Concrete Foundations for Offshore Wind Energy Converters subjected to fatigue loading

Prof. Dr.-Ing. Jürgen Grünberg
Dipl.-Ing. Joachim Göhlmann
Dipl.-Ing. Christian Ertel

Institute of Concrete Constructions
University of Hannover
Appelstr. 9A
30167 Hannover, Germany

Tel. +49 (0)511 / 762 - 3352
Fax. +49 (0)511 / 762 – 2175
Email: massivbau@ifma.uni-hannover.de
goehlmann@ifma.uni-hannover.de
Web: www.massivabu.uni-hannover.de

1 Introduction

The development of more efficient Wind Energy Converters (WEC) as well as the planning of offshore windfarms leads to strongly increasing requirements on the construction. Actual problems arise in the German area of the North Sea with water depths up to 35 m. WEC are subjected to high cycle loading with number of load cycles up to 10^9 for onshore locations and in addition 10^8 load cycles for offshore structures. Therefore, the fatigue design becomes more important for concrete concstruction and the influence of multi-stage and multiaxial fatigue loading have to be considered [1,2].

2 Uniaxial fatigue loading

In order to design concrete components and concrete construction for WEC under fatigue loading a linear damage accumulation law is often used [3-6] devised by Palmgren in 1924 and extended by Miner. This damage model is based on the assumption, that each load cycle generates a part of damage which is linearly accumulated until a critical damage value is exceeded and fatigue failure occurs, equation 1. It is also assumed, that the damage accumulation is independent of the order of load cycles and the order of load cycles does not affect the resulting fatigue life respectively.

$$D = \sum_{i=1}^{j} \frac{N_i}{N_{Fi}} \leq D_{lim} \qquad (1)$$

With:

N_i = Number of load cycles with the same amplitude and range
N_{Fi} = Corresponding total number of cycles to fatigue failure, e.g. [4]

But many experimental investigations have indicated, that a linear damage law couldn´t sufficiently consider real non-linear damage evolution in concrete under fatigue loading. Therefore, the application of the simplified linear damage law by Palmgren and Miner could lead to unsafe or uneconomical concrete constructions for WEC [7].

In figure 1 typical non-linear strain accumulation of concrete with increasing of fatigue loading is illustrated. Therefore, the fatigue process can be devided into three parts. The primary part covers the first twenty percent of the fatigue life and is initiated by extension of pre-existing microcracks. These microcracks are mainly caused by tensile stresses between the coarse aggregates and the mortar matrix resulting from the hydration process and shrinkage of concrete. Beyond the first part the strain accumulation is governed by a stable crack propagation and generation of new cracks. This part continues until eighty percent of the fatigue life is achieved. During the second part the microcracks join to macrocracks, so that in the remaining fatigue life an unstable crack propa-

gation can be observed, which leads to formation of fracture surfaces and finally to the failure of concrete under fatigue loading.

