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Manuscript title: Drive-In Torque for Self-Tapping Screws into Timber

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Abstract

Self-tapping screws have been widely used in timber constructions nowadays. Current practice considers self-tapping screws perform best in connecting two members when they are fully threaded, however the drive-in resistance caused by the friction between woods and screws can potentially damage the screw and reduce the effectiveness of its applications. The relationship between their thread configuration and the drive-in torque force has not been investigated, and how would knots in the member affect the drive-in force remains in question. This study conducted a series of tests aiming to demonstrate the influence of thread configuration on the drive-in torque of screws. Two types of self-tapping screws and three different thread configurations were studied. The drive-in torque for partially threaded screws was found to be significantly slower than that of the fully threaded ones. The results showed knots can significantly influence the positioning of screw and increase the drive-in torque. The application of pre-drilled hole was found to be an effective way to minimise the influence of knots. This article points out that with appropriate consideration of thread configuration, partially threaded self-tapping screws can not only achieve the same efficiency with fully-threaded ones, they will also benefit from reduced drive-in torque force.

Keywords: Timber structures; materials technology; buildings, structures & design

1. Introduction

Self-tapping screws are becoming increasingly popular in the construction industry. With their advanced manufacture techniques, they feature higher load-carrying capacity than traditional wood screws. Currently, they can be used as connectors or for reinforcement in timber structures. Examples of the use of self-tapping screws on continuous purlin and connections are demonstrated in Figure 1. In a continuous purlin, the screws are under compression and tension respectively when the load is parallel to the surface of the member, or both under tension when the load is perpendicular to the surface (Thelandersson and Larsen, 2003). The inclined screws enable the use of the high axial strength of a screw. Thelandersson and Larsen (2003) also reported that connections using inclined screws achieve an increase of 50% in the load-carrying capacity when compared to those with screws installed perpendicular to the grain.

For reinforcement purposes, self-tapping screws can be used in various situations. Studies by Blaß and Schmid (2001), Bejtka and Blaß (2005) and Blaß and Schädle (2011) demonstrate the improvement of load-carrying capacity and ductility of dowel-type connections reinforced by self-tapping screws which can control timber splitting due to excessive tensile load perpendicular to the grain. Zhang et al., (2019) also reported that using self-tapping screws can enhance the strength of a portal frame with dowel type moment connection. Ardalany et al., (2013) used self-tapping screws to effectively reinforce beams with holes having concentration of tensile stress around them. For beam supports, the load-carrying capacity is limited by the compressive strength of timber perpendicular to the grain. Bejtka and Blaß (2006) used self-tapping screws with high axial strength to reinforce the support region and achieved 3 times higher load-carrying capacity and 5 times greater stiffness than with unreinforced ones. Mestek et al., (2011) experimentally tested and confirmed the shear capacity of CLT elements improved by self-tapping screws. This brief overview of research shows the great potential of self-tapping screws for use in timber structures.

With an increasing market for self-tapping screws, more and more types of screws are available, and the thread profile of screw varies with brand. When the screw is being installed, friction appears as the thread is in contact with the wood. This driving resistance grows with increased contact area between wood and thread as the screw drills further into the wood. A fundamental question arises as to how the thread configurations of screws differ in terms of workability (how easily the screws can be installed). For a long self-tapping screw with full thread, a high torque for installation is often required, especially when passing through the knots. The requirement of a high torque may lead to the use of more powerful machines as well as requiring additional personnel, tools and time.

Currently, the approach to reinforcing connections using self-tapping screws is included in the national annex of countries like Germany (DIN, 2013). However, the difference between using fully threaded and partially threaded self-tapping screws is not known. In previous studies, self-tapping screws with 33% thread on the point end, achieved similar improvement in embedment strength to the screws with 100% thread (Zhang et al., (2015, 2016)).

Furthermore, the concept widely advertised by screw manufacturers is that it can penetrate either wood or metal and drill a path for itself without a pre-drilled hole. One critical issue is the problem caused by knots which inevitably exist in timber. A knot is the remaining part of a branch in the trunk of a tree and it normally has higher density than the surrounding wood (Nardin et al., 2000). It can damage the self-tapping screws by creating a surge of friction and slowing down the installation process. More importantly, as the screw always tries to find the easiest path, a knot may offset the drilling direction of the screw thus making the positioning of screws more difficult than expected. Unfortunately, the current knowledge for self-tapping screws to overcoming the mentioned issues is limited and the methods to correctly prepare pre-drilled holes require specification.

As the drive-in torque is related to thread length, this study aims to find the influence of screw configuration from a perspective of required installation torque. In addition, the effects from knots and the presence of pre-drilled holes are also investigated. Two kinds of screw involving three different types of thread configurations were tested. The drive-in torques of screws with and without pre-drilled holes were also compared.

2. Materials and methods

2.1 Material Preparation

A 300mm deep by 140mm wide GL24c glulam beam, made from European Whitewood (Picea abies), was chosen to conduct the torque test. The purpose of using only one beam is to ensure consistency of the timber density. The beam had a density of 421kg/m^3 and an average moisture content of 8.5% (CoV= 7.1%). The moisture content for each face (except the two cross-sections) was measured three times using a moisture meter. Two different self-tapping screws, R and S, were used in the test, as shown in Figure 2. Table 1 summarises the properties of screws used in this project. The thread configurations of the screws are shown in Figure 3. Screw R had a cylindrical head and its penetration length, L_{pen}, was 295m. It also had a Type 17 point (contains a flute to capture chips) which helps to penetrate wood more quickly. Screw S was partially threaded and had a double threaded point (for a faster insertion of the screw). A reamer was located next to the threaded part for preparing a smooth driving for the screw shank.

In previous studies by Zhang et al., (2015, 2016), screws with 100% thread, screws with 33% thread on both ends and screws with 33% thread on the point end achieved similar performance as reinforcement. It is therefore worth comparing the torque required to install Screw R with different thread configurations. In addition, as there are a vast number of self-tapping screws available on the market, screws with a different diameter can also influence the required torque so that a comparison between Screw R with 33% thread on the point end and Screw S is necessary. Furthermore, as self-tapping screws are designed to penetrate the wood without any pre-drilling holes, a comparison is made of the torque required to install screws with and without pre-drilled holes. This test can lead to a deeper understanding of the influence of having pre-drilled holes. The details of each testing group are given in Table 2. Groups A, B, C and G used pre-drilled holes and groups D, E, F and H used self-tapping screws without pre-drilled holes.

A grinder was used to remove the unwanted parts of threads, and sandpaper was then applied to polish the surface so as to minimise the friction, see Figure 3.

