

Design and Optimization of Aluminum Member's Sections for Building Efficient 120–160 kV Power Transmission Towers [†]

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Abstract: The use of aluminum in civil engineering applications has increased significantly over the past decades. Aluminum is a durable, lightweight, and recyclable material that can provide alternative structural solutions for building power transmission towers. In order to achieve this objective, it is necessary to develop structural members that take advantage of specific properties of the material, such as low density, high strength, resistance to corrosion, and the geometric flexibility that aluminum extrusions provide to design robust and easy-to-assemble structures. This paper presents a section optimization study of an existing medium-voltage steel 120–160 kV lattice tower owned by Hydro-Québec, considering the use of various extruded aluminum sections. The proposed optimized aluminum sections are compared with the steel sections of the existing tower. The study's main objective is to optimize the tower's aluminum sections. A SAP2000 structural finite element stick model of the tower coupled to a Matlab optimization routine is used to optimize the aluminum sections. ASCE10-15 and CSA-S157-17R22 standards are used to impose the design constraints for selecting the optimized aluminum square and octagonal hollow sections, with and without stiffeners. This study proposes optimized section shapes suitable for constructing aluminum lattice transmission towers. The study reveals that the proposed aluminum tower prototype is twice as light as its steel counterpart. The aluminum members' price is also very competitive compared to steel.

Keywords: aluminum; design; hollow section; optimization; stiffener; transmission tower



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1. Introduction

In recent years, there has been a rapid development of high-voltage and extra-high-voltage transmission line systems [1]. As a crucial component of these systems, the transmission tower requires an economically efficient design. Before using aluminum for building transmission towers, it is necessary to develop design concepts that take advantage of the geometric flexibility that extrusion production provides and also design strong and easy-to-assemble connections.

Steel leg angle profiles have been traditionally used as structural members in power transmission towers due to their ease of erection [2]. However, the eccentricity in these profiles leads to additional moments in the tower's legs, which reduce their overall strength. Using aluminum extrusions [3,4] makes it possible to implement concentric connections, which can help mitigate the strength-reducing effects of eccentricity.

Aluminum offers numerous advantages over steel, such as its lightweight nature and high corrosion resistance [5]. However, one significant drawback of aluminum is its considerably higher cost per unit of weight compared to steel. Therefore, to achieve cost-effective designs, optimizing the sections to minimize the weight when using aluminum

is necessary. By optimizing the sections [6], we can minimize material usage while still maintaining structural integrity and functional requirements [7,8]. This approach helps us strike a balance between the benefits of aluminum and the need for economical designs.

The aim of this study is to propose a new generation of transmission towers made of aluminum. This study seeks to transpose the scientific and technical expertise developed over the past years at the University of Sherbrooke, in the context of steel lattice tower analysis and design, to provide powerline owners and designers with (1) optimized section shapes and tower geometries to build cost-effective aluminum power lines; (2) practical tools to assess the validity of the new aluminum tower designs and provide guidelines for the designers.

2. Transmission Tower

Historically, trusses have been one of the most widely used structural concepts in civil engineering, encompassing a wide range of solutions to various engineering challenges. There are many different truss configurations suitable for various structural purposes. Lattice truss structures are the most common type of power transmission tower. They consist of legs, primary and secondary bracings, and redundant and cross-arm members that support overhead power lines.

There are two common types of lattice transmission towers: self-supporting towers and guyed towers. A guyed transmission tower is a type of tower that relies on guy wires or cables that are anchored to the ground or other supporting structures to resist horizontal loads. On the other hand, a self-supporting transmission tower is a type of tower that is designed to stand on its own without the need for additional support or guy wires. The choice between guyed or self-supporting towers is often highly dependent on the topology of the terrain and geographical location [9].

The primary objective of this study is to offer an alternative solution for transmission towers by introducing an innovative generation crafted from aluminum. It may be particularly advantageous for construction in remote locations where the lightweight and durability of structures might have a major impact on the cost of construction and maintenance of these structures.

