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Title: Strain distribution of dowel-type connections reinforced with self-tapping screws

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1 **Abstract**

2 Current limited guidance on the selection of screws together with undefined design specification
3 restricts the effectiveness of self-tapping screws as reinforcement on timber members to control crack
4 propagation. Using Digital Image Correlation (DIC), this study visualised surface strain distribution of
5 screw reinforced dowel-type connections to understand the influence of thread configuration and
6 screw to dowel distance on controlling crack propagation. The experiment was based on single-dowel
7 embedment tests using 16mm and 20mm diameter steel dowels. Three thread lengths (0%, 33% and
8 100% thread) and six screw to dowel distances (0.5d, 0.75d, 1d, 1.5d, 2d and 4d) were investigated.
9 Results show that screw with 33% thread on the point end can be as effective as screws with 100%
10 thread to control crack propagation under same geometrical parameters of the connections. Results
11 also reveal that screw placed more further away from the dowel (e.g. at 2d distance) can delay the
12 crack controlling effect. Self-tapping screws placed at 2d can still improve the embedment strength
13 and ductility, however, further doubling this distance (4d) did not enhance the embedment strength
14 but a higher ductility was still achieved.

15 **Introduction**

16 Earliest studies by Blaß, et al. (2001), Bejtka, et al. (2005) and Blaß, et al. (2011) showed that the
17 mechanical performance of dowel-type connections could be enhanced with fully threaded self-
18 tapping screws that can effectively control the splitting of timber. Dietsch, et al. (2015) and
19 Lathuilliere, et al. (2015) extensively introduced and discussed the use of screw reinforcement on
20 timber elements.

21 Currently, there is a large variety of self-tapping screws, with various thread configurations, available
22 on the market. The thread configurations, for instance, the pitch, depth, thread angle and thread
23 length often vary with brand. Manufacturers have developed different kinds of thread configurations
24 for different purposes: a partially threaded screw may have a reamer located at the end of the
25 threaded part to clear the wood for an easier entrance of the smooth shank while a fully threaded
26 screw is designed to take higher tensile and compressive load as well as further increase the pull-out
27 strength. Figure 1 shows different types of modern self-tapping screws. The variation of the forms of

28 self-tapping screws leads to a lack of guidance in current selection progress and a question of
29 whether such variation can make a difference relating to the performance of reinforcement.

30 As the drive-in torque of screws is related to the thread length, fully threaded screws require higher
31 drive-in torques and the risk of causing damage to the screw increases, especially when they are
32 applied on timber elements with large sizes or high density (e.g. members made of hardwood).
33 Previous studies have found that partially threaded screws, achieved similar reinforcement
34 performance as fully threaded screws (Zhang *et al.*, (2015, 2016)). For installing screws perpendicular
35 to the grain, the thread length on partially threaded screws is less than fully threaded screws,
36 ensuring an easy installation with lower drive-in torque. In Zhang *et al.*, (2018) (2019), partially
37 threaded self-tapping screws were used to reinforce 300mm deep timber members and improved the
38 moment-resisting capacity of dowel-type connections. Therefore, understanding the influence of
39 thread length on controlling crack propagation has become an interesting topic in order to select
40 suitable forms of self-tapping screws as reinforcement.

41 Current design codes (e.g. (CEN, 2004)) provide guidance of using screws as connectors but whether
42 they are useful for the design parameters of screws as reinforcement requires investigation. Uibel, et
43 al. (2010) established a numerical model to evaluate the splitting failure of the insertion of self-tapping
44 screws and provided insights into the design of spacings, end and edge distances. Some research
45 also focuses on the screw to dowel distance. Mastschuch (2000) compared the results of connections
46 reinforced by lag screws placed either at the mid-position between two bolts (half fastener spacing) or
47 at distance of almost one fastener spacing (reinforcement is further away from the reinforced bolt but
48 closer to the next bolt). It showed that lag screws placed further away from the bolt demonstrated
49 better ductility, as Mastschuch (2000) explained, the wood between the bolt and reinforcement acted
50 as a compressible material, providing a smoother load transfer mechanism. Blaß, et al. (2001),
51 Mohammad et al., (2006) placed the self-tapping screw at various distances from the fastener and
52 found slight improvement in the mechanical properties. According to Bejtka, et al. (2005), their
53 experimental test results confirmed the increase of both load-carrying capacity and stiffness, by
54 placing the screw closer to the dowel. The above research evidence indicates the performance of
55 screw reinforcement is influenced by screw to dowel distance and requires further investigation.

