research project
Active Fiber Composites for Adaptive Systems

short report

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The responsibility for the content of the report rests with the author.

project partners

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1 The aim of the research project

The approach in the research program „Active Fiber Composites for Adaptive Systems (AFAS)“ is to investigate the effectiveness of fiber composites for building applications and increase the use of innovative techniques. Various investigations on production of fiber-reinforced structures in the nature were conducted first. These findings and appropriate transfers to the building industry were discussed. This approach allows to use the materials according to their properties optimally.
Furthermore, knowledge of aviation- and space-industry in the use of active materials and control technology were presented. The transferability to options of use in the building industry were discussed.
To use the previously developed principles effective in construction-applications, it is necessary to include various software products. As part of the research project AFAS appropriate interfaces have been developed to facilitate data exchange between these systems.
The knowledge gained were finally verified on various objects and summarizes up the possibilities.

2 Implementation of the research task

The research project was developed over a period of 21 months in the years 2009 to 2011 edited at the Bauhaus-University Weimar by the chair of Structural Engineering and the chair of Design and Construction of Load-Bearing Structures. The research project was divided into the search of active materials and their applications, preparation of application tools for the practical use of the developed principles and verification of the gained knowledge on a demonstration object.

2.1 Research on active materials and identifying possibilities of application of active components in the construction industry

Smart materials are already used in current engineering practice. In the following is a presentation of some exemplary applications and materials. The possible fields of application are very broad because of the actuatory and sensory abilities and include among other things vibration control.

2.1.1 Smart materials in civil engineering

As part of the investigations piezoceramics and shape-memory-alloys could be identified as active materials for the construction industry.
Piezoceramics are piezoelectric materials which establish an electric field under external mechanical stress. The piezoelectric effect was first discovered in 1880 by Pierre and

Jaques Curie. This effect can be reversed by applying an electric field and so it is possible to generate forces. Piezoceramics have very high response times (> 10 Hz). The achievable expansion range is very low (approximately 0,1% of the length of the actuator). According to (Bas00) it is possible to transmit compression forces up to $50\frac{N}{mm^2}$ and tension forces up to $25\frac{N}{mm^2}$.
Shape-memory-alloys (SMA) can reversibly change their shape and stiffness dependence to temperature. This ability is based on the modification of the internal metallic grid structure. The transformation between both phases is reversible under certain conditions. SMA´s can realize expansions up to 8%. The theoretical deformation rate is relative low (about < 1 Hz) and the use only for low frequencies rational. There are vary possibilities of shape changing which are classified as one-way-. two-way and pseudoelasticity.

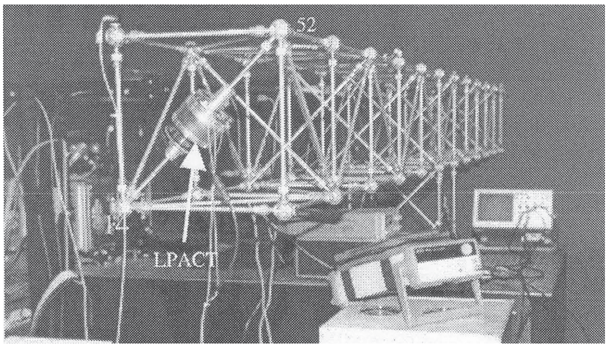


Abbildung 1: vibration control of truss (Lag08)

An exemplary application of piezoceramics in building industry is the vibration control of trusses. (SSL06) shows with this system the possibility of structure integrated force measurement and actuation in realtime.

The passive properties of shape memory alloys are suitable for damping and structural strengthening. Damping is the transformation of mechanical energy in to thermical energy. The material is internal reorganized in the low-temperature phase by exceeding the tensile strength and performs a hysteresis with opposite forces. In this way it is possible to dissipate a relative large amount of energy. In comparison to steel it is possible to restore the initial state (JCMR05).

Shape memory alloys are presented as active changeable systems. These concepts are very interesting and impressive because of the state changes. Nevertheless it is important to think critically about active applications (JCMR05).