According to Clause 10.4.5 in EC5 (BSI, 2004), the pre-drilled holes for screw shank should have the same diameter and depth of the screw shank and the diameter of pre-drilled hole for the threaded part should be 70% of the screw shank diameter. The requirements for the pre-drilled hole was difficult to achieve owing to the height limit of the specimen for the pillar drill machine and the available drill sizes at that time. As the pre-drilled holes did not fully met the requirements of EC5 due to the mentioned limitations, the screws were expected to experience a higher torque when compared to the ideal condition (full compliance with EC5). This is because the installation of screws for the last 120mm length in the wood was not covered by pre-drilling. In addition, the slightly large pre-drilled hole for the threaded part of the screw may reduce the drive-in torque as less amount of wood was expected to be in contact with the screw to generate friction. Overall, the influence of the depth of the pre-drill is considered as the dominate factor and the reduction of the drive-in torque is expected to be greater when full requirements of the pre-drilled hole are met.

In this study, the pre-drilled hole was set to be 180mm deep. For the groups with pre-drilled holes, a ratio of approximately 0.8 of pre-drilled hole size to screw inner diameter was applied to both types of screw as suggested by EC5 (BSI, 2004).

The glulam beam was marked for the location of the screws and pre-drilled holes. The end and edge distances of the screws followed BS EN 15737:2009 (BSI, 2009) and the spacing for screws followed the guidance from EC5 (BSI, 2004) on designing screws as connection fasteners. The arrangement of screws is shown in Figure 4. The beam was divided into five test sections with one section reserved for additional tests. The spacing arrangement was repeated for all sections. Tests from the same group were distinguished by assigning the section number to the group name and this is used later for analysing results.

2.2 Test set-up

The glulam beam was tightly fixed using instant clamps to ensure that the movement of the entire beam was minimised when installing the screw. To measure the torque to install the self-tapping screws, a Bacho TAM1430 digital torque analyser was used. To successfully connect the analyser to the screw, one end of an extension bar was clamped into the slot of the hand drill and the other end fitted into the socket on the analyser. Then, a drive socket was connected to the lower part of the analyser and the Torx screw driver bit was fitted into the drive socket. The hand drill could then drive the screw in, while the analyser gave the current torque reading, see Figure 5.

During the test, a video recording device was used to film the readings on the analyser. As the analyser gives an instant reading, the speed of the hand drill was controlled to as slow as possible. This was to avoid capturing blurred readings when the torque analyser spun too fast.

3. Results

During the test, some screws experienced a surge of torque, possibly as a result of knots inside the glulam beam. As for those groups without pre-drilled holes, a higher peak torque can be observed while visual observation did not find significant inclination of the screw.

Table 3 gives an overview of the maximum torque experience for each test. The coefficient of variation (CoV) displays the variability of values in each group to the mean value. As can be seen, the values of CoV in groups D, E, G and H are higher than 20% and it is very likely that the data was disturbed by outliers with high torques measured by the analyser. In fact, those groups with lower values of CoV were found to be less influenced by knots. The reason for the surge of torque in these tests could be due to knots hidden inside the beam. To validate this assumption, the glulam specimen was cut open using a band saw at the location of the screws.

3.1 Knots inspection

In total, 15 cuts in the transverse direction were made and the pieces were labelled for inspection, as shown in Figure 6. A detailed survey of each test after inspection is summarised in Table 4.

As can be seen from Table 4, the number of tests that are influenced by knots is evenly distributed in pre-drilled and non pre-drilled groups. For the three groups (A, B and C) using Screw R with pre-drilled holes, 5 out of 15 screws were inclined from the start of installation, among these five screws, four were inclined as the pilot holes were not straight and only one case was influenced by the knots. For the three groups (D, E and F) using Screw R without pre-drilled holes, 13 out of 15 screws were installed inclined from the start. None of the screws in group G (using Screw S with larger diameter) with pre-drilled holes were inclined, in contrast, all five screws in group H without pre-drilled holes were inclined from the start. The above comparison demonstrates one of the main roles of pre-drilled holes is to reduce the chance of inclination of self-tapping screws during installation. For both pre-drilled and non pre-drilled groups, inspection found that if the screw passes right next to the knot then it is more likely to bend in the direction along the edge of the knot, as shown in Figure 7 (a).

For groups (A, B, C and G) with pre-drilled holes, in total 20 screws, none of the screws were bent by the knot above the level of the pre-drilled hole (<180mm). Only one screw, B5, was bent below the level of the pre-drilled hole (>180mm) by the knot, see Figure 7 (b). For the groups (D, E, F and H) without pre-drilled holes, two screws were bent by the knot, see Figure 8. This might be explained that the high-speed steel (high hardness) drill bits for the pre-drilled hole are less vulnerable to bent when compared to self-tapping screws (made from carbon steel). It demonstrates that pre-drilled holes can help prevent the screws from bending due to the knot.

The growth of European Whitewood is seasonal. At the early stage of the growth period, thin-walled cells (tracheids) appear in the softwood for conduction purposes (the wood is called as earlywood). At the latter stage, thick-walled cells appear in the wood to mainly provide support (the wood is called as latewood). The transformation of the role of the cells leads to a difference in material density whereas early wood is less dense than latewood. As the screw enters to a level below the pre-drilled hole, it tends penetrate the wood where there is less resistance, thus, following the pattern of the annual rings.

For the four groups (A, B, C and G) with pre-drilled holes, some of the screws were found to be bent due to the annual rings, see Figure 7 (d). The bending of screws occurs below the level of the pre-drilled holes (180mm deep) indicating the positive effect of pre-drilled holes on screw positioning. As most of the screws were inclined from the beginning in groups without pre-drilled holes, observation of the influence of annual rings on screw positioning is not included in this study.

It was also found that Screw S with larger diameter was less likely to have significant bending due to knots by comparing groups C & G and groups F & H, respectively. In addition, if the screw passes through the knot, it will not bend significantly. However, the drive-in torque of the screws escalated whenever the screw passed by or through a knot. The count of surge of torque for each group is tabulated in Table 4 and the depth of knots that were causing the surge of torque in each specimen is provided in Table 5.

The tests that were significantly influenced by knots are discussed first and the torque-depth relationships for these tests are plotted in Figure 9.

In Table 5, if a knot is located near or at the surface of the beam, the corresponding graph will show a rapid increase of the torque with increasing depth; for instance, the curves for tests A1 and C2 in Figure 9. Otherwise, the curve will display a surge of torque at the locations of the knot. A good correlation between the knot depth range from Table 5 and the change in torque in Figure 9 can be found. Furthermore, Table 5 also summarises whether the screw passed by or passed through the knot. In Figure 9, an increase of torque is shown for both types of interaction. These specimens are therefore excluded from the analysis for better understanding of the influence of screw type, thread configuration and pre-drilled hole.

