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1 **SURFACE ROTATION CORRECTION AND STRAIN PRECISION OF WIDE-ANGLE**
2 **2D DIC FOR FIELD USE**

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8
9 **ABSTRACT**

10 The paper describes how 2D Digital Image Correlation is used on underneath surfaces of concrete
11 bridges with wide-angle lens camera during load testing, and how it has potential as a stop criterion in proof
12 loadings.

13 A method is proposed for correction of out-of-plane deflection including rotation of the surface. The
14 method is applied to laboratory tests, using well defined circular speckle patterns, as well as to a field tested
15 bridge (on raw concrete). The proposed correction corresponds to the level of pseudo strain, but is very
16 sensitive to precise surface deflection measurements.

17 In the laboratory tests, a strain precision of the wide-angle lens camera is compared to a regular lens
18 camera. The parametric study concludes that a Pattern Pixel Relation, in the interval from 4 to 9 pixels per
19 pattern circle diameter, provides the optimal precision regardless of the camera type.

20 The field tested bridge has less good precision compared to most parameter combinations of the
21 laboratory tests. Nevertheless, the field strain precision has potential for improvement based on learnings
22 from the laboratory tests.

23

24 **INTRODUCTION**

25 The following main approaches are typically used to monitor surface strains on concrete structures: i)
26 Direct contact measurements, which are used to measure in direct contact with the surface (by e.g. strain
27 gauges, extensometers, etc.) or ii) non-contact measurements (by e.g. photogrammetry, laser scanning,
28 Digital Image Correlation etc.) placed in a distance from the structure. Such equipment can potentially be
29 used for structural health monitoring, diagnostic loading, local strain evaluations, laboratory testing etc.

30

31 Proof load testing of existing concrete bridges is an extensive monitoring challenge, due to the
32 environmental exposure of the monitoring equipment, and limited testing time. Such application can require
33 simultaneous monitoring of a large number of locations, and that different monitoring sources are used to
34 ensure a robust identification of unique stop criteria with sufficient precision. The precision of the output
35 should be of a quality, which can be used to update theoretical models related to the capacity- or
36 probabilistic evaluations. Furthermore, fast mounting and dismantling of the monitoring equipment is
37 necessary to reduce traffic disturbance as much as possible.

38

39 This paper focuses mainly on the use of wide-angle Digital Image Correlation (DIC), which is a non-
40 contact methods that seems promising and useful as a mean to solve some of these challenges. Such
41 equipment can be fast to apply, and can potentially provide full field strain measurements of larger structural
42 surfaces. The use of wide-angle cameras have, to the author's knowledge, not been used for DIC evaluations
43 before, but is deemed to be an essential tool for evaluation of strains and cracks on large concrete surfaces.

44 DIC is an advanced method for evaluation of deformations on a test specimen by the use of digital
45 photographs, captured of the test specimen surface before (reference image) and during load testing (the
46 original technology is explained by Sutton et al. (1983)). DIC can be used for both 2D (in-plane
47 measurements with one camera) and 3D evaluations (out-of-plane measurements with two or more
48 cameras), where 3D DIC always, to the knowledge of the authors, require a more time consuming and
49 difficult calibration, and is designed mostly for laboratory conditions.

50 In the literature, 2D DIC is predominantly used for relatively small plane surfaces, where no out-of-
51 plane deflection is expected to occur during testing, and where the surface is parallel to the direction of the
52 image sensor of the camera (e.g. Wang et al. (2011), Hoult et al. (2013), Pan et al. (2014), and Chen et al.
53 (2015)).

54 Although some researchers have addressed the correction of out-of-plane deflection of 2D DIC (Schreier
55 et al. (2009)), no one has studied methods for correction of out-of-plane deflection on large in-situ concrete
56 surfaces, where surface rotations are present as well, and where application of painted speckles can be
57 difficult to apply due to the site conditions, surface accessibility, size of the surface, and available time.

58 This paper proposes a strain evaluation method, which takes surface rotations into account, when
59 correcting for out-of-plane deflection on large surfaces. The method was tested under laboratory conditions
60 and applied to a real load tested concrete bridge in Denmark, as an example. The bridge was a short span
61 (less than 12 m), simply supported, highway beam bridge, where DIC-cameras were applied to the
62 underneath bridge deck surface. Evaluation of strains, based on conventional out-of-plane displacement
63 correction methods alone, seems inapplicable in the case, since it differs significantly due to the additional
64 surface rotation. The discrepancies between the scenarios is depicted in Figure 1.

65 Furthermore, the paper includes a comparing evaluation of the precision applied to both large scale
66 laboratory tests, and field tests, where a wide-angle lens DSLR-camera was used, as a state-of-the-art DIC
67 equipment, to achieve the largest possible surface for evaluation.

