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Structural Application of New Materials

Utilisation de nouveaux matériaux dans la construction

Konstruktiver Einsatz neuer Materialien

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SUMMARY

New materials in the form of chemically produced materials are finding structural application in civil engineering. Following critical considerations of reliable determination of the resistance of such materials, new technologies are briefly introduced and subsequently examples are given from the special area of fiber-composite materials.

RÉSUMÉ

Dans le domaine du génie civil, on utilise de nouveaux matériaux synthétiques comme éléments porteurs. Après un examen critique des différentes méthodes permettant de déterminer de façon sûre la résistance de tels matériaux, on présente brièvement quelques nouvelles technologies. On donne finalement quelques exemples ayant trait au domaine particulier des matières synthétiques renforcées au moyen de fibres.

ZUSAMMENFASSUNG

Neue Materialien in Form sogenannter Chemiewerkstoffe finden Eingang in der konstruktiven Anwendung des Bauingenieurwesens. Nach einer kritischen Betrachtung über die sichere Feststellung der Belastbarkeit solcher Materialien werden neue Technologien kurz vorgestellt und anschließend Beispiele aus dem speziellen Bereich der Faserverbundwerkstoffe gebracht.

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1. INTRODUCTION

Due to the ever growing maze of new materials which the structural engineer finds on the market for other than building purposes, it is very necessary to make a systematic examination of the emerging tendencies and the fundamental application of such new materials. The structural engineer has certainly had enough basic training to be in the position of using even the newer products - the so-called plastics - of the chemical industry. Additional help can be had from the new safety concept which is now finding acceptance in the civil engineering field on a semi-probabilistic basis. [27,28]

Based on the experience of this writer in the development of reinforced plastic structures, the following paper will treat the fundamental determination of properties of composite materials and show how it is possible to arrive at reliable ultimate limits when dealing with these new materials. [23]

1.1 What is meant by these "new materials" ?

The following materials are considered traditional: stone, wood, reinforced concrete and steel. Materials used structurally and within the scope of what in Germany is presently called the "New Technologies" (NT) are plastics, reinforced plastics and combinations of these two with traditional materials.

Especially in the area of reinforced plastics there is the recent use of lightweight materials of very high strength. They were used originally only in airplane construction and for aerospace purposes, but are now being used as well in many areas of civil engineering due to favorable production costs. These new materials have become significant in structural engineering in the search for new energy sources (e.g. use of the flywheel for energy storage, windmill power stations, etc.). [3,5]

1.2 Materials potentially important in civil engineering

Two important groups of new materials for the structural engineer are a) particularly ductile or impact-resistant products structured on the basis of either chemically irregularly composed polymers in the form of copolymerides, polymer blends, or on the basis of polymer systems with physical superlatticing. Group b) includes extremely high-tensile lightweight materials in the form of pigmented, filler-reinforced and fiber-reinforced high-polymers. [2]

The first group contains mixtures of homo- and copolymers, used for especially ductile waterproof sheeting and foil. These new materials have extended the variety of plastics already available and make possible the development of even newer types of material behavior. This is an area which certainly deserves attention from those of us in the structural engineering field. We can expect a number of very interesting materials to come out of applied macromolecular chemistry in the next period of time. A particular branch of this field involves the production of semi-crystalline high-polymers and polymers with physical superlatticing. Efforts are being made to improve ductility to attain a better stabilization of form in certain duroplastic materials. Research areas concerned with plastics classify these new materials under the collective title of "multi-phase polymer systems". [8]

Of particular interest to structural engineering are the so-called "reinforced plastics" listed under b). The matrix of such plastics usually consists of duroplasts or, more recently and increasingly, of thermoplasts (see table 1). The reinforcing and structuring materials can be either particle shaped (globular) or filamentary. The former consist of TiO_2, pigment particles, talcum, kaolin, chalk, or glass globules. The filamentary components can be either of short length, medium-long strips ("cut-fibers"), or of continuous length. Such fibers (dia. 3-2o μm) are made of either glass, carbon or aramid; thicker fibers (dia. 1oo-15o μm) are made of silicon carbide, boron, boron carbide, boron silicide, zircon oxide, asbestos, aluminum oxide and metal. What is not considered are the so-called "whiskers", with the highest known mechanical parameters: E-moduli up to 99o GN/m^2 or tensile strengths up to 3o GN/m^2. [5,34]

1.3 What are the prerequisites for use in the NT ?

According to the international system of technical building regulations concerning materials, the actual conditions for the efficiency of a structure during its serviceable life may not deviate from those actually calculated. As well, one endeavors to calculate in such a way that the structure can hold out against even highly undesirable effects of a catastrophic nature. These risks and their consequences are to be limited either on the basis of the detailed construction design or on the basis of the general conception of the structure. To attain this goal, the present practice on the part of material testing is to statistically analyze experimental data and data gained through practical experience as much as possible so as to obtain reliable results.
The main aim is to control and limit the magnitude of inevitable imperfections. It is these imperfections, and not the calculation itself, which ultimately determine the serviceability and durability of a structure.
To transpose a situation of insecurity regarding material properties to one of insecurity in the actual building structure, it is absolutely necessary to have as much qualitative - or even better - quantitative data on such insecurities as possible. [27,28]

Thermoplastics	Density	Glassfiber	Tensile-strength	Tensile-modulus	Thermal expansion coefficient
	ρ	ψ	β	E	α
	KN/m^3	% weight	MN/m^2	GN/m^2	$10^{-5}/^{\circ}C$
HDPE	9,8	0	27	1,5	13
HDPE	11,3	30	75	6,5	-
PP	9,1	0	35	1,3	11
PP	11,4	30	50	7,0	210
PP chem.mod.	11,4	30	90	7,0	-
SAN	10,8	0	70	3,7	8
SAN	13,5	30	120	10,0	2,5
ABS	10,6	0	40	2,4	8
ABS	13,2	20	94	6,3	3
PC	12,0	0	65	2,2	6
PC	14,3	30	73	6,2	3
PA 6[5]	11,3	0	80	3,0	7
PA 6[5]	13,5	30	180	9,0	2-3
PA 6.6[5]	11,3	0	90	3,3	7
PA 6.6[5]	13,5	30	190	9,5	2-3
PBT	13,0	0	60	2,6	6
PBT	15,3	30	130	9,5	3-4
Steel St 37	78,5	0	370	210,0	1,2
Al-alloy	26,5	0	260	70,0	2

Table 1 Some FRP-thermoplasts [2]

Before a new material can be used structurally, it is necessary - as we will see - to first of all determine its suitability and then the possibilities of its production. Only after the latter has been determined can the quality of the material and its behavior in the structure be estimated. In this first phase one is dependent on analogies taken from observation of the behavior of existent structures made of the same material, or on other suitable structures. [17]

