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Development of Aluminium Tower for 420 kV AC line to reduce environmental impact and safety risks under construction

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SUMMARY

Statnett, the Norwegian TSO, constructs and maintains the high-voltage transmission grid, from 132 kV to 420 kV. Majority of these power lines are at 300 or 420 kV level. These are often constructed in mountainous terrain exposed to high wind and ice loads. The lack of accessibility to most locations requires equipment, materials and personnel to be flown to tower site during construction and maintenance. Erection of the towers requires use of helicopters to transport the tower sections to the erection site. The helicopter serves as a crane, while workers receive and join subsequent units. Reducing the number of trips and time the helicopter is used has a positive influence on the environmental impact, construction cost and risk of injuries during tower erection.

The main way to reduce the use of helicopter under tower construction is to allow it to carry larger sections. Since commonly used helicopters for line construction have a payload of 1100 kg, it means reducing the weight of the sub-sections. This can be done by using a lower density material and a tower design consisting of fewer parts. Statnett decided to develop new light-weight tower for the 420kV transmission network using aluminium.

Aluminium has good recycling properties, conferring significant positive environmental impact compared to towers made of other material. This is another reason for the choice of this material.

Due to the high cost of the raw material, a good understanding of the specificities of aluminium in structural design (strength, stiffness, welding, weight or extrusion constraints) and a proper evaluation of different technical solutions (global geometry, profile shapes, integration of functional or assembly features to the shapes, use of built-up members or big profiles, slender or compact elements, welded or bolted connections, pre-assembly, transportation…), must be conducted in order to do enlighten choices to achieve the design of an economically competitive tower made of aluminium. The material properties as well as the attempt to reduce the number of elements to assemble may lead to challenges (buckling, strength reduction with weld, vibrations, limit of production tools …) which make it difficult to reach that goal.

KEYWORDS

High Voltage – 420 kV - Tower – Aluminium – Environment

Background

As with most power line towers around the world in the higher high voltage levels, the standard towers used by the Norwegian TSO, Statnett, in the 420 kV grid are made of steel. These towers commonly weigh between 10-20 tons, and up to 30 tons for heavily loaded structures. In Norway, the lines often traverse mountainous area with difficult access. The towers are frequently transported to the erection site and erected with the use of helicopters. Use of these machines constitutes a significant safety risk both for the pilots and the workers who receive and connect the sections together. The rent of helicopters represents a cost and using them has a negative impact on the environment.

Statnett researched alternatives to reduce helicopter usage during line construction. The largest benefit would be obtained by reducing the number of trips it takes. This can be achieved by enabling the helicopter to carry larger tower sections on each trip. Since typical helicopter used has a fix maximum payload (1100 kg), the weight of the sections must be reduced, which is possible by reducing the material density. Aluminium is considered as one of the main alternative materials since it has relatively high strength and it is already widely used as a structural material in various applications. Production facilities and manufacturing processes for aluminium are well developed and follow high quality standards (for example EN 573 [1] for chemical composition, EN 485 [2] for mechanical properties and tolerances, EN 755 [3] for extruded products, Eurocode 9 [6] for structural design, EN 1090 [4] for manufacturing and execution).

Development stages

General

The aluminium tower development started as a project backed by the Norwegian Research Counsel. Besides Statnett and EFLA, it involved several academic and industry partners (NTNU, SINTEF, VP Metall, Kapp Aluminium, HAP, Hydro), which gave valuable input. Aluminium offers several benefits, such as a high strength-to-weight ratio and an impressive flexibility in cross section design, but it also suffers from weaknesses that must be addressed. Welding should be avoided wherever possible, and the light weight gives an aluminium member increased susceptibility to VIV (Vortex-Induced Vibrations). In addition, there are stricter size limitations to aluminium extrusion than there is for rolling of steel members. In summary, several general aims guided the design of column-beam cross sections:

- Material should be placed as far as possible from the neutral axis to reduce the slenderness of the members and give an optimal buckling capacity,
- Member profiles with closed cross-sections, like tubular shapes, should be used where possible to increase torsional and local buckling strength,
- Several functions should be included, such as attachments for a climbing system,
- Welding should be minimized.

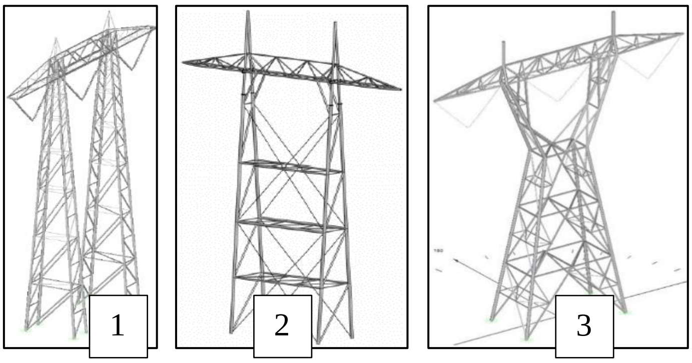
Overall tower design

Prior to initiating the development of the new aluminium suspension tower, several specifications were identified. The tower should be:

- Self-supporting,
- Able to withstand medium Norwegian loading conditions,
- Useable in rugged terrain,
- With conductors in a horizontal configuration.