56 Due to the geometry of the dowel, the surrounding wood around the dowel is subject to tensile
57 stresses perpendicular to the grain. Since wood has poor tensile strength in the perpendicular to the
58 grain direction, excessive stresses tend to split the timber member from the area that is loaded by the
59 dowel. Surface strain around the crack can escalate as the tensile stress increases (Sjodin, et al.
60 (2006) and Schweigler, et al. (2016)). With the application of screw reinforcement, resistance against
61 splitting can be achieved and the propagation of the crack can be controlled (Zhang, et al., 2019).
62 Therefore, it is of interest to visualise the strain distribution on the surface of reinforced specimens. In
63 this study, it is achieved by single dowel embedment tests combined with DIC technique.

64 DIC is a contact-free technique for strain measurement that has been used in the vehicle and aviation
65 manufacturing industries (Oscarsson, et al., 2012). In timber engineering, Sjodin, et al. (2006),
66 Kunecky, et al. (2015) and Milch, et al. (2017) adopted DIC to monitor strain and displacement in
67 timber joints for model verification. DIC were also applied to embedment tests of single-dowel timber
68 connection by Schweigler, et al. (2016) and Karagiannis, et al. (2016) for strain concentration
69 monitoring. Reynolds, et al. (2016) used DIC to investigate the difference of material behaviour
70 between bamboo and softwood with embedment tests. Studies on assessing the influence of knots on
71 timber elements by Oscarsson, et al. (2012) and Lukacevic, et al. (2014) also used DIC technique.
72 DIC assisted to validate numerical models that consider the existence of knots further improves the
73 accuracy of simulation tools. Sjodin, et al. (2006) recommended, when studying the initiation of a
74 crack, DIC offers the advantage to analyse the area prior to the crack being initiated. There are other
75 non-destructive optical testing method can be applied, such as grey-field photoelasticity demonstrated
76 by Foust, et al. (2014). However, the available literature proves the capability of DIC techniques to be
77 used by this study for monitoring the surface strain distribution of screw-reinforced single-dowel
78 timber connection under embedment tests.

79 The primary research objective of this study is to investigate the influence of thread configuration and
80 screw to dowel distance on the surface strain distribution through a series of embedment tests.

81 The secondary objective is to understand the influence of design parameters on the accuracy of
82 mapping the strain distribution. As DIC methods can only measure the strain distribution on the
83 specimen's surface Schweigler, et al. (2016), rather than the cross section where the reinforced screw
84 is placed, the influence of the thickness of specimen should be investigated. In addition, larger

85 diameter of dowels may increase the splitting tendency which is related to the effective number n_{ef} for
86 calculating the load-carrying capacity of timber connections (CEN, 2004). Therefore, tests for the
87 above two factors were carried out prior to the primary objective in this experiment. Knowledge gained
88 from these tests provided guidance for the primary experiments.

89 **Materials**

90 The timber specimens were prepared from multiple batches of European Whitewood (*Picea abies*)
91 graded to C24 (CEN, 2016). The timber beams were stored and prepared at 21.6°C and 59% relative
92 humidity. They had an average density of 431kg/m³ (CoV = 10.1%) and an average moisture content
93 of 7.8% (CoV=17.4%) (measured by a moisture meter).

94 The configuration of the original screw is shown in Figure 2. A grinder was used to polish the threaded
95 part of the screw in order to prepare different thread configurations (33% and 100% thread, a ratio of
96 approximately 1:3). This ensured the consistency of material properties of the screws. A 2.5mm
97 diameter pre-drilled hole with 60mm depth was drilled at the location of reinforcement to ensure the
98 accurate positioning of the screw.

99 **Methods**

100 ***DIC principle***

101 DIC is a non-contact optical method to calculate the displacement and strain on a specimen surface
102 through analysing a series of digital images taken during the mechanical test. It requires a picture of
103 the unloaded specimen as reference and pictures during the loading stage as deformed images. A
104 speckle pattern is applied on the specimen surface and is subject to deformation during the loading
105 stage. The deformation of patterns is compared to their initial unloaded image by DIC software which
106 then uses a mathematical correlation to find and generate the strain distribution for each deformed
107 image.

108 The resolution of a digital image represents the number of pixels it is divided into. Each pixel contains
109 a grey scale value varying from 0 to 255, based on the light intensity reflected by the object on the
110 picture. The DIC method uses this property to locate a pixel on the deformed image by using its grey
111 value from the non-deformed image. However, the grey value of a single pixel is not unique in the
112 entire picture. Thus, a collection of grey values of surrounding pixels is introduced. In DIC, this is

113 called a 'subset' or 'correlation window'. Then, to track a subset in another deformed picture as the
114 tested body moves, the subset is shifted around. The 'stepsize' defines the distance (in pixel) a
115 subset is moved when finding the best match in another picture. The best match is found based on
116 results of a correlation function of total difference in grey values of each pixel within the subset.

