Proceedings of the 3rd World Congress on Civil, Structural, and Environmental Engineering (CSEE'18)
Budapest, Hungary – April 8 - 10, 2018
Paper No. ICSENM 126
DOI: 10.11159/icsenm18.126

Relining of 100 Bar Water Power Pressure Pipes with CF/EP-Matrix Composites – A Case Study

Reinhold W. Lang[1], Markus Gall[1], Erich Wagner[2], Friedrich Hahn[2]
[1]Institute of Polymeric Materials and Testing, Johannes Kepler University Linz
Altenberger Straße 69, 4040 Linz, Austria
reinhold.lang@jku.at; markus.gall@jku.at
[2]VERBUND Hydro Power GmbH
Europaplatz 2, 1150 Vienna, Austria
erich.wagner@verbund.com; friedrich.hahn@verbund.com

Abstract - Following the permission for reconstruction by the Austrian federal water authority in 2000, the penstock of one of Austria's largest reservoir hydropower stations, built in the 1940/50ies near Kaprun (Salzburg) and operated by VERBUND Hydro Power GmbH, was rebuilt with modern grade high-pressure steel pipes. However, for economic and technical reasons it was decided to refurbish the final penstock pipe sections just prior to the turbines when entering the power house (i.e. the "turbine distribution penstock"), with a nominal pressure rating of 100 bar, via relining the inner surface of the original steel pipes with a specifically developed carbon fiber/epoxy matrix (CF/EP) composite prepreg. In this manner, a high-strength inner CF/EP composite pipe shell was built as self-supporting construction. Based on an extensive experimental program for material qualification incl. issues related to CF/EP prepreg production, handling and deployment and aspects of structural performance, permission by the water authority to implement the CF/EP relining was obtained in March 2003. The reconstructed power conduit of the Kaprun main scheme was put in operation in June 2004. The paper provides an overview of the material development, qualification and quality assurance work that led to applying this novel and worldwide unique CF/EP relining technique for refurbishing extreme high-pressure pipes.

***Keywords*:** High Pressure Steel Pipe Relining, Carbon Fiber Reinforced Polymer Composite, Qualification, Certification, Quality Assurance.

1. Introduction & Background

The Kaprun power scheme, now operated by VERBUND Hydro Power GmbH, was built in the 1940/50ies near Kaprun (Salzburg/A) and started energy production in 1944. It is one of Austria's largest reservoir hydropower stations with a mean annual power production of about 500 GWh, the peak power outlet of the 4 pelton turbines is 220 MW [1, 2]. The original waterway consisted of a 1,200 m long penstock above ground (4 steel pipes), leading into the "turbine distribution penstock" at the lowest fix-point just prior to the turbines when entering the power house (Fig. 1a). Following thorough investigations and a comprehensive safety analysis of the original steel pipes penstock in the late 1980's, a decision was made to define the end of the technical service life for the penstock with the end of 2003 (i.e. after some 6 decades of operation). Concurrently numerous technical options for rehabilitation were evaluated, leading to the decision of rebuilding a new penstock in an underground pressure shaft. In 2000 the permission for reconstruction was obtained by the Austrian federal water authority, and the reconstruction started in 2001 [1, 2].

While the original idea was to also install new steel pipes at the lowest fix-point in the "turbine distribution penstock" just prior to the turbines when entering the power house, this idea was discarded for economic and technical reasons. Instead, it was decided to refurbish the eight pipe sections of the turbine distribution penstock, each ranging from 8 to 13 m in length and with 700 mm and 850 mm diameter, respectively, by applying and curing a novel, specifically developed carbon fiber/epoxy matrix (CF/EP) composite prepreg onto the inner surface of the original steel pipes (Fig. 1b). In this manner, a high-strength inner CF/EP composite pipe shell was built as self-supporting construction. The 100 bar nominal pressure rating translates into a nominal circumferential stress design requirement in the CF/EP pipe shell of 1,200 MPa with regard to the stress-carrying net cross-section of fibers in circumferential orientation. Accounting for a safety factor of

2.5, this corresponds to a short-term tensile strength requirement for CF/EP laminates on a laboratory specimen level of at least 3,000 MPa, again with regard to the net cross-section of fibers in load orientation [3].

