3D static and dynamic displacement measurements by a system of three linear CCD-units

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Abstract

Large structures such as bridges, buildings, dams and parts of aeroplanes like wings, landing gear… are exposed to important dynamic forces during operation.

For the design, it is important to have an accurate evaluation of the structural response to the exciting loads. This knowledge can be gained by constructing proper Finite Element (FE) models. Experimental tuning of these models might be important because of the inherent uncertainties in the FE-modeling (e.g. boundary conditions, material properties, damping, ...). Testing can be done on scale models or on real-size structures.

An extension is the use of vibration measurements for condition monitoring of civil and mechanical structures: from changes in the identified modal parameters, the healthy or damaged status of the investigated structure can be detected [1].

This paper describes how an infrared-based contactless measurement system can be used for dynamic 3D and 6D displacement measurements. This system built up by three linear CCD-units is a valuable addition or even replacement for classic accelerometers when considering the lower frequency region up to 50 Hz. Obvious advantages are:

- Lower frequencies are better measured using displacements then accelerations.
- Displacements are closer related to strains (and hence stresses), then accelerations, resulting in a more appropriate information for design.
- Double integration of acceleration signals to obtain displacements will suffer from drift and phase distortion.
- The influence of the lightweight LED's on the dynamic characteristics is negligible.

In the context of health monitoring, the new system offers modal displacements in three orthogonal directions. Assuming that the small dynamic displacements can be measured sufficiently accurate, also modal strains can simply be derived. These modal strains can be used beneficially for damage identification.

The system has been used for the modal analysis of two prestressed concrete beams of 17.6m long. The modeshapes obtained by the CCD-system are compared with those from acceleration measurements and from numerical FE-calculations. A very good correspondence is observed.

1 Introduction

Service loads, environmental and accidental actions may cause damage to structures. Regular inspection and condition assessment of engineering structures are necessary so that early detection of any defect can be made and the structures updated safety and reliability can be determined. Early damage detection and location allows maintenance and repair works to be properly programmed. This minimizes not only the

annual costs of repair (e.g. for bridges estimated at 1.5% of their value) but also avoids a long out of use time which can represent an even higher economic cost (e.g. traffic delay due to major bridge repair).
Vibration monitoring of civil engineering structures (e.g. bridges, buildings, dams) has gained a lot of interest over the past few years, due to the relative ease of instrumentation and the development of new powerful system identification techniques [2].

Sometimes it is questioned whether the measured deviations of dynamic properties (eigenfrequencies, modeshapes) are significant enough to be a good indicator of damage or deterioration. The comparison of original and new dynamic properties can also be hampered by natural changes, caused by environmental influences (e.g. temperature changes). Another issue of continuing research is the localization of damage starting from any observed difference in dynamic properties. Attempts are made to include also modal strains in the set of measured quantities because they are inherently more dependent on damage at the measurement position. The new camera system built up by three linear CCD-units is able to measure three-dimensional displacements, static as well as dynamic. Question is if the accuracy is high enough to derive from them reliable modal strains.

2 Working principle of the camera system

2.1 General

The camera system is based on three linear CCD units. Each unit is composed of a 2048 pixel linear CCD, optics and a processing board. An optical unit is composed of an infrared filter, a normal lens and a cylindrical lens, which compresses the viewing area to a line. The processor of each unit calculates the peak of a light source on the CCD.

