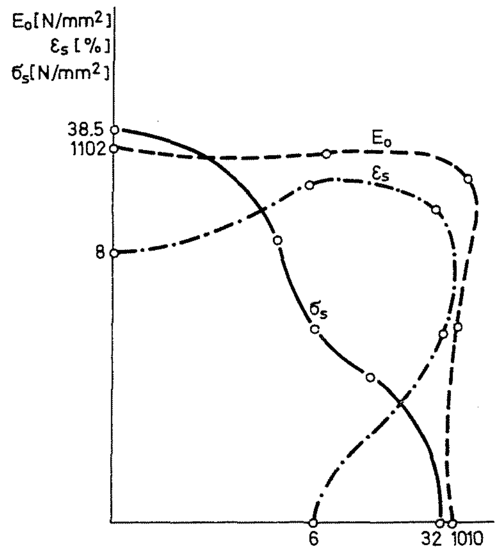

Fig. 11. Polar diagram of mechanical properties of the composite reinforced with fabric No. 2

In Fig. 12, for comparison, tensile strength and elongation to break *versus* number of reinforcing layers is plotted for composites prepared with Nomex and glass fabric, resp. As demonstrated by the figure, the composite reinforced with the aromatic polyamide is more favourable in terms of deformability and modulus of elasticity; it has, however, the disadvantage of substantially lower tensile strength.

Dynamic behaviour of the composites

In practical applications the loads on parts made of composites are frequently periodic, that is, dynamic, or else dynamic loads caused by vibration must be reckoned with as additional loads. It was of interest, for this reason, to

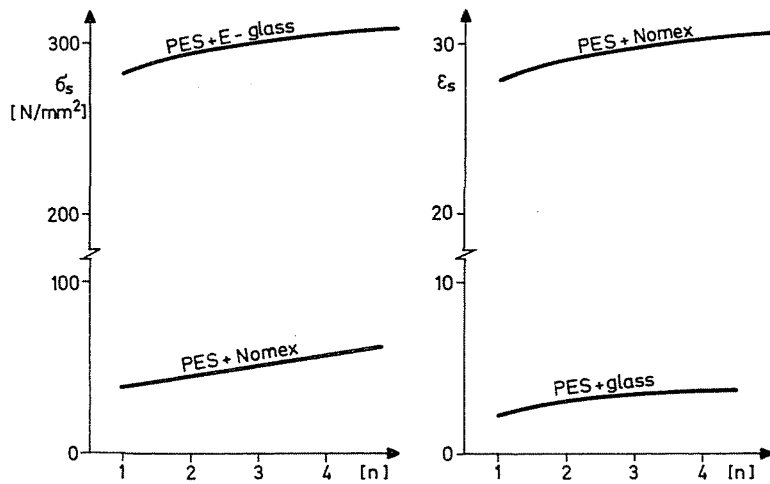

Fig. 12. Comparison of mechanical properties of composites reinforced with Nomex and glass fabric

study the test specimens under conditions when periodic dynamic loads are superposed to the static load. The instrument used in these tests was a high-frequency apparatus developed at the Department of Textile Technology of the Technical University, Budapest. The resonance frequencies and their harmonics, as well as vibration amplitudes in the regions of these critical points were measured. The tests clearly demonstrated that — as expected from higher deformability, lower initial modulus of elasticity and from the viscoelastic character of the composite — the damping capacity of the composites reinforced with Nomex is much superior to that of those reinforced with glass fabrics.

The resonance curves of composites reinforced with glass fabric and Nomex fabric are presented in Fig. 13. The figure indicates resonance frequencies of Nomex-reinforced speciemens shifted towards lower frequencies as compared to glass-reinforced composites, and that the amplitudes of the resonance frequencies causing particularly great damage during the service life of the part are significantly lower.

Discussion of the results

The discussion of the results will be performed from two viewpoints: first, the effect of aromatic polyamide reinforcement on the mechanical properties of the composite, and second, the interaction of fabric structure and matrix.