An extensive experimental program for material selection and qualification incl. issues related to CF/EP prepreg production, handling and deployment and covering aspects of structural performance was carried out. Based on the results of the comprehensive investigations, permission by the water authority to implement the CF/EP relining was obtained in March 2003, and the reconstructed power conduit of the Kaprun main scheme was put in operation in June 2004. After about a decade of operation, the service-collateral quality assurance investigations of the CF/EP relining material have recently started. The aim of this paper is to provide an overview of the so-far unpublished material development, qualification and quality assurance work that led to applying this novel and worldwide unique CF/EP relining technique for refurbishing extreme high-pressure pipes.

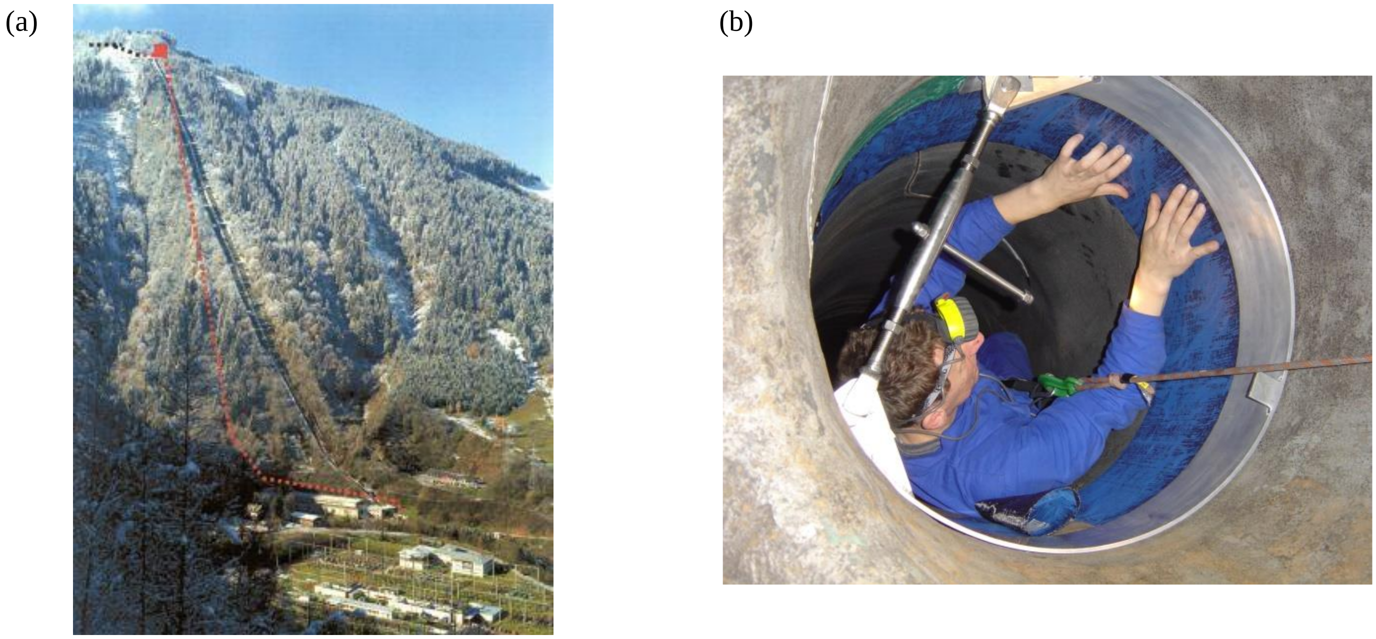


Fig. 1: (a) Original penstock and power house of the Kaprun power conduit scheme with indication of the reconstruction following the permission by the Austrian federal water authority in 2000; (b) Relining of the turbine distribution penstock via EP/CF prepreg application.

