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SHORT COMMUNICATION

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Study on torque and clamping forces of screw-connected plywood

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Abstract
In various engineering applications, screws are commonly used to connect wood and engineered wood products to each other. To describe the axial loads which may be transmitted with these components, it is important to quantify the resulting clamping forces in relation to the applied screw torques. In this initial study, birch plywood panels with thicknesses of $t = 12$, 16, and 20 mm connected with screws (major thread diameter $d \approx 5$ mm) are experimentally tested to establish screw driving, tightening and stripping torques. In addition to that, the resulting clamping forces that occur over a time period of 120 hours are monitored and analyzed. A good agreement was found between the established time-dependent clamping force functions compared to the regression model, which are recommended in the literature.

KEYWORDS
birch, clamping force, creep, screw, torque

1 | INTRODUCTION

At the beginning of the 20th century, wood was frequently used in combination with steel as structural parts of vehicles.[1] Due to the growth of the steel industry, wood was partially replaced with metals within vehicles. However, ongoing research projects like "Wood C.A.R.[2]" focuses on the reintroduction of engineered wood products made from hardwood (eg, birch) as load-bearing materials in vehicles.[3,4] Hardwood provides good strength-to-weight ratio, which can significantly decrease the fuel consumption of vehicles. To fasten hardwood with other structural elements, the use of screws can provide an economical and reliable fastening solution.[5] However, applying screws as connectors for lightweight materials like solid wood and engineered wood products exhibits challenges that need to be addressed. Several researchers[6-11] conducted different types of experimental tests with screws, that is, insertion, withdrawal, shear, pilot-hole, torque, clamping etc. on solid wood and engineered wood products to investigate the mechanical performance of the connectors. In order to describe which loads may be transmitted into the structural components of the vehicle with screw connections, it is important to investigate the residual clamping forces that remain after connecting the screw joining members to each other. Especially, the forces that occur within a long period of time are important features for the effective design of the screw-connections. There are also studies that deal with the time-dependent clamping forces and therewith creep behavior of wood materials.[12-17] Furthermore, there is a European standard[18] which recommends a procedure to determine the creep of solid wood and engineered wood products. Nonetheless, only a few studies have dealt with the investigation of the long-term clamping forces that appear in the screwed wood members, in direct relation to the applied screw torques. For that reason, a practice-oriented experimental set-up was tested and applied to measure screw torques (driving, tightening and stripping torques) and clamping forces that remain in the wood components after connecting them to each other with wood construction screws. Birch plywood panels were fastened to each other and the clamping forces that occurred over a time period of 120 hours were measured and analyzed. These clamping force functions were correlated with a regression model as inferred, for example, by Niemz and Sonderegger[19] to ensure the reliability of the measurements. Additionally, the driving, tightening and stripping torques were established in direct relation to different specimen thicknesses of t = 12, 16, and 20 mm. Matsubara et al,[20] Eckardt,[21] Steilner[11] for instance, investigated forces that appear in screwed engineered wood products. Kuang et al[22] and Tor et al[23,24] investigated the appearing screw torques in relation to applicable pilot holes and screw penetration depths in engineered wood products. Further, most fastener producers do not give maximum torque recommendations due to liability issues and those that do, do not guarantee desired results because of the variation of existing applications. However, applying the proper torque to fasteners to induce appropriate clamping forces is essential to provide a reliable screw joint. Therefore, the aim of this research study is to give fundamentals about the time-dependent progression of clamping forces in direct relation to the applied screw torques that can be expected when plywood elements are screwed to each other. Finally, it is believed that these data can be considered for the design of screw connections and input data for structural simulations.

2 | MATERIALS AND METHODS

2.1 | Specimens

Commercially available birch plywood boards (Sperrplatte Birke BB/BB 9-fach EN314-2/KL3: sourced from J. u. A. Frischeis GmbH, Stockerau, Austria) with the raw dimensions of 3000 mm × 1500 mm × 12 mm (width × length × thickness) was used to produce the specimens. The raw material was processed to panels of 60 mm × 75 mm × 12 mm (width × length × thickness) by means of a circular saw. To manufacture the specimens with a thickness of t = 16 and 20 mm, some of the panels were glued together with white wood glue (Ponal wood glue classic: sourced from Henkel Central Eastern Europe GmbH, Vienna, Austria) in the direction of thickness. The desired specimen thicknesses (t = 16 and 20 mm) were obtained through finishing by using a planer machine. Afterwards, all specimens were conditioned in a standardized climate chamber (20 ± 2°C, 65 ± 5% relative humidity) for two weeks to attain a moisture content of 12%, so that the average wood material density ρ_m was about 680 kg/m^3. The clamping elements (cf. Figure 1) were pre-drilled with 5 mm and the screw-in elements (cf. Figure 1) with 3.5 mm. Accordingly, ten specimens for three different test configurations (t = 12, 16, and 20 mm) were produced and tested.