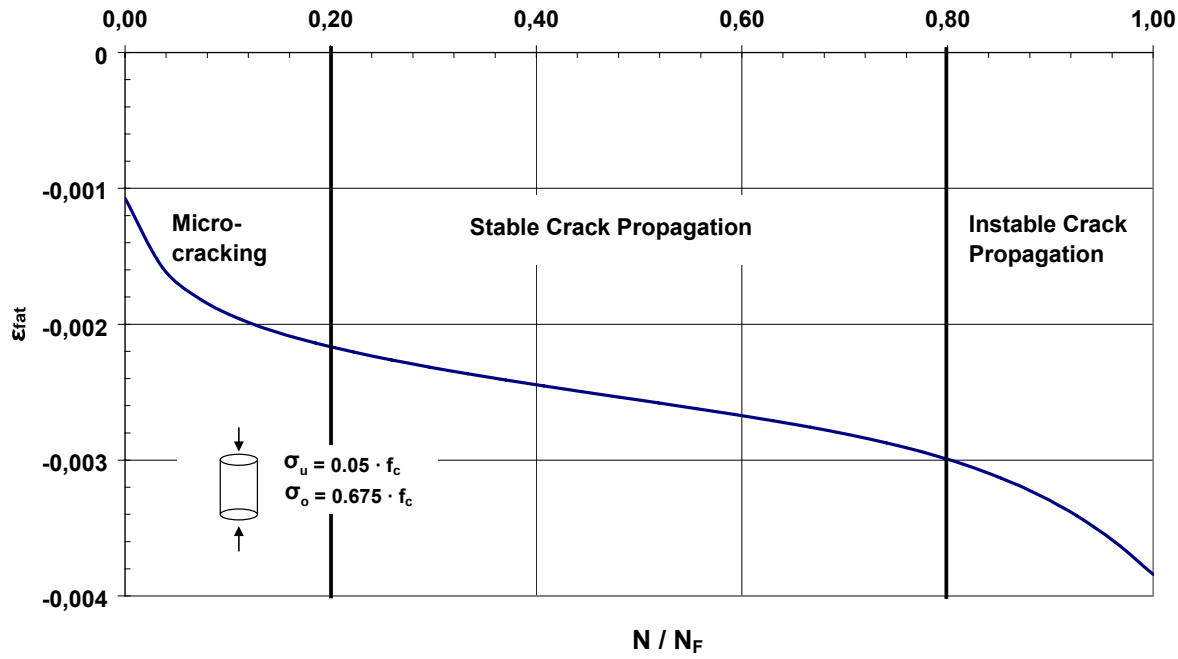

Figure 1: Strain accumulation under constant – amplitude loading

There are many modifications for adjusting the Palmgren-Miner assumption to the realistic fatigue behaviour of concrete. The most approaches are only limited on the description of separate experimental results and do not contain a mechanical constitutive failure model.

A new fatigue damage model for concrete under constant amplitude loading, basing on a fracture energy approach, was introduced by Pfanner [8].Through a comparison of the dissipative energy the fatigue damage state in concrete can be related to a monotonic damage state. Following, the damage state can be determined by a existing damage law for concrete under monotonic loading. If the damage state is calculated, the stiffness degradation can be determined in a common way by reducing the modules of elasticity, equation 2. Subsequently, a non-linear structure analysis can be performed.

$$E_c^{fat} = (1 - D^{fat}) \cdot E_c^{o} \qquad (2)$$

In figure 2 the damage evolution for several fatigue loading are illustrated. It is in evidence, the non-linear material behaviour of concrete can be very well reproduced by the established fatigue model and the computed fatigue damage values are in good conformity with experimental results. The fatigue model could be used for compression as well as tension fatigue loading. Consequently, there is a mechanical constitutive damage model for calculating damage evolution in concrete under fatigue loading.