117 For simplification, a classic correlation function in Equation 1 using sum of squared differences of the
118 pixel values are demonstrated:

$$119 \quad C(x, y, u, v) = \sum_{i,j=-n/2}^{n/2} (I(x + i, y + j) - I^*(x + u + i, y + v + j))^2 \quad (1)$$

120 Where:

121 C is the correlation function.

122 x, y are the pixel coordinates in the reference image.

123 u, v are the displacement in pixel.

124 n is the subset size.

125 i, j are in pixel values to define the location of each small block in the subset.

126 I represents the reference image.

127 I^* represents the deformed image.

128 A reference image of 9×9 pixel in Figure 3 (a) is shifted by 2 pixels to the right and upwards,
129 respectively, and the deformed image is shown on the right (Figure 3 (c)). The image contains a 3×3
130 square and a 1×1 square in black pixels. The black pixels have a grey value of 0 and the white pixels
131 have a grey value of 255. To find the displacement, a 5×5 subset is defined in Figure 4 (a). The
132 subset is then shifted around within the image for correlation calculation. For instance, moving the
133 subset by 2 pixels to the left and downwards (attempt 1 in Figure 4 (b)), respectively, produces a sum
134 of squared differences of 585225 (the lower the better) while shifting the subset by 2 pixels to the right
135 and upwards (attempt 2 in Figure 4 (c)), respectively, produces a sum of squared differences of 0
136 which is the best match for this case.

137 Finally, the software uses standard derivative filters to calculate the displacement gradients and is
138 then able to calculate the strain values (Sutton, et al., 2009).

139 To ensure the matching is accurate, a random, isotropic and high-contrast speckle pattern on the
140 surface is preferred. According to Lionello, et al. (2014), at least three speckle patterns should be
141 included in one subset. Currently, there are a large number of methods to apply the pattern on the
142 specimen, such as paint guns, spray cans and stencils. Salmanpour, et al. (2013) applied the above
143 methods and recommended using a paint gun to generate a fine random pattern. Lionello, et al.
144 (2014) investigated the impact of airflow and spraying distance when using an airbrush gun and used
145 it to generate high quality speckle patterns.

146 ***DIC preparation***

147 In this study, the timber specimens were planed to ensure that curvature on their surface was
148 eliminated. A background using matt white paint and speckle patterns using matt black paint was
149 applied to form a high-contrast speckle pattern so as to avoid false correlation.

150 The method used to paint the patterns on the surface of the specimen was the same as stencilling.
151 The speckle pattern was designed and applied to the 2mm thick cardboard using a laser cutter, as
152 shown in Figure 5. By selecting the appropriate cutting speed and output power, the laser beam
153 leaves openings in the cardboard. It was found that a small and intense pattern makes the cardboard
154 too fragile to use and it broke easily during cutting. Another issue was that small openings made it
155 difficult for the paint to pass through, leaving large blanks on the specimens as a result. Therefore, the
156 size of the pattern and the spacing between each pattern was adjusted to an acceptable range. The
157 adjusted pattern was successfully identified by the DIC software in the trial tests. To ensure the
158 quality of the speckle pattern on the specimen, cardboard stencils were discarded after a few uses, as
159 the black matt paint tended to stick on the surface of the cardboard and blocked the openings;
160 reducing the quality of the pattern. As the area of interest is located on the lower half of the specimen,
161 the speckle pattern did not cover its whole surface, see Figure 6.

162 ***Embedment test set-up***

163 The embedment test followed the procedure given in EN 383:2007 (CEN, 2007) and the test
164 configuration was demonstrated in Figure 6 (left). The load was applied to the specimen parallel to the
165 grain through a steel dowel and the displacement rate was set to 2mm/min. The loading was manually
166 stopped when 20% load drop from the peak load was observed. To allow comparison of strain fields
167 among specimens under similar loading, a load display was placed next to the specimen and its

168 readings were captured in the picture, as shown in Figure 6 (right). A DARTEC loading machine
169 (100kN capacity) was used to perform the tests. The displacement of the loading head was used as
170 the relative displacement of the fastener to the specimen assuming no tilting or bending of the steel
171 dowel. The errors due to the fastener tilting or bending were ignored.