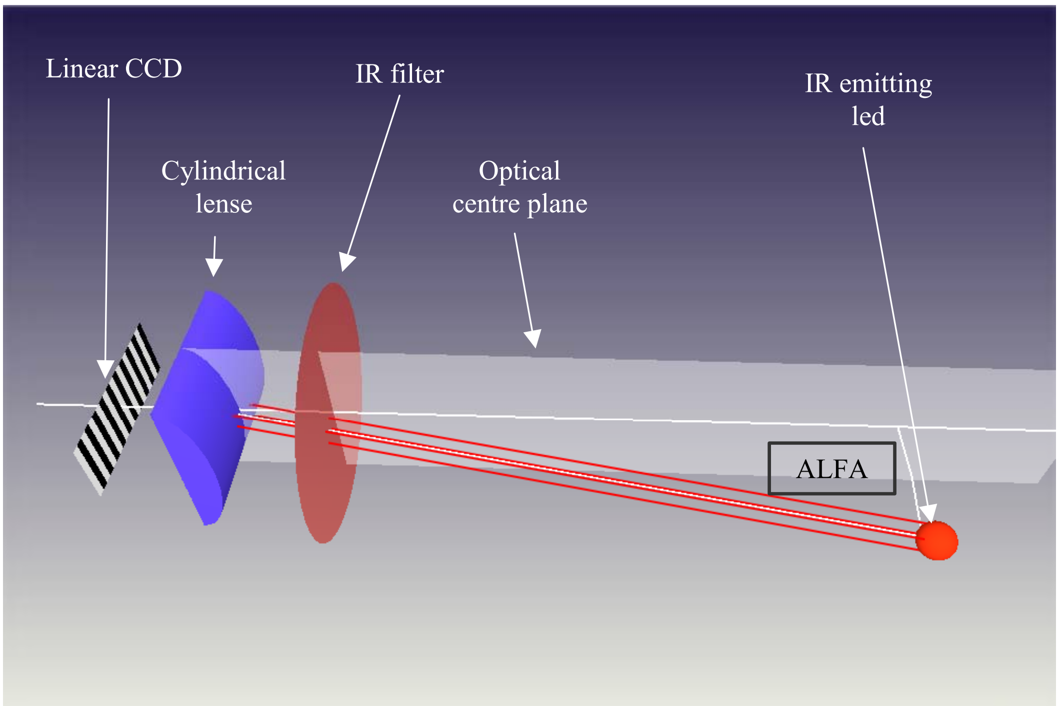

Figure 1: The components of an optical goniometer

The basic unit acts like a goniometer. Each unit is capable of measuring the angle that a light sources makes with the optical centre plane. The light source should be small and yet powerful enough to exceed the light level of the environment.

IR-emitting diodes are excellently suited for this task. They are small and can emit enough IR light. The IR filter prevents that environmental light influences the measurement.

Using triangulation techniques, one 3D position can be calculated from 3 angles.

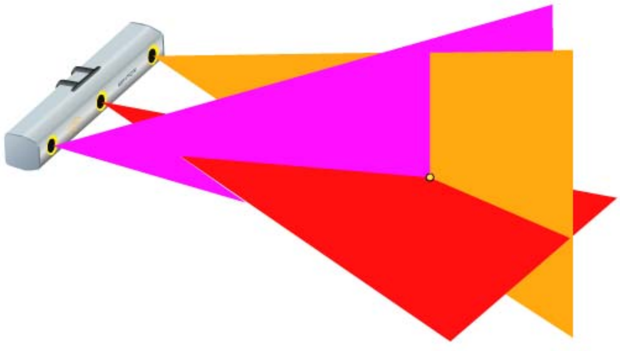

Figure 2: Combining three CCD cameras on a rigid structure

The three optical goniometers can be mounted on one rigid structure. Several configurations are possible, as long as the optical planes of the units are not parallel. The top and bottom camera provide the Z and the Y position. The middle camera mainly measures the X position

To track several markers simultaneously, the markers are flashed sequentially. The frequency at which the markers are flashed is called the marker frequency. The frequency at which the camera measures on frame of multiple markers is called the frame frequency.

It is clear that the frame frequency times the number of observed markers, can be no bigger than the marker frequency.

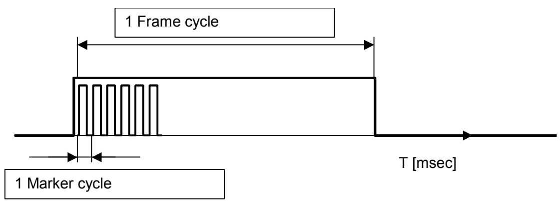

Figure 3: Timing of frame and marker cycles

The small latencies between the markers can be compensated by a quadratic time interpolation to the start moment of the first marker.

One marker gives a 3D position (X, Y and Z). If one marker is placed on a rigid body, it needs to be placed on a well-known position like the COG (Centre Of Gravity). One 3D marker gives no information on the orientation of the rigid body. By placing at least three markers on the rigid body, the position and orientation of the rigid body can be calculated. This results in 3 position numbers and 3 orientation numbers, hence the name 6D position.