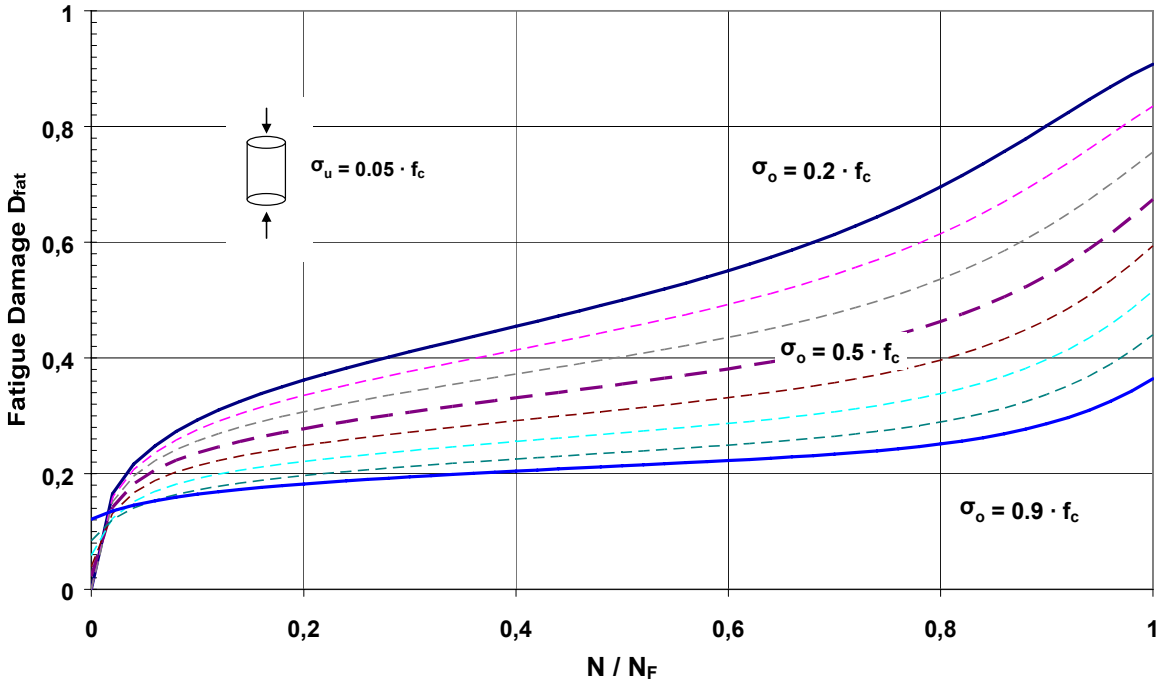

Figure 2: Fatigue damage evolution under constant – amplitude loading

In general, constructions for WEC are permanent subjected to different load levels and a high number of load changes during their life cycle. Therefore, at the institute of concrete construction we have started to extend the introduced fatigue model for application by multi-stage fatigue loading [7]. Figure 3 illustrated first researched results for a simplified two stage fatigue process estimating with the extended fatigue model. You can recognize that the order of load stages obviously affects the resulting fatigue process. For example, series 1, started with a lower amplitude and followed by a higher one, reduces the fatigue life compared with the linear Palmgren-Miner assumption. But a load order in the opposite direction, series 2, leads to an increasing of the fatigue life. These calculated effects agree in principle with testing results available in literature. But further theoretical and experimental investigations are necessary for validating this extended fatigue approach for multistage fatigue loading.

First numerical results of a simplified investigation for a pre-stressed concrete tower of a 5-MW-WEC subjected to multi-stage fatigue loading are illustrated in figure 4. The stress changes and the damage state due to the fatigue process could be simulated and determined respectively. The computed maximum damage state was much more less magnitude compared with the linear accumulation law by Palmgren and Miner.

