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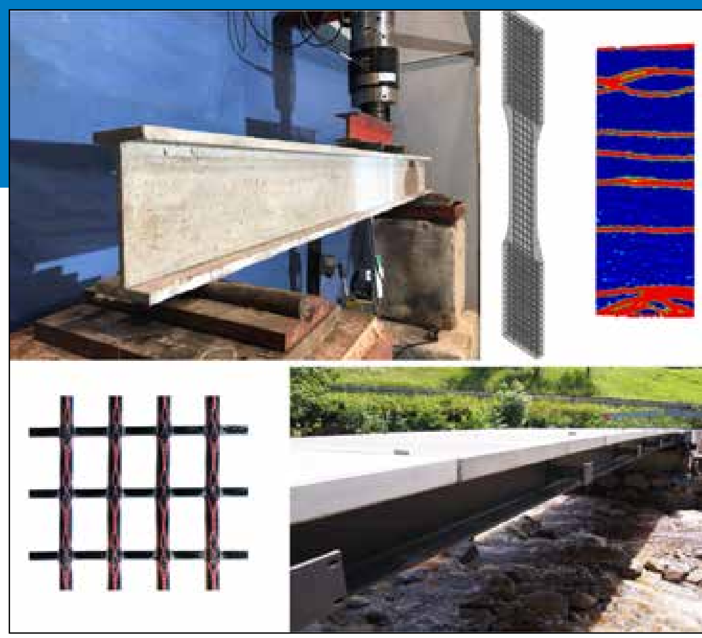

# Materials, Analysis, Structural Design and Applications of Textile Reinforced Concrete/Fabric Reinforced Cementitious Matrix

SP-345

Editors:
Barzin Mobasher and Flávio de Andrade Silva

American Concrete Institute
*Always advancing*

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# PREFACE

## Materials, Analysis, Structural Design and Applications of Textile Reinforced Concrete/Fabric Reinforced Cementitious Matrix

Several state-of-the-art sessions on textile-reinforced concrete/fabric-reinforced cementitious matrix (TRC/FRCM) were organized by ACI Committee 549 in collaboration with RILEM TC MCC during the ACI Fall 2019 Convention in Cincinnati, OH, and the ACI Virtual Technical Presentations in June 2020. The forum provided a unique opportunity to collect information and present knowledge in the field of TRC and FRCM as sustainable construction materials. The term TRC is typically used for new construction applications whereas the term FRCM refers to the repair applications of existing concrete and masonry. Both methods use a textile mesh as reinforcement and a cementitious-based matrix component and, due to high tensile and flexural strength and ductility, can be used to support structural loads. The technical sessions aimed to promote the technology, and document and develop recommendations for testing, design, and analysis, as well as to showcase the key features of these ductile and strong cement composite systems. New methods for characterization of key parameters were presented, and the results were collected towards the development of technical and state-of-the-art papers. Textile types include polymer-based (low and high stiffness), glass, natural, basalt, carbon, steel, and hybrid, whereas the matrix can include cementitious, geopolymers, and lightweight matrix (aggregates). Additives such as short fibers, fillers, and nanomaterials were also considered.

The sessions were attended by researchers, designers, students, and participants from the construction and fiber industries. The presence of people with different expertise and from different regions of the world provided a unique opportunity to share knowledge and promote collaborative efforts. The experience of an online technical forum was a success and may be used for future opportunities.

The workshop technical sessions chairs sincerely thank the ACI staff for doing a wonderful job in organizing the virtual sessions and ACI TC 549 and Rilem TC MCC for the collaboration.

August 2020
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# CARBON REINFORCED CONCRETE UNDER CYCLIC TENSILE LOADING

Arne Spelter, Juliane Wagner, Manfred Curbach and Josef Hegger

**Synopsis:** Carbon reinforced concrete (CRC) is a material composed of a high-performance concrete and a carbon reinforcement (textile grids, lamellas, rods). Composite materials with reinforcements of other fiber materials are called textile reinforced concrete (TRC). The investigations of CRC started more than 20 years ago and the continuous development as well as research findings have opened many fields of application. Today, the use of CRC includes the strengthening of reinforced concrete elements as well as the realization of new elements such as facades, shells and even bridges.

