ASSESSING STEEL STRAINS ON REINFORCED CONCRETE MEMBERS FROM SURFACE CRACKING PATTERNS

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Abstract

The measurement of steel strains in reinforced concrete structures is often critical to characterise stresses and forces 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 using 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, whereas 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. This will benefit in the near future from further improvements namely in what concerns camera resolutions.

Keywords: strains; monitoring; strain gauges; crack pattern; reinforced concrete; photogrammetry; image processing.

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 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 description of 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 100×100×800 mm³ 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 in the top extremity of the bar, being the other tip clamped. An interlocking sleeve system typically used for prestressing served as anchorage system – see Figure 1a. Loading was applied using a hydraulic servo-actuator attached to the reaction metallic frame shown in Figure 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 Figure 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.
(Figure 1b). All three monitoring systems (digital camera, actuator and data logger) were properly synchronised.

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

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/m³ [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 on 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.

Table 1. Concrete mixture (per cubic meter).

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement CEM I 52.5 R</td>
<td>320</td>
</tr>
<tr>
<td>Addition Limestone filler</td>
<td>80</td>
</tr>
<tr>
<td>Admixture Super plasticizer GS526</td>
<td>2.57</td>
</tr>
<tr>
<td>Water -</td>
<td>157.7</td>
</tr>
<tr>
<td>Aggregates</td>
<td></td>
</tr>
<tr>
<td>Fine sand 0/1</td>
<td>284.7</td>
</tr>
<tr>
<td>Medium sand II</td>
<td>528.7</td>
</tr>
<tr>
<td>Gravel</td>
<td>199</td>
</tr>
<tr>
<td>Coarse aggregate 8/14</td>
<td>805.3</td>
</tr>
</tbody>
</table>

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 (Figure 3a); (iii) the strain gauges with 10 mm length were glued along the notch and properly protected (Figure 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 cm².
A total of 11 and 9 strain gauges, spaced 100 mm, were used in RC ties I and II, respectively (see labelling in Figure 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.

3.2. Monitoring system settings for image processing

A digital camera was placed on a tripod at approximately 2.5 m and in front of the surface of the specimen. A remote shutter was installed to trigger the camera without compromising the stability of the monitoring apparatus. Images were acquired with a maximum resolution (4608×3072 pixel) and using a 55 mm lens. The camera-lens system was calibrated beforehand using Bouguet’s camera calibration procedure [15].

The surface of the ties was painted with a regular grid of 5 mm diameter circular targets spaced 10 mm. This was established according with previous experimental results and aiming at a precision of circa 0.3% on the strain field measured using photogrammetry [16]. Homogeneous and diffused lighting conditions were kept constant during the test to avoid influencing crack detection. The camera was triggered at pre-defined key-points during the test, from which six stages were considered relevant (per test).
Figure 5 shows the ‘load vs. time’ curve for both tests with the image acquisition stages (circular marks).

Figure 5. Loading of the ties including identification of the most relevant stages.

3.2.1. Surface strain calculation using photogrammetry

Photogrammetry was already successfully applied for monitoring experimental tests. Presently, there are several approaches available for tracking displacements using this technique [16-20]. In the present work, high contrast circular targets have been painted in the surface of the specimen and tracked for in-plane displacements during the test [16, 21]. Before starting the test, a first image was acquired and used to establish a homography matrix that relates image coordinates (in pixel) with real-world coordinates (in mm). This matrix was used to scale and orientate all remaining images (see more details in [22]). The displacements measured during the test were then used to calculate the strain field [20, 22, 23] using standard finite element post-processing techniques. For this purpose, a strain-nodal displacement matrix was built for each target and used to calculate the strain [16].

The error in the detection of target coordinates was experimentally estimated based on the repeatability of the method. The standard statistical measurement Root Mean Square (RMS) was applied to assess the errors in the coordinates calculated using a set of ten identical images acquired immediately before loading and within a short period of time. The RMS was 0.040 mm and 0.030 mm, respectively, for RC ties I and II (see
Using this information, the average error in the strain field was 0.35% [2].