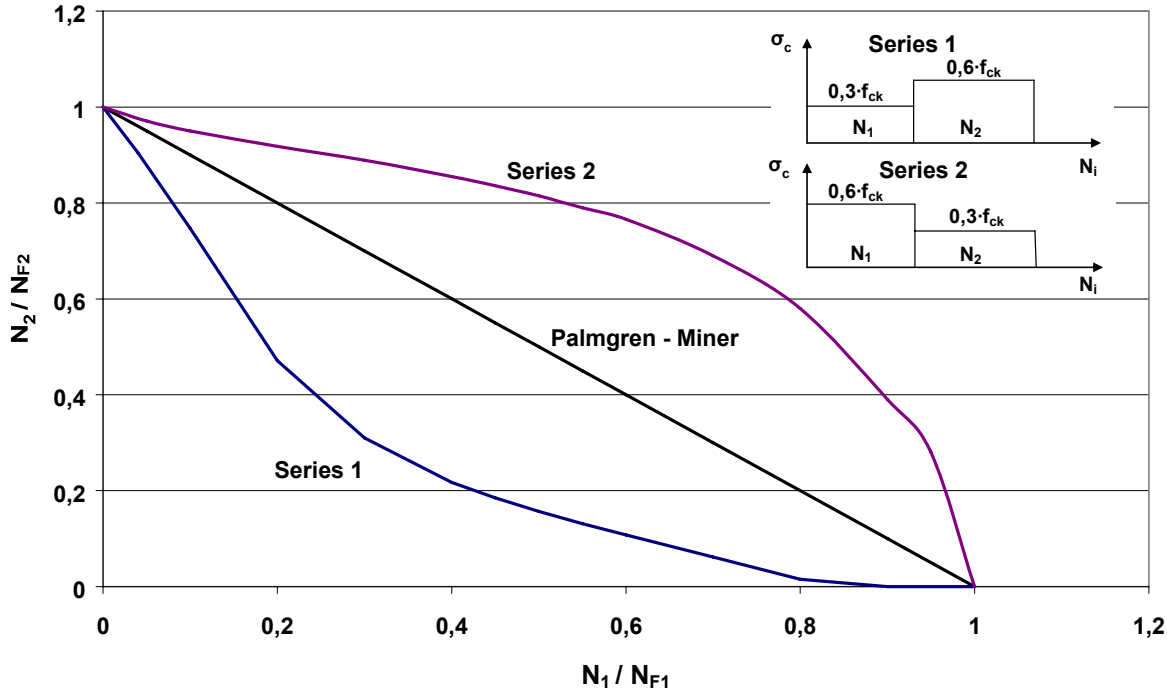

Figure 3: Computed two – stage fatigue process

Number of load cycles: $N = 10^9$

Fatigue damage: $D^{fat} = 0,1$

Elasticity modulus: $E_c^{fat} = (1 - 0,1) \cdot E_c^o$

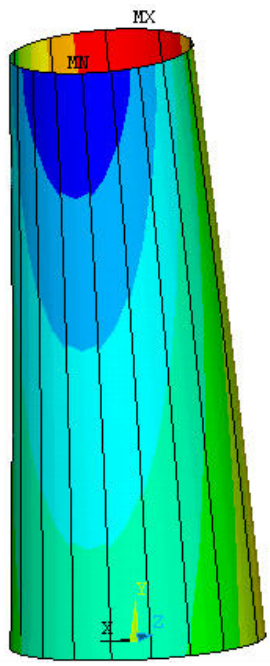

Figure 4: Preliminary damage analysis of a pre-stressed concrete tower for a 5 MW-WEC

3 Multiaxial fatigue loading

In many cases, concrete constructions for WEC are not only stressed by uniaxial loading. Especially at spatial shell structures but also in connecting zones for load transfers from steel adapters to concrete components as well as the leading-in of highly concentrated loads, figure 5 and figure 6, often lateral simultaneous pressure or tension loading occur reducing or increasing the effective fatigue strength [9].