Based on these specifications three main geometries were evaluated in a preliminary screening study:

1. Portal tower with self-supporting legs, without internal guys
2. Portal tower with internal guys
3. Lattice self-supporting Window tower



Tower type 1 could potentially be erected efficiently in large helicopter heaves, due to the stability of each leg. However, due to 8 foundations required, the increased number of joints and the higher overall weight, this design was quickly ruled out. Type 2 and 3 were of similar weight and complexity, but tower type 2 could more easily be used in existing transmission lines since it closely resembles Statnett's tower design. It was therefore decided to move forward with this design. No assessments of joint design were performed at this stage.

Design approach

The tower has been designed in accordance with EN 50341 [5] and EN 1999 [6]. In addition, the relevant rules in EN 1991-1-4 [7] were applied to achieve a VIV-resistant design. Load cases were specified for a typical span of 400 m, with duplex Parrot or triplex Grackle conductor configuration, ice loads of 6 - 11 kg/m (150 years return period) and gust wind speeds of 37 - 42 m/s (10 min. average, 50 years return period). The load cases were chosen to include wind and ice loading, a combination of wind and ice and several configurations of unbalanced ice loading.

PLS Tower was the main software tool to compute the loads in the members. The program is however developed to model primarily angle profiles in latticed tower. Shape of profiles in aluminium can be customized to suit requirements and can have many different forms. Due to the modelling limitations with PLS Tower (truss and beam elements only, member connection geometry and stiffness detailing not possible, linear elastic material behavior) and the need for more complex FE analyses, Strand 7 was also used in the design process. It was especially useful when evaluating the buckling capacity of various profile cross sections, both open and closed, and thus validating results from the EN 1999 [6] formulae, but also for detailed stress analyses. Working with aluminium profiles introduces a complexity unlike that for steel lattice towers, due to the vast amount of different cross sections conceivable for tower design.

Full scale test of tower prototype

A full-scale tower was manufactured in Norway and tested in Sevilla, Spain, in 2017. The prototype tower was carefully evaluated before undergoing destructive testing. During assembly Statnett employees involved in tower erection and control work were present to evaluate the design. Furthermore, to better evaluate the tower susceptibility to VIV, tower eigen modes and damping properties were evaluated prior to mechanical testing. In summary, results from all activities led to several design changes, i.e. form, assembly, VIV and mechanical testing, for example:

- New shape for the leg profiles with a better repartition of the material for higher stiffness, as well as better ergonomic for the workers,
- New connection of main diagonals to the bridge, to increase stiffness and strength,
- New pattern of the diagonals in the leg panels to reduce VIV sensitivity,

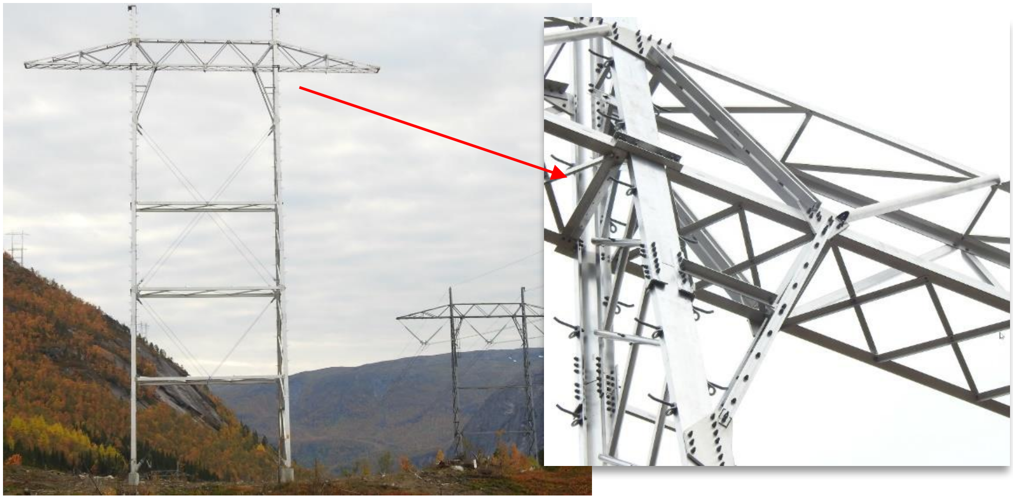
Prototype erected in transmission line

Following the full-scale test of the prototype, the design was evaluated for general use in Norway. It was decided that the tower should fulfill the following requirements:

- Be available in 17 – 47 m heights
- Allow for up to 5 m terrain difference normal to the line route
- Allow for up to 2 m terrain difference along to the line route

It became clear that the main leg profile used in the prototype test tower could not satisfy these requirements. Another profile type was developed (Figure 6) which addressed the concerns from the test. Nonetheless, the largest required profiles could not satisfy the worst combinations of tower heights and loading. Further work on this topic, in cooperation with Hydro, led to the development of yet another profile (Figure 7). This has removed the final technical risk to wide scale deployment in Norway.

