Fiberglass Tendons for Posttensioning Concrete Bridges

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Glass, if completely oriented in the direction of stress, can withstand forces as well as steel. Combining this strength with light weight and corrosion resistance in a high-quality prestressing tendon is conceivable. Bayer AG, a West German chemical concern with worldwide sales close to $20 billion, has developed a technique that yields unidirectionally oriented fiber-reinforced rods. The product, Polystal, has proven effective in applications where steel-like resistance to stress is required while affording users the advantages of electrical neutrality and corrosion resistance. Over the past 10 years, Bayer AG and Strabag, a West German civil engineering and construction firm, have jointly developed a fiberglass tendon and anchorage system to be used as posttensioning elements for concrete construction. Presently, these elements have been incorporated into a bridge outside of Düsseldorf and their performance is being monitored. In this paper, the development of Polystal as a posttensioning medium and some insight concerning the Ulenbergstrasse Bridge are reviewed.

In July 1986, there was an exceptional event in Düsseldorf; the first road bridge, of span 50 m, was prestressed not by means of steel tendons but using prestressed rods of a high-performance glass fiber composite material. Constructing this bridge is the culmination of nearly one decade of continuous extensive research and development that started in 1978.

DEVELOPMENT OF GLASS FIBER REINFORCEMENT OF CONCRETE STRUCTURES

The idea of using glass fibers to reinforce concrete members is in itself nothing new. The first proposals in this regard were made when glass fibers and glass-reinforced composites were still at an early stage of development, once enough was known about the inherent high tensile strength of these materials *(1)*. Putting the idea into practice, however, was a long and laborious process. Although a number of research engineers, especially in the United States and the Soviet Union, worked on the reinforcement of concrete with glass fibers instead of steel, these pioneers did not succeed in solving all the problems arising in the practical use of these rods. The main obstacle to progress was that they had neither suitable glass fiber reinforcing profiles nor anchors of sufficient load-bearing capacity at their disposal *(2–5)*.

A significant step forward was achieved by Rehm of the Technical University of Stuttgart, who evolved some important theoretical principles of glass fiber prestressing based on discontinuously manufactured high-quality glass fiber composite rods and verified them experimentally.

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It was shown, as might be expected, that there was generally no point in reinforcing concrete members with untensioned glass fiber rods in view of their comparatively low modulus of elasticity. The results of Rehm's tests with prestressed elements, however, were so favorable that he was optimistic regarding the technical and economic aspects of glass fiber prestressing, and proposed a broadly based study of the possibilities offered by this method of construction.

This suggestion was taken up by the two firms Bayer AG and Strabag that in 1978 formed a joint venture for development, trial, and application of glass fiber prestressing techniques. Competent research staff from universities also took part, and the project was substantially assisted by the West German Ministry of Research and Technology (BMFT) *(6, 7)*.

It was obvious from the beginning that there were a large number of closely interlinked problems to be solved, demanding close cooperation between basic research, process development, and application technology. It was clear from the complexity of these questions why the original pioneers, working on their own, were unable to achieve a breakthrough in this field.

For his basic research, Rehm had high-quality glass fiber rods with a tensile strength of between 1,400 and 1,700 N/mm^2 that were produced by an elaborate, discontinuous process. For economic reasons, rods of this type were no more suitable for industrial use than the many different types of pultruded profiles that did not normally have sufficiently high strength.

Initially, therefore, the main aim of the project was to develop a process for the continuous, repeatable, industrial-scale manufacture of high-tensile reinforcements from glass fibers and thermosetting resins. With these profiles, the high tensile strength of the glass fibers had to be fully used throughout the service life of the reinforced structure in question.

The second important aspect, which like the manufacturing process was crucial to the success of the whole project, was the development of suitable anchors so that full advantage could be taken of the strength of the glass fiber composite reinforcements under service conditions.

It is rather interesting that, while spectacular success has been achieved in the development of advanced composites based on carbon fibers and the like, there has been a tendency to overlook the fact that the properties of E-glass fibers—which were originally developed for electrical applications more than 40 years ago and are inexpensive and readily available—are fully used in only few applications.

