Construction and Building Materials 98 (2015) 265–275

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Assessing steel strains on reinforced concrete members from surface cracking patterns

R.N.F. Carmo [a,b,*], J. Valença [b], D. Silva [a], D. Dias-da-Costa [c,d]

[a] Polytechnic Institute of Coimbra, Instituto Superior de Engenharia de Coimbra, Rua Pedro Nunes – Quinta da Nora, 3030-199 Coimbra, Portugal
[b] CEris, ICIST, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[c] School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[d] ISISE, Dept. Civil Eng., University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal

HIGHLIGHTS

- Method to assess steel strains inside concrete members using surface measurements.
- This approach has non-contact and does not interfere with the bond between steel and concrete.
- Validation using concrete ties monitored using strain gauges placed inside the steel bars.
- The technique can be applied to narrow regions, surrounding a single crack, or to larger regions.
- Results proved the feasibility of the method.

ARTICLE INFO

Article history:
Received 23 May 2015
Received in revised form 31 July 2015
Accepted 9 August 2015
Available online 24 August 2015

Keywords:
Strains
Monitoring
Strain gauges
Crack pattern
Reinforced concrete
Photogrammetry
Image processing

ABSTRACT

The measurement of steel strains in reinforced concrete structures is often critical to characterise the stresses along the member. In this scope, this manuscript describes the development of a method to assess steel strains inside concrete members using solely surface measurements. These measurements were obtained using photogrammetry and image processing. The technique was validated using two concrete ties monitored with strain gauges placed inside the steel bars. The experimental results showed that one of the most important parameters affecting the accuracy of the technique is the measurement of crack widths. In comparison, the concrete strain has little effect on the final results. The technique is particularly advantageous since it is non-contact and does not impact on the bond conditions. It also does not require accessing the reinforcements. As a main conclusion, this work showed the feasibility of estimating strains inside the structure using surface measurements. This technique will benefit in the near future from further improvements namely in what concerns the camera resolution.

1. Introduction

Monitoring reinforced concrete (RC) structures is an important issue not only for assessing existing structures, but also to characterise the behaviour of new structures. In what regards experimental programmes, monitoring can be helpful for fully understanding the structural behaviour and properly relate all parameters. For reinforced concrete members, measuring steel strains in key-sections can be used for the calculation of stresses and/or forces along the member. In the case of steel bars in reinforced concrete members, strains are typically measured using electrical strain gauges. However, its installation can be rather difficult and time-consuming. In addition, strain gauges have to be small enough and be placed over a limited area, such that they do not change the bond and structural response. The main motivation of the research herein presented stems precisely from the experimental verification of the impact that strain gauges can have (see [1]). In this case, the measuring technique/device clearly influences the resulting response.

The development of new tools using photogrammetry and image processing can play an important role in structural monitoring. These techniques can be applied to a significant number of surface points and enable more refined measurements, which would be extremely difficult to obtain using other traditional methods. Photogrammetry and image processing are also non-contact and non-destructive techniques for characterising crack patterns and deflections (displacements, curvatures and rotations). Recently, it

* Corresponding author at: Polytechnic Institute of Coimbra, Instituto Superior de Engenharia de Coimbra, Rua Pedro Nunes – Quinta da Nora, 3030-199 Coimbra, Portugal.

E-mail address: carmo@isec.pt (R.N.F. Carmo).

http://dx.doi.org/10.1016/j.conbuildmat.2015.08.079
0950-0618/

was shown the feasibility of measuring bending moments in structural members using this approach [2,3].

The method discussed in the following sections constitutes a first step towards the application of photogrammetry and image processing in an innovative way. In particular, a new approach is introduced to estimate steel strains inside RC members using surface data extracted from digital images. This data includes the crack pattern, defined by crack widths and spacing [4–7]. The proposed approach, although clearly in its early steps, might become useful for estimating steel strains onsite together with more traditional monitoring techniques, and without impacting on the structural behaviour.

The following objectives are herein defined:

- explore new monitoring techniques and develop useful applications for RC members;
- use surface data to assess the deformation of steel bars within RC members;
- validate a new non-contact and non-destructive method for retrieving steel strains that does not modifies the concrete-to-steel bond.

The manuscript is organised as follows. The experimental programme and the material properties are described in Section 2. Section 3 details how the measurement of steel strains can be done using strain gauges and photogrammetry/image processing. Details on how to use these techniques to measure surface deformation, crack widths and spacing between cracks are also presented in this section. The analysis of results and corresponding discussion are dealt with in Section 4. Finally, the main conclusions are drawn in Section 5.