172 Images were taken with an 18MP Canon 60D DSLR camera using 18-200mm lens. The camera was
173 placed towards the patterned face of the specimen. A laptop was connected to the camera to control
174 the shutter so as to capture the images. In addition, a second camera was used to record the test.
175 Two LED working lights were placed at symmetrical positions next to the cameras to provide sufficient
176 light. The images for DIC used the highest resolution settings on the camera (5184 pixels × 3456
177 pixels). After the test, the original coloured pictures were converted to black and white format and
178 then analysed by DIC software. The details of each group are described in Table 1 and the tests are
179 separated into two stages: Stage 1 involves testing different diameters of dowels and thicknesses of
180 specimen while Stage 2 comprises testing different thread configurations and screw to dowel
181 distances. The groups without reinforcement are defined as 'unreinforced' and groups with screw
182 reinforcement are defined as 'reinforced'. Group A25N is designed to simulate the case when a nail
183 was used as reinforcement. It has 25mm thick specimen reinforced by screw with 0% thread and
184 previous studies (Zhang *et al.*, (2015, 2016)) have shown the reinforcement is inefficient and it is
185 therefore catalogued to the 'unreinforced' group. Figure 7 demonstrates the specimen configurations.
186 16mm and 20mm dowels are commonly used in practice and therefore they were chosen for the test.
187 This study used four terms to label each specimen configuration. The first term (i.e. A, B and C)
188 defines the lateral dimensions of the timber element and the diameter of the steel dowel. The second
189 term (i.e. 45, 30 and 25) stands for the thickness of the timber element. The third term either indicates
190 the configuration of reinforcement with different types of self-tapping screws (i.e. R, N, BS and ES) or
191 states that the specimen is unreinforced (labelled with U). The fourth term (i.e. a, b, c, d and e) comes
192 only with sample configuration A25R, it indicates the distance between the self-tapping screw and the
193 steel dowel and, for instance, $2d$ refers to two times the diameter of the steel dowel in mm.

194 **Results**

195 In the test, all the specimens displayed splitting failure and embedment failure, as shown in Figure 8
196 and Figure 9. In Figure 9, group A25N displayed a smaller amount of embedment in wood prior to

197 failure than other reinforced groups and no screw head embedment is observed for group A25N. The
198 failure of group A25N is similar to other unreinforced groups in Stage 1. It indicates that thread length
199 can influence the reinforcement performance. Screw head embedment was observed in the rest of
200 reinforced groups. Table 2 summarises the mechanical properties for each group and the calculation
201 of ductility followed the method described in EN12512 (CEN, 2001) using Equation 2 below:

$$202 \quad D = V_u/V_y \quad (2)$$

203 Where:

204 D is the ductility of the timber element.

205 V_u is the ultimate slip and this study used the slip at $0.8F_{max}$.

206 V_y is the yield slip at the yield load.

207 The embedment strength of the specimens was calculated using Equation 3 according to EN
208 383:2007 (CEN, 2007):

$$209 \quad f_h = \frac{F_{max}}{dt} \quad (3)$$

210 Where:

211 f_h is the embedment strength of the timber element.

212 F_{max} is the maximum load.

213 d is the diameter of the dowel.

214 t is the thickness of the timber element.

215 The stiffness of each specimen was found through calculating the gradient between $0.1F_{max}$ and
216 $0.4F_{max}$ on the load-displacement curve.

217 In Stage 1, the unreinforced specimens in configurations *A* and *B* achieved similar mean embedment
218 strength and stiffness even though the thickness of them varies from 25mm to 45mm. The
219 embedment strength of configuration *C* was slightly lower than that of configurations *A* and *B*.

220 The load-displacement curves in Figure 10 shows a less ductile behaviour for the unreinforced
221 specimens in all three configurations. However, the mean ductility of configurations *A* and *B* (see

222 Table 2) had similar values and were slightly higher than the value of configuration *C*. This result
223 matched the prediction, as the design of configurations *A* and *B* satisfied the minimum spacing
224 specification given in Eurocode 5 (EC5 hereafter) (CEN, 2004) while configuration *C* had a larger
225 dowel fitted into the same size of wood as configuration *A*. According to Thelandersson, et al. (2003)
226 using larger dowels enhanced the wedge effect which increased the splitting tendency of the wood
227 and led to lower embedment strength in configuration *C*.

228 In Stage 2, with the same thickness, the strength and ductility of reinforced group A45R were
229 significantly higher than the unreinforced group A45U. As for the 25mm thick specimens, the
230 unreinforced group A25U gave the lowest value in strength and ductility. The group A25N, which had
231 a so-called 'nail' reinforcement, showed higher strength than A25U but similar low ductility to that of
232 group A25U. The improvement in strength indicated that the dowel had touched the screw, a much
233 stronger material than wood. However, as the screw in group A25N had 0% thread on its shank, very
234 low resistance can be provided to control timber splitting. Therefore, the specimens in group A25N
235 had less ductile failures than those specimens reinforced by screws with thread on point end.