POLYSTAL

Analysis of the conditions necessary for greatest possible advantage to be taken of the fiber properties from both technical and economic points of view shows that the strength of a glass fiber composite material is due almost entirely to the reinforcing fiber. Basically, the only functions of the matrix resin are to hold the fibers together so as to prevent shear between them, to protect them, and to give the composite sufficient dimensional stability over the required range of service temperatures. If the fibers make up approximately 70 percent of the profile by volume, for example, the resin, although it accounts for 30 percent of the cross-sectional area, bears only about 1.5 percent of the load.

In an ideal fiber composite, the load on all the fibers should be equal. This condition is only possible, however, if

- All the fibers are oriented in the direction of the load,
- The fibers are evenly distributed over the cross section so that no stress inhomogeneities can arise, and
- The profile has nearly zero void content.

This, in turn, necessitates a high fiber content. Because stress inhomogeneities can also be caused by air entrapment, every effort must be made to prevent voids from forming when the fibers are impregnated with the matrix resin.

Taking the preceding demands into account, a patented process has been developed by which high-tensile rods can be manufactured continuously on an industrial scale from unidirectionally oriented glass fibers and thermosetting resins. Essential features of these profiles that have been marketed for some time under the trademark Polystal include

- High glass fiber content (80 percent by weight, 65 percent by volume),
- Strictly unidirectional fiber orientation even in the outer layers,
- Uniform fiber distribution over the cross section, and
- Optimum cure.

Some important material data for Polystal profiles are shown in Figure 1, in which the stress-strain curve for Polystal and those for a reinforcing steel (BSt 420/500 RK) and a high-quality prestressing steel (St 1470/1670) are shown for purposes of comparison. This graph is based on Polystal rods of 7.5 mm diameter with a glass fiber content of 83 percent by weight, 69 percent by volume.

The tensile strength—the decisive property as far as prestressed reinforcement is concerned—of Polystal and prestressing steel are similar, although there are considerable differences in the stress-strain behavior of the two materials. Whereas with steel a linear and a plastic range can be distinguished, the curve for Polystal follows Hooke's law exactly until failure. The diagram also shows the relatively large differences between the elasticity moduli of steel and Polystal, which are in the ratio 4:1.

The high elongation at break of over 3 percent and the sudden failure of Polystal when the strength limit is reached show that loads are borne virtually evenly by all the fibers. Any

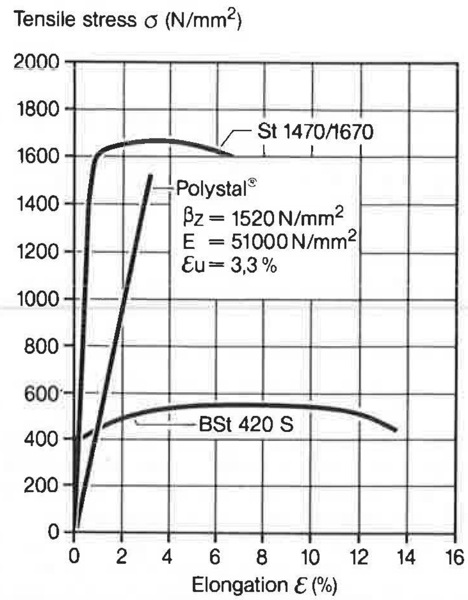

FIGURE 1 Stress-strain curves for Polystal, reinforcing steel, and prestressing steel.

misalignment of the fibers would result in inhomogeneous stress distribution in the rod, that is, in the overloading of certain areas and, therefore, in premature failure at a comparatively low elongation. Further characteristic data for Polystal are given in Table 1.

Apart from investigating these fundamental properties, extensive testing has been done to determine the behavior of Polystal under all relevant conditions in connection with its use in construction engineering. Regarding the use of the rods in prestressed concrete, the following factors have to be taken into consideration:

- A small loss of strength (about 4 percent) due to undefined aging effects and
- A drop in tensile strength by 25 to 30 percent compared to the corresponding short-term values as a result of long-term loading (Figure 2).