2.2 Advantages

The usage of 3 linear CCD camera's mounted on a rigid structure has many advantages, both from an installation and an operation point of view:

- Since the cameras are mounted on a rigid structure, calibration only has to be done once in the factory. This offers an important advantage when set-up time is critical.
- Since the system is pre-calibrated the performance of the system is not depending on the relative position of the individual units.
- Three linear CCD cameras of 2048 pixel only require processing 6144 pixels. This makes a 3KHz frame frequency on a linear CCD based system possible.
- Advantages over classical position transducers:
    - The absolute position of each sensor (LED) is known.
    - The instrumentation of a LED is easy compared to a classical position transducer.
    - One LED gives directly full 3D information.
    - Dynamic 6D coordinate system transformations make it possible to make relative measurements.
    - The complexity of the measurement set-up is reduced. This will automatically also reduce the risk of errors and the 'human factor'.
- Advantages in Modal analysis / Dynamic testing:
    - Lower frequencies are better measured using displacements then accelerations.
    - Displacements are closer related to strains, and hence stresses, then accelerations, resulting in a better measurement quality.
    - Double integrated acceleration signals will suffer from drift and phase distortion.
    - The influence of the lightweight LED's on the dynamic characteristics is negligible.

3 Experimental program

3.1 Test beam and test setup

In the framework of the FWO G0266.01 project [3], static and dynamic tests have been performed on three prestressed concrete beams.

Objectives were:

- to link changes of modal parameters to induced damage, e.g. by preceding static loading;
- to explore new measurement techniques, like e.g. optical strain sensors.

The prestressed concrete beam were poured and tested at the R.U.G., Labo Magnel. The length is 17.6m and has at both ends a square cross section of 0.8m x 0.8m. Figure 4 shows the top view and the bottom view of the beam. Figure 5 shows the section of the beam.

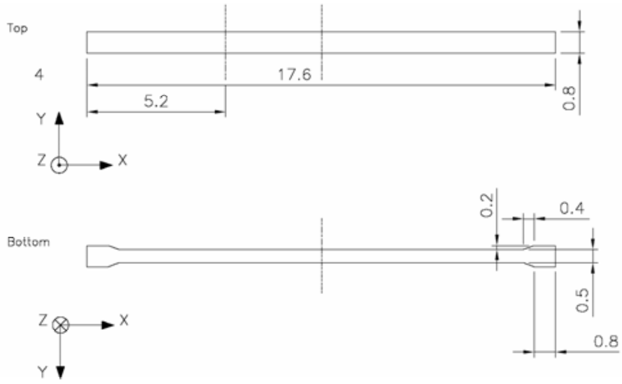

Figure 4: Top and bottom view

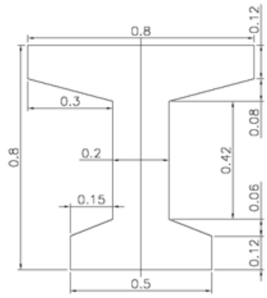

Figure 5: Section of the beam

Figure 6 illustrates one of the considered damage cases: 4 point loads are applied to induce bending cracks in the beam.