3.2 Results excluding the influence of knots

The depth versus torque results are plotted for the rest of the tests that are not influenced by knots, see Figure 10 and Figure 11. To fully understand the factors influencing the required torque for installing self-tapping screws, thread configuration, screw point length, reamer and pre-drilled hole depth are presented in the graph by coloured straight lines. The maximum torque for each test is tabulated in Table 6.

For the fully threaded Screw R, the torque linearly increased with depth, in both pre-drilled (group A) and without pre-drilled (group D) conditions. The rate of increase was much slower in the 180mm depth pre-drilled hole.

As for Screw R with two thread segments, the increase of torque can also be divided into three parts: entering of the first segment with thread, the middle segment without thread and the second segment with thread. In Figure 10 and Figure 11, both groups B and E show linear increase of torque for the first 100mm threaded segment, while group B with pre-drilled hole shows a smaller rate of increase. The torque then tends to stabilise with only a small increment as the middle part without thread enters the wood. Finally, the torque rapidly increased as the second segment with thread entered the wood without a pre-drilled hole.

For groups C and F using Screw R with 33% thread on the point end, the torque linearly increases, with group C showing a smaller rate, as the threaded part first entered the wood. The torque for both groups then tended to stabilise as the polished part started to enter the wood. For group C, the torque slightly increased when the screw reached the end of the pre-drilled hole as more resistance was experienced.

For groups G and H using Screw S with 33% thread on the point end, the overall trend is identical to that of groups C and F, respectively. However, with a larger size in diameter, the increase of torque is slightly higher as more resistance was experienced when the screw entered the wood. Group G with pre-drilled hole also shows smaller peak torque than that of group H which has no pre-drilled hole.

4 Discussion

4.1 Comparison between thread configurations

For the groups using Screw R with pre-drilled holes, groups B and C show a stage of stabilisation of torque as the polished shank entered the wood, compared to group A using a fully threaded screw, see Figure 10. This difference is also demonstrated on the peak torque. Screw R, with 33% thread on the point end, shows 24.6% reduction in peak torque compared to the fully threaded screw.

In groups without pre-drilled holes, a similar trend is found in the torque-depth curves. The fully threaded screw achieved an average peak torque of 8.85Nm, while the one with two segments achieved 8.66Nm, see Table 6. The difference between them is much less significant than for those groups with pre-drilled holes. The screw with one segment shows an outstanding result, an average peak torque of only 6.39Nm, 29% of reduction compared to the fully threaded ones.

Results show that the required torque reduces with thread length. In addition, screws with partial thread on the point end achieve the lowest maximum torque, demonstrating its robustness in both with and without pre-drilled hole conditions.

4.2 Comparison between conditions with and without pre-drilled holes

In Table 6, groups with pre-drilled holes show at least a 13.5% decrease in average maximum torque compared to the corresponding groups without pre-drilled holes (groups C and F). The maximum torque for Screw R with two thread segments is 36.5% lower than those without pre-drilled holes. The results imply that pre-drilled holes are most suitable for screws with 66% thread or more, where at least 18.6% decrease of maximum torque is found.

For Screw S, the difference of maximum torque is similar to that of Screw R; about 20% decrease of peak torque is found in group G with pre-drilled hole.

The impact of pre-drilled holes can also be identified on the torque-depth curves. By comparing the graphs in Figure 10 and Figure 11, it was found that the influence of a pre-drilled hole is to significantly reduce the increase rate of drive-in torque. The torque is shown to increase drastically when the screw reaches below the depth of the pre-drilled hole.

4.3 Comparison between two types of screw

This study used self-tapping screws, R and S, with 33% thread on the point end. As shown in Table 1, Screw R is about 14% smaller than Screw S in diameter, while the pitch length for screws R and S are 4.8mm and 5.6mm, respectively. Screw R has a total of 20 complete pitches, 3 more pitches than Screw S with one thread segment. With a finer pitch, the contact area between the wood and screw increases as well as the friction. The penetration depth of Screw R is about 5mm shorter than for Screw S but the difference of depth was not part of the present study.

For both conditions with and without pre-drilled holes, the torque-depth relationships for screws R and S are similar, with Screw S showing higher peak torque than Screw R, 44% and 54%, respectively.

Therefore, even with fewer pitches, Screw S, which is larger in diameter, resulted in a higher maximum torque. This implies that with a smaller difference in pitch counts, the diameter of the screw plays an important role in deciding the drive-in torque.

After the inspection of knots, it was found that Screw R left much deeper and clearer thread cuts on the wood than Screw S, as can be seen in Figure 12.

Screw S shows a shallower cut of the thread on the wood, especially the upper part of the track, than Screw R. One possible explanation is the reamer located 100mm away from the point end of Screw S cleared the passage for the screw shank. According to DeHaitre (1996), the reamer has a larger diameter than the shank and the cutting edges on it will clear the hole for the entrance of the screw shank. Therefore, the track of thread cut in the rectangle area in Figure 12 becomes less visible. As for the rest of the part in Screw S, the track of thread cut can be easily identified, but is still less evident than that of Screw R. In Figure 13, the double threaded point end on Screw S can cut the wood more than once when the screw spins one turn; thus, leaving a less clear track. The purpose of having the double threaded point is to enable a fast start of installing the screw.

The less obvious track of thread cut for Screw S indicates that the wood in between each thread pitch is reduced, as shown in Figure 14. As the withdrawal capacity of the self-tapping screw is determined by shear and the embedment strength of the wood, reducing the shaded part of the wood in and around Screw S can reduce the contact area. This increases the embedding stress and could lead to earlier embedment failure with lower withdrawal capacity of the screw.

4.4 Ratio of shear stress to shear capacity of the screw

To quantify the drive-in torque of the screw, equation (1) is used:

$$\tau = \frac{16T}{\pi d^3} \quad 1.$$

where:

τ is the shear stress;

T is the torque (Nm);

d is the outer diameter of the screw.

By substituting the torque capacity and diameter of each screw (from Table 2) into Equation 1, shear strength of 267N/mm^2 and 255N/mm^2 can be obtained for screws R and S, respectively. The maximum shear stress on the screw can be obtained by substituting the maximum torque into the equation. A ratio between the maximum shear stress and the shear strength is calculated and summarised in Table 7.

From Table 7, for groups using fully threaded screws, the ratio is 0.40 (group A) in the pre-drilled situation, and the ratio increases to 0.49 (group D), by approximately 23%, when a pre-drilled hole is not provided. For groups using screws with 33% thread on the point end, the ratio is 0.30 (group C) in the pre-drilled situation and it increased to 0.35 (group F), only by approximately 17%, when a pre-drilled hole is not provided. It demonstrated that a screw with threaded segment located on the point end is less vulnerable to damages in a no pre-drilled hole condition.