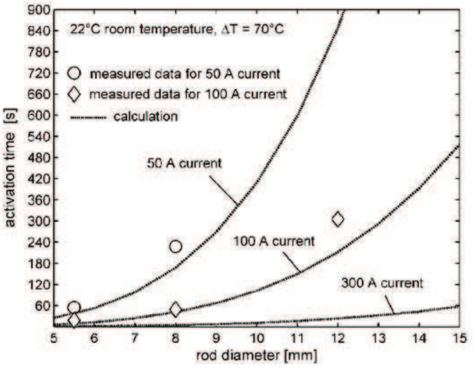


Abbildung 2: activation times of different diameters (JCMR05)

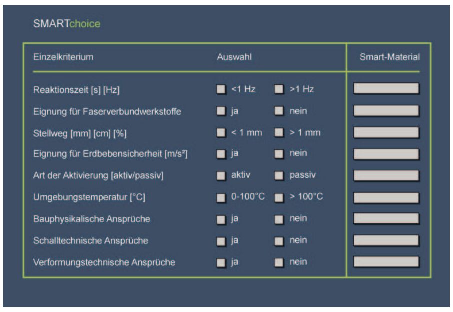
To activate SMA´s it is necessary to enter thermical or electrical energy. To deactivate it is necessary to realize the cool down of the element by heat withdrawal. The heating up is generally much faster than cooling. This process is dependent on the diameter of the SMA-wires and may take up to several minutes. The cooling-down can be realized with peltierelements.

2.2 Application Assistance SMARTchoice

Based on different material- and application investigations it was possible to create **SMARTchoice** a mock-up for an application Assistance Tool. With this tool engineers and practician are able to choose the right functional material with correct properties. Therefore different selection choices are presented.

Selection matrix sensors and actuators

In the moment it is possible to investigate sensorical materials for the properties compression, temperature, deformation and acceleration. In different expandable stages it is possible to present multiple selection criteria.


SMARTchoice

Einzelkriterium	Auswahl		Smart-Material
Reaktionszeit [s] [Hz]	☐ <1 Hz	☐ >1 Hz	
Eignung für Faserverbundwerkstoffe	☐ ja	☐ nein	
Stellweg [mm] [cm] [%]	☐ < 1 mm	☐ > 1 mm	
Eignung für Erdbebensicherheit [m/s²]	☐ ja	☐ nein	
Art der Aktivierung [aktiv/passiv]	☐ aktiv	☐ passiv	
Umgebungstemperatur [°C]	☐ 0-100°C	☐ > 100°C	
Bauphysikalische Ansprüche	☐ ja	☐ nein	
Schalltechnische Ansprüche	☐ ja	☐ nein	
Verformungstechnische Ansprüche	☐ ja	☐ nein	

Abbildung 3: selection matrix **SMARTchoice**

For the selection of materials for actuation there is a selection matrix similar to the sensorical materials available. In this matrix it is possible to choose materials regarding to the properties reaction time, suitability for fiber reinforced materials, stroke, suitability for earthquake engineering, way of activation, ambient temperature and claims of building physics as well as sound- and deformation related needs.

2.3 Lightweight Design and Structural Optimization

Lightweight Design and Structural Optimization are the key points to generate material-saving structures. Especially in nature are optimized structures very common. Biology is a great teacher in form optimization and material sciences. An optimized application on fiber composites are strings and armor-plates of grasshoppers, comp. (Deg09).

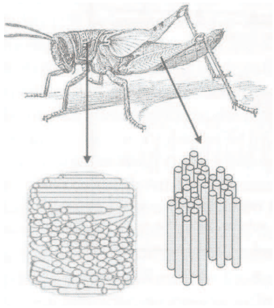


Abbildung 4: Chitin fiber tissue at grasshoppers (Deg09)

The fiber orientation is almost perfect adapted to the load flow. So fibers will be only in areas and parallel to tension loads. In contrast to the tensile fibers are the armor-plates (like wings and skulls) build up in several layers with mutually twisted fibers. Hereby it is possible to carry also loads crosswise to the fibers.

Next to the variation of the fiber orientation is it possible to change the e-modulus between the strings and the plates. Also within the plates (internal and external layers) the characteristics can differ in dependence to the load. Thus, the grasshopper is a very good example for a material minimized and adaptive structure.

Biological materials have a good relationship between dead load and load capacity. This includes cellular structures like timber. Timber is a fiber composite out of tensile cellulose fibers and lignin matrix where overstrained regions are strengthened by additional material gain. Bones contains short and weak collagen fibers in a minimal apatite matrix, comp. vgl. (Dou09). Especially natural systems are able to use self-organization for the fiber-orientation and topology optimization. The influences while growing trigger selective deposit of fiber materials. This adaptive growing process seeks to dynamical equal distribution of forces, comp. (Dou09).

