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Laboratory Testing of Old Bridge Girders: Preliminary Results

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ABSTRACT: This paper presents key results on the laboratory testing of old girders removed from a flood-damaged bridge located near Ljubljana, Slovenia. The structure was widened in 1989 to accommodate pedestrians and cyclists by integrating prefabricated prestressed reinforced concrete T-girders. To assess the structural behaviour of the bridge, six girders were subjected to a rigorous testing program involving bending and shear tests in a laboratory setting. The tests were performed on girders with static lengths of 12.20 meters and 9.90 meters. The program aimed to evaluate the structural performance of the girders. Preliminary results indicate satisfactory structural behaviour of the prestressed T-girders under the applied loads, with insights into their performance under both bending and shear stresses. This study contributes valuable data for assessing the long-term behaviour of bridges. The outcomes are particularly relevant for optimising resource allocation in bridge rehabilitation projects and ensuring safety and functionality in transportation networks.

KEY WORDS: laboratory testing, prestressed girders, assessment, load test, operational modal analysis, damage, acoustic emission

1 INTRODUCTION

Bridges are a key component of transport infrastructure, ensuring connectivity and traffic flow at both regional and national levels. However, as they age, they become susceptible to damage due to material degradation, traffic loads, and extreme weather events. Regular condition assessment through visual inspections and different structural monitoring systems is therefore essential to ensure the safety of both the structures and their users.

Bridge replacement typically entails significant financial costs, long execution times, and considerable logistical challenges. Consequently, it is crucial to leverage all available knowledge to accurately assess the actual safety and remaining service life of existing bridges. In this context, experimental data plays a vital role, as it provides direct insight into the structural behaviour [1, 2, 3].

This paper presents the ReNos project, a research initiative by the Slovenian National Building and Civil Engineering Institute (ZAG), which involved laboratory testing of prestressed concrete girders recovered from an existing bridge structure that had been exposed to flooding. The main objectives of the research were: (i) to determine the actual load-bearing behaviour and (ii) to monitor damage development using various sensor types, and (iii) to develop a protocol for potential reuse of the girders.

First, the bridge and the girders are described, including the entire process of the adapted demolition and transportation of the girders to the laboratory. This is followed by a description of the experimental program, preliminary results, and the future work plan.

2 DESCRIPTION OF THE BRIDGE, GIRDERS, AND DISASSEMBLY PROCESS

2.1 *Bridge and girders*

The five-span bridge with a total length of 52.6 m and width of 8.2 m was located on a state road near Ljubljana, Slovenia. The original superstructure consisted of a ribbed reinforced concrete slab with brick inserts, supported by thin walls.

In 1989, the bridge was widened on both sides to accommodate pedestrian and cyclist traffic. The extension incorporates prefabricated prestressed concrete T-girders supported by additional wall piers aligned with the existing substructure. These girders were connected transversely by a cast-in-place reinforced concrete slab. The extended bridge from the upper stream side is shown in Figure 1.

Figure 1. Existing bridge before the collapse (downstream).

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Following the catastrophic 2023 floods in Slovenia, the bridge partially collapsed, as shown in Figure 2 from the downstream side. While the intermediate supports were damaged, an inspection confirmed that the longitudinal girders remained in good condition. In agreement with the infrastructure manager and demolition contractor, selected girders were salvaged for laboratory testing (Figure 3).

Figure 2. Partly collapsed bridge after floods (upstream).

Figure 3. Lifting the girders with cranes.

2.2 *Disassembly process*

The process of disassembling the girders proved to be highly challenging. Nevertheless, all stakeholders involved, including the infrastructure management authority and the demolition contractor, demonstrated a commendable level of flexibility by adapting the demolition procedure to enable the safe recovery of the girders for further purposes, such as experimental testing or potential reuse.

The girder disassembly process comprised the following key steps: identification of reusable elements; preparation of the demolition method by the contractor; cutting of the concrete slab between the girders; removal of the edge girders; lifting of the girders using cranes; transportation of the girders; and placement at designated storage or testing locations.

3 EXPERIMENTAL PROGRAM AND TEST SETUP

The investigation program was based on the testing of six girders, focusing on the following parameters: the influence of girder length (span lengths of 9.9 m and 12.2 m), the influence of the load application point (shear/flexural test), the influence of the presence of a reinforced concrete (RC) slab on the girder (girders with and without slabs), and the impact of pre-existing damage to the girder.