2.2 | Experimental set-up

The screws (EJOT Dabo TKE - 4.8 × 70: sourced from EJOT Baubefestigungen GmbH, Bad Laasphe, Germany) which had a major thread diameter of 4.8 mm, minor thread diameter of 3.5 mm and screw-thread length of 70 mm[25] were inserted in the center of the specimens as shown in Figure 1. Before inserting the screws, a metal rosette (Full metal, M6-A4) was placed between the screw and the clamping element (cf. Figure 1) to ensure that the screw (countersunk head) is fully seated on the wood surface. The screw torques (driving, tightening and stripping torque) were monitored while the screw was inserted by using an electrical screwing device (AC-EDT-S74-20-I06-CTADST, Atlas Copco AB, Stockholm, Sweden)

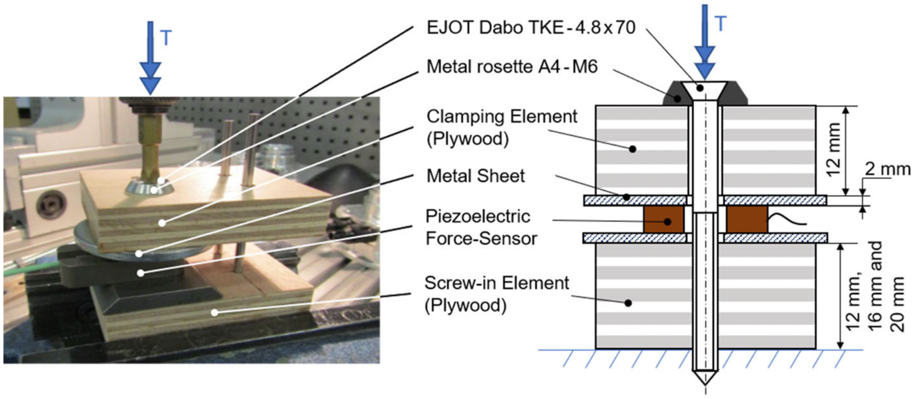

FIGURE 1 Test set-up of the screw torques and clamping force measurements

which was equipped with a torque measurement sensor (DR-2153, REC Fastening GmbH, Breidenbach, Germany). The clamping force measurements were performed with a piezoelectric force transducer (K-180, REC Fastening GmbH, Breidenbach, Germany) which was placed in-between the screw-connected plywood elements (see Figure 1). Metal sheets with a hole in the center (no contact between screws and metal sheets) were arranged above and beneath the force transducer in order to guarantee that the clamping force is gauged over a large specimen surface. Further, it was ensured that only the screw-in element (pilot-hole of 3.5 mm) was friction-locked by means of the screw thread, so that the clamping element (pilot-hole of 5 mm) was clamped between the screw head and thread.

3 | RESULTS AND DISCUSSIONS

Figure 2 shows a typical screw-insertion torque (T) vs screw-rotation angle (φ) diagram of the conducted experiments. The screw insertion process can be broken down into five main stages: "assembly start, completed thread forming, screw-head contact, creation of clamping force and destruction of joint."

The assembly process starts when the screw-tip contacts with the wall of the screw-in element. Then the thread forming starts and ends when the screw breaks first through the screw-in element, which means the driving torque (T_D) is reached. After the screw advances until the screw-head contacts the clamping element. This spot, which is defined as seating torque (T_{SE}) is the initiated starting of the clamping force. The final needed clamping force of the joint is attained, when the tightening torque (T_T) is reached. In any case of continuing the screw-inserting process, destruction of the joint (eg, screw-head pulled through clamping element, screw-thread sheared off, screw breakage, etc.) can be expected. This destruction point is defined by reaching the stripping torque (T_{ST}). Figure 3, shows the measured screw torques and clamping forces for different specimen thicknesses (t = 12, 16 and 20 mm).

