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# Preliminary Tests of a Hybrid Cable Splice (Synthetic–Metal) to Innovate Timber Harvesting in the Mediterranean Forestry Sector

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**Abstract:** Forest operations in the Mediterranean basin are still largely based on lowly mechanized systems. In this context, hauling is generally performed with equipment deploying steel cables, such as winches on farm tractors or skidders. In the last decades, several efforts focused on the substitution of steel cables with synthetic rope to improve safety, comfort and productivity. Despite the expected benefits, these efforts were generally frustrated due to the higher cost and lower duration of synthetic cables. These are relevant constraints, particularly for Mediterranean forest companies, which feature a relatively low financial capacity. As a possible solution, the present study introduces a hybrid splice of steel and synthetic cables, merging the benefits of the two materials. For that purpose, several possible splicing solutions were tested. The most efficient splice proved capable of withstanding up to 7.6 t of tension in the laboratory. In the forest, it allowed the extraction of about 450 t with a skidder before breaking. On a farm tractor, it extracted over 700 t without failure. Preliminary tests and the positive feedback of the operators proved the potential of this solution. Further research is ongoing to create a stronger splice and reduce its diameter to allow its deployment in any type of winch.

**Keywords:** forest operations; steel cable; synthetic rope; hybrid splice; timber hauling; winching



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## 1. Introduction

In recent years, the forestry sector has gained importance due to its significant role in climate change mitigation and adaptation [1]. Forests play a major role in the bioeconomy transition as the main source of renewable raw materials [2]. Additionally, they contribute to non-renewable fuel replacement with a widespread provision of solid biofuels, a function particularly relevant in a context of fossil fuel price uncertainty [3,4]. The use of timber and bioproducts also promotes an active forest management, reducing the biomass accumulated in forests and the related wildfire risk [5], particularly relevant in Mediterranean areas.

In this context, forests should be managed sustainably to meet the demand from the society of forestry products, timber and non-timber products and at the same time enhance the ecosystem services already provided [6–8]. Mediterranean forests generally have lower timber yields compared to Alpine, Atlantic or Central European forests [9], with a negative trend due to climate changes [10]. Associated with a high heterogeneity of species and a constrained timber market, this returns a difficult economic scenario for forest operations [11]. Therefore, local contractors have limited financial capacity to invest in modern harvesting equipment and the training of forest crews. Due to this, the Mediterranean forestry sector features a relatively large record of fatalities [12] and an increasing difficulty to attract new workers to the sector [13].

Mechanization can partially tackle the lack of forest operators and help to reduce the number and severity of accidents [12,14]. Cut-to-length systems based on a harvester and a forwarder are regarded as the higher level of forest mechanization, providing several benefits [15,16]. Yet, the application of this system is uneven throughout Europe due to several reasons [17] ranging from technical applicability (e.g., due to terrain and slope limitations) to the minimal size of forest plots or the low yield of timber [18,19]. In most of the Mediterranean basin, the dominant work system is based on chainsaw felling and extraction by a winch (on a farm tractor or a skidder) [17]. This can be defined as a low mechanization level but is locally appreciated for the low investment required, its high flexibility [20,21] and adaptability to the forest characteristics [22] and the management systems applied [23].

All winching equipment is based on steel cables as pulling tools. The wire cable has historically been an important actor in loggings, mainly for its versatility, durability and strength. However, it also entails a high weight, stiffness and bending failure characteristics, which may pose a challenge, particularly in manual operations [24]. In fact, these characteristics require high physical efforts to the operators when carrying out outhauling tasks [25,26]. Furthermore, there is a high risk of hand injuries for the forest operators if the wire cable breaks [27], and in case of complete cable breakage, even of deadly accidents due to load release or the whiplash effect [28,29].

