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STRAIN MEASUREMENT AND ADHESIVE SELECTION FOR STRAIN GAUGES ON CARBON ROVING IN TEXTILE-REINFORCED CONCRETE STRUCTURES

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Textile-reinforced concrete (TRC) is a promising building material that meets modern environmental protection and sustainability requirements. For the widespread use of this innovative building material, empirical models based on material properties determined by laboratory tests are needed. This study investigated the ability to measure the strain of carbon rovings with small strain gauges during standard tensile tests. The measured values were compared and validated using the digital image correlation (DIC) method. Another component of this study is the investigation of a suitable adhesive for the application of the sensors to SBR-coated (styrene-butadiene rubber) carbon roving. Three test series with three different adhesives, cyanoacrylate adhesive, epoxy resin, and polychloroprene, were produced and tested for tensile strength. The validation tests showed that a strain loss occurs in the adhesive joint of the strain gauges. It was found that cyanoacrylate adhesives, such as M-Bond 200, suffered the lowest losses and are recommended for further investigations. The epoxy resin influences the stiffness of the carbon fibers at the contact surface too strongly, while the polychloroprene adhesive could not transfer the actual roving strain due to insufficient stiffness of the bond line.

Keywords: Digital image correlation, Strain sensors, TRC, Carbon fiber.

1 INTRODUCTION

Meeting climate policy targets while taking into account progressive urbanization and the consequences of globalization represents an immense global challenge for the construction industry. At the same time, existing buildings usually do not meet the load-bearing and energy requirements, which is why priority is often given to demolition from an economic point of view instead of saving old buildings through extensive renovations. To counteract this approach, the construction industry relies on innovative retrofitting and repair measures that meet contemporary requirements for material and resource efficiency.

TRC is an innovative building material that has been the subject of research for several years now (Curbach and Ortlepp 2011, Curbach *et al.* 2023). Retrofitting concrete structures using TRC has several advantages over established measures such as shotcrete and carbon fiber reinforced polymers (CFRP). Unlike strengthening with CFRP the additionally applied fine-grained concrete can repassivate and stop the corrosion of the existing steel reinforcement. A significant advantage over shotcrete is the corrosion resistance of the textile reinforcement material. The concrete cover required to ensure durability is no longer necessary, which both saves material and reduces the space required for the reinforcement measure. At the same time as increasing the load-bearing capacity, the fire protection properties of the existing component can be improved.

Over the past decades, basic research has been conducted on TRC (Scheerer *et al.* 2019). For a deep understanding of the material and to develop appropriate design proposals and models, further research is warranted before TRC is used on a large scale. This requires the knowledge of the tensile mechanical properties of the textile reinforcement determined based on laboratory tests. However, investigations of the bonding and load-bearing behavior of TRC structures on yarn tensile and pull-out tests showed that the potential of the reinforcing fibers is not fully exploited (Curbach and Ortlepp 2011). Incomplete impregnation and damage during the production chain or installation on site are all conditions that are not taken into account when determining the axial tensile strength on a single roving. Another reason, as shown in Fig. 1, is the uneven distribution of stresses across the cross-section, which is caused by different bonding behavior in the outer and inner filaments.

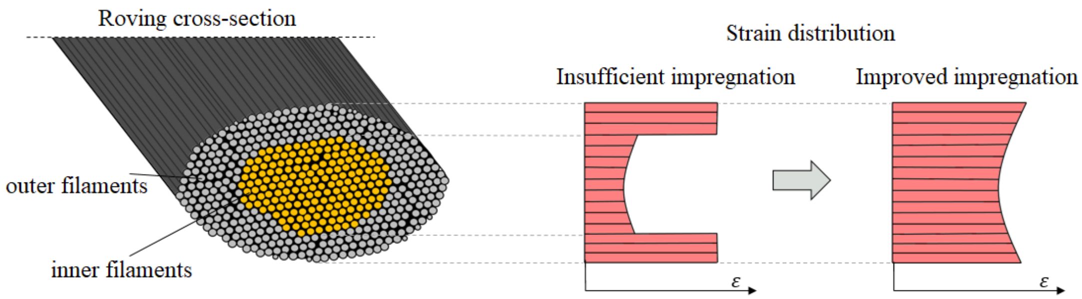

Fig. 1. Stress distribution due to poor impregnation according to Lepenies (2007).