In Figure 3A the mean values of the monitored screw-torques are illustrated throughout all test configurations, that is, screw-in plywood element with thicknesses of t = 12, 16, and 20 mm. All screws were inserted with a driving torque (T_D) of around 1 Nm. In pre-tests, the stripping torques (T_{ST}) were measured for all test configurations. Through visual investigation of the specimens (properly sunk metal rosette in clamping element) and based on previous testing experience, the tightening torques (T_T) were chosen. For instance, experiments with screwed polymers (eg, plastic panels) show that the tightening torques (T_T) of the joint should be the mean value calculated from the seating torque (T_{SE}) and stripping torque (T_{ST}). In this case, higher tightening torques (T_T) would only lead to larger material deformations without increasing the

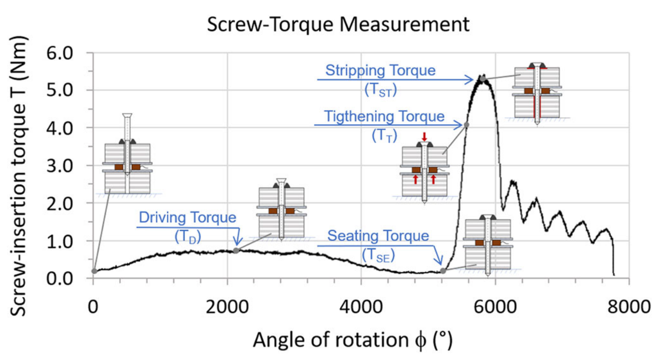

FIGURE 2 Typical screw-insertion torque vs screw-rotation angle curve of a screw-connected birch plywood specimen with a thickness t = 16 mm showing the different screw insertion phases

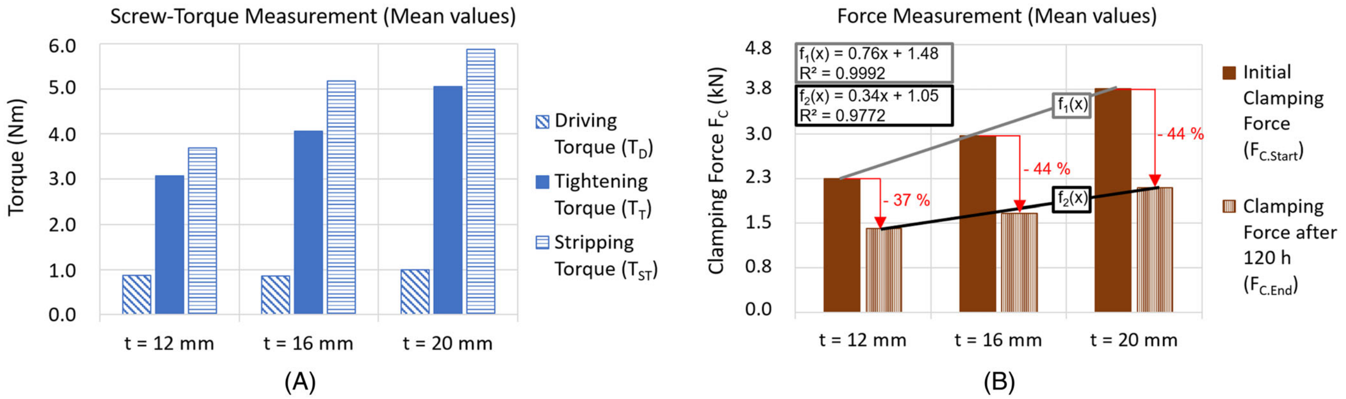

FIGURE 3 A, Measurement results (mean values) of the screw torques (driving, tightening and stripping torque) in relation to different specimen thicknesses (t = 12, 16 and 20 mm) of the screw-in elements. B, Measurement results (mean values) of the initial clamping forces and remaining clamping forces (after 120 hours) in relation to different specimen thicknesses (t = 12, 16 and 20 mm) of the screw-in elements