Ultra-high-molecular-weight polyethylene (UHMPE) cables [30,31] were introduced as an alternative to wire cables in timber logging [27,29,32]. Compared to steel cables, synthetic cables provide several benefits:

- Similar resistance as steel cables, depending on the diameter and composition (EIPS or Swaged), and a much lower weight, about eight or nine times less [25].
- Thanks to the lower weight, they reduce the physical effort and strain for forest operators during timber hauling tasks [33,34].
- Safer work conditions due to the loss of strength of the whiplash effect compared to wire cables [27,29].
- The decreased worker's fatigue leads to higher productivity, particularly in outhauling tasks [25], and to a decrease in the damage to the remaining trees [34].

Despite the operational benefits provided by synthetic cables, their adoption by forest companies in the Mediterranean basin is limited. This is due to the elevated wear rate [35] and the higher cost of the synthetic cables [32] compared to wire cables. These features lead to higher operational costs, which, for most forest operators, are not compensated by the safety and strain reduction benefits [36].

The opportunity and modality to introduce the use of the synthetic cable in forest operations were discussed with several forest operators who recently tested it in Catalonia (Northern Spain). While attracted by the benefits of this technology, most forest operators were sceptic regarding its economic viability in the Mediterranean forests, often characterized by a stony and steep terrain. According to their experience, these conditions would further reduce the useful life of the cable. On the other hand, the same operators observed that most of the wear and breaks occur in the last meters of the cable used to run the chockers or to directly hook roundwood for winching and skidding. This is consistent with the wear dynamic of steel cables, whose terminal sections are typically considered expendable [37]. Therefore, it was suggested that by terminating the synthetic rope with few meters of metal cable, it could be possible to increase its overall durability while maintaining the main benefits of the lighter material. The same forestry workers experimented partial solutions with skidders fixing a choker between a metal cable and a synthetic cable with promising results. But the solution was not operative due to the impossibility to completely roll up the cable on the drum.

The idea of this type of connection is not new, having been explored at the beginning of this century by several researchers [38,39]. According to these pioneer studies, the simplest solution to integrate metal parts (cable or chains) with a synthetic rope is by means of connections and terminations. Yet, this solution can be hindered by the lower coefficient of friction of the synthetic rope compared to that of the steel cable, leading to a lower yield (about 60%) of the most common terminals [38]. Additionally, the use of metal terminals to connect the two cables would make it difficult or impossible to wind the full length of the cable into the drum due to the increased diameter of the metal element and the possible damages that it would cause to the synthetic cable stored in the drum.

For these reasons, an actual splice designed to directly merge steel and synthetic cables could be a viable solution to innovate the timber hauling operations. The idea of a synthetic–metal hybrid splice is new to forest operations, but it has already some applications in the nautical sector with small-diameter cables [40]. Yet, given the different conditions in these two sectors, the concept needs to be adapted to the more challenging conditions of timber hauling.

Considering the above, the present study aimed at the following goals:

- Develop and test a new solution to merge synthetic and wire cables thus creating a "hybrid splice" featuring the benefits of the steel cable in the last few meters (resistance to abrasion) and those of synthetic cable in the remaining portion (lightweight);
- Test in the laboratory the strength of the hybrid splice and, in case of several viable solutions, identify the most suitable for forest hauling;
- Deploy the chosen hybrid cable in commercial forest operations to prove the reliability of the concept and guide its further developments.

## 2. Materials and Methods

### *2.1. Hybrid Splice Fabrication*

The splicing technique was tested and developed using the most common cables deployed in Mediterranean forest operations, namely, 10, 12 and 14 mm diameter steel cables (compacted 6 × 36 WS-IWRC, right ordinary lay, 2060 N/mm$^2$) and 12, 14 and 16 mm diameter synthetic ropes made with ultra-high-molecular-weight polyethylene, (UHMWPE), with a 12/24 structure (Table 1).

