Energy dissipation and absorption capacity influence on experimental modal parameters of a PC girder

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Abstract. This experimental investigation focuses on collecting vibration data after different loading scenarios in a PC girder while measuring the performance at the same time. The vibration data is used for modal analysis and since several samples were taken in each scenario with different impact hammer tips, a comparison of the outcomes is also possible. The performance is based on recorded displacements along the bottom surface of the girder, information that makes possible the calculation of energy absorbed before cracking and the energy dissipation that takes place after cracking. Furthermore, two major damage events, a tendon breakage and cracking, were induced and monitored respectively. This study also clarified the influence of change in energy on changes in modal parameters.

1. Introduction

Obtaining the current performance of concrete bridges typically implies exhausting non-destructive tests for each specific structure and also takes long periods of time with qualified engineers. Structural health monitoring has made a great progress in damage detection by using sensors that can collect information easily once installed. However, using monitored data to obtain performance parameters, such as degradation, serviceability and decision making is still under discussion. Also, dealing with the materials uncertainties is a big challenge for engineers because these uncertainties are merged with the monitored data and might be the reason of abnormal deviations.

The natural frequencies from deteriorated concrete beams have shown to be sensitive features for the strength reduction when evaluating the residual strength in bridges with 50 years of service life. At the same time, it rises the likelihood of using them as a symptom to be monitored in order to estimate the structural reliability [1]. Literature has also shown that the modal damping ratio can be a damage sensitive feature for reinforced and prestressed concrete structures [2]. Moreover, researches indicate that a trend of getting higher value of modal damping ratios with the age of the bridges could be a sign of possible deterioration, which is a strong reason to investigate the relationship between damping parameter and degree of damage [2]. Last but not least, discrepancies between the results from experimental testing and theoretical models come up due to variety of reasons that needs to be faced [3].

Prestressed concrete (PC) girders are essential elements in bridge stocks, and efficient inspection of the PC bridges is a keen technical issue. This study, thus, investigates vibration-based structural health monitoring for PC bridges especially focusing on the relation between energy absorption capacity and modal parameters, as well as the effect of energy dissipation.
2. Experimental setup and plan
The PC girder used for this experiment comes from an earlier investigation about the evaluation of grout failure process with tendon rupture by means of the acoustic emission [4]. Regardless of its previous use, the concrete element is still suitable for the purpose of the research. The girder has a total length of 4.5 meters, 0.5 meters height and 0.25 meters width. The free span or distance between the steel roller supports is 4.1 meters. Seven servo-accelerometers (A1-A7) and seven displacement transducers, as shown in Figure 1, were allocated. Two more displacement gauges were deployed at the ends of the concrete specimen to observe longitudinal displacements. The girder has four post-tensioned tendons, of which two were already severed as shown in Figure 2, but leaving the possibility of severing one more tendon for the experiment aim.

The displacement transducers are Tokyo Sokki Kenkyujo type CDP-50 and CDP-25. The loading actuator has a maximum capacity of 400 KN and it was connected to the PC girder through a steel beam that is in contact in two points separated by a distance of one meter. Both, the displacement transducers and the actuator were connected to a data logger TDS-530 from Tokyo Sokki Kenkyujo. The accelerometers are piezoelectric type ONOSOKKI NP-2120 with a maximum acceleration of 8000 m/s² and a sensitivity of 5pC/ (m/s²) +/-2dB.

The experiment plan is described in Figure 3 with a timeline. Along all the experiment, ten vibration tests were performed. Also, the static loading plan consists of eight total load-unload stages, from which the first four are the same load level (150 kN) that is below of the cracking load predicted. These four loads allowed to monitor the response behavior under analogous conditions. Besides, the tendon severing could be introduced in between to test the effect of this event on the response. Later, three more load-unload stages were introduced with an increase of 50 kN each time, where cracking begins and propagates subsequently, and finally a last load step until failure was performed.