2. Methodology & Experimental

2.1. Qualification Requirements and Materials

Considering the overall structural design and service-performance requirements, the structural design and material property criteria listed in Table 1 were defined regarding the cured CF/EP laminate state. The property criteria as to the CF dominated mechanical tensile performance are defined for a laminate specimen level again in terms of the net cross-section of fibers in load orientation. Hence, although to be determined experimentally on composite laminates, the tensile properties are designated as CF property requirements by using simple rule-of-mixture laws to transfer laminate results to corresponding values for the net cross-section of fibers in load orientation. The requirement as to the apparent interlaminar shear strength (ILSS), although not being a direct design criterion, was defined to cover the EP matrix and EP/CF interface dominated behaviour in the cured CF/EP laminate state.

Table 1: Structural design and material property requirements for cured CF/EP laminates.

Property	**Requirement**	**Remarks**
CF tensile strength (short-term)	≥ 3000 MPa	dry or as-received “initial” material state
CF modulus	≥ 200 GPa	dry or as-received “initial” material state
CF strain-to-break	≥ 1.5%	dry or as-received “initial” material state
Safety factor (CF tensile strength)	2.5	accounts for imperfections related to prepreg production and processing related strength reductions; application related prepreg layer overlaps, environmental effects related to temperature, humidity and water; corresponds to a lower-bound CF tensile strength of 1200 MPa as structural design strength value
Apparent interlaminar shear strength (ILSS)	≥ 36.8 MPa	dry or as-received “initial” material state; for a span-to-specimen thickness ratio of 5:1 (the corresponding ILSS requirement for span-to-specimen thickness ratio of 4:1 is ≥ 40 MPa)

While meeting the above requirements was essential for the material qualification (dry or as-received “initial” material state), a second set of requirements was defined for the continuous quality assurance test program to be performed concomitantly to the service application. Here reference property values are to be determined for tensile strength (again with regard to the net fiber cross-section of fibers oriented in loading direction) in a “fully-wet” (moisture saturated by immersion in water at room temperature) state. The allowable property reductions for the quality assurance test program were defined with -20% regarding laminate tensile strength and laminate flexural strength and -30% regarding the apparent interlaminar shear strength relative to the corresponding “fully-wet” initial states.

Based on the above requirements and some additional material pre-qualification investigations the following materials in terms of CF/EP prepreg constituents and prepreg design were specified and applied for the turbine distribution penstock. The 0°/90°-bidirectional CF textile pre-core was supplied by SAERTEX Wagener GmbH & Co. KG (Saerbeck/D). For the pipe circumferential direction (0°-direction in the CF textile pre-core or laminates) and the pipe axial direction (90°-direction in the CF textile pre-core or laminates) two different CF types were selected, both supplied by the European producer Soficar S.A. (Paris/F), a branch of Toray Industries Inc. (Tokyo/J). The CF type used for the 0°-direction was Torayca® T600S, for the 90°-direction it was Torayca® T700S. Based on structural design considerations, 0°/90°-bidirectional CF textile pre-core was specified to a nominal fiber areal weight of 435 g/m^2 and 150 g/m^2 for the 0°- and 90°-direction, respectively (i.e., 90°-fibers amount to about 34.5 % of the 0°-fibers in the 0°/90°-bidirectional CF textile pre-core).

As to the EP matrix system, a 40°C-curable two-component epoxy resin of the type BECOR® SX 10 with a hardener designated as Indurente SX 10LL, supplied by mates italiana srl (Pioltello/I), was used. The prepreg consisting of the above CF textile pre-core and the EP resin with a resin content of 38.5±2.5 % (w/w) was produced and supplied by ISOSPORT (Hall/A), a sister company of ISOVOLTA AG (Wiener Neudorf/A). Further details as to the materials including the material selection and specification are described in [3].