Figure 6. RMS [mm]: (a) map; (b) correlation between RMS in both x and y directions.

Figure 7 shows a comparison between displacements measured with both LVDTs and photogrammetry, considering the 10 boundary targets at each edge of the tie, during the test. An average difference of 0.12mm and 0.61mm was computed for ties I and II, respectively. It should be mentioned, however, that these differences are high and cannot be used for the validation of photogrammetric displacements. In fact, the traditional system was unstable during the tests and the points tracked with both techniques (LVDTs and photogrammetry) were close, but not coincident. The validation of this technique was already performed in two previous experimental studies (see publications [16, 22]).
3.2.2. Crack measurement using image processing

The crack width results directly from the slippage between steel and neighbouring concrete under tensile stresses. Since the slippage depends on the level of applied load, a careful characterisation of the crack pattern can be used to predict the behaviour inside the reinforced concrete member, namely the deformation in steel reinforcements.

The characterisation of crack patterns in surfaces can be done using image processing algorithms [24]. Most approaches require certain light conditions to avoid false detections due to stains or shadows existing on the surface [22, 24]. Despite this, the level of precision can be quite high and depends mainly on the spatial resolution of the image. Image processing algorithms usually output a binary image suitable for measuring crack widths or other geometric features. If the images are scaled, for instance using the homography procedure mentioned earlier, then all measurements can be directly converted into real dimensions. This technique was herein applied for characterising the crack pattern during the test (more details about the procedure can be found in [2, 24]). Measuring crack widths was performed along three distinct profiles on the binarised image (see Figure 8), where the number of pixels intercepted at each crack directly provides its width (for that profile). It should be mentioned that the spatial resolution of the resulting images was 0.2 mm/pixel, which was also the average error in the measurement. This error precludes measurements for lightly loaded specimens, in which case a second camera would be required for acquiring close-up images with increased resolution. In the following sections, the loading stages were carefully selected such that all measurements and crack widths are within the capabilities of the current set-up.

Figure 8. Crack widths: (a) measuring profiles; (b) detail of a profile crossing a crack.
3.2.3. From the crack pattern to steel strains

When the concrete ties reaches its tensile strength due to the applied load, cracking starts to develop. Simultaneously, its axial stiffness starts to progressively decrease. After the stabilisation of this process, the crack pattern no longer changes and further increasing loads will only change the existing crack openings. During this stabilised state, the crack width is equal to the crack spacing multiplied by the difference between average strain in reinforcement and concrete located between the cracks. The crack width therefore results from the different relative deformations, i.e. slip, of steel against concrete over a finite distance (shaded area in Figure 9). This information can be used to compute the average steel strain within this region, using the crack widths found at the surface of the member:

\[ w = \int_{0}^{s} (\varepsilon_s - \varepsilon_c) \, dx \approx (\varepsilon_{sm} - \varepsilon_{cm}) \cdot s \Rightarrow \varepsilon_{sm} = \frac{w}{s} + \varepsilon_{cm}, \]  

where ‘\( w \)’ is the width of the crack, ‘\( \varepsilon_s \)’ and ‘\( \varepsilon_c \)’ stand, respectively, for the steel and concrete strains; ‘\( \varepsilon_{sm} \)’ and ‘\( \varepsilon_{cm} \)’ are, respectively, the average strains for steel and concrete; and ‘\( s \)’ is the distance between cracks. Please note that the previous expression is formulated for the fibre where the bar is located and will be herein assumed valid through the thickness of the specimen at that particular location. This is the typical approach adopted by existing concrete design standards and guidelines, see e.g. [4, 5].