A roughly 30 m tall suspension tower in aluminium was constructed, by HAP and Kapp Aluminium, and assembled in a transmission line at 68 degrees North, see figure below taken one year after assembly. At the time, the conductors were not strung. As can be seen, the design resembles the existing steel design, but with a lighter appearance. Also, the figure illustrates the use of different beam types.



Design considerations

Material strength considerations

A starting point for choosing aluminium as a material for transmission line structures is the comparison of its characteristics against those of steel:

Material	Modulus of eleasticity	Specific weight	Y_ield stress (or 0.2 % proof strength)	Ultimate Tensile stress	Specific strength
	E	ρ	fy or f0	fu	fy/ρ
	N/mm^2	kg/m^3	N/mm^2	N/mm^2	kN/m^2 / kg/m^3
Steel S355	210 000	7 850	355	490	45.2
Al. EN AW-6082 T6	70 000	2 700	255	300	94.4

Table 1 Comparative mechanical characteristics of a steel grade and an aluminium alloy

As seen in Table 1, aluminum alloy (here 6082 T6) has a significantly higher specific strength than typical steel grade. This can give rise to a lighter construction by using aluminium.

Like there are various grades of steel with different strength, one can find various alloys of aluminium with different properties. It may appear appealing to select stronger alloys to contribute reducing weight, but these may be less malleable and more difficult to extrude depending on the shape and thicknesses of the profiles. They may cost a higher price as it may require heavier press to extrude. In certain circumstances, for example with slender elements whose strength for buckling is governed mostly by the material stiffness rather than its strength, it may be wise to select a weaker but more malleable alloy.

Aluminium properties are modified by welding and the material strength in the area close to the weld seam is roughly halved (see Table 2)(except for fully annealed temper (O)).

Alloy	Temper	0.2 % proof strength	Ultimate Tensile stress	0.2 % proof strength in HAZ	Ultimate Tensile stress in HAZ
		f0	fu	f0,HAZ	fu,HAZ
		N/mm^2	N/mm^2	N/mm^2	N/mm^2
5 083	O	110	270	110	270
5 083	H12	200	280	135	270
6 060	T6	140	170	60	100
6005A	T6	215	255	115	165
6082	T6	260	310	125	185
7020	T6	280	350	205	280

Table 2 Comparative strength in base material and heat affected zone (HAZ) for typical structural aluminium alloys

For the development of the transmission tower for Statnett, alloy 6082 is selected as the main alloy for all profiles, both for its strength, but also as it is widely used and easily available. Alloy 6063 and 6005A, which are softer and cheaper alloys, have been considered as an alternative where better extrudability was needed. 6063 has yet not been retained due to its lower strength. Finally, alloy 5083 is selected for the footplate, as it has good weldability and maintains good strength after welding.

Finally, it is interesting to note that the strength of the material increases as temperature decreases, while ductility and toughness is maintained or even improved. Aluminum is thus not as susceptible to embrittlement as steel is at low temperature. Steel structures used in cold environment usually need extra requirements regarding the toughness quality of the material. This is not the case with aluminium.

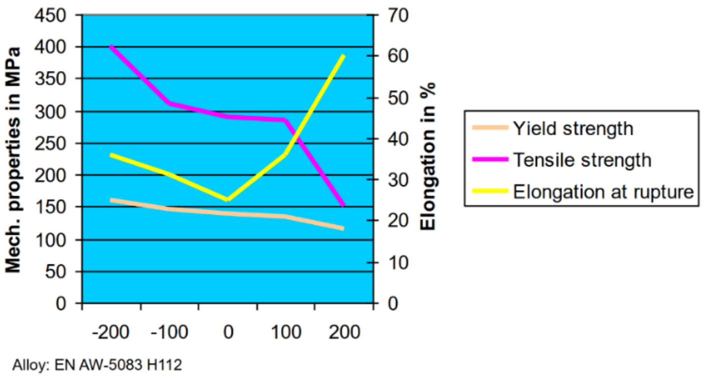


Figure 2 Effect of temperature on strength (source HAP)

Corrosion considerations

Aluminium is resistant to corrosion in most environments making it a good material for transmission line structures. It may corrode rapidly in highly acidic or alkaline environments. Its corrosion resistance properties vary depending on the alloy, the design and the protective measures taken. Some of these measures can be to:

- use insulating layers to prevent galvanic corrosion,
- design the connections with care placement of the bolts with respect to parts edges to ensure proper contact and avoid crevices,
- define enough part spacing where possible,
- anodizing.