**Table 1.** Main characteristics of the cables used for the splicing tests.

| Cable Material | Diameter (mm) | Failure Force (kN) | Linear Density (g/m) |
|---|---|---|---|
| Synthetic | 12 | 132.4 | 79.2 |
| Synthetic | 14 | 171.6 | 107.8 |
| Synthetic | 16 | 223.6 | 140.8 |
| Steel | 10 | 104.1 | 570 |
| Steel | 12 | 144.2 | 770 |
| Steel | 14 | 188.6 | 1040 |

The goal was to create a hybrid cable mainly composed of lightweight synthetic rope and featuring a final steel portion of variable length (Figure 1). The latter was defined according to the hauling/hooking system adopted. In fact, when the timber is hooked directly with the cable, about 10–15 m of steel terminal is needed due to the extended friction area on the hooked logs; in contrast, when chocker slides are used, the steel terminal can be reduced to 2–5 m because wear in the synthetic cable will only be caused by friction between the loaded chockers and the cable final meters.

The synthetic–metal hybrid splice was fabricated in three steps:

(1) A conic steel core was made by cutting the six strands of the cable at an increasing length (multiples of 10 cm) and following a rotatory order (Figure 2). As a result, moving clockwise, the first strand was cut at 10 cm, and the last one at 60 cm, creating a conic shape with a total length of 60 cm (Figure 3). This was inserted for 90 cm into the synthetic rope and constituted its conic steel core. This last operation can be facilitated by the use of a special needle (Figure 3a).

(2) Braiding of the synthetic and the wire cables was carried out. The first thirty centimeters of synthetic rope was unbraided up to the base of the conic steel core. This area was fixed with a loop of tape to avoid the accidental unbraiding of the synthetic rope (Figure 3b). The loose synthetic strands were joined in three bunches, each with the same number of strands, and braided, intercalated, under two consecutives steel strands (Figure 3c) until each bunch of synthetic strands was completely used (Figure 3d). This was the most complex and time-consuming step of the hybrid splicing. At the end of the process, the hybrid splice featured the conical steel core on one side, the steel cable inside the synthetic rope in the center and the braided part on the other side.

(3) A protective synthetic cover along the entire length of the splice was installed, braiding the cover on one splice side, within the strands of the steel cable and on the other side, with the strands of the synthetic rope. In order to properly adhere to the splice, the highest tension possible was applied on the cover.

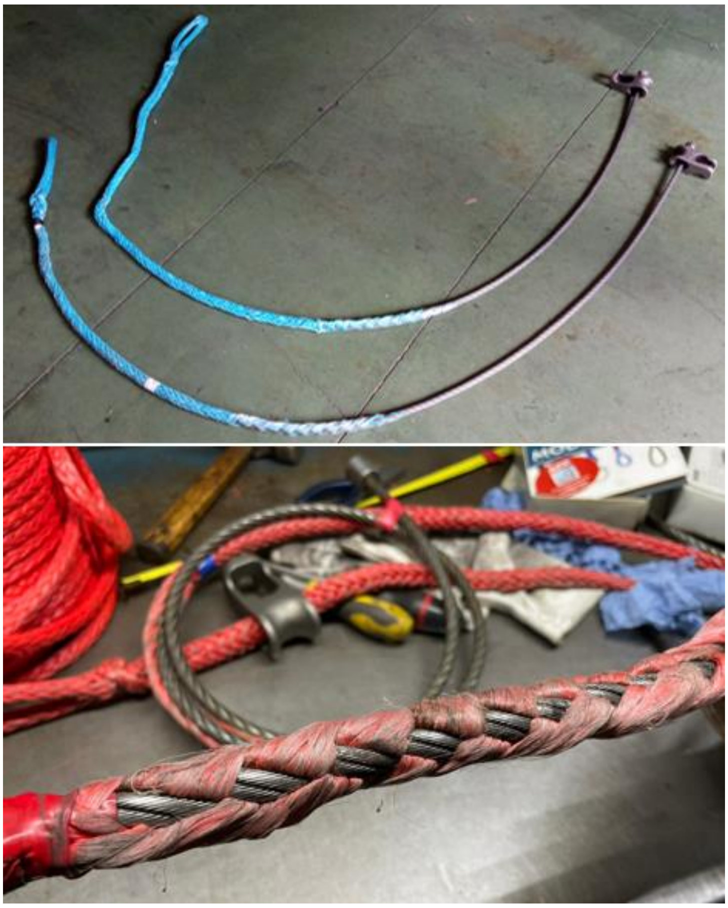

**Figure 1.** Synthetic–steel hybrid splice.

The product resulting from this three-step procedure was defined as the standard hybrid splice (SHS). Two alternative splicing methods were tested in order to compare the possible benefits of different layouts of the splice:

(a) Simple steel core (SSC): in this splice, the conic steel core was replaced by the simple core of the original steel cable. All strands were cut at 55 cm, leaving 5 cm between the braided part and the conic steel shape to ensure that the braid would not slip out of place.

(b) Decreased-length conic core (DLCC): the conic steel core was made with the same technique used for the standard core, but the strands were cut every 5 cm instead than every 10 cm. Therefore, the resulting length of the conic steel core was 30 cm instead of 60 cm as for the standard core.

**Figure 2.** The final layout of the conic steel core is visible in the bottom and on the right side. Above it, strand sections of different lengths are aligned.


**Figure 3.** Hybrid splice fabrication process steps: (**a**) conic steel core introduced with support of purpose-made needle (**b**) unbraiding up to the conic steel core is supported by a loop of tape (red) to avoid accidental unbraiding; (**c**) loose synthetic strands are joined in three bunches and braided intercalated under two consecutive steel strands and; (**d**) final layout of the braided hybrid splice.

All the hybrid splice samples in this study were fabricated by hand; therefore, there could always be slight variations between the samples, even if they were produced following the same procedure.

*2.2. Laboratory Tests*

Resistance tests to quantify the breaking strength were carried out using a 750 kN horizontal tensile test bench. The bench instrument featured 232 bar of maximum hydraulic pressure, between 1360 mm/min and 133 mm/min of traction velocity and 600 mm of inner length. The cables used for the breaking test were 12 and 14 mm synthetic cables spliced together with 10 and 12 mm steel cables. The test had the double purpose to determine the breaking strength of the different splices and to identify the future improvements that could be proposed for new versions of the splice.

Due to the cumbersome manual preparation, in this preliminary stage, just two samples per each type of splice were tested. The samples were placed with the splice in the center of a dynamometer to facilitate the visual control of its breaking dynamic and identify weak points to improve. Two eye splices were placed at the end of the cable in order to fix the sample to the instrument. For this purpose, no synthetic cover was applied over the splice length, providing a clear vision of the sample's behavior and enhancing the identification of the breakage point.

*2.3. Field Study*

With the aim to represent the entire hauling-by-winching sector, different hauling modalities and machineries were chosen, identifying three main groups:

- Group 1: three crews with a double-drum skidder (pulling force of 140–180 kN for each one), hooking the timber directly with the cable.
- Group 2: seven crews using a farm tractor equipped with a 60–100 kN winch, using chains as the hooking system and, therefore, with choker slides.
- Group 3: two crews using a farm tractor equipped with a 60 kN winch, hooking the timber directly with the cable.

The hybrid splice cable, featuring the last meters of steel cable, was compared in the field with a purely synthetic cable. No synthetic cover was applied on the cables deployed in the tests, while all hybrid splices were delivered with a synthetic cover along the splice length to provide protection. This was essential, because handling the synthetic filaments while fabricating the splice weakened them and made them more sensitive to wear. For the comparison, the forest companies were equipped with the following material:

- Group 1: all skidder crews received a new 16 mm diameter synthetic cable featuring a hybrid splice with 10–15 m of 14 mm steel cable. In case of breakage, the crew would continue working with the remaining 16 mm synthetic cable without the splice (no steel component). The second drum of the skidders was left with the common steel cable and was not involved in the study.
- Group 2: four crews received a new synthetic cable of 14 mm diameter featuring a hybrid splice with 5 m of 12 mm steel cable, and the remaining three crews deployed, since the beginning, a synthetic cable without the splice.
- Group 3: one crew used a hybrid splice, while the other worked with the purely synthetic cable.