In addition, supporting activities were carried out, including visual inspections of the girders, destructive and non-destructive testing of the girder materials/aggregates and laser scanning of specimens.

The test setup is presented in Figure 4. The girder was simply supported, with a pinned support at one end and a roller support at the other side. Both supports were rigidly anchored to the laboratory's strong floor. Lateral stability of the girder was ensured using a rigid steel frame. The load was applied by means of a hydraulic actuator, which was clamped into the steel reaction frame.

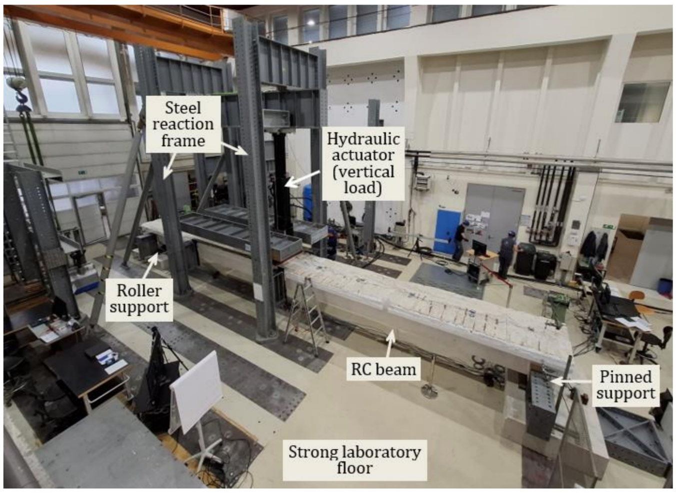

Figure 4. Experimental setup at ZAG's Laboratory for Structures.

The essential instrumentation for each test included a force transducer, displacement transducers, strain measurement devices (extensometers, strain gauges, digital image correlation (DIC) system, optical sensors), accelerometers, and acoustic emission sensors.

The testing procedure for the static cyclic tests was generally divided into two stages. The first stage was load-controlled, while the second stage was displacement-controlled. Each stage comprised several phases, defined either by force levels (in the first stage) or displacement increments (in the second stage). The load, whether force- or displacement-controlled, was progressively increased until the girder failed.

4 PRELIMINARY TEST RESULTS

Due to the limited scope of the paper, in the following, the preliminary results of only the flexural test on the B4 girder is presented. This girder, with a span length of 9.9 m, was loaded at mid-span during the test. It was tested without the top RC slab and had no pre-existing damage prior to the testing.

4.1 *Flexural behaviour of girder*

The flexural behaviour of the girder is represented by the hysteretic curve, which shows the relationship between applied force and mid-span displacement, as illustrated in Figure 5. The triangles indicate the state at initial cracking and the state just before failure. The labels S1, S2, and S3 denote engineering-

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defined states employed for damage detection accelerometers, as described in Section 4.2.

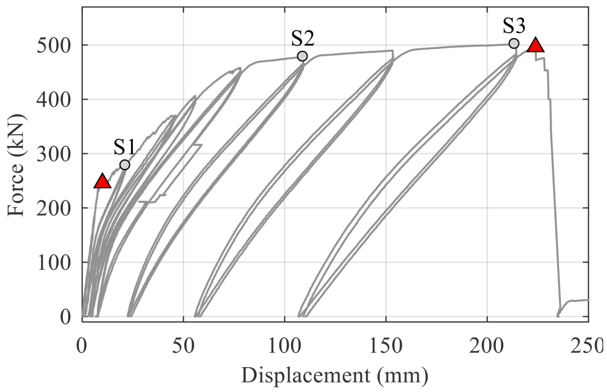


Figure 5. Hysteretic response of the girder at the middle.

The initial cracks appeared during the second loading phase, forming in the load application area with an initial width of approximately 0.1 mm (Figure 6). Cracking began at an applied force of 246.1 kN and a corresponding displacement of 10 mm. These cracks closed completely upon unloading. As the loading progressed through subsequent phases, the cracks widened and propagated, increasing both in number and extent. Inclined (shear) cracks also began to appear in supports' region.