The three main types of corrosion with aluminium are pitting corrosion, galvanic corrosion and crevice corrosion. The risk of galvanic and crevice corrosion can often be avoided or minimized by appropriate structural design solutions (parts shapes and position). Experience also shows that these are not necessarily an issue. Observations done on the transmission line Fortun-Øvre Årdal which was built with aluminium towers about 40 years ago in western part of Norway, indicate no sign of corrosion of the fasteners although galvanized bolts were used. No indication of crevice corrosion could be noticed either between the connection plates and the profiles.

Profile extrusion considerations

Although almost any shapes can be extruded, there is a certain number of limitations and recommendations to follow in order to be able to extrude a profile:

- dimensions of the profile: extrusion tools have limitations on the maximum dimensions that can be extruded, which is linked to the power of the extrusion press (see Figure 3),
- the minimum thickness of the walls of the profile is dependent on the overall dimensions (circumscribed circle diameter) of the profile (bigger dimensions require thicker walls for extrudability),
- for hollow profile, the perimeter or area of the internal void impacts how easy it is to extrude,
- variations of thickness should be limited to small changes, as they impact the facility to extrude the profile and may lead to issues with uneven cooling after extrusion, affecting the final shape or aspect of the profile,
- non-symmetrical shapes should be avoided. Symmetries ease the flow of the material through the die, reduce imbalance loading and risk of breakage of the die,
- Deep and narrow pockets and closed cavities should be avoided, as they may put high stresses on the die leading to breakage.

In general, the simpler the shape, the easier and cheaper it is to extrude. To keep competitive prices, one should avoid profiles that can only be extruded on biggest presses.

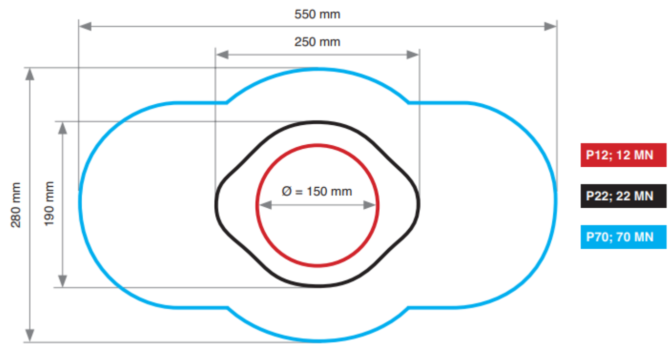


Figure 3 Example of profile dimension limits for extrusion (source HAP)

Profile cross-section considerations

The EN 1999-1-1 [6] standard for design of aluminium structures defines four classes for the cross-section of the aluminium profiles, in a similar way the EN 1993-1-1 [8] standard for steel structures does. Cross-sections in class 3 can be used up to their elastic limit state strength without risk of local buckling, while the strength of cross-sections in class 4 must be reduced to account for the likely occurrence of local buckling (see Figure 4). To compensate as much as possible for the higher price of the raw material of aluminium compared to steel, one will seek to take full advantage of the possibility to reduce the mass of the elements and use cross-section parts as thin as possible. A minimum reasonable thickness shall nevertheless be selected to avoid risk for local crushing or crumpling damages under handling and transport of the profiles. One can note that the limit (to class 4 cross-sections) of the width-to-thickness ratio of a part in pure compression is lower for aluminium than it is for steel (for example, for internal parts of a cross-section, the limit ratio is 21.6 for aluminium alloy 6082-T6 (without weld) vs. 34.2 for steel S355). This implies that even though one chooses an alloy

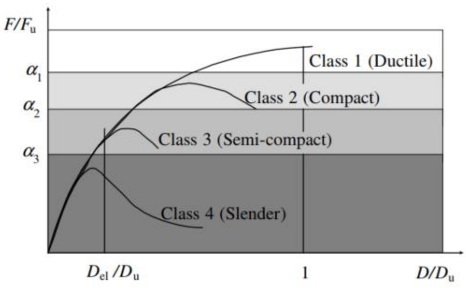


Figure 4 Cross-section classification principle (source Eurocode 9) : F=Force, D=Displ., u=ultimate

with a relatively high specific strength, the gain in mass due to the choice of class 4 cross-sections may be somewhat lower than what could be anticipated from the comparison of the yield strength of the alloy and steel material. To compensate for this, one will take advantage of the relative flexibility given by profile extrusion method, to create custom shapes which is optimal for the actual loading and length of the profiles. The extrusion production method also allows incorporation of features which may facilitate joining (for example via integration of flanges or fins) or mounting of equipment on the profiles (for example rails for climbing devices).

Examples of profiles developed for the legs of the tower for Statnett and their evolution through the development stages are given in Figure 5 to Figure 7.