All the involved companies used the tree-length work system, with occasional adoption of the whole-tree system. The instructions were to use the hybrid cable and the purely synthetic cable in an every-day-business fashion. This means aiming at productivity while avoiding excessive wear of the cable. The operators where motivated to care for the cable, since at the end of the tests, the cable would remain as their property. In case of breakage of the hybrid cable, the crews were requested to continue working with the remaining purely synthetic cable, in order to provide further data for comparison of the two systems.

The evaluation of the performance of the synthetic rope and the synthetic–metal splice was conducted by means of data-recording sheets, autonomously filled by the crews at the end of each working day. These reported the following data:

- Tons extracted by the drum; the data were reported on a daily basis as a cumulative figure (in the case of machines with a double drum, the data were requested for both drums);

- Number of hauling cycles per day (rope pulls);
- Average winching distance (general in the specific work site or on a daily basis);
- Main winching direction (uphill, downhill or both directions);
- Cable damage (meters lost and number of breaks);
- Splice damage (if any);
- Forest stand description (species, slope, type of terrain, silvicultural treatment);
- Distributed presence of stones that might damage the cables (stoniness);
- Further observations.

## 3. Results

### 3.1. Laboratory Results

As a preliminary step before the actual laboratory test, the authors trained extensively in the production of the hybrid splices, with the aim to reach the necessary homogeneity in the handmade production of the prototypes. Once the technique was mastered, the production of the samples began. Overall, seven samples of hybrid splice were tested with the tensile test bench. Of these, just one featured synthetic and steel cables with diameters of 12 and 10 mm, respectively. Following the suggestions of the forest contractors, whose opinion was constantly requested, the remaining six samples were produced using synthetic and steel cables of 14 and 12 mm, respectively.

Table 2 shows the results of the laboratory tests for the three types of hybrid splices.

**Table 2.** Results of the dynamometric test of the hybrid splices (two per type).

| Rope Diameter (mm) | Steel Diameter (mm) | Splice Type | Resistance Strength (kN) | Elongation (mm) | Test Duration (s) | Failure Area | Valid |
|---|---|---|---|---|---|---|---|
| 12 | 10 | SHS | 76.6 | 170 | 85.2 | End of conic steel core | Yes |
| 14 | 12 | SHS | 70.1 | 137 | 66.7 | End of conic steel core | Yes |
| 14 | 12 | SHS | 33 | 112.1 | 54 | Eye splice | No |
| 14 | 12 | SSC | 39 | 206.6 | 97.2 | Braided part | Yes |
| 14 | 12 | SSC | 29.5 | 143 | 69 | Braided part | Yes |
| 14 | 12 | DLCC | 54.6 | 100.2 | 88.1 | End of conic steel core | Yes |
| 14 | 12 | DLCC | 42.7 | 140.1 | 71.4 | End of conic steel core | Yes |

A single sample failed at the level of the eye splice used to fix it at the dynamometer rather than on the hybrid splice; therefore it was considered invalid. In the valid tests featuring the SHS or the DLCC, the splice broke at the end of the conic steel core, where it was enclosed into the synthetic rope. The SSC, featuring no conic steel core, showed the lowest resistance, and breakage occurred in the braided section of the splice. The samples with the longest conic steel core (SHS) resisted higher forces, proving to be the most suitable for the following test during real timber-hauling operations. Curiously, the best-performing sample, which resisted a force up to 76.6 kN, was the only one fabricated with cables of smaller diameters (12 and 10 mm for the synthetic cable and the steel cable, respectively).

### 3.2. Forest Work Results

Following the results of the laboratory tests, eight hybrid cables featuring the SHS splice were manufactured and distributed to the forest companies for installation on harvesting machinery, as described in Section 2.3.