Figure 1. Sensors location in the PC girder (displacement transducers and servo-accelerometers)

Figure 2. Tendons condition and breakage plan for the experiment

Figure 3. Loading stages and timeline of the experiment
3. Static load testing and energy calculation

Besides the tendon severing, the static load tests change the intrinsic parameters of the girder by producing cracks when increasing the load levels. These changes are to be monitored by examining the energy absorbed and dissipated in each load stage.

3.1. Cracks monitoring and failure

The beginning of cracking was detected roughly in 170 kN (by visual inspections every 5 kN of load increase), but it was noticed internal cracks sound in 165 kN. Also, the load-displacement curves show a change in the slope from approximately 166 kN. After that, the cracks were monitored and marked by hand in each stage (see Figure 4). Then, the calculation of the lengths was achieved by using a CAD software, and the summary is in Table 1.

The failure of the girder was reached by exceeding the compressive strength of the concrete in the top surface of the specimen. From the records it can be seen that one section of the girder started yielding around 330KN and then failed in 351KN. Locating and determining the exact load failure can be easily done by inspecting the displacement records in the final stage (see Figure 5).

Table 1. Total lengths of cracks in the PC girder after each stage

|                     | Cracks after 200 kN | Cracks after 250 kN | Cracks after 300 kN | Cracks after failure |
|---------------------|---------------------|---------------------|---------------------|----------------------|
| Front face          | 666.49 mm           | 2121.05 mm          | 3602.75 mm          | 5359.94 mm           |
| Back face           | 657.96 mm           | 2030.60 mm          | 3695.59 mm          | 4877.01 mm           |
| Average             | 662.23 mm           | 2075.83 mm          | 3649.17 mm          | 5118.48 mm           |

Figure 4. Cracks identification after different load stages: after 200KN (yellow); after 250KN (Blue); after 300KN (Green); after ultimate load (Red)

Figure 5. Displacement progress of a specific load range in the ultimate load stage: Green bars are displacements increase (down); Red bar is displacement jump (up)
Figure 6. Energy dissipation in different stages from displacement transducer located in the span center

Table 2. Energy dissipated and energy absorption capacity from all loading stages

|                      | 0-150 kN (1) | 0-150 kN (2) | 0-150 kN (3) | 0-150 kN (4) |
|----------------------|--------------|--------------|--------------|--------------|
| Energy dissipated (Joules) | 15.95        | 8.67         | 10.78        | 9.77         |
| Energy absorption capacity (Joules) | 3892.47      | 3888.18      | 3890.81      | 3891.28      |

|                      | 0-200 kN     | 0-250 kN     | 0-300 kN     | 0-ultimate   |
|----------------------|--------------|--------------|--------------|--------------|
| Energy dissipated (Joules) | 67.27        | 191.80       | 574.08       | 2841.17      |
| Energy absorption capacity (Joules) | 3886.86      | 3863.84      | 3797.60      | 3531.60      |

3.2. Energy calculation
The energy dissipation is the area within the load-unload curve vs. displacement (graphically described in Figure 6) and the energy absorption capacity is the area beneath the load-displacement curve under the assumption of reaching the failure load (see Figure 7). The sum of all transducers data allows the calculation of the total work in the entire girder and this is summarized in Table 2.

4. Dynamic testing and vibration monitoring
The equipment used for the dynamic testing consists of an impact hammer Bruel & kjaer type 8208 – Modal sledge hammer 3-pound head with a maximum compressive force of 44.4 kN and a sensitivity of 0.225 mV/N. The accelerometers and the impact hammer were connected to a Multi-input Data Acquisition System Keyence Series NR-600.

4.1. Impact Hammer test and FRF
The impact roving technique was performed to obtain the modal parameters where the impact points (seven) are located in the opposite face (top of the girder) of the accelerometers location (bottom part). Two impact tips were used to produce different amplitudes of excitation (soft tip and medium tip) and 30 hits with each tip were carried out in each impact point of every stage.