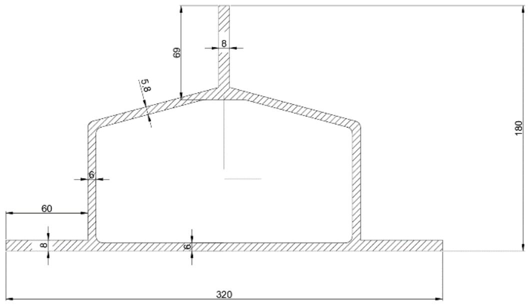


Figure 5 Profile for legs on the prototype

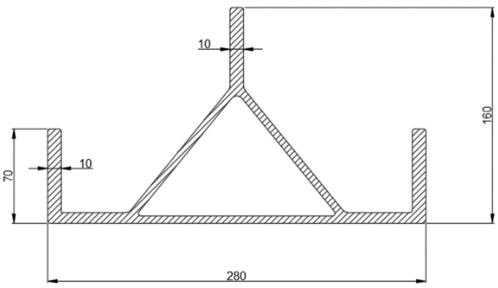


Figure 6 Profile for legs on the pilot tower

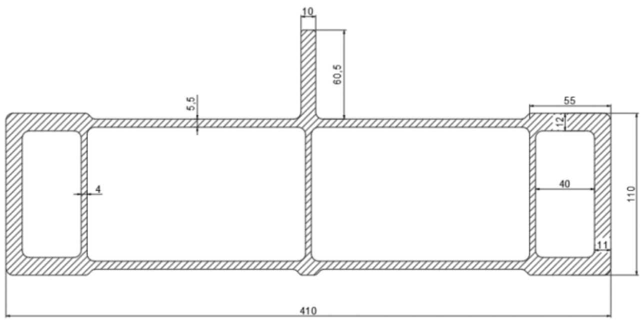


Figure 7 Newly developed profile for legs for long unsupported length (highest buckling strength and torsion stiffness)

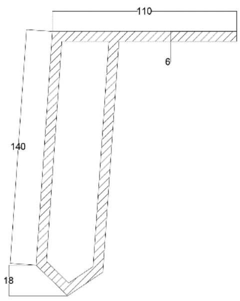


Figure 8 Example of profile developed to reduce risk of VIV, for chord of horizontal planes

Profile strength considerations

In the Eurocode 9 (EN 1999-1-1) [6], formulae for calculation of global buckling resistance are valid for all slenderness ranges. The Eurocode tackles local buckling by means of reduction in thicknesses in the slender parts of a cross-section. Yet, while local buckling may occur first on compact element, it is unlikely to be the case for slender members. In the design phase, one can thus use Finite Element analysis of specific members in addition to code check to bypass the application of the formula from the Eurocode, by demonstrating for example that the global buckling resistance of a member with class 4 cross-section, can actually be defined based on its full cross-section rather than its reduced one. Finite Element analysis may also be used to check the cross-section strength in tension or compression by means of a stress check rather than use of the resistances as per the code, in the cases where interaction formulae do not apply, typically for non-symmetrical and/or non-hollow cross-section.

Tests and simulations have been performed in collaboration with NTNU (Norwegian University of Science and Technology) for validation of buckling curves in Eurocode 9 [6]. The results show up to 10% underestimation of buckling capacity in EC9, and there seems to be about 7% difference in the yield strength of the material when submitted to axial compression versus axial tension. This might open for future revision of the standard curves.

Connection considerations

To contribute to reduce the installation cost, one can look at reducing the quantity of elements to assemble and optimizing their connections. In this context, one would consider in a first phase what potential lies in constructing the tower with welded parts, in a perspective of saving labor costs on the assembly site. Welding can also save a fair amount of weight compared to bolted connections. With welded modules, one can in addition take advantage of the rotation stiffness of the welded joints to reduce the buckling length of the bars and thus achieve further weight savings in comparison to joints where only the translational movements are prevented. However, the manufacturing cost of welded joints is usually higher than that of joints with mechanical fasteners. This may partly or fully annihilate the benefit of the saving of the on-site assembly work. Moreover, welding reduces the strength of the aluminium material as seen before, and the welded joints in aluminium have a relatively limited fatigue capacity. It is therefore important to pay attention to the location of the welded joints if any and how these are loaded by cases with potential dynamic or variable effects. The extrusion capabilities of aluminium profiles must be utilized fully to vary thicknesses across the profile sections, and place more material where needed as well as create shapes and details that minimize stress concentrations.

Regarding the jointing of elements with mechanical fasteners, one can either choose bolts in aluminium alloy, stainless-steel or steel material. Aluminium bolts or stainless-steel ones have a higher cost than usual steel bolts. While stainless-steel bolts may have equivalent strength as steel bolts, aluminium ones have a lower capacity. It requires thus generally more of these bolts than steel bolts to transfer the same load. This means more drilling and more assembly work to set and tighten the bolts, hence increasing costs.