Some of these structures require knowledge of the fatigue behavior due to cyclic loading (e. g. bridges). In a collaborative project of the Institute of Structural Concrete of the RWTH Aachen University and the Institute of Concrete Structures of the TU Dresden, the uniaxial tensile fatigue behavior of two carbon textile reinforcement types was systematically investigated. The specimens were subjected up to 107 loading cycles and stress ranges up to 261 ksi (1,800 MPa). The influence of the maximum load and amplitude were investigated as well as fatigue curves for these two reinforcement types derived.

**Keywords:** Carbon reinforced concrete (CRC), cyclic loading, fatigue curve, S-N curve, tensile fatigue, textile reinforced concrete (TRC)

**Author's Biographies:**

**Arne Spelter** is a research associate at the Institute of Structural Concrete at the RWTH Aachen University, Germany. He received his BS and MS from the RWTH Aachen University in 2014 and 2016. Within the scope of his research work he deals with the static and dynamic long-term behavior of non-metallic reinforcements.

**Juliane Wagner** is a research associate at the Institute of Concrete Structures, Technische Universität (TU) Dresden, Germany. She received her Dipl.-Ing. degree from TU Dresden in 2015. Her research interests include material behavior of textile reinforced concrete under quasi-static and cyclic load.

ACI member **Manfred Curbach** is the director of the Institute of Concrete Structures, TU Dresden. He studied at the TU Dortmund University until 1982 and received his doctoral degree in 1987 from Karlsruhe University, Germany. Manfred Curbach is university professor since 1994. His research interests include e.g. the mechanical behavior of concrete and textile reinforced concrete under multiaxial, dynamical or impact loading, as well as the repair and strengthening of old concrete structures with textile reinforced concrete.

**Josef Hegger** is professor of the Institute of Structural Concrete at the RWTH Aachen University since 1993. He is part of several standard committees for the Eurocode 2 – Design of Concrete Structures. In addition, he is a member of several committees of experts of the Deutsches Institut für Bautechnik (DIBt). His research interests include the use of novel reinforcement elements and materials such as carbon in addition to the conventional areas of building and bridge constructions in typical steel reinforced concrete design.

## 1. Introduction

For more than two decades the innovative composite materials textile and carbon reinforced concrete (TRC and CRC), which comprise reinforcements as textile grids, bars, and lamellas, have been investigated. As a result, extensive knowledge about fibers, impregnation materials and the composite material as well as about their testing methods has been gathered [1-13].

The continuous development of non-metallic reinforcements, especially of grids and bars, paved the way for the realization of several structures made of CRC including facades, shells, slab elements and even bridges [14-21]. Recent research projects show, in addition to the already known designs for foot and cycle path bridges, the applicability of the reinforcements for road bridges [22, 23]. Another innovative field of application is the strengthening of existing structures with thin layers of CRC. Especially the strengthening of the shear capacity is interesting for the future regarding the current shear problems in case of bridges [24, 25]. Here, the fatigue behavior is of great importance and requires the examination of the textile reinforcements for fatigue.

Only a few investigations on the fatigue behavior of textile grids are available, e. g. [26-28]. However, these were primarily intended to provide knowledge of the basic applicability under cyclic loading conditions. Wagner and Curbach recently started systematic investigations on the uniaxial tensile fatigue and bond behavior of CRC [3, 4].

To make CRC marketable in Germany, a huge research project 'C³ - Carbon Concrete Composite' was launched. The research project is divided into various subprojects. The subprojects 'C³ V1.2 – Standardization and Approval' as well as 'C³ V2.1 – Long-term Durability' deal with investigations regarding the static and cyclic long-term behavior of carbon reinforcements, which are partly summarized in [1-4, 28].