In the following sections, this manuscript explores the possibility of using Eq. (1) to retrieve the average strain in steel using the crack widths measured with image processing. It should be highlighted, however, that cracking is a semi-random process depending on the material properties, namely, the highly heterogeneous tensile strength of concrete [6]. Consequently, crack widths and spacing can vary relatively to its average value. This will be dealt with in the following sections.
4. Results

Figure 10 shows the load vs. displacement curve (F-\(\delta\)) representative of the overall behaviour of the concrete ties (continuous lines). In the same figure, the circular marks were used to represent the stages where images were acquired. The F-\(\delta\) curve shows that the axial stiffness before cracking was quite high and that the response was nearly linear until the onset of the first crack. After cracking, the deformation increased considerably with loading, revealing a steep loss of stiffness. In this stage the tension stiffening effect was significant, as the concrete between the cracks contributed to the tensile strength of the member and to a reduced deformation along the steel bar. Finally, the last stage was characterised by a horizontal plateau appearing when the steel reinforcement yielded. Considering the reduced area of cross-section of the bar, the cracking stabilisation occurred close to the point where steel started to yield.
The experimental results were used to assess the applicability of the method proposed to predict the steel strain steel using crack measurements on the surface of the ties. The following sections address the main results. Section 4.1 shows the evolution of the steel strains on several longitudinal sections and along the entire tie. In the Sections 4.2 and 4.3, the strains on the concrete surface obtained by photogrammetry and crack patterns (cracks widths and spacing) computed by image processing, are analysed for the six relevant stages. Finally, in Section 4.4, a comparison between prediction and measurements is performed.

4.1. Steel deformation measured using strain gauges

Despite the fact of some strain gauges being damaged, the analysis of the strain profile along the bar could be effectively made using the remaining gauges. Figure 11 shows the strain profile along 800 mm depicted using the strain gauges 2 to 10 (see Figure 4). Results are within the expected range of values and enable the identification of the onset of cracking, namely, cracks location (characterised by the highest strain). The increased strain in the region of the crack is related with the concrete tensile strength and cross-section. Before cracking, the stress in the reinforcing bar is approximately constant along the tie, whereas after cracking, the stress varies along its axis: (i) in cracked sections, the stress is higher and theoretically equals the stress considering the whole load applied onto the bar; and (ii) in uncracked sections between the cracks, the stress decreases significantly due to the concrete carrying part of the tensile forces in that region.
As mentioned in Section 3.2.3, the crack width depends on the relative deformation between steel and concrete within a corresponding region of interest (Figure 9). In this scope, the first step before applying Eq. (1) required the calculation of the length of the region related with each crack width. The crack pattern of both ties showed three different regions of interest, one per main crack. These regions were defined as half the crack spacing to each side (Figure 12). The second step included calculating the average steel strain for each region using the strain measured with all non-faulty gauges inside that region (later on to be used for validation purposes). The evolution of the steel strain with the load is shown in Figure 13 and Table 2. It can be noticed that the steel strain increased almost linearly with the load until approximately 30 kN. After that point, the strain increased significantly with small load increments, since the reinforcement was already yielding.

![Figure 11. Strains along the bar for: (a) RC tie I; and (b) RC tie II.](image-url)
4.2. Surface strain

Maps showing the surface strain distribution were computed using the displacement field measured by photogrammetry and according with the procedure described earlier – see Figure 14. Since the principal deformation takes place along the axis of the RC tie, the strain field was computed in that direction. This
The average strain was computed between two consecutive lines of targets (identical values in x-axis). The darker areas correspond to larger strains that exceeded the concrete strain limit. This is in accordance with the presence of cracks in those regions and the crack patterns presented in the previous section.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Image</th>
<th>Surface Deformation</th>
</tr>
</thead>
<tbody>
<tr>
<td>#2</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>#3</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>#5</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>#2</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>#3</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>#5</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Figure 14. Strain field distribution on the surface of the ties.

