FEM analysis of FRP RC members

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Abstract. The main reasons for choosing fiber reinforced polymer (FRP) materials in the process of designing reinforced concrete structures is their high strength and low weight-to-strength ratio. Also, the corrosion resistance of FRP is the reason for using this type of reinforcement in concrete in an aggressive environment. Since the number of long-term tests is insufficient, the long-term properties and behaviour of FRP reinforced concrete structures are not well-known, yet. The design codes offer the reduced utilisation capacity of FRP materials and it is becoming obvious that it would be appropriate to modify them according to the experiments of the last decades. Reduction factors limit mechanical properties ranging from 0.95 for CFRP to 0.5 for GFRP. The article presents a long-term experimental study based on a four-point bending test on simply supported concrete beams reinforced with GFRP reinforcement in comparison with the results of the FEM analysis.

1 Introduction

Fiber Reinforced Polymer (FRP) reinforcement represents a class of advanced materials designed to enhance the strength and durability of reinforced concrete (RC) structures. These reinforcements are made from a polymer matrix reinforced with fibres. FRP materials have emerged as a superior alternative to traditional steel reinforcement due to several key advantages, especially in contexts requiring resistance to environmental degradation or in structures exposed to aggressive environments.

Glass Fiber Reinforced Polymer (GFRP) reinforcement emerges as a premier solution in the domain of concrete structural reinforcement, attributing its prominence to the integration of glass fibres. The paramount advantage GFRP presents is its corrosion resistance, rendering it particularly advantageous for application in environments characterised by chemicals, moisture, or salinity, such as maritime constructions or infrastructure subjected to de-icing agents. This attribute of corrosion resistance substantially augments the longevity and diminishes the maintenance requisites of concrete structures fortified with GFRP. Additionally, the notable strength-to-weight ratio of GFRP reinforcement facilitates a significant enhancement in structural strength without the imposition of excessive weight, thereby presenting a strategic advantage in the reinforcement of concrete structures.

Finite Element Method (FEM) analysis plays a crucial role in understanding and predicting the behavior of RC members reinforced with GFRP bars. This computational

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technique enables engineers to create detailed models of complex structures to simulate their response under various loads and conditions. FEM analysis allows for the exploration of the structural behavior of GFRP-reinforced RC members, including stress distribution, deflection, cracking patterns, and failure modes. By accurately modeling the unique material properties of GFRP, such as its anisotropic nature and the bond characteristics between GFRP bars and concrete, FEM analysis can provide valuable insights into the performance of these reinforcements in real-world scenarios.

Benmokrane and Ali (2019) [1] conducted a comprehensive review assessing various theories for modelling the durability of GFRP reinforcement in concrete structures, emphasizing the need for accurate predictive models to understand long-term performance. Fergani et al [2]. delved into the long-term performance of GFRP bars in concrete elements under sustained load and environmental actions, presenting a crucial link between accelerated aging conditions and their impact on tension stiffening response and flexural behavior due to bond degradation**.** Lu et al. [3] presented a nonlinear analysis of reactive powder concrete beams reinforced with hybrid GFRP and steel bars, contributing to the understanding of how these materials interact under stress and the potential for optimizing beam designs

A large database of publications describes the behavior of elements reinforced with GFRP reinforcement. In comparison with this base is an examination of important data. Hall and Ghali [4], Vijay [5], Abdalla [6], Bischoff [7], Mia's et al. [8] conducted various researches in the field of short-term and long-term properties of FRP composites. However, further research is needed to expand the application of these materials and establish calculation procedures for elements reinforced with FRP reinforcement.

This paper describes the finite element (FE) modelling of a simply supported beam under a four-point test with long-term loading, subsequent unloading, and loading to failure of the member.

2 FE modelling of the beam under four-point bending test

In the finite element (FE) modelling of a beam under a four-point bending test, the Atena software was utilized , enhanced by GiD for mesh generation, all boundary conditions and interval of loads. The beam's dimensions were set to a height of 75 mm, width of 150 mm, and length of 1300 mm, with a 1200mm span between supports see **Fig. *1***. Forces were applied symmetrically, 100 mm from the mid-span on each side, to simulate real-world bending stresses see **Fig. 2**.