236 As for group A25BS reinforced by screws with 33% thread on the point end, its mean embedment
237 strength and ductility were approximately 1.8 times and 3 times higher than that of the unreinforced
238 group, respectively. Compared to group A25Rb using screws with 100% thread placed at $1d$ distance
239 to the dowel, group A25BS showed lower strength and ductility but the difference is not significant.

240 The last section of Table 2 compares the mechanical properties of specimens reinforced by the screw
241 with same thread configuration but placed at different distances to the fastener. All the groups
242 achieved higher mean embedment strength and ductility than the unreinforced group A25U.
243 Embedment strength peaked at 42.1N/mm^2 when the screw was placed at $0.75d$, and ductility peaked
244 at 34.4 when the screw was placed at $1d$. The values gradually reduced as the screws were placed
245 further away from the dowel. From Table 2, the reinforcements were highly efficient even if the screws
246 were placed at $2d$ distance and, as can be seen in Figure 11. The group A25Rd (screws placed at $2d$
247 distance) showed a significant improvement of load-carrying capacity starting from 20mm
248 displacement and achieved considerable ductility. As for group A25Re, (screws placed at $4d$
249 distance), it achieved similar improvement as group A25N (screws placed at $1d$ distance) but with
250 slightly higher ductility. The enhancement of self-tapping screws was limited as the crack propagated

251 freely before it reached the level where the screw was located. The large screw to dowel distance
252 undermined the capacity of the specimen and a high enhancement of embedment strength was not
253 achieved. However, a strong thread-wood anchorage was provided with 100% thread on the screw.
254 This allowed the screw to hold the specimen in one piece and therefore group A25Re achieved a
255 more ductile behaviour compared to groups A25U and A25N. In terms of stiffness, no significant
256 improvement can be found by using self-tapping screws.

257 **Analysis of results and discussion**

258 A series of graphs showing the strain distribution at each loading step for each specimen was
259 produced by DIC software. By observation, crack initiation and propagation mostly occurred beneath
260 the dowel and following the central line of the specimen. The principal strain reached high values near
261 the crack tip as shown in Figure 12. As discussed, the primary objective of this study is to understand
262 how thread configurations and screw to dowel distance can influence the strain distribution at a crack
263 location. But firstly, the influence of the specimen thickness and dowel diameter on the timber splitting
264 emergence is discussed through a parametric study.

265 ***Influence of the specimen thickness and dowel diameter on visualising strain distributions***

266 For reinforced specimens in Stage 2, it should be investigated whether the surface strain measured
267 by DIC is representative of the actual strain around the screw. Therefore, it is crucial to understand
268 how specimen thickness can influence the surface strain analysis using DIC and to what extent using
269 such technique is reliable.

270 Results of normalised principal strain vs depth are plotted in Figure 13 and each row stands for a
271 configuration type with three different thicknesses. The strain data were extracted from the location of
272 the most significant crack. It should be noted that the starting depth is not the centre of the fastener
273 but the bottom of it. As the crack initiated from the bottom of the dowel and developed downwards,
274 the strain would gradually drop to a value close to zero. To ensure that the results can be compared
275 between different thicknesses, the strain data at similar stress level were selected from a series of
276 DIC outputs. Due to the limitation of the equipment, the camera may not be able to capture pictures at
277 the same load level for comparison (e.g. one picture for B30U1 was capture at 24MPa and another
278 picture for B30U2 was captured at 23.5MPa). If a match of similar stress level is impossible, only the

279 ones within an acceptable range are presented in Figure 13, e.g. group A30U. The acquired strain
280 data is then normalised from zero to one (all the data points were divided by the maximum value in
281 each test), so that a clearer trend can be demonstrated.

282 For configuration *A*, specimens (A25U) with 25mm thickness showed a higher rate of decrease of
283 principal strain versus depth than that of the 30mm and 45mm thick specimens (A30U and A45U),
284 see top row of Figure 13. By comparing the plots at different thicknesses of configuration *B* and *C*,
285 respectively, it was found that all 25mm thick specimens displayed a higher rate of change in strain
286 than the rest of the thicknesses. In addition, the 30mm thick specimens for all three types of
287 configuration showed slightly higher rates of change than the 45mm thick specimens. With increasing
288 thickness, the accuracy of presenting the strain at the area of interest gradually drops.