2. DETERMINATION OF MATERIAL PROPERTIES

2.1 Customary determination

In order to determine whether a new material is suitable or not - just as in the case of traditional materials - it is necessary to find out the parameters involving tensile strength, compression strength, shear strength and flexural strength. Additional data on deformation is good to have as well, and so it is usually necessary to determine data also on elastic properties on the basis of suitable working characteristics of so-called material laws. As soon as this has been done, the next step is to consider influencing factors such as the temperature,moistness,test speed and structure of the new material.Fiber-reinforced composite materials, for example, can be considered as regards their orientation parameters - just like wood from the standpoint of the predominant direction of fibers (polar diagram). Such procedures are generally known and it is often the case, unfortunately, that one is fully satisfied with them. It is easy to understand, however, that the eventual production method too, and particularly in the case of construction elements the assemblage of the individual elements, also plays a decisive role in the final behavior of the structure. As concerns the determination of material laws, the primary question involves the reproducibility of the parameters. In case a test sample has to be made, it is not by accident that one speaks of a "laboratory" sample when referring to new materials. What is expressed here is that the respective material has not yet been "produced for practical use". One is really not certain about the attainable constancy of parameters in the context of economical production either. Collecting data about environmental prerequisites and long-term behavior is even more tedious. All these factors, however, finally determine the possible load carrying capacity of the new structure (see Figure 1). [18,31]

2.2 Known important influences on material properties

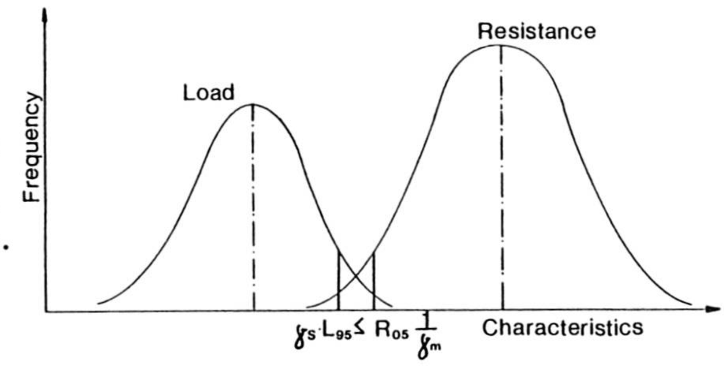


Fig.1 Safety concept

In the first stage of any development there is only technical realizability in the event that suitability tests have shown earlier that the new material could be usable in some way. Such "first attempts", as they are produced in pilot plants, are from experience usually of better quality than those produced in quantity later on. Because these first attempts are oriented only to realizability from a technical standpoint, their primary purpose is more to collect data on production requirements than to determine which possible imperfections occur. For that reason, if one pays attention only to economic factors in the development of the product and does not observe which flaws can develop, as for example when production speed is increased, one is often confronted with material structures reflecting usually a very broad scattering of the individual parameters. As well, it is usually the case that no difference is made between random sample tests (providing data on n-1 eventualities) and tests which determine properties (providing data on n eventualities). In the first case one needs only a number of samples for qualitative determination - perhaps the strength and elasticity parameters for about 2o. For the second type of test, however, one needs loo or more samples. Even then there is usually a certain feeling of uncertainty in the evaluation of the production process. [23]

In the opinion of this writer, the official licensing procedure - regardless of whether it is restricted to an individual case or is extended to include an entire manner of construction - is a necessary but insufficient measure as far as justifying the use of materials and construction elements is concerned.

Such authorizations turn out in many cases to hinder rather than help progress, above all in cases when they only record which base materials and which production processes have been selected. In the event of a change, the entire procedure would have to be started all over again.

The objective of authorization must be to help improve the constancy of properties and to delimit inevitable imperfections as much as possible, but not - as is often the case - to categorically accept randomly selected parameters.

What are the known and important negative influences on the properties of materials? Bluntly speaking, they are all those which determine the "profitability" of a product, for example cheaper base materials, or additives to make leaner mixtures - which supposedly change the end product only very little. We could also mention an increase in the production rate or, as in the case of assemblage, simplifications of the connecting elements and their standardization to the point of causing a great deal of confusion. A sensible authorization should exact pressure towards quality improvement of products and towards a basis for later standardization.

2.3 Procedures necessary to determine load-carrying capacity

To our present way of thinking, it seems best to set up clearly defined criteria for the desired behavior of a structure on the basis of limit states. Generally, a limit state is expressed as a loss of human life, economic consequences, general danger, and so on. A numerical factor expressing such states can differ from country to country. The loading on a structure and its load-carrying capacity are not fixed deterministic values, but fundamentally random values. It would be very desirable to have a method of procedure based on probability. In general, however, it is certainly enough at first to use a semi-probabilistic procedure as a basis. Let us assume that both the member forces and deformation values dependent on the load effects are known. The first question we have to ask is how high the load-carrying capacity of a structure is of a structural element or of a cross section of a new material.

In dealing with such things up until now the usual way was to proceed deterministically. "Building experience" served as a guideline. Such precepts gave materials and their structural application guidelines as to shaping and loading capacity. In many cases such standards were the result of hard-earned experience after bitter failures, had taken perhaps years to formulate, and then were passed on. As regards wood, it is still the case today that despite the occurrence of higher strengths and better elastic properties, lower values have been accepted for standardization, values which are certainly surpassed by most of the pieces of good structural timber passing inspection. Such a situation is designated as 1 in Figure 2. Here we see the number of occurring values for strength β and elastic modulus E plotted above the abscissa. The abscissa indicates the magnitude of the parameters; the ordinate indicates their frequency. 2 and 3 are the possible, actually occurring distribution curves of the parameters. Only in very few cases are there values below the abscissa. One could arrive at the same results - and that as well is usual - when secured, higher mean values reduce their strength values to an allowable value by means of suitable "safety factors"[18].

Let us assume that Figure 2 shows a record of different production methods for a new material. 2 and 3 then signify a possible statistical frequency distribution of parameters. 2 indicates a good production because there is a low standard deviation. 3 is not as good. If now along with a short period of load the influence of media (fluids, chemicals, etc.) is also considered, then curve 3, for example, could move to 3a. These and other considerations are drawn up in the new design concept on a stochastic basis. If we assume that a limit state can be described for the material by means of a strength factor - a so-called characteristic material strength factor - then a value is to be assumed from which we can expect that only a small percentage of the total number of all strength values (e.g. 5%) will fall short of it (5% fractile).