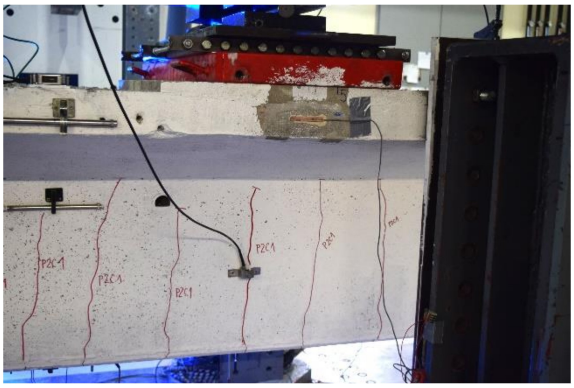


Figure 6. Damage state at the peak of the cycle when the first cracks appeared.

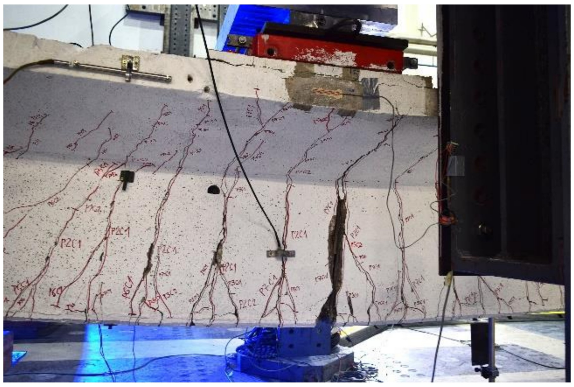


Figure 7. Damaged girder in the failure stage.

In the phase immediately preceding failure, the maximum observed crack width reached 4.5 mm, with a residual width of 3.0 mm after unloading. In the following phase at displacement of 22,4 mm and force 497 kN, the girder experienced flexural failure, accompanied by the rupture of the prestressing tendons in the load application zone (Figure 7).

4.2 *Monitoring of damage with accelerometers*

The damage of the girder at the end of individual loading cycles was monitored using 18 DEWESoft 3-axial MEMS accelerometers [4], placed on the top flange. This part of the experimental program aimed to evaluate the limits of acceleration-based monitoring systems to detect structural damage based on changes in the specimens' dynamic characteristics.

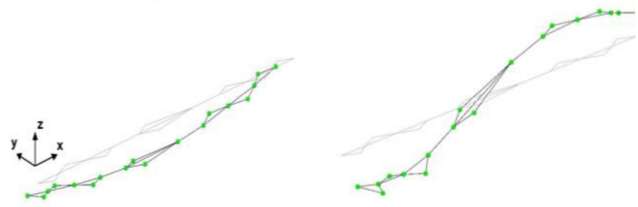
Damage progression was monitored through ambient vibration measurements conducted after each load cycle on fully unloaded girders, ensuring consistent initial boundary conditions. The specimen's dynamic properties, including natural frequencies, mode shapes, and damping ratios, were identified using Operational Modal Analysis (OMA) performed with the DEWESoft ARTeMIS OMA software [5].

This study presents and discusses the changes in natural frequencies of the first two vertical bending modes, shown in Table 1. A schematic illustration of the corresponding mode shapes is provided in Figure 8.

Table 1. Change in mode shape natural frequencies during experimental phases.

B4	f_1 [Hz]	f_2 [Hz]	Δf_1 [%]	Δf_2 [%]
Reference	12.4	45.8	\	\
S1: after crack phase	12.0	45.2	−3.2	−1.3
S2: after yield phase	10.3	43.8	−16.9	−4.4
S3: near collapse	8.0	40.8	−35.5	−10.9

The reference natural frequencies of the first and second vertical bending modes amounted to 12.38 Hz and 45.81 Hz, respectively. As damage accumulates during load cycles, the girder's stiffness diminishes, which is reflected in the corresponding reduction of natural frequencies in Table 1. A reduction of 3% to 36% in the first natural frequency was observed as the damage evolved from cracking (S1) to near-collapse limit state (S3). Smaller decrease was obtained for the second vertical bending mode (1% to 11%), which is due to the applied load causing more damage near mid-span, where the amplitude of the second mode is nearly zero (see Figure 8b).



(a) (b)

Figure 8. First (a) and second (b) vertical bending modes of B4 girder.

Initial findings indicate that acceleration-based monitoring can be used to detect structural damage in a controlled environment.