As previously mentioned, there is a possibility to produce fiber reinforced composites as free form structures. This means that the outer structure or form work can be shaped and the internal structure can be molded. Conventional fiber reinforced materials are often made out of fiber mats and a viscous and hardening matrix. With industrial produced fiber mats it is only in limits possible to change the fiber direction in a structural component to improve the specific properties regarding the requirement and function, comp. (Dou09). Christina Doumpioti used adaptive methods in iterative steps to arrange the fiber direction. Thus, it was possible to mimic growth and distribution processes from bionics.

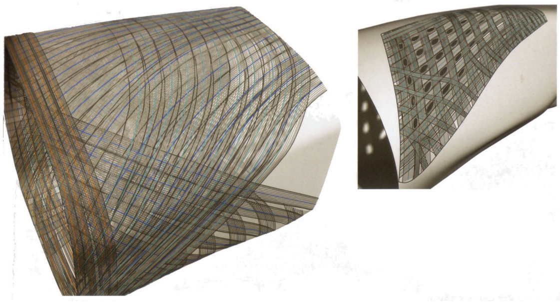


Abbildung 5: Iterative modification (Dou09)

Collagen-fibers and trabeculare bone structures are natural optimized structures by using form-optimization and material-design. By using this knowledge for architecture and civil engineering it is possible to develop fiber-layings which are optimized for the load-flow. The application was shown on different applications. Shown by different ways of form-finding and material-optimization adapted to the load conditions it is possible to create highly efficient „technical fiber-reinforced structures“ which are based on a biological paragon.

(Lip07) shows that therefore topology-optimization, form-optimization, design-optimization and material-design are used. Fiber-reinforced composites are able to accept any form while production. By this way it is possible to create structures out of these materials which follow the occurring load.

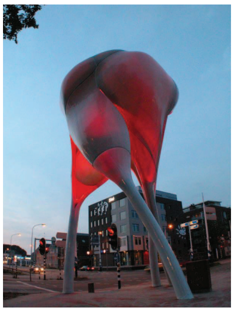


Abbildung 6: D-Tower (Henk Vlasblom)

In this way, there is the possibility that the load transfer completely, or in large part, to be worn over normal forces. Constructions which are claimed by normal forces can save a lot of material compared to structures which are claimed by bending forces. The D-Tower, designed and constructed by Nox architects and the engineering office Bollinger and Grohmann, is an example of a free form structure.

So if a building is to have a desired light and slim structure and the structure has to perform additional functions, the use of fiber-reinforced-plastic components are not only profitable, but often the only alternative. The main requirement is still the appropriate use of material and thus an economic use of material. The material is predestined for the reception of normal forces because of force-conducting fibers embedded parallel to the surface in shaping matrix, comp. (FOM03).

2.4 Prototypical Interface IFAS

The optimization of fiber-reinforced plastics and the successful use of active materials in construction is only possible by using innovative simulation tools.

In current architectural projects are many parametrical CAD-programs in use. Parametric open the possibility to vary single parameters. By this way it is feasible to create and optimize a lot of different models. In this manner it is also necessary to use parametrical design- and simulation software.
Between these different computer systems it is required to enable a proper data exchange. This exchange is by default not available. Therefore the prototypical Interface **IFAS** was developed.

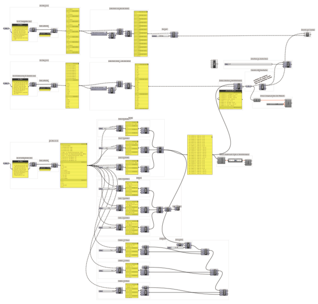


Abbildung 7: **IFAS**-Interface

In this way different programs can be used optimal by their different options. It is possible to use form-finding with Sofistik®, topology-optimization and analysis of the principal stresses with Ansys®. All data can be exchanged and processed with the CAD-tool Rhinoceros®. The main part in the exchange interface is the Rhinoceros®-plug-in Grasshopper®.