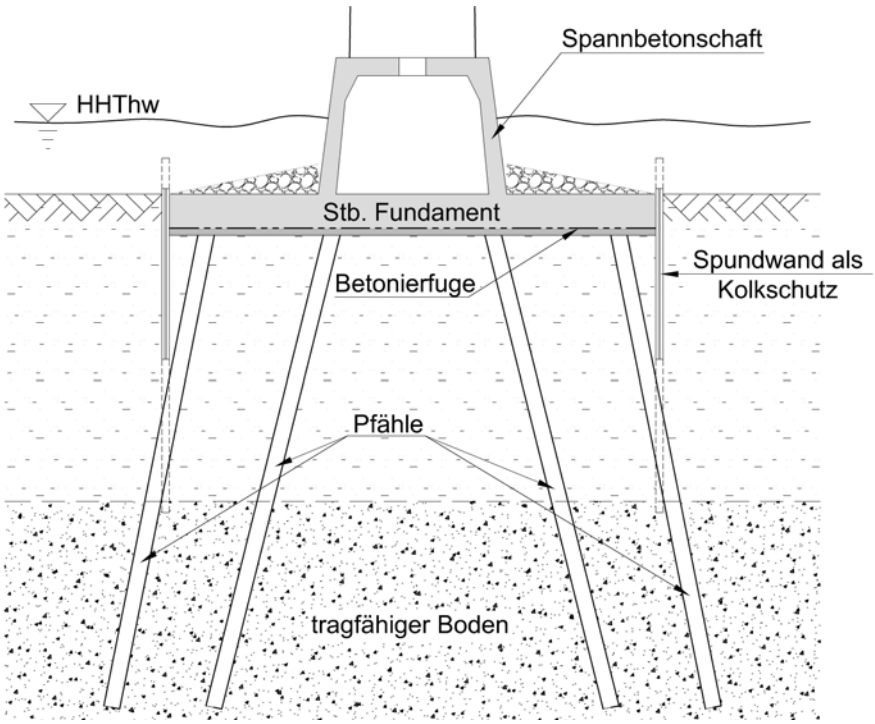

Bild 5: Pre-stressed concrete shank with piled foundation for multi megawatts WEC, Design©: G + S Planungsgesellschaft mbH , Hamburg

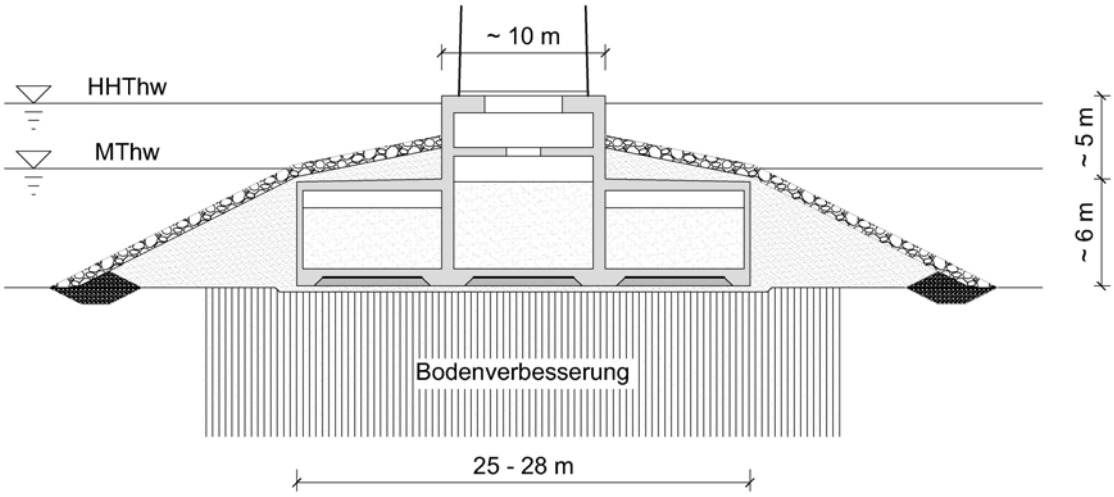

Bild 6: Floatable concrete gravity foundation Design: ©: G + S Planungsgesellschaft mbH, Hamburg

It is getting more complicated if a high performance concrete framework is analysed, figure 6, since in the central concrete joint multiaxial fatigue loading occurs and there are no design rules to consider the influences of multiaxial loading to the effective fatigue life

