TRC-STRENGTHENED COLUMNS

ORTLEPP Regine [1]

Abstract

The increase in the load-carrying capacity of columns strengthened with textile-reinforced concrete (TRC) is partly due to the additional concrete cover. However, the confinement effect of the textile reinforcement is also crucial. After research on differently shaped column heads had shown the considerable strengthening effect of TRC, the aim of the present research was to verify the validation of the developed calculation models in large-scale tests. The model, which was developed based on plain concrete columns in small-scale experiments, was enhanced for this purpose. The accuracy of the predictions of the model for reinforced large-scale columns was examined for three reinforced concrete columns with round cross sections. The load-bearing capacity of the TRC-strengthened columns increased considerably in comparison with the load-bearing capacity of the reference column. The developed confinement model had predicted the achieved ultimate loads very well. Besides an increase in the ultimate load, the textile reinforcement also led to a considerably improved prior-warning behaviour. During the load increase, fine and later clearly visible and homogeneously distributed cracks appeared. All in all, the reinforced columns, which were strengthened with TRC, reached a high ductility.

Keywords: Concrete, Columns, Strengthening, TRC, Textile

1. Introduction

The political class in Europe as well as the world at large have come to realize the importance of preserving the world's natural resources. It is expected that this shift in perspective will have a long-term impact on the building and construction industry. A debate on ecological building methods has been going on in Europe for the past 30 years. European energy and climate protection policies have aimed at reducing primary energy requirements by legislating, for example, to mandate energy-saving buildings. Less attention, however, has so far been paid to the ecological impact of material cycles and resource consumption related to the anthropogenic stock of buildings.

In Germany, for example, the replacement value of this building stock is estimated at around 11.8 trillion euros in the current national accounts of the Federal Statistical Office [1]. Clearly it is vital to take steps to preserve this value. Currently the average useful life of buildings is 66 years. More specifically, residential buildings are used for an average of 77 years, whereas the figures for public buildings and other non-residential buildings are 57 and 53 years respectively (Schmalwasser & Weber [2]). Any extension in the useful economic life of buildings would greatly contribute to value retention. Furthermore, a

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[1] ORTLEPP Regine, Leibniz Institute of Ecological Urban and Regional Development, Weberplatz 1, 01217 Dresden, Germany, r.ortlepp@ioer.de

longer utilization time is also desirable from an ecological perspective, as it conserves natural resources.

If buildings are to be reused after having served their original purpose, it is often necessary to make structural adjustments. This may involve altering the static system and perhaps enhancing the load-bearing capacity of structural elements. However, due to the frequent use of monolithic building techniques, it can be impossible to replace individual structural elements. In such cases the decision will often be made to strengthen columns. To this end, numerous strengthening measures have been developed.

Strengthening techniques using textile-reinforced concrete (TRC), which for some years have complemented traditional strengthening methods using steel-reinforced shotcrete and fibre-reinforced plastics (FRP), have already proved their value in practice, mainly by increasing bending capacity in situations with potentially little shear force (e.g. Weiland et al. [3], Schladitz et al. [4], Lorenz et al. [5]). Early textile reinforcement materials were unsuited to strengthening columns. Yet with the development of efficient, coated carbon textiles, it has become possible to obtain sufficiently high levels of stiffness to achieve an effective confining effect (see Ortlepp, Lorenz and Curbach [6]). Small-scale investigations of differently shaped column heads have shown the considerable strengthening effect of textile-reinforced concrete (TRC). The increase in the load-carrying capacity when TRC is applied to a column results not only from the column confinement by the reinforcing layer but also from an increase in the cross-sectional area. Taking these findings into account, Ortlepp, Lorenz and Curbach [7] developed an additive model for column heads based on TRM confinement models of Triantafillou et al. [8] and Ombres [9] as well as own experimental results.

The question now arises whether the developed calculation model is also valid for large-scale TRC-strengthened columns. The model, which was developed based on plain concrete columns in small-scale experiments, was enhanced for this purpose. Experiments on large-scale columns should now verify the validation of the developed calculation model.