Transfer functions were easily obtained and since the hammer and accelerometers were synchronized, the single-input multiple-output (SIMO) approach was also used for estimating the frequency response functions (FRF). Each value of the modal parameters represents the mean and standard deviation of 210 samples per tip of every stage (4200 samples in total for the whole experiment).
4.2. Frequency monitoring

Structural damage is interpreted as a decay of the mechanical properties of the structure, which means a decrease of stiffness. However, the trend of natural frequencies to the progress of damage shows an anomalous increase from one damage configuration to the next one even experimentally [5]. The first natural frequency (see Figure 8) shows a typical decrease as severity of damage increases, but there is a particular increment that occurs without any load step in between and the reason is because of changes in displacements since the elastic curve of the girder is recovering after the last load-unload step. The second frequency has diverse changes from the moment that cracks started and the location of these ones in the girder (see Figure 9). The third modal frequency might be the only one that shows a change due to the tendon cut and it also agrees with the increase of the first frequency cause of the elastic recovery (see Figure 10).

Figure 8. Percentage changes in the first bending mode frequency along specific events

Figure 9. Percentage changes in the second bending mode frequency along specific events

Figure 10. Percentage changes in the third bending mode frequency along specific events
4.3. Damping ratio monitoring

The damping ratio was calculated by identifying the half power (-3dB) points of the magnitude of the frequency response function and once having the frequency bandwidth between the two half power points, the damping ratio is the ratio of the bandwidth with two times the frequency resonance. Figure 11 shows the first modal damping ratio development with no clear trend of specific damage. The second modal damping ratio, as shown in Figure 12, seems to change after cracks begin. Figure 13 shows how the third damping ratio might be altered by the tendon cut once again as shown in the third bending mode frequency.

![Figure 11](image1.png)

**Figure 11.** Change in the first modal damping ratio along all experiment stages

![Figure 12](image2.png)

**Figure 12.** Change in the second modal damping ratio along all experiment stages

![Figure 13](image3.png)

**Figure 13.** Change in the third modal damping ratio along all experiments stages
4.4. Mode Shapes monitoring

Mode shapes were extracted from the imaginary part of the frequency response functions and as shown in Figure 14, Figure 15, Figure 16 and Figure 17; after being normalized it seems that there are no drastic changes, except for the third mode shape that showed a change due to cracking.
5. Discussions on experimental results
Similar results were obtained in Figure 18 to the ones in a previous investigation of concrete bridges [2], but this time it can be identified the mode that is more sensitive to damages, that is the second mode. In Figure 19, a correlation between normalized frequency and normalized damping ratio was investigated, but the only mode that has a strong fit is the second bending mode. Although, some clear data deviations were identified in all of them when specific events occurred. The effect of the tendon damage did not have relevant impact on the first two frequencies as happened in previous and similar studies [6], [7] and it also verifies that prestressing measurement force is not viable through frequencies only [8], but higher frequencies and damping ratios might be able to detect some changes as shown before.

Figure 20 might be an evidence that permanent deformations has a strong influence in modal parameters since the only ordinate that stores two stages data is when the displacement recovery happens. Changes in different modes at different times might be due to the crack state and its location. Figure 21 is the description of the girder health only cause of cracks, where 100% means no cracks and 0% is considering the total length of the cracks in the final stage. The resemblance of the changes with Figure 22 is a clear evidence that the second mode is the more sensitive to cracks and a corroboration of using frequency data for crack detection in beam-type structures [9].

![Figure 20. Correlation between energy dissipation and damping ratio](image)

![Figure 21. Effect of energy absorption capacity on the girder health due to cracks occurrence](image)

![Figure 22. Correlation between frequency and energy absorption capacity](image)
6. Conclusions
The amplitude of excitation when performing vibration tests has an effect on the accuracy of higher modes. There should be some precautions when interpreting the deviations of modal parameters because the deviation could be caused by damage or inadequate excitation. The elastic curve of the girder has a clear impact on modal parameters, which demonstrates that some attention must be paid to assess the permanent displacements, correlation with frequencies and damping ratio. There is a clear decrease in frequency as damage occurs but also an increase or decrease depending of the relative permanent displacements. The energy correlations with modal parameters are evidence that the last one can be developed and used for performance assessment.

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