2.2. Test Program and Test Procedures

According to the structural design and material property requirements listed in Table 1, the test program described in Table 2 contains the key characterization techniques defined for qualification testing and service concomitant quality assurance testing, respectively.

Table 2: Test program for qualification testing and service concomitant quality assurance testing of CF/EP composite laminates.

Qualification testing	**Service concomitant quality assurance testing**
Tensile testing at room temperature: 0°-tensile tests (dry or as-received state) 90°-tensile tests (dry or as-received state)	***Tensile testing*** at room temperature: 0°-tensile tests (as-received & water saturated state) 90°-tensile tests (as-received & water saturated state)
Apparent ILSS at room temperature: 0°-ILSS (dry or as-received state) 0°-ILSS (water saturated)	***Apparent ILSS*** at room temperature: 0°-ILSS (dry or as-received state) 0°-ILSS (water saturated)
	Flexural testing at room temperature: 0°-flexural tests (as-received & water saturated state) 90°-flexural tests (as-received & water saturated state)
	Dynamic mechanical analysis (DMA): Torsional modulus vs. temperature Determination of glass transition temperature (T_g)

To carry out the test program of Table 2, laminates were produced consisting of 4 prepreg layers and cured under identical cure conditions as for the turbine distribution penstock relining (40°C for 5 days). In addition, some laminates were first pre-cured at 20°C for 24 hours followed by a post-cure of 40°C for 24 hours to cover effects related to the actual installation conditions of the prepregs in the turbine distribution penstock and to provide evidence for cure path independent laminate performance. In total, five series of laminates designated as laminate series 19 to 23, each series consisting of up to 8 individual laminate plates, were produced. The laminate lay-up design is depicted schematically in Fig. 2a, the specimen orientation and positioning in a laminate plate is shown in Fig. 2b.

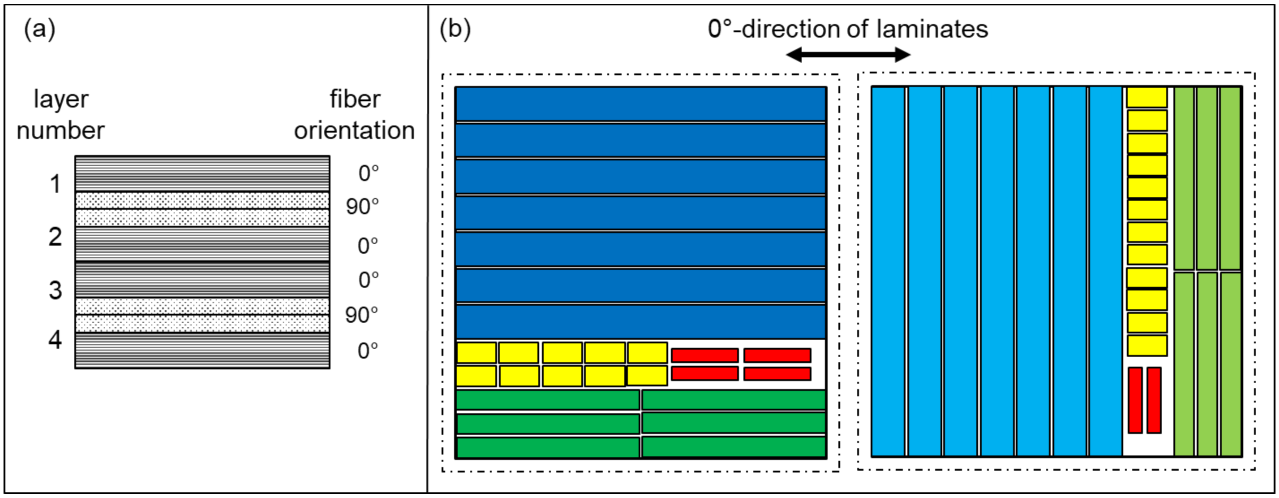


Fig. 2: (a) Laminate lay-up consisting of 4 symmetrical prepreg layers; (b) Specimen orientation in a laminate plate (plate dimensions 300x300 mm²) indicating the number and positioning of tensile specimens (blue), ILSS specimens (yellow), flexural specimens (green), and DMA specimens (red).