2. Model

2.1 Model of Ortlepp, Lorenz and Curbach [7]

Ortlepp, Lorenz and Curbach [7] developed an additive model for calculating the load-bearing capacity of column heads with TRC strengthening. The total load-bearing capacity N_u is obtained as the maximum value of N_{u1} (Eq. 1) and N_{u2} (Eq. 2):

$$N_{u1} = N_c + N_{fc} = f_{cm} \times A_c + 0.27 \times f_{fcm} \times A_{fc,eff} \tag{1}$$

with:

N_c	normal force in core concrete
N_{fc}	normal force in fine-grained concrete strengthening
f_{cm}	mean compressive cube strength of core concrete
A_c	cross-sectional area of core concrete
f_{fcm}	mean compressive strength of cross-sectional area of core concrete

$A_{fc,eff}$ effective cross-sectional area of fine-grained concrete (net area excluding textiles)

$$N_{u2} = A_c \times f_{cm} \times \left[1 + 0.27 \times \frac{\sigma_{lu}}{f_{cm}} + 5.55 \times \left(\frac{\sigma_{lu}}{f_{cm}} \right)^2 - 3.51 \times \left(\frac{\sigma_{lu}}{f_{cm}} \right)^3 \right] \tag{2}$$

with:

σ_{lu} confining stress in ultimate limit state (ULS), which is calculated using Eq. (3).

$$\sigma_{lu} = k_e \times \frac{(b+d)}{b \times d} \times a_f \times n_{eff} \times f_{fu} \text{ with } k_e = 1 - \frac{b_n^2 \times d_n^2}{3 \times A_c} \text{ (efficiency coefficient)} \tag{3}$$

with:

a_f fibre’s cross-sectional area per textile layer (referred to one metre of column height)

n_{eff} effective number of textile layers excluding anchorage lengths at start and end of confinement

f_{fu} tensile strength of TRC strengthening (referred to fibre’s cross-sectional area)

b_n, d_n free edge length between fillet radii of rectangular columns (zero for circular columns)

Eq. (2) is valid up to a ratio of $\sigma_{lu} / f_{cc} < 0.8$, where f_{cc} describes the triaxial compressive strength of the confined concrete. The ultimate load due to the normal force N_{u1} in the fine-grained concrete strengthening (Eq. 1) determines the result primarily for rectangular geometries and low confinement ratios. In all other cases, the total load-bearing capacity N_u is determined by the load-bearing capacity N_{u2} due to the confinement effect.

2.2 Extended model for large-scale RC columns

Eqs. (2) and (3) refer to a strength which was measured using 150 mm cubes. However, size effects affect the actual strength in case of large-scale columns. Löser et al. [10] specified conversion factors between cube strengths of different geometries. In order to include these effects, the model was extended by a size factor k_s:

$$N_{u1} = N_c + N_{fc} = k_s \times f_{cm} \times A_c + 0.27 \times f_{fcm} \times A_{fc,eff} \tag{4}$$

$$N_{u2} = A_c \times k_s \times f_{cm} \times \left[1 + 0.27 \times \frac{\sigma_{lu}}{f_{cm}} + 5.55 \times \left(\frac{\sigma_{lu}}{f_{cm}} \right)^2 - 3.51 \times \left(\frac{\sigma_{lu}}{f_{cm}} \right)^3 \right] \tag{5}$$

Eq. (4) includes in the factor 0.27 also a reduction factor of 0.6, which accounts for delamination of the TRC strengthening from the concrete core due to the load spread in the column head region. This effect does not exist in the middle of the column. Thus, in the middle region one obtains:

$$N_{u1} = N_c + N_{fc} = k_s \times f_{cm} \times A_c + 0.45 \times f_{fcm} \times A_{fc,eff} \tag{6}$$

Further, in the case of RC columns Eq. (6) must be augmented by the load-bearing capacity N_s of the longitudinal steel reinforcement, which involves the steel stress σ_s at the point of reaching the concrete’s ultimate strain ε_{cu} (Ortlepp, Lorenz and Curbach [11]):

$$N_{u1} = N_c + N_s + N_{fc} = k_s \times f_{cm} \times A_{c,net} + \sigma_s(\varepsilon_{cu}) \times A_s + 0.45 \times f_{fcm} \times A_{fc,eff} \tag{7}$$

with:

$A_{c,net}$ net cross-sectional area of core concrete: $A_{c,net} = A_c - A_s$

Eq. (7) holds for the middle of the column. The corresponding equation for the column head region is:

$$N_{u1} = N_c + N_s + N_{fc} = k_s \times f_{cm} \times A_{c,net} + \sigma_s(\varepsilon_{cu}) \times A_s + 0.27 \times f_{fcm} \times A_{fc,eff} \tag{8}$$

The steel stirrups participate insignificantly in the confinement effect and are therefore negligible. However, the participation of the longitudinal steel reinforcement in Eq. (5) cannot be neglected. Therefore, the load-bearing capacity of the longitudinal steel reinforcement must be added to extend Eq. (5):

$$N_{u2} = A_c \times k_s \times f_{cm} \times \left[1 + 0.27 \times \frac{\sigma_{lu}}{f_{cm}} + 5.55 \times \left(\frac{\sigma_{lu}}{f_{cm}}\right)^2 - 3.51 \times \left(\frac{\sigma_{lu}}{f_{cm}}\right)^3\right] + \sigma_s(\varepsilon_{cu}) \times A_s \tag{9}$$

3. Large-scale tests for model validation

3.1 Specimen geometry and materials

Three circular RC columns with a length of 2 m and a diameter of 300 mm were tested. One reference column (column 1) remained unstrengthened. Five layers of carbon textile were applied to the other two columns 2 and 3, one of them (column 3) being wrapped with two additional textile layers of half a metre width both at the column head and at the column base.

The three concrete columns had a cube strength of 28.3, 27.6 and 33.1 N/mm², for column 1, 2 and 3 resp. on the day of the column test. The longitudinal reinforcement corresponded to six Ø12 bars BSt 500 S based on the minimum reinforcement according to EC 2. Steel stirrups Ø6 were spaced 150 mm apart in the middle of the column and 90 mm apart in the head and base regions.

The TRC strengthening layer consisted of a ready-mixed fine-grained concrete matrix “Pagel TUDALIT® TF 10”. The compressive strength of the TRC layer amounted to 89.4 N/mm² for column 2 and 94.7 N/mm² for column 3, respectively. Standardized mortar prisms were used to measure these values.

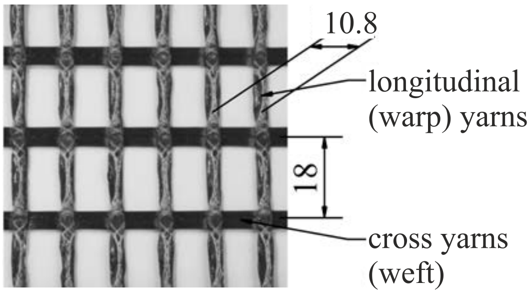


Fig. 1: Carbon textile

The reinforcing textile of the TRC strengthening was a carbon textile named “SIGRATEX Grid 600” from the company SGL CARBON SE. The longitudinal yarns of the textile used

(Fig. 1), which were applied to the columns in the confining direction, had a fineness of 3,300 tex, a density of 0.018 g/mm² and a cross-sectional area of 1.83 mm². The textile's tensile strength of 1,296 N/mm² and the ultimate strain of 628 ‰ (for the textile which is embedded in the fine-grained concrete matrix, i.e. including bond properties) were measured using uniaxial tension tests according to Jesse [12].

3.2 Model prediction of ultimate load

For the validation of the model, the ultimate loads of all three columns were predicted prior to the tests. The total load-bearing capacity of reference column 1 was calculated according to the model of Krause [13] as:

$$N_u^1 = 2{,}149\ \text{kN} \tag{10}$$

For column 2, which was strengthened with five textile layers, the column head determines the result for the first part of the calculation model. With the geometry and strength values of the materials (see Section 3.1), according to Eq. (8) the ultimate load due to the longitudinal force participation of the fine-grained concrete layer amounts to:

$$N_{u1}^2 = 1{,}722\ \text{kN} + 370\ \text{kN} + 0.27 \times 73.1\ \text{N/mm}^2 \times 12{,}566\ \text{mm}^2 = 2{,}340\ \text{kN} \tag{11}$$

