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Experimental Investigation on the Mechanical Characteristics of a Novel Hybrid Densified Wood-Filled Aluminum Tube Dowel for Timber Connections †

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Abstract: The structural performance of a novel hybrid dowel, made of a densified wood-filled aluminum tube (DWFAT), for structural timber joints was investigated experimentally, for the first time. Three-point bending tests have been conducted on both hybrid DWFAT dowels and densified wood dowels (DWD) in order to evaluate their strength and stiffness characteristics as well as their ductility and failure modes. The developed hybrid DWFAT dowels were then used and tested in the context of both slotted-in aluminum plate timber and timber-to-timber double shear connections and the obtained load-slip curves as well as the failure modes were analyzed and compared to their equivalent connections made with conventional steel dowels. The results showed that the developed hybrid DWFAT dowel is promising and can be a potential substitute for conventional steel dowels.

Keywords: dowelled timber joints; hybrid system; densified wood; aluminum

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1. Introduction

In the design of modern timber structures, the connections are commonly made of steel dowels or bolts and slotted-in steel plates. Connections using steel dowels are generally recognized, on one hand, as dissipative zones and, on the other hand, the weakest points of timber structures, as the large majority of collapses originate at connections [1]. The slotted-in steel dowelled connection type, when designed appropriately, is recognized to behave in a ductile manner, which is preferred over brittle failure, and to exhibit high strength, ductility and stiffness. It is also well-known that the deformation properties of connections have a crucial role on the overall stability of the structure and on the distribution of internal forces [2]. Thus, the most three important mechanical characteristics for the design of timber connections are their load-carrying capacity, stiffness and ductility values. Of course, other properties are also critical for reliability, fatigue and corrosion resistance.

Extensive and comprehensive experimental and numerical research studies on timber joints are available in the literature, where the relationship between the applied load and displacement of connections is measured [1–13], among others. In general, measurements include: slip modulus, load-carrying capacity, ductility and dissipated energy of joints, which are generally measured in accordance to the appropriate European or STM standards.

Driven by an increasing focus on environmental sustainability, the use of durable resources and advocates for sustainable development policies has resulted in several exploratory studies being undertaken in the last decade to investigate the structural performance of non-metallic timber connections. These non-metallic connections include GFPR or CFRP glued rods [14], FRP dowels [15], welded beech wood dowels [16,17], wood dowels combined with densified veneer wood plates [18–21] and more recently densified wood dowels (DWD) [22–24] combined or not with internal densified wood plate (DWP). A comprehensive literature review on non-metallic wooden connectors is given in [25].

Recent studies [22–24] have shown that densified wood dowels (DWD) are potential candidates to substitute conventional steel dowels for structural timber joints in terms of load-carrying capacity, in addition to delaying the brittle failure of timber members since the DWD/timber member stiffness ratio is lower as compared to that of the steel dowel/timber member [22–24]. However, the authors have reported that such connections suffer from a lack of ductility, which is of primary importance in the context of structural uses, by comparison to the steel dowels. In fact, densified (thermo-mechanically compressed) wood dowels were found to exhibit strength and stiffness characteristics which are adequate for structural bearing uses due to increased density and mechanical properties of the DWD thanks to the densification process. Some authors reported the increase of the mechanical properties of densified wood in comparison to virgin wood at between 250 and 300% [26].

In this regard, an experimental campaign has been undertaken at the Laval University to explore a novel way to overcome the lack of ductility of DWD using aluminum tubes filled with DWD. Wood and aluminum are both local lightweight materials in Québec (Canada), fully recyclable and supported by the governmental development policies [27,28]. In addition, a recent Life Cycle Assessment (LCA) study [29] comparing several hybrid structural systems, namely concrete-to-steel (CTS), aluminum-to-steel (ATS) and aluminum-to-timber (ATT), has shown that aluminum produced in Canada by hydroelectricity can be environmentally and economically more beneficial when combined with timber (ATT systems) as compared to CTS and ATS systems. Other advantages of aluminum material include: it is lightweight, offers good resistance to corrosion, is easy to work with, has increased mechanical properties at low temperature, etc.

In the proposed multi-material concept, the DWFAT performance is achieved by means of radial expansion of DWD due to moisture absorption, since the densification process (thermomechanical compression) makes the moisture content (MC) of the DWD between 6% and 7%, which is under the equilibrium level (generally around 12%). Thus, DWD is subject to partially recover its original shape with time and in turn it insures a tight fit and prevent loosening [22–24] thanks to the corresponding developed friction between timber and aluminum.

Composite or hybrid structural components, combining two or more materials selected based on their individual performances, have been extensively studied and have proven to be a cost-effective solution by saving weight and preserving durability and economic feasibility [30], in several domains. A comprehensive experimental study combined with analytical modelling on the compressive behavior of timber-filled steel tubular columns has been presented by Karampour et al. [31], where it is clearly stated that wood-filled steel tubular structures can substitute for traditional concrete-filled steel tubular structures, due to the light weight of timber infill and its high compressive strength. Vesenjak et al. [30] have conducted an experimental study to investigate the bending performance of aluminum alloy filled with different cellular metal cores. The study includes static and dynamic loadings to evaluate the energy absorption capability of the different hybrid systems.

In this paper, it is proposed to evaluate, for the first time, the structural performance of slotted-in aluminum plate timber connections assembled using novel hybrid dowels made of aluminum tubes filled with densified wood. Only very limited research has been conducted on the structural response of hybrid timber-to-aluminum composite systems or timber filled aluminum tubes. To the best of our knowledge, densified timber-filled aluminum tubes has never been studied. Even if previous studies have shown improvements of compression strength of confined wood [32–34], the bending response as well as the basic failure mechanisms of confined densified wood are not well-studied and an accepted theory in this area has not yet been established. The determination of the geometrical parameters such as the thickness of the aluminum tube to reach appropriate performances for structural uses is also an interesting aspect which has not been presented elsewhere and must be determined by specific studies, before a such hybrid dowel can be incorporated into new generation of joints. The ultimate goal is to develop lightweight structural elements or connectors, here dowels for timber joints, with predictable behavior and enhanced properties to substitute the conventional steel components (or dowels).

