Slovak University of Technology in Bratislava, Faculty of Civil Engineering, Department of Concrete Structures and Bridges

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**Dissertation Thesis Abstract**

The effects of long-term loading and different environmental conditions on the behaviour of GFRP reinforced concrete members

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# ABSTRACT

This dissertation examines the long-term behavior of concrete beams reinforced with glass fiber reinforced polymer (GFRP) bars, focusing on their performance under sustained loading and environmental exposure. The study aims to assess the influence of GFRP reinforcement on bending capacity and deflection development over time, addressing a key gap in durability and serviceability knowledge. The research combines theoretical analysis, nonlinear finite element modeling (ATENA 3D), and a comprehensive experimental program with full-scale beams tested in four-point bending. Long-term tests lasted one to three years with sustained loads at 25%, 50%, and 75% of the short-term capacity, alongside real-environment exposure in parking lots and wastewater treatment plants. Results show that GFRP-reinforced beams have similar initial stiffness to steel-reinforced beams but experience significantly higher long-term deflections, especially in humid and aggressive environments. Nonlinear simulations aligned closely with experimental data, confirming the model's reliability. The findings underscore both the benefits and serviceability challenges of GFRP reinforcement, offering practical insights for improving design standards and long-term performance of reinforced concrete structures.

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# Introduction

The use of fibre-reinforced polymer (FRP) reinforcement in reinforced concrete (RC) structures has gained growing interest in recent decades, particularly for applications in corrosive environments. Among the FRP types, glass fibre reinforced polymer (GFRP) represents a cost-effective alternative to traditional steel reinforcement due to its non-corrosive nature, high tensile strength, and low weight. Despite these advantages, the lack of comprehensive long-term data has hindered its widespread adoption in practice, especially under sustained loading and aggressive environmental exposure.

This dissertation addresses a critical gap in the durability and serviceability assessment of GFRP-reinforced RC members by investigating the long-term effects of sustained mechanical loading and various environmental conditions. It employs an integrated approach combining theoretical modelling, finite element analysis (FEM), and experimental testing of full-scale beams subjected to real-time exposure and loading durations ranging from one to three years.

## 1.1 State of the art

The literature indicates significant differences in the short- and long-term behaviour of GFRP-reinforced concrete elements. While the material's high tensile strength and corrosion resistance offer design benefits, its relatively low modulus of elasticity and brittle failure characteristics present challenges under long-term service conditions.

Hall and Ghali (1999), Vijay (1999), and Abdalla (2002) reported that GFRP-reinforced beams exhibit greater long-term deflections compared to steel-reinforced elements. This is primarily due to reduced stiffness and lack of plastic deformation. Environmental factors, such as temperature fluctuations, moisture ingress, and alkaline exposure, were found to accelerate deterioration, particularly when combined with mechanical stress.

Advanced studies, including those of Barris et al. (2009) and Esmaeili et al. (2023), identified significant losses in bond strength and tensile capacity over time, reinforcing the importance of protective measures and careful detailing. Nassif et al. (2018) and Yang et al. (2021) suggested hybrid systems and improved surface treatments to mitigate these effects. Despite the inclusion of conservative reduction factors in guidelines such as ACI 440.1R-15, CSA S806-12, and fib Bulletin 40, long-term data from real environments remain sparse, which underscores the necessity of in-situ, full-scale testing.

# 2 Objectives of the dissertation thesis

This thesis aimed to investigate the long-term properties of GFRP bars used in RC members. These properties will be examined mainly through the sustain load applied on RC beams and its influence on bending resistance and deflections of RC beams. To achieve the aim the following objectives are presented:

- Verification of the effect of sustained high stress levels on flexurally loaded beams reinforced with GFRP, thereby verifying the long-term performance of this type of reinforcement.
- Monitoring of the progression of deformation over time in beams reinforced with GFRP under sustained long-term loading for verification of the predictions of existing design methodologies.
- Verification of the possibilities of nonlinear analysis methods for predicting the behaviour of GFRP-reinforced beams under loading conditions that change over time.
- Verification of the performance and durability of GFRP-reinforced beams in aggressive environmental conditions.

# 3 Study methods

In this chapter the methods of investigation for determination of creep rupture effects and sudden failures after high levels of long-term loading are presented.

To rigorously evaluate the behavior of GFRP-reinforced beams subjected to long-term exposure to high stress levels and different environmental conditions, and to empirically determine whether the existing reduction factors are justified, it was necessary to proceed as follows:

1. Short- term tests of pilot project to specify the resistance
2. Long-term tests - to simulate sustained load on assembly in period of 1 year and 3 years
3. Long-term tests- to simulate degradation in different environments

The behaviour of the beams was verified using three methodologies: theoretical calculations, nonlinear analysis, and experimental testing.

An initial theoretical calculation was conducted to predict the expected behavior of the beams.

The beams evaluated in this study had the following geometry:

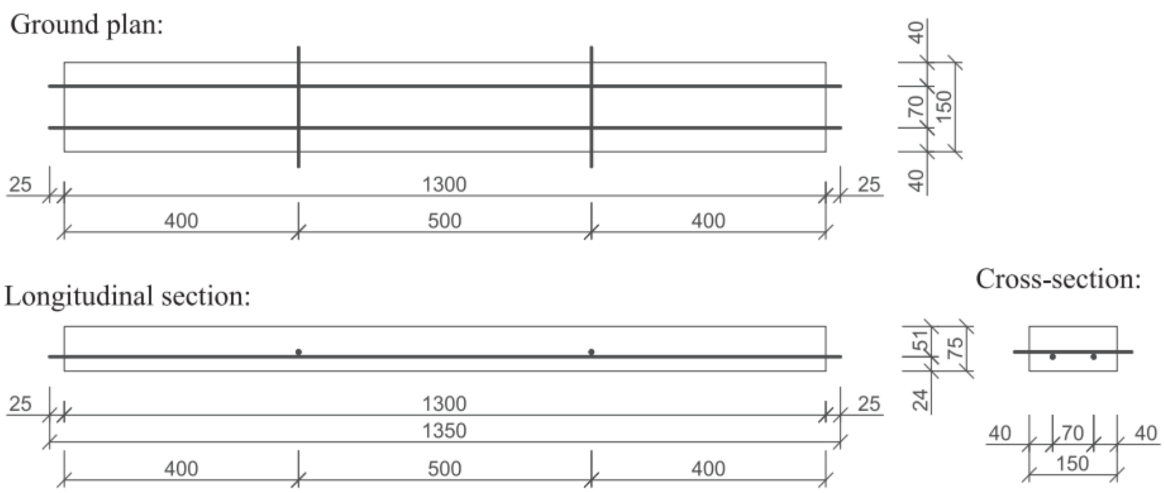


*Figure 3-1 Dimensions of concrete beam reinforced with GFRP reinforcement*

Following the preliminary theoretical calculations, the beams were fabricated (see the Section 3.3). After determining their actual material properties, the theoretical calculations were refined using these empirical material properties, as presented in Section 3.1.

## 3.1 Theoretical analysis

The subject of the analytical solution is the determination of the bending resistance of the element and calculation of deflection of the element.

### 3.1.1 Calculation of bending resistance

Material characteristics:

- in the calculation, the average values of the properties of the materials (see Chapter **Chyba! Nenašiel sa žiaden zdroj odkazov.** of Dissertation thesis)

The summarisation of inputs and obtained values from bending resistance calculation are presented in Table 3-1.

*Table 3-1 Summarization of inputs and obtained values from bending resistance calculation*

| h (mm) | Ø (mm) | $c_{nom}$ | $A_f$ (mm$^2$) | d (mm) | $f_{ck}$ (MPa) | $f_{fu}$ (MPa) | F (kN) | $\sigma_f$ (MPa) | $M_R$ (kNm) |
|---|---|---|---|---|---|---|---|---|---|
| 75 | 7 | 20 | 77 | 51 | 24.29 | 1070 | 7.18 | 531.2 | 1.972 |

Force F that is noted in the table is total force that should be applied to the beam at the loading scheme according to Figure 3-3

According to the calculations, the stress in the GFRP reinforcement at failure should be of about 530 MPa in tested beams. All the beams should fail by crushing of concrete in compression zone during bending. This value is important for determining the level of stress in GFRP reinforcement during long-term loading. Accordingly, it is assumed that under long-term loading at 75% of the tensile strength in the reinforcement 498 MPa.

### 3.1.2 Calculation of deflection

The basic theoretical analysis of short-term and long-term deflection was provided according to EC2-04 and EC2 -23 with modification of the parameters of reinforcement and editing of formulas according to balance reinforcement ratio. Another analysis was done according to American and Canadian design codes because of significant differences in reduction factors **Chyba! Nenašiel sa žiaden zdroj odkazov.**. In these comparisons the design process according to Bischof [10] and Mias[32] could also be included. Detail form of formulas can be find in Chapter **Chyba! Nenašiel sa žiaden zdroj odkazov.**

In Table 3-2 the summarization of results for numerically calculated immediate deflection in mid span are presented.

*Table 3-2 Values of prediction of immediate deflection at theoretical failure according to different formulas*

| | EC2-04 | EC2-23 | $B_{ST\text{-}ACI}$ | $M_{ST\text{-}ACI}$ |
|---|---|---|---|---|
| Deflection w (mm) | 30.368 | 30.368 | 29.455 | 29.455 |

## 3.2 Finite element model

The possibility to predict the actual behaviour of beams under bending tests and their deflections would be modelled in software for FE modelling. The important factors to be considered are the bond-slip relation and also the linear stress-strain relationship for GFRP reinforcement.

The objective of the nonlinear analysis is to approximate the actual behavior of the beams, allowing to perform parametric studies by adjusting parameters without the need for costly experimental research.

### 3.2.1 Numerical solution

Numerical analysis of concrete beams with GFRP reinforcement was performed in ATENA 3D software. The ATENA software was developed for the nonlinear analysis of reinforced concrete structures. The analysis in the given software allows to follow the development cracks, crushing of concrete or creep effect.

Numerical model was created for three different cases:

1. Short- term test of pilot project
2. Long-term tests- to simulate sustained load on assembly in period of 1 year and 3 years
3. Long-term tests- to simulate degradation in different environments

All three cases are consistent in topology. However differences can by find in material models and loading stages. Therefore in first and second case are material models equal and for the third case are values of material model different because of degradation of concrete.

For second case are sets of load cases different because of process of unloading of samples from assembly and subsequent reloading of the beams in the press machine until failure.

### 3.2.2 Results of non linear FEM analysis

The results of the numerical analysis are shown as a force dependence (sum of reactions in the support) and deflection of the beam. Other results (stress and proportional deformation of concrete and reinforcement) are shown for load step 62. Load step 62 was evaluated as one in which the bearing capacity of the beam is reached.