Regarding the two groups (G & H) using Screw S, they required higher torque than other groups, but their ratio is not the highest. This can be explained through equation (1), as the torque is inversely proportional to the screw diameter. Therefore, with slightly higher torque, the screw with larger diameter will have smaller shear stress and thus a smaller ratio.

In addition, this explains that, in the pre-drilled situation, increasing the screw diameter does not show a tendency to increase the ratio, by comparing group C (with 7mm outer diameter) and G (with 8mm outer diameter). When pre-drill holes are not provided, group H (with 8mm outer diameter) shows an increase of 8.6% in ratio when compared to group F (with 7mm outer diameter).

4.5 Driving self-tapping screws into timber members

Previous studies demonstrated the use of self-tapping screws as reinforcement on small specimens for embedment and tensile connections tests (Zhang et al., (2015, 2016)). With smaller specimens, one may easily identify the knot and avoid installing screws around it. However, with deeper glulam members, surface inspection cannot ensure the screw completely avoids the area affected by knots; the knots can bend the screw as well as creating a surge of torque, increasing the risks of damaging the screw.

In this study, the use of a pre-drilled hole reduced the maximum driving torque by 13.5%-36.5%. It also prepared an entrance for the self-tapping screw, thus reducing the influence of the knot and reducing the damage to the screw. In addition, the screw can be more accurately driven into position. However, this process is relatively time-consuming in practice. Another method is to use a guide to hold the screw at the exact angle during the driving process. This method can ensure that the screw is initially driven into the correct direction. However, it is unlikely to prevent deviation of the screw at the location of knots.

When installing self-tapping screws as reinforcement on connections, preparing pre-drilled holes is a more reliable method than using a guide. An additional benefit of providing pre-drilled holes is to lower the chance of the screw being bent when passing by a knot, see Figure 7 (a). When the screws are bent due to the knots, the screws may accidentally pass the prepared hole for the dowels and consequently block the installation of the dowels, especially when the screws are placed at a close distance to the dowels (for instance, at the 1d distance often used in the tests in Zhang et al., (2015, 2016)). As discussed in previous section, the methods to correctly perform a pre-drilled hole are not specified in EC5. Further investigation on the equipment and methods to ensure a fast and accurate pre-drilling is beneficial to the application of screw reinforcement.

5. Conclusion

This study investigated the relationships between drive-in torque, thread configuration, screw diameter and pre-drilled holes. In total, 40 tests were conducted and the torque to install the screw was measured by a torque analyser. Two types of screws involving three different thread configurations were applied. The required drive-in torque of screws, in conditions with and without pre-drilled holes, was also compared. The torque-depth graphs are plotted and demonstrate how the drive-in torque changes with various parameters, such as pre-drilled hole depth and thread length.

The following points can be concluded:

- A screw passing by or passing through a knot can lead to a surge of torque to drive the screw; inspection of the wood helped to identify which of the tests were affected by knots.
- The required drive-in torque is proportional to the thread length; the screw with 33% thread on the point end achieved the lowest torque, 75% of the required torque for fully threaded screw in conditions with pre-drilled holes. In groups without pre-drilled holes, the screw with one segment showed an outstanding result, only 71% of the required drive-in torque of fully threaded screws.
- In the pre-drilled hole condition, the screw with two thread segments required slightly higher drive-in torque than the screws with 33% thread on the point end. For the non pre-drilled hole condition, the screw with two thread segments required almost the same amount of drive-in torque of a fully threaded screw.
- From the results, the presence of a pre-drilled hole can significantly reduce the increase of torque. In addition, it is more effective for fully threaded screws and screws with two segments where at least 18.6% of maximum torque is reduced. The presence of a pre-drilled hole can also ensure that the screw is installed as vertically as possible. About 65% of screws are inclined when installed without pre-drilled holes.
- In pre-drilled and without pre-drilled conditions, Screw S with larger diameter achieved higher maximum torque by 52% and 55% compared to Screw R with the same thread configuration. By considering the increase of shear resistance due to a larger diameter, it was found that the larger diameter of Screw S did not increase the shear stress to shear strength ratio, in the pre-drilled condition, when compared to Screw R with 33% thread on the point end. However, it had a net increase of ratio by 8.6%, comparing to Screw R with 33% thread on the point end, in a condition without pre-drilled hole.

In timber construction, adequately reducing the drive-in torque of self-tapping screws not only reduces the risks of damaging the screw but also leads to faster installation and reduced costs. In the future, it will be essential to understand how wood density, screw diameter and pitch length can influence the drive-in torque of self-tapping screws.

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List of notations

d_1	is the outer diameter of the Screw R
d_2	is the outer diameter of the Screw S
L_{pen}	is penetration depth of the screw
L_{point}	is the length of the screw point
L_{reamer}	is the length of the reamer on the screw
T	is the torque
τ	is the shear stress

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Table 1. Specifications for the self-tapping screws

Screw type	**L_{pen} (mm)**	**L_t (mm)**	**L_{point} (mm)**	**L_{reamer} (mm)**	**Outer Ø (mm)**	**Inner Ø (mm)**	**Pitch (mm)**
R	295	290	25	N/A	7	4.6	4.8
S	300	100	13	10	8	5.3	5.6

Table 2. Summary of each group

With pre-drilled hole	Group	A	B	C	G
	Screw type	R	R	R	S
	Torsional strength (Nm)	18	18	18	25.6
	Threaded length (mm)	290	200	100	100
	Thread location	Fully threaded	100mm on both ends	Point end	Point end
	Screw inner diameter (mm)	4.6	4.6	4.6	5.3
	Pre-drilled hole to screw inner diameter ratio	0.87	0.87	0.87	0.90
	Diameter of the drill (mm)	4	4	4	4.76
	Pre-drilled hole depth (mm)	180	180	180	180
	Repetitions	5	5	5	5
Without pre-drilled hole	Group	D	E	F	H
	Screw type	R	R	R	S
	Torsional strength (Nm)	18	18	18	25.6
	Threaded length (mm)	290	200	100	100
	Thread location	Fully threaded	100mm on both ends	Point end	Point end
	Repetitions	5	5	5	5

Table 3. Maximum torque for each test in this study

With pre-drilled hole		Group A	Group B	Group C	Group G
	1	5.48	5.09	5.59	9.95
	2	7.53	5.23	5.53	8.60
	3	6.43	5.95	5.13	7.40
	4	6.59	5.73	5.17	8.19
	5	8.25	7.33	5.59	12.56
	Average max torque	6.86	5.87	5.40	9.34
	CoV	16%	15%	4%	20%
Without pre-drilled hole		Group D	Group E	Group F	Group H
	1	10.49	14.39	8.33	9.79
	2	8.29	8.93	6.49	14.39
	3	8.23	10.03	6.25	9.33
	4	8.39	8.55	6.07	10.05
	5	15.2	8.39	6.73	10.93
	Average max torque	10.12	10.06	6.77	10.90
	CoV	30%	25%	13%	19%