The tensile tests were performed at a temperature of 23°C in accordance with DIN EN ISO 527-4 using a 250 kN Zwick Z1485 universal testing machine. Specimens were saw-cut from laminate plates in both a 0°- and a 90°-orientation (see Fig. 2b). The specimen geometry was set to a length of 280 mm and a width of 25 mm. The specimen thickness was measured to the nearest 10 microns. To facilitate load introduction ±45° glass fiber reinforced plastic tabs with a length of 45 mm, a width of 25 mm and a thickness of 1 mm were adhesively bonded onto the specimens using a room-temperature curing adhesive. Tab edges were not tapered. Five specimens were tested for each laminate series in both fiber orientations. No pre-drying was imposed on specimens prior to testing.

Interlaminar shear strength (ILSS) tests were also carried out at 23°C using a 5 kN Zwick Z005 universal testing machine. The ILSS setup included a loading fin with a tip radius of 5 mm and a two-point support with a tip radius of 2 mm and a span of 15 mm (equivalent to five times the nominal specimen thickness). A pre-load of 5 N and a testing speed of 1 mm/min were applied. The specimen geometry for ILSS tests was set to a length of 30 mm and a width of 20 mm in accordance with EN ISO 14130 (deviations from the recommended 20 mm x 10 mm geometry are allowed as long as the length-to-width and the width-to-thickness proportions, 2:1 and 5:1 respectively, are met). The specimens were cut out from laminate plates in 0°-orientation using a circular saw. A total of ten specimens were tested for each laminate series in order to account for uncertainties arising from production-induced variations in laminate thickness. The evaluation of apparent interlaminar shear strength τ_{ILSS} was carried out according to:

$$\tau_{ILSS} = \frac{3}{4} \times \frac{F}{\mathrm{w} \times \mathrm{t}} \tag{1}$$

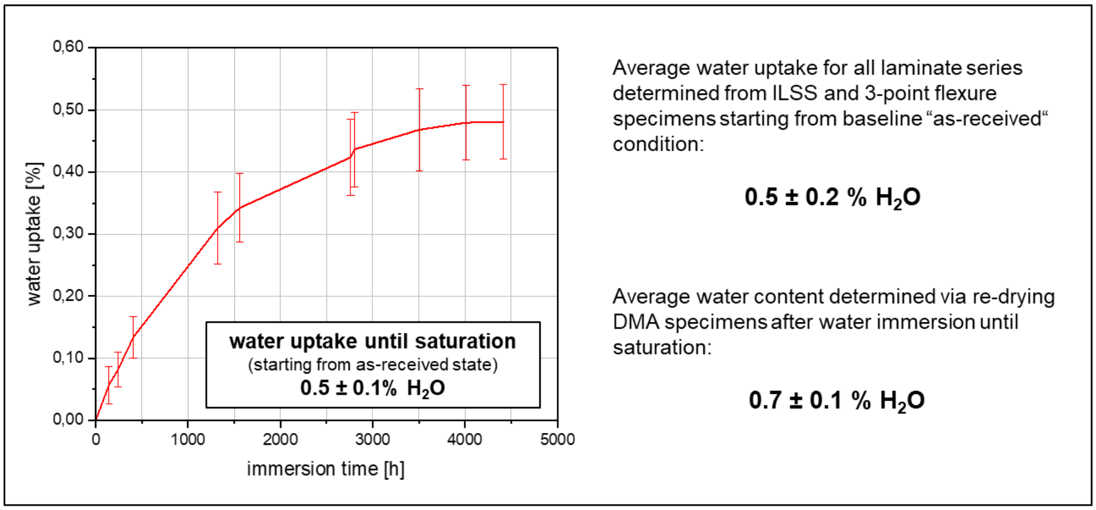
where F is the recorded force in N at the moment of delamination or the first local force maximum of the force-displacement-curve, and w and t are the specimen width and thickness, respectively.