#### *3.2.2.1 Long-term tests- to simulate sustained load on assembly in period of 1 year and 3 years*

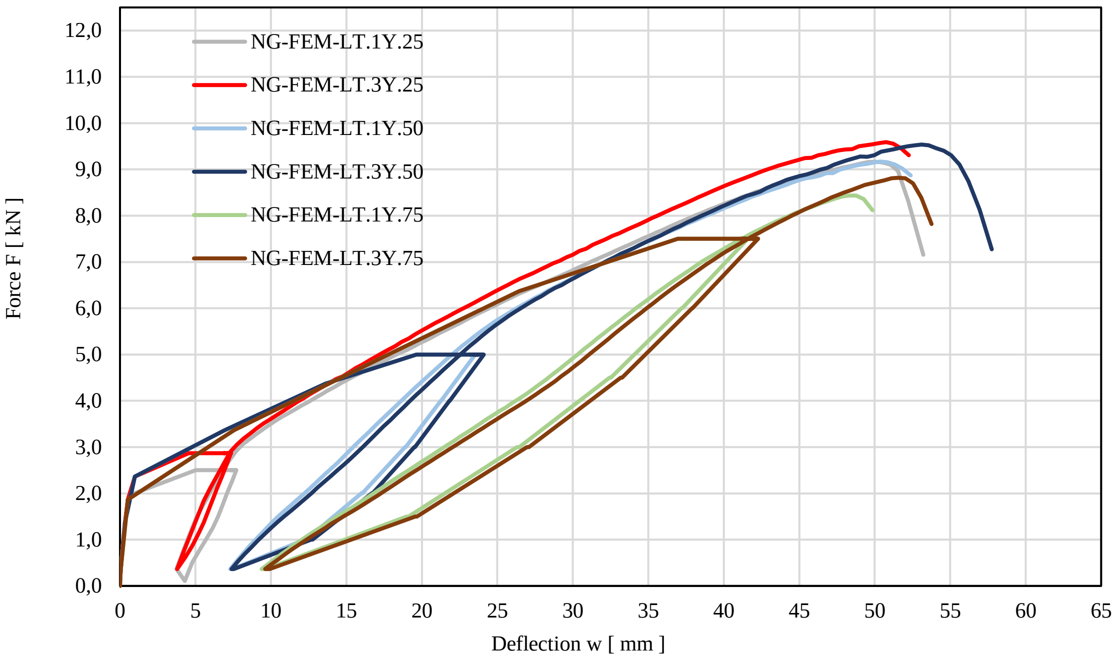


*Figure 3-2 Force to deflection diagram - beam with GFRP reinforcement- 1and 3 year 25to 75 %*

## 3.3 Experimental study

The experimental study was divided into three parts:

1. Short- term test of pilot project
2. Long-term tests- to simulate sustained load on assembly in period of 1 year and 3 years
3. Long-term tests- to simulate degradation in different environments

The first one, the pilot study, was used for determination of various parameters of tested beams and used materials and for verification of hypothesis. Synchronously were tested concrete samples to verify properties of concrete mixture.

The second one, the long-term study, is designed for different levels of sustained loading of GFRP bars in concrete beams.

The third part of the study are used for verification of environmental effects on GFRP RC concrete beams.

### 3.3.1 Load scheme

For all parts of experimental study was used equal loading scheme. It is a modified four-point bending test. The span between supports was 1 200 mm and forces were acting in the distance of 100 mm from the middle of beam on each side (see Figure 3-3). Modification of typical four-point bending test was done because of demanded failure mode- concrete crushing and bending failure. Although this type of loading scheme was chosen to simulate sustained load on loadbearing concrete members.

For the tests by hydraulic jack the loading was performed by increasement of the force in 0.5 kN per steps. During the process of loading the value of force and resulting deflection were monitored on each beam.

The prime objective of the investigation was to examine the relationship between the deflection at mid-span and the acting force and define the bending resistance of the beams. As the most accurate measurement method linear variable displacement transducer (LVDT) was used. The prediction of the deflection and resistance force were calculated according to various design codes and they were presented in[21]. The parameters obtained during the testing were recorded by computer software. The test was stopped after the cross-section failure.

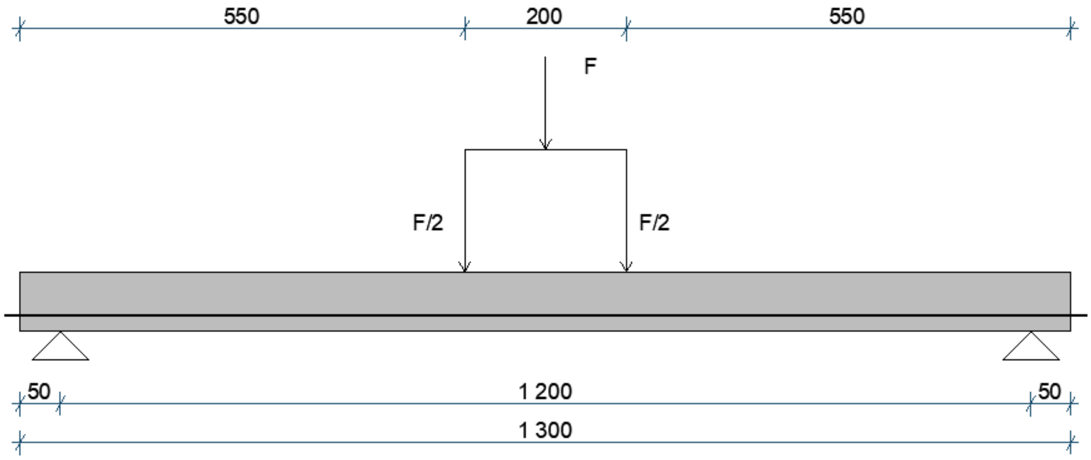


*Figure 3-3 Load scheme of beam in a four-point test*

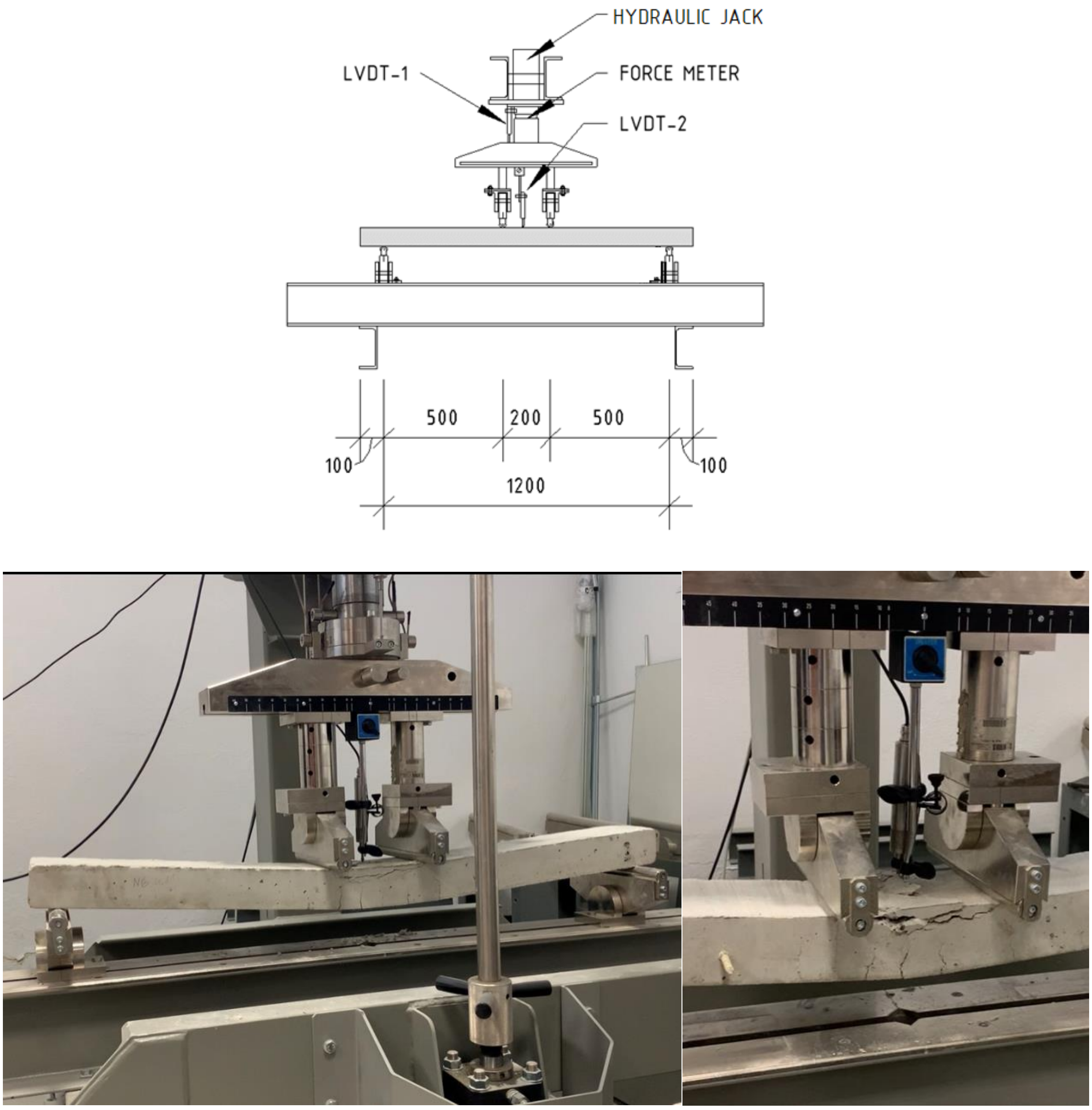


*Figure 3-4 The failure of the concrete crushing during a four-point test*

## 3.4 Pilot study

A pilot experimental study was designed to verify the mechanical properties of GFRP reinforcement and its behaviour in the concrete section. The aim of the experiment was to verify the bending resistance of beams and check their deflections.

During short-term tests, the acting force and deflection at the mid-span were monitored. The test was stopped after the cross-section failure. In total 9 beams were tested, five beams with GFRP reinforcement and four beams with steel reinforcement. From group of GFRP reinforcement three beams were cast down on 4$^{th}$ of November and two on 6$^{th}$ of November. In group of beams with steel reinforcement three beams were cast down on 4$^{th}$ of November and one on 6$^{th}$ of November.

All nine beams failed by concrete crushing at mid-span.

These teste were done on 14$^{th}$ of April 2021 in laboratories at Slovak University of Technology at Faculty of civile engineering.

The detailed course of the loading of the mentioned beams is presented in the following Figures.