Table 4. Overall inspection result for each group

		Inspection	Count of cases			
			Group A	Group B	Group C	Group G
With pre-drilled holes	Pre-drilled (<180mm)	Knots in the area*	3	2	3	2
		Screw inclination from start	3	1	1	0
		Screw bent/inclined due to knots	0	1	1	0
		Surge on torque due to knots	1	0	2	2
	Below pre-drilled level (>180mm)	Knots in the area*	0	2	3	3
		Screw bent due to knots	0	1	0	0
		Surge on torque due to knots	0	1	0	2
		Screw bent due to annual rings	3	1	3	1
Without pre-drilled holes		Inspection	Count of cases			
			Group D	Group E	Group F	Group H
		Knots in the area*	2	4	3	4
		Screw inclination from start	5	3	5	5
		Screw bent/inclined due to knots	0	2	0	0
		Surge on torque due to knots	1	2	3	2

*Defined as the number of knots located within the adjacent area (see Figure 7).

Table 5. Summary of the depths of knots that are causing surge of torque

Group	**A1**	**B5**	**C2**	**C4**	**G1**	**G2**	**G5**	
Range of knot depth (mm)	46-70	195-230	0-23	55-70	184-200	138-150	46-60; 200-210	
Screw-knot interaction	Pass through	Pass by	Pass through	Pass through	Pass through	Pass through	Pass through	
Group	D5	E1	E3	F1	F3	F5	H2	H5
Range of knot depth (mm)	70-92; 230-270	50-60; 230-276	276-290	180-210	23-46	0-10; 46-55	92-120; 160-184	70-92
Screw-knot interaction	Pass through	Pass through	Pass through	Pass through	Pass through	Pass through	Pass by	Pass through

Table 6. Test results after excluding those influenced by knots

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
1		5.09	5.59	10.49				9.79
2	7.53	5.23		8.29	9.03	6.49		
3	6.43	5.95	5.13	8.23			7.4	9.33
4	6.59	5.73		8.39	8.55	6.07	8.19	10.05
5	8.25		5.59		8.39			
Average max torque (Nm)	7.20	5.50	5.43	8.85	8.66	6.28	7.80	9.72
CoV	12%	7%	5%	12%	4%	5%	7%	4%

Table 7. Ratio of maximum shear stress to shear capacity of each group

Group	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Ratio of max shear stress to shear capacity	0.40	0.31	0.30	0.49	0.48	0.35	0.30	0.38
(CoV)	12%	7%	5%	12%	4%	5%	7%	4%

Figure captions

Figure 1. Examples of self-tapping screws as connectors for beam (left) and connections (right)

Figure 2. The two types of screws used in this study

Figure 3. Prepared self-tapping screws in this test

Figure 4. Screw arrangement for the torque test, the spacing satisfies the minimum requirement of design geometries

Figure 5. Setting up the analyser

Figure 6. A part of the specimen was cut in the transverse direction for inspection

Figure 7. Explanation to the terms in Table 4, screw bent due to passing by a knot (a), screws inclined inward as the trace of the cut of the screw gradually disappeared inside the specimen (b), screw passing through a knot (c)

Figure 8. Bent of self-tapping screws due to knots

Figure 9. Torque-depth relationships for tests that were significantly influenced by knots

Figure 10. Depth versus torque plot for groups with pre-drilled hole (excluding tests significantly influenced by knots)

Figure 11. Depth versus torque plot for groups without pre-drilled hole (excluding tests significantly influenced by knots)

Figure 12. Tracks of thread cut of Screws R and S left in the wood

Figure 13. Point of Screw S

Figure 14. Drawing shows the wood-screw interface

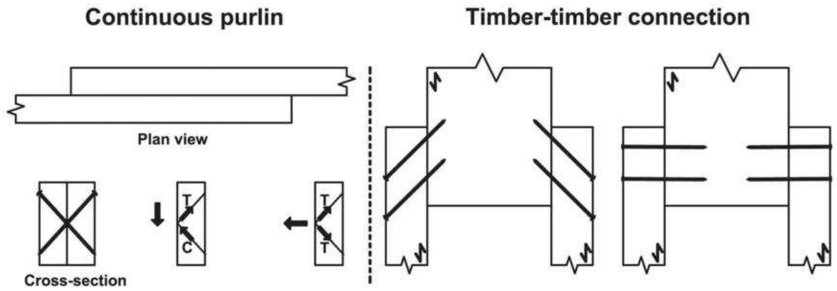

Continuous purlin
Timber-timber connection
Plan view
T
C
T
T
Cross-section

FIG1

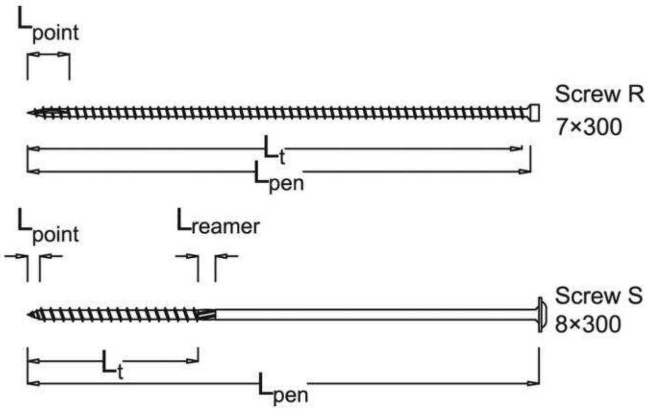

L_{point}
Screw R
7×300
L_t
L_{pen}
L_{point}
L_{reamer}
Screw S
8×300
L_t
L_{pen}