2.1. Steel Transmission Tower (Benchmark Structure)

The benchmark structure studied herein is a guyed transmission tower designed by Hydro-Québec (HQ). The structure's geometry is depicted in Figure 1. The tower has a total height of 40 m and a base width of 1.2 m. The tower is composed of two primary modules, 4 and 6 m in height. Angle steel sections are used for all members. The material density of the steel is 7850 kg/m^3 , and Young's modulus is 200 GPa.

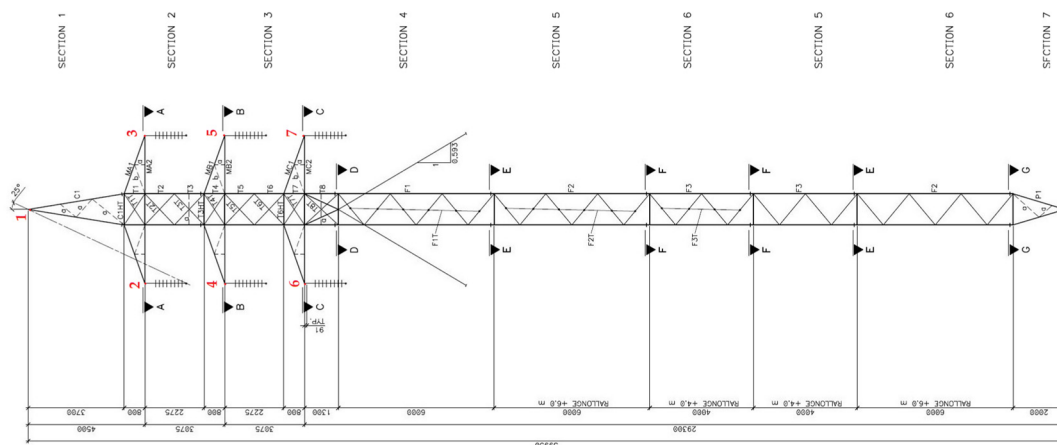


Figure 1. Transverse face of guyed transmission tower presents isolated sections for applying gravity and wind loads.

The lower part of the tower, which is the focus of the design, corresponds to six separate modules that are assembled on-site. This study examines various load cases based on wind velocity and ice thickness. The design load cases are based on the IEC 60826 (International Electrotechnical Commission) standard, with wind and ice being the main loads. One of the load cases is shown as an example in Table 1. Point loads are presented in red in Figure 1. Table 2 provides comprehensive information on the magnitude of both gravity and transverse wind loads acting upon the sections/modules of the tower. For this preliminary analysis, wind and gravity loads on the tower are not updated. It is assumed that the mass of the top part of the tower remains unchanged. In addition, updating wind and gravity loads on the top part of the mast (Section 4, Figure 1), which is the critical part in the optimization process, has a negligible effect on the design of these sections.

Table 1. Critical design load transferred from conductors to tower considering ice thickness of 50 mm and wind velocity of 100 km/h.

Point Load	Back Span (kN)			Front Span (kN)			Total (kN)		
	T *	L *	V *	T	L	V	T	L	V
1	4.29	−77.89	21.74	4.49	101.57	21.74	8.78	23.67	43.48
2	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87
3	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87
4	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87
5	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87
6	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87
7	4.99	−127.01	26.44	5.04	132.3	26.44	10.03	5.29	52.87

* T: Transverse wind load, L: Longitudinal load, V: gravity/vertical load.

Table 2. Magnitude of gravity loads and transverse wind loads on the tower.

Sections	1	2	3	4	5	6	7
P2 * (kN)	17.5	24.0	39.4	Gravity loads 30.9	21.3	15.6	4.7
HT1 (kN)	0.9	1.1	1.9	Transverse wind loads 1.6	1.4	0.9	0.3

* P2 includes the self-weight of the tower's members.

2.2. Design of Aluminum Transmission Towers with Angle Sections

Angle sections are the most common sections used for steel transmission towers due to their facility of erection. Table 3 presents the sections used in the benchmark tower. The comparison between the members used in the steel and aluminum transmission towers is presented considering the use of angles in both cases. The aluminum member were sized using the same load cases as the steel tower. Steel has a higher tensile strength and yield strength compared to aluminum, which means it can withstand higher loads and stresses for a given section. Steel also has a higher modulus of elasticity, which means that a steel structure is less prone to deform than an aluminum structure under the same loading. The two aforementioned facts contribute to aluminum sections being larger in size than their steel counterparts. Therefore, it is concluded that aluminum angles are not preferable. This is the reason why we choose other sections for aluminum tower study.