TABLE 1 MATERIAL CHARACTERISTICS AND COMPARISONS

	Reinforcing Steel BST 420 S	Prestressing Steel ST 1470/1670	Polystal (68% Glass-fibers)	Carbon fibers
Tensile Strength (N/mm²)	> 500	> 1670	1520	2800
Yield Strength (N/mm²)	> 420	> 1470	Not Applicable	Not Applicable
Ultimate Strain (%)	10	6	3.3	0.7
Modulus of Elasticity (N/mm²)	210,000	210,000	51,000	400,000
Specific Tensile (Tensile Density), km	6.4	21.5	72	160
Specific Weight (g/m³)	7.85	7.85	2.0	1.75

*These are typical properties given for information purposes only. They are approximate values and are not necessarily part of the product specification.

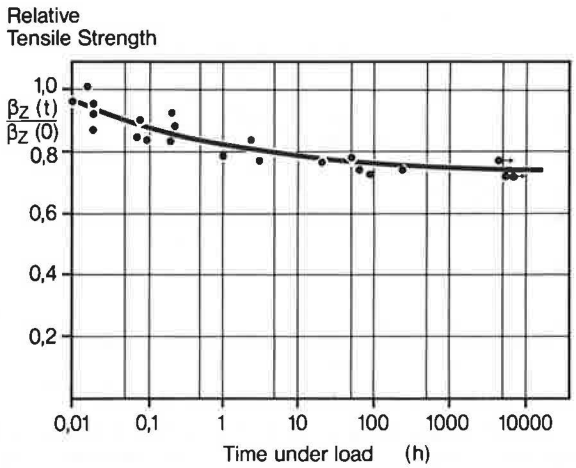

FIGURE 2 Creep strength of Polystal depending on time *(8)*.

Creeping of glass fiber composites as a function of time depends on the fiber content and amounts to approximately 3 percent of the elastic initial elongation (Figure 3). As an extrapolation over a period of 60 years indicates, the loss of tension (relaxation) of a prestressed Polystal rod also amounts to about 3 percent. Moreover, investigations of dynamic behavior have shown that the tolerable stress range of Polystal rods is 34 N/mm^2 at a base load of 50 percent of the short-term tensile strength and at 33×10^6 cycles.

The glass fibers themselves are less sensitive to high and low temperatures than steel. The resin matrix surrounding them, however, loses some of its strength even at about 100°C. For this reason, all the areas in which its force-transmitting properties are required from the point of view of statics, for example, the anchorage, must be protected from excessive heat. This can

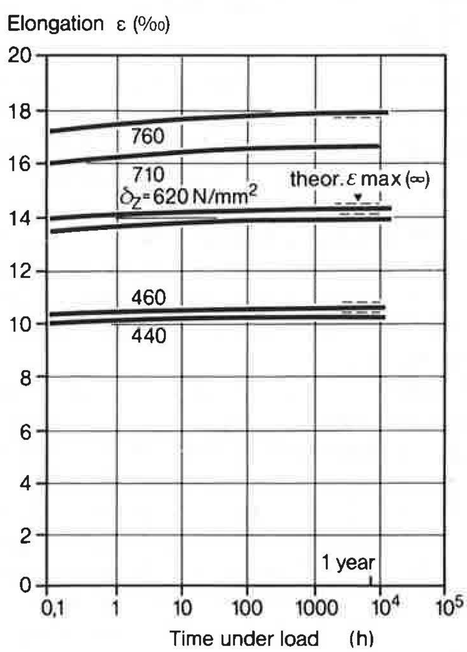

FIGURE 3 Elongation of glass fiber composite rods (56 percent by volume glass fibers) as a function of time *(8)*.

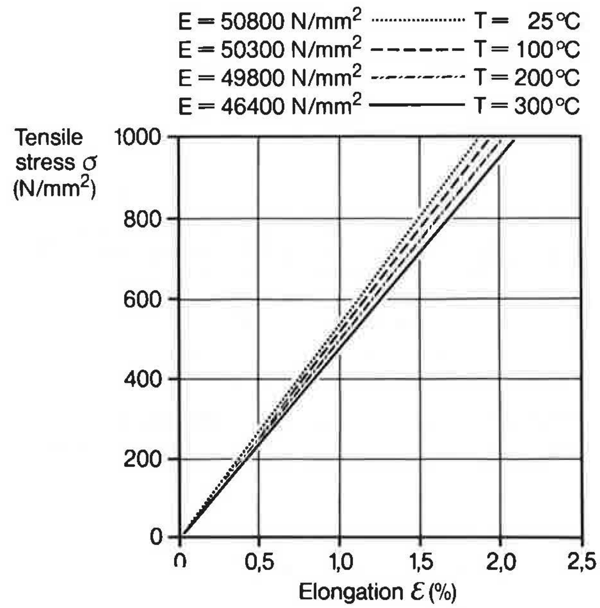

FIGURE 4 Stress-strain curves for Polystal at 25°C, 100°C, 200°C, and 300°C *(10)*.