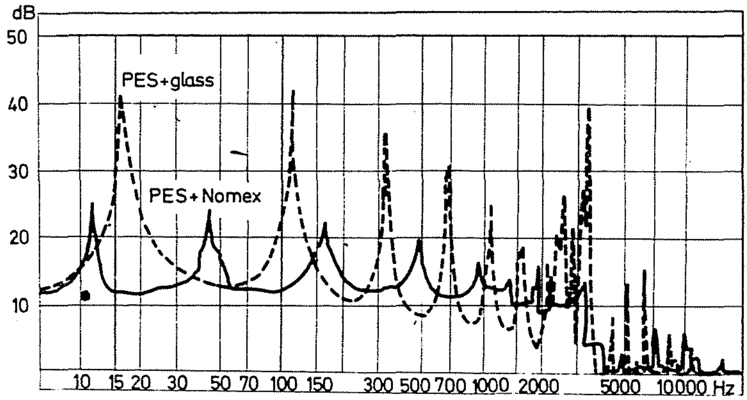

Fig. 13. Comparison of resonance curves of composites reinforced with glass and Nomex fabrics

As compared to traditional glass fibre reinforcement, the experimental results indicate:

— higher deformability,
— lower initial modulus,
— higher damping capacity, lower resonance frequencies and lower resonance amplitudes,
— lower density

of the composites reinforced with Nomex fabrics. The only disadvantage against composites reinforced with glass fabrics is that of lower tensile strength. (This is, however, not the case with Kevlar fabrics, since tensile strength of Kevlar is higher than that of glass, as shown in Figs 1/a and 2).

Particularly the experimental results on the dynamic behaviour of the composites prepared with Nomex fabrics are of interest. By applying Nomex reinforcement, novel potentials for their application as materials of construction are opened by virtue of changed resonance properties. For example, in an application where the work point, that is, the frequency of periodical load on the component is close to the resonance frequency of a glass-reinforced composite, this composite is unsuitable as material of construction, since rapid failure will take place due to resonance vibrations. The non-desirable coincidence of frequencies can be avoided by using aromatic polyamid-reinforced composites, and long service life of the component can be provided.

Regarding the structure of the reinforcing fabric, that is, its interaction with the matrix, experimental results indicate that:

— higher strength, higher deformability and lower initial modulus, that is, generally better properties of the composite are achieved by utilizing, for the same mass of reinforcement and same mass of resin, a higher number of lighter fabric layers than a lower number of heavier fabric layers,

— the matrix pronouncedly diminishes the orthotropic character of the reinforcing fabric,

— the utilization of the strength of the elementary fibres in the spun yarn is decidedly better in the composite than in the unimpregnated fabric, by virtue of friction forces between fibres and yarns in the unimpregnated fabric being replaced, due to impregnation, by adhesion forces. The utilization factor η_{yarn} of yarn strength will correspondingly change differently with yarn density in the two cases, as shown schematically in Fig. 14a and 14b.

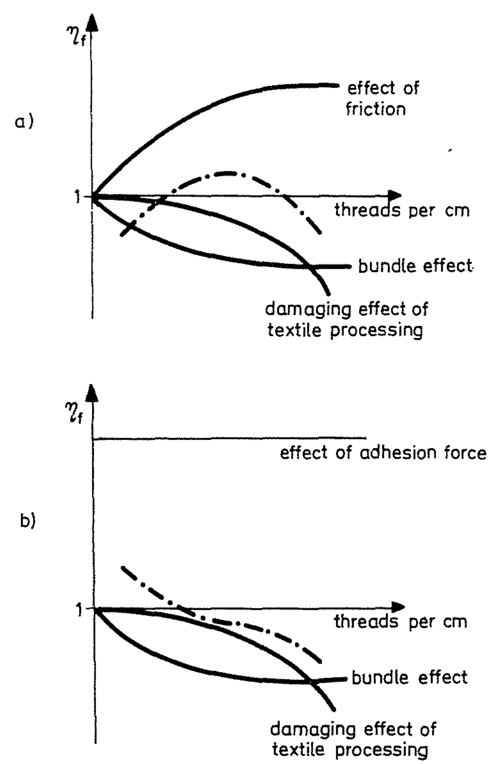

Fig. 14. Strength utilization factor η_{yarn} *vs.* threads per cm in unimpregnated fabric (a) and in composite (b)

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