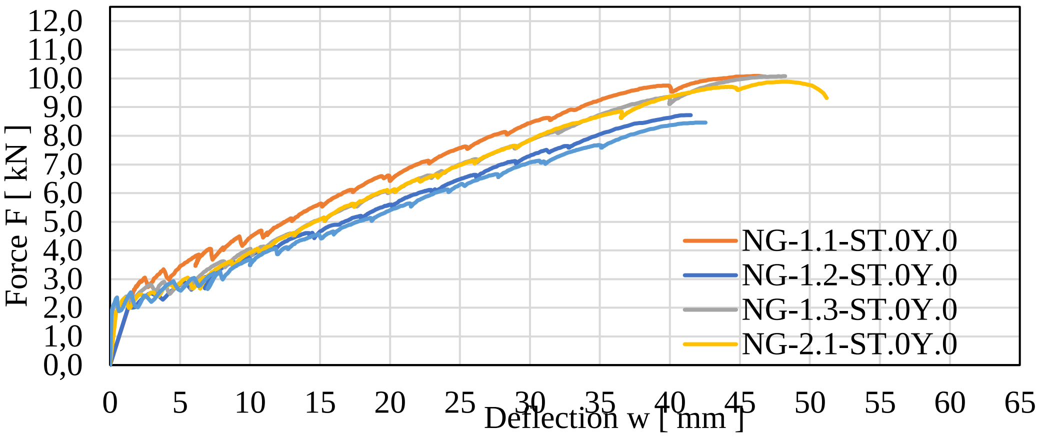


*Figure 3-5 Force- deflection diagram for beam reinforced with GFRP reinforcement from 1. and 2. series*

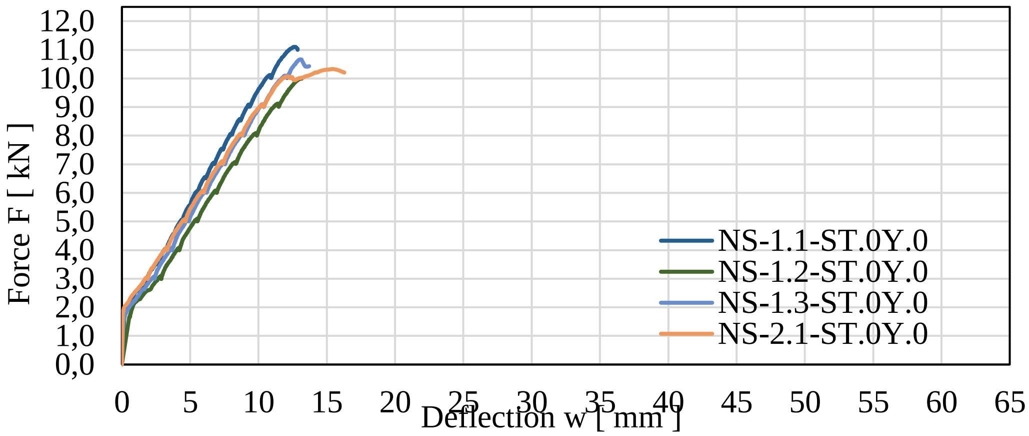


*Figure 3-6 Force- deflection diagram for beam reinforced with steel reinforcement from 1. and 2. series*

Summarisation of all obtained result is shown in **Chyba! Nenašiel sa žiaden zdroj odkazov.** at Dissertation thesis

From the results it can be concluded that average forces of beams reinforce with GFRP reinforcement are quite similar compared to those reinforced with steel reinforcement although deflection of these two groups is significantly higher at beams reinforced with GFRP reinforcement.

## 3.5 Study of long-term loading

After the experimental pilot study and determination of resistance, the set-ups for long-term tests-to simulate sustained load on assembly in period of 1 year and 3 years was possible to prepare.

In total thirty beams with GFRP reinforcement were loaded to 25%, 50%, and 75% of the immediate load capacity obtained by short-term testing.

In total there are ten set-ups made of three beams- on the top there is beam loaded to 25%, in the middle the beam loaded to 50 %, and at the bottom there is a beam loaded to 75%. Load includes self-wight of beams, steel parts of assembly, and the additional load.

The beams were supposed to be loaded for three different time periods: 1 year, 3 years, and 10 years for selected beams.

The distances between the supports and scheme of load are the same as in the modified short-term tests. It is important to mention that the beam in the middle, loaded to 50%, is turned upside down to get the tension on correct part of loaded beam. Immediately after loading, the actual deflection was measured on four of these set-ups, and current dial gauges were installed for long-term deflection measurements Figure 3-8.

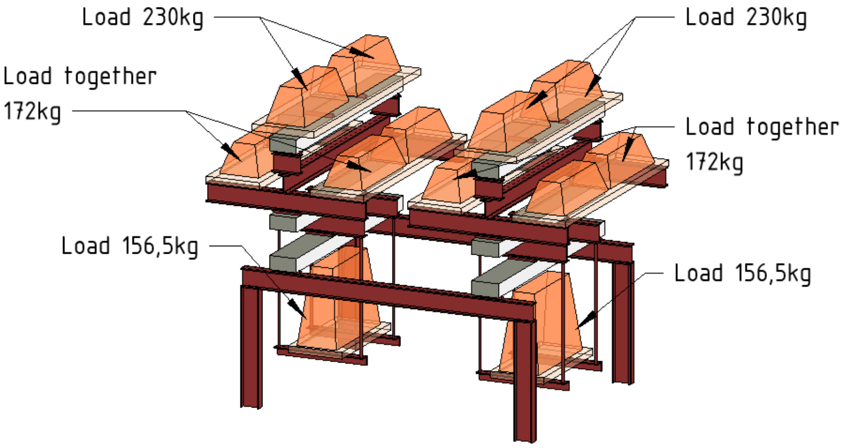


*Figure 3-7 Axonometry of loading scheme*

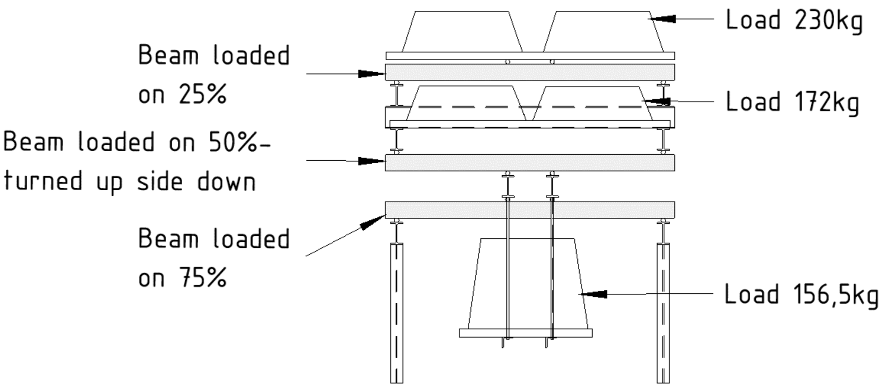


*Figure 3-8 Sets of beams- long-term loading*

Once the time period has been reached the actual deflection was measured. The load and beams were dismounted from assembly and residual deflection was measured. In next step the beams were tested in hydraulic jack till failure of beams as during Pilot study.

Tests after time period of one year were done on 20th of April 2022 in laboratories at Slovak University of Technology at Faculty of civil engineering and results are presented in following figures.

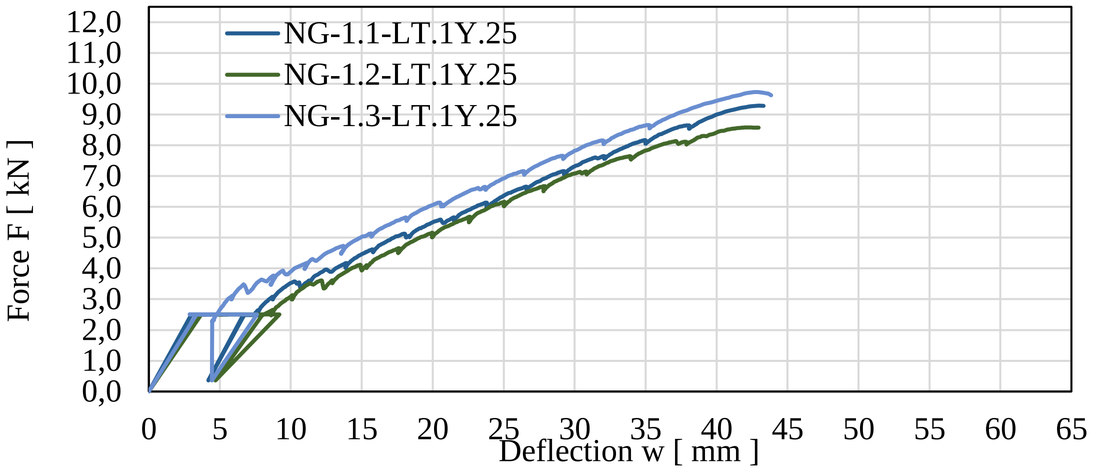


*Figure 3-9 Force-deflection diagram for beams from 1.serie reinforced with GFRP reinforcement loaded for time period of 1 year for 25% of resistance*

Tests after time period of three year were done on 7th of March 2024 in laboratories at Slovak University of Technology at Faculty of civile engineering and results are presented in following figures.

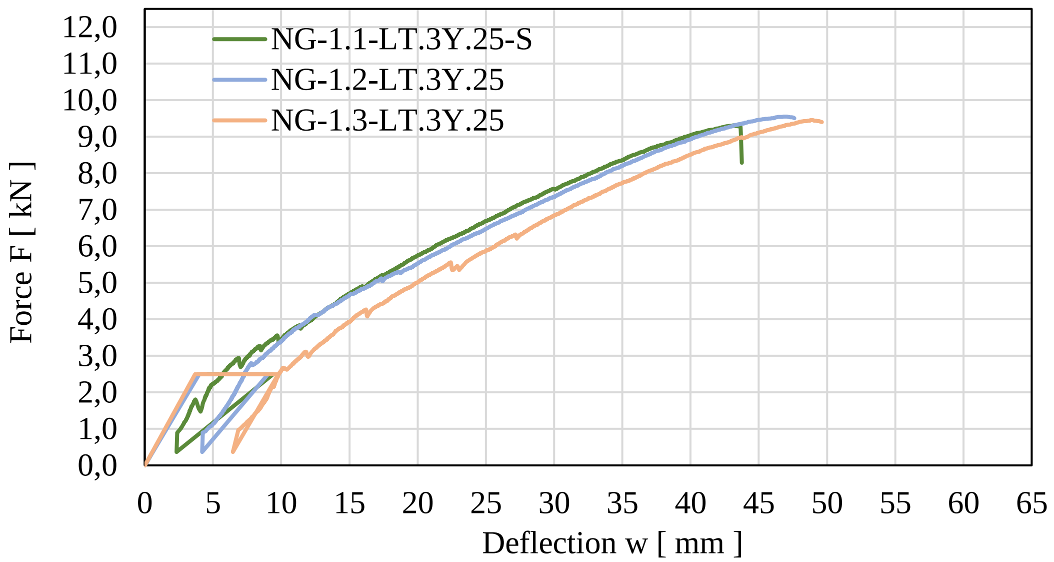


*Figure 3-10 Force-deflection diagram of loading force F for beams from 1.serie reinforced with GFRP reinforcement loaded for time period of 3 year for 25% of resistance*

Summarisation of all obtained result is shown in **Chyba! Nenašiel sa žiaden zdroj odkazov.** in Dissertation thesis.

Contrary to initial expectations, the beams subjected to the highest levels of sustained loading did not exhibit a decrease in material strength over time. It was anticipated that at a stress level of 75%, these beams might fail prematurely due to creep rupture. However, this did not occur. In fact, the most heavily loaded beams demonstrated the greatest durability when they were finally tested.

## 3.6 Study for environmental effects

It is well known that one of the main advantages of FRP reinforcement is its corrosion resistance. With this factor the effective depth of cross- section is directly affected because of lower cover layer of GFRP bars. According to this knowledge GFRP reinforcement could be a suitable replacement for steel reinforcement in structures exposed to aggressive environment. For this reason, was decided to expose some of beams to aggressive environment. All beams used in this part of experimental study were cast down on 6$^{th}$ of November.

