

SYNTHESIS REPORT FOR PUBLICATION

BRITE - PROJECT 4142 -BREU CT 910515

**FIBER COMPOSITE ELEMENTS AND TECHNIQUES AS
NON-METALLIC REINFORCEMENT OF CONCRETE**

COORDINATOR: SUSPA Spannbeton GmbH, Dipl.-Ing. A. Düsterhöft
Max-Planck-Ring 1,40764 Langenfeld
Tel.: 02173-79020
Fax: 02173-790220

TECHNICAL COORDINATOR: iBMB/TU Braunschweig, Prof. Dr.-Ing. F. S. Rostásy
Beethovenstra13e 52, 38106 Braunschweig
Tel.: 0531- 391/5421
Fax: 0531- 391/4573

PARTNERS: SUSPA Spannbeton GmbH (D)
AKZO NOBEL (NL)
iBMB/TU Braunschweig (D)
RU Ghent, Laboratorium Magnel (B)
DYWIDAG Systems International GmbH (D)
Nederlandse Draadindustrie, NEDRI BV (NL)
Hollandsche Beton Group, HBG (NL) - until 30.06.1994

STARTING DATE: 01.11.1991 **DURATION:** 60 MONTH



**PROJECT FUNDED BY THE EUROPEAN
COMMUNITY UNDER THE BRITE/EURAM
PROGRAMME**

DATE: 06.01.1997

FIBER COMPOSITE ELEMENTS AND TECHNIQUES AS NON-METALLIC REINFORCEMENT OF CONCRETE

Prof. Dr.-Ing. F.S. Rostásy, Dipl.-Ing. M. Scheibe
iBMB/TU Braunschweig, Beethovenstr. 52, D-38 106 Braunschweig

Dipl.-Ing. A. Düsterhöft
SUSPA Spannbeton GmbH, Max-Planck-Ring 1, D-40764 Langenfeld

Prof. Dr. Ir. L. Taerwe, Ir. S. Matthys
Magnel Laboratory, Technologiepark-Zwijnaarde 9, B-9052 Gent (Zwijnaarde)

Prof. Dr.-Ing. D. Jungwirth, Dr.-Ing. J. Noisternig,
DYWIDAG-SYSTEMS International GmbH (DSI), P.O. Box 810268, D-8 1902 Munich

AKZO NOBEL, Dr. Ir. J.J. Frijlink
Research Laboratories, Velperweg 76, Postbus 9300, NL -6800 SB Arnhem

NEDRI BV (NL), Mr. K. de Waal
Groot Egtenrayseweg 13, P.O. Box 3040, NL -5902 RA Venlo

Abstract

Within the programmers frame, extensive research and development work was performed to study the behaviour and performance of FRP as well as the structural behaviour of concrete elements reinforced or prestressed with FRP (fiber reinforced polymer) reinforcement. Several FRP-materials were developed and preselected for application in concrete through comprehensive materials research. Within the tests programmed, glass-FRP (GFRP), aramid-FRP (AFRP) and carbon-FRP (CFRP) were investigated. From the results and the analysis of these tests it is concluded that the behaviour of concrete elements reinforced or prestressed with FRP is predictable and generally satisfactory. Furthermore, it became clear that FRP-reinforcements are not simply a replacement of steel. Therefore, the use and design of FRP reinforced or prestressed elements is governed by the specific characteristics and aspects of FRP-materials. Mechanical behaviour, durability etc. of the FRP-materials were studied on single tensile elements as well as on tendons with a plurality of elements in suitable anchorages. As result of the project, several forms of application with these FRP's are possible. Pilot applications proved the market chances.

1. Introduction

Deterioration of concrete structures due to corrosion of steel reinforcement is a world-wide problem, especially in case of exposure to **aggressive** environment (e.g. marine atmosphere, aggressive chemicals, de-icing brine). Alternative **reinforcing** and **prestressing** materials which do not corrode in **such** environments due to their nonsusceptibility to ionic dissolution maybe a valuable alternative. Most important properties of these **FRP** materials for the application for **civil** engineering structures are: very high tensile strength in fiber direction, excellent corrosion resistance and **very** low density. More durable concrete structures and a range of new kinds of structural elements **and of** new applications are realizable with FRP reinforcement **and/or** prestressing.