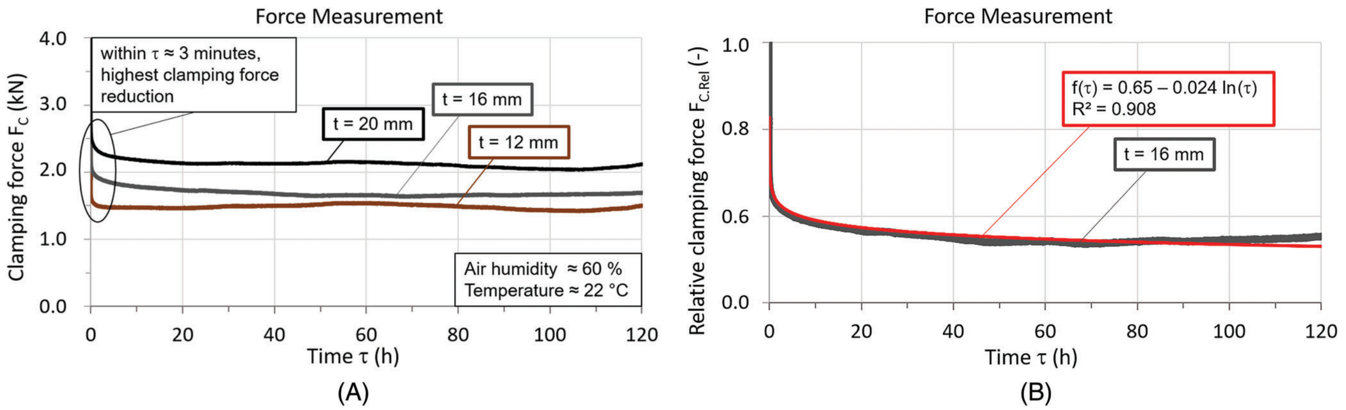

FIGURE 4 A, Typical clamping force to time function in relation to different specimen thicknesses (t = 12, 16 and 20 mm) of the screw-in elements. B, Typical relative clamping force function of the specimen with the thickness of t = 16 mm in comparison to the logarithmic regression model with the general form: "$f(\tau) = A + \ln(\tau^B)$"

clamping effect. Compared with the tested plywood elements, higher tightening torques (T_T) could be achieved, due to the higher yield strength of wood material. It was assumed that specimens with a thickness of t = 12, 16, and 20 mm should be tightened with screw torques of $T_T = 3$, 4, and 5 Nm, respectively. To guarantee on the one hand, clamping without wood material degradation and on the other hand, a gap-free connection between the clamped plywood elements. All specimens that were tested until the stripping torques (T_{ST}) was reached, showed a shearing off of the screw-thread of the screw-in element and first damages on the clamping element surfaces. As mentioned, the initial joint clamping forces ($F_{C.Start}$) initiated through the tightening torques (T_T) and further, the clamping forces remaining after a certain time period ($F_{C.End}$) are essential to ensure the functionality of the connected structure. Therefore, in Figure 3B the mean values of the initial clamping forces and the clamping forces that remained in the screwed connection after 120 hours are plotted against each other. Accordingly, for all three test configurations, a reduction of about 40% of the initial clamping forces was detected after an investigating time of $\tau = 120$ hours. Similar experiments confirmed that isotropic materials like aluminum showed comparable clamping force reduction. With regard to the applicable clamping forces as a function of the thickness of the screwed elements, there is a strong linear dependence. The initial clamping forces and the remaining clamping forces increased with the investigated specimen thicknesses, so that a linear fitting throughout the three test configurations (t = 12, 16, and 20 mm) led to coefficients of determination of $R^2 = 0.9992$ for the initial clamping force and $R^2 = 0.9772$ for the remaining clamping force. From these data, applicable torques and expecting clamping forces in plywood structures beneath or above the investigated thicknesses can be derived, which is needed for the design of screw connections. To investigate the creep behavior of test specimens, the clamping force (F_C) vs time (τ) measurements of representative examples are shown in Figure 4.