This part of experimental study can be divided in four parts according to the type of environmental conditions to which were beams exposed

- Parking lot conditions
- Inflow channel of sewage water treatment plant
- Conditions nearby digestion tanks of sewage water treatment plant
- Laboratory conditions

The sewage water treatment plant is located near the city Trnava in small village Zeleneč.

*Table 3-3 Summarisation of values obtained from tests from of environmental effect- parking*

| Beam number | Maximum Force F (kN) | Average Force F (kN) | Deflection w (mm) | Average Deflection w (mm) |
|---|---|---|---|---|
| NG-2.1-P.1Y | 9.38 | 9.73 | 48.02 | 44.65 |
| NG-2.2-P.1Y | 9.71 | | 44.26 | |
| NG-2.3-P.1Y | 10.08 | | 42.34 | |
| NG-2.4-P.1Y | 9.73 | | 43.95 | |
| ~~NS-2.1-P.1Y~~ | ~~10.85~~ | 10.51 | ~~23.19~~ | 14.57 |
| NS-2.2-P.1Y | 10.47 | | 13.15 | |
| NS-2.3-P.1Y | 10.27 | | 13.89 | |
| NS-2.4-P.1Y | 10.81 | | 16.69 | |
| NG-2.1-P.2Y | 9.18 | 8.54 | 42.17 | 43.19 |
| NG-2.2-P.2Y | 8.18 | | 41.25 | |
| NG-2.3-P.2Y | 8.18 | | 44.34 | |
| NG-2.4-P.2Y | 8.60 | | 45.00 | |
| NS-2.1-P.2Y | 10.10 | 9.94 | 13.29 | 13.53 |
| NS-2.2-P.2Y | 9.91 | | 13.82 | |
| NS-2.3-P.2Y | 9.75 | | 12.80 | |
| NS-2.4-P.2Y | 10.00 | | 14.19 | |

All beams failed by concrete crushing, indicating that the failure mode was consistent across both materials and over time. The GFRP-reinforced beams maintaied their deflection characteristics despite a small reduction in load capacity, suggesting good durability under the tested environmental conditions. The steel-reinforced beams showed a marginal decrease in both load capacity and deflection.

### 3.6.1.1 Inflow channel of sewage water treatment plant

Another nine beams were placed in sewage water treatment plant. Six of them are placed directly in inflow channel. All beams were reinforced with GFRP reinforcement from series cast down at 6$^{th}$ of November. Two beams were exposed for time period of 1 year and two beams for 2 years. Two beams will be exposed to environmental effect for 5 years. The chemical properties of incoming sewage water were monitored- values can be find in **Chyba! Nenašiel sa žiaden zdroj odkazov.** and **Chyba! Nenašiel sa žiaden zdroj odkazov.** in Dissertation thesis.This environment can be described as highly aggressive and fully wet thought beams are immersed directly in to the chemically contaminated water contaminated.

*Figure 3-11 Beams before and after being placed into the inflow channel*

All beams failed by concrete crushing. Summarisation of all obtained result is shown in Table 3-4.

*Table 3-4Summarisation of values obtained from tests from of environmental effect- inflow channel of sewage water treatment plant*

| Beam number | Maximum Force F (kN) | Average Force F (kN) | Deflection w (mm) | Average Deflection w (kN) |
|---|---|---|---|---|
| NG-2.1-SWTC.1Y | 8.48 | 8.47 | 43.61 | 43.40 |
| NG-2.2-SWTC.1Y | 8.46 | | 43.19 | |
| NG-2.2-SWTC.2Y | 7.28 | 7.63 | 39.04 | 38.84 |
| NG-2.1-SWTC.2Y | 7.97 | | 38.63 | |

The GFRP-reinforced beams demonstrated satisfactory performance in a highly aggressive, chemically contaminated, and fully wet environment over periods of up to two years. The slight reductions in load capacity and deflection suggest minimal impact from the environmental exposure. These findings support the viability of using GFRP reinforcement in structures subjected to harsh environmental conditions, highlighting its potential for long-term durability and reliability in such applications

#### *3.6.1.2 Conditions nearby digestion tanks of sewage water treatment plant*

Another six beams were placed in nearby digestion tanks where the beams are influenced by aerosols of sewage water and also by climatic conditions. Two beams were reinforced with GFRP reinforcement and another four with typical steel reinforcement. All beams were from series cast down at 6th of November These samples were exposed to external changes of temperature during summer and winter season. During the winter season to frozen and water and by whole period to aerosols from digestion tank. This description of environment can be identical to slightly aggressive environment The average spread of temperatures according to the data available from the given location can be determined within the values from -4.3 till + 29.6°C. The average value of humidity in the outdoor environment can be considered 76.5 %, although in this case we should consider slightly higher values as beams are close to level of aggressive water. These data were collected by Slovak Hydrometeorological Institute at local hydrometeorological station at Kráľová pri Senci which is the nearest hydrometeorological local station from Zeleneč. Also this group of beams were divided according to time period exposed to environmental effect for 1 and 2 years. When time period was reached beams tested in laboratories at Slovak University of Technology at Faculty of civile engineering. Teste were done on 7th of Oktober 2022 and on 24th of July 2024.

As it can be seen from previous figures all beams failed by concrete crushing. Summarisation of all obtained result is shown in Table 3-5.

*Table 3-5 Summarisation of values obtained from tests from of environmental effect- sewage water treatment plant*

| Beam number | Maximum Force F (kN) | Average Force F (kN) | Deflection w (mm) | Average Deflection w (mm) |
|---|---|---|---|---|
| NG-2.1-SWT.1Y | 8.82 | | 42.20 | |
| NS-2.1-SWT.1Y | 9.99 | 10.05 | 12.49 | 12.34 |
| NS-2.2-SWT.1Y | 10.11 | | 12.19 | |
| NG-2.1-SWT.2Y | 9.68 | | 44.40 | |
| NS-2.2-SWT.2Y | 10.06 | 10.16 | 11.75 | 13.92 |
| NS-2.1-SWT.2Y | 10.26 | | 16.08 | |

The GFRP-reinforced beams demonstrated satisfactory structural performance in a slightly aggressive environment over exposure periods of up to two years. While they exhibited higher deflections compared to steel-reinforced beams—attributable to the material properties of GFRP—their load-bearing capacity remained stable.

#### 3.6.1.3 Laboratory conditions

The last set of beams were placed inside of laboratory environment. Laboratory conditions can be described as stabile inside building environment with standard average temperate of 20°C and average value of humidity 55%.

In total there were 4 beams with GFRP reinforcement and 4 Beams with typical steel reinforcement left in laboratory for one year. Another group of 6 beams with GFRP reinforcement and 4 beams with typical steel reinforcement were left in laboratory for three years. Teste were done on 27th of April 2022 and on 24th of April 2024.

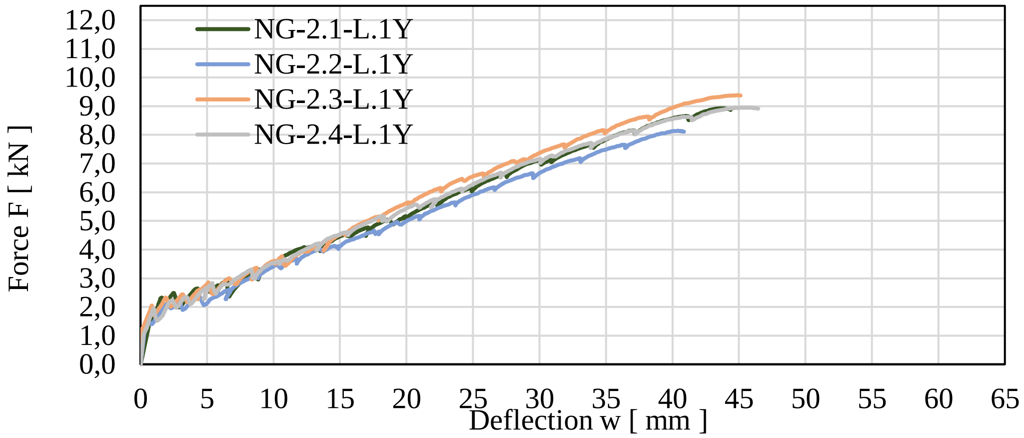


*Figure 3-12 Force-deflection diagram for beams from 2.serie reinforced with GFRP reinforcement exposed in laboratory - for time period of 1 year*

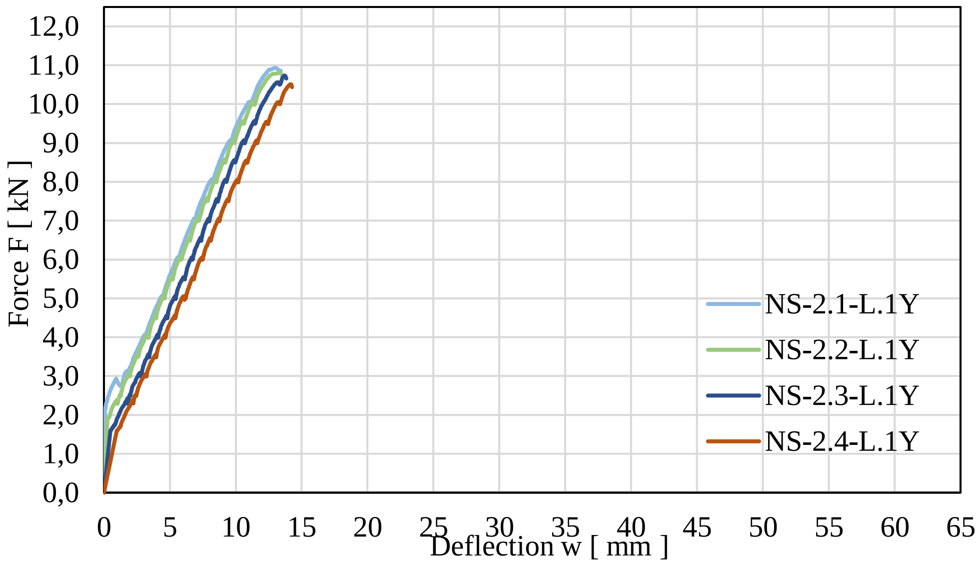


*Figure 3-13 Force-deflection diagram for beams from 2.serie reinforced with steel reinforcement exposed in laboratory - for time period of 1 year*

As it can be seen from previous figures all beams failed by concrete crushing. Summarisation of all obtained result is shown in Table 3-6.