In 1990 the partners **STRABAG, AKZO, HBG, iBMB/TU Braunschweig** and the RU Gent came to an understanding to formulate a research proposal with the aim to develop and to investigate FRP for the application of high strength tensile elements in concrete structures, The project was aiming at the introduction as **far** as relevant of tendons of **GFRP, AFRP** and **CFRP** utilizing the specific advantages and avoiding misunderstandings of the specific **behaviour**. The prime objective of the proposal was the acquisition of **fundamental** knowledge and know-how of **FRP-application** for civil engineering structures:

1. Adjustment of material properties of **FRP-elements** and production technologies to the demands of structural engineering, particular in contrast to the **steel** properties.
2. Investigations of static and dynamic **behaviour** of concrete members reinforced or **prestressed** with FRP, subjected to **flexure** and shear.
3. Development of application techniques (anchorage assemblies).
4. Development of design criteria, rules of detailing and for execution of concrete members which are compatible with the present philosophies of design and quality assurance.

2. Technical description

The main research points were introduced in the working **programme** of the project. The work programme chart (Fig. 1) below shows the **thematical** sequence of the technical tasks and the subtasks as well as their interdependence.

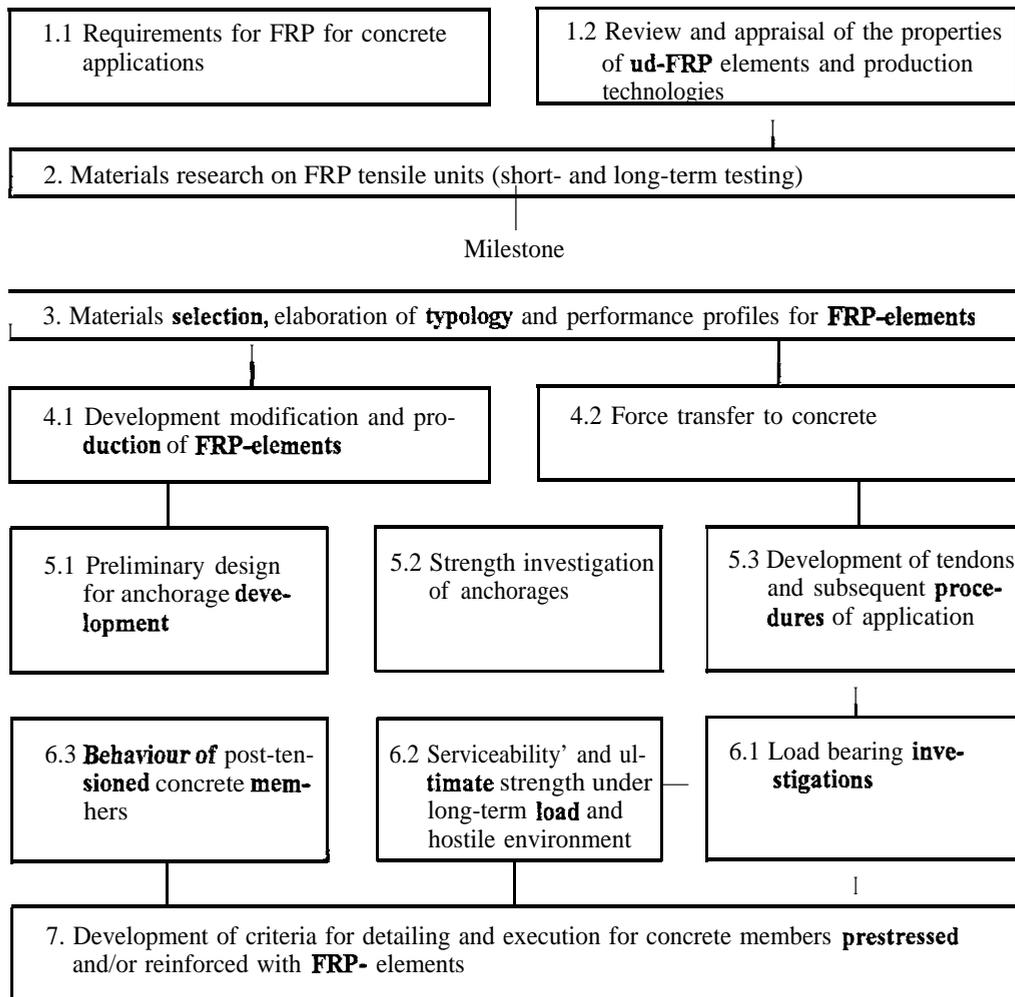


Fig. 1: Flow chart of the tasks of the working programme of BRITE 4142 / CT 91-0515