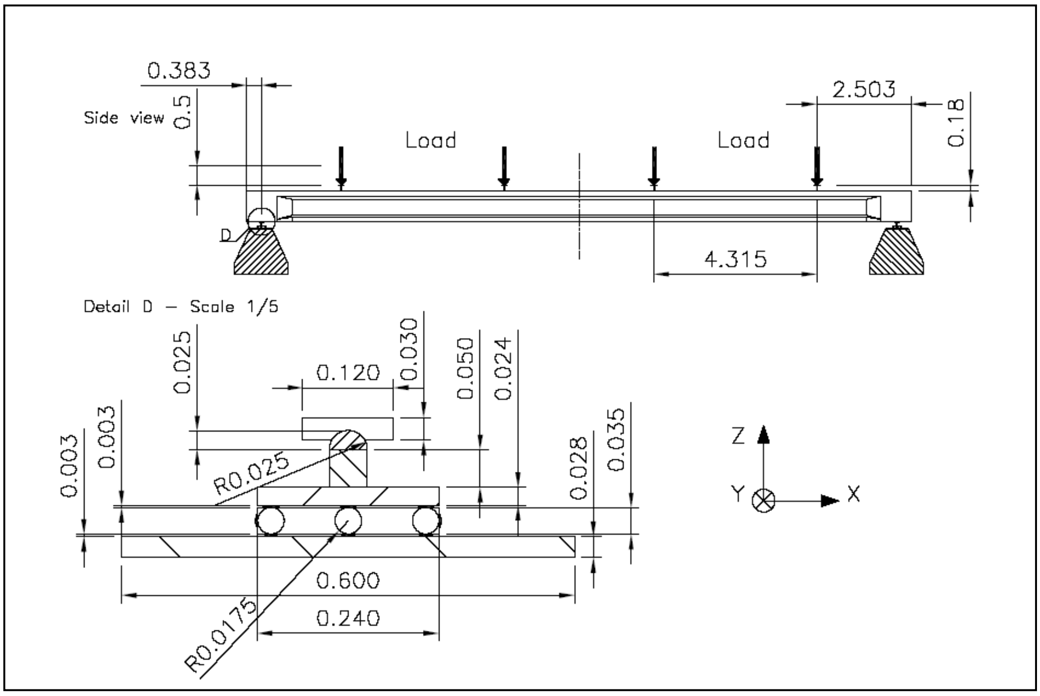

Figure 6: Static test setup

For the dynamic tests, the beam is put on 2x2 air springs in order to obtain free-free conditions. The girder is impacted by a falling weight. This mass has a weight of about 115 kg and falls from a height of about 1 m from the surface of the beam. The weight falls on an hydraulic damper, which acts as a mechanical low pass filter with a cut-off frequency of about 120 Hz. The falling weight is placed eccentrically in order to excite torsion modes as well. Figure 7 shows the setup for the dynamic tests.

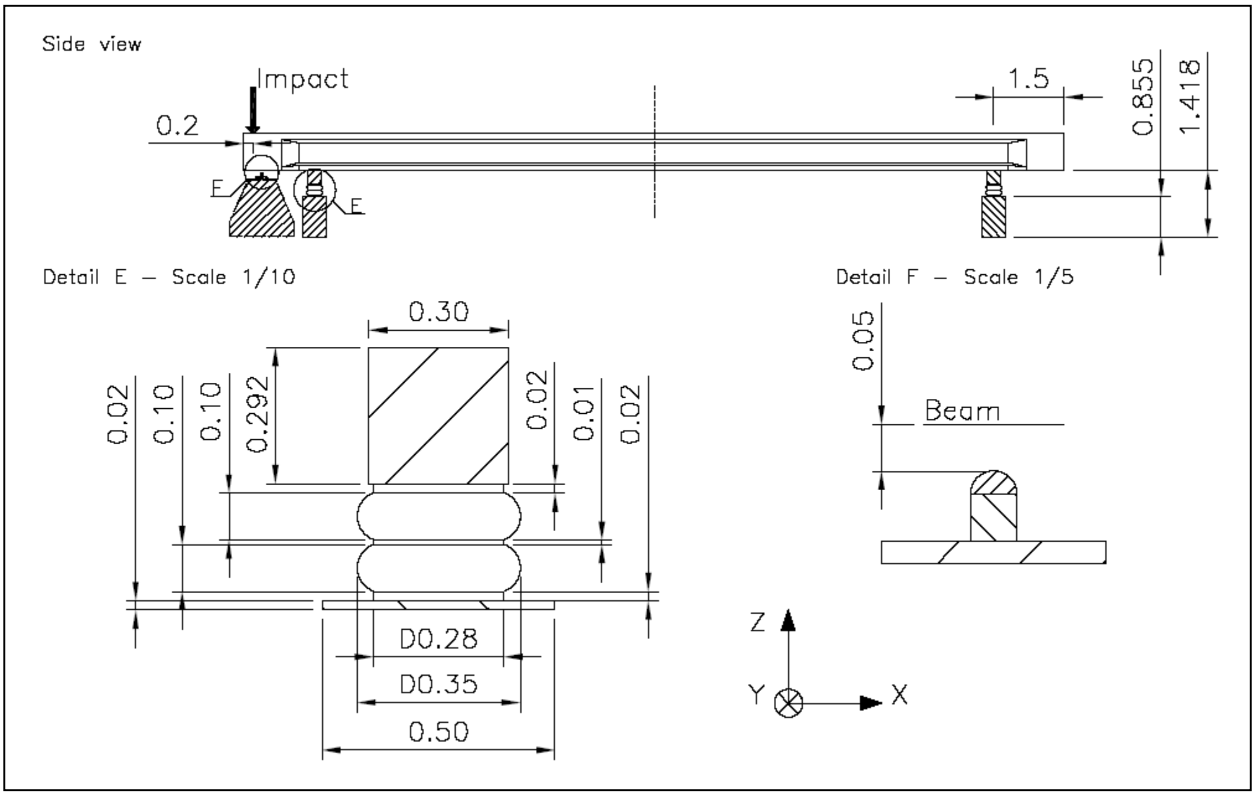

Figure 7: Dynamic test setup

3.2 Test sequence

A third beam has been alternately tested dynamically and statically. Table 1 shows the testing sequence of beam 3 starting from the pouring of the beam. As part of the test program, the Krypton-camera system is used for later comparison with acceleration measurements and numerical simulations.