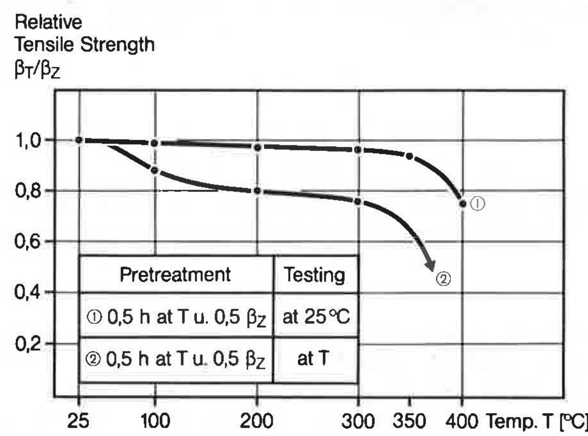

FIGURE 5 Effect of temperature on the short-term strength of Polystal pretreated under various conditions.

be done with a concrete covering, for example. The effect of temperature on the tensile properties of Polystal profiles is shown in Figures 4 and 5.

Reinforcing profiles for use in prestressed concrete must have good long-term chemical resistance to concrete, which is an alkaline medium, and must also be able to transmit large forces to the anchorages. Both these requirements make considerable demands on the base materials and on the processing technology. In retrospect, it turns out that the selection of suitable glass fibers and matrix resins, which was carried out in parallel with process development and optimization, was particularly important regarding the level of technical properties attainable, but also particularly difficult. Special attention has, therefore, been paid to the question of media resistance of the profiles.

Apart from basic laboratory research, methods have been developed for testing prestressed Polystal elements under conditions similar to practice. A so-called "time accelerated test"

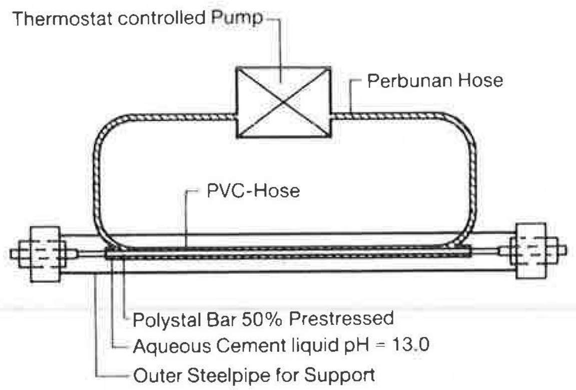

FIGURE 6 Time-accelerated media test of prestressed Polystal rods (60°C, 4 to 14 days) *(11)*.

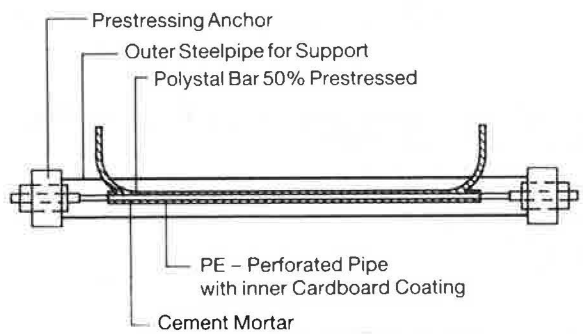

FIGURE 7 Standard media test of prestressed Polystal rods (ambient temperature, 18 to 52 weeks) *(11)*.

(Figure 6) carried out at working load and using aqueous cement liquid (ph = 13) at 60°C continuously circulated by pump allows deduction of the basic serviceability of a profile type relatively quickly (4 to 14 days), while standard tests (Figure 7) characterized by embedding prestressed bars in concrete kept permanently moist, give a more realistic impression of the actual long-term resistance of a certain Polystal type.

As a result of these investigations, a coating based on a highly filled Polyamide has been developed to help the Polystal rods resist chemical attack as well as mechanical damage.