Fig. 2 shows the distribution and the interdependence of the activities of the partners in the project. There, a clearly structured system of production, experimental and theoretical research and of application is recognizable. The activities of the partners to attain the project goals and to adhere to the requirements of the project are summarized in the following:

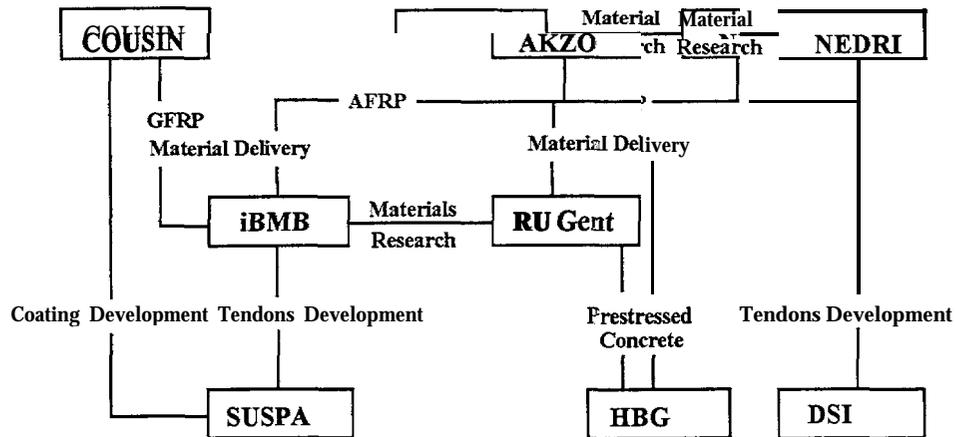


Fig. 2: Relations between the partners of BRITE 4142 /CT 91-0515 and their main tasks

STRABAG AG / SICOM / SUSPA Spannbeton GmbH

The main concern dealt with the development and marketing of FRP for prestressed concrete elements, prestressing tendons, ground anchors, stay cables, mast bracings and other applications. The investigations for the development of GFRP-tendons were discontinued due to problems in the GFRP-bar development. SUSPA changed from the GFRP-material to AFRP, whose mechanical properties and durability make this material suitable for FRP-tendons.

AKZO Nobel

Their main activity dealt with research and evaluation of properties of AFRP and with the improvement of the technologies of AFRP.

IBMB, TU Braunschweig

The main interest focussed on experimental and theoretical material research. In view of the sensitivity of FRP against lateral pressure and surface injury the investigations were concentrated on the development of laboratory anchorages for materials testing of FRP, on short- and long-term laboratory tests of single bars under different environments and on concrete elements prestressed with FRP.

Magnel Laboratory for Concrete Research of Rijksuniversiteit Ghent

The research concentrated on the study of the structural behaviour of concrete elements reinforced or prestressed with FRP. The work focussed on the behaviour of prestressing

elements in the anchorage zone of **pre-tensioned** concrete elements (force transfer to concrete), on the structural **behaviour** of **pre-tensioned** slabs under different loading conditions, on relaxation and on the structural **behaviour** of slabs reinforced with **FRP-grids** under the ultimate limit and serviceability limit state.

DYWIDAG SYSTEMS INTERNATIONAL

developed, produced and tested ground anchors, tendons and cables with **GFRP-** and **CFRP-bars** with emphasis on anchorage development. At DSI, theoretical and experimental investigations of different anchoring systems for **GFRP-** and **CFRP-elements** were performed.

NEDRI BV

was concerned with the development and manufacture of **CFRP-bars** for ground anchors, tendons and cables.

The investigations of the partners started in November 1991 in conformity with the work programme. At the on-set of work, a Technical Report on Task 1 was formulated [1], which dealt with the review and appraisal of the properties of unidirectional FRP tensile elements as they are commercially available, e.g. **POLYSTAL® (GFRP)** and **ARAPREE® (AFRP)**. Also the present production technologies of FRP had to be critically reviewed .