The scope of the present study is to develop and validate a comprehensive and predictive finite element model to assess the different failure mechanisms and understand the experimental work performed with the ultimate objective to optimize the geometrical and material parameters, namely the thickness and material properties of the aluminum wall, to reach the appropriate performance level to substitute for traditional steel dowels. To this end, the so-called Verification and Validation Methodology (VVM) was applied to evaluate the performance and effectiveness of the developed FE model [35]. The verification stage consists of comparing the numerical results obtained by the FE model with highly accurate solution of a reference mechanical model. In our case, the highly accurate solution is numerically obtained with a fine FE model [35–37]. The validation stage deals with the comparison between the numerical solution obtained with the verified FE model against experimental results.

The present manuscript is organized as follows: Section 2 is dedicated to the experimental campaign, including the manufacturing method of the aluminum tubes filled with densified wood dowels, Section 3 is devoted to the main experimental results and discussion. Finally, Section 4 deals with the conclusion.

2. Experimental

In this section, three sets of experimental tests are presented, namely three-point bending tests, push-out double shear tests on timber-to-timber joints and tensile tests on slotted-in aluminum plate timber connections. The bending tests were conducted on both DWD and DWFAT dowels to evaluate their bending performances. The slotted-in aluminum plate timber connections are assembled using either conventional steel dowels or DWFAT dowels (hybrid dowels), while the timber-to-timber double shear connections were assembled using either DW or DWFAT dowels. Five specimens have been tested for each set of tests. All tests have been conducted until final failure, where the global load-displacement curves are recorded as well as the failure modes.

2.1. Materials

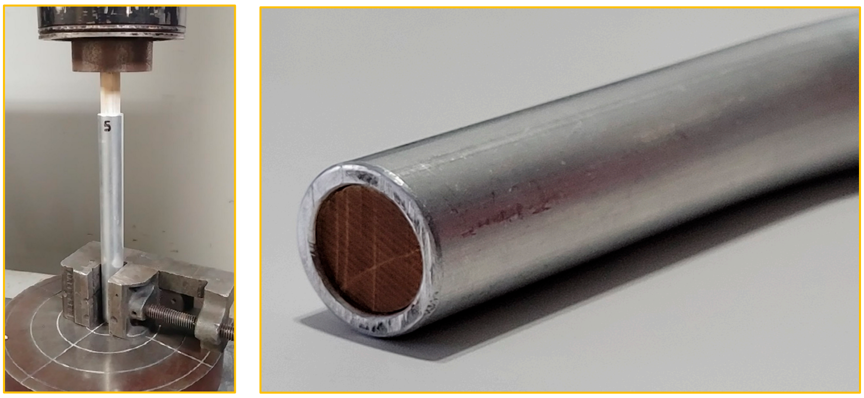
The material used in this study for the connection members was glued laminated spruce-pine-fir timber, stress grade 24F-ES-NPG, with a mean density of 560 kg/m^3. All the assembled timber members were conditioned, in a climatic chamber, at ambient temperature of 20 °C and kiln-dried to an equilibrium moisture content which fluctuated from 10% to 12%.

The densified wood dowels were obtained from radial thermo-mechanical compression of spruce, having initial mean density of 460 kg/m^3, up to 68% of compression ratio (CR). The compression ratio refers to the difference between the initial and final thickness of the densified wood piece as a percentage of the initial thickness. A detailed description of the thermo-mechanical compression process is given in [23]. The mean density of the obtained densified wood dowels after compression was 1158 kg/m^3. The densified wood dowels have a mean diameter of 15.9 mm.

The aluminum tubes as well as the aluminum plates are made of AA6005-T61 aluminum alloy, with yield stress of 240 MPa. The plates were 6.4 mm thick and the tubes have an inner diameter of 16 mm.

2.2. Manufacturing of the Hybrid Dowels

The hybrid dowel consists of aluminum tube filled with densified wood dowel. Both the densified wood dowels and the aluminum tubes have a length of 210 mm. Height densified wood dowels were inserted in the aluminum tubes to obtain the desired hybrid dowels. The densified wood dowels were driven into the aluminum tubes using the Instron testing machine (Figure 1a). The specimens were fixed at their lower base to avoid movement/rotation during insertion of the wooden dowel using a displacement control at a stroke rate of 5 mm/min.



(**a**) (**b**)

Figure 1. Densified wood-filled aluminum tube dowel: (**a**) manufacturing method, (**b**) prototype of hybrid dowel.

2.3. Three-Point Bending Test Dowels

Six DWD and five DWFAT dowels were tested under three-point bending tests (Figure 2) to assess the contribution of the aluminum tube to the bending strength and stiffness characteristics. The experimental loading procedure was conducted according to the experimental set-up depicted in Figure 3 using a 500 kN MTS universal testing machine at a stroke rate of 5 mm/min. An LVDT transducer was mounted to record the mid-span deflection of the specimen as load increases. All the tests were conducted up to final failure.

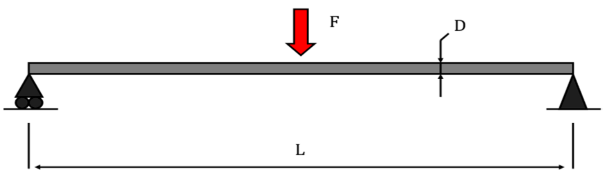


Figure 2. Three-point bending test scheme (L = 210 mm).