The main objective of the conducted fatigue investigations is the derivation of stress-cycle-curves, which are known from steel construction as S N curves (fatigue / Woehler curves). The German standard DIN 50100 'Load controlled fatigue testing - Execution and evaluation of cyclic tests at constant load amplitudes on metallic specimens and components' [29] serves as basis for testing and evaluation of the fatigue tests.

The cyclic load as a sinusoidal load-time-function is illustrated in Fig. 1. The terminology is based on [30].

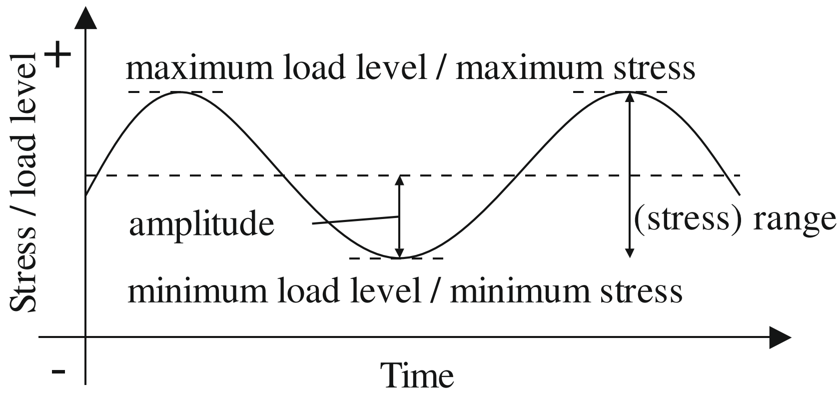


Fig. 1–Terminology used for fatigue (Graphic: Arne Spelter).

For design of cyclically loaded structural elements, S N curves are a mandatory requirement. S N curves are divided into different sections. In case of metallic materials, S N curves are divided into three sections, as shown in Fig. 2. The first section describes the low cycle fatigue up to 104 cycles. The fatigue strength under high cyclic loading describes the second section and runs up to the endurance cycle limit which describes the transition from the finite life to the infinite life at which no further loss of strength occurs. The relevant question is therefore inevitably whether this division also applies to CRC.

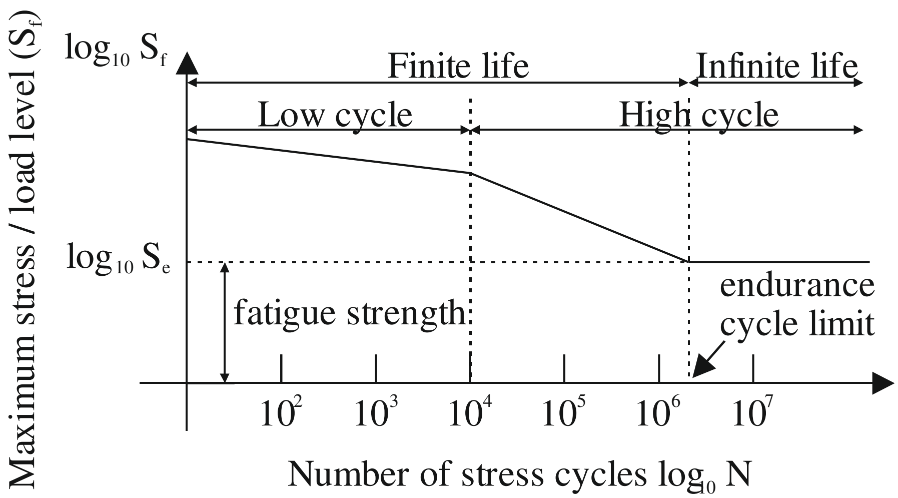


Fig. 2–Example of a typical S N curve (Graphic: Arne Spelter).