The results of the Technical Report of Task 1 led to the formulation of requirements with respect to the material **behaviour**, to the necessary test work and to modifications of production techniques to achieve improved materials. The report has proved that the database of the technical properties of **FRP** is incomplete and several properties are not sufficiently understood, It was shown that the determination of the mechanical properties requires suitable experimental techniques and subsequent test regulations. As result of these facts, comprehensive new descriptions and rules for the testing and measuring devices and prescriptions for the test procedures were elaborated [2].

On basis of the Technical report on Task 1, the materials research on AFRP and GFRP commenced in the laboratories of **all** partners in accordance of the **different** goals following Task 2. The materials were provided initially by the partners **AKZO** and **SICOM (SUSPA)**. As R&D proceeded, the findings led to continuous modifications of the basic materials and of the production technologies in the works and laboratories of the latter.

One of the main items of R&D on AFRP was the improvement of ARAPREE, as produced by AKZO at the on-set of programme. The necessity of such improvement arose from the thermal incompatibility between the AFRP-bar and surrounding concrete of pre-tensioned elements. This incompatibility resulted in an unexpected cracking of the concrete cover of pre-tensioned structural elements. To overcome these problems, AKZO carried out extensive studies on aramid fibers in conjunction with suitable and economic epoxy resins for the core and skin of AFRP-bars. These studies were followed up by concurrent tests on the mechanical properties of ARAPREE at iBMB and RU Ghent. As result of these combined and comprehensive efforts a mature production technology for technically sound and economic AFRP-bars is today available.

The activities of Task 2, 3 and 4, dealing with the mechanical short-and long-term properties of the FRP and the force transfer to concrete fully correspond with the work programme, although with a certain delay due to difficulties in materials development. Loading tests on slabs and other concrete elements prestressed with ARAPREE were performed to investigate the deflection, the cracking and the ductility of such elements. Also long-term loading tests with pre-tensioned slabs under bending were performed.

GFRP are the most widely used FRP in the world, being the least expensive composite type. SICOM (and their successor SUSPA) commenced their R&D in the project with the material they had previously and jointly developed with BAYER AG: POLYSTAL. The main item of R&D was the improvement of these GFRP with respect to the known unsatisfactory durability in alkaline environment (moist concrete or cementitious grout, eventually aggravated by the ingress of and contact with de-icing salt solution). To overcome this deficiency, SICOM teamed-up with COUSIN-FRÈRES as subconstructor for the production of GFRP using now high-quality epoxy matrix resin instead of the susceptible unsaturated polyester resin matrix of POLYSTAL. However, extensive investigations showed that -inspite of a significant improvement of the durability of the new GFRP-material- the goal of obtaining a GFRP-bar with the durability in alkaline environment comparable with AFRP could not be reached along this avenue. Hence and consequently, great effort was invested to develop a protective powder-epoxy coating. After promising initial results, it was however decided to finally relinquish this approach as its development would have by far -in cost and time- exceeded, the

frame of the project. All subsequent subtasks of SICOM (SUSPA) of the programme proceeded with the before-mentioned AFRP-material.

In the last two years of the project, CFRP-materials could be included in the programme because of NEDRI's joining as partner. In all, the Task 2 proved to be not only highly successful with respect to the practical outcome of the project. Beyond that, it required considerably more effort as envisaged at the on-set of the project.

In view of the manifold difficulties in the development of durable GFRP as afore-mentioned and due to the increased effort for the successful accomplishment of the Tasks 2 to 4, it has to be consented that the work on the Tasks 5, 6, 7 commenced with a certain delay. Nevertheless, the development of suitable and economic anchorages by SUSPA and DSI as needed for tendons, rock and ground anchors, structural ties etc. has advanced satisfactorily.

3. Description of results

3.1 Development of FRP-materials, materials research

Due the efforts of AKZO and in the past two years of NEDRI AFRP- and CFRP-wires from 5,0 to 7,5 mm diameter with excellent mechanical, physical and chemical properties are available for the construction market today.

The GFRP rods of 7,5 mm diameter as jointly developed by SICOM (SUSPA) and COUSIN FRÈRES represent a very suitable composite for tendons, structural ties etc. for all such applications where the immediate contact of composite with alkaline aqueous fluids can be obviated. The threaded GFRP composite rod as developed by DSI was already on several occasions successfully used as temporary rock nail in underground construction.

