

Improvement of Serviceability and Strength of Textile-Reinforced Concrete Elements with Short Fiber Mixes

by M. Hinzen and W. Brameshuber

Synopsis: Nowadays, thin-walled load bearing structures can be realized using textile-reinforced concrete (Brameshuber and RILEM TC 201-TRC, 2006). The required tensile strength is achieved by embedding several layers of textile. By means of the laminating technique the number of textile layers that can be included into the concrete could be increased. To further increase the first crack strength and the ductility and to optimize the crack development, fine-grained concrete mixtures with short fibers can be used. By simultaneously using different types of short fibers, the positive properties of each fiber may be combined. By a schematic stress-strain curve, the demands on short-fiber mixtures are defined. Within the scope of this study, short fibers made of glass, carbon, aramid, and polyvinyl alcohol are investigated in terms of their ability to fit these requirements. Furthermore, examinations to determine the fiber types and fiber volumes are presented. Finally, two hybrid fiber-reinforced concretes are introduced. On the basis of stress-strain curves of textile-reinforced concrete, the advantages of these fiber mixtures are discussed.

Keywords: ductility; fine-grained concrete; first crack strength; short fibers; textile-reinforced concrete

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CHAPTER 1 - INTRODUCTION

In this paper the main focus is directed on an improved tensile behavior of textile reinforced concrete concerning strength and serviceability. It is the aim to improve the behavior of textile reinforced concrete precisely in the area of the crack formation in terms of an increased first crack strength and a more ductile behavior which means to achieve a distinct multiple cracking with smaller crack widths. The increase in strength and the improved ductility shall be achieved by the use of a ductile fiber reinforced fine grained concrete mix.

The positive properties of steel, glass or polypropylene fibers for the application in concrete have often been emphasized in the literature (Banthia and Soleimani 2005; Butler et al. 2006; Markovic et al. 2003). The more special types of short fibers as carbon (Banthia, 1994; Deng 2005), aramid and polyvinyl alcohol (PVA) (Li et al. 2001; Saito et al. 2003) and especially the interaction of short fibers with glass textiles have so far been considered to a lesser extent. Moreover, due to the special properties of the fine grained concrete mixes developed within the scope of the Collaborative Research Center 532 "Textile reinforced concrete", a re-examination of all fiber types was necessary.

In previous examinations, an increase in the tensile strength of the fine grained concrete as well as a more ductile behavior after the first crack of the matrix due to single short fiber types could be verified (Hinzen and Brameshuber 2006, 2007). The present paper deals with the combination of short fibers and the interaction with the glass textile of the textile reinforced concrete. At first, the general tensile load bearing behavior of textile reinforced concrete with additional short fiber reinforcement is schematically depicted. After specification of the short fiber requirements, different fiber types are assessed regarding their suitability and suitable volume contents are determined experimentally. Finally, the improved bearing behavior of the textile reinforced concrete is presented for two fiber combinations.

CHAPTER 2 – TARGET TENSILE LOAD BEARING BEHAVIOR

It is the target of the investigations to increase the first crack load of the textile reinforced concrete and to render the process of the crack formation more ductile. Fig. 2.1 schematically depicts the behavior of conventional textile reinforced concrete. After the first crack of the matrix (part I), tensile specimens feature a crack formation phase with small increases in load and high strains (part IIa). Having been completely transferred to the textile, the load is increased until the textile fails (part IIb). Likewise Fig 2.1 schematically shows the target stress-strain curve of textile reinforced concrete with additional short fiber reinforcement. The first part F1 describes the contribution of the short fibers to a higher first crack load of the concrete. Part F2 is characterized by a strain hardening behavior with initial crack formation. During the phase of crack formation the short fibers help to bridge the cracks and improve the crack pattern. The stiffness and the load level as compared to that of mere textile reinforced concrete may be increased by the effective increase in the reinforcement ratio. The transition F2/F3 describes the maximum contribution of the short fibers. As soon as the initial bond of the fibers changes into a friction bond or the short fibers break the load-bearing capacity of the short fibers is reduced and the stiffness decreases. The short fibers are pulled out and the gradient of the stress-strain curve approaches the original load bearing behavior of the textiles. In previous investigations (Hinzen and Brameshuber 2007) it turned out, however, that before the transition from F2 to F3 a failure of the glass textile occurs when high-strength short fibers with a good matrix bond are used. In this case, the addition of short fibers leads to an increased load level covering the entire gradient of the stress-strain curve.

It is the aim to supplement the conventional load bearing behavior of textile reinforced concrete by the two parts I and II. As both these parts place different demands on short fibers, the combination of fibers of different materials, sizes and shapes with different functions seems advantageous. In many cases, micro-fibers are combined with

macro-fibers. Both fiber types provide reinforcement at different fracture levels and may complement each other. Micro-fibers are capable of increasing the first crack stress of the concrete by reducing and delaying the micro-crack formation. After the formation of a first macro-crack the macro-fibers may allow a further increase in load bridging the cracks (Banthia, and Soleimani 2005; Lawler et al. 2002). Hence, the interaction between micro-fibers and macro-fibers mostly leads to an improvement of strength and ductility. Therefore, in a first step different investigations are reverted to in order to obtain suitable short fiber types and volumes for each of the presented parts of the stress-strain curve.

CHAPTER 3 – EXPERIMENTAL PROGRAM

3.1 – Materials, mixes and specimens

The fine grained concrete mix used for the short fiber reinforced concrete is based on a standard mix developed in the Collaborative Research Center 532 (Brameshuber and Brockmann 2001). Basically, the mixes feature a very flowable consistency which is made possible by limiting the maximum grain size to 0.6 mm ($2.362 \cdot 10^{-2}$ in.), a high binder content as well as different pozzolanic additives and superplasticizers. In the basic mix applied here, the binder content was further increased to yield a better workability and the content of silica fume was increased to improve the contact area between fiber and matrix. The mix proportions of the basic mix FC without fibers are shown in Table 3.1.

As a result of previous examinations (Hinzen and Brameshuber 2006), the number of short fiber types to be examined could be reduced considerably. In preliminary bending tests it became obvious that carbon fibers can very effectively be applied to increase the first crack load. Furthermore, water dispersible glass fibers led to considerable improvements in terms of first crack strength and crack development. In the range of crack bridging short fibers, PVA fibers are promising due to their good chemical bond to the matrix and relatively high tensile strength. Additionally, aramid and non-water dispersible glass fibers were included to the examinations. A survey of the fibers applied here is given in Table 3.2. As textile reinforcement, a bi-directional alkali resistant glass textile with a cross sectional area of $71.65 \text{ mm}^2/\text{m}$ ($4.724 \text{ in.}^2/\text{ft}$) in the longitudinal direction was applied (see Fig. 3.1A).

Within the framework of this investigation tensile tests were conducted on dumbbell specimens (see Fig. 3.1B) with a cross sectional area of $10 \times 60 \text{ mm}^2$ ($0.394 \times 2.362 \text{ in.}^2$) and a length of 500 mm (19.685 in.). However, for the tensile load bearing behavior in Fig. 5.2, similar specimens with a cross sectional area of $10 \times 100 \text{ mm}^2$ ($0.394 \times 3.94 \text{ in.}^2$) and a length of 1000 mm (39.37 in.) had to be applied. 3-point-bending tests were carried out on flat prisms with the dimensions of $40 \times 20 \times 160 \text{ mm}^3$ ($1.574 \times 0.787 \times 6.299 \text{ in.}^3$) and a span of 100 mm (3.94 in.).

3.2 – Production and execution of the test

All mixes were mixed in a mortar mixer for five minutes. For the mixes containing short fibers, the short fibers were stirred in during a mixing break. All tensile specimens were produced horizontally. For the specimens produced without textiles, the mixes containing short fibers were cast into the formwork and properly screeded. Specimens containing textiles were produced with the so-called laminating technique. Here, layers of fine-grained concrete and textile are alternately rolled into the formwork until the requested amount of layers is reached. Two layers of textile were used for the specimens examined here which corresponds to a reinforcement content of $143 \text{ mm}^2/\text{m}$ ($9.448 \text{ in.}^2/\text{ft}$) in the cross section. All test specimens were cured at a temperature of 20°C (68°F) and a relative humidity of 95 % for 24 hours. Afterwards, the tensile specimens were sealed and stored for 26 days at 20°C (68°F). One day before testing, the specimens were prepared and stored at 20°C (68°F) and 65 % RH. The flat prisms were stored under water until testing. The tensile tests were carried out on a universal testing machine controlled by cross-head displacement at a rate of 0.5 mm/min ($1.969 \cdot 10^{-2} \text{ in./min}$). The uniaxial load was applied in the waist shaped area of the test specimens. The force was measured by a load cell and the elongation by one inductive gauge on each side.

CHAPTER 4 – SELECTION OF FIBER TYPES

4.1 – First crack strength

To investigate the influence of different short fiber types on the first crack strength four short fiber mixes consisting

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of the basic mix and the respective short fiber type were tested. With the exception of the carbon fibers, a fiber content of 2 % by volume was chosen for comparison. For reasons of workability, the carbon fiber content had to be reduced. A content of about 0.6 % by volume was determined in preliminary tests and results in a workability comparable to that of the 2 % mixes. Tensile specimens were produced of all short fiber concretes. One stress-strain curve of each fiber type is exemplarily shown in Fig. 4.1. When evaluating the first crack load it can be assumed that two layers of AR-glass textile do not increase the first crack load of the concrete (Jesse, 2004). Therefore, an additional stress-strain curve for a specimen with only two layers of AR-glass serves as reference curve.

As the tensile specimens were manufactured with the laminating technique described above, the surface structures of the specimens on the formwork side are not identical to those on the casting side. This may lead to irregular shrinkage deformations which were also observed by Jesse, 2004. Therefore, the specimens were not perfectly straight before the test which resulted in a reduction of the absolute first crack strengths. This influence of the different manufacturing techniques will be subject of further investigations.

If only the increase of the first crack load is desired this goal can be achieved just by adding short fibers. Whereas the addition of aramid and PVA fibers leads only to a minor rise, the first crack load is considerably increased by the addition of carbon and water dispersible glass fibers. The carbon fibers used are available in different lengths. Fibers with a length of 12 mm (0.472 in.) proved to be unsuited. To find out which carbon fiber length had the best strength-improving properties, bending tests on flat prisms (40 x 20 x 160 mm³) (1.574 x 0.787 x 6.299 in.³) were conducted. In doing so 3 mm (0.118 in.) as well as 6 mm (0.236 in.) long carbon fibers in different fiber contents were examined. To document the effects on the workability, the spread of the fresh concretes was determined additionally. The results are depicted in Fig 4.2. The diagram comprises the flexural strength as well as the workability as functions of the fiber volume for both fiber lengths. It becomes obvious that the flexural strength can not be increased as of a fiber content of 0.6 % by vol. The reason is the decreasing workability and the inherent higher introduction of air into the matrix. Furthermore, it becomes evident that, at a slightly better workability, the 3 mm (0.118 in.) long carbon fibers tend to lead to higher strengths. The tests served to select the carbon fiber length considering workability and strength. Up to now water dispersible glass fibers were only used at a length of 6 mm (0.236 in.). Examinations regarding the influence of the glass fiber length will be carried out shortly.