Looking more in-depth into the results, it can be observed that the highest clamping force reduction is reached within the first 3 minutes (cf. Figure 4A). Basically, to investigate which curve progression, these data follow a logarithmic regression model as suggested by Niemz and Sonderegger[19] to describe the creep behavior of wood material was assumed. In order to pursue a mathematical description independently of the specimen thicknesses, a normalized clamping force to time function was created for the specimen with a thickness of t = 16 mm, as shown in Figure 4B. The fitted logarithmic model ($f(\tau) = A + \ln(\tau^B)$) has indicated a very good correlation ($R^2 = 0.908$), which means that the established experimental set-up is suitable to measure clamping forces and in addition to that, creep that occurs in screw-connected plywood elements. Other wood-based materials (eg, OSB, MDF, WPC, etc.) should be considered for further evaluation and validation of applicable screw torques and clamping forces. Moreover, an in-depth look into varying pilot holes and wood moisture contents is an asset that needs to be addressed in future. Beyond the experimental investigations, a comparison to computer-based structural simulations such as finite element analyses (FEA) will be considered for statistically sound data across different test configurations.

4 | CONCLUSION

The screw torque and clamping force measurements performed in the present research study show that there is a strong linear dependency in correlation to the thickness of the tested plywood specimens. It is assumed that specimens with a thickness of t = 12, 16, and 20 mm should be tightened with screw torques of $T_T = 3, 4$, and 5 Nm, respectively. The initiated clamping forces ($F_{C.Start}$) related to these tightening torques (T_T) were 2.3, 3, and 3.8 kN. The monitored residual clamping forces after 120 hours ($F_{C.End}$) were reduced by about 40% with the highest force reduction within the first 3 minutes of investigation. A profound examination of the clamping forces over time, clarified that a logarithmic regression model with the general form: "$f(\tau) = A + \ln(\tau^B)$" is suitable for describing the clamping force progression ($R^2 = 0.908$). These fundamental results can help to design screwed wood joints more effectively. Finally, it was shown that the applied experimental set-up is appropriate for measuring torque and clamping forces of screwed engineered wood structures. Future studies will focus on additional engineered wood products and parameter studies with varying wood moisture content and also pilot-holes. Moreover, a comparison of the measurements results to structural simulations is also considered.

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AUTHOR CONTRIBUTIONS

Cedou Kumpenza: Conceptualization; data curation; formal analysis; investigation; methodology; software; validation; visualization; writing-original draft. **Gerhard Schmidt:** Data curation; investigation; methodology. **Adeayo Sotayo:** Formal analysis; writing-review and editing. **Andreas Ringhofer:** Methodology; validation; writing-review and editing. **Ulrich Müller:** Conceptualization; funding acquisition; project administration; resources; supervision.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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REFERENCES