*Table 3-6 Summarisation of values obtained from tests from of environmental effect- laboratory*

| Beam number | Maximum Force F (kN) | Average Force F (kN) | Deflection w (mm) | Average Deflection w (mm) |
|---|---|---|---|---|
| NG-2.1-L.1Y | 8.93 | 8.85 | 43.47 | 43.40 |
| NG-2.2-L.1Y | 8.15 | | 41.11 | |
| NG-2.3-L.1Y | 9.38 | | 44.01 | |
| NG-2.4-L.1Y | 8.95 | | 45.01 | |
| NS-2.1-L.1Y | 10.93 | 10.75 | 12.84 | 13.39 |
| NS-2.2-L.1Y | 10.81 | | 12.98 | |
| NS-2.3-L.1Y | 10.73 | | 13.63 | |
| NS-2.4-L.1Y | 10.51 | | 14.11 | |
| NG-2.1-L.3Y | 9.00 | 8.76 | 42.72 | 42.52 |
| NG-2.2-L.3Y | 9.39 | | 42.71 | |
| NG-2.3-L.3Y | 8.37 | | 44.08 | |
| NG-2.4-L.3Y | 8.79 | | 42.54 | |
| NG-2.5-L.3Y | 8.56 | | 40.65 | |
| NG-2.6-L.3Y | 8.60 | | 42.39 | |
| NS-2.1-L.3Y | 10.62 | 10.52 | 13.93 | 14,46 |
| NS-2.2-L.3Y | 11.00 | | 15.14 | |
| NS-2.3-L.3Y | 10.13 | | 14.32 | |
| NS-2.4-L.3Y | 10.34 | | 14.44 | |

The GFRP-reinforced beams demonstrated stable structural performance over one and three years in laboratory conditions. Despite having lower load capacities and higher deflections than steel-reinforced beams, the GFRP beams did not show significant changes over time.

## 3.7 Post-Test Analysis

After the completion of the study on the environmental effects on eight selected beams, four cylindrical samples each beam were extracted using core drilling. Compressive tests were subsequently performed on these cylindrical samples to determine their cylindrical strength. The outer diameter of the core drilling bit was 62 mm. The results of the individual test samples are presented in the following

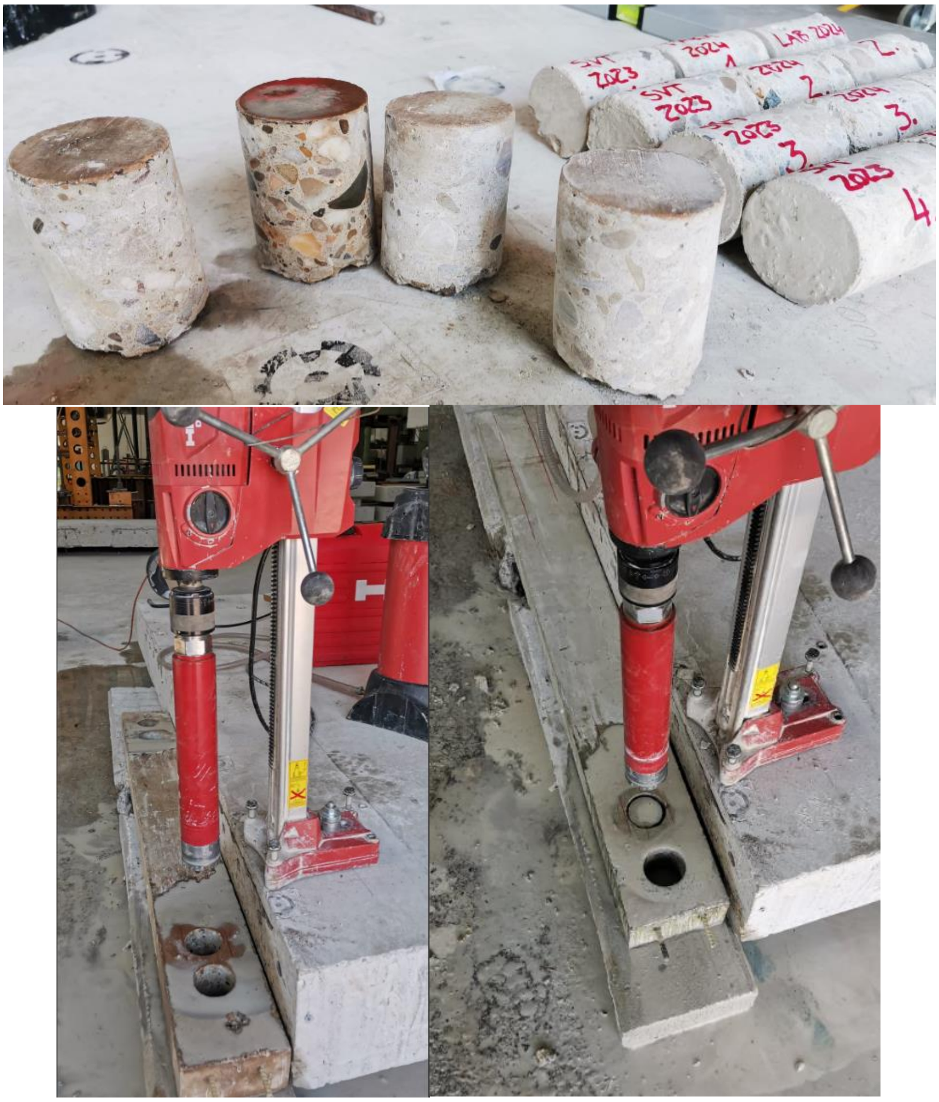

*Figure 3-14 Extracting of samples for post test analysis*

Following this pattern would be an appropriate way for analysis of GFRP RC members under environmental loading.

# 4 Discussion

## 4.1 Comparison of test results with theoretical predictions

In this section, a detailed comparison is made between the experimental findings and the initial theoretical predictions of this study. Theoretical models were established to predict the bending resistance and deflections of GFRP reinforced concrete beams. It was predicted that the beams would exhibit a bending resistance slightly over 7 kN and deflections approximately at 30 mm.

Measured values of immediate deflections were recorded upon the assembly of loading setups for long-term testing. These setups were designed to apply stress levels at 25%, 50%, and 75% of the beam's load-bearing capacity measured experimentally, corresponding to forces of 2.5, 5, and 7.5 kN, respectively. The measured deformations (higher than during short-term testing as mentioned before) were then meticulously compared with the deformations predicted by theoretical models according to different standards at these specific loading levels.

This comparison is aimed at validating the accuracy of the theoretical approaches used to predict the structural behaviour under varying load conditions. It provides insights into the material's performance and its response to sustained loads, which is essential for both the verification of theoretical models and the practical application in structural engineering design.

The calculated values and the results of the comparison are presented in the following figures. These visuals not only illustrate the alignment between predicted and actual deformations but also highlight any significant discrepancies that could inform adjustments to modelling techniques or material selection criteria in future projects.

The subsequent analysis discusses the implications of these findings, focusing on the potential for refining current prediction methods and enhancing the reliability of materials used in long-term structural applications.

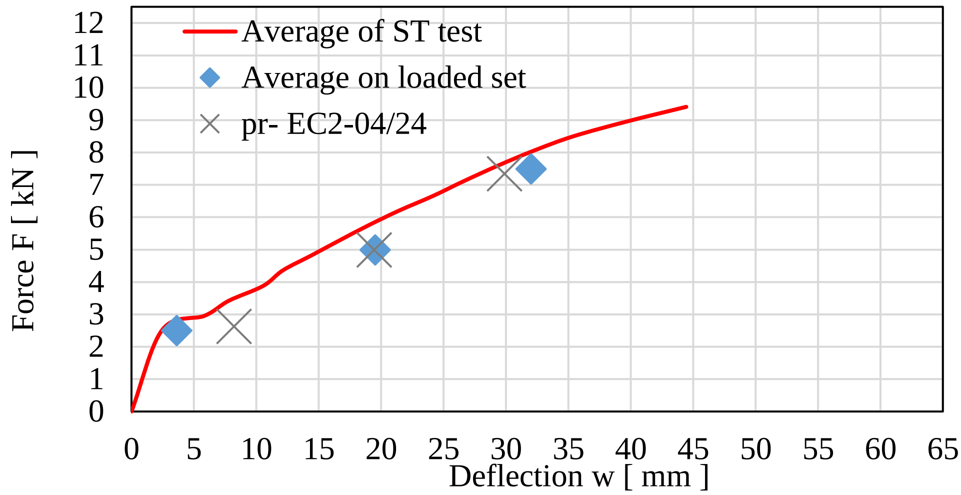


*Figure 4-1 Force-deflection diagram comparison of average of short-term tests to results from assembly for long-term tests immediately after loading and prediction according to EC2-04/24*

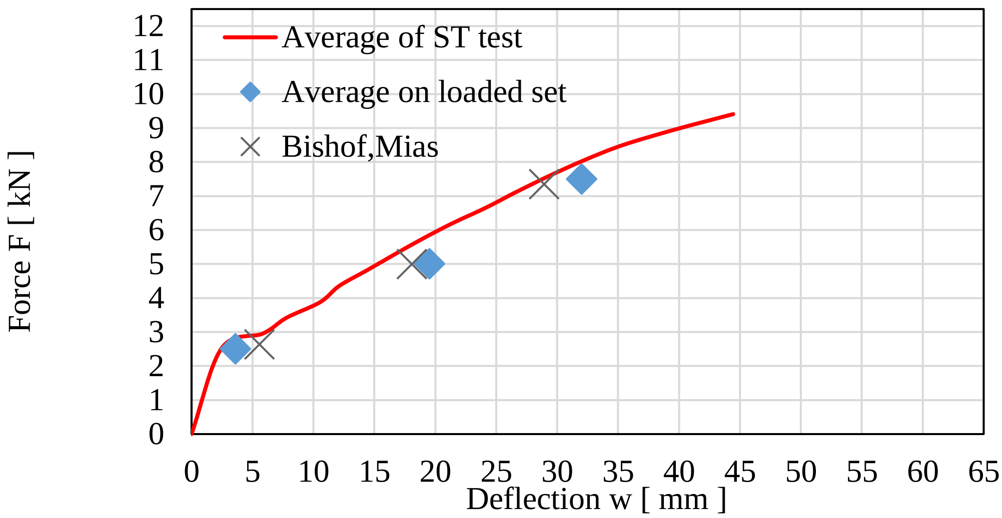


*Figure 4-2 Force-deflection diagram comparison of average of short-term tests to results from assembly for long-term tests immediately after loading and prediction according to Bishoff, Mias*

Figure 4-1 presents a comparison between the short-term test results and the predicted values according to the pr-EC2-04 and pr-EC2-24 standards. The experimental averages ("Average on loaded set") demonstrate that the deflections under applied loads are consistently higher than those predicted by the pr-EC2-04 and pr-EC2-24 standards. At a 25% loading level, the calculated deflection value is significantly higher (almost twice) than the measured one. Conversely, at a 50% loading level, there is a very good agreement (5% difference) between the calculated and measured values. However, at a 75% loading level, the calculated value deviates from the measured one, moving into a potentially unsafe range as the calculation underestimates the actual deflection (10%). It is also important to note that when comparing the calculated values with the curve from the short-term test, they are consistently on the safer side, indicating a conservative approach in the predictions provided by the standards.

Figure 4-2 compares the experimental results with the prediction according to the Bischoff & Mias model described in Chapter **Chyba! Nenašiel sa žiaden zdroj odkazov.** . The Bischoff & Mias model exhibits a somewhat better correlation with the experimental data at lower deflection levels. The results exhibit a high degree of congruence. At higher loading values, the performance of both methods closely aligns, similar to the behaviour observed in assemblies under slow loading conditions. This consistency across different loading scenarios underscores the reliability of the Eurocode in most practical applications, despite its minor deviations at lower stresses.