The high strength of Polystal tendons can only be properly exploited in conjunction with anchoring systems in which allowance is made for the extremely anisotropic structure of the composite material. Such anchorage must

- Be highly efficient, so as to make fullest use of the properties of the material;
- Not, if possible, be larger or more expensive than comparable anchoring systems for steel tendons;
- Be easy to handle on site.

In the anchorage areas, the rods are subject to combined longitudinal tensile loads, transverse pressure, and shearing loads, concentrated at certain points. Initially, therefore, the comparatively low interlaminar shear strength of unidirectional

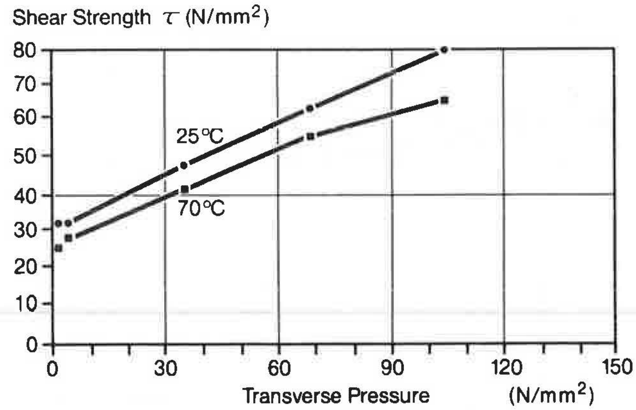

FIGURE 8 Shear strength determined experimentally, as a function of transverse pressure at room temperature and 70°C *(10)*.

fiber composites is likely to result in long anchors. However, Rehm demonstrated experimentally that the interlaminar shear strength can be increased by superimposition of transverse compressive loads (Figure 8). The more concentrically these are transmitted to the cross section of the rod, the larger they can be. This means that the anchors can be made significantly shorter without losing any of their efficiency.

These results are of special importance for clamp and wedge anchors, as well as anchors in which the rods are embedded in polymer concrete; the latter depend on transverse pressure for their effectiveness. In any anchoring system, the shear stress peaks occur where the rods enter the anchors as a result of the incompatibility between the elongations of the composite rods and the anchors. These shear stress peaks must be kept as low as possible.

ULENBERGSTRASSE BRIDGE AT DÜSSELDORF

When a small bridge for the City of Düsseldorf was built early in the research project, various types of anchors could be tested under realistic conditions. This first implementation of glass fiber prestressing occurred in 1980, and demonstrated the fundamental practicability of this new technique, and above all, the suitability of casting type anchors. This bridge supplied much valuable experience that in connection with the results of additional optimization and testing of rods and anchorages as well as tests of construction members encouraged the start of larger constructions.

In 1985, the City of Düsseldorf again made it possible to demonstrate the new prestressing technique in construction of a road bridge for heavy traffic. Before construction of the bridge, competent representatives of science prepared the following expert opinions: "Stability and Durability of the Structure" by Professor König, Frankfurt, "Material and Bonding Characteristics of Polystal in Connection with Prestressing" by Professor Rehm, Stuttgart, and "Judgment on Construction and Anchorage" by Professor Rostasy, Braunschweig (private communications).

Collectively, 59 Polystal prestressing tendons, each composed of 19 7.5-mm-diameter tendon rods, were necessary to