289 It is of importance to acquire the strain distribution as close as possible to the central plane where the
290 screw is located. Thus, this study used the minimum thickness $1.5d$ ($t=24\text{mm}$), as suggested by BS
291 EN 383:2007 (CEN, 2007) to obtain the strain distribution at Stage 2. The above results also show
292 that a larger thickness of specimen may not accurately display the strain distribution around the
293 screw. Furthermore, in configuration *C*, the thickness was $1.25d$ (25mm thick specimen with 20mm
294 dowel) and the strain distribution can be acquired successfully. Therefore, in future studies, the use of
295 a smaller thickness of specimen may be considered.

296 Different diameters of steel dowels are expected to vary the strain distribution. According to
297 Thelandersson, et al. (2003), large and stout dowels act as wedges, increasing tensile stresses
298 perpendicular to the grain. In this study, configuration *C* is expected to have higher splitting tendency
299 and slower strain reduction than other configurations. As can be seen in Figure 13, with 25mm
300 thickness configuration, *A* and *B* displayed slightly faster rates of change in strain than configuration
301 *C*. To be more specific, at similar loading stresses at 20mm depth, group A25U had 0.4 normalised
302 strain left, while group C25U had 0.6 normalised strain remaining. This indicated that at similar depth,
303 configuration *C* had developed longer and wider cracks than the rest. By increasing the thickness of
304 the specimen to 30mm and 45mm, see Figure 13, all three configurations displayed similar trends for
305 the change of normalised strain versus depth. To summarise, using larger dowels has a tendency to
306 increase the strain distribution and exacerbate crack propagation. In addition, it becomes much easier

307 to observe the influence of the diameter of the dowel on strain distribution at smaller specimen
308 thickness.

309 ***Strain distributions in unreinforced and reinforced specimens***

310 As screw reinforcement provides effective restraint to crack propagation, it is considered that strain
311 distribution will be influenced. A prediction is that principal strain will decrease at a faster rate in
312 reinforced specimens than in unreinforced ones. To validate this hypothesis, a measurement was
313 taken by extracting the principal strain values at the crack location of both reinforced and unreinforced
314 specimens at similar loading stresses.

315 The normalised strain versus depth plot for unreinforced and screw reinforced specimens using
316 Configuration A with 16mm diameter dowel at different thicknesses are shown in Figure 14. The
317 reinforcement in the three reinforced groups (A25BS – 25mm thick specimen reinforced by screw with
318 33% thread, A25Rb – 25mm thick specimen reinforced by screw with 100% thread and A45R – 45mm
319 thick specimen reinforced by screw with 100% thread) were all placed at $1d$ distance. The most
320 important finding is that the reducing rate of normalised strain in reinforced specimens was much
321 faster than that of the unreinforced ones (A25U – 25mm thick specimen, A25N – 25mm thick
322 specimen reinforced by screw with 0% thread and A45U – 45mm thick specimen in Figure 14). In the
323 reinforced groups, the normalised strain reduced to 0.1 at approximately 40mm depth while for the
324 unreinforced specimens, the normalised strain remained to around 0.2-0.4. This indicates that the
325 crack propagated faster in unreinforced groups. In other words, the screw reinforcement can
326 effectively control strain distribution and reduce the splitting tendency. For specimens that were
327 reinforced by a screw with 0% thread, in group A25N, it showed similar trends as the unreinforced
328 ones. The normalised strain remains at high values at large depth indicating severe crack propagation
329 occurred to the specimens. This further confirms that a nail-like reinforcement is inefficient in
330 preventing splitting.

331 Comparing groups A25BS (reinforced by screws with 33% thread placed at $1d$ distance) with A25Rb
332 (reinforced by screws with 100% thread placed at $1d$ distance), no significant differences is found
333 between their curves. This comparison indicates that using screws with 33% thread on the point end
334 can effectively prevent splitting. The results also correspond well with previous studies (Zhang *et al.*,

335 (2015, 2016)) in embedment strength and load-carrying capacity. The test results match the
336 prediction that screw reinforcement can restrain crack propagation.

337 The unreinforced groups did not achieve the same high level of stress as the reinforced groups,
338 therefore the strain data at their peak stresses are presented in Figure 14 only for reference.