By using the **IFAS**-interface it is possible to use results of the different calculations and design optimizations as vectors, which are mostly graphical available. For example is it possible to use the results of the topology-optimization for 3D-plots. Also the calculated principal stresses can be used to lay up the fiber-strands optimal for different loads and it is possible to assign different strands different material properties. In the future the simulation and calculation of active properties (smart materials) is being considered. But also from production point of view this method has many advantages. For example it is possible to lay up fiber bundles computer controlled by robots. The production of free-form structures will be easier and much more efficient.

2.5 The Demonstrator

The findings of the research programme concerning to active fiber-reinforced composites should examined more closely, illustrated and verified on a demonstration object. Therefore a light, material-saving and multifunctional component was developed and computationally examined. The most important design criteria´s are light construction, mobility, multifunctionality, extensibility and integration of active materials.
The choice for the demonstration- and verification object fell on a parametrical arc structure. This structure can also be a connecting component for shell structures.

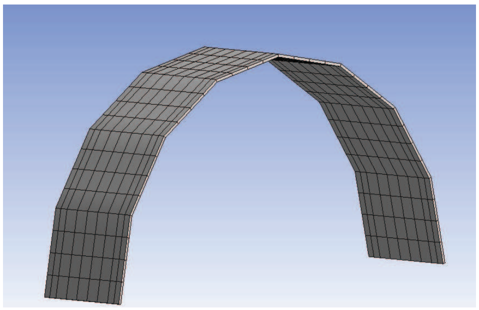


Abbildung 8: DO2 - arc structure for gaps

The demonstration object DO2 was calculated for different load cases (dead load, statical and dynamical wind load). For the single load cases the optimization tools and possibilities of material savings were shown. These processing steps are also a test phase for the **IFAS**-interface.

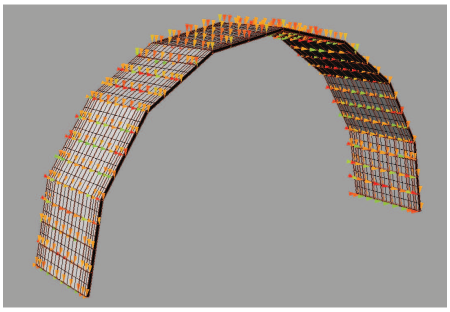


Abbildung 9: principal stresses vectorially shown in CAD-systems

After data transfer of the principal stresses to the CAD-tool Rhinoceros® it is possible to work with the vectorized data and it is possible to fit the fiber position to constructive conditions. Beside the fiber-laying accordingly to the principal stresses there is a possibility to minimize the required amount of material throw the topology-optimization.

Abbildung 10: topology-optimization vectorized throw **IFAS**-interface — topology-optimization shown as graphic in the FE-program Ansys®

3 Summary of Results

The aim of the research project AFAS was to extend the applications of composite materials in the building industry by demonstrating the potential for further optimization. Therefore optimized load-bearing structures in nature (bionic) and aerospace industry have been investigated. For the development of fiber reinforced structures it is possible to learn a lot from the nature. Many plants are „natural fiber-reinforced composites.“ The main forerunner on the field of form-finding is the nature with all these optimized trees, leafs and shells of bugs. All these structures are evolutionary optimized over thousands of years. These knowledge is very important for the development of „technical fiber-reinforced structures“ and has lots of advantages. Through the optimization of the form (external appearance) and the material fabric (internal appearance) it is possible to use all the potentials of material-savings.

Beside the form- and material-optimization it was possible to demonstrate all the advantageous possibilities of active structure adaption. In this way it is possible to react simultaneous to varying load conditions. Therefore different active materials have been compared and categorized regarding to their possible applications. The **SMARTchoice** mock-up was developed and presented to get a clear way of operation with this informations. This tool allows practioners to choose for different applications the right functional material.

The integral planning of active fiber-reinforced structures requires different software products. The prototypical interface **IFAS** was developed to enable the data exchange between the FE-program and the CAD-tools. So it is possible to use the results of the calculation also as vectorized data. The results can be used for further processing steps. The research programme AFAS shows that the application of optimized fiber-reinforced structures in the building industry is a future-oriented possibility and has lots of economical and ecological advantages. In terms on further studies and research programs are these results relevant approaches. In any case there should be a focus on parametrical structural-development and -optimization by using evolutionary algorithms. Also the prototypical interface **IFAS** should be elaborated. The control techniques should be extended and in the focus of further research programs.

The results of the research programme AFAS will be consolidated by bachelor-, master- and doctoral thesis. The topics of fiber-reinforced composites will be integral part of the teaching.

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