The results of uniaxial tensile fatigue tests on CRC specimens with textile grids from the two previously mentioned subprojects are presented in this paper. In the following, a distinction is made between two material combinations (type 1 and type 2). Type 1 consists of an epoxy resin impregnated carbon textile grid in combination with a high-strength concrete. Type 2 is made of a polyacrylate-impregnated carbon textile grid and a sprayable fine-grained concrete. After the examined materials are presented, the differences between the specimens as well as the experimental setups of the two research facilities are outlined. Subsequently, the test results and evaluations for derivation of S N curves for the two material combinations are introduced. Finally, the cyclic material properties are compared.

**RESEARCH SIGNIFICANCE**

The investigations of TRC and CRC elements were often limited to the short-term load-bearing behavior. However, the extended application possibilities lead to open questions concerning the static and cyclic long-term strength of the textile reinforcements so that creep and fatigue, is increasingly becoming focus of today's material investigations. Since S N curves for textile reinforcements are required for the design of TRC and CRC structures or reinforced concrete structures strengthened with TRC / CRC, the presented investigations in this paper are very important for the broad application of this innovative composite material.

## EXPERIMENTAL INVESTIGATION

The fatigue behavior of two material combinations (type 1 and type 2) with carbon textile grids was systematically investigated. For this purpose, first static reference tests were carried out to determine the stress levels for the fatigue tests (maximum and minimum load / medium load and amplitude). In the following, the materials, the test specimens and set ups as well as the test program is explained. The results of the experimental investigations are published in [18].

### Materials

The carbon reinforcement of type 1 is an epoxy resin impregnated textile. In the following it will therefore be referred to 'EP grid'. It was selected as a representative reinforcement for new building components. The cross-sectional area of the symmetrical reinforcement is 0.045 in.² per foot (95 mm² per meter). The characteristics of the warp fiber strand of the symmetrical grid reinforcement are summarized in Table 1.

The textile reinforcement was investigated in combination with a high-strength, self-compacting concrete with a maximum grain-size of 0.2 in. (5 mm) which was developed in another subproject project of C³ [31]. The mix design of the cementitious matrix is for example given in [2]. The concrete compressive and flexural strengths were determined on prisms with dimensions of 6.3 x 1.6 x 1.6 in. (160 x 40 x 40 mm) [32]. At the Institute of Structural Concrete of the RWTH Aachen University, the concrete compressive strength was determined after 28 days to 17,300 psi (120 MPa) and the flexural strength to 2,000 psi (14 MPa) (average values from 21 prims).

Type 2 is made of a polyacrylate-impregnated carbon-reinforcement and a sprayable fine-grained concrete. In the following, the reinforcement is therefore referred to as 'PA grid'. The textile grid has a cross-sectional area of 0.067 in.² per foot (140 mm² per meter) in warp direction and 0.013 in.² per foot (28 mm² per meter) in weft direction. The characteristics of the warp fiber strand of the biaxial grid are shown in Table 1.

The PA grid was investigated in combination with a sprayable fine-grained concrete (maximum grain size 1 mm). The compressive and flexural strength of this concrete were also determined on small concrete prisms. The testing of 12 prisms resulted in an average compressive strength of 12,900 psi (90 MPa) and a flexural strength of 1,200 psi (8.1 MPa) after 28 days. Fig. 3 shows sections of the two investigated carbon textile reinforcements.

| Characteristics | EP-grid (type 1) | PA-grid (type 2) |
|---|---|---|
| Effective cross-sectional area, in.$^2$ (mm$^2$) | 0.0056 (3.6) | 0.0028 (1.8) |
| Axial spacing, in. (mm) | 1.5 (38) | 0.5 (12.7) |
| Mean ultimate tensile strength, ksi (MPa) | 467 (3,200) | 513 (3,500) |
| 5%-quantile ultimate tensile strength, ksi (MPa) | 397 (2,700) | 483 (3,300) |
| Young's modulus of elasticity, ksi (GPa) | 35,530 (240) | 33,650 (230) |
| Mean ultimate elongation, ‰ | 13.2 | 15.3 |

Table 1–Characteristics of the warp fiber strands of the textile grids from [33, 34] according to the methods of [35, 36].