The previous figures were used to compute the average concrete strain between the cracks for each region of interest (see Figure 12). This calculation used the displacements measured along the line of vertical targets located nearer the limits of each region. The strain precision reached out in this case is directly related with the length of the regions – see Table 3. The concrete strain for different loads is shown in Figure 15 and also in Table 3. In general, and as expected, the average concrete strain increases with the load, being this growth linear for the early stages. The values measured are higher than the ultimate concrete strain, since these include cracks existing at the surface for each region. In the following sections, two limit situations will be considered to check the role of this parameter in the accuracy of the method.
Figure 15. Load vs. concrete strain on the surface: (a) RC tie I; and (b) RC tie II.

Table 3. Concrete strain computed by photogrammetry.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Load (kN)</th>
<th>RC tie I Average strain (x10^-6)</th>
<th>Load (kN)</th>
<th>RC tie II Average strain (x10^-6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Region 1 (error &lt;0.67‰)</td>
<td>Region 2 (error &lt;0.46‰)</td>
<td>Region 3 (error &lt;0.36‰)</td>
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<tr>
<td>#1</td>
<td>24</td>
<td>486</td>
<td>1051</td>
<td>2445</td>
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<td>#2</td>
<td>34</td>
<td>719</td>
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<td>2957</td>
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<tr>
<td>#6</td>
<td>42</td>
<td>1175</td>
<td>1746</td>
<td>2782</td>
</tr>
</tbody>
</table>

4.3. Crack measurement

The superficial cracks on both ties were detected and measured using the image processing technique described earlier [22, 24]. Figure 16 shows the location of all cracks for the last stage, since the process of crack formation is already fully stabilised. The corresponding cracks widths were measured for each stage using the procedure in Section 3.2.2. Figure 17 shows the evolution of the widths during the test, whereas Tables 4 and 5 summarise all data for both ties including the average, minimum and maximum widths obtained using the three profiles shown in Figure 8.

Figure 16. Average crack width for each crack: (a) RC tie I; (b) RC tie II.
Figure 17. Crack width evolution: (a) RC tie I; (b) RC tie II.

Table 4. Crack widths – RC tie I

<table>
<thead>
<tr>
<th>Stage</th>
<th>Load (kN)</th>
<th>Crack 1 (mm)</th>
<th>Crack 2 (mm)</th>
<th>Crack 3 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W_{min}</td>
<td>W_{max}</td>
<td>W_{min}</td>
</tr>
<tr>
<td>#1</td>
<td>24</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>0.20</td>
</tr>
<tr>
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<tr>
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<td>42</td>
<td>0.27</td>
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<td>0.40</td>
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Table 5. Crack widths – RC tie II

<table>
<thead>
<tr>
<th>Stage</th>
<th>Load (kN)</th>
<th>Crack 1 (mm)</th>
<th>Crack 2 (mm)</th>
<th>Crack 3 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W_{min}</td>
<td>W_{max}</td>
<td>W_{min}</td>
</tr>
<tr>
<td>#1</td>
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<td>-</td>
</tr>
<tr>
<td>#2</td>
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<td>-</td>
<td>-</td>
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<td>#3</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>#6</td>
<td>43</td>
<td>0.67</td>
<td>0.60</td>
<td>0.80</td>
</tr>
</tbody>
</table>

4.4. Assessing the steel strain

The assessment of the steel strain using surface measurements was done using the following parameters: (i) average crack width; (ii) length of the region of interest neighbouring each crack; and (iii) the average concrete strain. The calculated strain, $\varepsilon_{s,photo}$, was then compared with the values measured using strain gauges, $\varepsilon_{s,gauge}$. The following three different approaches were applied:

- Approach 1. Concrete deformation between cracks, $\varepsilon_{c,m}$, was considered negligible since it is usually significantly smaller than the average steel strain, $\varepsilon_{s,m}$. 
– Approach 2. Concrete deformation between cracks, $\varepsilon_{cm}$, obtained using photogrammetry was considered in the calculations to check for the sensitivity of the calculation of the steel strain relatively to this parameter.