3-point flexure (3PF) tests were carried out at 23°C using the same 5 kN Zwick Z005 universal testing machine as for ILSS testing. However, for the 3PF setup a span of 100 mm between supports was chosen roughly in accordance with the suggestions contained in EN ISO 14125, and a displacement gauge was employed for strain determination at the lower mid-span point of the specimens. Test were performed with a compliant polymer film layer below the central loading fin. The pre-load was kept at 5 N as for ILSS testing. The testing speed was set to 5 mm/min. Specimens with a length of 140 mm and a width of 15 mm were cut out from laminate plates again in 0°- and 90°-orientation (see Fig. 2b) using a circular saw. At least five specimens were tested for each orientation and each laminate series. No pre-drying was imposed on specimens before testing.

Dynamic mechanical analysis (DMA) was performed with an Anton Paar Physica MCR 502 rheometer in torsional mode using rectangular specimens with a length of 50 mm and a width of 10 mm cut out from the laminate plates in 0°-orientation using a circular saw (see Fig. 2b). Two specimens were tested for each laminate series. Actual width and thickness values were determined to the nearest 10 microns as the average of five measurements taken with a calliper along the specimen long axis. The DMA procedure comprised a test frequency of 1 Hz, a torsional deformation magnitude of 0.1%, a normal clamping force of 1 N, and a constant heating rate of 3°C/min in a temperature range from 0°C to 120°C. Nitrogen was used as a purge gas. Specimens were not dried before testing. Values for the glass transition temperature T_g were deduced from the maximum of the loss factor tanδ.

3. Results

Some key requirements for material qualification and for continuous quality assurance are related to laminate property values in the fully water saturated state. Hence, the water uptake for cured laminate specimens (in total 9 ILSS specimens were used) immersed in water at 23°C is depicted in Fig. 3. As illustrated, moisture saturation is achieved after about 4500 hours (ca. 6 months). While the moisture uptake from the as-received condition (already containing some undefined level of moisture) was found to be ca. 0.5 %, upon re-drying of moisture saturated specimens a moisture saturation level of ca. 0.7 % was determined, the latter value believed to be more representative of the true moisture content.



Average water uptake for all laminate series determined from ILSS and 3-point flexure specimens starting from baseline "as-received" condition:

0.5 ± 0.2 % H_2O

Average water content determined via re-drying DMA specimens after water immersion until saturation:

0.7 ± 0.1 % H_2O

Fig. 3: Water uptake determined with cured laminate specimens from an as-received condition after water immersion at 23°C and after re-drying from the fully water saturated state.

The key fiber-dominated mechanical properties of the cured laminates are shown in terms of normalized CF tensile modulus values, normalized CF tensile strength values, and laminate strain-to-break values in Fig. 4. The bar charts contain the mean values of all five laminate series, both in 0°- and in 90°-direction, also indicating numbers for the lowest and highest mean values measured. The standard deviations obtained for normalized CF modulus measurements in 0°- and 90°-directions ranged from 2.1 to 10.8% and 4.8 to 10.9%, respectively, depending on the laminate series. Normalized CF tensile strength values in the 0°- and 90°-direction exhibited standard deviations of 2.2 to 5.1% and 2.4 to 11.3%, respectively. The standard deviations of laminate strain-to-break values ranged from 4.3 to 16.1% for 0°-oriented specimens and from 8.6 to 25.1% for 90°-oriented specimens.