339 ***Influence of screw to dowel distance on strain distributions***

340 The distance between screw and fastener is an important factor to be considered in the design of
341 screw reinforcement. This study tested six different distances to examine their influence on the strain
342 distribution of reinforced specimens. The strain data were extracted at similar load ranges as shown
343 in Figure 15. The screws were placed from $0.5d$ (in contact with the dowel) to $4d$ distances and the
344 locations of the screw are marked with black straight lines. A clear trend indicated, in Figure 15, is that
345 the reducing rate of normalised strain gradually decreases as the screws are placed further away
346 from the dowel. To be more specific, for group A25ES, which had screws in touch with the dowel, the
347 strain reduced to about zero at 30-40mm depth. This depth of zero strain increased to around 45mm
348 for group A25Rb, which had screws placed at $1d$ distance to the dowel. Then, in group A25Rd, the
349 strain reduced to zero at 60mm depth, which means the crack had propagated much further than
350 those in group A25ES. For group A25Re, the strain reached to zero at around 80mm, which had
351 screws placed 30mm away from the bottom edge of the specimen. This similar behaviour can also be
352 found in group A25N in Figure 14. In other words, placing the screw within $2d$ distance of the dowel is
353 still effective to slow down the process of timber splitting and this effect increases as the screw is
354 placed closer to the dowel.

355 **Conclusion**

356 This study conducted a series of embedment tests to investigate the influence of changing thread
357 lengths (0%, 33% and 100% thread length) and screw to dowel distance ($0.75d-4d$) on the strain
358 distribution of dowel-type connections reinforced with self-tapping screws, in order to control the
359 timber splitting beneath the dowel along the grain. This study has demonstrated the outstanding
360 capability of DIC technique for strain measurement. The impacts of the dowel diameter and specimen
361 thickness on the timber splitting emergence have also been discussed.

362 The following points can be concluded from this study:

- 363
- The normalised strain versus depth graphs reveal that having reinforcement can effectively
364 reduce the strain experienced in unreinforced specimens. Using screws with 33% thread on
365 the point end achieved similar results to those using screws with 100% thread. By having 0%
366 thread on the screw, the specimen showed a less ductile failure, which was similar to the
367 unreinforced groups. The results correspond well with previous studies (Zhang *et al.*, (2015,
368 2016)).
 - The test results confirmed that the screw to dowel distance is essential in preventing splitting
369 failure of wood. The closer the screw is placed to the dowel, the earlier it can control crack
370 propagation. The reinforcement was still efficient in controlling crack propagation when the
371 screw was placed at $2d$ distance to the fastener. The mechanical properties and strain
372 distribution obtained from this study provide an insight into where self-tapping screws should
373 be installed in order to achieve better reinforcement efficiency.
 - By plotting the normalised strain vs depth graphs, variation between different specimen
374 thicknesses is found. Specimens with 25mm thickness are recommended because the
375 surface strain is at a closer distance to the plane where the screw is located thus being more
376 accurate. The graphs show that under similar loading stresses, a larger steel dowel displays a
377 lower rate of reduction in strain which indicates more severe wood splitting and crack
378 propagation has occurred. This trend can only be identified in specimens with 25mm
379 thickness. The study also demonstrates the importance of specimen thickness and
380 recommends using the minimum allowed thickness for similar applications, to achieve better
381 accuracy when mapping the strain distribution.

384 In this study, the limitation of commercial cameras restricted the comparison of strain field at the same
385 stress level between each group, instead, high speed cameras are recommended. More repetitions
386 are also required for the confirmation of the results in this paper. This study only focused on the
387 influence of thread length and screw to dowel distance. For the development of screw reinforcement,
388 it is also necessary to examine the impact of screw diameter, thread design and reinforcement
389 arrangement on the reinforcement performance.

390

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472 **Tables**473 **Table 1.** Summary of tested group details

	Group	Dowel diameter (mm)	Specimen size (mm)	Sample size	Description		Mean density (kg/m ³) (CoV)	Mean M.C.% (CoV)
					Thread length	Screw to dowel distance ^a		
Stage 1	A45U	16	224×96×45	3	No reinforcement		434 (10.0%)	7.7 (18.9%)
	A30U	16	224×96×30	3	No reinforcement		422 (15.3%)	8.0 (11.2%)
	A25U	16	224×96×25	3	No reinforcement		405 (13.7%)	9.3 (20.3%)
	B45U	20	280×120×45	3	No reinforcement		432 (10.4%)	8.5 (19.1%)
	B30U	20	280×120×30	3	No reinforcement		501 (19.7%)	9.5 (8.1%)
	B25U	20	280×120×25	3	No reinforcement		427 (17.4%)	9.0 (12.6%)
	C45U	20	224×96×45	3	No reinforcement		420 (15.5%)	8.4 (12.7%)
	C30U	20	224×96×30	3	No reinforcement		442 (19.0%)	8.1 (4.4%)
	C25U	20	224×96×25	3	No reinforcement		418 (16.4%)	9.8 (19.3%)
Stage 2	A45R	16	224×96×45	3	100% thread	1d	410 (15.0%)	8.0 (17.7%)
	A25N	16	224×96×25	6	0% thread	1d	437 (7.4%)	6.3 (2.5%)
	A25BS	16	224×96×25	3	33% thread on the point end	1d	442 (1.0%)	9.6 (3.3%)
	A25ES	16	224×96×25	6	100% thread	0.5d	418 (3.7%)	7.0 (2.6%)
	A25Ra	16	224×96×25	6	100% thread	0.75d	438 (7.6%)	6.8 (6.7%)
	A25Rb	16	224×96×25	7	100% thread	1d	419 (3.8%)	7.1 (1.8%)
	A25Rc	16	224×96×25	10	100% thread	1.5d	430 (5.3%)	7.8 (13.7%)
	A25Rd	16	224×96×25	3	100% thread	2d	433 (9.0%)	6.4 (4.0%)
	A25Re	16	224×96×25	3	100% thread	4d	435 (9.1%)	6.3 (4.2%)