4.2 – Post-cracking behavior

With regard to the combination of short fibers, in this chapter short fibers shall be considered which are activated after the first crack and feature good crack-bridging properties. Based on the target tensile load bearing behavior shown in Fig 2.1, at first the requirements on these short fibers are phrased:

- **Maintenance of the load level after the first crack**
The short fibers presented in chapter 3.1 increase the first crack load. This places high demands on the fiber-matrix bond of the crack-bridging fibers. The fibers must be capable of absorbing the increased energy set free at the crack without an unstable load decrease occurring in the tensile test. This calls for a high tensile strength, a high stiffness and a good bond to the matrix.
- **Formation of a fine crack pattern**
At the simultaneous application of textiles and short fibers a tension stiffening behavior of the total system is normally ensured by the textile. The wrong fiber selection may, however, especially at high first crack loads lead to a coarse crack pattern with large crack spacings and crack widths. Therefore, the fibers used must feature a good crack-bridging effect. To this end a high stiffness to minimize the crack widths and a good bond to the matrix to minimize the crack spacings are necessary.
- **Stiffness of the total system**
The combination of textiles and short fibers may lead to an altogether stiffer stress-strain behavior because of the increased reinforcement ratio. This requires a good initial bond between matrix and fiber (see Part II, Fig 2.1). It is important as well that the short fibers feature a subcritical fiber length. They shall not suddenly fail but be pulled out of the matrix when the initial bond fails.

It results from the requirements mentioned that the crack-bridging short fibers must feature a high stiffness, a high Young's modulus as well as a sufficient bond to the matrix. Therefore, of all short fiber types hitherto examined, the

selection is restricted to aramid fibers (A), non-water-dispersible glass fibers (G2) and PVA fibers (P). Steel fibers are not intended for the application in textile reinforced concrete. To assess the post-cracking behavior of the respective fiber concretes the stress-deflection curves of flat prisms were determined in a preliminary test. The volume content of the fibers amounts to 2 % by vol. The results are depicted in Fig. 4.3. It is obvious that the aramid fibers are superior to the glass - and PVA fibers regarding their strain hardening and fiber pull-out behavior. Moreover, the aramid fibers which are provided with an alkali-resistant coating have a relatively low water demand. Hence, first of all the aramid fibers are further investigated for the application as crack-bridging fibers. Investigations with PVA fibers will be carried out in the near future.

CHAPTER 5 – COMBINATION OF SHORT FIBERS

For an increase in the first crack strength the 3 mm (0.118 in.) carbon fibers as well as the water dispersible glass fibers were chosen in chapter 4.1. For bridging the macro-cracks the aramid fibers seem most suitable. The result are two short fiber combinations consisting of glass and aramid fibers as well as of carbon and aramid fibers which will be closer examined in the following regarding their fiber volume contents.

When combining short fibers the effects on the workability of the concrete mix has to be taken into account. In consideration of the common water demand, the different fiber types have to be applied in minor quantities each compared to fiber volumes in concretes with only one fiber type. As the short fibers shall be applied mainly in building members under tensile stress, above all the uniaxial tensile strength depending on the fiber content must be clarified. For the glass and carbon fibers uniaxial tensile tests were therefore carried out on the tensile specimens described in chapter 3.1 with varying fiber content. For carbon fibers the fiber content was increased by 0.3 % by vol. For water dispersible glass fibers increase rates of 0.5 % by vol. were chosen because of the slightly better workability. In Fig 5.1 the average tensile strengths of the fiber concretes are illustrated for the different fiber contents. Per data point three specimens were tested. At both fiber types the selected fiber quantities always entailed an abrupt failure of the specimens after the formation of the first crack. Hence, the displayed strengths can be regarded as first crack load of the concrete. In the case of the carbon fibers, the results were similar to Fig. 4.2. It turned out that already very small added quantities lead to a significant increase in the first crack load. Larger quantities lead to no significant increases in the crack load because of the growing deterioration of the mix workability and the resulting trapped air. Therefore, with regard to the common water demand, the carbon fiber content was reduced to 0.5 % by vol. which turned out to be a good compromise between workability and strength. This behavior was not exhibited by the glass fibers. The crack loads of the concrete grew proportionately to the added fiber quantity. As the glass fibers compared to the carbon fibers feature a decisively lower water demand, larger added quantities have a minor influence on the workability and homogeneity of the concrete. Therefore, a content of 1.5 % by vol. was specified for the glass fibers. With the chosen fiber contents the specific surface and thus the water demand of both fiber types are nearly the same.

The fractions of aramid fibers have not been investigated systematically so far. In a first step, the fiber contents were chosen considering the workability of the concrete and static requirements. Former investigations (Hinzen and Brameshuber 2007) showed that the combination of only carbon fibers and textiles furnishes no satisfactory results as the carbon fibers fail in a brittle way at the crack of the matrix and are unable to bridge cracks. To improve the crack-bridging behavior a content of 2 % by vol. was specified for the combination with carbon fibers. Contrary to the carbon fibers, the combination of glass fibers and textiles furnished better results. However, the specimens featured a reduced stiffness after the first crack of the matrix. Altogether, an aramid content of 1 % by vol. was regarded as being sufficient to support the strain hardening behavior.

Thus, the previous considerations result in the following short fiber mixes: FC-0.5C-2A, consisting of 0.5 % by vol. carbon fibers and 2 % by vol. aramid fibers as well as FC-1.5G-1A, consisting of 1.5 % by vol. glass fibers and 1 % by vol. aramid fibers. The compositions of both mixes are compiled in Table 5.1. Fig 5.2 shows the tensile stress-strain curves of textile reinforced concrete with two layers of AR-glass and the respective short fiber mix. Additionally, there is a reference curve with only two layers textile without short fibers. Basically, it is shown that the addition of short fiber combinations fulfills the target phrased in chapter 2. Both presented short fiber concretes lead to a significant increase in the first crack load and to a uniform load transfer to the textile. The formation of a finer crack pattern, which can also be recognized by the undisturbed gradient of the stress-strain curve, entails altogether higher ultimate strains compared to the textile reinforced concrete without short fibers. As implied in chapter 2, the textile fails before the effect of the short fibers is reduced by loss of bond.

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Compared to the results of Fig. 5.1, in the case of the carbon fiber mix, the first crack load is increased once more by the interaction between the aramid fibers and the glass textile and thus slightly exceeds the first crack load of the mix FC-1.5G-1A. Hence, the interaction of carbon and aramid fibers seems to be more advantageous regarding the first crack load. An evaluation of the crack pattern is still pending. Apparently the combination of glass and aramid fibers, however, leads to a better crack formation behavior. In previous investigations the water dispersible glass fibers also yielded the shortest crack spacings of less than 1 mm (Hinzen and Brameshuber 2007). As a result of the better crack formation behavior and the higher ultimate strain as well as the only minor difference at the first crack load, the mix FC-1.5G-1A seems to be better suited for the application in textile reinforced concrete. Furthermore, it features a slightly better workability. Important fresh and hardened concrete properties of the basic fiber mix FC and the mix FC-1.5G-1A are compiled in Table 5.2.

By regarding former results of specimens with only one fiber type (Hinzen and Brameshuber, 2007) it seems that the positive properties of single fiber types can also be combined at textile reinforced concrete. The mostly high water demand of the fiber concretes, however, significantly reduces the workability. Therefore, the improvement of concrete properties and the loss in workability must always be weighed up against each other. These optimizations and in particular the comparison between single and hybrid fiber reinforcement are subject of current research work.

CHAPTER 6 – SUMMARY

The present paper describes the improvement potential of the tensile load bearing behavior of textile reinforced concrete by adding short fiber combinations. In a first step, the general tensile behavior of textile reinforced concrete with short fibers is described by an schematically stress-strain curve. Three parts are introduced: the increased first crack stress (F1), the strain hardening (F2) and the loss of initial bond of the short fibers (F3). In order to improve the first crack stress and the strain-hardening behavior short fiber types and volumes were determined for each part. The highest increase of the first crack stress could be obtained with water dispersible glass fibers (6 mm / 0.236 in.) or carbon fibers (3 mm / 0.118 in.). For both fiber types optimized fiber volumes with regard to strength and workability were determined. To improve the post-cracking behavior aramid fibers seem most suitable. On the basis of the findings obtained, carbon fibers and glass fibers were each combined with aramid fibers to combine the advantages of the respective fiber types. As a result, the first crack stress could be improved by about 40 % with the glass fiber mix and 60 % with the carbon fiber mix. Furthermore, the load transfer from the concrete to the textile is more ductile with both fiber mixes, which also results in finer crack patterns. As a result of the increased multiple crack formation, the short fibers were also still efficient in the areas of high strains. This leads to higher loads and higher ultimate strains. The results demonstrate that the positive properties of the short fibers can be combined. However, due to the limited total fiber content, there will always have to be a distinct adjustment between the improvement potential and the workability of the concrete.