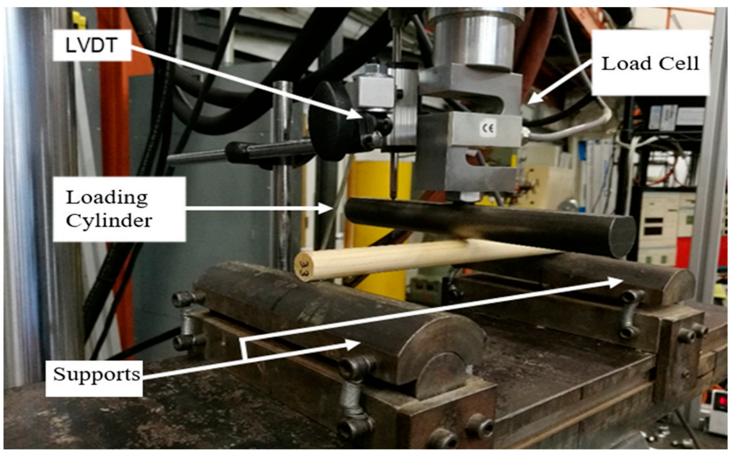
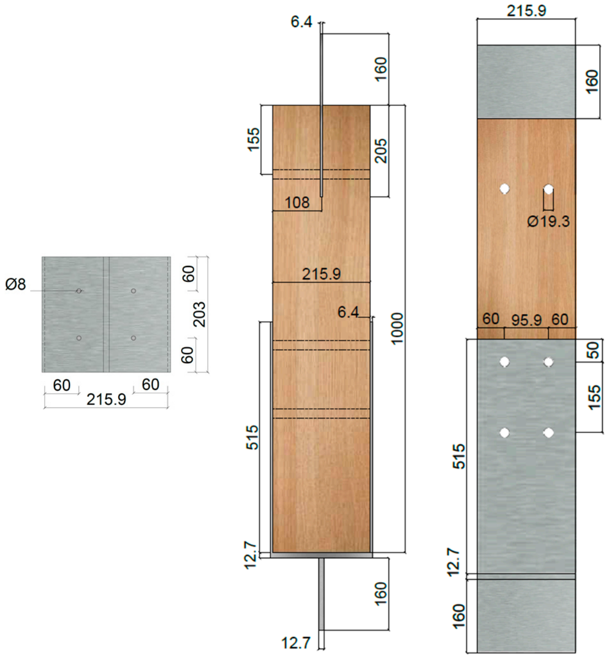


Figure 3. Experimental three-point bending tests set-up.

From the load-mid deflection curves, the bending stiffness (or effective bending stiffness for the hybrid dowel) and maximum bending strength were determined.

2.4. Slotted-In Aluminum Plate Timber Connection Tests

The dimensions of the slotted-in aluminum plate timber connections are presented in Figure 4. The desired dimensions of the assembled members as well as the spacing between dowels were chosen to meet the Canadian standard (CSA-O86-14) requirements [38] in order to avoid premature brittle failure of wood members. The dimensions (width and thickness) of the aluminum plate have been determined according to the Canadian standard CSA-S157-17 [39] in order to avoid premature failure by net tension. The slotted-in aluminum plate connections were assembled using either two densified wood-filled aluminum tube dowels or two steel dowels of 19.3 mm of diameter, for comparison purpose, involving in two series of tests (a total of 10 specimens were tested). The experimental set-up is shown in Figure 5c, where it can be seen that the lower part of the connection was clamped using two per side 6.4 mm thick steel plates with four steel bolts of 19.3 mm of diameter, while the upper part was loaded in tension through the aluminum plate. Two LVDT transducers (one per side) were used to record the mean relative slip between the aluminum plate and the timber member.



(**a**) (**b**) (**c**)

Figure 4. Geometrical description of the slotted-in aluminum timber connection: (**a**) bottom view, (**b**) front view and (**c**) side view.

Five specimens were tested for each test according to the EN 26891 standard requirements [40]. For each series of tests, a preliminary test was carried out until complete failure to determine the parameters of the loading procedure based on the maximum estimated load (F_{est}). Figure 6 displays the loading procedure for the monotonic loading. The connections have been, first, loaded until 40% of F_{est} and the crosshead position held during 30 s. After this stage, the connections have been unloaded until 10% of F_{est} and the crosshead position maintained again for 30 s. Finally, the connections have been loaded until reaching complete failure. For each test, the maximum load, the slip modulus and the ductility are evaluated.

The relation (1) suggested by the EN 26891 standard was used to evaluate the serviceability slip modulus, K_{ser} of connections.

$$K_{ser} = \frac{0.4\, F_{est}}{4/3(v_{04} - v_{01})} \tag{1}$$

where v_{04} and v_{01} represents the slip of the aluminum plate at 40% and 10% of the maximum load, respectively.

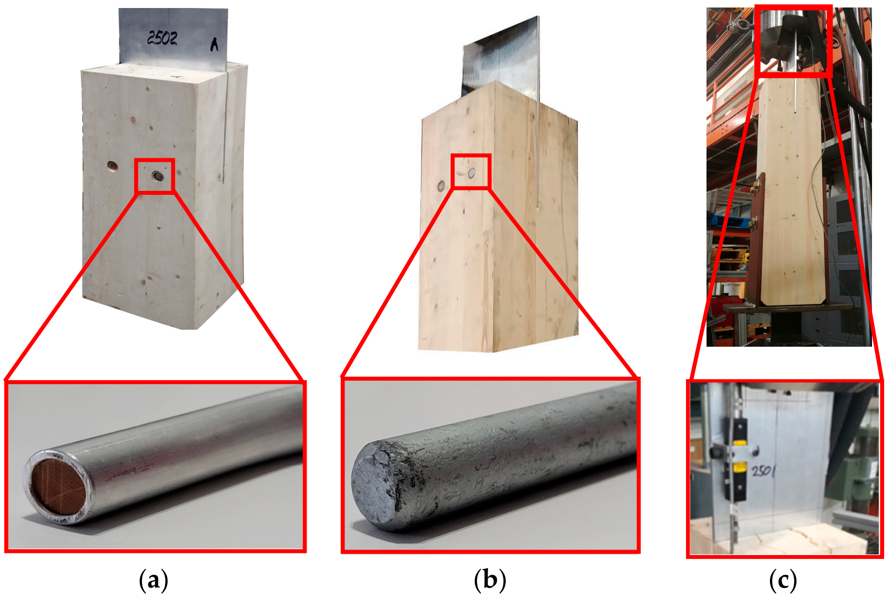


Figure 5. Experimental set-up of the slotted-in aluminum plate timber connection: (**a**) DWFAT dowel, (**b**) steel dowel and (**c**) experimental set-up.