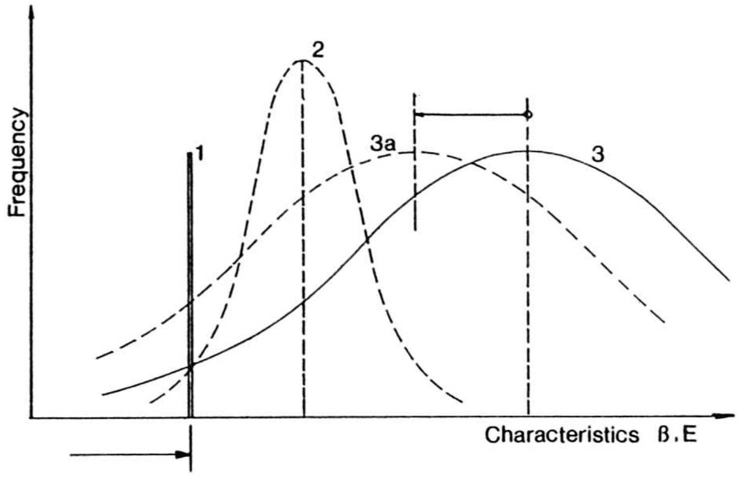


Fig.2 Diagram of the resistance of the material (1 = deterministic; 2,3 = probabilistic)

With new materials this is not always immediately posible. How then does one proceed? If it can be assumed that the suitability tests have been positively completed and it is known that by finding a suitable production method the production of the material is economically feasible, then one can ascertain theoretical values for strength and elastic properties through selection of an analytical model. Assuming that such theoretically determined values are mean values of possible, random, actual values, then one could attempt to set up deterministically by means of a separate selection of coefficients or factors a separate mathematical safety factor against limit states. For example, a statically determined structural element has to be checked in relation to either a strength or deformation value. In both cases, however, one could select different safety coefficients. If it is known, however, that for example a multi-layered fiber-reinforced composite material undergoes a shear break in the matrix, then this is checked separately. The most unfavorable comparative value between loading and load carrying capacity is decisive. This would be a second possible step.

As regards structures made of glass-fiber reinforced plastics, this writer has already suggested such a manner of procedure for supporting structural elements and has also personally carried out practical tests during the development of such elements in Austria [18].

The third and final step to aim at is based on a semiprobabilistic manner of procedure. Characteristic material strengths or material parameters are defined and given added partial safety factors. Limit states are assigned to the checks, for example a crack limit or a matrix shear-break, so-called delaminations (i.e. shear-breaks between the individual layers), or other types. In doing this, quasi-constant loadings are postulated for the assessment of the new material in regard to long-term behavior.

A new material indicating parameters like those in Figure 3, and showing the clearly defined ranges a, b and c, can only then be used when these ranges are definitely assignable to certain production parameters or base material parameters. If this is not the case, and curve d is applicable, then this material has not been sufficiently defined and cannot be regarded in the suggested manner.

3. THE NEW TECHNOLOGIES (NT)

3.1 Plastics of the new type

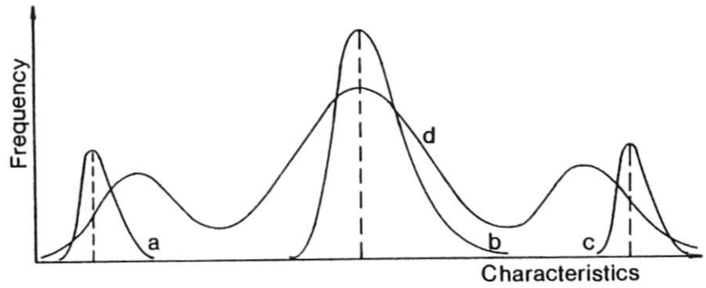


Fig.3 Usable (a,b,c) and unusable parameters (d) as determined in a initial suitability test

Plastics such as those of the first group listed earlier under 1.2, belong to those studied by the NT. As has already been mentioned, these materials are mainly highly ductile products which combine the properties of natural rubber with techniques used in the plastics industry. These products are important, for example, in sealing off flat roofs in building construction, in certain insulation areas in tunnel construction or in dam building. The structural principles which would have to be observed in such areas cannot be treated here as, to a great extent, they are still very much in the development stage. We want to devote ourselves in the following to a discussion of reinforced plastics. [7,8]

3.2 Fiber-reinforced plastics

This group of composite materials in the most important one for the structural engineer. Besides the fiber- reinforced plastics there are, as indicated in 1.2, also the particle-reinforced plastics. Both of these types are used whenever higher flexural strengths are required. In Table 2 we can see just how large the field of fiber-reinforced plastics is.

Characteristics				Matrix		Reinforced Materials FIBERS		
				Thermoplastics	Duroplastics	E-glass	Carbon	Aramid
TENSILE	MODULUS	E	GN/m²	1 - 4	3,5	84	690	70
	STRENGTH	β	MN/m²	8 (PE) 70 (PSU)	30 (UP) 60 (EP)	3500	3450	3000
	ELONGATION AT RUPTURE	ε	%	3 - 600	2 - 7	4,2	0,5	4,0
THERMAL EXPANSION COEFFICIENT		α	$10^{-6}/°C$	250 (PE) 70 (PSU)	60 - 80 (UP) 40 - 90 (EP)	6	0	0

Table 2 Parameters of available new base materials from which composite materials can be made

These materials are usually structured in layers. Since production involves laminating, one refers to these layered fiber-reinforced composite materials as laminates. More recently, especially in the auto industry, the multi-directional reinforced plastics have been finding application. The base materials are resin compounds to which particle and fiber-reinforcement have already been added. These compounds are pressed into forms and congealed in part by applying heat. Differently reinforced composite materials, also in relation to the possibilities of orientation, are shown in Table 3. [3o]

The table below shows the distinction in fiber-reinforced plastics between those reinforced by structuring in a plane and multi-directionally, and between those reinforced by random orientation and orientation. Principally, both forms can be produced of so-called continuous fibers or sectionally cut so-called cut-fibers. The highest values for strength and elastic properties, and at the same time a low rupture strain, are attainable with materials with oriented continuous fiber-reinforcement. Particularly impressive is the representation in Figure 4 of the related E-moduli and related strength values (so-called breaking lengths).

REINFORCEMENT		EXAMPLES
ENDLESS-FIBERS	ORIENTED	ROVINGS, WOVEN-GLASS FABRIC
	RANDOM-ORIENTED	ENDLESS-FIBERS; CONTINOUS-STRAND MATS
FIBER	LAMINAR	(2-DIMENSIONAL) CUT-FIBERS (L = 1.5 - 150 mm), MATS
	3-(MULTI) DIMENSIONAL	SHORT-FIBERS (L = 0.15 - 1.5 mm)
PARTICLE	3-DIMENSIONAL	GLASS GLOBULE, GRANULE, POWDER, LAMELLA ...

Table 3 Types of fiber-reinforcement [3o]

This diagram shows the superiority of the new reinforced materials as compared with traditional materials. This is also shown by a comparison of the parameters of both types. In Table 4 one can see that the properties of aluminum have been equaled through carbon-fiber reinforced plastics and even surpassed in terms of strength with lower specific weight. It is of course not possible to treat specific details here, for example interlaminar and intralaminar shear strength.