CHAPTER 7 – REFERENCES

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Table 3.1 – Proportions of the basic mixtures FC

Mixture components	Unit	Amount
Cement CEM I 52.5 N	kg/m ³ *	700
Fly ash		150
Silica fume		150
Water		400
Quartz powder		218
Sand		384
Superplasticizer	% by mass of binder content	0.75
Binder content	kg/m ³	1000
w/b ratio	—	0.4

* 1 kg/m³ = 6.2426 · 10⁻² lb/ft³

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Table 3.2 – Short fiber types and properties

Fiber	Type	Dimensions			Young's modulus	Tensile Strength	Density
		L	D	Geometry			
		mm [*]	μm [†]		N/mm ² [‡]		g/cm ³ [§]
A	Aramid	20	12	Straight, strands	73000	3400	1.39
G1	Glass	6	20	Straight, water dispersible	72000	1700	2.68
G2	Glass	12	20	Straight, strands	72000	1700	2.68
C	Carbon	3	7	Straight, water dispersible	238000	3950	1.79
P	PVA	8	40	Straight, water dispersible	42000	1600	1.3

*1 mm = 3.937 · 10⁻² in

†1 μm = 3.937 · 10⁻⁵ in

‡1 N/mm² = 0.14504 ksi

§1 g/cm³ = 62.426 lb/ft³

||Polyvinyl alcohol

Table 5.1 – Fiber cocktail mixtures

Name	Fine-grained concrete	Fiber material	Content in % by vol.
FC-0.5C-2A	Basic mixture (Table 3.1)	Carbon (C)	0.5
FC-1.5G-1A		Aramid (A)	2
		Glass (G1)	1.5
		Aramid (A)	1

Table 5.2 – Mechanical properties of the basic mixture FC and the short fiber mixture FC-1.5G-1A

Concrete properties		Unit	FC	FC-1.5G-1A
Density		kg/m ³ *	2219	1974
Air content		% by vol.	0.8	3.8
Spread (mortar)		mm †	-	177
Compressive strength	7d	N/mm ² ‡	67.1	75.0
	28d		91.1	93.2
Flexural strength	7d	N/mm ²	9.5	25.0
	28d		13.0	23.6
Young's modulus		N/mm ²	25400	24600

*1 kg/m³ = 6.2426 · 10⁻² lb./ft³

†1 mm = 3.937 · 10⁻² in

‡1 N/mm² = 0.14504 ksi

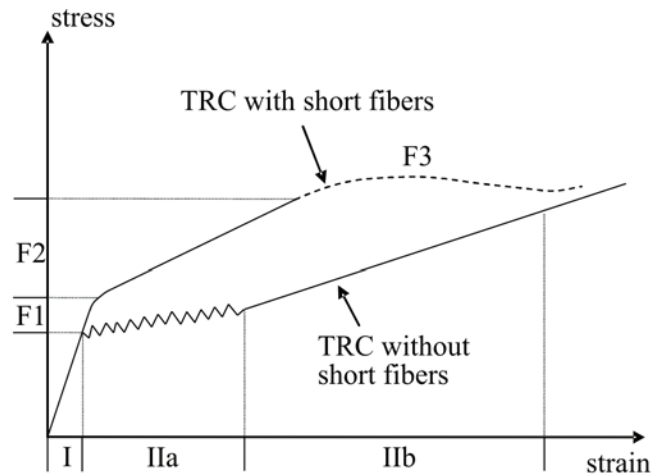


Fig. 2.1 – Schematic stress-strain behavior of textile reinforced concrete with and without short fibers.

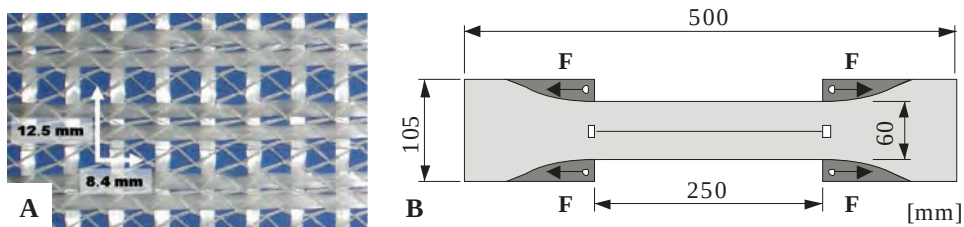


Fig. 3.1 – A) Applied AR-glass fabric manufactured at the Institut für Textiltechnik, RWTH Aachen University, Germany. B) Dumbbell tensile specimen with dimensions. ($1 \text{ mm} = 3.937 \cdot 10^{-2} \text{ in.}$)

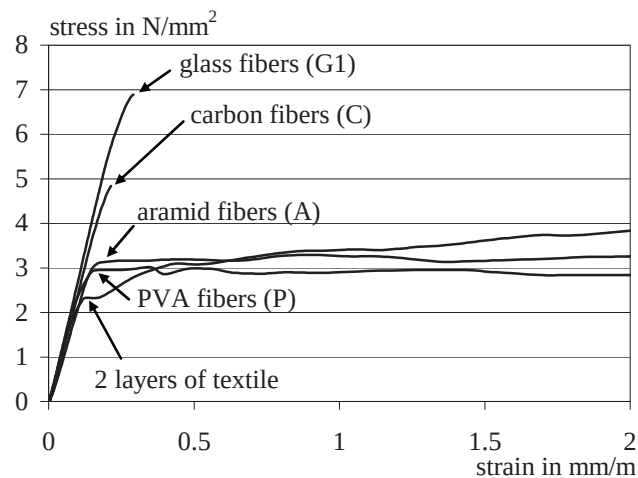


Fig. 4.1 – First crack stresses of specimens with different short fiber types.
($1 \text{ N/mm}^2 = 0.14504 \text{ ksi}$, $1 \text{ mm/m} = 1 \text{ ‰}$)

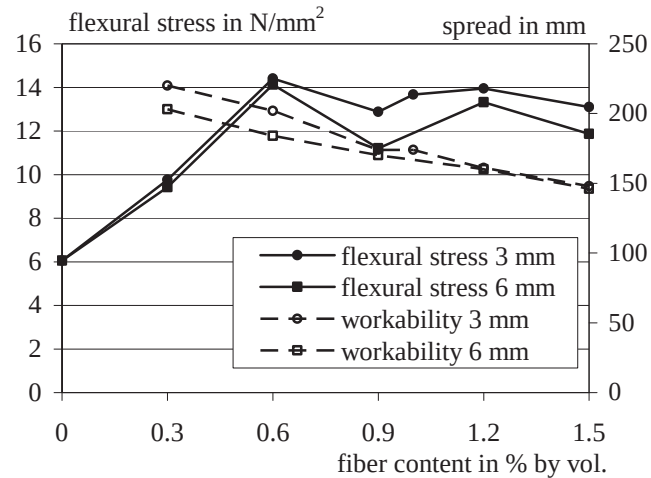


Fig. 4.2 – Influence of fiber content and fiber length on the flexural strength and the workability of concrete containing carbon fibers.
(1 N/mm² = 0.14504 ksi, 1 mm = 3.937 · 10⁻² in.)

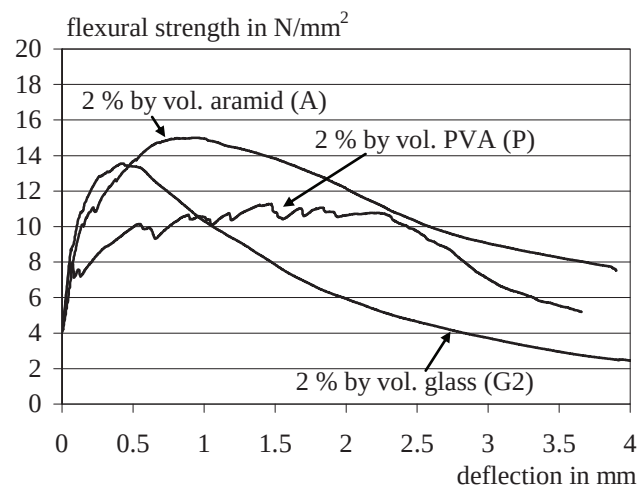


Fig. 4.3 – Post-cracking behavior of flat prisms with different macro fibers in bending tests. (1 N/mm² = 0.14504 ksi, 1 mm = 3.937 · 10⁻² in.)

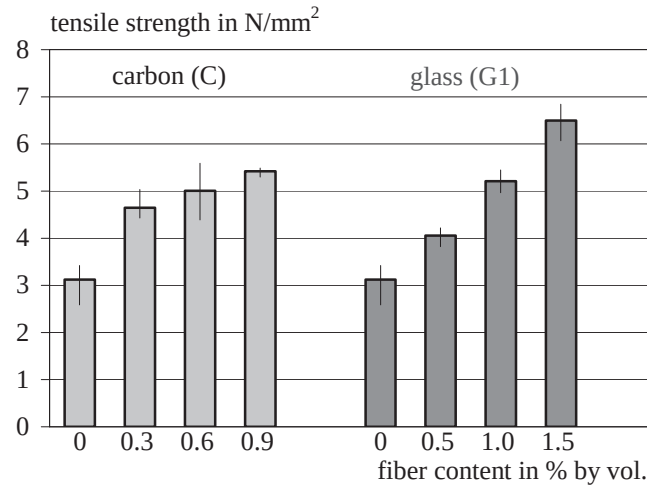


Fig. 5.1 – Influence of the carbon and glass fiber content on the tensile strength.
(1 N/mm² = 0.14504 ksi)

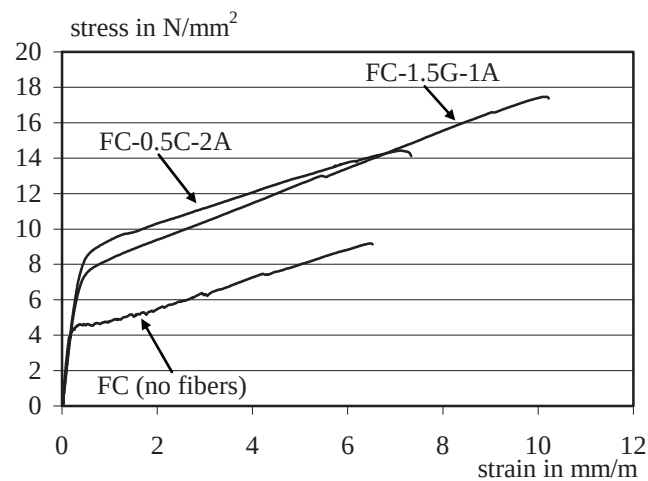


Fig. 5.2 – Stress-strain behavior of textile reinforced concrete with 2 types of short fibers.
(1 N/mm² = 0.14504 ksi, 1 mm/m = 1 ‰)

Textile-Reinforced Concrete for Flexural Strengthening of RC-Structures— Part 1: Structural Behavior and Design Model

by A. Bösche, F. Jesse, R. Ortlepp, S. Weiland, and M. Curbach

Synopsis: The use of technical textiles to reinforce concrete (i.e., textile reinforced concrete [TRC]) extends into entirely new areas of application. The thick concrete covers, as required for steel reinforced concrete, are no longer needed due to the corrosion resistance of textile materials. Slender structural members with thicknesses as small as 10 mm (appr. 4 in.) are possible. Additional characteristic features of textile reinforcement include two-dimensional planar characteristics, as well as ease of deformability and adaptability to complex and curved geometries. This can be exemplified by a pedestrian bridge built of TRC [1, 2, 3]. Various geometric forms, such as slabs, beams, T-beams, shells, and columns can easily be strengthened using TRC [4, 5].

Dimensioning of elements and structures using TRC requires detailed knowledge of the load-bearing behavior of this composite material. Indeed, such behavior resembles that of steel reinforced concrete; however, this behavior is more heavily influenced by the bond between the textile reinforcement and the fine concrete, as well as the bond between filaments within the textile reinforcement [6].