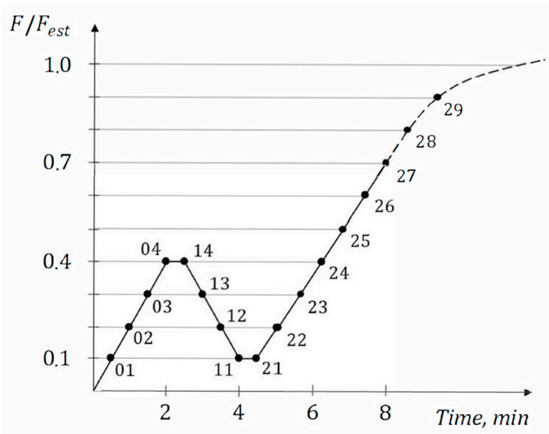


Figure 6. The standard loading procedure for monotonic loading [39].

The ductility was evaluated according to the EN 12512 standard requirements [41] and was calculated as the ratio between the experimental yield slip, v_y, and the ultimate slip, v_u, (relation (2)). The ultimate slip, v_u according to the requirements of the EN 12512 is displayed in Figure 7. The yield slip, v_y, is obtained based on the so-called 1/6 method given in the EN 12512 standard requirements and presented in Figure 8.

$$D_u = \frac{v_u}{v_y} \tag{2}$$

2.5. Push-Out Shear Tests on Timber-to-Timber Connections

To evaluate the mechanical performances of timber-to-timber connections using DWFAT dowels, double shear push-out shear tests have been undertaken. In addition to connections assembled through DWFAT dowels (hybrid dowels), complementary connections assembled using DW dowels were tested for comparison purpose in order to evaluate the relative contribution of the aluminum tube. A total of nine double push-out shear tests under monotone loading were conducted according to the standard EN 26891 [40] requirements.

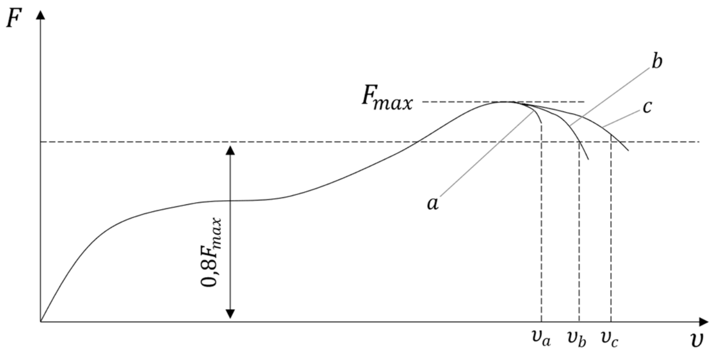


Figure 7. Definition of the ultimate force level for ductility according to the EN 12512 [40].

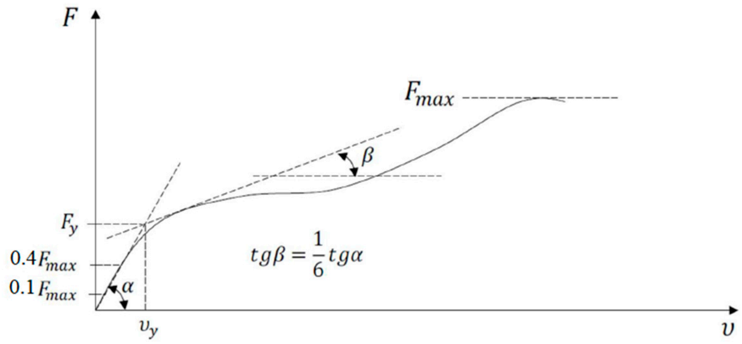


Figure 8. The so-called 1/6 method according to the EN 12512 [40].

The specimens are composed of three identical glulam members (Figure 9a), with a 16 mm hole for those connected with both DW dowels (five specimens), while 21 mm hole diameter was used for those assembled using DWFAT dowels (four specimens).

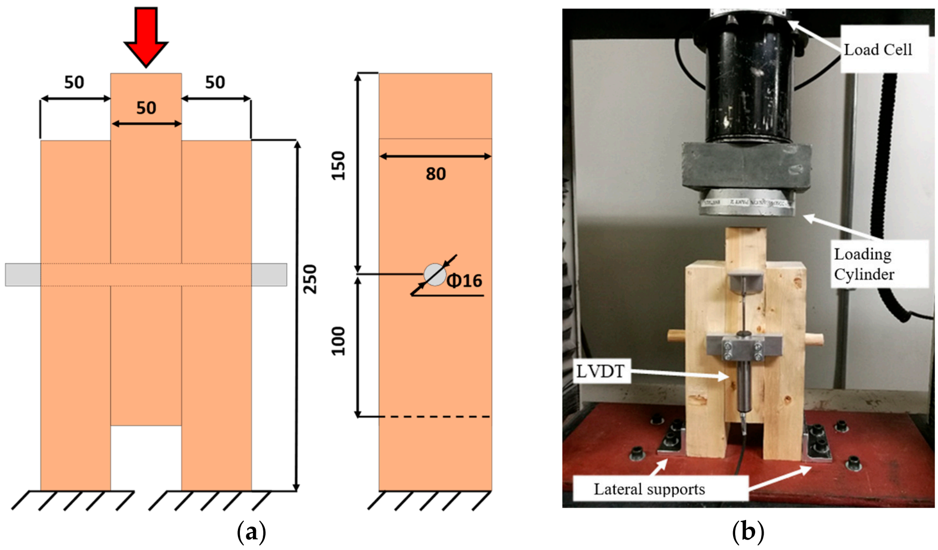


Figure 9. The push-out shear test: (**a**) geometrical description and (**b**) experimental set-up.

The parameters and loading procedure are defined according to the maximum estimated load (F_{est}), determined with a first sacrificial test conducted until failure. As for the slotted-in aluminum plate timber connections, the loading procedure depicted in Figure 6 was adopted.