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4.3 *Monitoring of damage with acoustic emission*

During the load test, the evolution and propagation of damage were also assessed using acoustic emission methods (AEM). Three Physical Acoustic Corporation type PK6I sensors were mounted half height of the girder's web. Physical Acoustic Corporation AEWin for Sensor Highway Smart Monitor Ver. E5.00 software was used to record the acoustic emission parameters and the load. The threshold was set to 40 dB.

General acoustic emission activity, represented by the amplitude of each hit, the applied load, are time-dependent and presented in Figure 9. Nevertheless, The AE activity, i.e. damage evolution during loading and unloading phases, is visible. In addition, the b-value and the damage parameter as used by Vidya Sagar and Raghu Prasad [6] and Elbatanouny et al. [7] in similar investigations were calculated to evaluate the damage evaluation. The decrease of b-value and the increase of damage parameter with increased load are clearly visible.

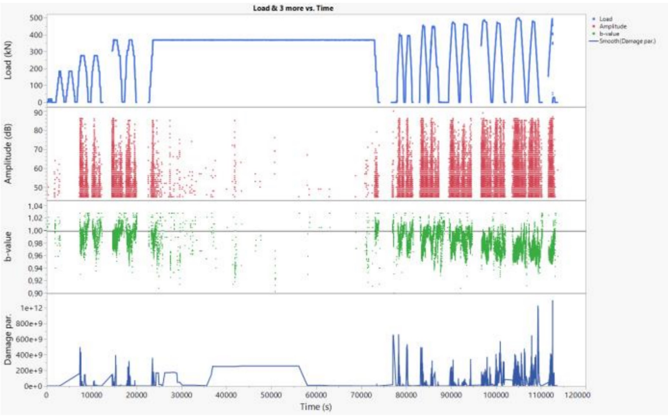

Figure 9: Load and amplitude of individual hits, and b-value and damage parameter as a measure of damage evolution and propagation.

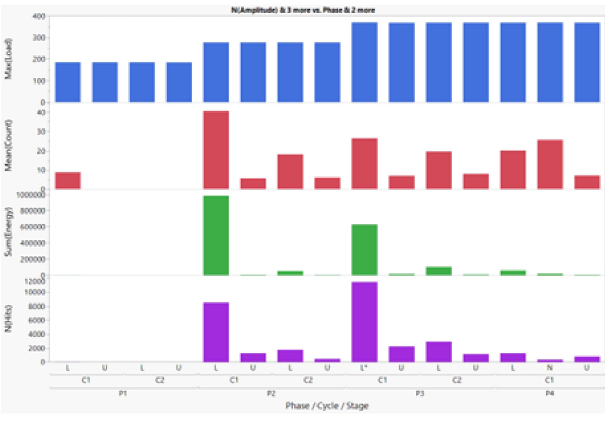

Figure 10: Maximum loads (Max - blue), and number of hits (N - purple), total energy (Sum - red) and mean count (Mean - green) of the hits for individual phases (P1, P2, P3), cycles (C1, C2) and stages (loading L and unloading U).

As an example of a more detailed analysis the number of hits, total energy and mean counts of the first three phases are presented in Figure 10. Each phase consists of two cycles of loading and unloading. A significant difference in AE activity between different phases, cycles within individual phases and loading/unloading stage was recorded. A more detailed analysis is foreseen. It must be noted that some data of the phase 3, cycle 1, loading stage (marked L* on graph), was unfortunately lost.

5 CONCLUSION

The experimental investigation carried out within the ZAG's research project ReNos provides valuable insights into the structural behaviour and bearing capacity of prestressed concrete bridge girders recovered from a flood-affected structure. Preliminary results demonstrate that acceleration-based monitoring systems as well as acoustic emission can identify the progression of damage and help identify critical states in the girder's response. This confirms that such systems are suitable for structural health monitoring applications.

Additionally, the study highlights that, with coordinated stakeholder involvement, dismantling procedures can be executed in a way that preserves structural components for further testing and potential reuse.

Future work will focus on the analysis of remaining test results taking into account the main objective of the study: (1) to determine the actual load-bearing behaviour and compare it with the original design assumptions, (2) to monitor damage development using various sensor types, and (3) to develop a protocol for the potential reuse of the girders in line with circular economy principles.

Acoustic emission techniques can clearly detect and monitor damage evaluation, but a more detailed analysis of the results is needed.

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