68

69 **2D Digital Image Correlation – precision and errors**

70 The principle of DIC is that captured digital photographs are evaluated by dividing them into subsets of
71 a certain size (e.g. 80x80 pixels). These subsets are assessed in terms of the grey level. A DIC-software can
72 distinguish the subsets from each other, and they are tracked continuously during the surface deformation
73 to determine the direction and size of strains and displacements. Interpolation done by the DIC-software
74 provides precision at sub pixel level (Bruck et al. (1989)) and different researchers have aimed to optimize

75 the correlation computation method to achieve precisions as good as 1/10 to 1/20 of a pixel (Ruocci et al.
76 (2016)).

77 The precision of DIC can be affected by numerous influencing parameters (Lecompte et al. (2006 and
78 2007), Bornert et al. (2009), Triconnet et al. (2009)), such as:

79 a) The surface texture (must have a distinct high contrast pattern). The standard method in the
80 literature is to manually apply painted speckles, even though few researchers have applied DIC
81 without a painted pattern (Waterfall et al. (2014) and Schmidt et al. (2014)). Painted speckles on
82 concrete bridges for in-situ tests have also been applied in rare occasions (Yoneyama and Kitagawa
83 (2007) and Halding et al. (2016)), but the creation of painted speckles on larger surfaces is deemed
84 very time consuming (Sutton et al. (2017)). The speckles on a concrete bridges by Halding et al.
85 (2016) were monitored at close proximity to the bridge surface, and in the investigation by
86 Yoneyama and Kitagawa (2007), it was from a far distance.

87 b) The subset size. The choice of subset size has been discussed throughout the literature for small
88 scale laboratory tests (e.g. Crammond et al. (2013), and Park et al. (2017)). A general conclusion is
89 that larger subsets generate a better precision when evaluating the strain. However, when evaluating
90 crack initiations smaller subsets should be used.

91 c) The subset size to speckle size relation. It is deemed that the precision is highly dependent on this
92 relation but it is still an open question, how these mutually affect each other for in-situ tests on raw
93 concrete surfaces. In addition, the speckle sizes often vary on a painted surface, and similarly the
94 texture roughness differ on raw concrete surfaces, which potentially means that the precision can
95 vary depending on the identified subset. This seems not fully understood and may be essential when
96 evaluating large surfaces.

97 For small scale experiments, Triconnet et al. (2009) proposed that the standard deviation of the grey
98 level distribution within each subset should have a minimum value of 6 grey levels, and that the
99 maximum speckle size should be 1/4 of the subset size. Later Sutton et al. (2017) stated that the
100 number of pixels per speckle should not be less than three, to achieve adequate DIC interpolation.

101

102 *Pseudo strain errors from lens distortion and out-of-plane deflections (optical strain errors)*

103 One recurring error in the literature is lens distortion. To correct the distorted image plane, different
104 methods have been suggested (e.g. Yoneyama et al. (2006)). Today, the commercial software Adobe
105 Photoshop (Photoshop 2018) have incorporated anti-lens-distortion algorithms for a large range of cameras
106 and lenses, and the authors have previously checked the correctness of lens distortion correction via this
107 method (Halding et al. (2018)).

108 In regard to out-of-plane deflections (pure translation towards the camera), Hoult et al. (2013) did an
109 experimental study on thin steel specimens in tension, with cameras for 2D DIC on both sides of the
110 specimens. They showed, by incremental movement of the cameras, that errors from out-of-plane
111 deflections had major influence on the measured strain, and summed up a number of solutions from their
112 own research and from the literature: i) By calculated correction based on geometrical consideration (from
113 Schreier et al. (2009)), ii) by minimization of the problem by increasing the distance to the camera, iii) by
114 estimating the error from knowledge of the Poisson's ratio of the material, iv) by using cameras on both
115 sides of the specimen, v) and by comparing to an object without deflection next to the specimen.

116 Only i) is applicable for in-situ load tests of concrete bridges by DIC of the underneath surface. The
117 authors have also previously investigated a calculation similar to i) that is solely valid, where no surface
118 rotation occur (Halding et al. (2018)), see Figure 2:

$$L_d = \frac{L \cdot h}{h - n} \quad 1$$

119 L_d is the detected distance between two points on the evaluated surface after out-of-plane deflection has
120 occurred, and L is the original distance between the points before deflection. The out-of-plane deflection is
121 denoted, n , while, h , is the camera to surface distance before deflection. The strain alteration from out-of-
122 plane deflection was then determined as:

$$\varepsilon_{oop} = \frac{L_d - L}{L} = \frac{h}{h - n} - 1 \quad 2$$

123 The above is based on photographs without lens distortion, and the correction method applies in practice
124 in areas, where the surface rotation is insignificantly small during testing (for instance at the mid-span of a
125 simply supported, uniformly loaded beam).

126 For evaluation of larger surfaces by e.g. use of wide-angle lens DSLR-camera, the correction for out-
127 of-plane deflection is only part of the required total strain correction, when using 2D DIC. The inclination
128 (or rotation) of the deflected surface leads to an error as well.