In order to set up a safe design model that takes the above-mentioned influences into account, it is necessary to determine the axial tensile strength of the textile reinforcement embedded in a fine-grained concrete matrix. However, measuring the ultimate strain on which the model is based is problematic. In traditional reinforced concrete, the ultimate strain is measured using strain gauges applied directly to the steel reinforcement. CFRP is also measured using strain gauges bonded externally on the reinforcing layer in the epoxy resin. With TRC, however, the application of strain gauges directly to the reinforcement structure is almost impossible due to the geometry and its fine-meshed structure. Moreover, determining the ultimate strain using linear variable differential transformers (LVDT) or optical measurement methods leads to large scattering and thus introduces uncertainties into the design model (Meßerer *et al*. 2018).

The aim of this study is to test the application of small strain gauges with a focus on the adhesives used for fixing the strain gauges at the textile reinforcement. Especially with pre-impregnated textiles with either epoxy or SBR, the choice of adhesive has an important role. The strains of the substrate should be transferred without losses in the adhesive bond gap, while the sensor should remain applied until failure. To be able to recognize possible deviations, the results of the strain gages are validated using the digital image correlation (DIC) method.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Experimental Program

The main objectives of the experimental program were:

(a) to analyze the possibility of using strain gauges for strain measurement on textile reinforcements of TRC,

(b) to compare several adhesives with each other, and
(c) to validate the results using digital image correlation (DIC).

A total of nine pull-out specimens divided into three series with different adhesives were produced. The test specimens consisted of a 50 cm long carbon roving, the ends of which were embedded in a steel tube with an expanding cement mortar (BETONAMIT®). The experimental program is shown in Table 1.

Table 1. Experimental program.

Series No.	Label	No. of spec.	Type of adhesive	Name of the adhesive	Manufacturer of the adhesive
1	CA	3	Cyanoacrylate	M-Bond200	Micro Measurements
2	EP	3	Epoxy	Epoxidharz L	R&G
3	PC	3	Polychloroprene	Scotch-Weld™ 1357	3M™

2.2 Specimens Preparation and Specifications

The test specimens were made of a 50 cm long carbon roving taken out of a grid textile. Both ends of the roving were placed in two 12 cm long steel tubes with a diameter of 12 mm, see Fig. 2. Then, the tubes were filled with an expanding mortar and stored vertically under constant climatic conditions for at least 24 hours.

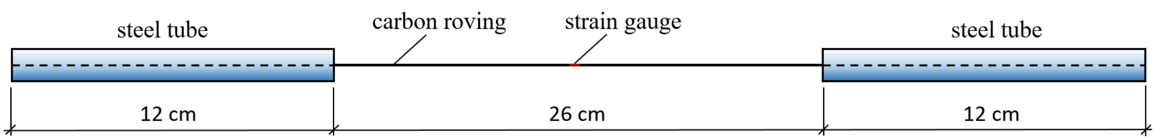

Fig. 2. Specimen geometry.

In pre-tests, epoxy resin was also tested for embedding the carbon roving in the steel tube. The maximum load was rarely reached due to slippage and failure in the connection zone. Clamping the roving directly into the testing machine with leather in between, as proposed by Wendler *et al.* (2020), did not lead to successful results either. The roving was mostly damaged by the clamping and failed prematurely. The test method presented here provides reliably reproducible results. The transverse pressure applied by the expanding mortal in the steel tube ensures that the roving can be tested without pre-damage and slip. A disadvantage will be the time required to prepare the specimens.

2.3 Strain Gauge Application

Due to the small size of the rovings, the strain gauges commonly used in the construction industry could not be used. Therefore, strain gauges with a length of 2 mm were used. Due to the inhomogeneity of the carbon fiber and the SBR impregnation, proper surface treatment was necessary before the application. The surface was prepared using mechanical pre-treatment measures. This involved roughening the surface with fine sandpaper and removing the SBR impregnation at the same time. Loose particles were removed several times with isopropanol and a fuzz-free cloth. Surface preparation was the same for all specimens.

M-Bond 200 was applied in accordance with the application recommendations. A primer was used to reduce the absorbency of the open filaments, after which the adhesive and the stain gauge were applied. The application with polychloroprene was identical. First, a thin layer was applied to the substrate and the strain gauge, after which it was applied on the roving and pressed with a thumb for one minute. With epoxy, the stain gauge had to be carefully positioned and allowed to harden for at least one day.