Step	Date	Comment
1	13/10/03	Pouring of the beam
2	27/10/03	Pre-stressing of the cables
3	14/11/03	Dynamic reference measurements
4	17/11/03	Static test 1 – 45 kN (below decompression)
5	18/11/03	Dynamic test 1
6	19/11/03	Static test 2 – 65 kN (above decompression)
7	20/11/03	Dynamic test 2
8	21/11/03	Static test 3 – 75 kN (above crack load)
9	24/11/03	Dynamic test 3
10	25/11/03	Static test 4 – 95 kN
11	26/11/03	Dynamic test 4
12	27/11/03	Cutting,of 2 prestressing strands
13	27/11/03	Dynamic test 5
14	28/11/03	Static test 5 – 95 kN (start yielding reinforcement) + *Krypton measurements*

Step	SteDate	Comment
15	28/11/03	Static test 6 + *Krypton measurements*
16	04/12/03	Static test 6 – 100 kN (yielding of the reinforcement) + *Smartec measurements*
17	05/12/03	Dynamic test 7
18	08/12/03	External reinforcement – glueing CFRP
19	09/12/03	Dynamic test 8 + *Smartec measurements*
20	10/12/03	External reinforcement – anchoring CFRP
21	11/12/03	Static test 7 – 100 kN
22	12/12/03	Dynamic test 9 + *Smartec measurements*
23	18/12/03	Static test 8 – Failure of the beam

Table 1: Testing sequence beam 3

3.3 Sensors

3.3.1 Acceleration measurements

For the acceleration measurements, PCB 338B05 accelerometers were used. These ICP-fed piezo-electric accelerometers have a sensitivity of about 100mV/g.
The accelerations are measured is 74 positions and in two reference points. The numbering and the position of the accelerometers is given in Figure 10.

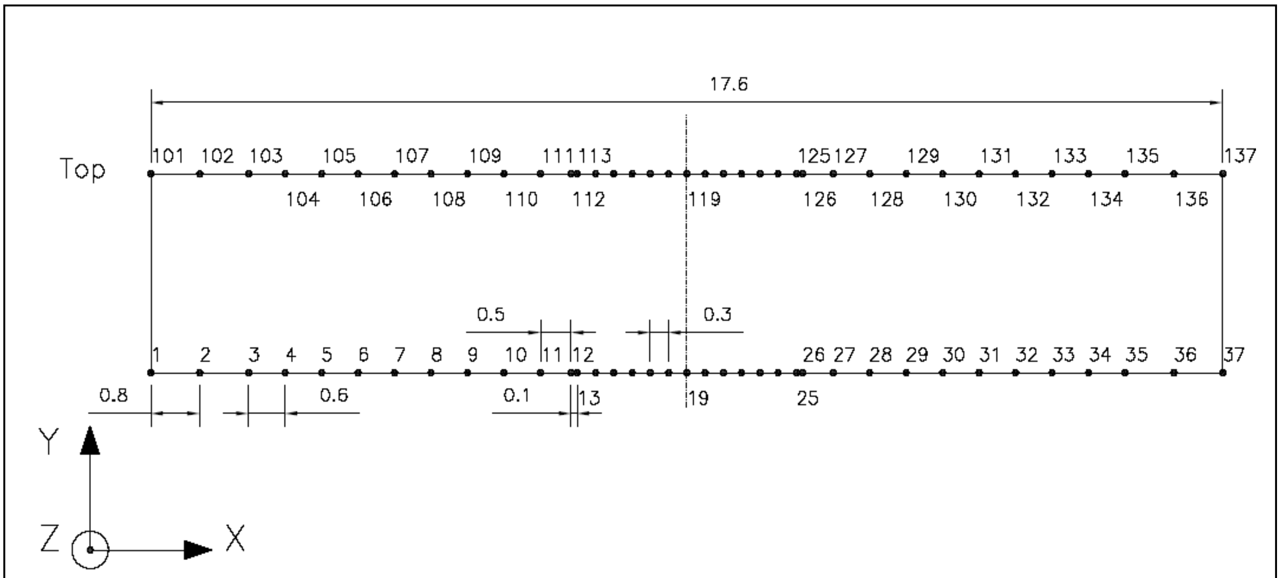

Figure 10: Position of accelerometers

3.3.2 Displacement measurements

For the static and the dynamic measurements of 28 November 2003, the Krypton measurement system was used in addition to the accelerometers and some optical fiber strain sensors.
A grid of 8x7 points was placed on the beam. The grid was displayed between 60cm and 165cm right from the center of the beam, with a column every 15cm. The rows are placed at 8 different heights.
Figure 11 shows the grid of LED's placed by Krypton. Figure 12 shows the Krypton camera-system.