Figure 10 displays the tested three sets of push-out shear connections. As it can be seen in Figure 9b, an LVDT transducer was mounted to record the relative slip between the central timber member and the two lateral ones. From the recorded load-slip curves, the load-carrying capacity, the stiffness as well as the ductility were evaluated.

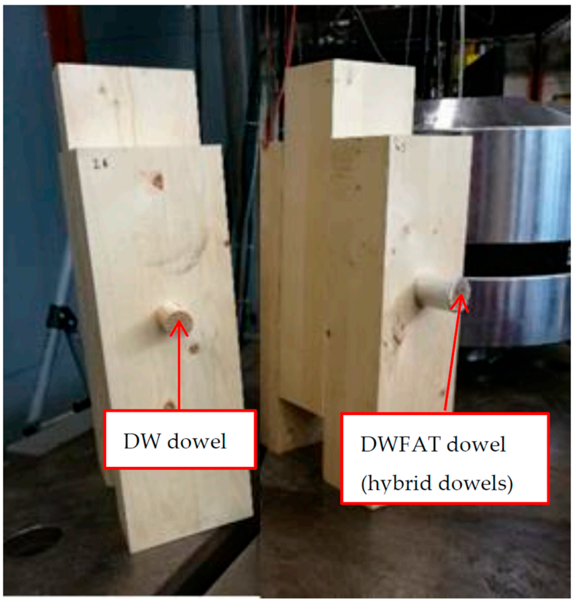


Figure 10. The different sets of tested timber-to-timber connections.

3. Results and Discussion

In this section, results from bending tests on dowels, push-out shear tests on timber-to-timber connections and tensile tests on slotted-in aluminum plate timber connections are presented and analyzed. Additionally, the failure modes of each type of tests are discussed.

3.1. Three-Point Bending Tests

In this section, results from bending tests on DWD and DWFAT dowels are presented. The bending stiffness and maximum bending strength as well as the failure modes are the quantities of interest.

Figure 11 displays the load-mid span deflection curves for both DWD and DWFAT dowels, where it be observed a clear increase in both the stiffness and bending strength characteristics of the DWFAT dowels by comparison to the DW dowels. The global behavior of both type of dowels (DWD and DWFAT dowels) is characterized by three main regions: (1) the linear elastic zone, (2) the post-elastic nonlinear plateau and (3) the damage progression and final failure. However, the DWFAT dowels exhibit a first abrupt drop of the load-deflection curve before the final failure. This first drop of the load occurs at a deflection level of approximately 10 mm, which corresponds to the failure of the densified wood dowels (DWD) inside the aluminum tube. Note that a high variability can be observed for both DW and DWFAGT dowels, in the first drop of the load corresponding to the failure of the DWD, which is mainly due to the well-known high variability of failure strengths of timber. After this abrupt drop of the load, the DWFAT dowel tends to recover its bending strength by exhibiting a plateau-like behavior until the aluminum tube cracked in the tension zone.

Furthermore, Figures 12 and 13 display the experimental failure modes for DW dowel and the DWFAT dowel, respectively. It can be seen from Figure 12 that the main observed failure mode of the DWD combines failure of fibers by longitudinal tension and shearing. For some dowels, this failure mode is followed by crushing in the compression zone.

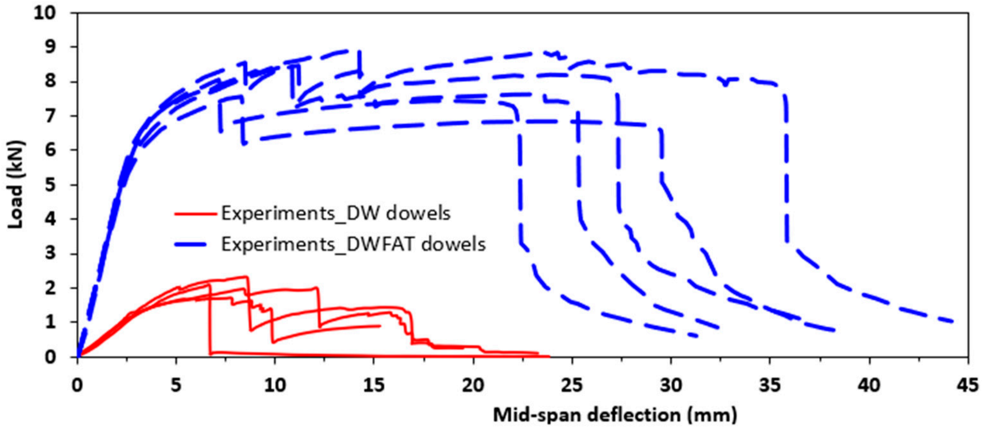


Figure 11. The load-mid span deflection curves.

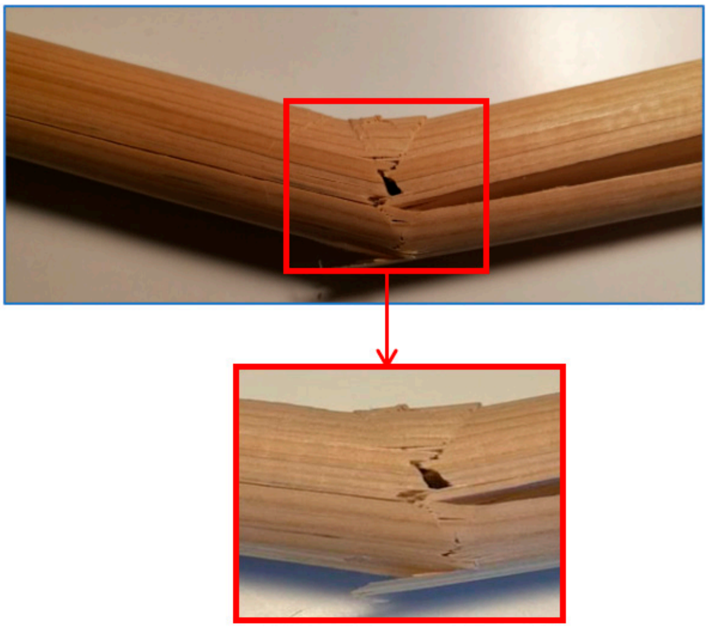


Figure 12. The main failure mode of the densified wood dowels (DWD).