Minimal thicknesses also make it possible to strengthen existing concrete structures using TRC. Such strengthening increases both the ultimate load bearing capacity, as well as the serviceability, of the structure. Experimental results of strengthened slabs and beams, as well as a design model for flexural strengthening, is presented in this paper.

Keywords: bond; fiber; reinforced concrete; strengthening; textile-reinforced concrete

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INTRODUCTION

The development of textile reinforced concrete (TRC) is based on the fundamentals of glass fiber reinforced concrete (GFRC). TRC is a cementitious composite material reinforced by technical textiles of yarns/rovings. These yarns are aligned in the direction of the tensile stresses as is reinforcement in ordinary reinforced concrete (RC) structures. Such alignment leads to an increase in yarn effectiveness and load-carrying capacity compared to that of GFRC and its randomly distributed short fibers. The reduction in the amount of expensive, high-performance fibers needed in TRC (compared to GFRC), in turn, reduces the cost.

In recent years, the need for strengthening and retrofitting of existing structures has increased. Over the course of normal building use, many issues may arise that require the strengthening of RC structures—for example: structural damage; increased loads; design and construction faults; and changes to the system. A variety of methods can be used to increase the load-carrying capacity. The use of textile reinforced concrete can be an ingenious alternative [7, 8, 9] particularly since it is closely related to traditional, established procedures for strengthening (externally bonded carbon fiber reinforced polymers (CFRP), shotcrete, etc.).

Advantageous properties of externally bonded CFRP include, among other things, high tensile strength; low weight; ease of handling; and high corrosive resistance. Disadvantages include high cost; sensitivity to moisture and UV-radiation; low ductility; lack of fire resistance; as well as cross pressure and soaking. Repassivation of uncovered steel reinforcement, as a result of damage, requires additional measures [7].

Shotcrete, which is based on a cementitious matrix, is a suitable rehabilitation method that provides new protection against corrosion for existing reinforcement. Its primary advantage is the repassivation of existing reinforcement, as influenced by the alkaline milieu of a new shotcrete layer absent any sensitivity toward soaking and UV-radiation. Unfortunately, the use of traditional steel reinforcement in combination with shotcrete has several drawbacks. These include the costly production and installation of the strengthening layer(s); enlarged dimensions of the original total cross-section and required concrete covering; and the high dead weight of the additional layer.

The advantages of both externally bonded fiber reinforced polymers (FRP) and shotcrete with steel reinforcement are incorporated in the use of TRC strengthening. The combination of textile reinforcement and concrete results in a composite material with prime qualities—high tensile strength; minimal layer thickness; low weight; high corrosion resistance; and additional corrosion protection for existing concrete reinforcement.

This TRC-strengthening, which is applied as a spray or a laminate, is suitable for nearly every type of force that may act upon it. It is possible to strengthen for bending, shear, torsion, and axial forces. The flexibility of textile reinforcement also makes it possible to strengthen complex and curved geometries such as shell structures and columns. These three criteria must, however, be taken into account in each case in which textile reinforcement is used:

- load-carrying capacity;
- criterion to ensure the minimal amount of reinforcement needed; and
- appropriate anchorage necessary for the TRC layer.

The result, of strengthening reinforced concrete with TRC, is a complex composite structure. Before strengthening can be applied, the surface of the RC-member must be prepared, for example, by sandblasting. The surface must be sufficiently rough so as to ensure that a sufficient bond will form between the existing concrete and the strengthening layer. TRC strengthening is then accomplished by applying alternating layers of fine-grained concrete and textile reinforcement to existing RC-members.

EXPERIMENTAL INVESTIGATIONS

The properties of flexural strengthening with TRC were investigated within an extensive experimental survey. A total of four series, consisting of 38 slabs with 1.80 m (5.9 ft) length; 1.60 m (5.25 ft) effective span; 0.10 m (0.33 ft) thickness; and 0.60 m (2.0 ft) width and seven beams with 4.50 m (13.1 ft) span; 0.30 m (1.0 ft) height; and 0.15 m (0.49 ft) width, was examined. A C20/25 concrete was selected for RC specimens in order to make the tests as realistic and practicable as possible. Specimens were tested using four-point-bending tests (Fig. 1) to study the behavior in mid-span under pure bending and absent any shear. The load was applied using subsequent cycles of increased loading and unloading. During the tests, several parameters—number of textile layers, type of fiber material (AR-glass or carbon), type of anchoring, amount of steel reinforcement, pre-damage—were varied, respectively.

- Two different **types of AR-glass orthogonal structure textiles** were used. Longitudinal reinforcement was positioned in the direction of the load orientation. Transverse reinforcement was 20% of the longitudinal direction (Fig. 2). The textiles used consisted of uncoated, AR-glass fiber yarns with a fineness of 1100 tex (a second generation textile referred to as NWM3-022-00) and 2400 tex (improved third generation textile referred to as NWM4-011-03). The number of textile layers was varied between three and eight layers within each particular series.
- The **type of anchoring** examined can be classified as either slabs with (a) a strengthening layer extending beyond the support line or (b) a strengthening layer ending just prior to the support line. The advantage of situation (a) is that sufficient anchoring of the strengthening layer is ensured. In existing buildings, however, the support areas of the RC-member are not accessible; thus, anchoring must end prior to the support area (i.e., support line) as in scenario (b). Generally, anchoring that terminates immediately prior to the support line (i.e., in front of the support) is sufficient since TRC-layers have a short bond length.
- These investigations were divided into four series to examine the influence of different **steel reinforcement ratios** on achievable load increases. Each series differed in its steel reinforcement content. The following components were examined: un-reinforced concrete components; as well as steel concrete components with respective steel reinforcement ratios of 0.2% (low), 0.34% (medium), and 0.5% (high).
- The influence of the **effective depth** on the achievable load increases brought about by the TRC strengthening layer was also a question to be answered. This is why the series containing a high steel content (i.e., 0.5%) included the analysis of beams (height of 0.30 m [1.0 ft]) in addition to slabs (height of 0.1 m [0.33 ft]).

Reference specimens, without strengthening, were examined within each series, as well.

TEST RESULTS

Load-Deformation-Curves

The results of all bending tests are shown in Table 1. Figure 3 summarizes the achievable load increase for TRC strengthening. The first three digits, within the identification numbers in Fig. 3, indicate the serial number (derived from the percentage of steel reinforcement); the digit before the letter 'L' indicates the number of textile layers,

while the letter that follows the letter “L”, identifies the structural member as either a slab, ‘P’, or a beam, ‘B’. A load increase of the strengthened structures, compared to that of the reference specimens, can be observed in almost all load-deformation-curves.

The stress-strain-curve of the strengthened specimens shows a steeper incline before cracking takes place; furthermore, cracking starts at a considerably higher load level. This is clearly identifiable by the change in the gradient of each load-deformation-curve. Increased stiffness results from an increased moment of inertia of the strengthened specimens. The increased load level at initial cracking can, first, be attributed to the higher concrete tensile strength of the TRC-layer and, second, to the increased section modulus of the strengthened specimens. The section modulus of a slab with a TRC-layer of 8 mm (0.3 in.) thickness (i.e., three layers of textile fabric) is increased by 17%, while the increase of a 12 mm (0.45 in.) TRC-layer (i.e., five layers of textile fabric), amounts to about a 25% increase. Obviously, increased stiffness and delayed cracking are positive features.

Stiffness decreases after initial cracking (Fig. 4); nevertheless, the stiffness of the strengthened specimens is higher compared to the reference specimens. Yielding of steel reinforcement is indicated by an additional decrease in stiffness at a higher load level. Reference specimens show a pronounced yielding plateau with large deformations maintained at a constant load level. The ultimate load of strengthened specimens in each case is followed by rupture of textile reinforcement which is normally characterized by a relatively sudden load decline in the level of the reference specimen.

Generally, in addition to increased load-carrying capacity, overall performance characteristics are positively influenced. The deformations of strengthened specimens are clearly reduced, and an evenly distributed crack pattern is observed at the service-load level. (The service-load level is defined by the ultimate load of the un-strengthened specimen divided by 1.75). The overall form of the load-deformation-curves recurs, in principle, in each series.

Strengthening effect

The test results are summarized in Fig. 3 where moments absorbed by the specimens are illustrated as mean values of like components. These show that, by using textile reinforcement, the ultimate bending capacity can be increased compared to that of an un-strengthened RC reference slab. An increase of the ultimate capacity by a factor of two was possible, but this effect clearly depends on the steel reinforcing ratio and amount of strengthening. The strengthening effect is greater for slabs with lower steel reinforcement ratios, as shown in Figure 3.

Figure 3 also shows that the strengthening effect that is attainable depends on the special material properties of the textiles used. The increase of the ultimate load of slabs strengthened with textile NWM4-011-03 (second generation) is distinctly higher compared to slabs strengthened with textile NWM3-022-00 (third generation).

The increase possible in the ultimate bending capacity is dependent on the amount of steel reinforcement. An already high use of the concrete compressive zone in an un-strengthened state results in a greater effective depth in this zone from TRC strengthening. Consequently, the inner lever arm shrinks. Test results show that the strain in the tensile zone, at ultimate load, is lower compared to an un-strengthened condition. It then follows that the steel and textile should not be used to the fullest extent for high reinforcement ratios due to compression zone initiated failure.

A comparison of slabs and beams with 0.5% steel reinforcement indicated that an increase in the component height and, thereby, the effective depth, positively affects the increase of ultimate bending moment. The decrease in the value of the inner lever arm, resulting from an increase in the concrete compression zone depth, is very small and can be neglected, at least for the specimen size examined in this study. These findings helped to establish a design model for flexural strengthening using TRC layers.

DESIGN MODEL FOR FLEXURAL STRENGTHENING

Basic Assumptions

A design model for flexural strengthening was developed based on generally accepted design methods for RC components. Apart from the tensile force of the steel bar reinforcement in the tension zone, a tensile force of the textile

strengthening layer was added. The development of a model to calculate the flexural load-carrying capacity of textile strengthened members was based on the German DIN 1045-1 standard.

Particular assumptions, based on usual assumptions for calculating bending capacity of RC sections, were necessary prerequisites for this model. These assumptions were:

1. Concrete is assumed to be cracked, i. e., tensile forces are carried by steel and textile reinforcement only. Concrete tensile strength and tension softening are neglected.
2. Bernoulli's hypothesis is applied, for the time being, i. e., strains of concrete, steel, and textile reinforcement form a straight line—the difference in bond behavior of steel reinforcement and textile reinforcement is neglected. There is no slip between steel and concrete, as well as between textile reinforcement and concrete.
3. Material specific stress-strain-curves are used to calculate local stresses from global strain distributions for each component.
4. Ultimate capacity is limited by failure strains—(i) steel tensile failure strain; (ii) textile tensile failure strain; and (iii) concrete compressive failure strain.