129

130 **The full-scale concrete bridge field testing program**

131 The paper is part of a Danish bridge testing project that was initiated in 2016 by the project partners:
132 The Danish Road Directorate, the Technical University of Denmark, and the consultancy firm COWI A/S.
133 The aim of the project is to develop a method for proof load testing of existing bridges with the purpose of
134 determining if the tested bridges can achieve a higher loading class than predicted by the use of established
135 theoretical methods. The developed method includes advanced monitoring of the bridge response (for stop
136 criteria), where 2D DIC is chosen as one of the most promising approaches to evaluate thresholds during
137 testing.

138

139 **CORRECTION FOR SURFACE ROTATION DURING OUT-OF-PLANE DEFLECTION**

140 In-situ tests of larger surfaces are in many cases difficult to perform without some level of out-of-plane
141 deflection- and rotation of the loaded specimen. For field applications, like bridge load testing with
142 evaluation of the underneath bridge surface, it is therefore required to extend the existing out-of-plane
143 correction calculation method to include the rotation of the deflected surface. This is, if it is not an option
144 to position the camera far away or to have a camera on both sides. For the following method to be applicable,
145 the out-of-plane deflection must be measured as well in several locations and with high accuracy. The total
146 correction method is employed in three tempi:

147 1. Correction for out-of-plane translation of the surface, based on measurements of the deflection.

148 2. Correction for rotation of the surface, based on measurements of the deflection.

149 3. Correction for lens distortion, based on the camera and lens type.

150

151 In Figure 3, the parameters for calculation of the surface rotation correction is presented.

152 The rotation of the surface is not corrected by the lens distortion correction since the viewed angle
153 between two points on the surface will change from α to β when the surface rotates. The perpendicular
154 distance from camera to surface before deflection is denoted, h , and the deflection in point A is, n . The
155 parameter, x , is the horizontal distance to the first point, B, on the surface, and, L , is the distance between
156 A and B. The change in deflection from B1 to B2 as the surface rotates around A is called dn . dL is the
157 horizontal change in position of point B. By trigonometry, dL , and the angles, α and β , are found as:

158

$$dL = L - \sqrt{L^2 - dn^2} \quad (3)$$

$$\alpha = \arctan\left(\frac{L+x}{h-n}\right) - \arctan\left(\frac{x}{h-n}\right) \quad (4)$$

$$\beta = \arctan\left(\frac{L+x}{h-n}\right) - \arctan\left(\frac{x+dL}{h-n-dn}\right) \quad (5)$$

159

160 The angles, α and β , can be utilized when determining the strain correction from the rotation on the lens
161 distortion correction. This is because the relative change in the viewed angle between the two points on the
162 surface, is the same as the relative change in distance between the points:

163

$$\varepsilon_{rot} = \frac{\alpha - \beta}{\alpha} \quad (6)$$

164 It should be noted that the above correction is for longitudinal strains in sections in straight line with the
165 camera, which is what is investigated in this work. An extended version of the correction, for a 2D
166 representation, could be developed by considering the component of the strain in the directions that are not
167 in line with the camera.

168

169 The strain correction contributions (ε_{oop} and ε_{rot} from Eq. (2) and Eq. (6)) must then be added to achieve
170 the total correction. For a simply supported beam or deck, the largest strain error (pseudo compression)
171 caused by the rotation of the surface is found near the supports (position of maximum surface rotation), and
172 the maximum strain error (pseudo tension) from the deflection is found at mid-span (position of maximum
173 out-of-plane deflection). Hence, both correction contributions are essential in regard to analysis of full-field
174 studies of large areas. Figure 4 shows an example of such correction contributions.

175 To determine the true surface strain, the corrections must be subtracted from the directly measured DIC-
176 strains (from digital photographs without lens distortion):

177

$$\varepsilon_{true} = \varepsilon_{DIC} - \varepsilon_{rot} - \varepsilon_{oop} \quad (7)$$

178

179 **LABORATORY TESTS**

180 To compare the laboratory tests with an example from field load tests, the same DIC camera equipment
181 was used in both cases. The overall purpose of the laboratory tests was to, in a controlled environment,
182 provide a more standardized reference for the field tests as well as a direct comparison between a DSLR-
183 camera with and without wide-angle lens. The standard of reference was regarding the strain precision, and
184 the precision of the correction method. It should be noted that the strain analysis differs from crack initiation
185 identification, where the optimal subset size is different.

186

187 **Test setup**

188 A Canon 6D with 20 Mpx (Megapixel) resolution and a wide-angle lens (Canon EF 16-35mm f/2.8L II
189 USM), and a Canon 750D with 24 Mpx resolution and a regular lens (Canon EFS 18-55mm IS STM) was
190 used in the tests. During the tests, the camera was positioned on a tripod facing a rigid steel frame with an
191 installed vertical board of approximately 2.4 m x 4.8 m (height x length), see Figure 5. The board was

192 pushed sideways in between horizontally positioned H-beams in the bottom and top of the frame, and there
193 was a small gap of approximately 10 mm between the top of the board and the flange of the top H-beam
194 after installation. The orientation of the camera was perpendicular to the non-deflected board surface in all
195 tests. The large board consisted of four smaller boards, connected by five horizontal laths, which were
196 screwed into the backside. The boards were made by 10 mm MDF (Mittel-Dichte Faserplatte: glued wood).