474 ^a d is the diameter of the dowel.

475 **Table 2.** Mechanical properties for each tested group

	Group	Mean strength (N/mm ²) (CoV)	Mean ductility (CoV)	Mean stiffness (CoV)
Stage 1	A45U	22.6 (19.6%)	4.4 (72.5%)	10.0 (20.0%)
	A30U	24.4 (27.8%)	4.7 (33.9%)	9.4 (28.0%)
	A25U	19.4 (20.9%)	6.7 (69.0%)	7.7 (36.5%)
	B45U	23.4 (12.0%)	3.1 (61.0%)	13.6 (15.5%)
	B30U	20.7 (31.7%)	6.5 (53.9%)	11.2 (55.7%)
	B25U	19.8 (16.1%)	4.8 (60.3%)	10.5 (34.9%)
	C45U	22.9 (4.8%)	2.2 (53.1%)	10.7 (40.1%)
	C30U	19.4 (18.1%)	3.6 (19.5%)	11.0 (36.0%)
	C25U	20.1 (16.6%)	6.0 (47.2%)	10.6 (42.1%)
Stage 2	A45R	33.0 (16.7%)	15.6 (4.4%)	8.9 (18.3%)
	A25N	31.3 (20.2%)	7.0 (61.5%)	6.2 (36.4%)
	A25BS	35.2 (4.6%)	21.9 (12.6%)	5.4 (21.3%)
	A25ES	40.3 (6.3%)	23.3 (21.3%)	8.3 (11.9%)
	A25Ra	42.1 (10.5%)	26.0 (36.8%)	9.2 (14.5%)
	A25Rb	39.1 (8.6%)	34.4 (26.0%)	9.8 (35.6%)
	A25Rc	38.5 (9.7%)	30.0 (21.2%)	10.3 (17.3%)
	A25Rd	39.5 (4.9%)	24.1 (42.4%)	9.1 (46.4%)
	A25Re	32.2 (12.3%)	14.7 (36.1%)	7.8 (17.7%)

476

477 **Figure captions**

478 **Fig 1.** Different forms of self-tapping screws.

479 **Fig 2.** Configuration of the self-tapping screws used in this study.

480 **Fig 3.** Example showing the calculation of displacement by DIC. (a) reference image, (b) grey values
481 for the reference image, (c) deformed image and (d) grey values for the deformed image.

482 **Fig 4.** Example showing the matching attempt of DIC. (a) reference image and a defined 5×5 subset.
483 The centre block of the subset is located at (5,5). (b) a matching attempt moves the subset to the
484 bottom-left corner. (c) another matching attempt moves the subset to the top-right corner.

485 **Fig 5.** Laser cutter prepared patterns on a cardboard.

486 **Fig 6.** Test configurations (left) and picture of specimen in black and white for DIC analysis (right).

487 **Fig 7.** Specimen configurations of the two stages.

488 **Fig 8.** Specimens from Stage 1 after failure.

489 **Fig 9.** Specimens from Stage 2 after failure and pictures of the lateral side of the specimens showing
490 screw head embedded into the wood except for group A25N.

491 **Fig 10.** Load-displacement curves in Stage 1.

492 **Fig 11.** Load-displacement curves in Stage 2.

493 **Fig 12.** Strain concentration at crack location in specimen A45U2.

494 **Fig 13.** Principal strain comparison with changing specimen thickness, using configuration A (top), B
495 (middle) and C (bottom).

496 **Fig 14.** Principle strain comparison for reinforced and unreinforced 25mm and 45mm thick
497 specimens.

498 **Fig 15.** Principal strain comparison for different screw to dowel distances using 25mm thick
499 specimens.