The abovementioned differences indicate that existing models might predict a somewhat stiffer response than what is observed in reality, particularly under higher loading conditions. Therefore, relying exclusively on these standards without considering the observed discrepancies could potentially result in designs that do not fully meet serviceability performance expectations, possibly leading to slightly larger deflections than anticipated in practice.

In the next step, the gradual increases in deformations of the beams due to the creep effect were measured on assemblies under long-term loading. These measurements provide important insight into the long-term behaviour of beams subjected to loading constant over time, allowing for observation of how deformations change over time due to the cumulative effects of material creep. In **Chyba! Nenašiel sa žiaden zdroj odkazov.**, progressively increasing deflections are depicted after 1 and 3 years. These results show that time-dependent creep causes significant changes in beam deflection, which has a substantial impact on the predictions of their long-term load-bearing capacity and serviceability in real conditions.

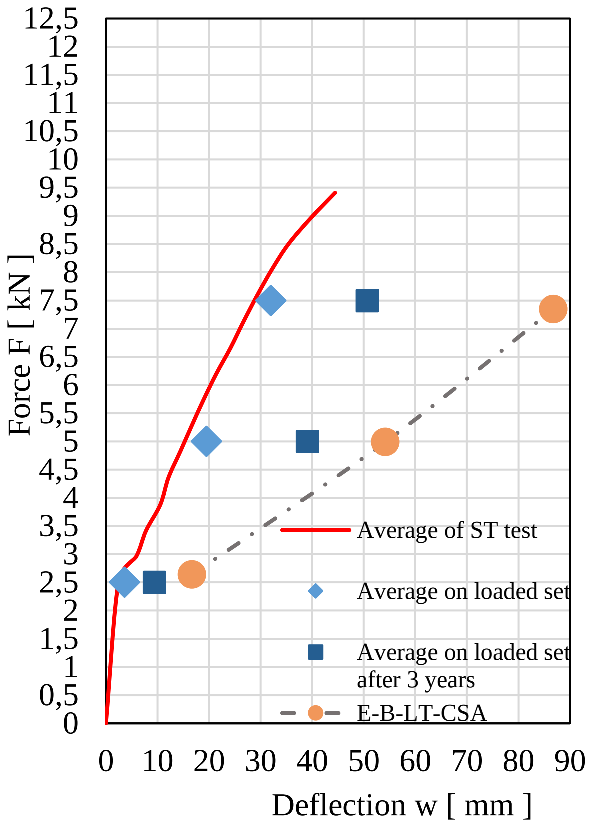


*Figure 4-3 Force-deflection diagram comparison of average of short-term tests to results from theoretical calculation for long-term tests at the time period of 3 years according to Bischoff -CSA*

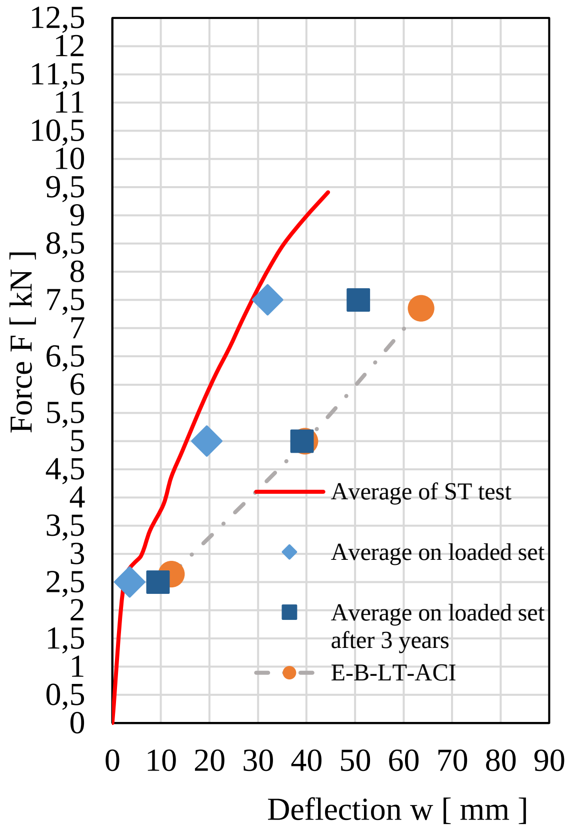


*Figure 4-4 Force-deflection diagram comparison of average of short-term tests to results from theoretical calculation for long-term tests at at the time period of 3 years according to Bischoff -ACI*

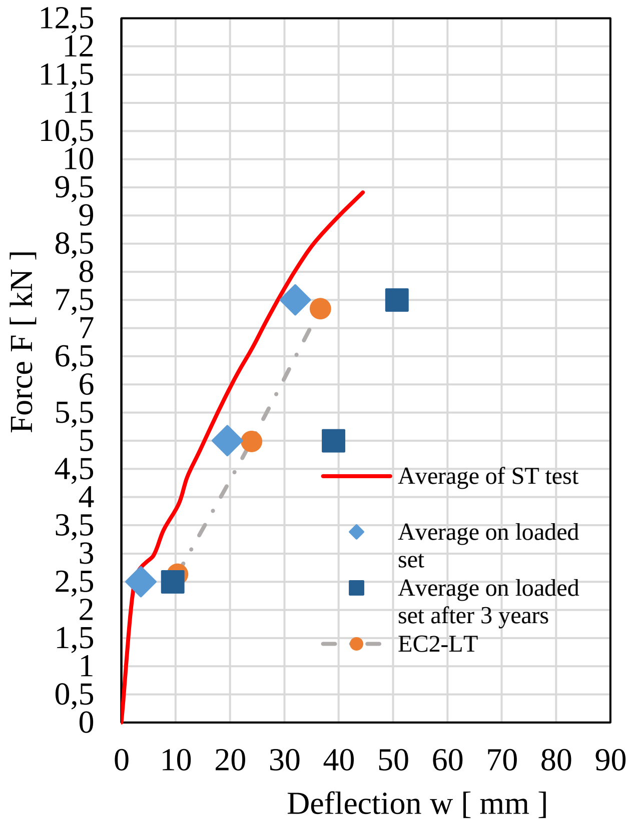


*Figure 4-5 Force-deflection diagram comparison of average of short-term tests to results from theoretical calculation for long-term tests at the time period of 3 years according to EC2-04/24*

Based on the presented figures, the comparison between experimental and theoretical deflection predictions highlights notable differences that vary across different models and loading levels.

Across the models, distinct trends can be observed. For example, according to the ACI predictions, the measured deflections after three years already align closely with the deflection values predicted for 3 years. This suggests that the ACI model might underestimate the rate of deflection increase over time. Conversely, the CSA model appears to provide the most realistic estimates, as the measured deflections remain below the predicted values, leaving room for potential growth in deflections over time. The EC2 predictions tend to show varying degrees of underestimation at higher loading levels, indicating insufficient consideration for real long-term behaviour.

These observations suggest that while standards such as ACI, CSA, and EC2 offer useful frameworks for estimating immediate deflection behaviour, their long-term predictions may not fully align with real-world performance. In particular, the ACI model may require further refinement to better capture the progression of deflections under sustained loads, while the CSA model shows promise but should be monitored for its long-term applicability. The most questionable is the assumption of the design in long-term view according to EC2.

For practical applications, engineers should approach these models with caution, particularly when designing for long-term serviceability under sustained loads. Additional safety factors or adjustments may be necessary to account for time-dependent factors like creep and sustained loading effects, which are not fully addressed in the existing models.

In conclusion, while these standards provide a solid foundation for deflection prediction, the discrepancies observed between the theoretical predictions and the experimental results underscore the need for continued refinement. Future research should focus on improving the accuracy of long-term deflection predictions to ensure reliable serviceability design and enhanced safety in reinforced concrete structures over their lifespan.

## 4.2 Effect of long-term loading on final resistance of beams

In addition to observing the gradually increasing deflection in long-term loaded samples, the results of which were presented in Chapter 4.1, some assemblies were dismantled after two different time periods (1 year and 3 years). The previously long-term loaded beams were unloaded, transferred to a test setup with a hydraulic jack, and tested to failure. The results of the load-bearing capacity of these experimentally tested beams are shown in the following figures.

The average values presented in the results were generally calculated from three tested beams. However, in the case of beams loaded for 1 year at 50% of the maximum load (group 1Y-Ave.50%), the average was calculated from only two beams, as one of tested beams failed due to shear.

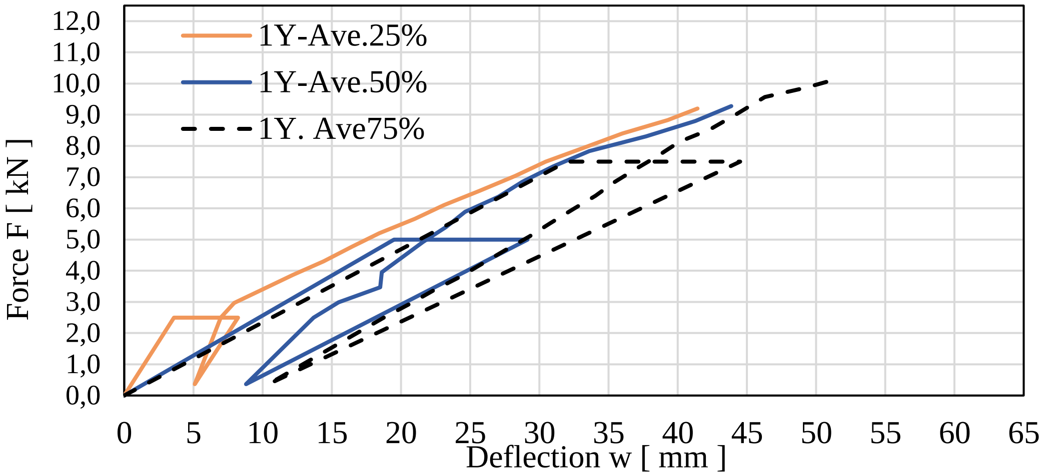


*Figure 4-6 Force-deflection diagram comparison of average of term-term tests with 25, 50 and 75 % of loaded sustained load for time period of 1 year*

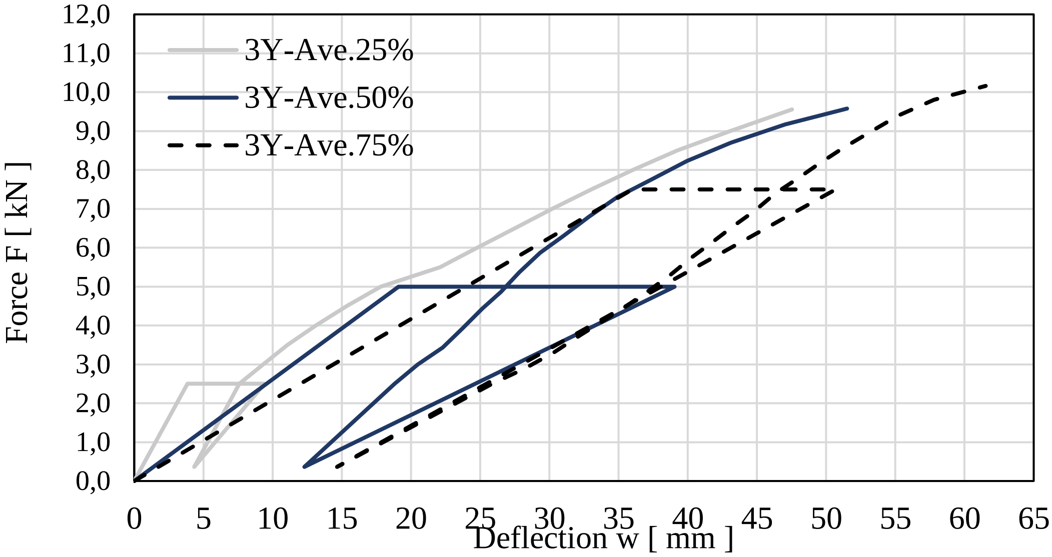


*Figure 4-7 Force-deflection diagram comparison of average of term-term tests with 25, 50 and 75 % of loaded sustained load for time period of 3 year*

The results reveal an interesting phenomenon. While the assumption in standards is that long-term exposure to high stress levels, which causes issues with the creep behaviour of GFRP reinforcement, necessitates the use of reduction factors to prevent sudden creep rupture Chapter **Chyba! Nenašiel sa žiaden zdroj odkazov.**, experiments have shown a different outcome. Although the deformation of the element increases over time proportionally to its load level, the final strength of these pre-loaded elements is, in fact, higher than the strength of beams subjected to lower levels of stress. Additionally, this strength exceeds the results of immediate tests conducted on beams that were not previously loaded.