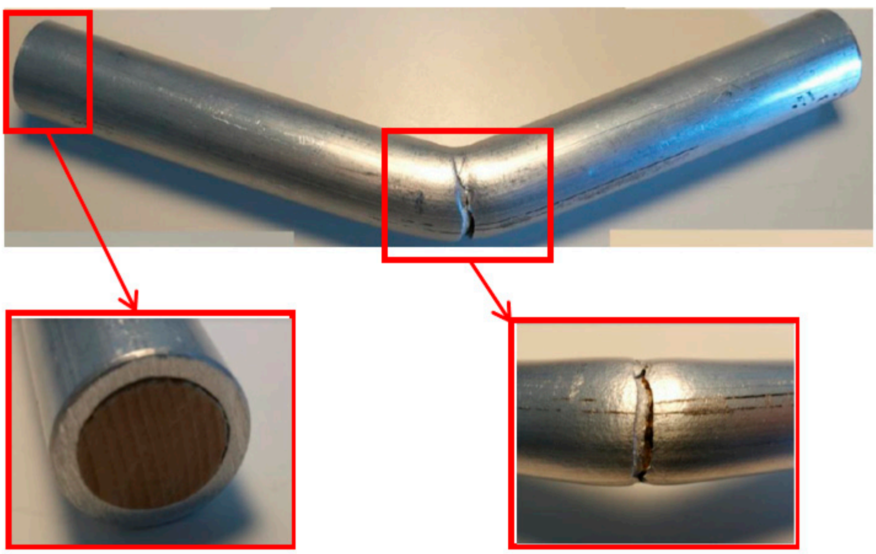


Figure 13. The main failure mode of the densified wood dowel filled aluminum tube (DWFAT) dowel.

The final failure of the DWFAT dowel is occurred by tensile crack of the outer aluminum tube, which is visible in the tensile zone of the specimen (Figure 13). Note that a first failure was occurred in the filler (DWD). From Figure 13, it can also be seen that the filler (DWD) is not pushed outside the outer aluminum tube during the bending test, which demonstrate clearly the efficient load transfer between the filler (DWD) and the inner aluminum tube wall due to the moisture swelling of the DWD.

3.2. Push-Out Shear Tests

Figure 14 depicts the load-slip curves for the push-out double shear tests assembled using DW and DWFAT dowels. As expected, the stiffness and the bending strength characteristics of connections assembled using DWFAT dowels are higher than those obtained from connections assembled using DW dowels. The results including coefficient of variations (C.o.V.) are summarized on Tables 1 and 2. The ultimate load (maximum load up to failure) and stiffness of connections assembled using DW dowels is about 64% and 84%, respectively, lower than that of connections assembled using DWFAT dowels. This can be explained by the comparison of the two behaviors of DW and DWFAT dowels depicted on Figure 11. Of course, the outer diameter of the DWFAT dowels was 21 mm, while the DW dowels were 16 mm diameter. Note that the observed high variability of the ductility (Tables 1 and 2) is mainly due to the high variability of the failure strengths of timber.

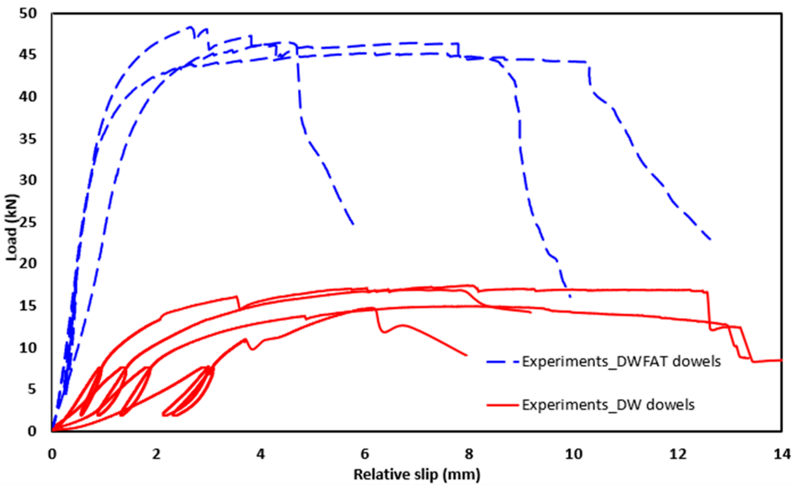


Figure 14. The main failure mode of the densified wood dowel filled aluminum tube (DWFAT) dowel.

Table 1. Main characteristics of the push-out double-shear tests using DW dowels.

	F_{max} (kN)	K_{ser} (kN/mm)	D_u
Test 1 *	15.0	5.4	6.2
Test 2	16.9	5.8	5.3
Test 3	17.4	9.4	10.4
Test 4	14.8	3.3	2.2
Test 5	19.0	2.8	4.7
Mean	16.0	6.0	5.9
C.o.V.(%)	1.4	2.5	3.5

* Preliminary test.