The beam was reinforced with two 8mm diameter GFRP (Glass Fiber Reinforced Polymer) bars. This study aimed to analyze the interaction between GFRP bars and concrete, focusing on flexural behavior.

By integrating Atena and GiD, the beam's material properties and loading conditions could be modelled accurately [9].

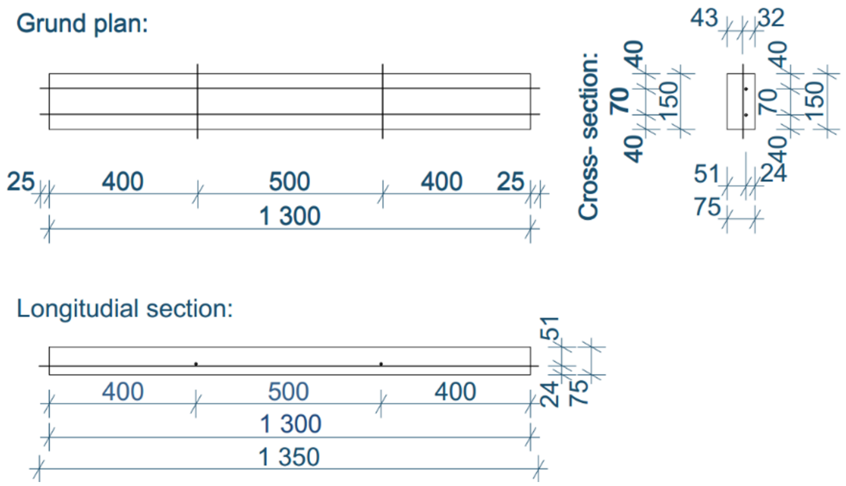

Fig. 1. Dimension of the concrete beams.

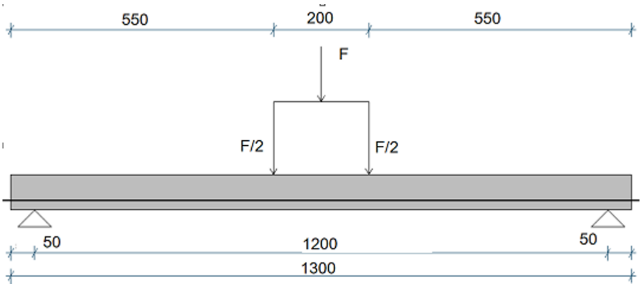

Fig. 2. Scheme of four-point loading tests.

2.1 Materials

The material characteristics used in the finite element model were selected on the basis of real material tests. Concrete is modelled as SOLID Creep Concrete with Model B3 Improved type, where Cementious2 material with the cylindric compressive strength f_{cu} = 24.29 MPa, tensile strength f_t = 1.82 MPa and modulus of elasticity E = 30.72 GPa is used as Base Material. For steel plates, 3D Elastic Isotropic material is used. For GFRP reinforcement, 1DReinforcement material with the linear stress-strain law with the modulus of elasticity E = 50 GPa is used. Bond properties are defined as Reinforcement bond with use of the bond model by Bigaj (1999) [10]. The bond model by Bigaj is pre-defined according to concrete strength and bar diameter [11]. The brittle behavior of Bigaj´s model is attributed to the splitting mode of the bond behavior and is more realistic than the plastic behavior [9]. For GFRP reinforcement, good bond was selected.

2.2 Topology

The model represents the whole four-point loading beam test with the vertical line of symmetry in the middle of the specimen, see **Fig. 3**. The exact number of macroelements models the concrete beam according to the necessity of getting the exact mesh in the places of supports. The investigated GFRP reinforcement is modelled as lines with added material properties as in the 1DReinforcement with specific properties and in the Reinforcement bond section, the bond model and bond material for each type of bar are selected. Steel plates are modelled in the areas of the beam supports and loading. For the mesh generation all elements were selected as Structural or SemiStructural and were meshed with Hexahedra or Tetrahedra element-type. All structural elements were set in a number of divisions to get the exact mesh. However, reinforcement is meshed as one element.