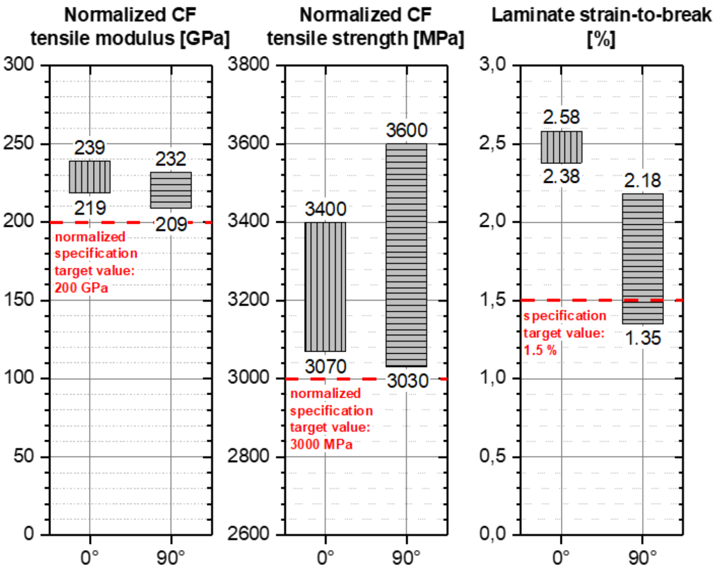


Fig. 4: Fiber-dominated tensile properties of cured laminates in 0°- and 90°-direction with indication of the relevant specification target values. Bar charts provide the range obtained for mean values of all five laminate series investigated.

The respective normalized specification target values for the various properties also depicted in the figure reveal that essentially all laminate series meet the qualification/specification requirements in terms of modulus and strength.

Some exceptions were found for the case of laminate strain-to-break, which are due to difficulties in accurately measuring the strain-to-break up to ultimate failure via mechanical extensometers and/or imperfections in specimen preparation (i.e. fiber misalignment when cutting out specimens). As discussed elsewhere, a better indication and additional information as to strain-to-break values may be obtained from flexural experiments [4, 5].

Conversely, the key matrix- and interface-dominated properties of cured laminates are illustrated in Fig. 5 for both the as-received and the water saturated laminate states, again indicating the range of mean values for the five laminate series. Figure 5a provides apparent ILSS data in comparison to the specification target values, which turned out to be surpassed by all laminate series. The standard deviations obtained for ILSS of specimens in the as-received state ranged from 5.3 to 10.1%, depending on the laminate series. Water-saturated ILSS values showed standard deviations of 4.3 to 8.0%. Figure 5a also shows the remaining "security window" for ILSS deterioration for the service-concomitant quality assurance measurements to be conducted over the next decades (30 % drop of values relative to the initial fully water saturated state). Furthermore, and although not specified in the material qualification, Fig. 5b contains information on the range of T_g values determined from DMA measurements again for all five laminate series in the as-received and fully water saturated states. Indicated numerical values are the average of two measurements rounded to the nearest full degree Celsius (hence, no standard deviations provided). The drop in T_g values from an average of about 80°C (as-received state) to about 72°C on average (fully water saturated state) is typical for the plasticization effect associated with moisture uptake in epoxy resins. These T_g data also represent the reference values for future investigations as part of the service-concomitant quality assurance scheme.