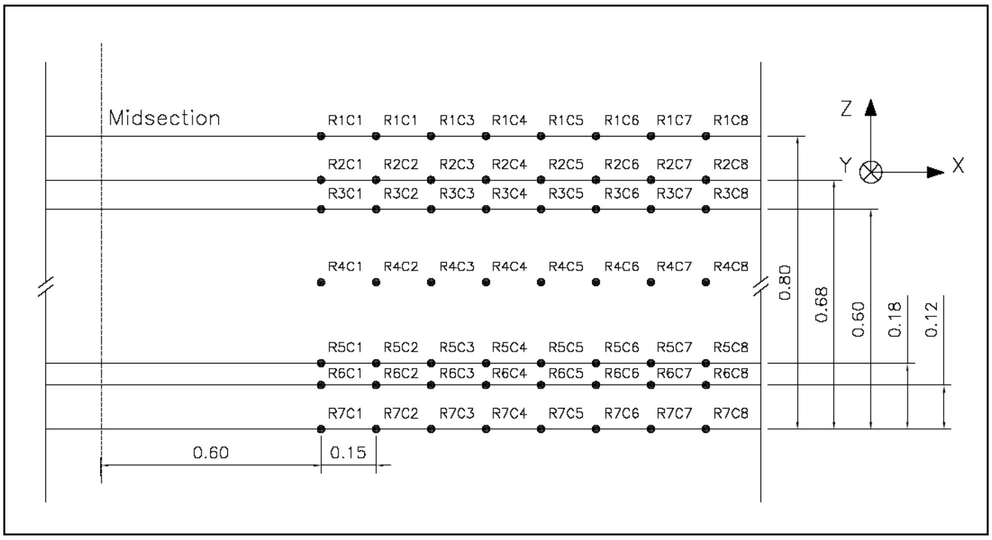

Figure 11: Grid of LED's

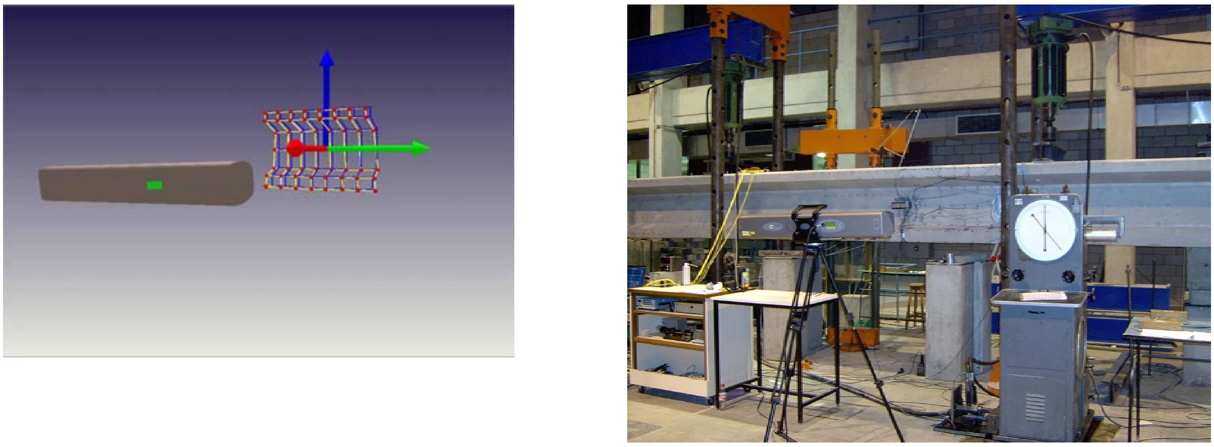

Figure 12: Krypton camera in front of the beam.

4 Comparison between experimental and numerical results

4.1 Comparison of the vertical modal amplitudes

The vertical modal amplitudes (scaled to a unit value at the left free end), measured by the Krypton system (displacements) and by the SCADAS-III front-end (accelerations) are compared with the ANSYS-values. Table 2 shows the vertical displacements U_z scaled to the reference channel for mode 1 (f_1 = 10.7 Hz).