Within the first days following the installation of the hybrid cables, a first issue was highlighted: at the present stage of development, the hybrid splice entails a localized increase in diameter, up to 6–8 mm when using a 14 mm steel cable. When installing the hybrid cable on forest machinery, this enlargement made the use of the prototype cable on smaller winches (<100 kN) difficult, due to the size of the exit pulley. This was often jammed at the passage of the larger section of the splice, which in turn suffered visible damage on the external strands. Due to this issue, several crews removed the splice to continue the test using the purely synthetic cable. The hybrid cable could be effectively tested by one crew in group 2, deploying a winch large enough (100 kN) to use the spliced cable, and a crew in group 3. The latter, after identifying the issue autonomously, decided to slightly modify the exit pulley of the winch in order to facilitate the passage of the splice and be able to use it in commercial operations.

The forest companies were requested to provide a minimum of 20 daily data sheets filled for a period of about 6 months. The final number of data sheets provided by each company varied largely, depending on the work schedule, the operative capacity, accidents and cable breakages that occurred during the test period. The results ranged from a minimum of 22 to a maximum of 113 workdays recorded. The collected documents were thoroughly evaluated to assess their validity for the purposes of the study. This analysis highlighted that filling the sheets represented a challenge for some forest crews, resulting in hurried and occasionally inaccurate entries. Therefore, inaccurate records were excluded from the study, leaving a total of nine valid tests in real working conditions with and without the synthetic–metal hybrid splice installed on different types of forest machinery.

Table 3 displays the main factors considered in the study, as well as the results for the different machine/cable combinations. It includes the average load (in tons) hauled in each case, the wear of the purely synthetic rope expressed as the number of breaks per 1.000 tons of wood extracted, the meters of cable lost per 1000 tons of wood extracted and the resistance of the cables featuring the hybrid splice, expressed as cumulative tons extracted before breakage.

The values reported on each row refer to a single machine/crew, with the exception of Group 2–no splice (operating just the synthetic rope), for which the data reported are the average of the results reported by four crews.

Among the machines deploying the hybrid cable, the skidder was the only one to cause a breakage within the recorded period, after the extraction of 462 cumulative tons of timber. The two farm tractors equipped with the hybrid splice did not report any failure and, even if no additional data have been provided by the crews, both cables are still operative. During the reporting period, the company with the larger tractor (Group 2) hauled over 714 cumulative tons of roundwood, while the company with the modified pulley (Group 3) extracted 676 cumulative tons.

The “control” skidder deploying the purely synthetic cable reported the loss of over 25 m of cable per each 1000 tons of timber extracted. This figure was lowered to 14.3 as the average of the amounts indicated by the four control machines reporting in Group 2, operating with chockers, with individual values ranging from a minimum of 4.7 m to a maximum of 22.8 m lost per each 1000 tons hauled. Finally, the machine attaching the timber directly with the synthetic cable in Group 3 reported the loss of 31.9 m of cable per 1000 tons extracted.

**Table 3.** Data summary for the hybrid spice and the synthetic cable deployed on different groups of hauling systems and machines.

| Group | Splice and Steel Length (m) | Machine | Hooking System | Workdays | Avg. tons per Cycle | Avg. Loads per Day | Avg. Winching Distance (m) | Main Hauling Direction | Stoniness | Wear (n. Breaks/1000 t) [1] | Wear (m Cable Lost/1000 t) | Resistance (tons) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Yes (15 m) | Skidder (140 kN winch) | Directly with the cable | 47 | 0.47 | 20.7 | 44.1 | Uphill | yes | - | - | 462 |
| 1 | No (purely synthetic) | Skidder (180 kN winch) | Directly with the cable | 28 | 0.95 | 23.6 | 35.5 | Both directions | no | 6.4 | 25.5 | - |
| 2 | Yes (5 m) | Tractor (100 kN winch) | Choker slides | 22 | 2.06 | 13.3 | 7.6 | Both directions | yes | - | - | >714.5 |
| 2 | No (purely synthetic) | Tractor (60–80 kN winch) | Choker slides | 71.8 [1] | 0.72 [1] | 27.1 [1] | 26.8 [1] | Both directions | no | 11.25 [1] | 14.3 [1] | - |
| 3 | Yes (10 m) | Tractor (60–80 kN winch, pulley adapted) | Directly with the cable | 74 | 0.21 | 40.8 | 29.4 | Downhill | no | - | - | >676 |
| 3 | No (purely synthetic) | Tractor (60 kN winch) | Directly with the cable | 64 | 0.67 | 21.8 | 47.4 | Uphill | no | 8.5 | 31.9 | - |

[1] the data reported are the average of those provided by four crews operating different tractors.