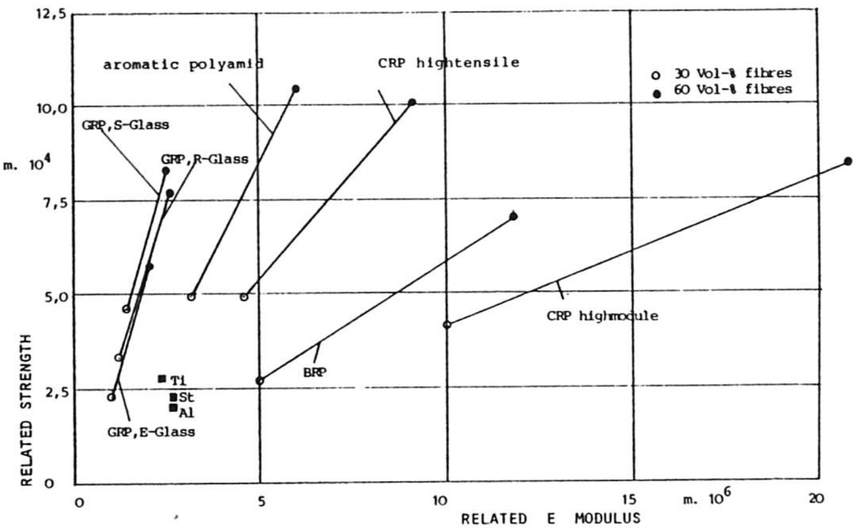


Fig.4 Related properties of fiber-reinforced composite materials [26]

Random oriented or particle-reinforced plastics of type A are orthotropically continuously reinforced; for those of type B see Figures 5 and 6.

The reinforcement effect (dependent upon the type of orientation) as compared with that of the actual matrix material is also shown in these figures.

			WOOD	AL-ALLOY	STEEL	GFK 1)	CFK 1) HM HT
TENSILE STRENGTH	β	MN/m^2	100	450	1400	750	600 - 750
PROP.TENSION	σ_p	MN/m^2	100	350	1100	600	600 - 750
E-MODULUS	E	GN/m^2	12	75	210	25	100 - 74
SHEAR MODULUS	G	GN/m^2	-	28	81	6	25 - 19
SPEC.GRAVITY	γ	N/dm^3	5	28	78	19	17 - 16

Table 4 Parameter comparison between traditional and new materials [1]

3.3 Possibilities of improvement of traditional materials

The still relatively young field of plastics research will soon play an important role in structural engineering. Theoretically, it is very possible that almost all traditional materials can be combined with the materials of the NT.

There are, for example, efforts now being made to reinforce laminated wood beams with high-strength fibers. In this respect, the writer has already carried out experiments using wire-sheets. It was seen that shear strength resulted as a limit for material stress. The possibility exists that this weak point can be eliminated by suitable application of carbon fibers in the region of high shear stress.

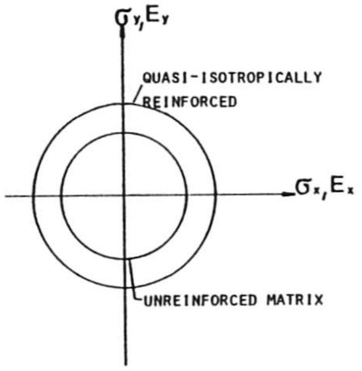


Fig.5 Polar diagram - laminate type A (quasi-isotropic)

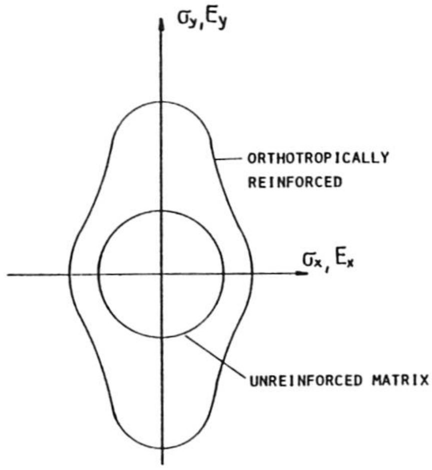


Fig.6 Polar diagram - laminate type B (orthotropic)

Another traditional area of use could be stone structures. Studies are being made to glue together pre-cut stones and to reinforce the area of tensile stress with high-strength fibers, for example carbon fibers. A further very interesting area is in concrete and reinforced concrete construction, whereby the weak points - usually due to shear stress - could be vastly improved using plastic resins. Furthermore, research is also being done on applying these new techniques to reconstruction work.

Above and beyond all the abovementioned areas of use, in the very near future it will be possible to construct small-scale bridge structures and broad-span shell-structures. Design studies along these lines have been carried out at the writer's institute.

4. SOME STRUCTURAL EXAMPLES OF FRP (=GLASS-FIBER REINFORCED PLASTIC)

4.1 Laminates with layered-oriented continuous fiber-reinforcement

Laminates of layered identically oriented continuous fibers (Rovings) have been produced up to now generally with arbitrary curvature. The fully mechanized production methods, which are already acknowledged as conventional for such Rovings, are, however, precision winding methods for the production of closed or cylindrical forms. These methods have undergone further development as well for the mixed types of reinforcement listed in 4.3. A special form of reinforcement is the purely unidirectional. Disregarding extruded products, there are at least two orientation directions, or rather three, used for technically applied laminates of cylindrical form. For other more general forms the fiber direction is restricted to a maximum of four directions ($0^\circ, \pm 45^\circ$ and 90°). To prevent warping of such generally formed laminates, the individual layers have to be arranged perfectly symmetrically to the middle plane of the laminate.

Due to the dominating mechanical properties of the fibers it was evident that the first calculations along these lines took only the fiber mesh into consideration (mesh theory). This theory was later extended for three different orientation directions through adoption of a flexurally rigid, triangular bundle-element as an analytical model [6].

A method of pre-assessment which has remained valid up to the present is an approximate calculation based on empirically determined parameters. Taking specific fiber directions as a basis, for example $0^o, \pm 45^o$ and 90^o, we obtain [1]:

$$E_x = \frac{1}{s_{ges}} \cdot \left[E_{0^o} \cdot s_{0^o} + E_{90^o} \cdot s_{90^o} + E_{\pm 45^o} \cdot s_{\pm 45^o} \right] \tag{1}$$

$$\sigma_{xB} = \beta_x = \frac{\sigma_{0^o B}}{E_{0^o}} E_x = \frac{\beta_{0^o}}{E_{0^o}} E_x \tag{2}$$

The E-theory of an anisotropic elastic body would result in a rigidity matrix $\hat{D}$ of the magnitude 6 x 6, whereby several mixed elements outside of the diagonal would become zero. [14]

$$\{\sigma\} = [\hat{D}] \cdot \{\varepsilon\} \tag{3}$$

Taking the layer composition into consideration, and the fact that the laminates are thin, the E-theory of this composite material can be summarized (disregarding interlaminar shear stresses nyz and nxz and the pertinent rigidity values) as it is seen in Table 5:

ε_{12} in the above table is the shear modulus of intralaminar shear, this is to say as a result of a shear deviation ε_{12} in the fiber-reinforced individual layer. Through progressive load increase the check for fiber rupture can be carried out layer by layer. Usually the first fiber rupture is adopted as the cross section rupture. As a failure criterium of the structuring plastic matrix a concept is often used which is related to the deformation hypothesis and results in an equation of the second order. The analogy to the isotropic material aluminum, with which reinforced plastics are best compared, is shown in Figure 7 (stemming from CONEN, [1]). (Here the rupture stresses represented by $\sigma_{/\!/ B}$ and $\sigma_{\perp B}$ $\tau_{\#B}$ were designated in Austria by β_{ii} and β_{ik}).