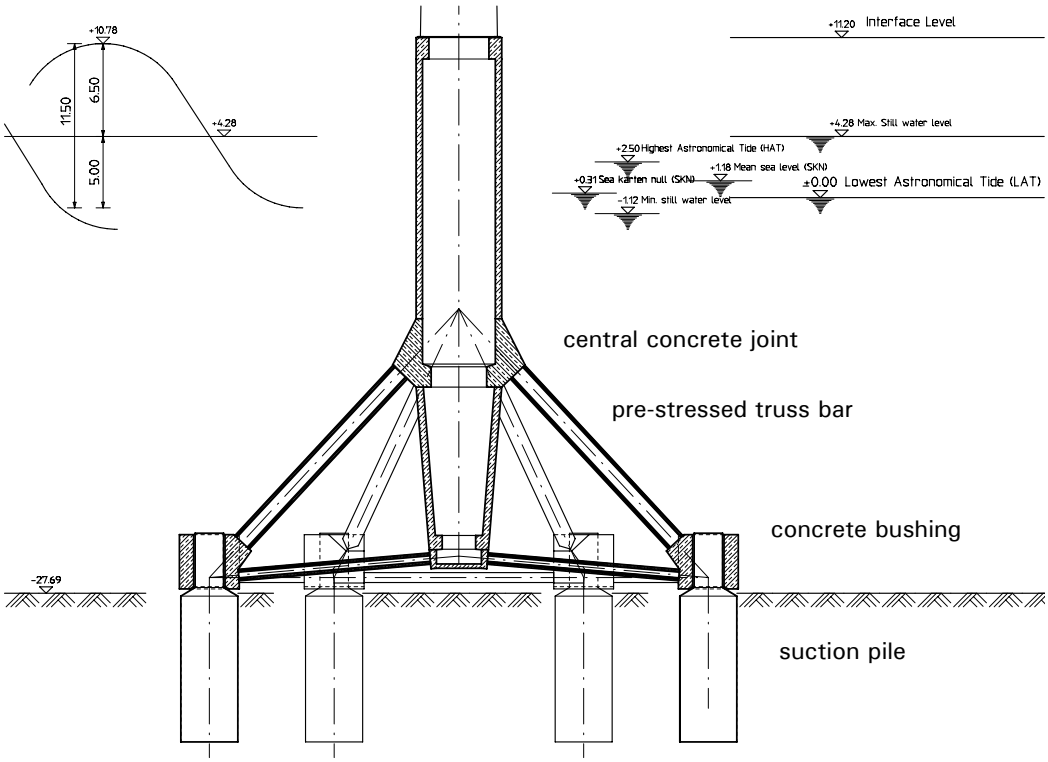

Bild 7: High performance concrete framework for foundation of Offshore-WEC. Design ©: Fa. Oevermann GmbH & Co. KG, Münster, Germany

Only a few measurements data for concrete subjected to biaxial fatigue loading are available in literature. Biaxial compression fatigue test have been performed by Su [10]. The aim of this research was to determine the biaxial compression fatigue strength for concrete under different principial stress ratios. The results are assembled as failure envelopes in figure 8. It is in evidence, that the fatigue strength for all load cycles under biaxial compression is higher than the uniaxial fatigue strength. Furthermore, you can realize a decreasing of the distance between the several failure curves for different total numbers of cycles, which is caused by an embrittlement of concrete behaviour during the fatigue process. For combined loading in the tension – compression or tension – tension area, the fatigue test haven´t been performed and general there are hardly measurements data available in this respect.

In order to define failure curves for this area, we derived different damage parameters for the tensile and compression meridians by the experimental results as shown mentiond before [11]. Following, the damage evolution of the main meridians have been induced in the common five –parameter concrete model by Willam – Warnke [12]. So

failure curves for biaxial fatigue could be computed and calibrated with the measurements data. Such computed failure curves are shown in figure 9. Further experimental test are necessary for validating and verification this approach for the failure curves for biaxial fatigue loading.