Section	x(m)	ANSYS	Krypton	SCADAS-III
0	8.8	-0.774		-0.815
1	9.4	-0.763	-0.777	-0.809
3	9.7	-0.749	-0.785	-0.792
5	10.0	-0.730	-0.740	-0.767
7	10.3	-0.705	-0.738	-0.743

Table 2: Vertical displacements of mode 1

4.2 Modal rotation angles

First of all, the axial modal displacements are plotted for the different cross sections (Figure 13). When comparing with Figure 11, section i is corresponding to Ci. A linear regression is also applied to the results:

$$y = A * u + B$$

with:

- u : axial modal displacement (scaled to a unit value at the left free end)
- y : vertical distance in m from the center of the cross section of the beam
- A : inverse of the rotation angle of the cross section
- B : position of the point with zero axial displacement (measured relative to the center of the beam).

Table 3 shows the results of the linear regression for all sections.

From Table 3 and Figure 13 it is clear that the position of the neutral axis changes along the x-axis: in section 1 (at 8.8m) the distance to the center is 0.1655m (to the bottom (0.5655m); in section 8 (at 10.45m) the distance is 0.0823m (0.4823m to the bottom). The theoretical neutral line of the uncracked beam is calculated at a distance of 0.453m from the bottom.

Section	regression equation	R^2
1	$y = -27.273 * u + 0.1655$	0.9968
2	$y = -23.261 * u + 0.1293$	0.9945
3	$y = -18.059 * u + 0.1226$	0.9965
4	$y = -15.910 * u + 0.1035$	0.9992
5	$y = -14.333 * u + 0.1031$	0.9997
6	$y = -12.535 * u + 0.0779$	0.9997
7	$y = -11.187 * u + 0.0951$	0.9990
8	$y = -10.815 * u + 0.0823$	0.9980

Table 3: Linear regression applied to axial displacements

The axial modal displacements are much smaller than the vertical ones (1 - 6%). From the slope of the axial displacements the rotation angle can be calculated (= 1/A) and compared with the ANSYS-calculated value. Table 4 shows the rotation angles ROT_y (in radians) scaled to the reference channel. There seems to be a very good correspondence!

Section	x(m)	ANSYS	Krypton	$\frac{ANSYS}{Krypton}$ (%)
0	8.8	0		
1	9.4	0.0363	0.0367	99
3	9.7	0.0542	0.0554	98
5	10.0	0.0719	0.0698	103
7	10.3	0.0893	0.0894	100