Laminates with continuous fiber reinforcement are highly stressable and were developed particularly in the field of airplane construction and aerospace research in the direction of the carbon and aramid fiber types. In the field of structural engineering such laminates have been used to make

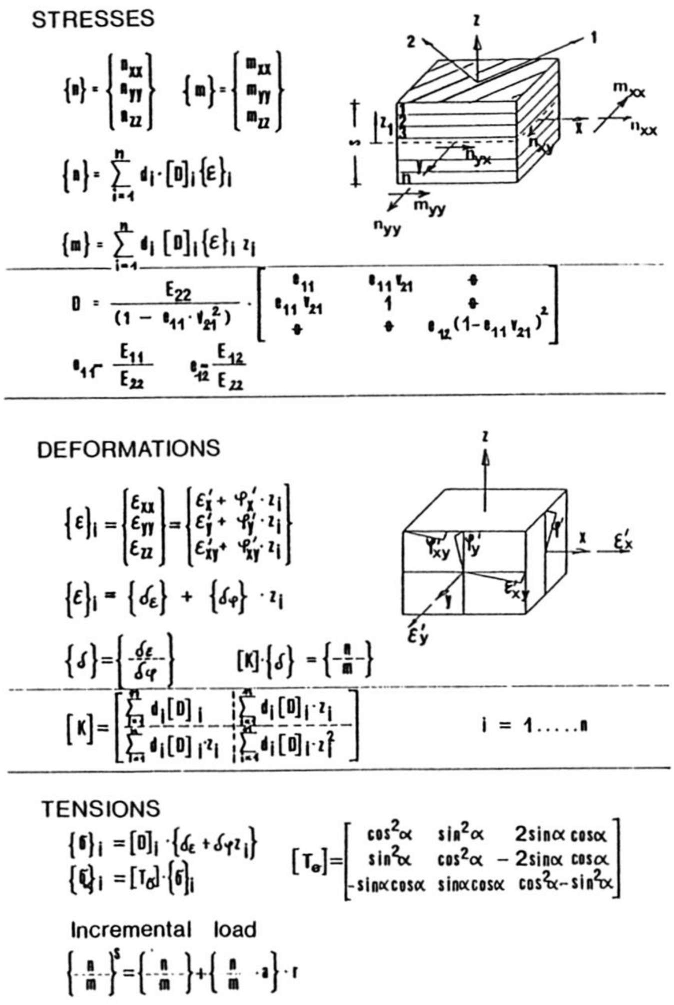


Table 5 Elasticity values of the thin laminate [2o]

individual structures, for example chimneys and towers (see Figure 8). Pressure pipelines have also been constructed, but studies undertaken at the writer's institute have shown that, seen on the whole, certain laminates (as listed in 4.3) simply turn out better. This is particularly the case when loading cases occur which change their directions. [19]

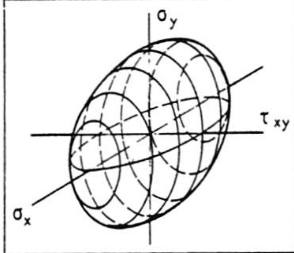
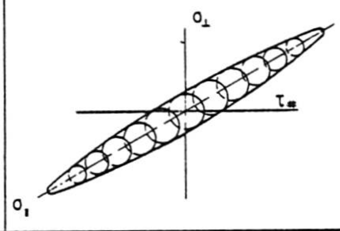
Al - Legierung isotrop		CFK - UD - Schicht anisotrop
$\sigma_x^2+\sigma_y^2+3\tau_{xy}^2 > \sigma_B^2$	break	$\left(\frac{\sigma_\parallel}{\sigma_{\parallel B}}\right)^2+\left(\frac{\sigma_\perp}{\sigma_{\perp B}}\right)^2+\left(\frac{\tau_\#}{\tau_{\# B}}\right)^2 > 1$
		
τ_{xy} = 260 N/mm^2 σ_y = 450 N/mm^2 σ_x = 450 N/mm^2		$\tau_\#$ = 100 N/mm^2 $\sigma_\perp$ = 100 N/mm^2 $\sigma_\parallel$ =1000 N/mm^2

Fig.7 Failure criteria of traditional and new composite materials [1]

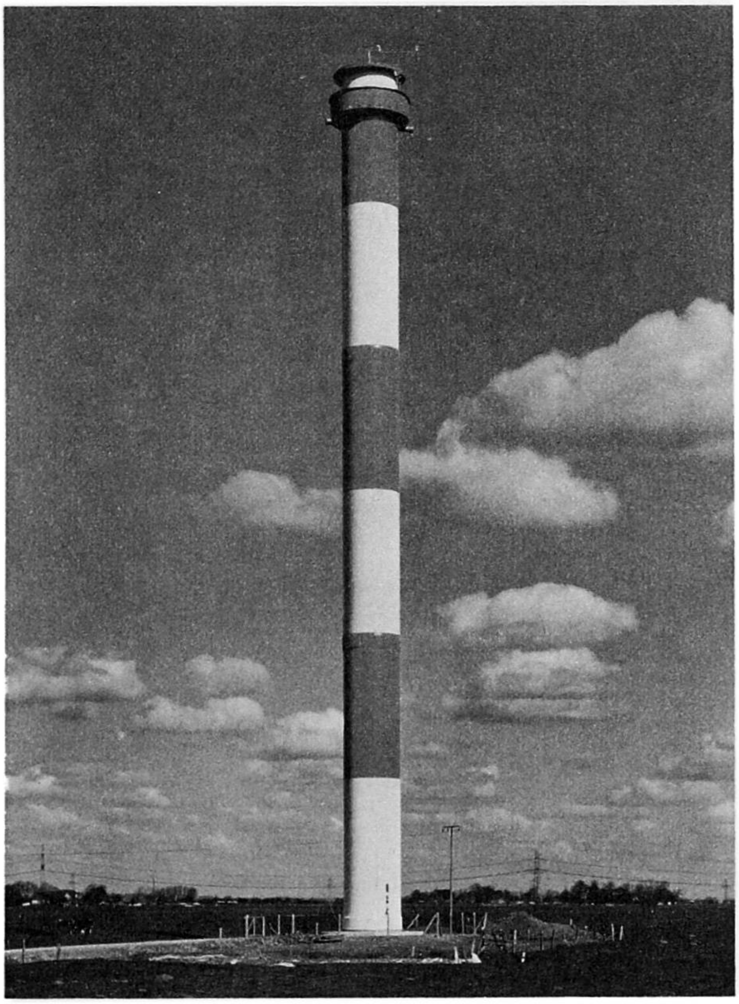


Fig.8 Scheelenkuhlen lighthouse (Constr. by Deutsche Gerätebau Salzkoten and Chemische Werke Hüls AG). Height 46 m, diameter 3 m