# 4. Discussion

## 4.1. Hybrid Splice Fabrication

The comparison among the alternative splicing methods tested in the laboratory showed that the SHS provided the higher tensile resistance, with breaking points above 70 kN. Due to the invalid test of one of the SHS splices with 14/12 mm synthetic/steel cables, the recorded data were obtained for two SHS splices featuring different diameters of the composing cables, respectively, 12/10 mm and 14/12 mm (Table 2). When compared to the minimum resistance of the steel cable used for their construction, these two splices showed very different performances, failing at 73% (12/10 mm splice) and 48% (14/12 mm splice) of the reference value. This performance is in line with the average resistance achieved by Harttner, who tested 14 end connections with synthetic cables [41]. In this comprehensive analysis, about half of the end connections failed at less than 50% of the minimum resistance of the cable deployed. Among the best-performing solutions, the buried-eye splice (very common in forest operations) achieved over 94% of resistance [41]. These could provide a possible alternative to the hybrid splice, particularly when short metal sections are sufficient for the task. For this specific use, metal chains were successfully tested, being easily linked with the buried-eye splice [39]. Nevertheless, Kirth et al. [29] claimed that synthetic cables are highly sensitive to compression, which limits the reliability of their use with end connections that concentrate the strain on bended sections of the cable, as would be the case of an eye splice connected through the link of a metal chain.

Considering the splicing methods featuring a minor length of the conic steel core (DLCC) or splices using as a core the sole core of the wire cable (SSC), the results are not satisfactory. The achieved performance was well below 50% of that of the original cables composing the splice, making these solutions unviable for the development of a commercial hybrid splice. On the contrary, the results of the SHS can be regarded as satisfactory at this early stage of development, given the positive trend observed by the authors when comparing the earlier splices with the most recent samples of the same type. This trend also suggests that even when the splicing technique has reached a mature stage, the manual skills of the operator performing it will still play an important role in the performance of each individual hybrid splice. The time required to execute the splice is still relevant (over 2 h), yet also in this regard, the improvements brought by the growing experience was relevant. This is encouraging, as the ultimate goal is to establish a splicing system that may be produced directly in the forest when a damaged splice must be substituted.

During the breakage testing phase, it was noticed that the failure point was always in the area of the conic steel core (for the SHS and DLCC splices). Upon closer examination of this information, it was observed that the hybrid splice break occurred due to an internal damage caused by the steel of the core cutting through the synthetic rope. When the splice was tensioned, the synthetic rope was compressed and flattened, increasing its contact with the steel cable. At the same time, the tension applied opened outwards the strands of the conic steel core section of the splice. This, together with the increased contact between steel and synthetic cables caused an internal cut in the hybrid splice. This issue could be solved by applying a cover to the conic steel core, avoiding the opening of its strands when tension increases and reducing the friction between the metal and the synthetic material. Additionally, the comparison between the SHS and DLCC performances suggested that further increasing the length of the conic steel core over 60 cm may improve the overall performance of the splice. This idea was further confirmed by the fact that the SSC samples, featuring a single steel strand as the core of the splice, broke directly on the braided section, which occurred even under relatively low tensions of about 30–40 kN.

## 4.2. Performance in Timber Extraction

The samples of metal–synthetic hybrid cables tested in commercial hauling operations provided valuable feedback for the evaluation and improvement of the hybrid splice.