Because of the lack of experimental investigations of common FRP the university partners were especially involved in material research. At the iBMB/TU Braunschweig and the Magnel Laboratory for Concrete Research different research programmed were performed to study the material behaviour of several kinds of FRP's and the structural behaviour of concrete elements reinforced or prestressed with FRP. From both, a practical and scientific point of view the behaviour of prestressing elements in the anchorage zone of pre-tensioned concrete, the structural behaviour of pre-tensioned slabs under different loading conditions (short-term, long-term and cyclic loading) and the structural behaviour of slabs reinforced with FRP-grids

under ultimate limit and serviceability limit state were closely investigated. In the test programmed both aramid FRP (AFRP) and carbon FRP (CFRP) were investigated.

3.2 Material testing procedures

For the establishment of design data, for materials qualification, certification and quality assurance in general suitable and unambiguous test procedures are a must. Due to the efforts of especially IBMB and RU Ghent a complete set of internal test standards could be attained which may justifiably serve as a basis for internationally acknowledged test standards. One decisive item in these test rules was the development of optimal laboratory anchorages which guarantee the utmost utilization of the mechanical potential of FRP. Hence, extensive theoretical and experimental investigations became necessary in order to obtain laboratory anchorages which do not reduce the true material strength. The result of anchorage development is a wedge-bond anchorage, predominantly for round bar diameters, with optimal handling Fig. 1.

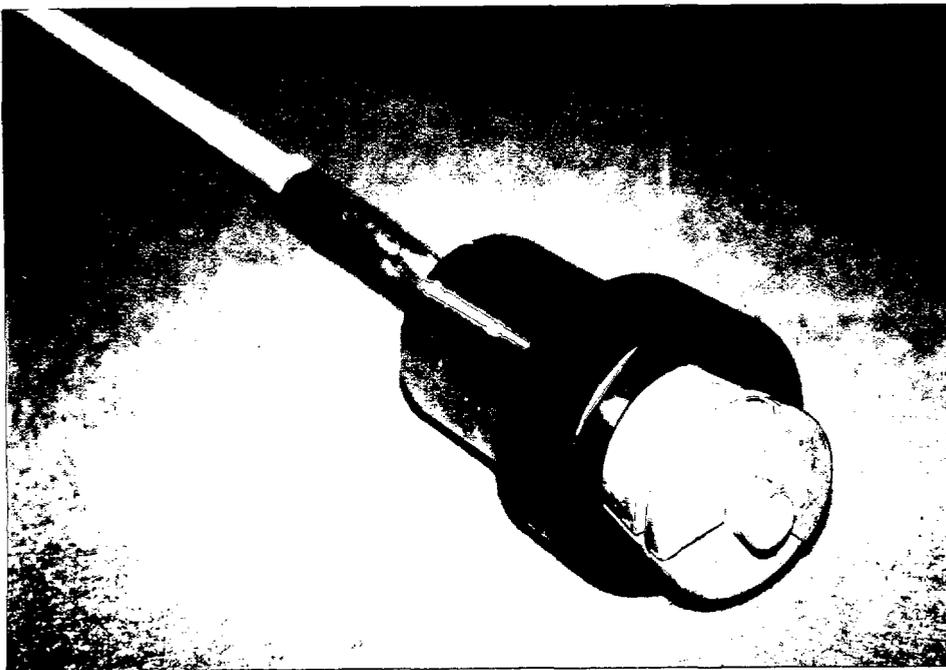


Fig. 1: Wedge-bond anchorage for round FRP

The results of short-term tensile testing showed, that with this anchorage it is possible to attain nearly 100 % of the calculated material strength. The principle of anchorage design could be transferred to other bar diameters. The anchorage assembly was made known to the other partners.

3.3 DYWIDUR - system

The DYWIDUR-system of DSI is a competitive reinforcing system for the construction industry. It consists of the GFRP-bar and the threaded anchoring system. It can be used for the stabilization of ground and rock, especially for temporary applications with subsequent removal of the bar facilitated by the brittleness of the material. Fig. 2 shows the threaded DYWIDUR-bar. Thereby a thread is ground onto the GFRP-bar. Anchorage consists of a polymer plate and nut which has a thread formed-on during injection moulding. Because the GFRP-bar, uses a polyester resin as matrix material instead of epoxy resin, the system is rather inexpensive. The grinding of the bar's thread is a cost-effective manufacturing method in comparison to the forming of the thread in course of the pultrusion process. The polymer plate and nut, consisting of polyamide filled with short glass fibres guarantee a high load bearing capacity of the threaded anchoring system. The pitch and form of the flat thread of the anchoring system have been optimized in combination with the GFRP-bar and the polymer nut.