– Approach 3. The analysis was performed globally for each tie, with and without considering the concrete deformation. The purpose of this global analysis is to obtain a more reliable approximation that is not only focused in a narrow region of the member.

Results from the first approach show some dispersion in tie I, particularly in region 2 and for the two last stages of analysis – see Figure 18a. The remaining data points are relatively close to the line (y=x) for regions 1 and 3, meaning that calculated strains tend to approach the values measured with the strain gauges. For RC tie II, the points are also close to the reference line for all regions, highlighting the feasibility of this procedure for calculating steel strains (Figure 18b).

When using the second approach, and as expected according with Eq. (1), strain estimates are slightly increased – see Figure 19. Theoretically, including this parameter would lead to more rigorous calculations.
In third approach, all crack widths were used together for the entire length of the tie, to check whether this approach would provide more reliable estimates. Results are summarised in Figure 20 and showed a smaller dispersion compared with the previous two approaches. However, it should be mentioned that this approach should only be applied after all cracks are indeed stabilised, which is not the case for all the stages in this analysis.

With the purpose of understanding the influence of the crack width on the strain estimates, the third approach was applied with both minimum and maximum crack values, also with and without $\varepsilon_{cm}$. Figure 21
summarises the main results and shows that the crack width has a major impact on the calculation of the steel strain, being actually the most relevant parameter. Figure 21 also shows how using the minimum and maximum crack widths would impact on the results. This points out to the importance of measuring the crack widths using high precision methods. It should be mentioned that the calculation using both minimum and maximum values, although illustrative, leads to unreal estimates of the strain, since not all cracks are probabilistically expected to have such values. The average value is the one that is the reference and can be used for measuring steel strain, in spite of the limitations on the image resolution mentioned before. The analysis also confirms that $\varepsilon_{cm}$ has little impact on the results when compared with the crack width.

Finally, the steel stress can be calculated from the estimated strains by using directly the constitutive model for the adopted steel.

5. Conclusions

This manuscript focused on the development of a method to assess steel strains in reinforced concrete members using surface measurements, namely, crack widths and spacing. Since the crack widths can be related with the relative slippage between steel and concrete, it can be used to estimate the steel deformation. In the proposed approach, photogrammetry and image processing were used to characterise the surface of the
members. The study carried out aimed at assessing the applicability of this technique and the feasibility of proposing useful innovative tools for structural engineering.

The results showed that the method can be applied to assess the steel strain and support both monitoring and diagnosis of the structural behaviour. Currently, the limited resolution of existing digital cameras does not allow a more accurate evaluation of steel strains. The main advantage is in the retro analysis or for prediction of steel strains whenever strain gauges are not available (or cannot be easily installed). The new technique does not interfere with the bond between steel and concrete. However, it can only be applied after concrete cracking and, in some situations, after stabilised cracking. Therefore, the technique may not be suitable for structures under small service loads.

The proposed analysis can be applied in the narrow regions surrounding a single crack, or to larger regions. In the latter case, only the average strains can be retrieved. From the experimental tests, larger areas showed slightly less dispersion in terms of results, thus decreasing the error in the calculations. It was also shown that the crack width is the most important parameter for the calculation of the steel strain. Therefore, the accuracy will depend on the procedure adopted for obtaining crack width measurements. The adopted experimental set-up only allowed a resolution of 0.2 mm/pixel, which precludes monitoring lightly loaded concrete specimens. This situation, however, can be overcome by using a second camera for close-up image acquisition with increased resolution.

In this scope, the crack widths seem to have more impact on the strain estimates, particularly when compared with the concrete deformation between the cracks. In fact, since the concrete strain is within the precision of the method, this parameter can be slightly overestimated and, hence, the same happens with the steel strain. Results showed that the method is feasible and that can have a great potential for structural monitoring that will benefit from further improvements, namely in what concerns the camera resolution.

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References