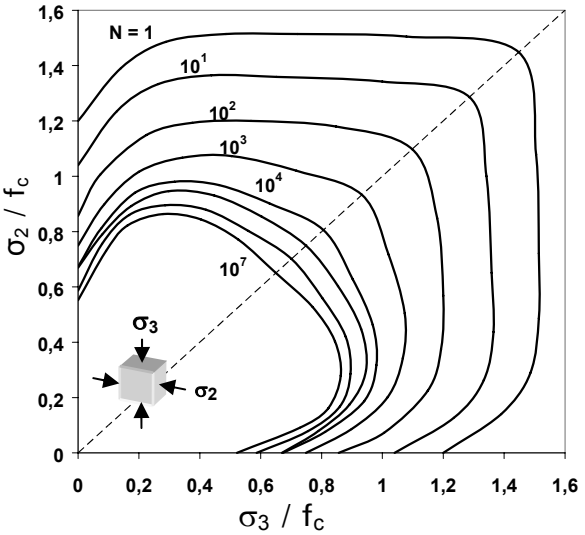

Bild 8: Fatigue test results for concrete in biaxial compression [10]

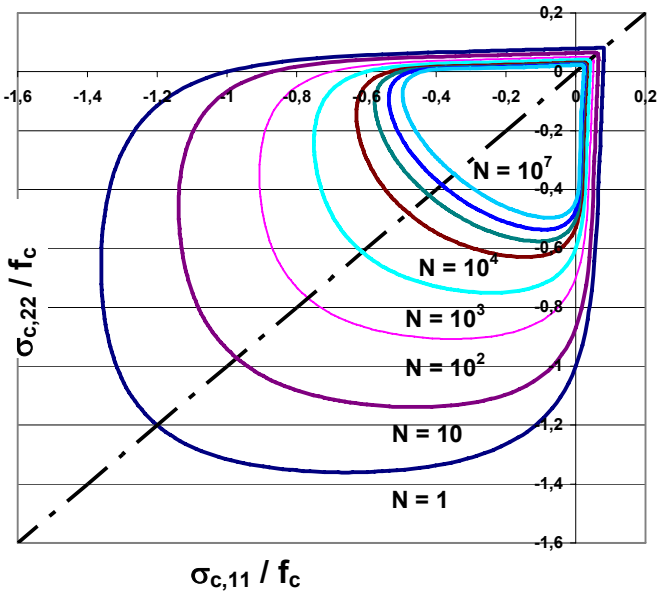

Bild 9: Computed failure curves for biaxial fatigue loading [10]

The computed results permit the assumption, that the positive influence of a lateral pressure to the fatigue strength could be taken into account for a structural analysis for WEC. Corresponding to the proceeding under monotonic loading [4], the biaxial fatigue in compression may be considered by modification of the uniaxial compressive fatigue strength and adjusted Wöhler – curves respectively. But you can also recognize in figure 9, that a simultaneous lateral tension loading leads to a significant decreasing of the uniaxial fatigue strength. This influence should also have been regarded by structural analyses and could be essential for the fatigue life of the structures.

Based on the introduced proceeding anisotropic failure surfaces for different total numbers of cycles have been computed [11]. So fracture surfaces of plain concrete under multiaxial fatigue loading could be determined. The resulted boundary curves are shown in figure 10. Actually, an external algorithm is developed and associated with a nonlinear finite element program. The calculated damage state will be transferred to the concrete plasticity damage model of the FEM-Program during the nonlinear processing. Therefore, the damage evolution of concrete constructions for the foundation of OWEC subjected to multiaxial fatigue loading will be computed.