Fig. 2: GFRP-bar DYWIDUR with a threaded anchoring system

The DYWIDUR-system was applied in two pilot projects, the Ziegenbergtunnel (Germany) and the Hånkleiva tunnel (Norway). The brittleness of GFRP turns out to be an advantage. Steel reinforcement -placed radially from a pilot tunnel- has to be excavated during enlargement of the cross-section either by tunnel boring machines or road headers. Steel rock bolts require a permanent reliable corrosion protection which increases their costs sub-

stantially. The DYWIDUR-system fulfills the requirements of corrosion resistance without additional protective measures.

3.4 CFRP - Tendons (CARBON STRESS)

Due to the efforts of the partners DSI and NEDRI the development of tendons, structural ties, stay cables etc. using CFRP received a strong impuls. Although the development of tendon-anchorage assemblies for CFRP-wires of 5,2 mm diameter could not be finalized with the anchorage optimization, very promising results were achieved.

DSI performed extensive theoretical and experimental investigations for resin-grouted bond anchorage systems. A conical potting system for a bundle of seven CFRP-wires was designed on basis of these analyses and test results from investigations of the potting material and pull-out tests.

3.5 Posttensioning systems with GFRP and AFRP

The FRP-tendons of SUSPA up to now, were produced from glass fiber reinforced plastics (GFRP)-bars called POLYSTAL®. It is common knowledge, that glass fibers are liable to alkali attack, An additional protection of the GFRP-bar became necessary.

Investigations of SICOM/SUSPA were orientated to develop a GFRP-bar with a high durability against hostile environments without an external protection in combination with a more efficient and more economical anchorhead for FRP-tendons. The problems with the external protection (epoxy powder coating) could not be successfully solved. Extensive tests have been carried out with the newly developed, uncoated material. Now, a new material with short-term tensile strength values of ca.1.700 N/mm² is available whose tensile strength equals that of comparable GFRP-bars of high production quality (POLYSTAL produced by Bayer AG). This material is suitable for such applications in which an alkaline attack does not occur.

In order to obtain a more durable alternative to the susceptible GFRP, AFRP-bars (ARAPREE) were used for tendons. The prestressing tendons consist of a specific number of AFRP-bars grouped together. The required working load defines a number of AFRP-bars in the bundle. The anchorages of tendons used, are of the bond type. Today, tendons are available for several admissible prestressing forces (Tab. 1).

Tab. 1: Survey of available AFRP-tendons

Series 1		
Kind of tendons	Number of bars n $\varnothing 7,5 \text{ mm}$	Characteristic ultimate breaking force of AFRP-tendons ¹⁾ $\text{cal } F_u = n \cdot F_{cm}$ [kN]
1	3	179,1
2	5	298,5
3	10	597
Series 2		
1	8	477,6
2	19	1.134,3

¹⁾based on short-term tensile tests with ARAPREE ($F_{cm} = 59,7 \text{ kN/bar}$)

Tendons of series 1 were used as tendons for a large suspension structure construction of an antenna bracing. In priority, tensile elements of type 2 (Fig. 3) are used for the load transfer, which resulted from a horizontal grid system of the antenna construction.