This, however, did not occur. Even beams with reinforcement stressed to nearly 500 MPa over a three-year period did not fail under this load in the assembly; on the contrary, after dismantling, they exhibited the highest resistance. This clearly indicates that the reduction factors specified in the standards, derived from accelerated testing, significantly underestimate the actual performance potential of GFRP reinforcement.

## 4.3 Comparison of test results with non-linear analysis

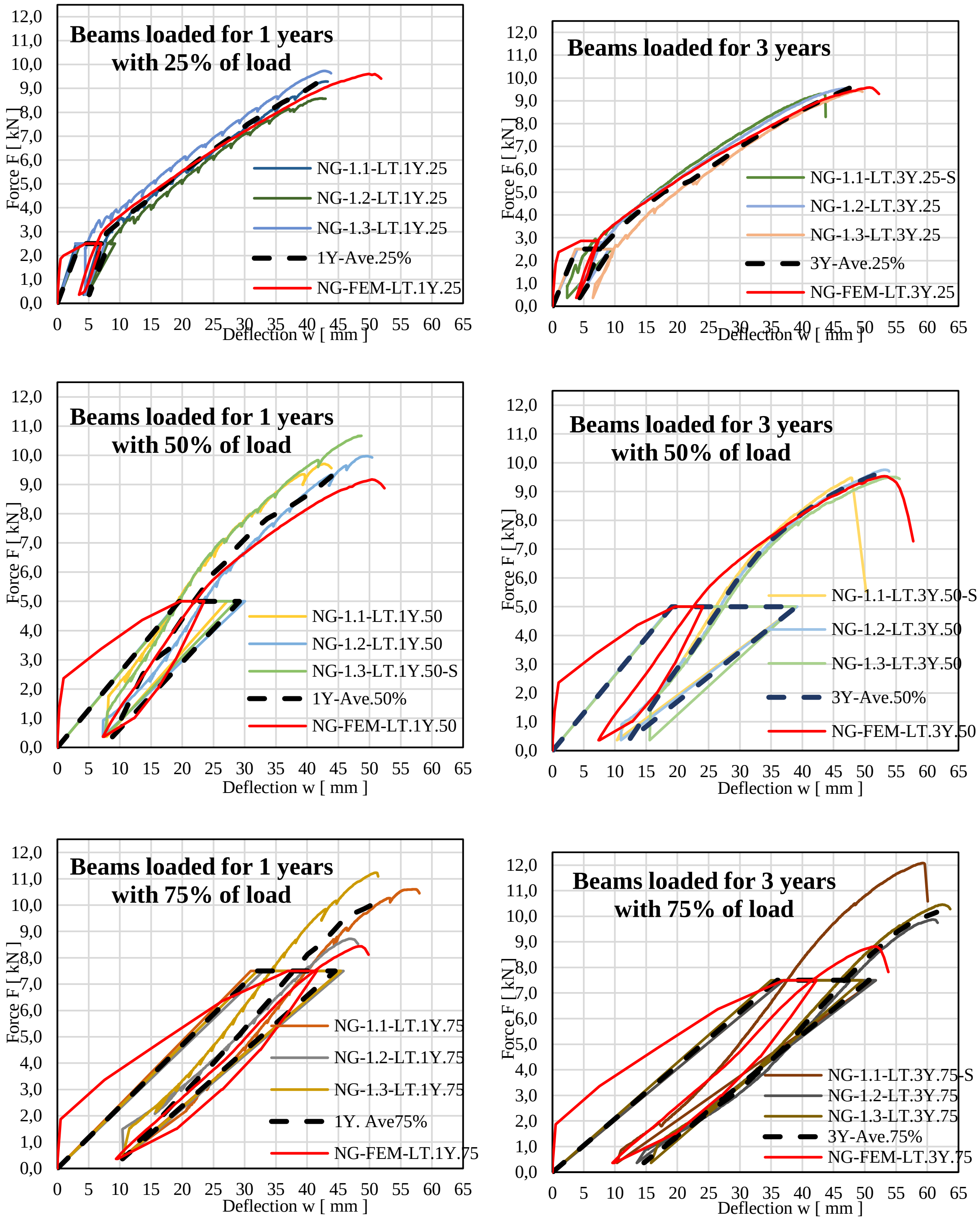


*Figure 4-8 Force-deflection diagram comparison of average of term-term tests and average of these value to FEM analysis in Atena*

In conclusion, while the numerical model is effective for predicting the behavior of beams under moderate long-term loading, experimental validation remains essential, especially for higher preloading levels. This ensures that the design and analysis of reinforced concrete beams can rely on accurate, realistic data that reflects actual performance under long-term loading conditions.

## 4.4 Environmental effect

In the following figure, the results for beams that were not directly exposed to aggressive runoff but were subjected to aerosol exposure are presented. Both steel-reinforced and GFRP-reinforced beams were included in this analysis.

The observations indicate the following:

- **After 1 year**: The GFRP-reinforced beams showed results comparable to those stored in laboratory conditions, indicating similar performance. In contrast, the steel-reinforced beams exposed to the outdoor environment exhibited a clear decline in resistance.
- **After 2 years**: The GFRP-reinforced beams appeared to demonstrate favorable behavior under exposure to such aerosols, as there was no recorded decrease in resistance; in fact, a slight increase was noted. However, as this result was based on a single beam, it is difficult to draw significant conclusions. On the other hand, the steel-reinforced beams showed a continued decline, consistent with the results observed after 1 year.

These findings suggest that GFRP reinforcement maintains its performance better under aerosol exposure compared to steel, but further testing would be needed to draw more definitive conclusions.

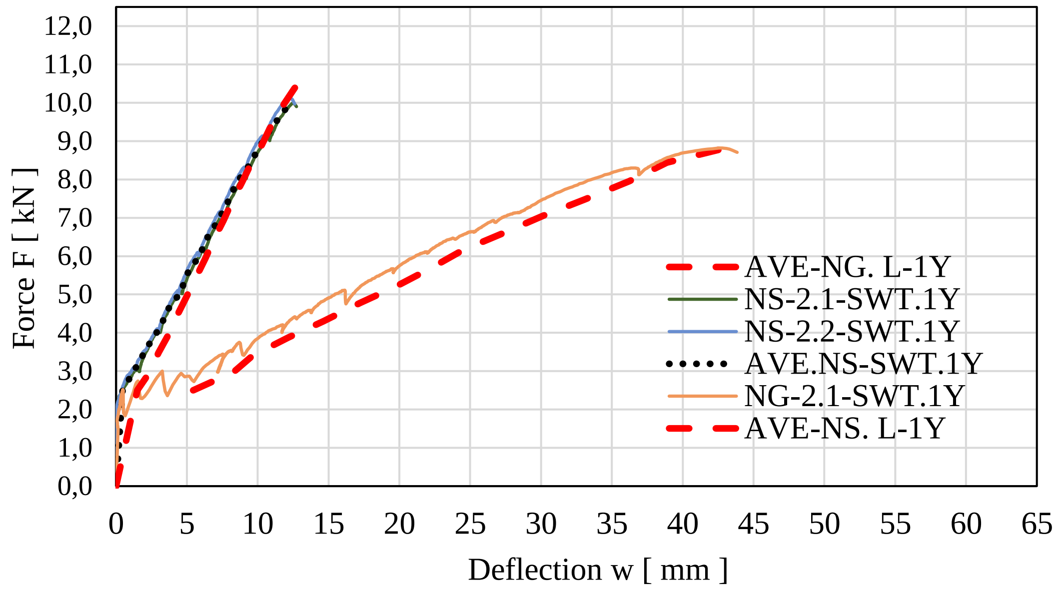


*Figure 4-9 Force-deflection diagram comparison short-term tests of beams reinforced with GFRP and steel reinforcement left near digestion tanks condition for time period of 1 year compared to beams in laboratory*

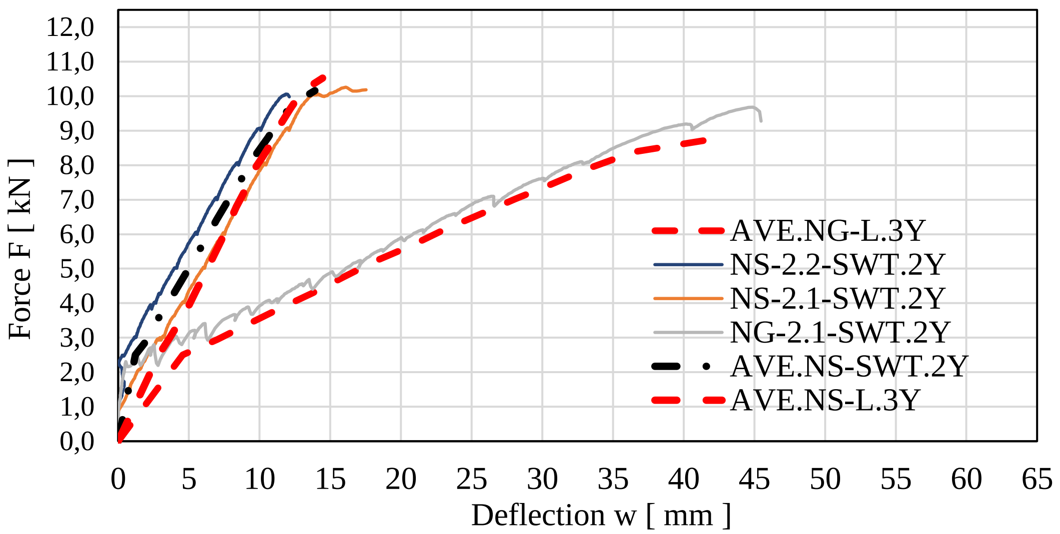


*Figure 4-10 Force-deflection diagram comparison short-term tests of beams reinforced with GFRP and steel reinforcement left near digestion tanks condition for time period of 2 year compared to beams in laboratory*

The comparison of behaviour in different environments is shown in Figure 4-11. Based on the results, it can be concluded that, with a properly maintained concrete cover, even the aggressive environment of the runoff channel does not lead to a reduction in the ultimate resistance of beams reinforced with GFRP. However, the experiment would likely benefit from being expanded with a larger number of samples and longer observation periods. Additionally, the influence of cracks in loaded elements would also be a point of interest.