4.2 Application of quasi-isotropic (= random-oriented) reinforced laminates

Not only cut-fibers, but continuous fiber mats as well can form the type A laminate shown in Figure 5. Such laminates are used preferentially in those cases where no foreseeable principal stress directions are given. Façades are one example of this (Figure 9, 1o and 11). With this type of laminate it is possible to economically produce both large series of structural elements and also large-surfaced, thin-walled structures of any desired form, for example domes, shells, and suitably folded or otherwise stiffened roof constructions. Such laminates are not so highly stressable as those shown in connection with 4.1.

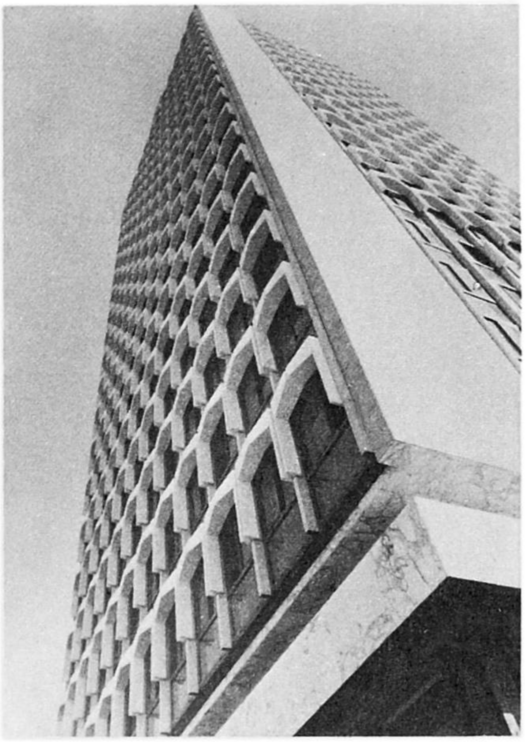


Fig.9 High-rise building façade (Constr.by Koloseus-Epple Wels, Austria)

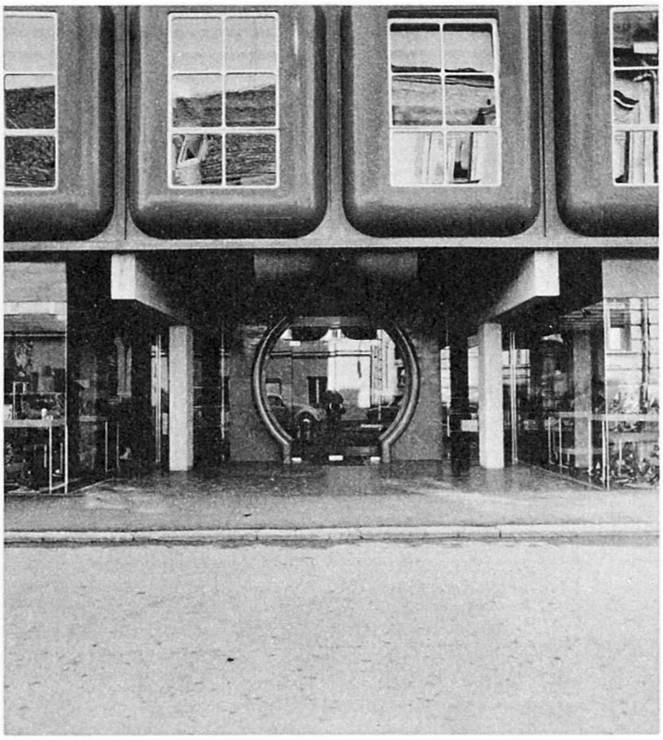


Fig.1o Store portal (Constr.by Koloseus-Epple Wels, Austria)

Specially developed methods [22] permit optimal laminates of higher quality. Through incorporation of suitable filler materials degrees of rigidity can be attained only with cut fiber reinforcements which permit the production of silos with volumes of 1oo m^3 and more in one operation.

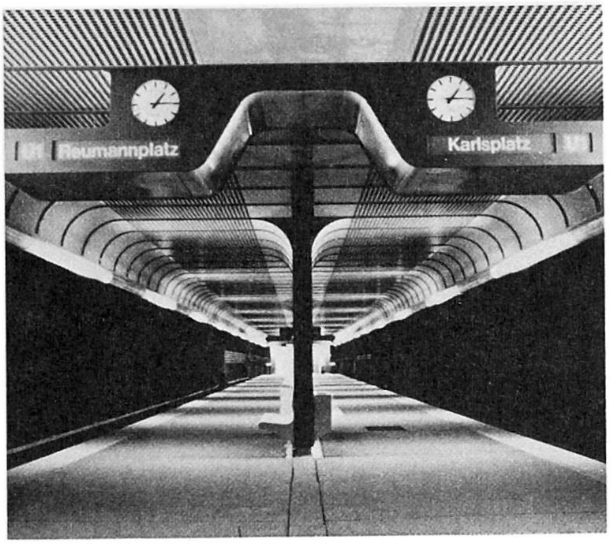


Fig.11 Underground train station Vienna (Constr.by Koloseus-Epple Wels, Austria)

Fig.12 Transport of a FRP-silo (Constr.by Koloseus-Epple Wels, Austria)

The silo shown in Figure 12 was, as shown in 2.3., systematically developed. Even though the first production showed fluctuations in the wall thickness (see Figure 12) - to focus on this particular geometric value - appropriate measures could be taken which achieved the more favorable conditions as shown in Figure 13 and 14. Similarly, all strength parameters were systematically optimized, so that it is presently possible to produce a high-quality construction from a relatively inexpensive base material.