Using galvanized steel bolts is the desirable choice. Yet, connecting mixed material components (aluminium parts and steel fasteners) together is a questionable matter that must be assessed. The aluminium parts may quickly degrade as galvanic corrosion may develop. This is especially relevant where conditions are favorable to the cathodic reaction, like wet saline environment, found typically in marine atmosphere or locations exposed to slush resulting of road de-icing salt. One can however consider the following:

1) a conductive solution must cover the contact area of the components for the galvanic process to happen. Humidity alone (condensed water without salty matter) may not be enough to allow for the reaction to occur;
2) the reaction speed is related to the ratio between the surface of the cathode (aluminium) and the surface of the anode (steel);
3) the electrode potential between zinc and aluminium is relatively small as zinc has a lower potential than aluminium.

To choose the material for the mechanical fasteners, one can thus evaluate if the following beneficial circumstances are applicable:

- the towers generally stand inland, sufficiently off from the coast to consider that the atmosphere is generally not saline. Special circumstances, like transported pollution, should be evaluated,
- the towers dry relatively quickly after rain,
- the surface of the jointed aluminium parts is large compared to the surface of the steel fasteners,
- steel fasteners will be galvanized.

Selecting galvanized steel as the material for the fasteners appears a reasonable choice. This choice is reinforced by field experience with the line Fortun-Øvre Årdal, built about 40 years ago in Norway, where galvanized steel bolt is used, and where no sign of corrosion of the bolts is noticed.

Design must nevertheless be done such to avoid geometry or assemblies where water is not well drained and may be collected.

Note that rivets may be an alternative to bolts, at least for some sections where those can be easily employed. Flat sections can be pre-mounted with rivets at factory where specific tools can be used, increasing efficiency of the pre-assembly contra using bolts. The benefit of the gain on pre-assembly efficiency must be evaluated against a higher cost of the rivets.

Geometry considerations

In the design process, changes in the geometry and the number of elements is assessed. Experience has shown that for structural components it may be easier to meet performance and productivity requirements by changing geometry than by changing material properties. The use of fewer elements in a different geometrical pattern could contribute to the weight reduction. For example, considering the diagonals between the main chords or legs, one can reduce their quantity by increasing the distance between the connection points to the legs. This leads however to longer diagonals which need to be bigger in cross-section to have enough buckling capacity. The increased unsupported length of the legs may also lead to an increase of the dimensions of the leg profiles. One longer, bigger diagonal is not necessarily lighter than two shorter, smaller ones. Yet, the connection of one bar may use fewer components (plates, bolts, washers, nuts) than the connection of two. The overall weight including the connection parts might be in favor of the longer bar. One must however consider the susceptibility to vibration of the members. The results obtained from the vibration study performed on the prototype tower, where single long diagonals where used, led to the choice of a diagonal pattern with cross-bracings on the pilot tower (see Figure 11 and Figure 12 and *"Vibration and fatigue considerations")*.

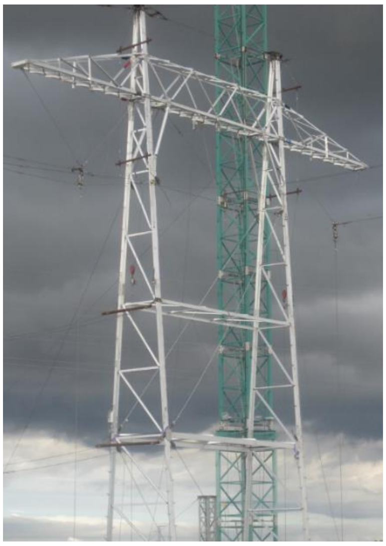


Figure 11 Diagonal pattern on prototype – single long diagonals

Figure 12 Diagonal pattern on pilot tower – shorter cross diagonals

Bolted joints commonly require connecting plates to be inserted to make room for all necessary bolts. In a transmission line tower made of steel, the weight of bolts and plates typically add 10% to 15% to the mass from the profiles. Paying attention to the design of the connections and looking at reducing the quantity of bolts and eliminating connection plates where possible may be worthwhile. This may not only result in additional saving in weight but will also reduce the time necessary to assemble the parts together and contribute to compensate for the higher material cost.

Finally, due to the lower strength of aluminium, bigger bolts and/or thicker parts must generally be used compared to steel elements. This impacts negatively the weight of the structure. A balance must thus be found between the use of fewer larger bolts and more smaller ones, keeping in mind that more bolts means also more holes to drill.

Vibration and fatigue considerations

Vortex-induced vibration, VIV, is a phenomenon arising from wind-structure interaction. It occurs when the vortex shedding frequency comes close to the eigen (natural) frequency of the structure, leading to large deflection amplitudes. If the eigen frequency of a member is sufficiently high, it is unlikely to experience VIV. For lower frequencies, i.e. more slender members, VIV is more probable to occur. For a sufficiently slender member, i.e. with very low eigen frequencies, member weight and geometry also affect its susceptibility to VIV. A slender, yet heavy member is not so easily accelerated by wind vortices. The connection of the members also impacts their vibration susceptibility. Members with low connection stiffness like small mounting plates or thin profile flanges, are likely to have their support behave like a spring and will have low structural damping. All these effects are described by the Scruton number of a member, where a large number means high resilience to VIV.