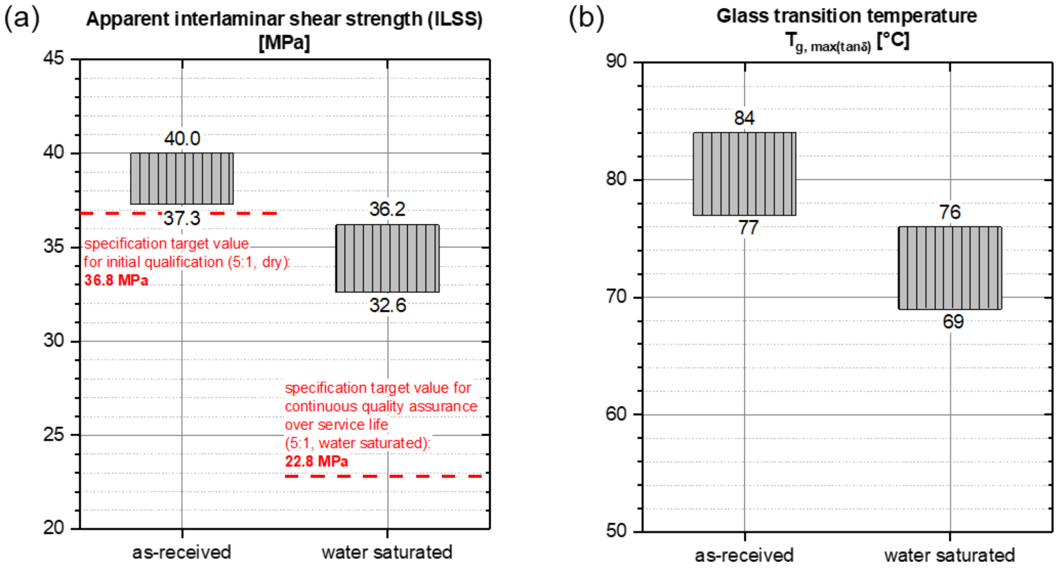


Fig. 5: Matrix- and interface-dominated properties of cured laminates in the as-received and water saturated state; (a) Apparent interlaminar shear strength (ILSS); (b) Glass transition temperature T_g determined via DMA.

4. Conclusion

As part of the certification for refurbishing the high pressure pipes of the turbine distribution penstock of the Kaprun hydro power main scheme, a comprehensive test program was carried out on CF/EP laminates to generate a data base for material qualification and specification. The experimental results obtained are shown to meet the structural design target values and provide a reference data base for the ongoing service-concomitant quality assurance testing.

Numerous difficulties related to specimen preparation, specimen conditioning, and regarding details of the test and data reduction procedures had to be resolved to ensure a high quality and reproducibility of experimental data. Thus, the rehabilitation of the high pressure turbine distribution penstock in Kaprun by relining with CF/EP prepregs may serve as an exemplary case study for other similar high pressure steel pipe refurbishments in the future.

Acknowledgements

The authors wish to acknowledge the support and contributions by others involved in parts of the work presented. The tensile tests were conducted by Dipl.-Ing. Andreas Mainz at the Department of Polymer Engineering of the University of Bayreuth, Germany (department head: Prof. Volker Altstädt).

We are also grateful to Ulrich Stadler, Arpitkumar Macwan, and Alexander Lovas of the Institute of Polymeric Materials and Testing (Johannes Kepler University Linz) for conducting the other mechanical tests and DMA measurements. Furthermore, the contribution by Mathias Leitl (Verbund Hydro Power) in the administration of the project is highly appreciated.

References

[1] P. Stering, E. Wagner, P. Widauer, “Reconstruction of the power conduit of the Kaprun main scheme,” Report, Verbund-Austrian Hydro Power AG, 2002.

[2] P. Stering, E. Wagner, “Experiences made at the new pressurised shaft of AHP Kaprun Hydro Power Plant,” *Conference on High Strength Steels for Hydropower Plants*, Graz University of Technology, Graz, Austria, 2005.

[3] R. W. Lang, “Erneuerung Kraftabstieg Kaprun – Hauptstufe: Sanierung der Turbinenzulaufleitungen durch CFK-Relining – Werkstoffauswahl, Werkstoffqualifikation und Qualitätssicherung,” Statusbericht als Beilage 12 zur wasserrechtlichen Einreichung, 2003.

[4] M. Gall, R. W. Lang, et al., “Mechanical Characterization of CF/EP laminates (working title),” in preparation.

[5] R. W. Lang, “Erneuerung Kraftabstieg Kaprun – Hauptstufe: Sanierung der Turbinenzulaufleitungen durch CFK-Relining – Werkstoffspezifikation und begleitende Qualitätssicherung,” Statusbericht für Kollaudierung, in preparation.