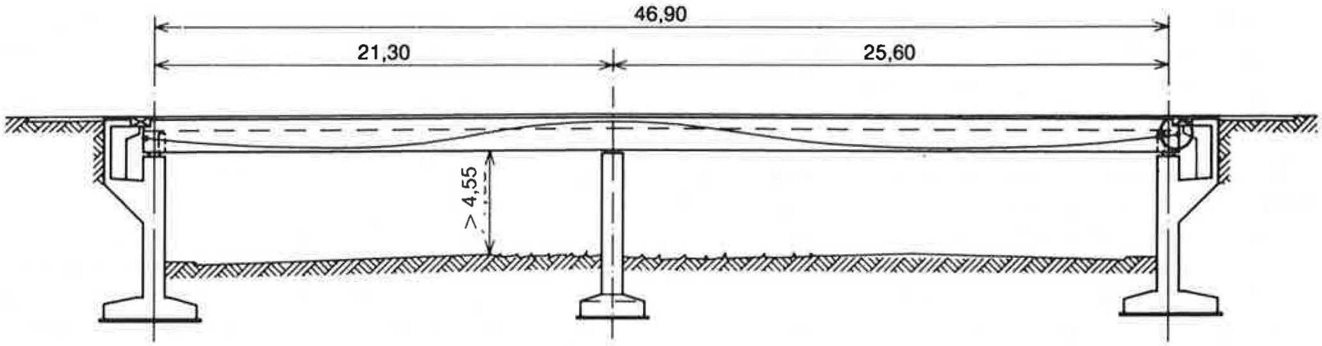

FIGURE 9 Ulenbergstrasse Road Bridge, Düsseldorf, longitudinal section.

produce the calculated initial stressing force of 3,500 tons (60 tons per unit). After prestressing, the cable ducts were filled by an also newly developed resin injection mortar, characterized by excellent flow and outstanding mechanical properties. Technical data for the bridge are summarized in Table 2. Figures 9 and 10 show a longitudinal section and a cross section of the bridge. Figure 11 shows details of the anchorage. Figure 12 shows deflection in a prestressed Polystal test beam.

Practical long-term examinations for different types of soil anchors are underway at this time. The load-bearing capacity of

TABLE 2 TECHNICAL DATA FOR THE BRIDGE

Spans:	L1:L2 = 21.30:25.60 m
Slab width:	15.00 m
Slab thickness:	1.44 m
Clear height:	4.75 m
Loadclass (DIN 1972):	60/30 tons
Degree of prestressing:	partial
Nature of the composite action:	post tensioning with subsequent bond
Bending radius of tendons:	R greater than 32.00 m

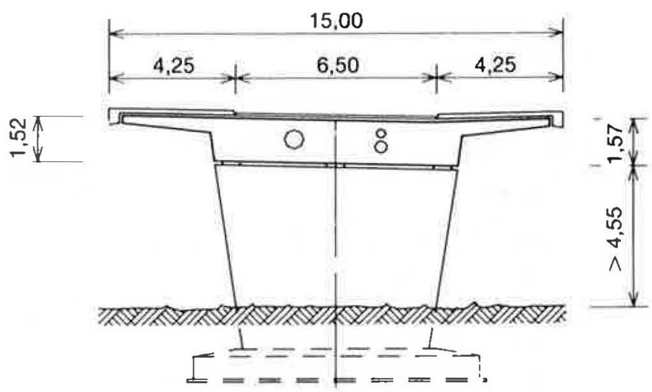

FIGURE 10 Ulenbergstrasse Road Bridge, Düsseldorf, cross section.

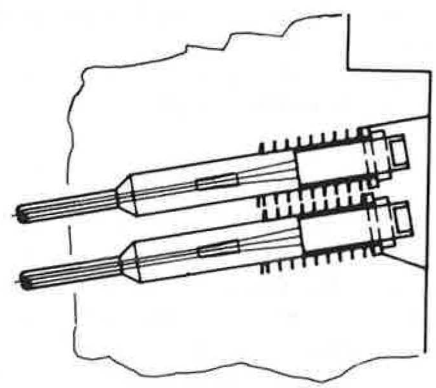

Figure 11 Detail of anchorage.

