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Surface Rotation Correction and Strain Precision of Wide-Angle 2D DIC for Field Use

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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

INTRODUCTION

24 The following main approaches are typically used to monitor surface strains on concrete structures: i)

25 Direct contact measurements, which are used to measure in direct contact with the surface (by e.g. strain

26 gauges, extensometers, etc.) or ii) non-contact measurements (by e.g. photogrammetry, laser scanning,

27 Digital Image Correlation etc.) placed in a distance from the structure. Such equipment can potentially be

28 used for structural health monitoring, diagnostic loading, local strain evaluations, laboratory testing etc.

29

30 Proof load testing of existing concrete bridges is an extensive monitoring challenge, due to the

31 environmental exposure of the monitoring equipment, and limited testing time. Such application can require

32 simultaneous monitoring of a large number of locations, and that different monitoring sources are used to

33 ensure a robust identification of unique stop criteria with sufficient precision. The precision of the output

34 should be of a quality, which can be used to update theoretical models related to the capacity- or

35 probabilistic evaluations. Furthermore, fast mounting and dismantling of the monitoring equipment is

36 necessary to reduce traffic disturbance as much as possible.

37

38 This paper focuses mainly on the use of wide-angle Digital Image Correlation (DIC), which is a non-

39 contact methods that seems promising and useful as a mean to solve some of these challenges. Such

40 equipment can be fast to apply, and can potentially provide full field strain measurements of larger structural

41 surfaces. The use of wide-angle cameras have, to the author's knowledge, not been used for DIC evaluations

42 before, but is deemed to be an essential tool for evaluation of strains and cracks on large concrete surfaces.

43 DIC is an advanced method for evaluation of deformations on a test specimen by the use of digital

44 photographs, captured of the test specimen surface before (reference image) and during load testing (the

45 original technology is explained by Sutton et al. (1983)). DIC can be used for both 2D (in-plane

46 measurements with one camera) and 3D evaluations (out-of-plane measurements with two or more

47 cameras), where 3D DIC always, to the knowledge of the authors, require a more time consuming and

48 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 occations (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:

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

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:

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

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

$$dL = L - \sqrt{L^2 - dn^2} \tag{3}$$

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

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

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

$$\varepsilon_{rot} = \frac{\alpha - \beta}{\alpha} \tag{6}$$

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

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

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 Extech 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:

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

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

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

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 pronounces 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

523

524 **REFERENCES**

525 Bornert, M. et al. (2009). "Assessment of Digital Image Correlation Measurement Errors: Methodology

526   and Results." *Experimental Mechanics,* 49(3), 353–70.

527 Bruck, H. A., McNeill, S. R., Sutton, M. A., and Peters, W. H. (1989). "Digital Image Correlation Using

528   Newton-Raphson Method of Partial Differential Correction." *Experimental Mechanics*, 29(3), 261–

529   267.

530 Chen, Z., Quan, C., Zhu, F., and He, X. (2015). "A Method to Transfer Speckle Patterns for Digital Image

531   Correlation." *Measurement Science and Technology,* 26(9), 95201.

532 Crammond, G., Boyd, S. W., and Dulieu-Barton, J. M. (2013). "Speckle Pattern Quality Assessment for

533   Digital Image Correlation." *Optics and Lasers in Engineering,* 51(12), 1368-78.

534 GOM, (2018). GOM Correlate Professional.

535 Halding, P. S., Hertz, K. D., Schmidt, J.W., and Kennedy, B.J. (2016). "Full-scale load tests of Pearl-

536   Chain arches." *Eng Structures*, 131, 101–114.

537   Halding, P. S., Schmidt, J. W., and Christensen, C. O. (2018). "DIC-monitoring of full-scale concrete

538   bridge using high-resolution wide-angle lens camera." *Proc., IABMAS Melbourne 2018,* Powers,

539   Frangopol, Al-Mahaidi and Caprani, ed., Taylor & Francis Group, London, 1492-99.

540   Halding, P. S., Schmidt, J. W., Jensen, T. W., and Henriksen, A. (2017). "Structural response of full-scale

541   concrete bridges subjected to high load magnitudes." *Proc., 4th Conference in Smart Monitoring,*

542   *Assessment and Rehabilitation of Civil Structures*, 266.