2.3 Load cases

To simulate the test in proper way modul Creep of Atena was used.In total, five load cases or intervals in Atena terms were set. The first interval constituted boundary conditions-constraint for line in support, self-weight- for volumes, and monitoring points- deflection in the middle of the beam. In the second interval, the loads are set-load for points with negative values in both plates on top of the beam. The third interval is for long-term deflection – just the creep process. In the fourth interval, the unloading process is recorded-load for point with positive values on bottom of plates. The beam is crushed in the final fifth interval, and the exact displacement is set.

2.4 Monitoring points and solution method

Monitoring points are describing a load-displacement response. The load is measured in the joint, where the prescribed displacement and load is applied.
The solution uses the Newton-Raphson method with a loading history of exact load steps per interval.

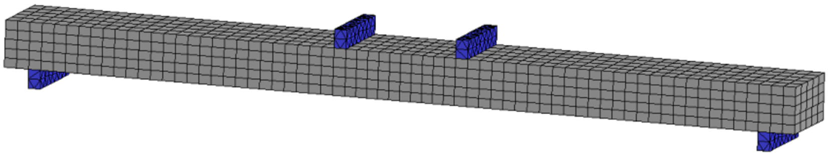

Fig. 3. FE model of four-point long-term loading test for beam.

3 Experimental analysis of four-point long-term loading test for beams

To calibrate the numerical model, identical experimental tests were performed. In total three beams were loaded to 25% of the immediate load capacity obtained by short-term testing. The beams were supposed to be loaded for a period of 1 year. The distances between the supports and scheme of load are the same as in the short-term tests, see **Fig. 4**.

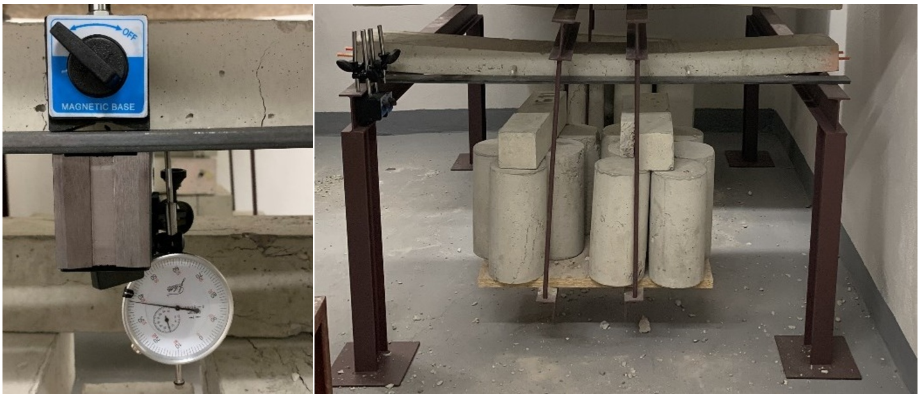

Fig. 4. Set of beams loaded to 25% of short-term resistance– long-term loading.

Immediately after loading, the actual deflection was measured on all of these sets, and current dial gauges were installed for long-term deflection measurements. After one year, the set-up was demounted, and beams were unloaded. Before removing the load from the beams, the value of actual deflection was measured on dial gauges to calculate the increase in total deflection after 1 year. When the load was removed the residual deflection was also measured on the beams. After unloading, the beams were tested by a four-point bending test until failure. All the beams failed in bending by concrete crushing. No rupture of GFRP reinforcement was recorded despite of relatively high level of stress in it. The parameters obtained during the testing were recorded by computer software.

Table 1 Results on beams.

Beam no.	Maximum force (kN)	Deflection (mm)
N1	9.73	43.50
N2	8.58	41.58
N3	9.29	43.92
Average	9.2	43.00

Table 2 Average value from mesuraments.

Precentage of load (%)	Deflection after 1 year (mm)	Deflection after unloading (mm)	Maximum deflection just before failure (mm)	Maximum force at failure (kN)
25.00	8.23	5.10	43.00	9.20

4 Comparison of experimental and FEM analysis results

Figure 8 present the results form experimental tests and FEM analysis, including the increase in long-term deflection during 1-year loading, residual deflections after unloading and deflections measured during final testing of beams (average values), see **Fig. 5**.