Using Eqs. (3) and (9), the load-bearing capacity of the confined column was predicted to be:

$$\sigma_{lu} = 1 \times \frac{(300+300)}{300 \times 300} \times 0.17 \times 4.44 \times 1{,}296 = 6.5\ \text{N/mm}^2 \tag{12}$$

$$\begin{aligned} N_{u2}^2 &= 24.6 \times 70.686 \times \left[1 + 0.27 \times \frac{6.5}{24.6} + 5.55 \times \left(\frac{6.5}{24.6}\right)^2 - 3.51 \times \left(\frac{6.5}{24.6}\right)^3\right] + 370 \\ &= 2{,}795\ \text{kN} \end{aligned} \tag{13}$$

Augmented by an insignificant contribution from the stirrups' confinement effect, the value from the second part of the calculation model determines the total load-bearing capacity of the strengthened column 2:

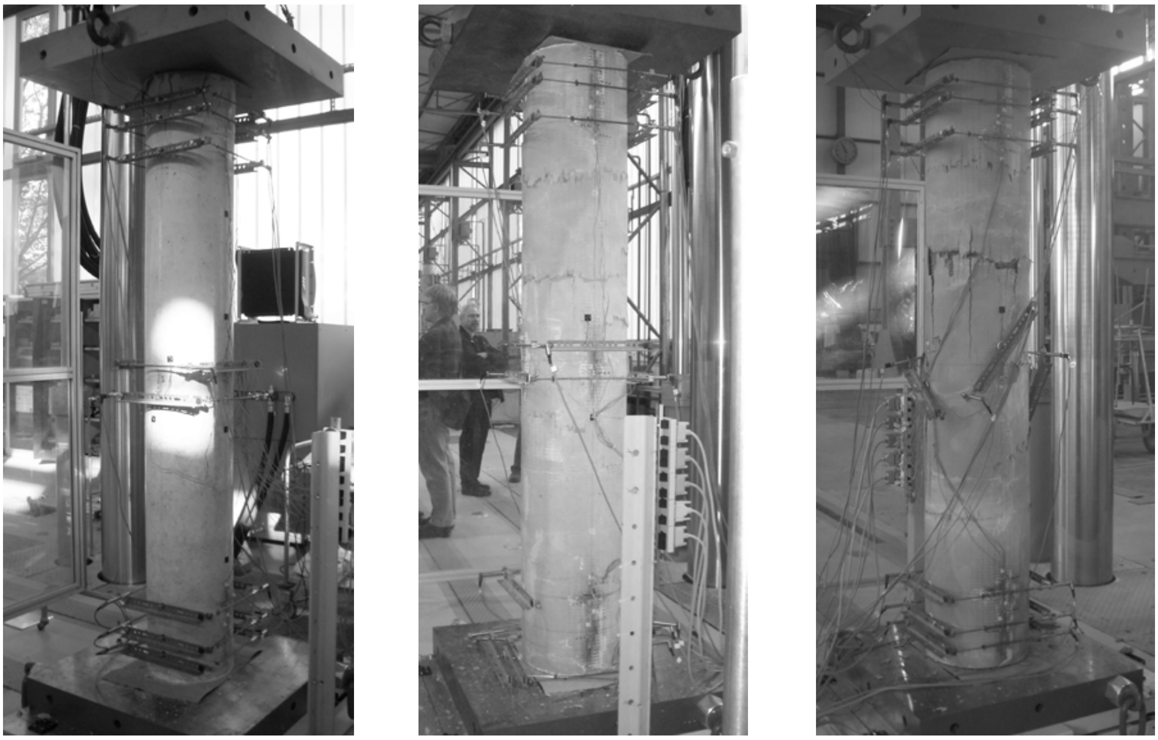
$$N_u^2 = 2{,}795\ \text{kN} + 57\ \text{kN} = 2{,}852\ \text{kN} \tag{12}$$

The prediction of the load-bearing capacity of column 3 follows the same procedure, except that the middle of the column is now the critical design point due to the enhancement of the column's head and base. Here, too, the confinement effect determines the result, yielding a predicted load-bearing capacity of:

$$N_u^3 = 3{,}134\ \text{kN} \tag{12}$$

3.3 Large-scale tests

The columns were tested in a 10 MN compression testing machine. The tests were carried out under displacement control with a loading velocity of 0.01 mm/s. A load cell measured the load and strain gauges, and an LVDT measured the deformations (Fig. 2).



a) column 1 – unstrengthened

b) column 2 – strengthened, 5 layers

c) column 3 – strengthened, 5 + 2 layers

Fig. 2: Test setup of the columns

Fig. 3 shows the results for the tested columns. The reference column failed at the column head. Column 2 with 5 textile layers showed a uniform failure over the entire height of the column. The failure of column 3, which was strengthened with 5 textile layers and 2 additional layers at the column head and base, occurred in the middle of the column. Both strengthened columns showed fine, evenly distributed cracks.