2. Experimental programme

An experimental programme was undertaken to support the development of the new technique and provide benchmark data regarding crack patterns and steel stresses. Two RC concrete ties under tensile loading were carefully prepared and monitored. The specimens were produced using the same materials and were $100 \times 100 \times 800$ mm^3 prisms. The reinforcement was a single bar placed at the centre of the cross-section.

2.1. Test set-up

The reinforced concrete ties were loaded with a vertical force applied at the top extremity of the bar, being the other tip clamped. An interlocking sleeve system typically used for prestressing served as anchorage system – see Fig. 1a. Loading was applied using a hydraulic servo-actuator attached to the reaction metallic frame shown in Fig. 1b. This equipment has a maximum capacity of 180 kN in tension and applied load at a constant speed of 0.02 mm/s under control of displacements. The tensile force was measured using a load cell in the hydraulic servo-actuator.

Additional instrumentation devices allowed measuring displacements and strains. Two linear variable differential transformers (LVDTs), each one attached to a metallic bar, were placed vertically on both sides of the RC tie to measure the deformation/elongation during the experimental test – see Fig. 2. Steel strains were measured using electric strain gauges, which were connected to a portable data-logger. Photogrammetry and image processing techniques were also used to characterise the behaviour of the ties (Fig. 1b). All three monitoring systems (digital camera, actuator and data logger) were properly synchronised.

2.2. Material properties

The steel reinforcement was a hot rolled and ribbed, S500NR-SD class, 12 mm bar with 500 MPa nominal yield stress and 200 GPa Young's modulus [4,8]. The concrete used to cast the RC ties had a normal design density of 2446 kg/m^3 [9–12] and the corresponding mixture is shown in Table 1. The average compressive strength, f_{cm}, was 66 MPa and was experimentally measured 31 days after casting using three 150 mm cubic specimens [13,14]. The formwork was prepared and cleaned before casting and the concrete was vibrated after pouring to release air pockets and achieve suitable compactness.

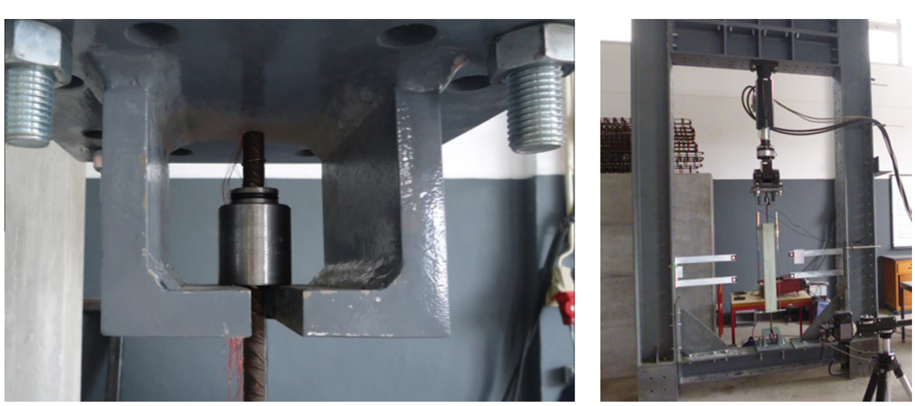
3. Strain and crack measurement

This section provides detailed information concerning the measurements with strain gauges, photogrammetry and image processing.

3.1. Strain gauges

Strain gauges were placed inside the steel bar with the purpose of having benchmark values without changing the bond behaviour [1]. This task required a significant amount of specialised workmanship during which: (i) four bars were progressively trimmed until reaching half-section; (ii) the resulting half-sections were further processed to create a notch along the centreline (Fig. 3a); (iii) the strain gauges with 10 mm length were glued along the notch and properly protected (Fig. 3b); (iv) the wiring was placed along the notch and then connected to the data-logger; (v) the effective average area of each halve was measured and the two halves were finally glued together to obtain a complete bar (with an inner notch along the axis). The resulting effective average area was 0.785 cm^2.

A total of 11 and 9 strain gauges, spaced 100 mm, were used in RC ties I and II, respectively (see labelling in Fig. 4). It should be mentioned that some strain gauges were damaged during installation, namely, strain gauge 4 in RC tie I and strain gauges 2, 3, 9 and 10 in tie II.



(a) (b)

Fig. 1. Set-up: (a) detail of the interlocking sleeve system; (b) general overview.