543   Hoult, N. A., Take, W. A., Lee, C., and Dutton, M. (2013). "Experimental Accuracy of Two Dimensional

544   Strain Measurements Using Digital Image Correlation." *Eng Structures,* 46, 718-26.

545   Lecompte, D., Bossuyt, S., Cooreman, S., Sol, H., and Vantomme, J. (2007). "Study and Generation of

546   Optimal Speckle Patterns for DIC." *Proc., of the SEM Annual Conference and Exposition on*

547   *Experimental and Applied Mechanics,* Society for Experimental Mechanics, 3, 1643–49.

548   Lecompte, D. et al. (2006). "Quality Assessment of Speckle Patterns for Digital Image Correlation."

549   *Optics and Lasers in Engineering,* 44(11), 1132–45.

550   Pan, B., Yu, L., and Wu, D. (2014). "High-Accuracy 2D Digital Image Correlation Measurements Using

551   Low-Cost Imaging Lenses: Implementation of a Generalized Compensation Method." *Measurement*

552   *Science and Technology,* 25(2), 25001.

553   Park, J., Yoon, S., Kwon, T. H., and Park, K. (2017). "Assessment of Speckle-Pattern Quality in Digital

554   Image Correlation Based on Gray Intensity and Speckle Morphology." *Optics and Lasers in*

555   *Engineering,* 91, 62-72.

556   Photoshop (2018), Adobe Photoshop CS6.

557   Ruocci, G. et al. (2016). "Digital Image Correlation and Noise-filtering Approach for the Cracking

558   Assessment of Massive Reinforced Concrete Structures." *Strain*, 52(6), 503–521.

559   Schmidt, J. W., Halding, P. S., Jensen, T. W., and Engelund, S. (2018). "High Magnitude Loading of

560   Concrete Bridges." *Evaluation of Concrete Bridge Behavior through Load Testing - International*

561   *Perspectives — 2018,* ACI, SP 323-9.

562   Schmidt, J. W., Hansen, S. G., Barbosa, R. A., and Henriksen, A. (2014). "Novel shear capacity testing of

563   ASR damaged full scale concrete bridge." *Eng Structures*, 79, 365–374.

564 Schreier, H., Orteu J. J., and Sutton M. A. (2009). "Image Correlation for Shape, Motion and Deformation

565   Measurements: Basic Concepts, Theory and Applications." *Springer US*, 1-321.

566 Sutton, M. A. et al. (2017). "Recent Progress in Digital Image Correlation: Background and

567   Developments since the 2013 W M Murray Lecture." *Experimental Mechanics,* 57(1), 1–30.

568 Sutton, M.A., Wolters, W. J., Peters, W. H., Ranson, W. F., and McNeill, S. R. (1983). "Determination of

569   Displacements Using an Improved Digital Correlation Method." *Image and Vision Computing,* 1(3),

570   133–39.

571 Triconnet, K., Derrien, K., Hild, F., and Baptiste, D. (2009). "Parameter Choice for Optimized Digital

572   Image Correlation." *Optics and Lasers in Engineering,* 47(6), 728–37.

573 Wang, Y. Q., Lava, P., Debruyne, D., and Houtte, P. V. (2011). "Error Estimation of DIC for Heterogeneous

574   Strain States." *Applied Mechanics and Materials,* 70, 177–82.

575 Waterfall, P., McCormick, N., and Owens, A. (2014). "Optical Imaging for Low-Cost Structural

576   Measurements." *Proc.*, *The Institution of Civil Engineers: Bridge Engineering*, Thomas Telford

577   Services Ltd, 167, 33–42.

578 Yoneyama, S., Kikuta, H., Kitagawa, A., and Kitamura, K. (2006). "Lens distortion correction for digital

579   image correlation by measuring rigid body displacement." *Optical Engineering*, 45(2), 023602.

580 Yoneyama, S., Kitagawa, A., Iwata, S., Tani, K., and Kikuta, H. (2007). "Bridge Deflection Measurement

581   Using Digital Image Correlation." *Experimental Techniques*, 31(1), 34–40.

582