Firstly, the tests highlighted hindrance due to the increased diameter in the spliced area. This proved to be a constraint for using the hybrid cable in most winches applied to farm tractors, which are among the main targets of this solution. This issue was overcome just by modifying the entrance pulley of the winch or by using larger winches (>100 kN). This problem should be solved by identifying a splicing technique that does not lead to an excessive increase in the diameter of the spliced section. As an alternative, cables with a lower diameter can be used for the splice, but in this case, the work capacity of the machine would be downsized by the lower tensile strength of the cables used.

Regarding the performance of the hybrid cable, it resulted less durable on skidders than on farm tractors. This was expected due to the higher pulling force of the skidder's winch and the larger loads typically hooked per work cycle. The splice failed after the extraction of 462 tons of timber (cumulative). The control system, represented by a purely synthetic rope installed on a second skidder, reported 6.4 breaks every 1.000 t, which, compared to the 462 t of the previous system, corresponds to about 3 breaks during the tests and to about 12 m of cable actually lost. A direct comparison of these results with other studies is difficult, as previous research focused mainly on the definition of a method to plan cable replacement based on visual abrasion analysis [37,42]. Kirth et al. performed abrasion tests on three synthetic cables protected by a cover. The tests were run under controlled conditions on flat terrain and reported no breakage and minimal tensile strength losses, with the exception of an HMPE cable with a PET cover, whose tensile strength almost halved [29]. The relative higher level of failures that occurred during harvesting in our tests could be partly explained by the fact that the synthetic cable was deployed without a cover, which bore all the abrasion stress in the tests of Kirth et al. [29]. Clearly, being based on a single test, these results cannot be generalized. Yet, it seems that the prototype cable did not provide a clear advantage over the purely synthetic cable utilized on skidders.

When considering the performance of the system involving a farm tractor, the cable allowed the extraction of over 714 t when using chockers and of 676 t when using the cable directly to hook the timber. In both cases, the hybrid cables continued working, but no further data are available, as the crews were relocated and discontinued filling the data sheets. The interruption of the data collection did not allow us to examine if the hooking system has an influence over the wear of the hybrid splice. In the last reports by Group 3, the cable used appeared to have a very worn cover over the splice. This is always needed to extend the useful life of synthetic cables, but in the case of the hybrid splice, the manipulation of the strands may further decrease the resistance of the rope to abrasion, making the use of a protective cover even more necessary [29]. The reference synthetic rope compared with the hybrid solution provided some hints of the dynamics of wear of this material when used without the steel cable terminal. Group 2, deploying chockers, reported that the cable suffered frequent breakages (over 11 per 1000 t extracted), but with the loss of short sections, on average (14.3 m per 1000 t corresponding to less than 1.5 m per breakage). Differently, the use of the synthetic cable directly for hooking and hauling the logs seemed to lead to fewer breaks (8.5 per 1000 t), though each involved a longer section of cable (almost 32 m per 1000 t; thus, over 3.5 m lost each time). This led to a higher value loss, which could be avoided with the adoption of a hybrid cable. Again, the results cannot be generalized due to the low number of observations but are consistent with the impressions reported by the operators involved in the tests.

## 5. Conclusions

This study developed a new hybrid splice designed to merge synthetic and steel cables. According to the laboratory tests, the resulting hybrid cable has an average resistance corresponding to 60% of that of the original cable with lower tensile strength (the steel cable).

The results of the field tests showed that this solution is not suitable as such for deployment on skidders. This is probably due to the higher loads involved in this case, causing a high strain on the splice. On the contrary, the tests with farm tractors as well as the feedback of the crews deploying it suggest that the hybrid splice has the potential to improve the work conditions in winch-based timber hauling while avoiding financial losses due to frequent synthetic cable replacement.

This research also highlighted the most relevant future developments required to obtain a mature and reliable solution. In order to facilitate its uptake from the productive sector, the hybrid splice must feature a lower increase in diameter and a higher tensile resistance, ideally no less than 90% of that of the original cables. The establishment of a fast splicing technique, feasible also directly in the forest, would be a further requirement to facilitate its adoption by forest companies.

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