The stress-strain-curve used for normal strength concrete slabs with steel reinforcement was taken from the German standard, DIN 1045-1. The material-specific stress-strain-curves for steel and textile reinforcement were determined in separate tests and transformed into idealized stress-strain-curves. Failure strain for textile reinforcement was also derived from separate tensile tests. The situation assumed is illustrated in Fig. 5.

Calculation Procedure

Determining the flexural capacity basically means to attain the balance of inner forces, and this is solved using an iterative procedure. A linear strain distribution was assumed for which the balance between inner and outer moments was given for a specified design moment. Initially, a strain state was chosen for which the strain of the concrete and textile (which is lower than allowable for steel failure strain) were set to the ultimate concrete compressive strain and textile tensile strain, respectively. The steel strain was calculated from the assumed linear strain distribution. The depth of the strengthening layer was assumed to be a layer thickness of 2 mm (0.079 in.) for each individual layer of embedded textile. A final covering consisting of a 2 mm (0.079 in.) fine concrete layer-coat was applied to the top of each specimen.

The stresses that correspond to each respective strain can be calculated given the knowledge of the stress-strain-curves of steel and concrete. Therefore, the cross-sectional area of steel and concrete, as well as the concrete compressive force, steel compressive force, and steel tensile force can be calculated. In this manner, the appropriate textile tensile force can be held within a state of balance with inner forces. In those instances where the required balance between the action moment and internal moment was not able to be reached using the initial, assumed strain condition, then a new strain condition was chosen. Beyond this point, the advantage of the ultimate strain of the textile should be used, and therefore, the concrete strain should be reduced accordingly during iteration.

For components with a high steel reinforcement ratio, failure is introduced through a highly exploited concrete compression zone. In these cases, a re-calculation of the un-strengthened RC cross-section, using a standard RC design model, can show whether or not the compression zone is able to withstand additional loading. If not, strengthening of such cross-sections is not advisable for two reasons. First, the textile is not used economically, and second, the failure must still be introduced through the use of the concrete compression zone. The resulting load-carrying increase that can be attained is low and mainly achieved by the presence of a larger inner lever arm (through the reinforcement layer).

Iterations were complete once the balance between inner and outer stress resultants was reached and the required textile tensile force was attained and held constant. It was then possible to deduce the amount of textile reinforcement required by taking the strain condition into account. The establishment of these relationships was based on three aspects:

- (1) The first fundamental aspect was the stress-strain-relationship of a single yarn from tensile tests; see Fig. 6, [10, 11]. The information obtained resulted in the ultimate strain ϵ_{tu} of the yarn material.

- (2) The second aspect was the stress-strain-relationship of TRC under uniaxial tension; see [6]. The specimens' dimensions were: a length of 500 mm (16.5 in.), a width of 100 mm (3.94 in.), and a thickness of 8 mm (0.32 in.); see Fig. 7. As a result of the tensile tests, stresses (i.e., throughout the cross-sectional fiber area) were plotted in relationship to strains. The strains were obtained at a length of 200 mm (7.9 in.). These strain values could not be used for the stress-strain-relationship of the textile material since the local maximum strains were a determining factor in the calculation as described. The stresses did, however, illustrate the effects of mounting the textile materials (pre-damage) and particular failure mechanisms in TRC. The stress-strain-relationship of the strain member proceeds in three distinct linear sections: the un-cracked state (State I); initial cracking through crack completion (State IIa); and crack completion through and up until failure (State IIb). The resultant strains after complete cracking and the ultimate strength f_{tk} must be derived in order to establish a stress-strain-relationship for a textile.
- (3) The third fundamental aspect was the analysis of the flexural tests performed on strengthened slabs and beams. At a minimum, the ultimate strain of the textile was required, to comply with the ultimate strain of a single yarn. This particular strain proportion was diminished by yet another proportion which has not yet been examined. During this analysis it became apparent that an additional strain proportion was needed before the yarns could be fully activated and engaged. Unfortunately, this strain proportion cannot be described in more detail at this time. It is possible, however, to make the assumption that this particular proportion may be rooted in the tightening of corrugated fibers and the slip between core fibers and outer fibers of the yarn. The core fibers are able to elongate over a substantial length within the “sheath” of edge fibers as a result of bond properties. This phenomenon is comparable to a pre-stressed tendon. The strain proportion needed for this was determined by the bending tests performed since examinations concerning the bond stress-slip-relationship have not yet been completed. A yarn-parallel slope, with a value falling between the two levels of stress and derived from strain member tests, was selected to indicate the stress-strain relationship for textiles.

Figure 8 illustrates the stress-strain-relationship that was found for two types of textile reinforcement. Using these enables calculating the amount of textile reinforcement A_t from textile strain ε_t . This design model was dedicated for components that were affected by bending tension failure; bond failure or shear failure were not included in this particular analysis.

Current stress-strain-relationships of textile materials were determined via mean value approaches. A statistical analysis using characteristic material parameters was not possible given the existing data. In order to conduct such an analysis, material tests using more specimens are necessary. In addition, a partial safety factor must be established for the materials, as well; [12].

Equations for dimensioning

Figure 9 provides an overview of indices used for the: strains; stresses; forces; cross- sections; and reference depths for textiles within strengthened structural members.

Concrete compressive force

The concrete compression force was determined as:

$$F_{cd} = \alpha_R \cdot f_{cd} \cdot b \cdot x$$

This equation was based on the parabolic-rectangular-diagram according to the German DIN 1045-1 standard.

Steel tensile force

The tensile force of steel was determined as follows:

$$F_{sd} = A_s \cdot \varepsilon_s \cdot \frac{f_{yd}}{\varepsilon_{yd}} \quad \text{for} \quad 0 \leq \varepsilon_s \leq \varepsilon_{yd}$$

$$F_{sd} = A_s \cdot \left(\frac{\varepsilon_s - \varepsilon_{yd}}{\varepsilon_{su} - \varepsilon_{yd}} \cdot (f_{td,cal} - f_{yd}) + f_{yd} \right) \quad \text{for} \quad \varepsilon_{yd} < \varepsilon_s \leq \varepsilon_{su}$$

Steel compressive force

Forces located within compression reinforcement members, if available, were computed using the following equation:

$$F_{s2d} = A_{s2} \cdot (\sigma_{s2d} - \sigma_{cd,s2})$$

whereas

$$\sigma_{s2d} = \varepsilon_{s2} \cdot \frac{f_{yd,s2}}{\varepsilon_{yd,s2}} \quad \text{for} \quad \varepsilon_{s2} \leq \varepsilon_{yd,s2}$$

$$\sigma_{s2d} = \frac{\varepsilon_{s2} - \varepsilon_{yd,s2}}{\varepsilon_{su,s2} - \varepsilon_{yd,s2}} \cdot (f_{td,cal,s2} - f_{yd,s2}) + f_{yd,s2} \quad \text{for} \quad \varepsilon_{s2} > \varepsilon_{yd,s2}$$

$$\sigma_{cd,s2} = -f_{cd} \cdot \left(1 - \left(1 - \frac{\varepsilon_{c,s2}}{\varepsilon_{c2}} \right)^n \right) \quad \text{for} \quad \varepsilon_{s2} \geq \varepsilon_{c2}$$

$$\sigma_{cd,s2} = -f_{cd} \quad \text{for} \quad \varepsilon_{s2} < \varepsilon_{c2}$$

The calculation of steel tensile force and steel compressive force is based on the bi-linear stress-strain relationship with a rising second branch of the steel reinforcement based upon the German DIN 1045-1 standard.

Textile tensile force

Tensile force, as a function of the textile strain, was determined based upon the following equations and given the bi-linear stress-strain-curve:

$$F_{td} = \frac{\sigma_{ty}}{\varepsilon_{ty}} \cdot \varepsilon_t \cdot A_t \quad \text{for} \quad 0 \leq \varepsilon_t \leq \varepsilon_{ty}$$

$$F_{td} = \left[m_g \cdot \varepsilon_t + n(\varepsilon_{ty}) \right] \cdot A_t \quad \text{for} \quad \varepsilon_{ty} \leq \varepsilon_t \leq \varepsilon_{tu}$$

This approach is summarized in Fig. 10. The expression $n(\varepsilon_{ty})$, in conjunction with the determination of the textile tensile force, shows the dependence of n on the term ε_{ty} .

Model Verification

In order to accurately verify the model, material parameters of steel (see Table 2) and concrete were determined for each test to ensure that re-calculation most closely resembled reality. Figure 11 illustrates the comparison between calculated and measured ultimate load, for both strengthened and un-strengthened components under this model. Deviations between model calculations and test results fell within an acceptable range, of approximately $\pm 10\%$ which is also an acceptable range for RC structures and standard design models.

CONCLUSIONS

The results presented here show that TRC is a suitable means by which to increase the ultimate load of flexural components. The strengthening effect depends on the particular material properties of the textiles used. Other determining factors are the geometrical surroundings of the component to be reinforced including the existing amount of steel reinforcement and the degree to which the compression zone is used.

Principally, the design model presented is suitable for use in determining the amount of textile reinforcement required. The calculation method is based on parameters from material tests. The model was calibrated for two particular types of textiles, as well as verified by flexural tests of RC slabs that were strengthened using these textiles. The stress-strain-relationships used are not valid for other textiles. Supplementary tests, relative to a variety of input parameters, are necessary before the procedure can be generalized as a design model. Among other things, the bond behavior of the textiles must be examined in more detail as it is significant to the force distribution between steel and textile reinforcement. Furthermore, characteristic values and partial safety factors for textiles need to be determined, as well. Enhanced load-carrying properties resulting from textile modifications must also be investigated.