FIG2

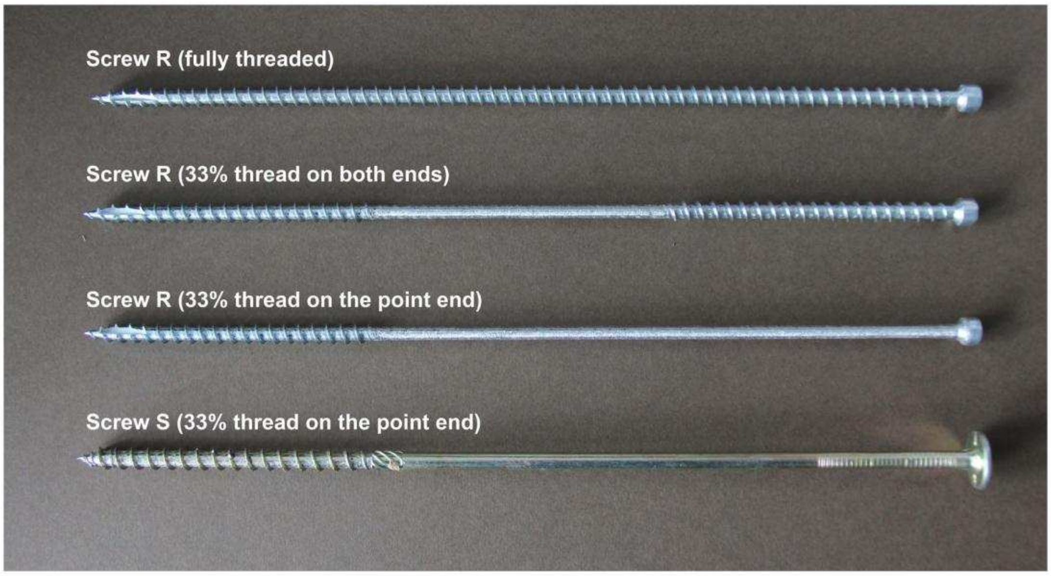
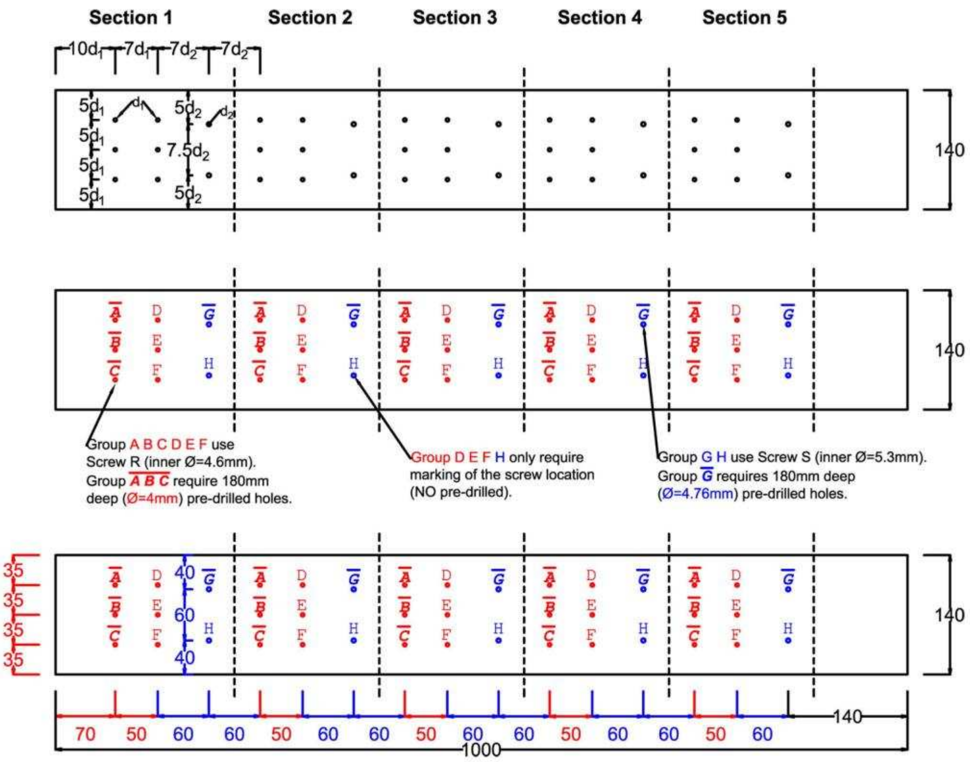

Screw R (fully threaded)
Screw R (33% thread on both ends)
Screw R (33% thread on the point end)
Screw S (33% thread on the point end)

FIG3



Group A B C D E F use Screw R (inner Ø=4.6mm). Group $\overline{A}$ $\overline{B}$ $\overline{C}$ require 180mm deep (Ø=4mm) pre-drilled holes.

Group D E F H only require marking of the screw location (NO pre-drilled).

Group G H use Screw S (inner Ø=5.3mm). Group $\overline{G}$ requires 180mm deep (Ø=4.76mm) pre-drilled holes.