Conversely, in the case of beams with steel reinforcement, a reduction in resistance due to the aggressive environment is already evident in these samples see Figure 4-13.

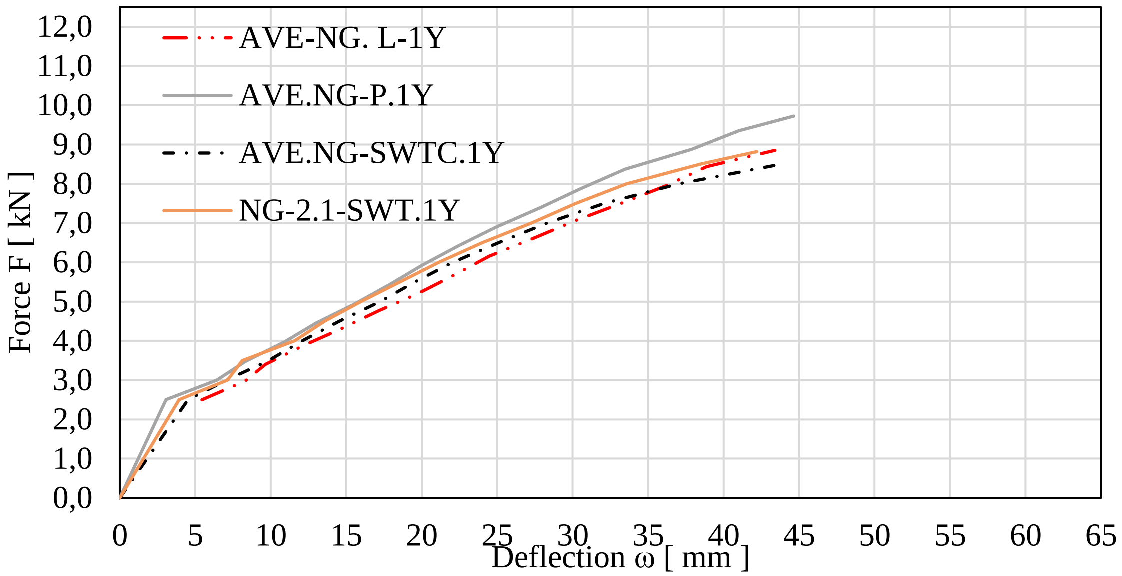


*Figure 4-11 Force-deflection diagram comparison short-term tests of beams reinforced with GFRP reinforcement left in various condition compared to beams in laboratory after 1 year*

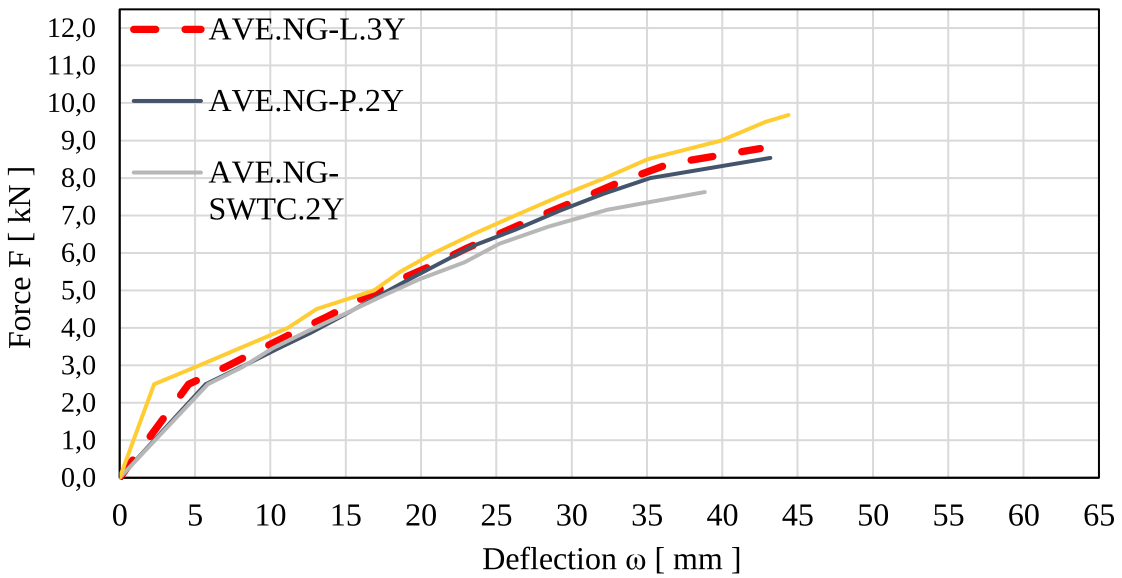


*Figure 4-12 Force-deflection diagram comparison short-term tests of beams reinforced with GFRP reinforcement left in various condition compared to beams in laboratory after 2 or 3 years*

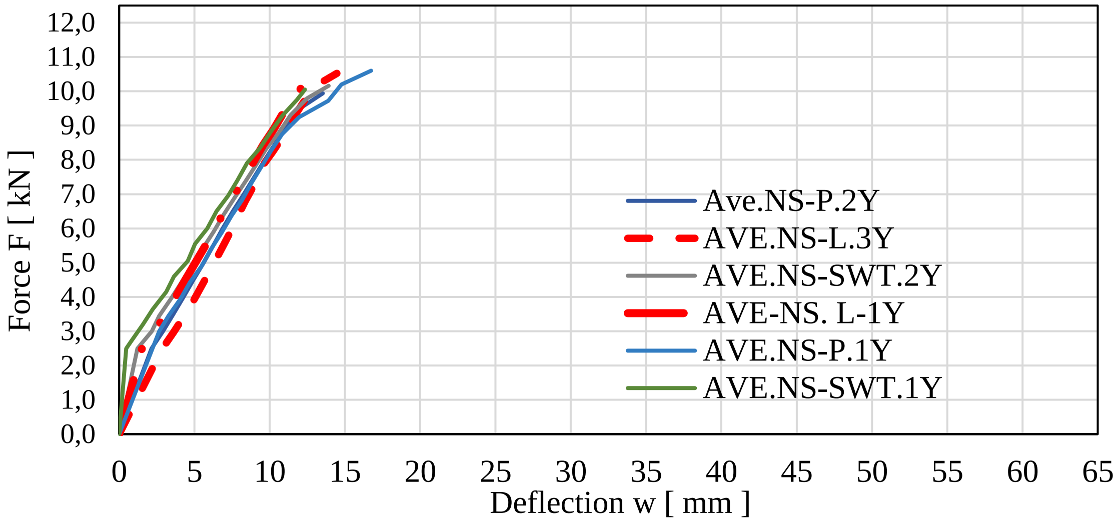


*Figure 4-13 Force-deflection diagram comparison short-term tests of beams reinforced with steel reinforcement left in various condition compared to beams in laboratory*

# 5 Conclusion

## 5.1 Development of the scientific field

The results of this dissertation provide valuable insights into the behaviour of GFRP-reinforced concrete beams under various loading and environmental conditions. Based on the findings, the following points should be considered for future research and improvements in design standards:

- **Immediate Deflections**: The calculations of immediate deflections based on current standards align well with the measured values, suggesting that these standards are reliable for short-term predictions. However, further studies might explore whether this agreement holds across a wider range of structural configurations and loading conditions.
- **Long-Term Deflections**: The observed long-term results highlight inconsistencies among different standards. The Eurocode tends to underestimate deflections, the ACI predicts deflections after 50 years that were already measured experimentally after three years, and the CSA often overestimates deflections. These discrepancies might indicate that the long-term predictive models used in these standards should be reconsidered to more accurately reflect real-world behaviour. Additional experimental data over extended periods could help refine these models and improve their reliability.
- **Ultimate Resistance**: The ultimate resistance of beams subjected to sustained loading for one and three years did not decrease as might be expected; in fact, it was slightly higher. This finding suggests that the reduction factors prescribed by current standards could be overly conservative. A review of these factors might be warranted to ensure that GFRP reinforcements are not unnecessarily limited in their structural applications.

## 5.2 Environmental Effects:

- Alternating Wet and Dry Conditions: Alternating wet and dry environments, particularly with aerosol exposure, have a noticeable negative impact on the performance of concrete beams. While GFRP reinforcements performed slightly better than steel, this behaviour suggests that further testing might be beneficial to better understand the long-term effects of these conditions and optimize material selection.
- **Aggressive Environments**: In aggressive environments, the primary degradation was observed in the concrete. However, with proper cover thickness, no significant signs of GFRP degradation

were detected. This indicates that appropriate design measures should continue to be emphasized to mitigate environmental effects and ensure durability.

These findings suggest that more comprehensive experimental studies, particularly over extended timeframes and under diverse environmental conditions, might help refine existing standards and improve their accuracy. Such efforts would lead to more reliable, efficient, and broader applications of GFRP reinforcements in structural engineering.

## 5.3 Recommendation for practice

Based on the findings of this study, the following recommendations are proposed for the practical application of GFRP reinforcements:

- **Use in Applications with Less Sensitivity to Deflection**: While GFRP reinforcements demonstrate excellent strength and durability, special attention should be given to deflections. GFRP is particularly suitable for structures where deflection monitoring is not a critical factor, such as non-serviceability-critical elements or temporary structures.
- **Application in Aggressive Environments**: The results suggest that GFRP reinforcements perform well in harsh environments, including alternating wet and dry conditions or exposure to aggressive agents. Therefore, GFRP can be confidently recommended for use in such environments, provided adequate concrete cover and proper design measures are implemented.
- **Re-evaluation of Strength Reduction Factors**: Given the good resistance of GFRP reinforcements observed over the years, it is advisable to reconsider the use of highly conservative strength reduction factors in some standards. Adopting less restrictive factors from standards with lower safety margins could enhance the material's utilization while maintaining safety and reliability in design.

## 5.4 Recommendation for further research

To advance the understanding and application of GFRP reinforcements, the following areas are recommended for future research:

- **Investigation of Environmental Effects**: Further studies should focus on examining the long-term impact of various environmental conditions on GFRP-reinforced structures. This includes evaluating performance under aggressive environments and alternating wet and dry conditions.
- **Comparison of Accelerated Tests with Real-World Exposure**: It is essential to compare results from accelerated laboratory tests with data obtained from structures exposed to real-world conditions. Such comparisons would help validate testing methodologies and ensure that accelerated tests accurately predict the long-term behavior of GFRP reinforcements.
- **Larger Statistical Samples**: Future experimental studies should incorporate larger statistical samples to enhance the reliability of conclusions and allow for more robust evaluations of variability and uncertainty in GFRP performance.
- **Parametric Studies Using Nonlinear Numerical Analysis**: The application of nonlinear numerical analysis for parametric studies is strongly recommended. This approach can provide a deeper understanding of how various parameters influence the behaviour of GFRP-reinforced structures, leading to more optimized and efficient designs.

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