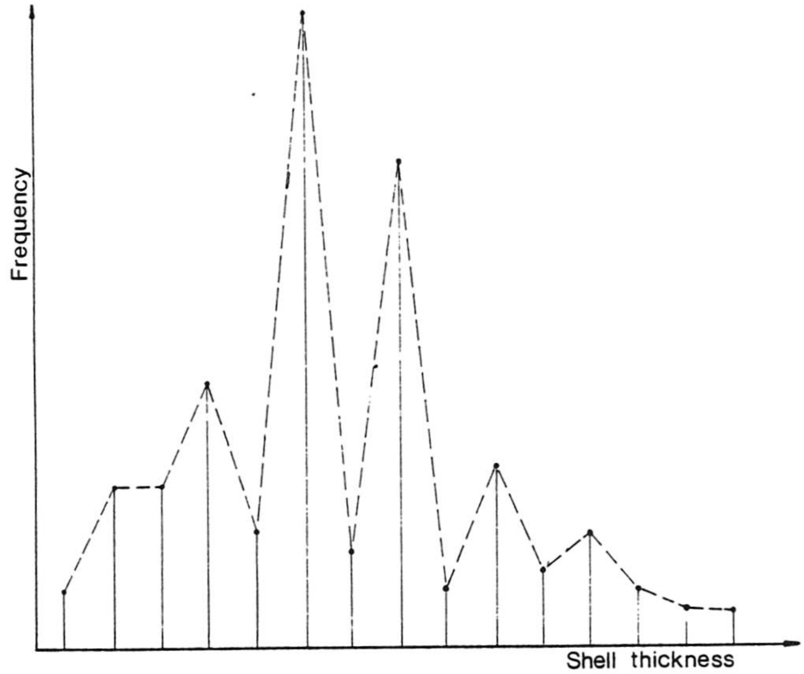


Fig.13 Wall thickness check (poorly manufactured example)

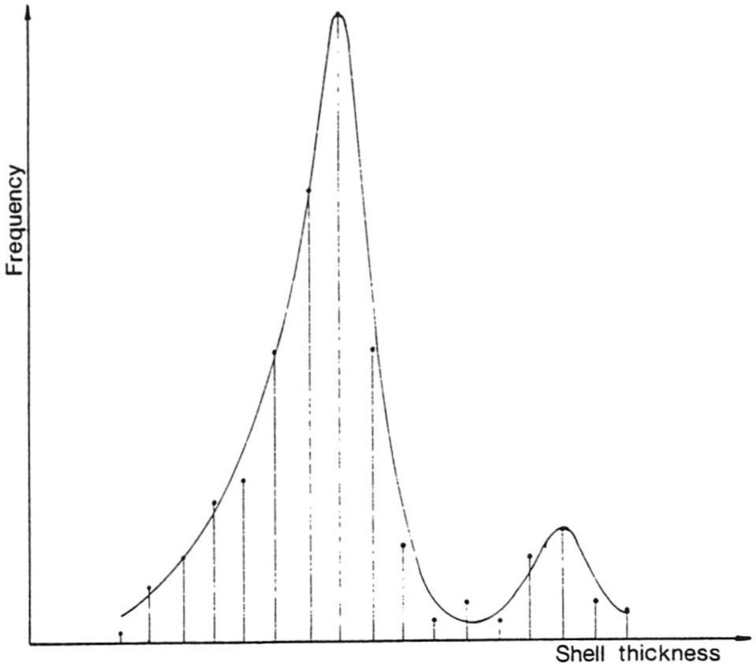


Fig. 14 Wall thickness check (well manufactured example)

4.3 Complexly built-up laminates

The FRP-wall construction described in 4.2, strictly speaking, already belongs to this group of reinforced plastics. In the case of FRP-constructions it was the occasionally large difference between the crack limit (matrix shear-break) and the rupture limit which ultimately led to the application of crack stoppers in the form of cut-fiber reinforced layers in the cross section of the otherwise continuous-fiber reinforced laminates. Attempts to increase rigidity through application of filler reinforcement between the fiber reinforcements - a kind of sandwiching - resulted as well in practice in complex by built-up laminates. Practical examples of these constructions are the various types of pressure pipelines as seen in Figure 15. These complex laminates can also be calculated according to the method outlined in 4.1 (layer by layer composite calculation based on the E-theory).

Fig. 15 Laying of FRP-pressure pipeline in Africa (Constr. by Durit-Werke, Kärnten, Austria)

The individual loads, such as resulting longitudinal stress, bending stress and intralaminar shear stress, or the required rigidities or distortions (e.g. strains), are best represented in a polar diagram in comparison with the resistance of the total complex laminate.

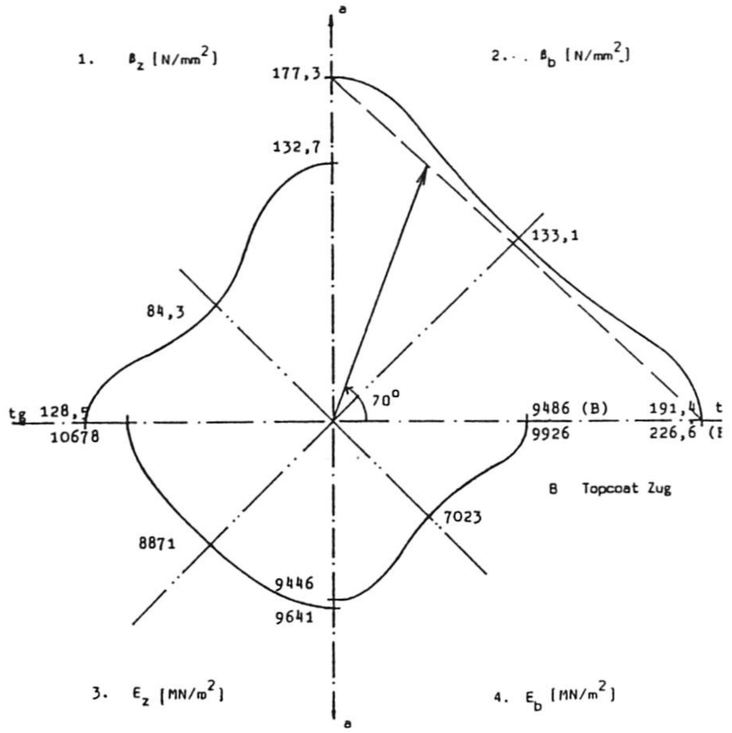


Fig.16 Polar diagram of different parameters of a complex laminate

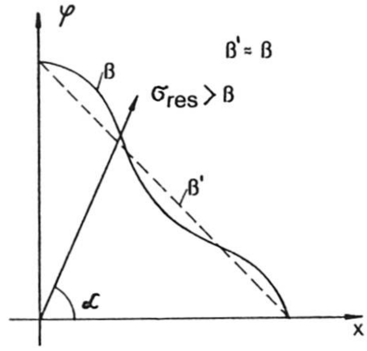


Fig.17 Example of a stress check proving insufficient (to be checked approximately also regarding β^1)

Comparative investigations carried out at the writer's institute on practically applied laminates for cylindrical structural elements showed interesting differences as to rupture strain values as a result of bending of composite materials made principally of cut-fibers or principally of continuous fibers (see Fig.18). [21,4o]