Table 4: Rotation angles ROT_y of mode 1

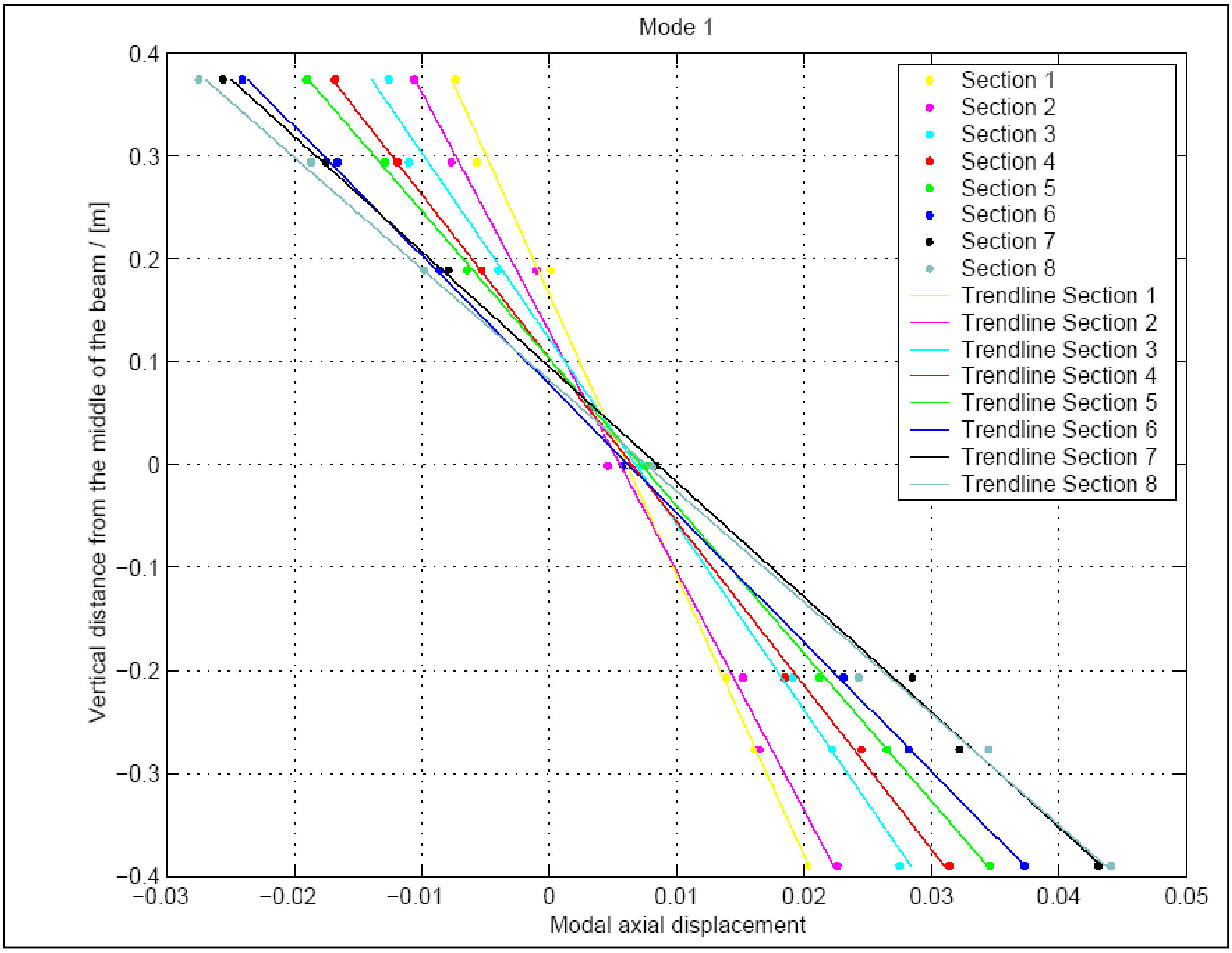

Figure 13: Axial displacements of mode 1

4.3 Mean strains

Mean modal strains between the cross sections at 9.4m and 10.3m can be calculated:

$$\varepsilon_{\text{xbottom}} = \frac{U_x(R1C6) - U_x(R1C1)}{0.9m}$$
$$\varepsilon_{\text{xtop}} = \frac{U_x(R7C6) - U_x(R7C1)}{0.9m}$$

Table 5 gives an overview of the calculated and measured mean strains at the top and at the bottom.

ε	ANSYS(1)	Krypton(2) (3)
Top	0.0174	0.0192
Bottom	0.0231	0.0230

Table 5: Comparison between the mean strains measured with Krypton and calculated with ANSYS.

Remarks:

(1): The neutral line lies at 0.453m from the bottom for the ANSYS calculations. The upper Krypton measurement points are located 0.329m above the (theoretical) neutral line. The lower Krypton measurement points are located 0.435m below the neutral line.

(2): For the ANSYS calculations, linear behavior is assumed: the position of neutral line doesn't change position. This is not the case for the Krypton measurements on the cracked beam.

(3): U_x-values after applying linear regression were used.

4.4 Mean curvature

The average modal curvature between the sections at 9:4m and 10:3m is:

$$\kappa = \frac{ROT_y(10.3m) - ROT_y(9.4m)}{0.9m}$$

From Table 6 the good correspondence with the FE-calculated curvature is evident!

x(m)	ANSYS	Krypton
9.4 – 10.3	0.0589	0.0586

Table 6: Comparison between the mean curvature measured with Krypton and calculated with ANSYS

7 Conclusions

From the Krypton-measurements, the modal longitudinal displacements of a tested prestressed concrete beam could be identified. The results are surprisingly good, taking into account that these displacements are much smaller than the vertical ones. The relation of longitudinal displacements over the height of the beam is quite linear, what further demonstrates the accuracy of the measurements.

The derived modal rotation angles, modal strains and modal curvatures correspond very well with the FE-calculated values for the first bending mode.

Up to now, although it was proven theoretically that modal strains and curvatures can be used beneficially for damage identification by vibration monitoring, it was very difficult to measure these deformations directly and reliably. So, the Krypton-system can contribute to the more widespread utilization of vibration monitoring of civil and mechanical structures.

Moreover, in many cases dynamic displacements rather than accelerations are of importance for the designer. Double integration from accelerations is rather cumbersome, especially when there is an important 'static' component in the displacements like in the case of bridges crossed by moving trains or vehicles [4].

Acknowledgements

The authors wish to acknowledge the financial support by the Fund for Scientific Research - Flanders (project G.0266.01)

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