197 Foil strain gauges (HBM type: 10/120 LY11) and extensometers (Instron clip-on dynamic 2620-604)
198 for direct contact surface strain measurements were positioned on the front surface of the board as known
199 (discrete) references to the DIC strain measurements. The vertical distance between all gauges was 450
200 mm, and the strain gauges were glued to the surface after the layers of paint had carefully been grinded off
201 (a painted pattern had been applied in the laboratory tests). The extensometers were positioned next to the
202 strain gauges (100 mm horizontal gap) in the same height, and were being secured to the surface with elastic
203 bands through small holes drilled in the plate. Similarly, the wires from the gauges passed through drilled
204 holes in the plates to avoid too much interference with the DIC system.

205 See Figure 6 for the exact positions of the monitoring equipment. In Figure 7, photographs show the
206 setup from the front (top photograph), from the front zoomed in to two strain gauges and an extensometer
207 (bottom left photograph), and from the backside, where LVDT's (Novotechnik 0-5 V) and bolts for manual
208 application of the deflection is seen (bottom right photograph).

209 The frame was designed so that deformations could be applied via bolts and nuts at mid-span on the
210 backside of the plates (via the columns) and generate a desired deflection of the plate. The boundary
211 conditions were assumed simply supported. LVDT's and dial gauges were positioned on the rear surface
212 as well, to measure the size of the deflection in a number of locations. The LVDT's measured in the same
213 location as the vertical strain gauges (on the front surface), while the dial gauges were positioned next to
214 where the bolts and nuts for deformation was applied.

215

216 **Test specimens and grey levels**

217 Three MDF boards were painted to get background color #949494 - grey nuance number 148 (number
218 255 corresponds to pure white). A pattern of circle dots was then applied by spray paint - color #585858
219 and grey nuance number 88 (number 0 corresponds to pure black) through perforated steel boards with
220 different sizes of holes for each board, see Figure 8. The perforated steel plates were positioned above the
221 boards, and the paint was sprayed through the holes:

222 Plate 1) Hole diameter 3 mm, a hole-percentage of 33, and triangular hole distribution with center
223 distance of 5 mm

224 Plate 2) Hole diameter 5 mm, a hole-percentage of 35, and triangular hole distribution with center
225 distance of 8 mm

226 Plate 3) Hole diameter 10 mm, a hole-percentage of 40, and triangular hole distribution with center
227 distance of 15 mm

228 The hole-percentage is the area percentage of voids of the total plate area. The similar hole-percentages
229 ensured that the area of each of the two grey nuances, and therefore the grey levels, ought to be comparable.
230 The idea was to create a painted surface with characteristics similar to raw concrete. The grey nuances were
231 chosen based on evaluation of concrete surfaces from digital photographs underneath two actual bridges
232 during in-situ load testing in Denmark (one on a summer day, and one on a winter day). One representative
233 photograph from both in-situ tests were utilized in determining grey levels for the boards in the laboratory
234 tests. An average grey level histogram (based on all pixels of the whole photograph) for both in-situ
235 photographs was determined, and the nuances corresponding to the grey intensity at the 25 and 75 percentile
236 values of the histograms, see Figure 9, were chosen as the two nuances of the paint in the laboratory tests.
237 The type of histogram shown in the figure can be found via Photoshop, MatLab or similar programs.

238

239 **Test procedure and test parameters**

240 Before each test, the level of light was measured in front of the camera lens (by handheld luxmeter:
241 Exttech HD400. With a precision of ± 5 Lux). Each plate was then initially tested in non-deflected condition
242 to achieve a strain-precision of the DIC-monitoring by capturing five Raw-format photographs of which
243 two were chosen for evaluation in a DIC software. In theory, the measured surface strain should be zero
244 from the first to the second photograph, but in practice, some erroneous strains occurred, which could be
245 used in determining the precision under the chosen settings. The precision was calculated as the standard
246 deviation of the strains in every point along a chosen section.

247 The board was then tested with an applied deflection of 10 mm, 20 mm, and 30 mm at mid-span. The
248 primary objective with deflection of the plate, was to be able to compare strain measurements from the
249 DIC-system with strain gauge and extensometer measurements before and after performing the lens
250 distortion correction, and the 2D out-of-plane deflection and surface rotation correction of the DIC-values.

251 The test parameters were: The camera distance, the subset size, the pattern circle diameter, and the
252 camera type. The distance from camera to surface was set to 1.0 m, 2.6 m, and 3.8 m. The 2.6 m and 3.8 m
253 distances were chosen since they were used in the in-situ tests as well.

254 In the post testing analysis, subset sizes of 40x40 pixels, 80x80 pixels and 120x120 pixels were
255 investigated. All evaluations were performed with a point distance of 50% of the subset side length in the
256 calculations, and by using the software GOM Correlate (2018).