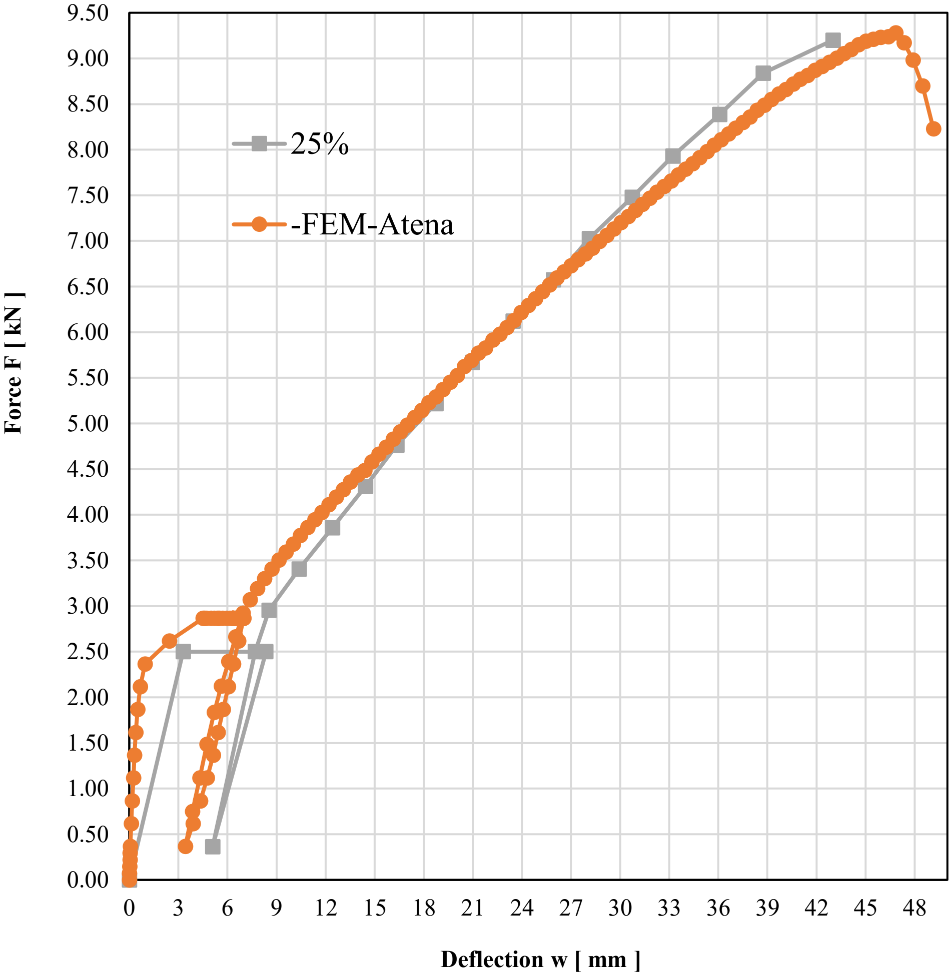

Fig. 5. Comparison of the result of beams after one year, including unloading and residual deflections.

5 Conclusion

The findings from the long-term experimental testing, extending over a year, reveal that despite the high stress levels experienced by GFRP bars, failure through reinforcement rupture was not observed. Instead, beam failure predominantly occurred through concrete crushing as it was designed. Durability and reliability of GFRP reinforcement under sustained load conditions can be highlighted.

The Bigaj´s bond model in ATENA FEM analysis of bond behavior of GFRP bars showed very similar results in behaviour for bending tests compared to values obtained from the experiments. In this context, it is pivotal to acknowledge the material's commendable malleability and shaping capabilities. The deflection observed after a year corresponds accurately to the measured values, demonstrating the material's reliable performance over time. Furthermore, the integration of Atena and GiD software presents a valuable tool for simulating load progression over time. This feature is particularly advantageous for reconstructions, where the ability to model temporal load changes can significantly contribute to the precision and effectiveness of the engineering solutions applied.

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