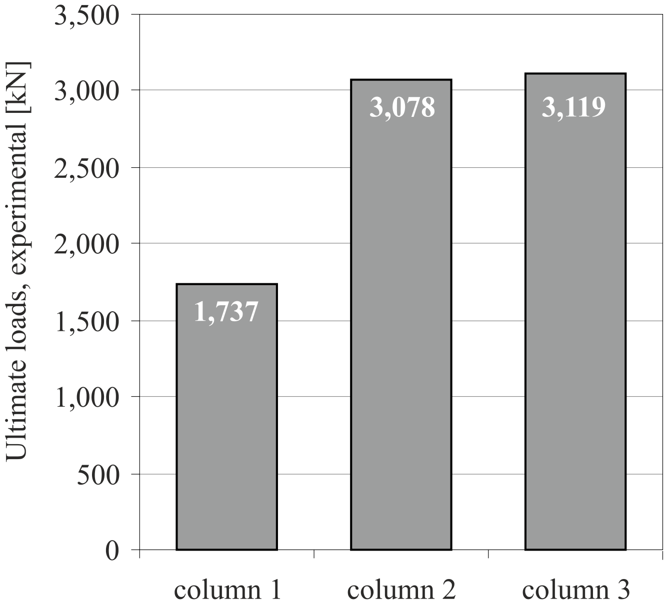


Fig. 3: Ultimate loads obtained from the large-scale column tests

The load increase of both TRC-strengthened columns reached approx. 80 %. This is composed of approx. 8 % strengthening effect due to the normal force participation of the fine-grained concrete layer and approx. 72 % confinement effect of the carbon textile reinforcement. The TRC-strengthened columns showed a considerably larger ductile behaviour compared to the unstrengthened reference.

4. Conclusions

The experimentally obtained load-bearing capacity of the TRC-strengthened columns was predicted very well with the developed model (Fig. 4, black). Only the load-bearing capacity of the unstrengthened column was overrated, because the longitudinal steel rebar's effect was included in the prediction but the failure occurred at the column head, where the steel was out of action due to its development length. A new prediction without the steel rebar's effect yielded good agreement (Fig. 4, grey).

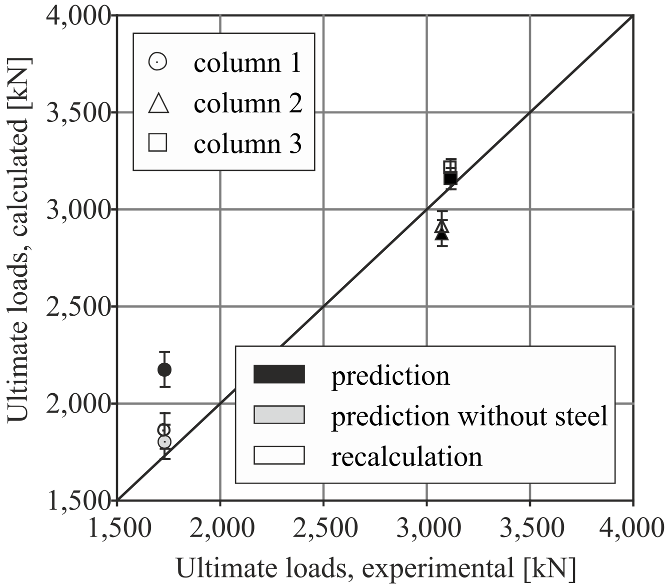


Fig. 4: Comparison of experimentally measured ultimate loads with the predictions of the model and a recalculation using the material parameters actually measured

The predicted loads were calculated based on the 28-day strength values of the concretes. The actual material parameters were measured on the days of the column tests. A recalculation with these values shows only a slight difference in comparison with the prediction.

All in all, the comparison has shown that the model is suitable for reliably predicting the load-bearing capacity of TRC-strengthened RC columns, in particular with real-life dimensions.

Acknowledgements

The author wishes to thank the German Research Foundation (DFG) for its support of the experimental research.

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