257 Information of the pattern circle diameters (3 mm, 5 mm and 10mm) and the camera types (normal- and
258 wide-angle lens) was presented earlier in the chapter, and the total test matrix is provided in Table 1. The
259 matrix is similar for both camera types.

260

261 **DIC-PRECISION OF LABORATORY TESTS**

262 The readings of the level of light in front of the camera, before photographs were captured, showed to
263 have limited influence on the strain precision results under the laboratory conditions. For the 1.0 m camera

264 to board distance, the level of light was approximately 30 % lower than the other distances, which did not
265 result in a tendency of increase in the camera exposure time.

266

267 **Precision with no deflection (zero strain)**

268 The precision was determined, after correction of lens distortion, for all combinations of parameters,
269 before deflection was applied to the tested surface. A vertical section was applied in the middle Region Of
270 Interest (ROI), and the strain was determined in all measured points along the section. The standard
271 deviation of these strains was then used as a precision quantity.

272

273 *The influence of the subset size and camera distance*

274 For strain precision evaluation, the precision was expected to improve as the subset size increased. Note
275 that large subsets can be less appropriate in regard to crack detection (not within the scope of this work).
276 Figure 10 shows the relationship between subset size and precision, and as expected, the precision improves
277 with increasing subset size

278 The subset sizes were 40x40 pixels, 80x80 pixels, and 120x120 pixels, and the values at these subset
279 sizes are joined with lines in the figure. This is to give an overview, and does not mean that there is a linear
280 relationship between the measured points. The legend in the figure shows the different combinations of
281 camera to surface distances (1.0 m, 2.6 m and 3.8 m), and the circle pattern size (3 mm, 5 mm and 10 mm).
282 The camera to surface distance did not show any tendency in relation to the strain precision, which was also
283 expected. Nevertheless, the camera distance is deemed to influence the PPR (Pattern Pixel Relation –
284 number of pixels per pattern circle diameter). The PPR is affected by both the camera to surface distance,
285 the pattern size, as well as the specific camera specifications (e.g. the resolution).

286

287 *The influence of the Pattern Pixel Relation (PPR)*

288 Figure 11 shows how the precision is influenced by the PPR of the detected surface. An example view
289 of the pattern of PPR for different variations of parameters of the wide-angle lens camera is seen in Figure
290 12. Each photograph is zoomed to fit 50x50 pixels.

291 For all subset sizes, and for both cameras there is a significantly better precision for PPR in the interval
292 from 4 to 9 pixels per circle diameter, even though the surfaces were well detected by the camera and
293 software. When the PPR increases beyond 9 (equivalent to a digital camera capturing photographs relatively
294 close to the surface or a high camera resolution) or decreases below 4 (equivalent to a digital camera
295 capturing photographs relatively far from the surface or a low camera resolution), the standard deviation
296 increases.

297 In Figure 12, the marked (highlighted edge) combinations are outside the optimum PPR interval.

298

299 **Out-of-plane deflection**

300 In the laboratory test, the surface was deflected in increments of 10 mm from 0 to 30 mm. The strain
301 was determined in the same sections as in the above analysis where no deflections were applied (vertical
302 sections right in front of the camera).

303

304 *Direct contact strain measurements*

305 The readings from the extensometers and strain gauges were compared to check the validity of the two
306 types of strain measurements based on direct contact to the surface. The extensometer readings were in
307 average 19.3 % higher than the values obtained by strain gauges at the same locations. A probable cause of
308 this is that the board surface had to be grinded down (removing the paint layers) to the raw wood in order
309 to attach the strain gauges, and hereby the board thickness was reduced compared to areas with painted
310 surface. This variation shows that even contact measurement methods can provide deviations and
311 underlines the complexity in large surface measurements, even in laboratory conditions. Furthermore, the

312 results of the strain measured in the middle of the boards and in the side of the boards gave similar results,
313 which indicate that the boards were deflected evenly over the width.

314

315 *DIC strain measurements*

316 The strains measured with DIC (without the corrections included) were higher than the strain gauge and
317 extensometer measurements around mid-span, and lower closer to the supports. This was expected, due to
318 the shape of the developed total correction curve (from Figure 4). In the top of Figure 13, a digital
319 photograph of the evaluated board is seen with the position of the vertical section for evaluation, and the
320 location of the strain gauges and extensometers. Below the photograph is a full field plot from GOM
321 Correlate of the vertical strains of the entire surface when 30 mm out-of-plane mid-span deflection was
322 applied. The shown strain plot is based on direct non-corrected measurements from the captured digital
323 photographs. In the bottom of Figure 13, as an example, the strain distribution of the shown vertical section
324 is presented for 10, 20 and 30 mm mid-span deflection of the board.

325 The tendency to enlarged (pseudo) strain due to out-of-plane deflections in the chosen section was seen
326 both vertically and horizontally. For the horizontal direction, the theoretical strain for the setup was zero
327 (which was also, what the horizontal strain gauges measured). However, due to the deflection towards the
328 camera, a large tensile pseudo strain was present as well. Hypothetically, this strain ought to be similar to
329 the out-of-plane strain correction in equation 2, which was approximately the case in the performed tests.