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NOTATION

Latin capitals

A_s	area of (non-prestressed) longitudinal tensile steel reinforcement
A_{s2}	area of longitudinal compressive steel reinforcement
A_t	area of longitudinal tensile textile reinforcement
$A_{t, erf}$	required area of longitudinal textile reinforcement
F_{cd}	design value for concrete compressive force
F_{sd}	design value for steel tensile force
F_{s2d}	design value for compressive force of steel reinforcement
F_{td}	design value for tensile textile force
$F_{t, erf}$	required tensile textile force
H	horizontal force
M_{Ed}	design value for applied internal bending moment
M_{Rd}	design value for absorbed internal bending moment
$M_{Rd,s}$	design value for absorbed internal bending moment relative to the center of gravity of tensile steel reinforcement
N	tensile force in concrete

Latin lower cases

a	distance between resulting compressive force and outer-most fiber of the compression zone
b	width of member
d	effective depth
d_{s1}	distance between center of gravity of tensile steel reinforcement and outer-most fiber of tension zone of un-strengthened cross-section
d_{s2}	distance between center of gravity of compressive steel reinforcement and outer-most fiber of compression zone
f_{cd}	design compressive strength of concrete
$f_{td, cal}$	design tensile strength of steel reinforcement
$f_{td, cal, s2}$	design tensile strength of tensile steel reinforcement
f_{yd}	design yield strength of steel reinforcement
$f_{yd, s2}$	design yield strength of tensile steel reinforcement
h	overall thickness or depth of cross-section
h_t	thickness or depth of the textile reinforced concrete (TRC) layer

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k_a	height coefficient
l	length or span of member
m_t	gradient for the second branch of the bi-linear textile stress-strain-relationship
n_t	intersection of the second branch of the bi-linear textile-stress-strain-relationship with the y-axis
x	neutral axis depth (height of compression zone)
z	lever arm of internal forces
z_{s1}	distance between cross-sectional center of gravity in the uncracked state and center of gravity of tensile steel reinforcement
$z_{s,s2}$	distance between resulting compressive force of steel reinforcement and center of gravity of cross-section
z_t	distance between resulting tensile force in TRC layer and center of gravity of tensile steel reinforcement

Greek letters

α_R	factor defining the effective height of the compression zone
ε_c	strain of concrete
ε_{c2}	strain of concrete where maximum strength is reached
$\varepsilon_{c,s2}$	strain of concrete at compressive steel reinforcement fiber
ε_{cu}	ultimate compressive strain of concrete
ε_s	strain of steel reinforcement
ε_{s2}	strain of tensile steel reinforcement
ε_{su}	ultimate strain of steel reinforcement
$\varepsilon_{su,s2}$	ultimate strain of tensile steel reinforcement
ε_t	strain of textile reinforcement
ε_{tu}	ultimate strain of textile
$\varepsilon_{tu,g}$	ultimate strain of textile (from uniaxial tensile test on yarns)
ε_{yd}	design yield strain of steel reinforcement
$\varepsilon_{yd,s2}$	design yield strain of tensile steel reinforcement
$\sigma_{cd\ s2}$	design concrete stress at compressive steel reinforcement fiber
σ_{s2d}	design steel stress in compressive steel reinforcement

FIGURES



Figure 1 — Test set-up of TRC-strengthened RC-slabs

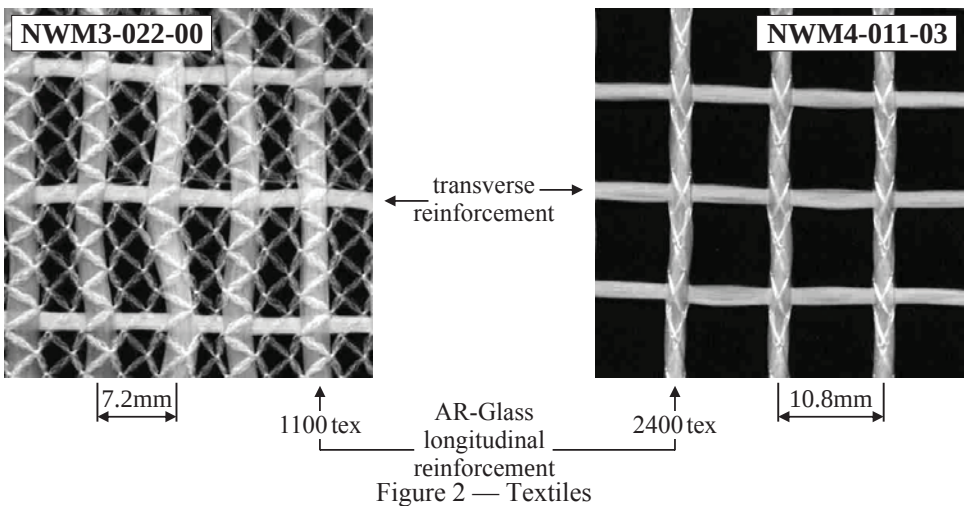


Figure 2 — Textiles

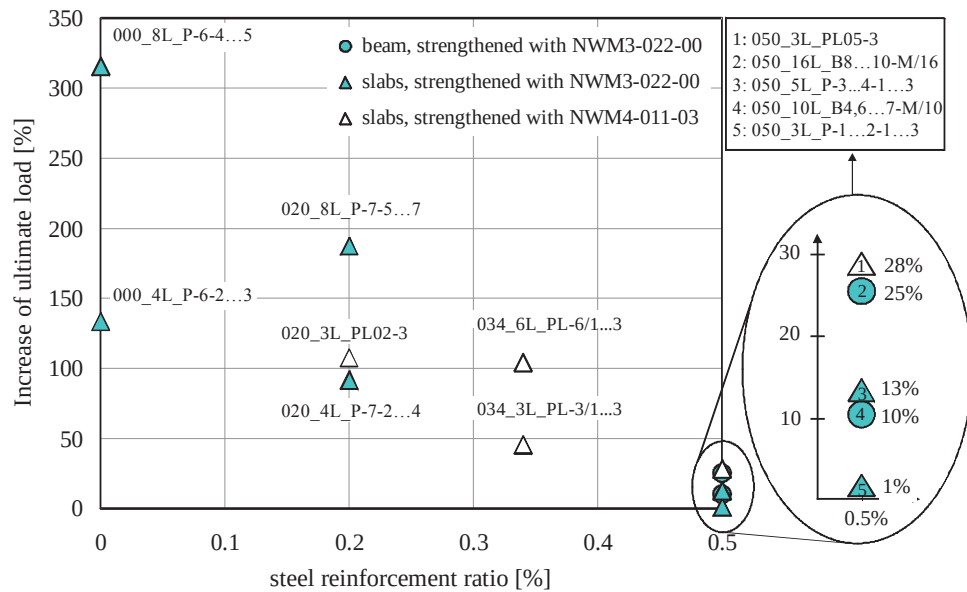
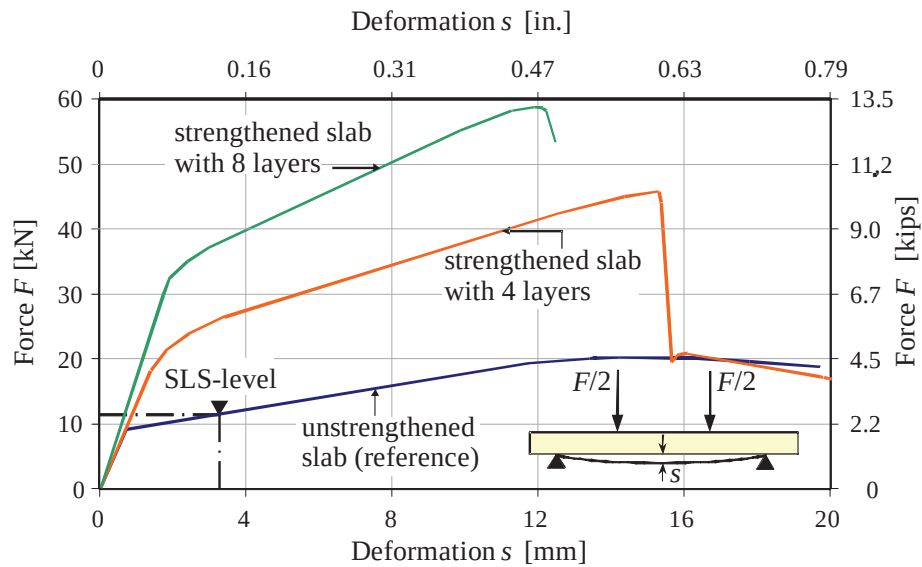
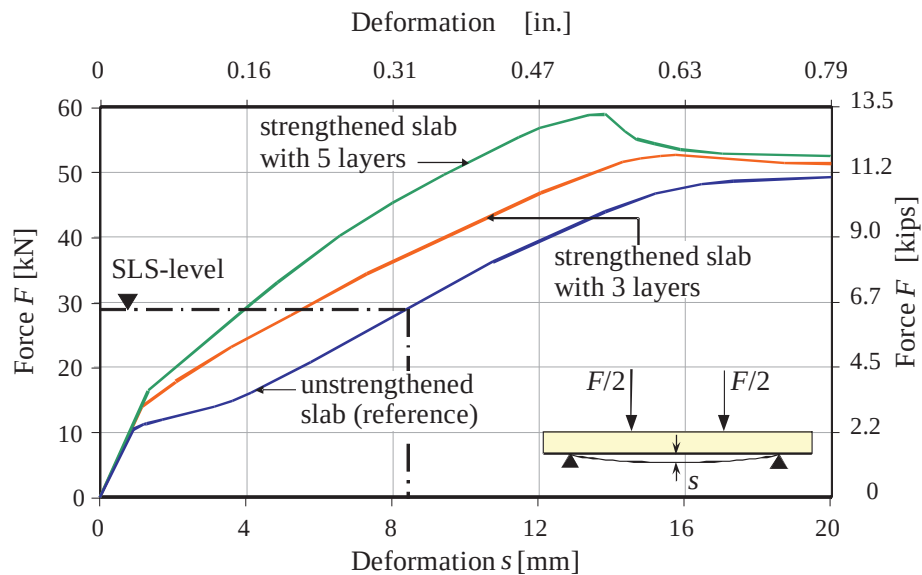


Figure 3 — Percentage of steel reinforcement versus increase of load-carrying capacity



(a) percentage of steel reinforcement 0.2%



(b) percentage of steel reinforcement 0.5%

Figure 4 — Load-deformation-diagrams, textile reinforcement NWM3-022-00

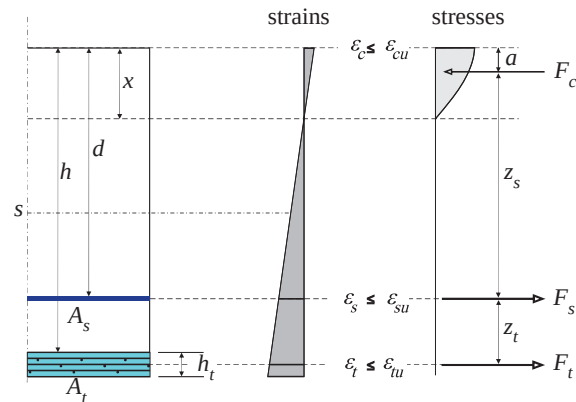


Figure 5 – Linear strain distribution along the height of the cross-sectional area of a textile strengthened RC slab, including possible strain limits