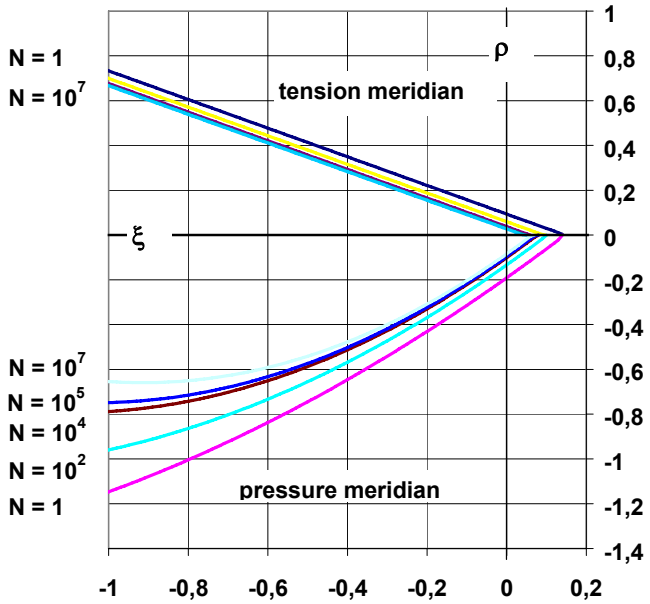

Bild 10: Boundary curves of multiaxial fatigue damage (in the main meridian section)

4 Conclusion and further research

- The fatigue design rules for concrete could lead to unsafe or uneconomical structures for Wind Energy Converters.
- A new fatigue damage approach based on the regard of fracture energy could realistically compute the damage evolution in concrete and could be extended for multi-stage fatigue loading.
- Derived from measurement data for biaxial fatigue tests, damage parameter could be developed for considering multiaxial fatigue loading and should be associated with a FEM-Program.
- Purpose: Modification of the design rules for concrete construction of WEC in order to consider the influence of multiaxial loading.

Acknowledgement

The authors would like to thank ForWind, Center for Wind Energy Research, and the "Deutsches Institut für Bautechnik (DIBt)" for the partly financial support of this research work.

Literature

[1] Grünberg, J.; Göhlmann, J.: Zum Ermüdungsnachweis von Windenergieanlagen in Spannbetonbauweise. VDI Tagung: Windkraftanlagen – Sicherheit und Zuverlässigkeit. Nov. 2004. Darmstadt.

[2] Grünberg, J.; Göhlmann, J.: Concrete Shell Structures for Wind Energy Converters subjected to multiaxial fatigue loading. 5th International Conference on Computation of Shell and Spatial Structures. Salzburg, Austria. June, 2005.

[3] Richtlinie Windenergieanlagen. Einwirkungen und Standsicherheits-nachweise für Turm und Gründung. Deutsches Institut für Bautechnik (DIBt). Fassung März 2004

[4] Comité Euro – International du Béton: CEB – FIP Model Code 90. Bulletin d'Information No. 213/214, Final Draft, Lausanne, July 1993

[5] Design of Offshore Wind Turbine Structures. Det Norske Veritas Offshore Standard, DNV-OS-J101, June 2004.

[6] Offshore Concrete Structures. Det Norske Veritas Offshore Standard, DNV-OS-502, July 2004.

[7] Grünberg, J.; Göhlmann, J.: Schädigungen im Beton unter Ermüdungsbeanspruchungen. Erneuerbare Energien, 14. Jahrg., Ausgabe 12/2004 und 01/2005.

[8] Pfanner, D.: Zur Degradation von Stahlbetonbauteilen unter Ermüdungsbeanspruchung. Konstruktiven Ingenieurbau. Ruhr-Universität Bochum. VDI Verlag GmbH, 2003

[9] Grünberg, J.; Funke, G.; Stavesand, J.; Göhlmann, J.: Fernmeldetürme und Windenergieanlagen in Massivbauweise. Beitrag im Beton-Kalender 2006. Ernst & Sohn Verlag.

[10] Su, E.C.M.; Hsu, T.T.C.: Biaxial Compression Fatigue and Discontinuity of Concrete. ACI Material Journal, Vol. 85, No. 3, May - June(1988), pp. 178-188

[11] Grünberg, J.; Göhlmann, J.: Versagensmodelle für Beton unter monotoner Beanspruchung und Ermüdung. Der Bauingenieur. Springer VDI Verlag März 2005.

[12] Willam, K.J.; Warnke, E.P.: Constitutive model for triaxial behaviour of concrete. Vol. 19, ISMES, Bergamo, Italy, p. 174 (1975).