FIG4

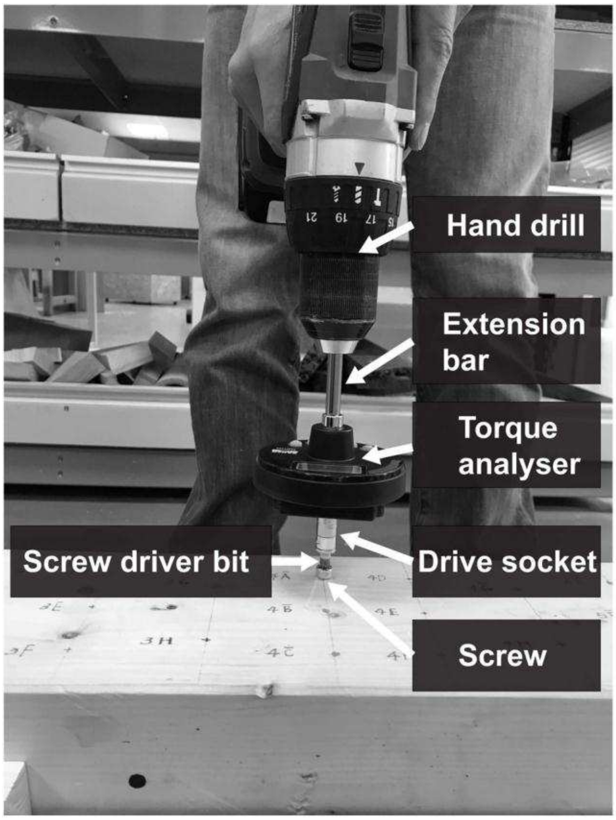

Hand drill
Extension bar
Torque analyser
Screw driver bit
Drive socket
Screw

FIG5

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10.1680/jcoma.18.00087

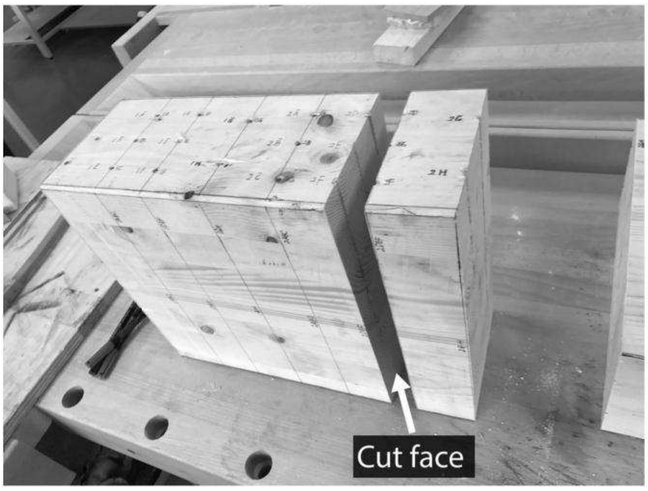
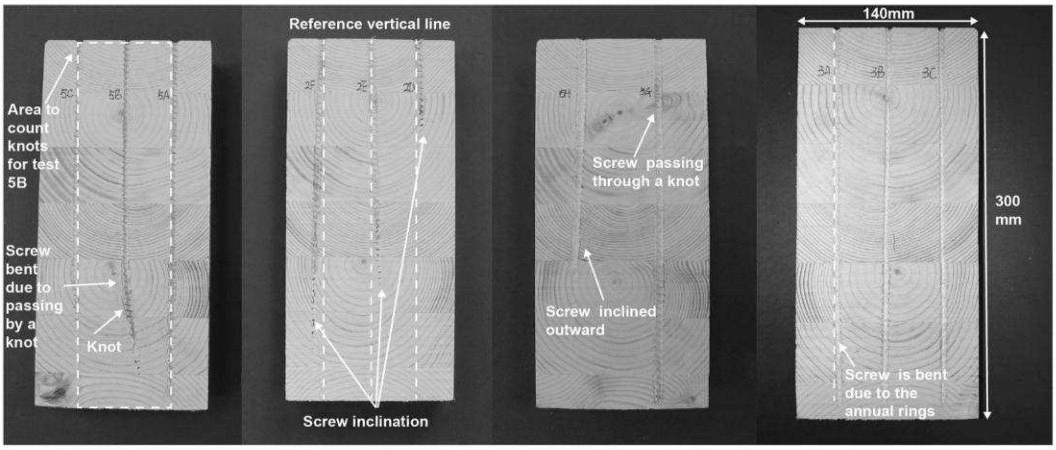


FIG6


Area to count knots for test 5B
5C
5B
5A
Screw bent due to passing by a knot
Knot
Reference vertical line
2F
2E
2D
Screw inclination
6H
5G
Screw passing through a knot
Screw inclined outward
140mm
3A
3B
3C
300 mm
Screw is bent due to the annual rings

(a) (b) (c) (d)

FIG7

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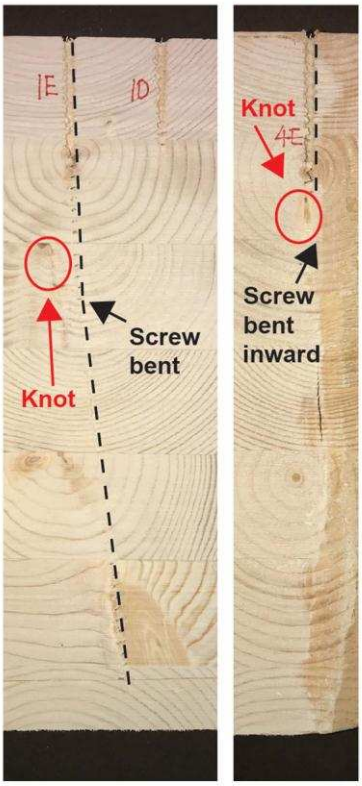


FIG8

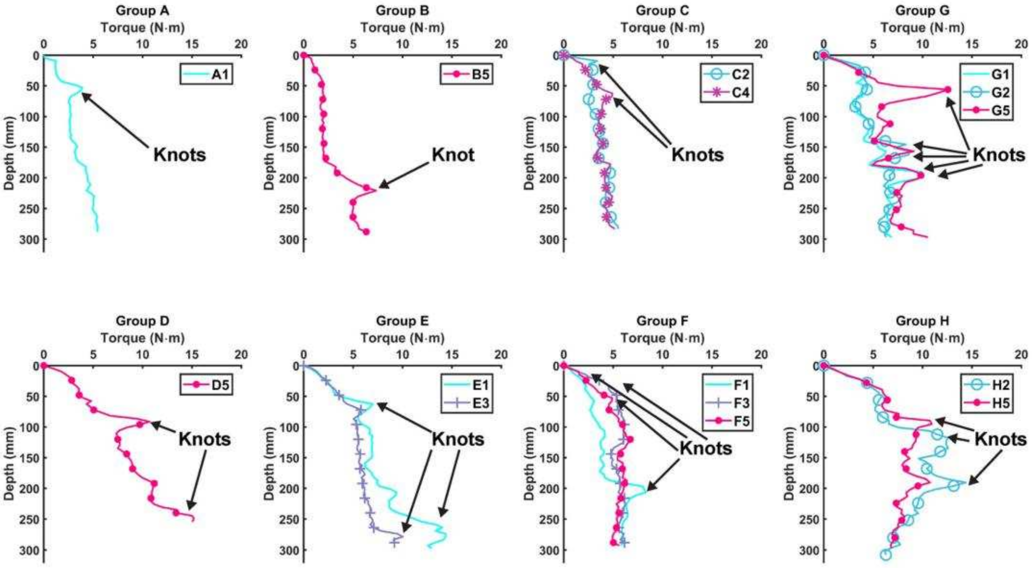
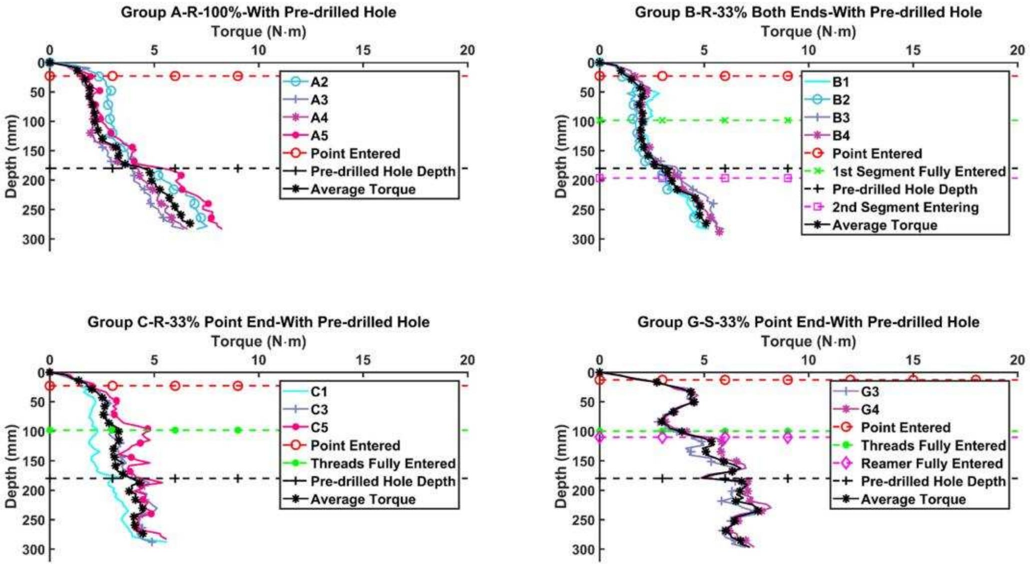