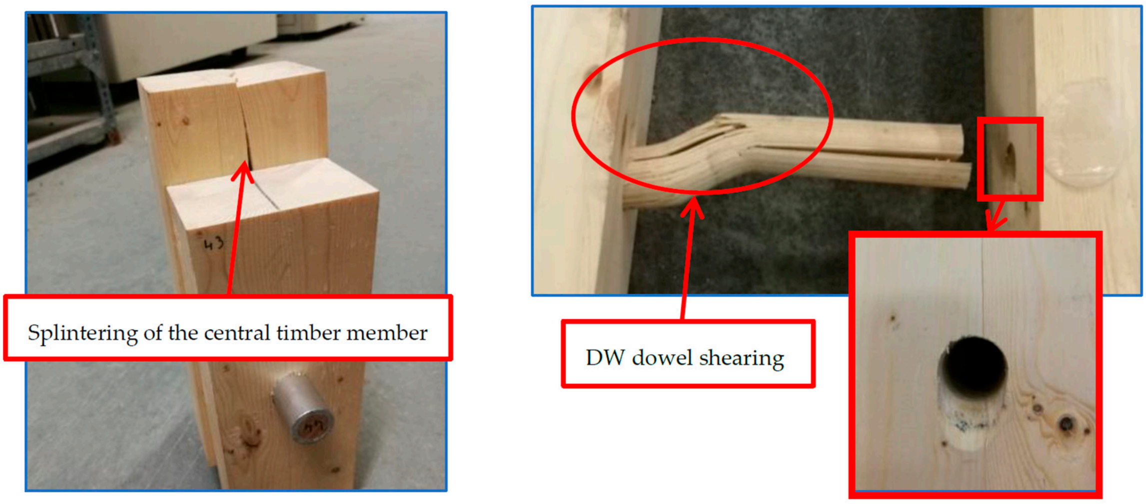
However, the ductility of connections assembled using DW dowels is only about 30% lower than the ductility of connections assembled using DWFAT dowels. This can be attributed probably to the difference between the ratios of assembled timber member thickness to the DWFAT dowels and DW dowels diameter.

Table 2. Main characteristics of the push-out double-shear tests using DWFAT dowels.

	F_{max} (kN)	K_{ser} (kN/mm)	D_u
Test 1 *	46.4	22.5	8.7
Test 2	39.5	28.7	3.1
Test 3	48.3	45.0	6.7
Test 4	45.2	45.1	15.7
Mean	44.4	39.6	8.5
C.o.V. (%)	4.5	9.4	6.5

* Preliminary test.

Furthermore, Figure 15 displays the failure modes of timber-to-timber connections assembled using either DW or DWFAT dowels.



(**a**) (**b**)

Figure 15. The main failure modes of push-out shear timber connections: (**a**) assembled using DWFAT dowels and (**b**) assembled using DW dowels.

It can be observed that the failure of connections assembled using DW dowels are mainly governed by dowel shearing and timber embedment, while the failure of connections assembled using DWFAT dowels occurs mainly by timber embedment and splintering of the timber central member. From the above results, it can be concluded that even if the connections assembled using DW dowels exhibit lower characteristics as compared to those assembled using DWFAT dowels, their main advantage is to prevent brittle failure of the assembled timber members, due to lower stiffness ratio between the timber member and the DW dowel.

3.3. Slotted-In Aluminum Plate Timber Connection Tests

The load-slip curves obtained from the slotted-in aluminum plate timber connections assembled using either steel or DWFAT dowels are displayed on Figure 16.

It can be observed from Figure 16 that both connections exhibit a similar tendency in terms of global behavior. A comparison between connections assembled using steel and DWFAT dowels shows that the steel dowels exhibit higher load-carrying capacity as well as a more ductile behavior. The average ultimate load carrying capacity of connections assembled using DWFAT dowels is about 33% lower than that obtained for connections assembled using steel dowels (Tables 3 and 4). The stiffness and the ductility of connections assembled using steel dowels are about twice higher than that obtained for connections assembled using DWFAT dowels (Tables 3 and 4).

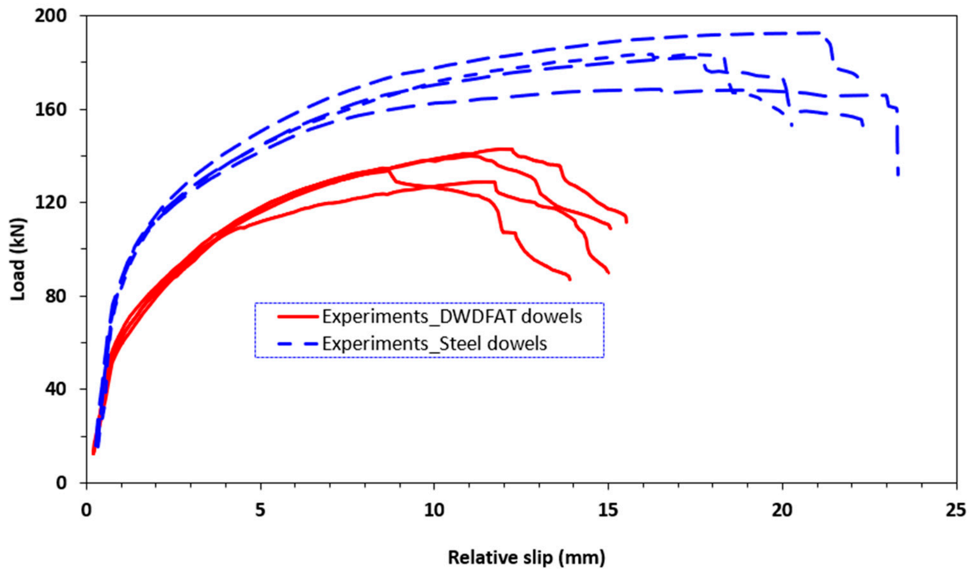


Figure 16. The load-slip curves for slotted-in aluminum plate timber connections assembled using steel or DWFAT dowels.

Table 3. Main characteristics of the slotted-in aluminum plate timber connections using steel dowels.

	F_{max} (kN)	F_y (kN)	K_{ser} (kN/mm)	D_u
Test 1 *	168.9	98.9	/	/
Test 2	183.4	76.9	79.9	18.8
Test 3	193.0	78.0	85.7	23.4
Test 4	182.3	79.2	76.1	21.7
Test 5	168.6	78.0	74.1	22.0
Mean	181.8	78.1	78.9	21.5
C.o.V.(%)	4.8	1.1	5.6	7.8

* Preliminary test.

Table 4. Main characteristics of the slotted-in aluminum plate timber connections using DWFAT dowels.

	F_{max} (kN)	F_y (kN)	K_{ser} (kN/mm)	D_u
Test 1 *	128.0	82.4	/	/
Test 2	133.5	61.6	33.0	7.2
Test 3	139.5	61.0	23.1	6.4
Test 4	128.7	60.7	46.4	11.2
Test 5	142.5	58.4	42.5	11.4
Mean	136.0	60.4	36.3	9.1
C.o.V.(%)	4.0	2.0	25.0	26.0

* Preliminary test.

