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

Author 1

- Cong Zhang, MEng, Ph.D
- Department of Architecture and Civil Engineering, University of Bath, Bath, UK
- ORCID number: 0000-0002-6719-7026

Author 2

- Richard Harris, BSc, C.Eng, FICE, FIStructE, FIMMM, Honorary Professor
- Department of Architecture and Civil Engineering, University of Bath, Bath, UK
- ORCID number:

Author 3 (corresponding author)

- Wen-Shao Chang, BS Arch, MS Arch, Ph.D, FHEA, Senior Lecturer
- Sheffield School of Architecture, University of Sheffield, Sheffield, UK
- ORCID number: 0000-0002-2218-001X

Abstract

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

Introduction

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

Currently, there is a large variety of self-tapping screws, with various thread configurations, available on the market. The thread configurations, for instance, the pitch, depth, thread angle and thread length often vary with brand. Manufacturers have developed different kinds of thread configurations for different purposes: a partially threaded screw may have a reamer located at the end of the threaded part to clear the wood for an easier entrance of the smooth shank while a fully threaded screw is designed to take higher tensile and compressive load as well as further increase the pull-out strength. Figure 1 shows different types of modern self-tapping screws. The variation of the forms of self-tapping screws leads to a lack of guidance in current selection progress and a question of whether such variation can make a difference relating to the performance of reinforcement.

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

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

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

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

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

The secondary objective is to understand the influence of design parameters on the accuracy of mapping the strain distribution. As DIC methods can only measure the strain distribution on the specimen’s surface Schweigler, et al. (2016), rather than the cross section where the reinforced screw is placed, the influence of the thickness of specimen should be investigated. In addition, larger diameter of dowels may increase the splitting tendency which is related to the effective number n_{ef} for calculating the load-carrying capacity of timber connections (CEN, 2004). Therefore, tests for the above two factors were carried out prior to the primary objective in this experiment. Knowledge gained from these tests provided guidance for the primary experiments.

Materials

The timber specimens were prepared from multiple batches of European Whitewood (Picea abies) graded to C24 (CEN, 2016). The timber beams were stored and prepared at 21.6℃ and 59% relative humidity. They had an average density of 431kg/m^3 (CoV = 10.1%) and an average moisture content of 7.8% (CoV=17.4%) (measured by a moisture meter).

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

Methods

DIC principle

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

The resolution of a digital image represents the number of pixels it is divided into. Each pixel contains a grey scale value varying from 0 to 255, based on the light intensity reflected by the object on the picture. The DIC method uses this property to locate a pixel on the deformed image by using its grey value from the non-deformed image. However, the grey value of a single pixel is not unique in the entire picture. Thus, a collection of grey values of surrounding pixels is introduced. In DIC, this is called a ‘subset’ or ‘correlation window’. Then, to track a subset in another deformed picture as the tested body moves, the subset is shifted around. The ‘stepsize’ defines the distance (in pixel) a subset is moved when finding the best match in another picture. The best match is found based on results of a correlation function of total difference in grey values of each pixel within the subset.

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

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

Where:

C is the correlation function.

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

u, v are the displacement in pixel.

n is the subset size.

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

I represents the reference image.

I* represents the deformed image.

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

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

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

DIC preparation

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

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

Embedment test set-up

The embedment test followed the procedure given in EN 383:2007 (CEN, 2007) and the test configuration was demonstrated in Figure 6 (left). The load was applied to the specimen parallel to the grain through a steel dowel and the displacement rate was set to 2mm/min. The loading was manually stopped when 20% load drop from the peak load was observed. To allow comparison of strain fields among specimens under similar loading, a load display was placed next to the specimen and its readings were captured in the picture, as shown in Figure 6 (right). A DARTEC loading machine (100kN capacity) was used to perform the tests. The displacement of the loading head was used as the relative displacement of the fastener to the specimen assuming no tilting or bending of the steel dowel. The errors due to the fastener tilting or bending were ignored.

Images were taken with an 18MP Canon 60D DSLR camera using 18-200mm lens. The camera was placed towards the patterned face of the specimen. A laptop was connected to the camera to control the shutter so as to capture the images. In addition, a second camera was used to record the test. Two LED working lights were placed at symmetrical positions next to the cameras to provide sufficient light. The images for DIC used the highest resolution settings on the camera (5184 pixels × 3456 pixels). After the test, the original coloured pictures were converted to black and white format and then analysed by DIC software. The details of each group are described in Table 1 and the tests are separated into two stages: Stage 1 involves testing different diameters of dowels and thicknesses of specimen while Stage 2 comprises testing different thread configurations and screw to dowel distances. The groups without reinforcement are defined as ‘unreinforced’ and groups with screw reinforcement are defined as ‘reinforced’. Group A25N is designed to simulate the case when a nail was used as reinforcement. It has 25mm thick specimen reinforced by screw with 0% thread and previous studies (Zhang et al., (2015, 2016)) have shown the reinforcement is inefficient and it is therefore catalogued to the ‘unreinforced’ group. Figure 7 demonstrates the specimen configurations. 16mm and 20mm dowels are commonly used in practice and therefore they were chosen for the test.