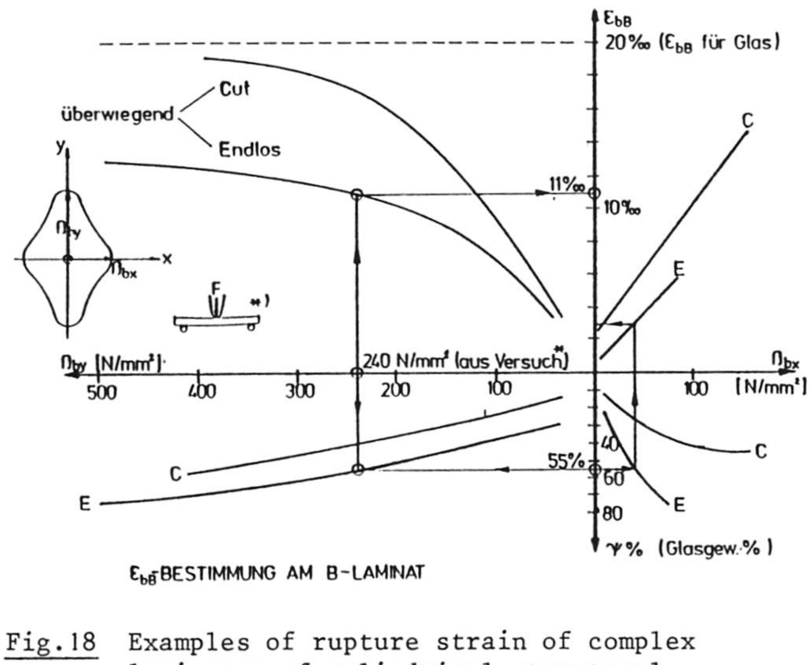


Fig.18 Examples of rupture strain of complex laminates of cylindrical structural elements

The fiber-reinforced composite materials described here were subjected during practical application not only to the load as seen in Table 5, but also to interlaminar shear stresses. So that delaminations (ie, ruptures between the individual layers) do not occur before the load-carrying capacity of the layers themselves is reached, these shear strengths have to lie above a minimal value. Figure 19 shows this range for FRP for several traditional production methods.

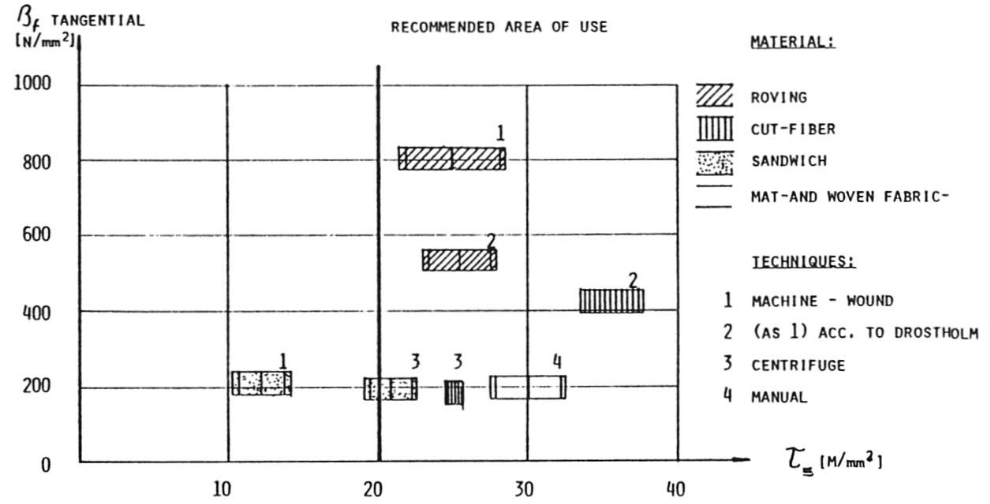


Fig.19 Interlaminar shear strength of some FRP-products

The respective loads both in and to the middle plane of the laminate were separately checked; in doing so, the orientation of both the applied actions (e.g. forces) and the resistance of the material have to be constantly considered. A simple structural example is shown in Figure 2o, where the interaction between the individual structural elements can be observed at the support of a pressure pipeline.

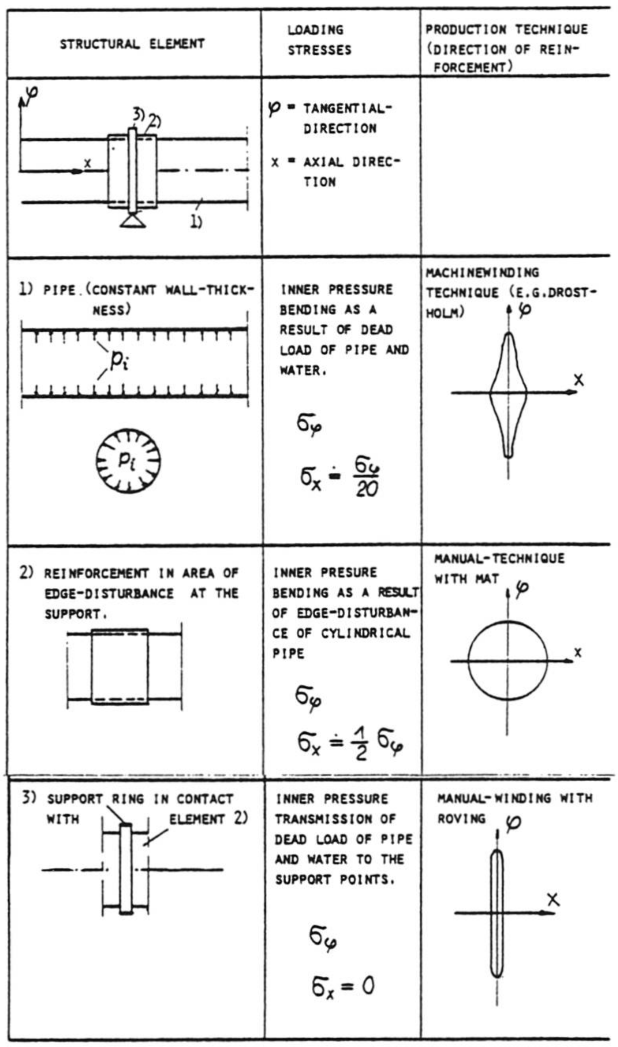


Fig.2o Example of a support for a pressure pipeline made of fiber composite material

5. FUTURE PROSPECTS

New materials with initially unknown properties can, as has been shown, be used structurally in civil engineering with little difficulty by proceeding systematically according to the principles of the new probabilistic design concept.

It is important to recognize inevitable imperfections dependent upon the method of production used. The writer has shown that a licensing procedure must fullfill its original task in order to be a secure foundation for later standardization. The consequence of this is that changes in parameters must be possible during the course of the licensing procedure-especially with parameters which can be optimized as regards quality control. Any and all inflexible establishing of random values is to be avvided.

It is certainly no accident that one often sees composite structures in nature. Bones and wood are not the only examples of this type. Fiber-reinforced composite materials, when cracked, do not lead to failure in the same degree as homogeneous isotropic materials.

The structural application of new materials opens up new possibilities and will eventually be used to better significant weak points of conventional construction.

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