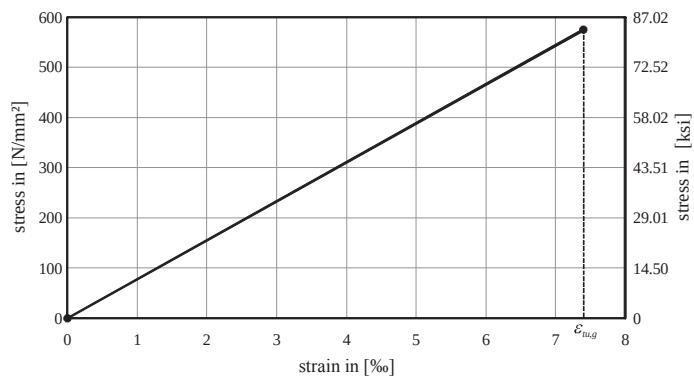


Figure 6 – Stress-strain-relationship from single yarn tensile tests and test set-up—yarn of NWM3-022-00

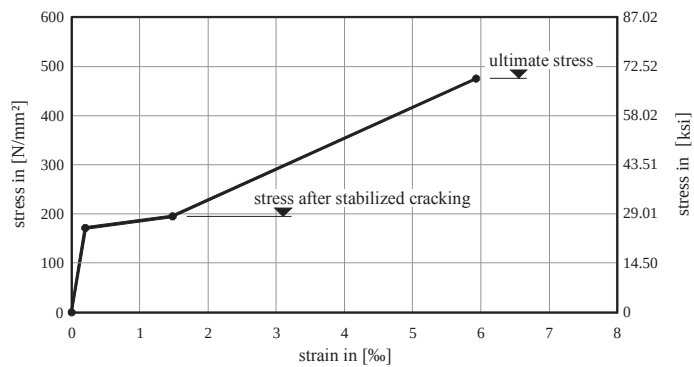


Figure 7 – Stress-strain-relationship from uniaxial tensile tests of TRC-specimens and test set-up—fabric type NWM3-022-00

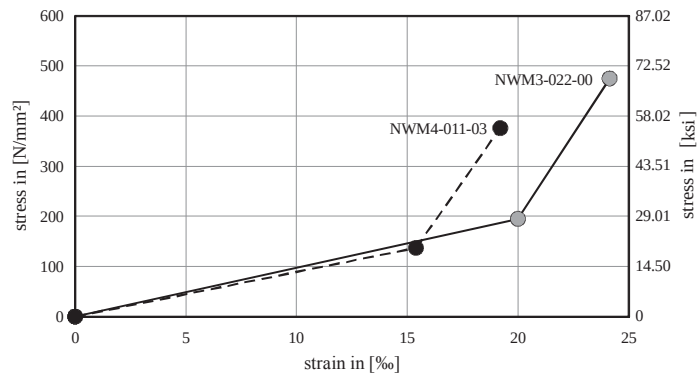


Figure 8 – Stress-strain-relationship for the textile materials used

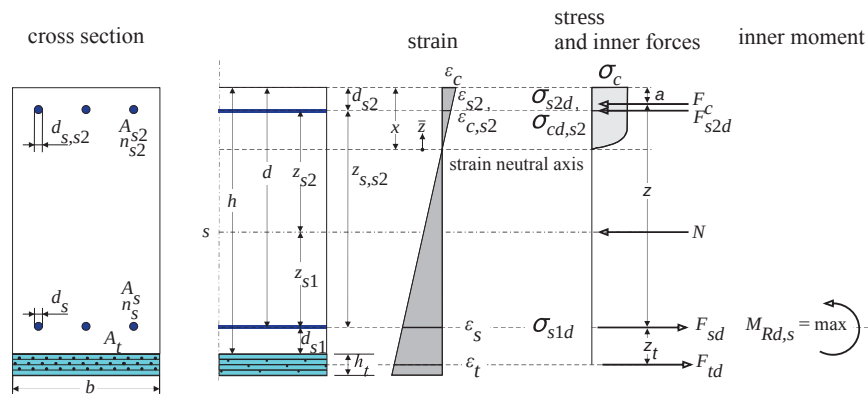


Figure 9 – Strengthened cross section with compression reinforcement notation

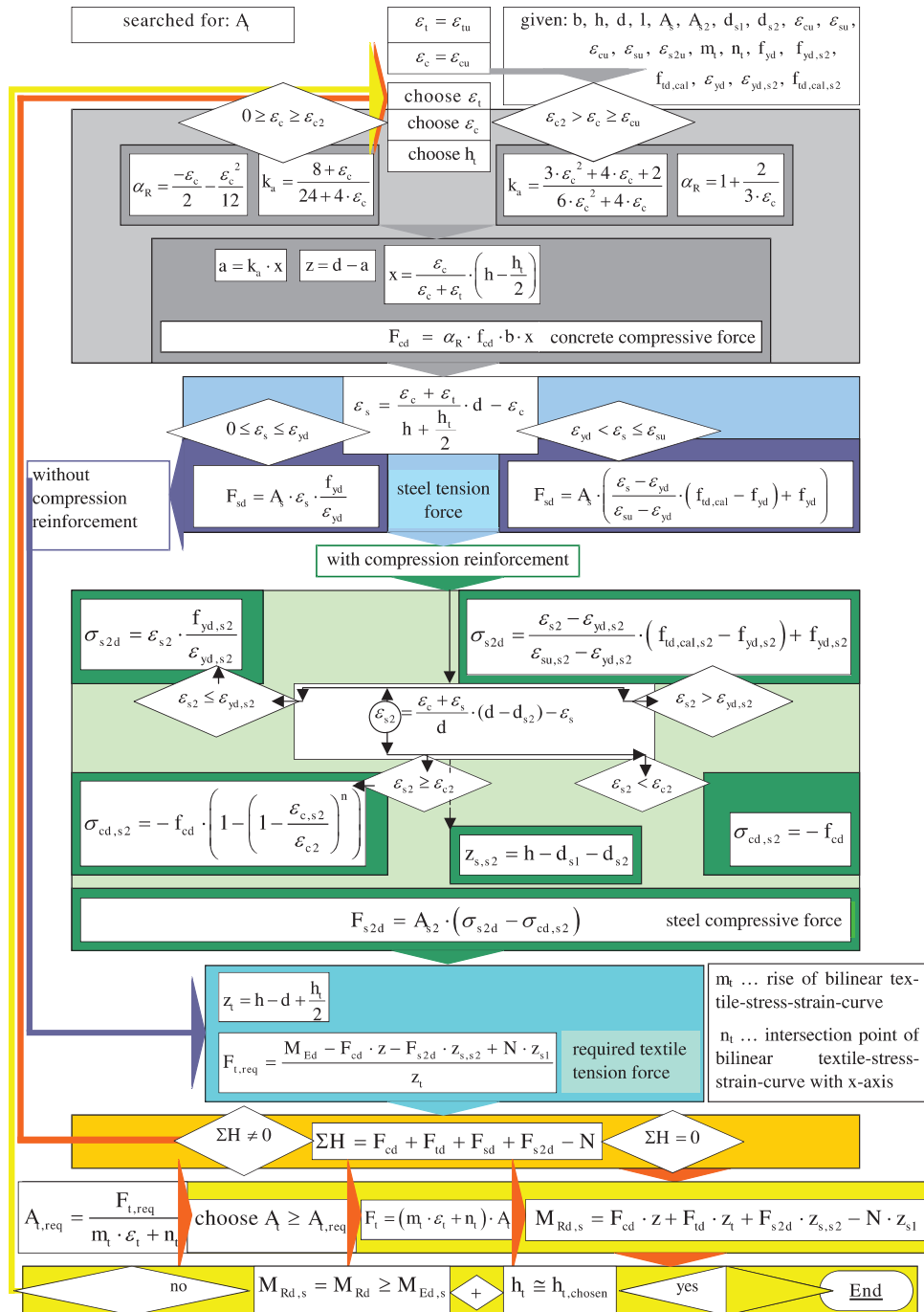


Figure 10 – Procedure for calculating ultimate bending moment

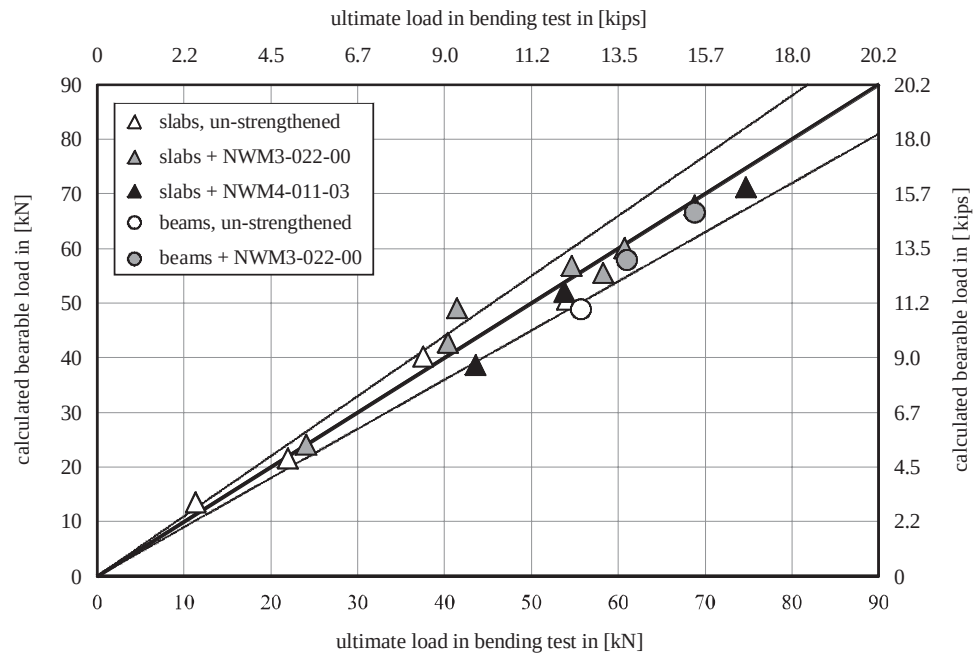


Figure 11 – Ultimate load of slabs—model prediction versus test results

TABLES

Notation of specimen: Series, percentage of steel content, number of layers, specimen-working-title (P, PL = slab, B = beam), textile used