This study used four terms to label each specimen configuration. The first term (i.e. A, B and C) defines the lateral dimensions of the timber element and the diameter of the steel dowel. The second term (i.e. 45, 30 and 25) stands for the thickness of the timber element. The third term either indicates the configuration of reinforcement with different types of self-tapping screws (i.e. R, N, BS and ES) or states that the specimen is unreinforced (labelled with U). The fourth term (i.e. a, b, c, d and e) comes only with sample configuration A25R, it indicates the distance between the self-tapping screw and the steel dowel and, for instance, 2d refers to two times the diameter of the steel dowel in mm.

Results

In the test, all the specimens displayed splitting failure and embedment failure, as shown in Figure 8 and Figure 9. In Figure 9, group A25N displayed a smaller amount of embedment in wood prior to failure than other reinforced groups and no screw head embedment is observed for group A25N. The failure of group A25N is similar to other unreinforced groups in Stage 1. It indicates that thread length can influence the reinforcement performance. Screw head embedment was observed in the rest of reinforced groups. Table 2 summarises the mechanical properties for each group and the calculation of ductility followed the method described in EN12512 (CEN, 2001) using Equation 2 below:

$$D = V_u / V_y \tag{2}$$

Where:

D is the ductility of the timber element.

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

V_y is the yield slip at the yield load.

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

$$f_h = \frac{F_{max}}{dt} \tag{3}$$

Where:

f_h is the embedment strength of the timber element.

f_{max} is the maximum load.

d is the diameter of the dowel.

t is the thickness of the timber element.

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

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

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

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

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

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

The last section of Table 2 compares the mechanical properties of specimens reinforced by the screw with same thread configuration but placed at different distances to the fastener. All the groups achieved higher mean embedment strength and ductility than the unreinforced group A25U. Embedment strength peaked at 42.1N/mm^2 when the screw was placed at 0.75d, and ductility peaked at 34.4 when the screw was placed at 1d. The values gradually reduced as the screws were placed further away from the dowel. From Table 2, the reinforcements were highly efficient even if the screws were placed at 2d distance and, as can be seen in Figure 11. The group A25Rd (screws placed at 2d distance) showed a significant improvement of load-carrying capacity starting from 20mm displacement and achieved considerable ductility. As for group A25Re, (screws placed at 4d distance), it achieved similar improvement as group A25N (screws placed at 1d distance) but with slightly higher ductility. The enhancement of self-tapping screws was limited as the crack propagated freely before it reached the level where the screw was located. The large screw to dowel distance undermined the capacity of the specimen and a high enhancement of embedment strength was not achieved. However, a strong thread-wood anchorage was provided with 100% thread on the screw. This allowed the screw to hold the specimen in one piece and therefore group A25Re achieved a more ductile behaviour compared to groups A25U and A25N. In terms of stiffness, no significant improvement can be found by using self-tapping screws.

Analysis of results and discussion

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

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

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

Results of normalised principal strain vs depth are plotted in Figure 13 and each row stands for a configuration type with three different thicknesses. The strain data were extracted from the location of the most significant crack. It should be noted that the starting depth is not the centre of the fastener but the bottom of it. As the crack initiated from the bottom of the dowel and developed downwards, the strain would gradually drop to a value close to zero. To ensure that the results can be compared between different thicknesses, the strain data at similar stress level were selected from a series of DIC outputs. Due to the limitation of the equipment, the camera may not be able to capture pictures at the same load level for comparison (e.g. one picture for B30U1 was capture at 24MPa and another picture for B30U2 was captured at 23.5MPa). If a match of similar stress level is impossible, only the ones within an acceptable range are presented in Figure 13, e.g. group A30U. The acquired strain data is then normalised from zero to one (all the data points were divided by the maximum value in each test), so that a clearer trend can be demonstrated.

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

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

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

Strain distributions in unreinforced and reinforced specimens

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

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

Comparing groups A25BS (reinforced by screws with 33% thread placed at 1d distance) with A25Rb (reinforced by screws with 100% thread placed at 1d distance), no significant differences is found between their curves. This comparison indicates that using screws with 33% thread on the point end can effectively prevent splitting. The results also correspond well with previous studies (Zhang et al., (2015, 2016)) in embedment strength and load-carrying capacity. The test results match the prediction that screw reinforcement can restrain crack propagation.

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

Influence of screw to dowel distance on strain distributions

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

Conclusion

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

The following points can be concluded from this study:

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

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

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Tables

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%)

[a] d is the diameter of the dowel.

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%)

Figure captions

Fig 1. Different forms of self-tapping screws.

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

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

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

Fig 5. Laser cutter prepared patterns on a cardboard.

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

Fig 7. Specimen configurations of the two stages.

Fig 8. Specimens from Stage 1 after failure.

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

Fig 10. Load-displacement curves in Stage 1.

Fig 11. Load-displacement curves in Stage 2.

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

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

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

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