An aluminium beam/coulumn of similar strength to a steel beam/column must have a larger diameter, to account for the reduced elastic modulus. In addition, the density is lower. The lower intrinsic material stiffness combined with connection on thin plates or profile parts is likely to induce a lower structural damping compared to steel. All these factors act to reduce the Scruton number. It can thus be expected that an aluminium tower member is more VIV susceptible than a similar strength steel member. As a result, careful evaluations of the tower VIV response have been carried out. A numerical model of the prototype tower was first set up by Svend Ole Hansen in the software GT Strudl to provide an initial assessment of the structural dynamics, then full-scale vibration measurements were executed on the erected prototype tower and wind tunnel testing of individual members was performed (see Figure 13).

With reasonably low eigen frequencies and low Scruton numbers for most of the tower members, focus was on reducing the forces from the induced vortices. This can be done by introducing asymmetry, so that vortices vary along the length of a member, such as with spiral strakes. For extruded profiles this is not possible. The cross-braced members, however, were found to give good VIV resistance due to their asymmetric behavior. Where cross bracing was not an option, optimized beam cross-sections were needed (see Figure 8). These were found in a cooperation with Svend Ole Hansen AS, and wind tunnel testing at their premises.

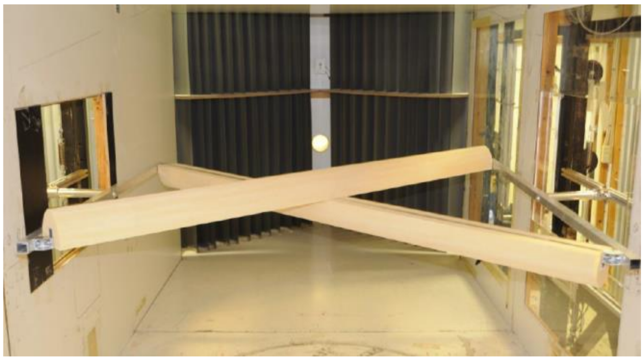


Figure 13 Wind tunnel testing of leg diagonal profiles

Observations done during inspection of the pilot tower after it had stood for a year did not show any sign of loose bolts or fatigue. The conductors were not strung at that time, which should represent a worse case situation for the tower elements with respect to vibration, as installed conductors will give some damping to the structure. At the time this article is written, 2,5 years after erection, still no negative feedback has been returned from site. VIV has therefore not been an issue during this time.

Transport considerations

The tower sections can be imagined divided in a certain number of welded modules. For the typical Statnett towers, the leg panels could for example be several welded modules, likewise for the bridge, the cross-arms and the horizontal planes. Each of them could be transported to the assembly site and then lifted by helicopter from there to be mounted together at the erection spot. This would probably induce a reduction of the assembly work. Yet, transporting large units from the factory to assembly site, is likely not as economical as sending individual parts that are economically packed in containers or on trucks. Manufacturing cost is also likely higher with welded parts as demonstrated earlier.

Experience from the design of 420 kv aluminium tower

After different evaluations, it was decided to design the tower as a bolted structure. The reasons behind this choice were the fatigue strength, production costs, transport costs. The only weld in the tower is at the footplate.

The focus was on reducing the number of bracings, to reduce the assembly cost. This led to using longer diagonals on the prototype tower. Yet, the susceptibility to VIV of long members resulted in choosing to have shorter cross-braced diagonals on the pilot tower. This also allows limiting the dimensions of the leg profiles for one of the buckling axes which makes it easier to meet the dimension requirements for extrusion.

In the seek of optimal use of aluminum, larger closed cross-sections with thin walls creates a greater moment of inertia and compensates for the lower modulus of elasticity compared to steel. This is especially true for long, slender members. In this respect, it becomes more difficult for aluminium to compete against steel, as bigger profiles become more difficult (if not impossible) and more costly to extrude. Aluminium looks thus to be better suited for more compact (shorter and wider) members.

An assembly scheme was planned so that the number of helicopter trips would be roughly halved. Due to inexperience with the tower design, the efficiencies were not fully harvested. However, the leg sections of the 30 m tower were assembled in two lifts, roughly 15 m tall each (see Figure 14). This demonstrated the flexibility of the aluminium tower.


Figure 14 Leg panel lift with helicopter

Statnett has reached out to European and Turkish aluminium manufacturers to participate with price estimates for 50 – 100 tonnes of aluminium towers. Comparing an average of the received prices with that for construction of steel towers, it appears that price parity is not very likely, even when the benefits to tower assembly and erection are considered. Also, one factor to recognize is the potential lock-in for manufacturers. This stems from the need to purchase a rather large set of extrusion dies. If one manufacturer has already written off this expense due to a prior project for Statnett, it may have a cost advantage.

Another learnings of the development of these aluminium towers is that significant resources (in terms of expertise and time), must be mobilized to decide where the material must be placed, what alloy is best suited, which connection and detail production method is most appropriate in order to achieve an optimal use of aluminium and design competitive solutions (Figure 15).