Table 1 — Test results of four-point bending tests

Structural Member Textile Type	Ultimate load in test [kN]/[kips]	Increase of ultimate load [%]	Mid span deflection (average value) [mm]/[in.]
050_3L_P-1-1, NWM3-022-00	54.45/12.24	4.1	23.5/0.93
050_3L_P-1-2, NWM3-022-00	52.00/11.69	-0.5	17.5/0.69
050_3L_P-1-3, NWM3-022-00	52.45/11.79	0.3	16.5/0.65
050_3L_P-2-1, NWM3-022-00	53.68/12.07	2.7	16.0/0.63
050_3L_P-2-2, NWM3-022-00	52.80/11.87	1.0	16.0/0.63
050_3L_P-2-3, NWM3-022-00	51.70/11.62	-1.1	28.0/1.10
050_5L_P-3-1, NWM3-022-00	67.13/15.09	28.4	14.5/0.57
050_5L_P-3-2, NWM3-022-00	59.00/13.26	12.8	14.0/0.55
050_5L_P-3-3, NWM3-022-00	56.83/12.77	8.7	12.3/0.48
050_5L_P-4-1, NWM3-022-00	56.90/12.79	8.8	13.0/0.51
050_5L_P-4-2, NWM3-022-00	55.78/12.54	6.7	14.5/0.57
050_5L_P-4-3, NWM3-022-00	57.93/13.02	10.8	12.5/0.49
050_0L_P-5-1	51.65/11.61	-	49.5/1.95
050_0L_P-5-2	54.90/12.34	-	36.0/1.42
050_0L_P-5-3	50.30/11.31	-	37.5/1.48
050_3L_PL05-3, NWM4-011-03	66.98/15.06	28.1	24.4/0.96
000_0L_P-6-1	9.53/ 2.14	-	0.8/0.03
000_4L_P-6-2, NWM3-022-00	21.81/ 4.90	128.7	3.3/0.13
000_4L_P-6-3, NWM3-022-00	22.71/ 5.11	138.3	5.5/0.22
000_8L_P-6-4, NWM3-022-00	38.94/ 8.75	308.4	9.2/0.36
000_8L_P-6-5, NWM3-022-00	40.29/ 9.06	322.7	9.0/0.35
020_0L_P-7-1	20.13/ 4.53	-	14.8/0.58
020_4L_P-7-2, NWM3-022-00	45.75/10.28	127.2	15.5/0.61
020_4L_P-7-3, NWM3-022-00	39.61/ 8.91	96.8	9.4/0.37
020_4L_P-7-4, NWM3-022-00	30.32/ 6.82	50.6	6.8/0.27
020_8L_P-7-5, NWM3-022-00	58.66/13.19	191.4	12.1/0.48
020_8L_P-7-6, NWM3-022-00	57.26/12.87	184.4	12.5/0.49
020_8L_P-7-7, NWM3-022-00	57.66/12.96	186.4	13.5/0.53
020_3L_PL02-3, NWM4-011-03	41.78/9.39	107.5	24.4/0.96
034_3L_PL-3/1, NWM4-011-03	53.25/11.97	49.1	19.7/0.78
034_3L_PL-3/2SD, NWM4-011-03	51.06/11.48	42.9	20.4/0.80
034_3L_PL-3/3, NWM4-011-03	51.64/11.61	44.5	19.0/0.75
034_6L_PL-6/1, NWM4-011-03	71.72/16.12	100.8	20.6/0.81
034_6L_PL-6/2, NWM4-011-03	71.62/16.10	100.5	19.5/0.77
034_6L_PL-6/3SD, NWM4-011-03	75.34/16.94	110.9	20.0/0.79
034_0L_PL-0/1	36.26/ 8.15	-	49.2/1.94
034_0L_PL-0/2	35.09/ 7.89	-	50.4/1.99
034_0L_PL-0/3	35.82/ 8.05	-	49.6/1.95
050_0L_B5-M/0	51.90/11.67	-	> 70.0/>2.76
050_10L_B4-M/10, NWM3-022-00	56.37/12.67	8.6	41.8/1.64
050_10L_B6-M/10, NWM3-022-00	59.04/13.27	13.8	45.9/1.81
050_10L_B7-M/10, NWM3-022-00	56.21/12.64	8.3	43.6/1.72

050_16L_B8-M/16, NWM3-022-00	64.84/14.58	24.9	43.8/1.73
050_16L_B9-M/16, NWM3-022-00	61.17/13.75	17.9	40.1/1.58
050_16L_B10-M/16, NWM3-022-00	69.03/15.52	33.0	45.0/1.77

Table 2 — Characteristics of steel bar reinforcement

STRUCTURAL MEMBER Textile Type	CHARACTERISTIC VALUES OF STEEL				
	Young's modulus [N/mm ²]/ [ksi]	Yielding		Rupture limit	
		f_{yk} [N/mm ²]/ [ksi]	ε_{yd} [‰]	f_{tk} [N/mm ²]/ [ksi]	ε_{su} [‰]
050_3L_P-1-1, NWM3-022-00 050_3L_P-1-2, NWM3-022-00 050_3L_P-1-3, NWM3-022-00 050_3L_P-2-1, NWM3-022-00 050_3L_P-2-2, NWM3-022-00 050_3L_P-2-3, NWM3-022-00 050_5L_P-3-1, NWM3-022-00 050_5L_P-3-2, NWM3-022-00 050_5L_P-3-3, NWM3-022-00 050_5L_P-4-1, NWM3-022-00 050_5L_P-4-2, NWM3-022-00 050_5L_P-4-3, NWM3-022-00 050_0L_P-5-1 050_0L_P-5-2 050_0L_P-5-3	201,000/ 29,153	556.80/ 80.76	2.77	608.26/ 88.22	32.5
050_3L_PL05-3, NWM4-011-03	194,637/ 28,230	545.00/ 79.05	2.80	617.23/ 89.52	40.0
000_0L_P-6-1 000_4L_P-6-2...3, NWM3-022-00 000_8L_P-6-4...5, NWM3-022-00	-	-	-	-	-
020_0L_P-7-1 020_4L_P-7-2, NWM3-022-00 020_4L_P-7-3, NWM3-022-00 020_4L_P-7-4, NWM3-022-00 020_8L_P-7-5, NWM3-022-00 020_8L_P-7-6, NWM3-022-00 020_8L_P-7-7, NWM3-022-00	193,160/ 28,015	550.70/ 79.87	2.85	663.25/ 96.20	70.0
020_3L_PL02-3, NWM4-011-03 034_3L_PL-3/1, NWM4-011-03 034_3L_PL-3/2SD, NWM4-011-03 034_3L_PL-3/3, NWM4-011-03 034_6L_PL-6/1, NWM4-011-03 034_6L_PL-6/2, NWM4-011-03 034_6L_PL-6/3SD, NWM4-011-03 034_0L_PL-0/1 034_0L_PL-0/2 034_0L_PL-0/3	194,637/ 28,230	545.00/ 79.05	2.80	617.23/ 89.52	40.0
050_0L_B5-M/0 050_10L_B4-M/10, NWM3-022-00 050_10L_B6-M/10, NWM3-022-00 050_10L_B7-M/10, NWM3-022-00 050_16L_B8-M/16, NWM3-022-	194,600/ 28,224	545.21/ 79.08	2.8	631.61/ 91.61	196.0

00 050_16L_B9-M/16, NWM3-022- 00 050_16L_B10-M/16, NWM3-022- 00					
Compression zone:	201,232/ 29,186	571.50/ 82.89	2.84	669.23/ 97.06	32.0

Textile Reinforced Concrete for Flexural Strengthening of RC-Structures—Part 2: Application on a Concrete Shell

by S. Weiland, R. Ortlepp, B. Hauptenbuchner, and M. Curbach

Synopsis: The first practical application of the innovative strengthening method using textile reinforced concrete was carried out in October/November 2006 in the retrofit of a reinforced-concrete roof shell structure at the University of Applied Sciences in Schweinfurt, Germany. Since textile-reinforced concrete had not yet been standardized as a construction material, a single “special-case” technical approval was sought from and granted by the appropriate authorities for this particular application of textile reinforced concrete. This strengthening method entailed the layer-by-layer application of three layers of fine-grained concrete and textile fabric comprising 800 tex carbon rovings onto a rough, sandblasted concrete surface. The resulting strengthening layer has a thickness of only 15 mm (0.6 in.) and extended the roof structure’s service life.

Keywords: fiber; hypar shell; reinforced concrete; strengthening; textile-reinforced concrete

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INTRODUCTION

Textile reinforcement represents an excellent alternative and compliment to existing means for strengthening and repairing concrete structures today. The effectiveness of textile reinforced fine-grained concrete, relative to flexural and lateral forces, was proven by [1-3] with the help of investigations done by the Collaborative Research Centre 528 at the Technische Universität Dresden. Influential variables on the load-carrying capacity, as well as force transmission mechanisms into the reinforced layer, were characterised and described. Weiland [2] and Curbach [3] specifically examined the influence of premature damage primarily caused by existing reinforcement measures – for example, existing cracks, pre-deformation and/or pre-loading. Numerous experimental flexural tests were conducted on reinforced concrete slabs, both with and without premature damage.

Those components supported in the tensile areas of specimens clearly showed smaller deflections, crack widths, and crack distances relative to the serviceability load level as compared to non-strengthened reference specimens. Furthermore, a considerable increase in the flexural load-bearing capacity of strengthened specimens was also attained. Figure 1 provides diagrams that represent a comparison between various types of textile reinforcement materials and non-strengthened reference slabs of reinforced concrete.

One significant advantage of textile reinforcement is its deformability which allows it to adapt easily to complex, free-form geometries. Therefore, strengthening layers on profiles or shell-shaped components are possible. As such, fibers can be positioned in the desired direction so as to fully exploit their load-bearing capacities.

This simple reinforcement technology offers clear and definite advantages for the repair and strengthening of both flat and curved surface bearing structures. Simple and tested application procedures can be relied upon since the application is merely a multi-ply application of a fine-grained matrix – which is quite similar to that of modern plaster with embedded reinforcement and can be used and viewed similarly to standard plaster tissues. A further advantage beyond that of lamellar strengthening methods is the existence of two-dimensional load transfer which has the propensity to reduce any tendency for delamination.

DESCRIPTION OF THE STRENGTHENING MEASURE

In 2002, the rehabilitation of a hyperbolic paraboloid, 1960's roof structure of a lecture hall at the University of Applied Sciences at Schweinfurt was set to be repaired and modernized with other buildings on the university's campus. The 80 mm (3.15 in.) thick reinforced concrete hyper-shell spans the quadratic outline of the "Grosser Hoersaal" (Large Lecture Hall; see Figure 2) with a side length of 27.60 m (1087 in.) and a maximum span of approximately 39 m (1535 in.). The shell is sloped in a north-south direction so that the southern most high point lies at 12 m (472 in.) and the northern most high point 7 m (275 in.) above the lowest point of the shell. The low points, lying in an east-west direction, are connected to massive pylons. The hull thickness measures 80 mm (3.15 in.) in the central area and increases in the direction of the edge girder to a maximum of 367 mm (14.4 in.) at its highest points