330 The tests showed also that, areas of the evaluated surface could be difficult for the DIC-software to
331 recognize when the out-of-plane deflection was applied, and erroneous strains could be seen horizontally
332 or vertically in the strain plots. The reason for this type of error was the chosen pattern, which was (in some
333 zones) not “random” enough. Nonetheless, the problem only had minor influence on the evaluations of the
334 strain.

335

336 *Correction of out-of-plane deflection*

337 Figure 14 shows the measured vertical strains in the section, for an out-of-plane deflection of 20 mm at
338 mid-span of the plate. The example is for: Wide-angle lens camera, 3.8 m camera distance, and 10 mm
339 circle diameter pattern (the combination is within the optimal PPR-interval). A 120x120 pixels subset size
340 is used. Furthermore, the figure shows the total correction (including both lens distortion, surface rotation
341 and out-of-plane deflection) and the measured strains from the applied foil strain gauges, which were
342 positioned next to the analyzed DIC-section. The strain gauge readings are presented on the secondary axis.
343 Theoretically, the relation should be:

$$\varepsilon_{true} = \varepsilon_{strain\ gauge} = \varepsilon_{DIC} - \varepsilon_{rot} - \varepsilon_{oop} \quad (8)$$

344

345 In the example in Figure 14 at mid-span, the true strain can be calculated to be 0.54885 % - 0.53276 %
346 = 0.0161 %, where the strain gauge in the same position measured a strain of 0.0174 % - a deviation of 7
347 % from the strain gauge reading. The standard deviation of the non-corrected DIC-strain was 0.0015 %.

348 For all combinations of parameters, the precision at mid-span was good, but the tests also showed that
349 the precision between mid-span and support deviated more. Since the level of the total correction could be
350 more than a factor 30 larger than the true strain, the true strain was sensitive to the precision of the
351 correction, and hence, highly sensitive to the precision of the deflection measurements by the LVDT's.

352 Positioning of the LVDT's had to be very precise, and more measuring points could therefore be
353 beneficial. This seems to be the main reasons why it was difficult to achieve a perfect fit between the
354 corrected DIC-strain and strain gauge readings, although the correction curves were of the right size and
355 shape. Nevertheless, it is seen that there is a close fit between the two curves, with the correction curve
356 positioned below the directly measured DIC strains in most areas, as expected.

357 In Figure 14, parts of the correction curve is positioned above the directly measured DIC-strains, which
358 indicate that the surface would be in compression. This was not the case, and the reason for this deviation
359 might have been the precision of the measured deflection, and that the shape of the deflection of the plate

360 was not perfectly symmetrical, which was the basis of the calculation of the correction curve. The strain
361 gauge measurements were non-symmetric as well, which also indicate that the board did not deflect as
362 would be expected theoretically.

363 Consequently the laboratory testing, highlights some of the governing parameters which affects the
364 sensitivity of the method related to strain measurements of 2D DIC corrected for out-of-plane deflection
365 and surface rotation.

366

367 **IN-SITU TESTS**

368 In-situ tests during concrete bridge load testing were performed in two occasions in Denmark in late
369 summer 2016 and winter 2017. At both tests, the bridge was safely loaded via a loading rig in a number of
370 pre-defined tempi (semi deformation controlled loading), and the corresponding deflections were measured
371 as well, Schmidt et al. (2018). The load application setup is seen in Figure 15.

372 In both tests, 2D DIC was applied to the underneath bridge surface, as well as other monitoring
373 equipment. Furthermore, the bridge from 2017 was loaded in three sub-tests: One test, where the full bridge
374 width was loaded, and two tests of cut-out longitudinal strips of the bridge deck.

375

376 **Bridge specifications**

377 The tested bridges were identical one span bridges (9 m and 11 m span) and consisted of a number of
378 (theoretically) simply supported pre-fabricated, pre-tensioned beams. The beams were overturned T-cross
379 sections, and in-situ concrete was cast on top of the beams. A bitumen membrane was applied above the
380 in-situ concrete, and finally, a layer of protecting concrete was applied before the asphalt layers. The build-
381 up is depicted in Figure 16.

382 The bottom slab surfaces were smooth and the raw concrete had adequate contrast for DIC-
383 measurements. Below both bridges were rural roads, where the tri-pods with cameras were positioned. The
384 underpasses were closed during the load testing.

385

386 **Test method and parameters**

387 Each test was conducted by first positioning monitoring equipment for deflection- (land surveyor,
388 LVDT's and distance lasers) and strain measurements (strain gauges) under the bridge. The type of
389 equipment was the same as for the laboratory tests, and the distance lasers were of type Leutze ODSL 30.
390 All the monitoring equipment for the in-situ tests is reviewed further in Halding et al. (2017). See Figure
391 17 for a photograph of the setup for the 2017 winter test of the full width bridge.