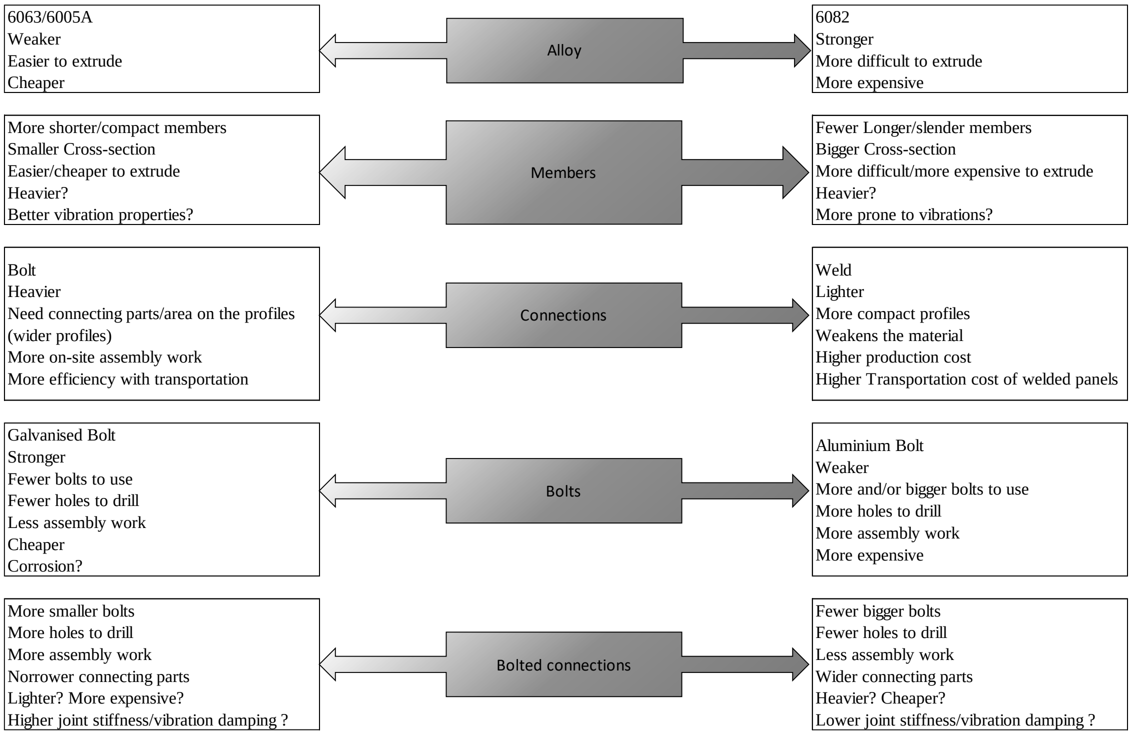


Figure 15 Tradeoffs balancing chart for the project (« ? » indicates there is no final answer ; a case-by-case study can precise what the outcome is for each specific application)

It must also be recognized that the tower design is not as mature as that for steel towers, and that further developments can be expected.

Environmental aspects

Aluminium can be recycled indefinitely without loss of quality. Recycling the material cost little energy compared to primary production (5% of the original input). Therefore, the emissions of greenhouse gases, and particularly CO_2, are significantly reduced when producing "new" aluminium towers through recycling.

Comparative life cycle analysis was conducted by EFLA on transmission lines in Norway where either standard steel towers, aluminium tower or composite towers are used. The study concluded that over the life of a transmission line (mining for ore and producing the raw materials, design, production, transportation, construction, maintenance, dismantling and recycling), the use of aluminium towers result in a reduction of CO_2 emissions by a factor of 2. Most of the gain in CO_2 reduction is offset to the end of life when the material is recycled after dismantlement of the line. Yet, immediate gain may be achieved at the beginning of the project if the material ordered is produced from a significant amount a recycled aluminium. This might however set limiting competitive criteria for the selection of the producers.

Conclusion

As often with the design of a new product, one seeks to make the design of a new structure as economically competitive as possible to facilitate its use in projects. This is challenging when the price of the raw material is significantly higher to start with. Every source of potential savings must be analyzed and exploited to achieve this goal. Going down this way is however not a straightforward journey, as different aspects of aluminium tends to draw in opposite directions. Careful study should be made to lead to wise choices, but trade-offs are inevitable. Despite all efforts, one may find out when designing an aluminium tower that price parity with their "old sisters" in steel is not very likely. The geometry of the tower may have influence on this, and the results might be different when comparing structures with short, compact members which are probably better suited for use of aluminium than long slender members. Other aspects come into the balance: structures in aluminium have a significant benefit when it comes to environmental impact, particularly regarding CO_2 emissions; or it may increase the safety during erection, depending on the assembly method and the design of the assembly details that are provided. These aspects may be enough to counterbalance a cost disadvantage when the price difference with steel tower is limited.

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