Group A
Torque (N·m)
0
5
10
15
20
Depth (mm)
0
50
100
150
200
250
300
A1
Knots
Group B
B5
Knot
Group C
C2
C4
Knots
Group G
G1
G2
G5
Knots
Group D
D5
Knots
Group E
E1
E3
Knots
Group F
F1
F3
F5
Knots
Group H
H2
H5
Knots

FIG9


Group A-R-100%-With Pre-drilled Hole

Group B-R-33% Both Ends-With Pre-drilled Hole

Group C-R-33% Point End-With Pre-drilled Hole

Group G-S-33% Point End-With Pre-drilled Hole

FIG10

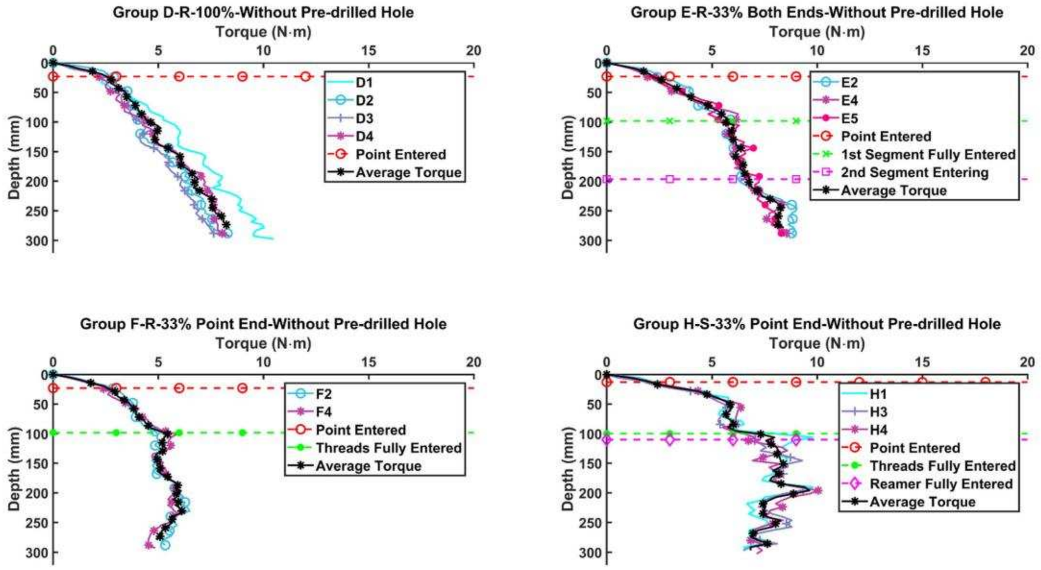

Group D-R-100%-Without Pre-drilled Hole
Torque (N·m)
0
5
10
15
20
Depth (mm)
0
50
100
150
200
250
300
D1
D2
D3
D4
Point Entered
Average Torque
Group E-R-33% Both Ends-Without Pre-drilled Hole
Torque (N·m)
E2
E4
E5
Point Entered
1st Segment Fully Entered
2nd Segment Entering
Average Torque
Group F-R-33% Point End-Without Pre-drilled Hole
Torque (N·m)
F2
F4
Point Entered
Threads Fully Entered
Average Torque
Group H-S-33% Point End-Without Pre-drilled Hole
Torque (N·m)
H1
H3
H4
Point Entered
Threads Fully Entered
Reamer Fully Entered
Average Torque

FIG11

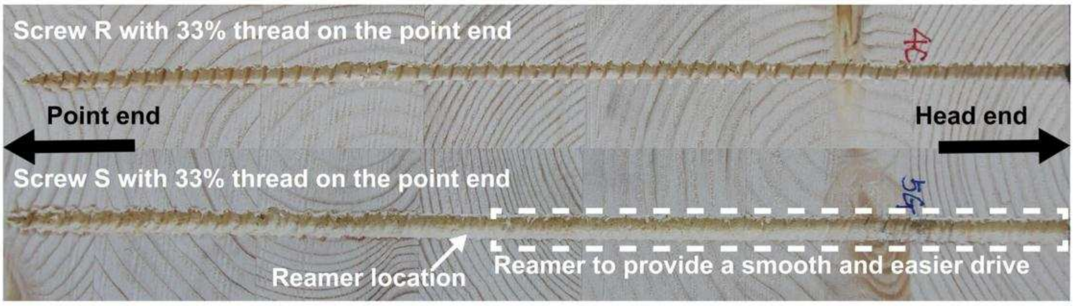

Screw R with 33% thread on the point end
4C
Point end
Head end
Screw S with 33% thread on the point end
5G
Reamer location
Reamer to provide a smooth and easier drive

FIG12

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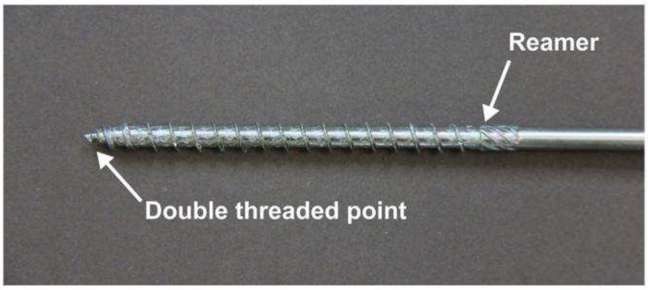

FIG13

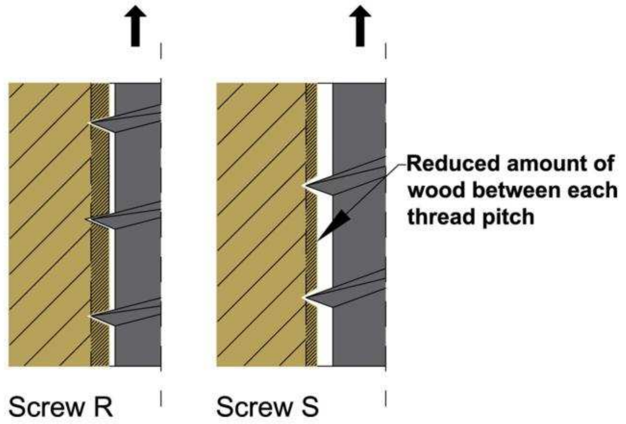
Reduced amount of wood between each thread pitch
Screw R
Screw S

FIG14