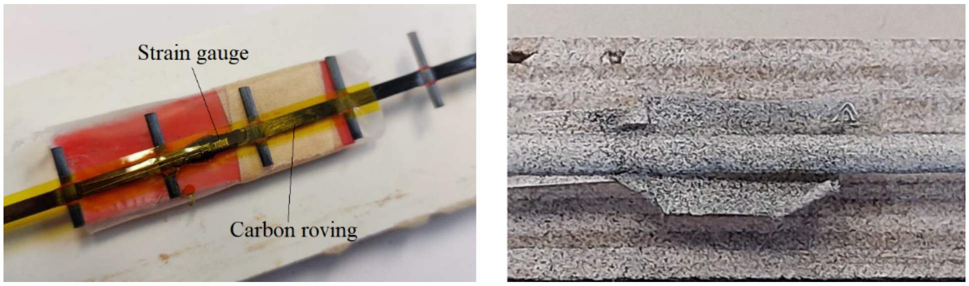

Fig. 3. Applied strain gauge and gray-scale pattern for the DIC.

A gray-scale pattern was applied on the opposite side of each roving in order to be able to record the strain using DIC method (Fig. 3).

2.4 Test Procedure

The tests were carried out in three successive load stages. The maximum values of the stages roughly equated to a 40% or 60% workload of the rovings, whereupon they were tested to failure in the final stage. The testing machine was set to a measuring range of 10 kN. The load was applied by displacement control, which was set to 2 mm/min. The two steel tubes in which the roving was placed were clamped into the machine at 30 bar. For DIC, three cameras were mounted at a distance of 35 cm from the specimen. The distance between the cameras was 10 cm. The focus of the cameras was set to the height of the strain gauge on the test specimen.

3 RESULTS

Table 2 presents the test results in tabular form. The maximum tensile strength values shown here are calculated based on the roving cross-sectional area of 1.82 mm² provided by the manufacturer. The tensile strength of 1,700 N/mm² and Young's modulus of 170,000 N/mm² are also listed in the technical approval (DIBt 2021). The values of Young's modulus shown in Table 2 are average values formed from the load stages.

Table 2. Experimental results.

Label	**F_{max} Machine**	**F_{max} Gauge**	**F_{max} DIC**	**f_{ax} Gauge**	**f_{ax} DIC**	**$E_{cm,mean}$ Gauge**	***CoV* Gauge**	**$E_{cm,mean}$ DIC**	***CoV* DIC**
[-]	[kN]	[kN]	[kN]	[N/mm²]	[N/mm²]	[N/mm²]	[%]	[N/mm²]	[%]
CA-1	3.06	3.06	3.12	1679	1713	195560		367304	
CA-2	4.00	3.99	3.65	2195	2003	162327	14.27	177843	36.24
CA-3	4.17	4.15	3.43	2280	1887	216523		247889	
EP-1	3.65	3.66	3.45	2009	1793	302070		175821	
EP-2	4.27	4.25	3.76	2336	2068	394330	13.22	184650	3.68
EP-3	4.40	4.40	3.65	2419	2005	357872		171895	
PC-1	3.66	3.66	3.12	2009	1732	408113		179710	
PC-2	4.13	4.07	3.65	2236	2047	277245	45.09	178059	1.09
PC-3	4.09	4.11	3.72	2256	2043	155441		181979	

Fig. 4 shows the stress-strain diagrams of each specimen. The stress-strain curves of the strain gages values of the CA specimens are linear for all test specimens up to failure. The ultimate stress of CA-2 and CA-3 is approximately identical, whereas CA-1 does not reach this range. In comparison to other series, DIC shows here a large scatter between the measuring lengths. Except CA-2 shows good agreement. It is important to note that the creation of the gray-scale pattern on the small and absorbing surface of the carbon rovings is challenging. This is the most important measure to achieve good and consistent results.