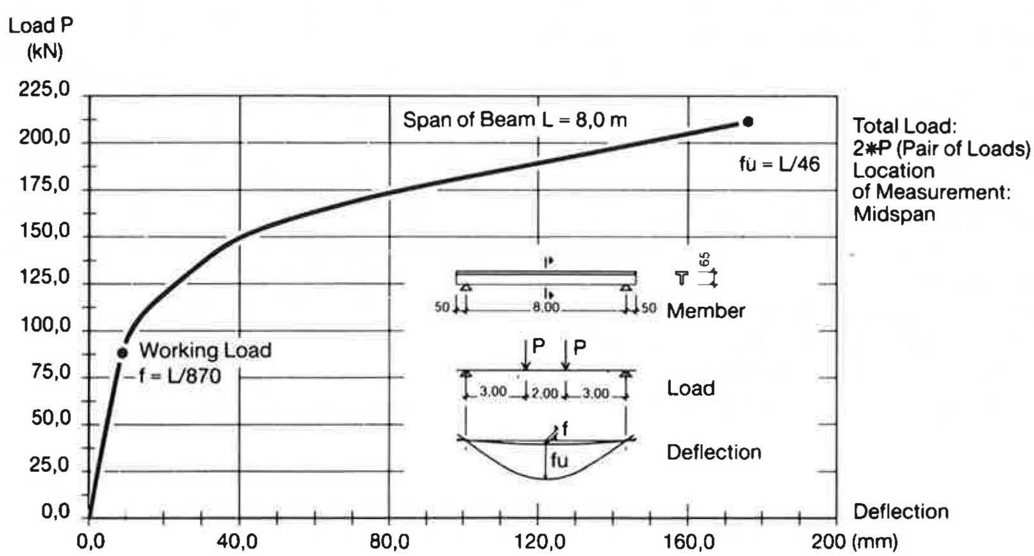

FIGURE 12 Prestressed Polystal test beam (ultimate bending).

such anchors under different load conditions allow for later tests and certification. Another innovation, tested for the first time in prestressed concrete structures, are sensor elements manufactured by integration of optical wave guides into the Polystal rods. Such effects prsage realization of "intelligent" prestressing tendons. With changes in their physical characteristics (e.g., attenuation of light), states of the structural strain may, for example, be detected on any location by those sensors. Significant future progress is expected in this area.

At this point, some comments should be made referring to the fundamental benefits of Polystal with prestressed constructions. One of the special advantages of Polystal in prestressed concrete is its modulus of elasticity, which is only one-quarter that of steel. Although this means initially that the rods have to be stretched four times as much, it also reduces by the same factor the inevitable loss of tensioning forces resulting from shrinkage and from contraction of the concrete due to creep. A further advantage of the low elasticity modulus is that the undesirable flexural stresses caused by curvatures in the rods at intentional deflection points within a structure or when the profiles are wound onto reels for transport and storage are also reduced to one-quarter of the levels of comparable steel rods.

In view of its low elasticity modulus, Polystal is also suitable for prestressing building or other materials having a low elasticity modulus or higher creep values than concrete. Those are applications for which steel cannot be used. Because the density of Polystal is only approximately 2 g/cm^3—about one-quarter that of steel—there are additional advantages in shipment and installation.

In order to demonstrate the break resistance of glass fiber tendons, and then be able to exploit their maximum load-bearing capacity despite the low elasticity modulus, the permissible elongation at the edge of the tensile zone of the concrete at the time of fracture must be increased from 0.5 to 1.0 percent. Whereas the safety theory for steel and prestressed steel reinforcements is based on the assumption that once the yield point is exceeded in the tendons the construction signals its imminent failure through large plastic deformations, glass fiber tendons—which have no yield point or yield zone—are subject to large elastic deformations at the transition from service to failure by virtue of their low elasticity modulus. They give early warning of any impairment of the safety of a structure caused by an error in design; at this point, a glass fiber rod still has a greater load-bearing capacity with which to absorb further increases in the load than does a steel tendon beyond its yield point. This is a distinct advantage of the new material, which could become a technically worthwhile alternative to prestressing steel in nearly all areas and for almost all methods of prestressing.

Its combination of special properties also makes Polystal suitable for numerous applications outside the civil engineering field. Practical experience has already been gained with load-bearing and tensioning members for a high-level antenna; in this application, not only the tensile strength but also the electromagnetic neutrality of the glass fiber rods is of great importance.

Polystal products are already used successfully on a large scale for tension members in fiber-optic telecommunication cables. It is used in this area not only due to its strength properties but also because of its low coefficient of expansion and its absolute insensitivity against electric fields.

The incorporation of Polystal rods in components made from other materials such as glass-reinforced plastic laminates, sheet molding compound, polymer concrete, or cast elastomers may greatly improve the service properties of the components without significantly increasing their weight.

The fortunate combination of rigidity, flexibility, and high abrasion resistance makes Polystal highly suitable for cable insertion devices. These selected examples demonstrate that there are many application areas in which high-strength glass fiber composites such as Polystal have advantages over isotropic materials. Generally, however, they can only be expected to offer solutions to problems from technical and economic points of view where advantage can be taken not only of their high strength but also of other characteristic properties such as low density, corrosion resistance, or electromagnetic neutrality.

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