392 The distance from the wide-angle lens camera to the surface was approximately 3.8 m in both tests. The
393 camera with a regular lens was positioned as well (only in the 2017 winter strip tests) at a distance of 2.6
394 m from the surface. The position and ranges of the DIC-cameras, and the number of applied deflection and
395 strain measurement equipment are shown in Figure 18 for the bridge tests in winter 2017. The bridge tested
396 in the summer of 2016 had a setup similar to the full-width bridge test in the figure, except for the span
397 being 11 m and the wide-angle lens camera being rotated 90 degrees.

398

399 **EVALUATION OF PRECISION OF IN-SITU TESTS**

400 The in-situ test was evaluated using the same approach as the laboratory tests, by DIC-analysis of a
401 section along the span. A full longitudinal section was assessed before any deflection was applied to the
402 surface. The Summer test 2016 was used as an example, and in Figure 19, it is seen, how the precision is
403 best, closest to where the camera was perpendicular to the surface. This is of significant importance when
404 evaluating over large surfaces and with a large section length (especially due to the use of wide-angle lens).
405 The figure is based on sub-evaluations of 500 mm along the span, with 250 mm included before and after
406 the calculated point precision. The reason for the increasing standard deviation in the sides is deemed due
407 to the lens distortion correction, where the distortion is more pronounced near the edges of the digital
408 photograph. Hence, the photograph is “deformed” more in the sides, and a higher degree of pixel
409 interpolation is required to straighten out the photograph here.

410 Results from all available in-situ tests over an entire longitudinal section length are shown in Figure 20.
411 The evaluation was performed for subset sizes of 40x40 pixels, 80x80 pixels and 120x120 pixels, and the
412 joining lines are applied to achieve an overview. The strain standard deviation of the Summer test 2016
413 example, was approximately 0.05 % for subset size 120 pixels. Note that all the precisions by the wide-
414 angle lens camera were based on photographs captured from the same distance, and of the same type of
415 concrete surface. Hence, the discrepancy of the strain standard deviations, seen in Figure 20, was due to the
416 specific local weather and light conditions at the time of the tests.

417 The sections are chosen to be directly above the cameras (see Figure 18). In the evaluation, there has
418 been accounted for areas of the surfaces, where e.g. cables for the LVDT's were crossing the evaluated part
419 of the photograph. This could potentially have affected the strain readings (as described earlier).

420

421 **In-situ corrections of out-of-plane deflection with surface rotation**

422 In regard to corrections for out-of-plane deflection and surface rotation in the in-situ tests, the example
423 from the Summer 2016 test is depicted in Figure 21 during load testing (in the figure, the load was 2444
424 kN and the mid-span deflection was 6.6 mm). The points of the DIC-results are scattered around the trend
425 line. These deviations may be considered as the discrepancies in PPR in different location over the evaluated
426 section length, where some areas have a more optimal PPR than others, in regard to the precision.
427 Consequently, if the PPR can be optimized in these positions, it is deemed that they will move closer to the
428 trend line. The best trend line, in the specific case, is a second degree polynomial. The two curves seem to
429 have a correct relation, since the true strain is calculated as the difference between the measured strain and
430 the corrected strain along the span, cf. Equation 7.

431

432 **COMPARISON BETWEEN LABORATORY AND IN-SITU STRAIN PRECISION RESULTS**

433 In regard to the precision of the directly measured strains in sections without out-of-plane deflection, the
434 laboratory tests showed significantly lower standard deviations, when compared to the field test results.

435 The discrepancy does, however, not mean that the DIC-equipment has an inadequately low strain precision
436 for field use, but rather that the method has a very high level of strain precision under controlled laboratory
437 circumstances.

438 For the wide-angle lens camera, the field strain standard deviation was, for subset size 120 pixels, in the
439 order of magnitude 0.05%, while the interval of the standard deviations for the laboratory tests at the same
440 subset size was from 0.0015% to 0.0072%, depending on the combination of parameters.

441 The regular lens camera showed higher standard deviations in the laboratory tests compared to the wide-
442 angle lens camera (in the interval from 0.005% to 0.013%), and this indicated that the image quality of the
443 full field Canon 6D had an influence as well, since the focal lengths used were almost the same for both
444 cameras (16mm and 18mm, respectively). Even though the regular lens camera showed less good strain
445 precision in the DIC laboratory tests, the precision was similar to the wide-angle lens camera in the in-situ
446 tests, where the regular lens camera was positioned closer to the surface than the wide angle-lens camera.

447 A 0.05% standard deviation, similar to the in-situ precision, was found in the laboratory tests, but only
448 for a subset size of 40 pixels, for the wide-angle lens camera. Two specific parameter combinations gave a
449 similar standard deviation, when comparing the laboratory- and in-situ tests, which is worth noticing:

- 450 1) The combination of subset size 40, 2.6 m camera distance, and 10 mm circle pattern gave a strain
451 standard deviation of 0.047%. That specific combination of parameters gave a PPR of 14 pixels per
452 circle diameter.
- 453 2) The combination of subset size 40, 3.8 m camera distance, and 3 mm circle pattern gives a strain
454 standard deviation of 0.046%. A PPR for that combination was 3 pixels per circle diameter.