1. Braess HH, Seiffert U. *Vieweg Handbuch Kraftfahrzeugtechnik (Handbook Automotive Technology)*. 7. Auflage ed. Wiesbaden, Germany: Springer Vieweg; 2013. ISBN 978-3-658-01691-3 (eBook)
2. Wood C.A.R. Computer aided research. http://www.woodcar.eu/index.html. Accessed April 22, 2020.
3. MüllerU, Jost T, Kurzböck C, et al. Crash simulation of wood and composite wood for future automotive engineering. *Wood Mater. Sci. Eng*. 2019;0(0):1-13. https://doi.org/10.1080/17480272.2019.1665581.
4. Baumann G, Stadlmann A, Kurzböck C, Feist F. Crash-proof wood composites in lightweight bodyworks of the future. *ATZ Worldwide*. 2019;121(11):48-51. https://doi.org/10.1007/s38311-019-0138-8.
5. Brandner R. Properties of axially loaded self-tapping screws with focus on application in hardwood. *Wood Mater. Sci. Eng.* 2019;14(5):254-268. https://doi.org/10.1080/17480272.2019.1635204.
6. Miyamoto BT, Sinha A, Morrell I. Connection performance of mass plywood panels. *For. Prod. J.* 2019;70(1):88-99. https://doi.org/10.13073/FPJ-D-19-00056.
7. Brandner R, Ringhofer A, Reichinger T. Performance of axially-loaded self-tapping screws in hardwood: properties and design. *Eng Struct*. 2019;188:677-699. https://doi.org/10.1016/j.engstruct.2019.03.018.
8. Wang F, Wang X, Cai W, Chang C, Que Z. Effect of inclined self-tapping screws connecting laminated veneer lumber on the shear resistance. *BioResources*. 2019;14(2):4006-4021. https://doi.org/10.15376/biores.14.2.4006-4021.
9. Matsubara D, Wakashima Y, Fujisawa Y, Shimizu H, Kitamori A, Ishikawa K. Relationship between clamp force and pull-out strength in lag screw timber joints. *J. Wood Sci.* 2017;63(6):625-634. https://doi.org/10.1007/s10086-017-1660-1.
10. Tor O, Yu X, Zhang J. Characteristics of torques for driving screws into wood-based composites. *Wood Fiber Sci*. 2015;47(1):2-16.
11. Steilner M. Pre-stressing of wood with full thread screws. In: Kay-Uwe Schober (Ed.), Conference proceeding: COST Action FP1004, Experimental Research with Timber, 21-23 May 2014, Czech Technical University in Prague. England: University of Bat; p. 50-55. https://doi.org/10.5445/IR/1000041134.
12. Tong D, Brown SA, Corr D, Cusatis G. Wood creep data collection and unbiased parameter identification of compliance functions. *Holzforschung*. 2020;1:1-10. https://doi.org/10.1515/hf-2019-0268 [Epub ahead-of-print].
13. Wang J, Wang X, He Q, Zhang Y, Zhan T. Time-temperature-stress equivalence in compressive creep response of chinese fir at high-temperature range. *Constr. Build. Mater*. 2020;235:117809. https://doi.org/10.1016/j.conbuildmat.2019.117809.
14. Hu WG, Guan HY. Study on compressive stress relaxation behavior of beech based on the finite element method. *Maderas, Cienc. tecnol.* 2019;21(1):15-24. https://doi.org/10.4067/S0718-221X2019005000102.
15. Mohammed AI, Ocholi A, Ejeh SP, Amartey YD. Compression creep model for nigeria grown *Terminalia Ivorensis* (Black Afara) timber. *Niger. J. Technol.* 2019;38(2):311-316. https://doi.org/10.4314/njt.v38i2.6.
16. Ozyhar T, Hering S, Niemz P. Viscoelastic characterization of wood: Time dependence of the orthotropic compliance in tension and compression. *J. Rheol.* 2013;57(2):699-717. https://doi.org/10.1122/1.4790170.
17. Farid SI, Kortschot MT, Spelt JK. Wood-flour-reinforced polyethylene: viscoelastic behavior and threaded fasteners. *Polym. Eng. Sci.* 2002;42(12):2336-2350. https://doi.org/10.1002/pen.11120.
18. DIN EN 1156:2013-10. Wood-based Panels – Determination of Duration of Load and Creep Factors. *European Committee For Standardization*. 2013.1–18.
19. Niemz P, Sonderegger W. *Holzphysik: Physik des Holzes und der Holzwerkstoffe (Wood Physics: Physics of Wood and Wood-Based Materials)* (*Wood Physics: Physics of Wood and Wood-Based Materials*). Munich, Germany: Carl Hanser Verlag GmbH Co KG; 2017. ISBN 978-3-446-44546-8 (ebook).
20. Matsubara D, Wakashima Y, Fujisawa Y, Shimizu H, Kitamori A, Ishikawa KA. A novel method for estimating ultimate clamp force in lag screw timber joints with steel side plates. *Trans Mater. Res. Soc. Japan*. 2019;44(3):109-113. https://doi.org/10.14723/tmrsj.44.109.
21. Eckardt R. Untersuchungen an Verbindungselementen für Holzkonstruktionen im Maschinen-und Anlagenbau (Investigations on fasteners for wooden constructions in mechanical and plant engineering applications) [dissertation]. Germany: Institute for Conveying Technology and Plastics, Technical University Chemnitz; 2012.
22. Kuang F, Xing Y, Wu Z, Zhang J. Characteristics of screwdriving torques in wood-plastic composites. *Wood Fiber Sci*. 2017;49(2):206-218.
23. Tor O, Yu X, Demirel S, Hu L, Zhang J. Factors affecting critical screw-driving torques in particleboard. *BioResources*. 2019;14(3):6645-6656. https://doi.org/10.15376/biores.14.3.6645-6656.
24. Tor O. Effects of pilot hole diameter on screw-driving torques in medium density fiberboard. *CERNE*. 2019;25(1):54-59. https://doi.org/10.1590/01047760201925012608.
25. ETA-07/0013. EJOT flat roof fasteners. European Technical Approval, Bad Laasphe, Germany: EJOT Baubefestigungen GmbH; 2017.

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