The failure modes for the connections assembled using both steel and DWFAT dowels are displayed in Figures 17 and 18, respectively. It can be seen from Figure 17 that the failure is, first, occurred by plastic deformation through the combination of the embedment of both aluminum and timber member with the formation of the plastic hinge in the steel dowel, followed by the splintering of the timber member.

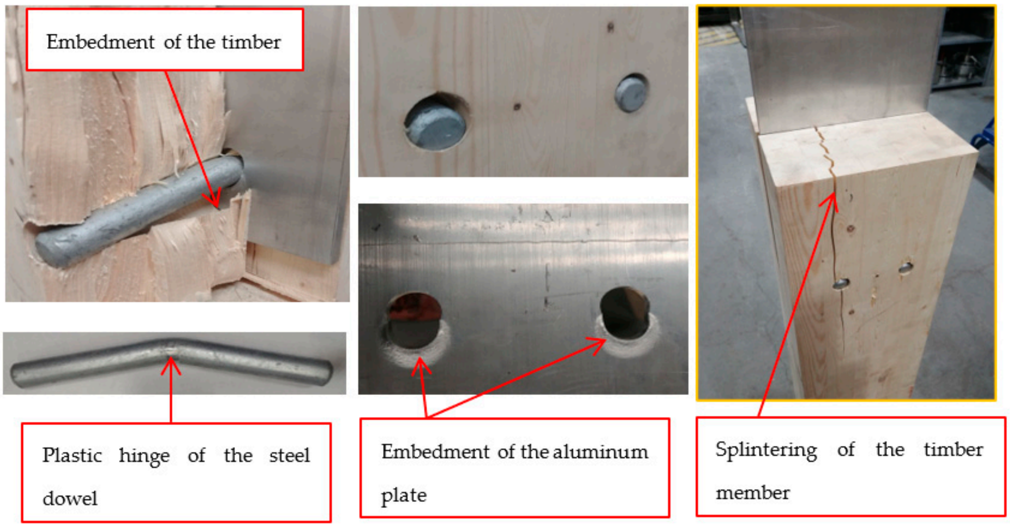


Figure 17. The main failure modes of slotted-in aluminum timber connections assembled using steel dowels.

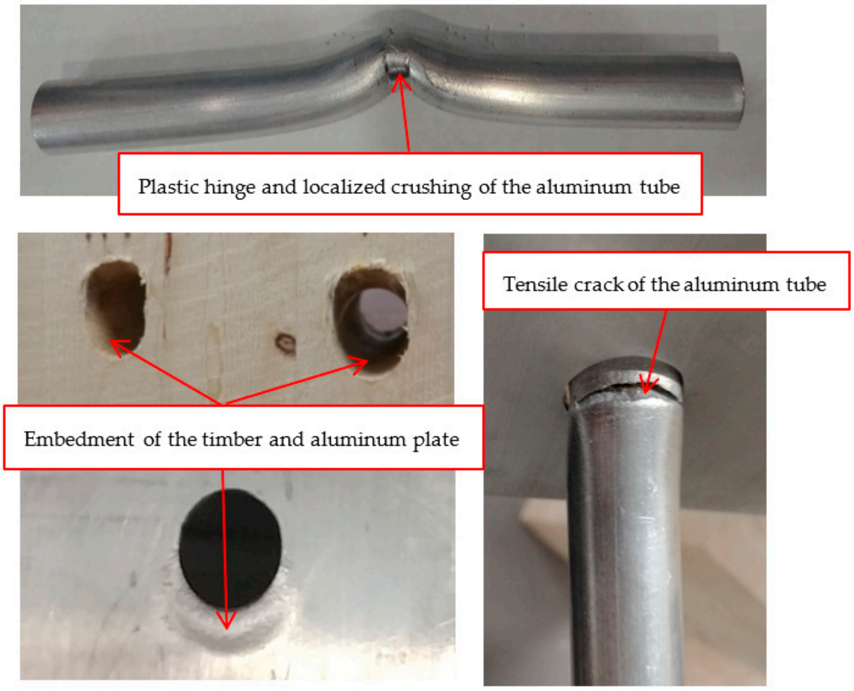


Figure 18. The main failure modes of slotted-in aluminum timber connections assembled using DWFAT dowels.

Similarly, the failure modes of connections assembled using DWFAT dowels are depicted in Figure 18, where it can be seen that the failure occurs by embedment of both aluminum plate and timber hole combined with a plastic hinge formation in the DWFAT dowel, followed by tensile crack of the aluminum tube, which corresponds to the final failure. It is worth noting that a localized deformation (crushing) is visible in the middle of the DWFAT dowel, which corresponds to the location of the loading area of the aluminum plate, leading to high shear stress in the aluminum. Contrarily to the connections assembled using steel dowels, those assembled using DWFAT dowels do not exhibit brittle failure of the timber member by splintering.

4. Conclusions

The paper reports an experimental investigation on the structural performance of a novel densified wood-filled aluminum tube (DWFAT) dowel for timer connections. To this end, the following tests have been undertaken:

(1) Three-point bending on both densified wood (DW) dowels and densified wood-filled aluminum tube (DWFAT) dowels;
(2) Push-out double shear timber-to-timber connections assembled either using DW dowels or DWFAT dowels;
(3) Slotted-in aluminum plate timber connections assembled using either steel dowels or DWFAT dowels;

The performance of the novel DWFAT dowels has been compared to both DW and steel dowels, including analysis of damage, deformation mechanisms as well as failure modes.

The results show clearly that the developed DWFAT dowel is promising and can be a potential substitute for conventional steel dowels. As an interesting perspective of this research work, a predictive finite element model is under development to cost-effectively explore the geometrical and materials optimization of the filler (DW) and the aluminum tube to improve the stiffness, bending and ductility of timber connections assembled through the novel densified wood-filled aluminum tube (DWFAT) dowel. The ultimate goal is to obtain a lightweight hybrid dowel with equivalent or even better mechanical characteristics as compared to the conventional steel dowel.

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