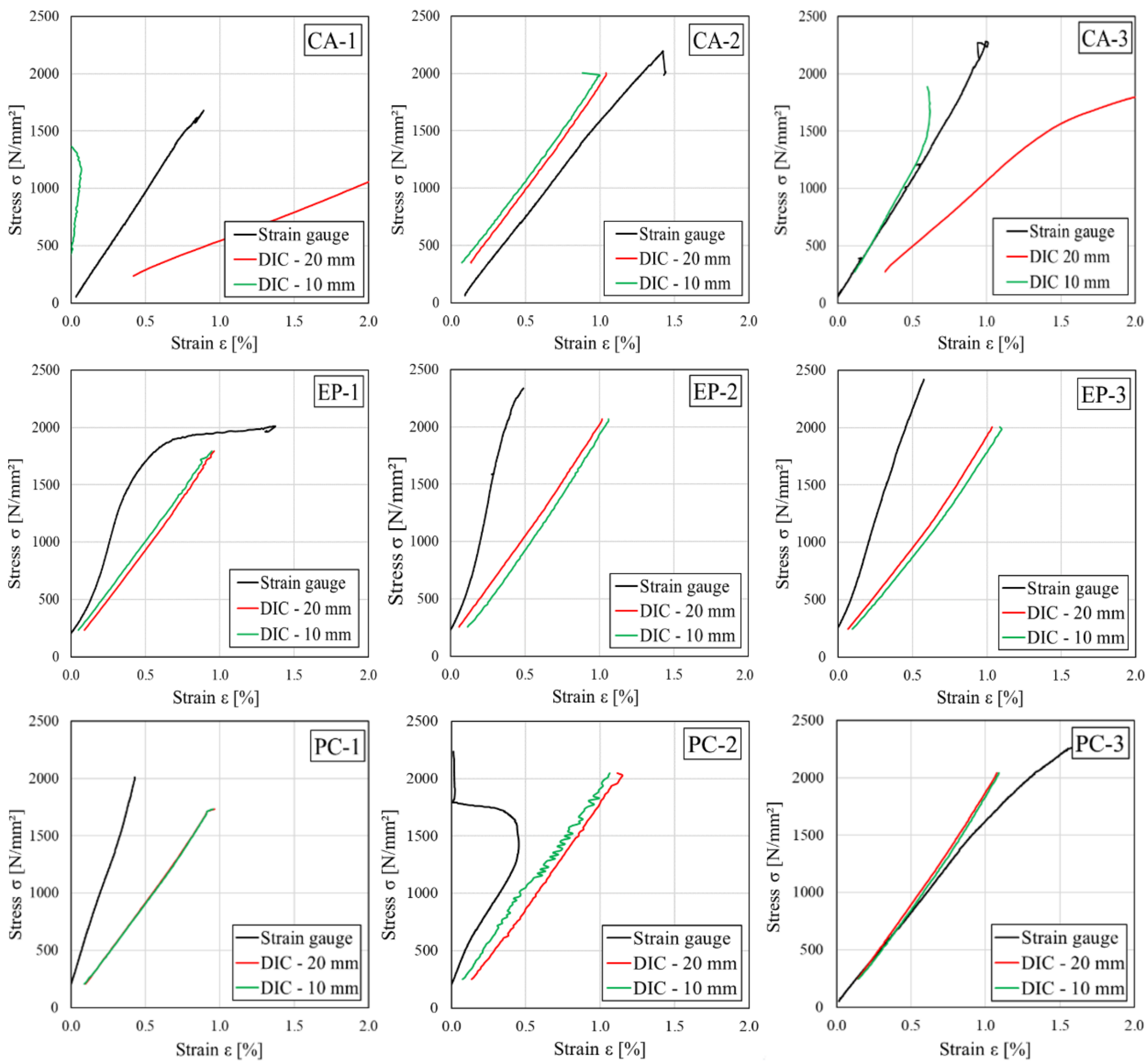

Fig. 4. Stress-strain diagrams of the test results.

Furthermore, it can be observed that the failure pattern of the rovings causes early damage to the gray-scale pattern, whereupon no more measured values can be recorded from an average of 0.50 kN before failure. The chipping of the outer filaments destroyed the applied pattern so that no reference points could be found when validating the recorded images and therefore no comparison between the images could be made. In addition, chipped filaments can cover the remaining intact pattern. Good results were achieved with the DIC system in the EP series. Both measuring lengths show approximately identical and linear curves. The results of the strain gauge, however, are not linear and show a moderate divergence from each other. In general, it can be noted that the gradients of the curves are much steeper than those of the DIC. The authors assume that the epoxy resin with which the strain gauge was adhered has penetrated the absorbing roving locally and increased its stiffness. This can also be recognized by the values of Young's modulus shown in Table 2. Finally, series PC shows clear scattering to the validation using DIC. The gradient of the curves is not linear and not constant across all specimens. PC-3 shows that the curve has a progressive course, which makes it clear that the actual strain is not transmitted through the adhesive bond gap in the strain gauge. The high ultimate strain also indicates that this type of adhesive is too elastic for this application.

4 CONCLUSION

In this study, three different adhesives for the application of strain gauges on carbon roving were tested. The suitability of the adhesives was investigated by carrying out tensile tests. The results were validated using a DIC system. The results show that the cyanoacrylate-based adhesive is the most suitable for the application of strain gauges to SBR-impregnated carbon rovings. However, this requires thorough surface preparation. Therefore, the SBR should be removed as far as possible with isopropanol and the surface roughened with fine sandpaper. The EP specimens showed that the epoxy resin interacts with the substrate and so influences its strains. In addition, the very long curing time is impractical for positioning the sensors. Due to its elasticity, the polychloroprene adhesive seems also unsuitable. In contrast, the DIC method delivered reliable and consistent results. However, the quality of the results depends highly on the quality of the gray-scale pattern, which should be given the most priority.

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