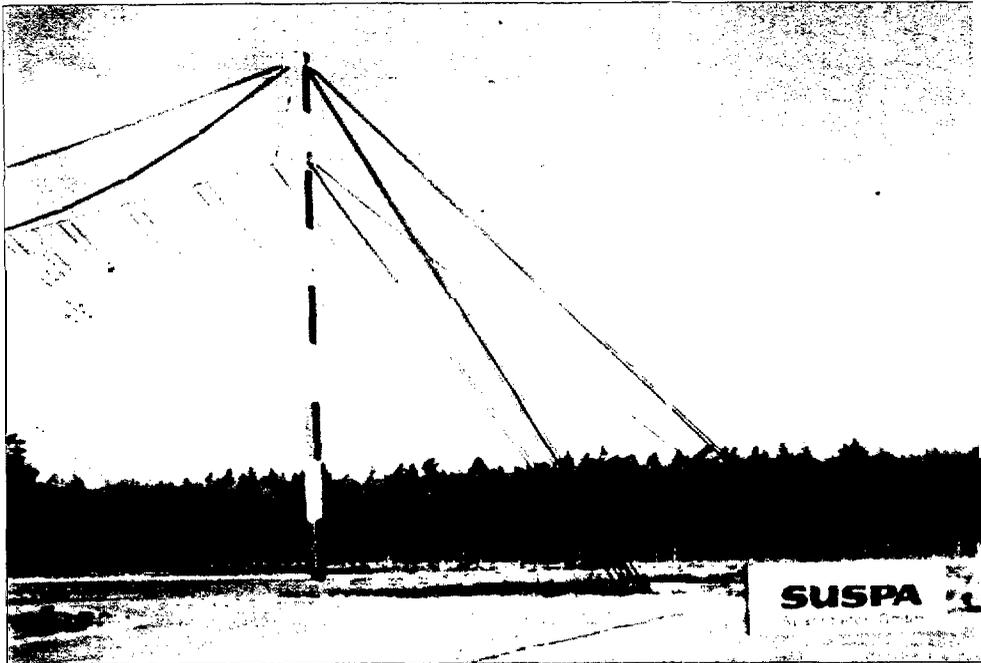


Fig. 3: FRP-tendons for antenna bracing

4. Conclusions

As the international development shows, there are several fields of structural engineering application in which high-strength unidirectional FRP-bars, strands etc. not only gain in momentum but in which they already successfully compete with conventional high-strength

prestressing steel. One of these fields relates to the use of **ud-FRP** tensile elements for post-tensioning tendons, ground- and rock anchors, stay **cables** and structural ties for various purposes also for the strengthening and repair of damaged structures. In all these applications, the high strength and excellent corrosion resistance of **FRP** can be utilized. But besides these assets, the successful competition with high-strength **prestressing** steel tendons requires efficient anchorages. **In view of** the sensitivity of FRP against lateral pressure and surface injury, great efforts were undertaken by the partners regarding research on and development of suitable anchorages, At the **iBMB/TU Braunschweig** and the **Magnel Laboratory** large experience and know-how from a mainly scientific point of view has been built-up in the field of non-metallic (**FRP**) **reinforcement** for concrete structures through this **BRITE-project**. As European research **centres** working in this area in a systematic way, both are internationally recognized for their research work in this new and innovative field. The established research knowledge, will be used and **further** developed in **future** research projects and collaborations.

The **DYWIDUR-system** with the **GFRP-bar** (\varnothing 25 mm) has been developed by DSI. First applications in Germany and Norway have shown the potential of the **DYWIDUR-system**.

NEDRI and **DSI** will vigorously pursue the marketing of **CFRP (CARBON STRESS)** to tendons, stay cables, ground and rock anchors. **AKZO** -with their product **ARAPREE-** are today Europe's front runner of **AFRP-producers**. An Italian **licencee** has **already** been won.

SUSPA is very experienced to **perform** prestressing works with FRP-tendons made from **GFRP** and **AFRP** for permissible forces given in Tab. 1. **SUSPA** as leading prestressing company for conventional prestressing **steel** tendons **will** continue their **R&D** work and marketing for the **licensed** **HLV-prestressing** system. It is planned to extend the acceptance for the **HLV-system** to other FRP (**GFRP** and **AFRP**) for one specific bar diameter ($d = 7.5$ mm).

There will also be valuable benefits for the European Construction Industry not only **in** Europe but also for its activities in the Middle East and developing countries in direct competition with Japanese and American companies, which have already considerable experience with fiber composites in structural engineering.

5. Acknowledgments

As many R&D efforts all over the world show, advanced high-strength and highly corrosion resistant fiber composites are becoming viable alternative materials to reinforcing and prestressing steel which are prone to corrosion in aggressive environments. This fact was acknowledged by the European Community by awarding the BRITE/EURAM-programme, BRITE-project 4142, CT 91-0515 dealt with in this project. For the financial support the partners express their gratitude to the European Community.

6. References

- [1] Rostásy, F. S.: Evaluation of potentials and production technologies of FRP. Technical Report Task 1, IBM 1-92, BREU-CT-91 0515, BRITE/EURAM - PROJECT 4142.
- [2] Rostásy, F. S.; Hankers, Ch.; Scheibe, M.: Test methods for the assessment of mechanical properties of FRP. Report BRITE/EURAM 1-93, BRITE-Project 4142, 1993.