455
456 Both combination were lying outside the boundaries of the optimal PPR interval found in the laboratory
457 tests, see the example in Figure 12.

458 In Figure 22, an example is given to clarify the difference between the grey distribution of typical
459 appearing subsets from the in-situ tests and the laboratory tests. The example is based on photographs by
460 the wide-angle lens camera at a distance of 3.8 m, and the laboratory subset are with 10 mm pattern circle

461 diameter. Given the random choice of location, the standard deviations in this example are coincidentally
462 higher than the average standard deviations. In the figure, the texture of the raw concrete surface is clearly
463 finer than the comparable pattern of the painted boards in the laboratory. This indicates that the raw concrete
464 surface is most comparable to a painted pattern with a PPR below the optimal interval. An optimization of
465 the field precision could therefore be expected by raising the PPR by either testing with a smaller camera
466 distance (which can be an in-situ challenge) or by having a higher camera resolution, in combination with
467 a further increase in the subset size. It should be noted that the optimal strain precision, is not at the same
468 time equal to the earliest detection of cracks, which would require another type of study. Consequently,
469 such investigation is ongoing and not a part of this paper.

470

471 **CONCLUSION**

472 The ongoing Danish bridge load testing program involves the use of 2D Digital Image Correlation
473 monitoring equipment applied to the underneath surface of concrete bridges during load testing. The
474 presented purpose of the researched 2D DIC system is to evaluate some of the governing parameters
475 affecting the strain precision and additionally provide some user boundaries. The method is deemed an
476 important tool to provide one or more stop criteria, when used in relation to in-situ proof loading of concrete
477 bridges. In-situ testing and related DIC monitoring is extremely challenging compared to laboratory testing,
478 due to environmental conditions, short testing time, structural size, light conditions, accessibility etc. The
479 paper proposes a method, which can be used as an input, regarding strain precision and out-of-plane pseudo
480 strain corrections, before addressing DIC-monitoring in conjunction with in-situ bridge load testing.

481

482 It is seen in this study that the bridge surface deflects towards the camera as load is applied on the top
483 surface of the bridge deck. A wide-angle lens DSLR-camera was applied, to achieve the largest possible
484 ROI. The wide-angle lens camera was compared to another DSLR-camera with a regular lens, and the strain
485 precision of both was analyzed in laboratory tests and compared to examples from field tests.

486 In the laboratory tests, where wooden boards were painted (in representative grey concrete nuances)
487 with circle patterns, the following parameters were studied: Camera to surface distance, subset size, pattern
488 circle diameter, and camera type. The laboratory tests showed that the Pattern Pixel Relation (PPR), which
489 is the number of pixels per circle diameter, was an important indicator of the DIC precision. The lowest
490 level of standard deviation in the evaluated sections on the boards, seemed to be within an interval from 4
491 to 9 pixels per circle diameter, regardless of the camera type.

492 The wide-angle lens camera was studied in regard to the strain section precision over the width of the
493 photographs, and the precision was best, where the camera direction was perpendicular to the surface (right
494 in front of the camera) and decreased towards the sides of the photographs. This was due to the higher level
495 of lens distortion correction in the sides.

496 The DIC-evaluation of an example field tested bridge showed a higher standard deviation of the strain
497 in sections on the raw concrete surfaces, compared to most of the laboratory test results. Nevertheless, the
498 level of precision by wide-angle lens camera, from the in-situ bridges were comparable to laboratory tests
499 (with certain combinations of parameters), which had a PPR of either 3 pixels per circle diameter or 14
500 pixels per circle diameter, which is smaller and larger than the boundaries of optimal proposed PPR interval.
501 When analyzing the raw concrete surfaces against the laboratory pattern at close proximity at subset level,
502 it was clear that the raw concrete had a much finer texture, indicating a texture corresponding to a low PPR.

503 Based on the learnings from the laboratory tests, an optimization of the DIC strain precision (if needed)
504 for the field tests could be done by e.g. moving the camera closer to the surface (which would reduce the
505 ROI), or purchasing a camera housing with an even better resolution.

506 In addition to the investigations of the non-deflected surfaces, the out-of-plane correction, including
507 surface rotations, were applied in both the laboratory tests, and in the in-situ bridge tests. In both cases, the
508 correction curves fitted well with the directly measured DIC strains, which indicate that the method seems
509 correct. It was shown that the proposed new contribution to the strain correction from the surface rotation
510 was of significant importance, and must be included in 2D DIC evaluations of larger surfaces with out-of-
511 plane bending. Furthermore, it was noticed that the precision of the out-of-plane deflection and surface

512 rotation corrections were extremely sensitive to correctly measured deflections (for instance by LVDT's),
513 and placing of the equipment. The strain analysis differs from a crack initiation analysis, which is therefore
514 not a part of this paper.

515 The findings have provided important information in regard to understanding monitoring thresholds as
516 well as means to optimize the strain precision further. Ongoing research therefore concerns optimization in
517 regards to multidirectional strain evaluation combined with crack initiation detection.

518

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523

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