2.3. Design of Aluminum Transmission Towers with Extrusions

Another advantage of aluminum alloys over steel is the ease of fabrication when employing the extrusion process. One of the most attractive aspects of aluminum as a structural material is that it can be extruded. An Extrusion's cross-section can be made in almost any shape (Figure 2 [4]). Designers can thus add additional features to section shapes, such as stiffeners or other features to accommodate special details. Limitations to the size and shape of extrusions are mainly based on the press used to fabricate the

extrusions. Making such cross-sections using hot-rolled shapes or cold-formed steel is almost impossible or impractical due to limitations inherent in the fabrication processes.

Table 3. Angle sections used for the steel and aluminum structures under the same critical load cases.

Member	Steel Tower (Designed by HQ)	Aluminum Tower	Weight Ratio Aluminum/Steel
F1	L127 × 127 × 9.5	L254 × 254 × 16	137.43%
F2	L102 × 102 × 9.5	L254 × 254 × 16	173.09%
F3	L102 × 102 × 9.5	L152 × 152 × 16	101.33%
F1T	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%
F1L	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%
F2T	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%
F2L	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%
F3T	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%
F3L	L64 × 51 × 4.8	L64 × 51 × 4.8	34.39%

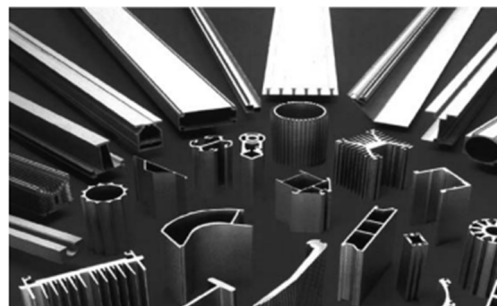


Figure 2. Examples of complex aluminum extrusions [4].

The novel tower concepts that are developed in this project make use of aluminum extrusions to lead to highly efficient design using fully optimized sections and truss geometries. The extrusion also enables the use of concentric connections, which are not possible in towers made with single angles. Figure 3 presents our preliminary concept of bolted concentric connection between two diagonals and a leg member using aluminum extrusions.

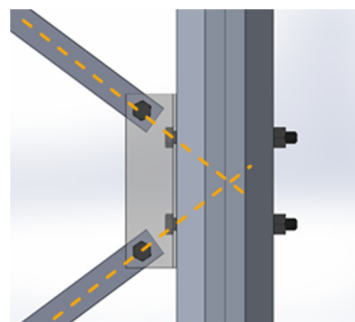


Figure 3. Concentric connection between two diagonal and a leg member.

3. Modelling and Design Assumption

The benchmark tower was modelled using the SAP2000 finite element (FE) software. Linear Bernoulli beam elements were used to model the structural members. Leg members were modelled as continuous elements in each individual section of the mast. The connections between the legs of adjacent sections were modelled as pinned. The diagonal, redundant, and cross-arm members were modelled as pinned–pinned. The guy wires were modelled using SAP2000 cable objects which are geometrically nonlinear elements that solely have axial stiffness under tensile loading. The geometrically nonlinear model of the

tower was submitted to 126 load cases provided by HQ. A model of the benchmark tower was used to validate its adequateness by comparing the critical tension and compression forces in the structural members to those calculated by HQ. The results obtained from the FE model were almost identical to those of HQ, never differing by more than 5%.

The SAP2000 model was used to evaluate the critical member forces considered in the design of the tower members. The design of the aluminum tower was performed in accordance with the ASCE10-15 [10] and CSA-S157-17R22 [11] standards. The design constraints for these standards were incorporated into the Matlab code explicitly developed for this project. The modes of failure that were considered are the following: (1) gross section yielding in tension, (2) local buckling in compression, (3) global buckling at the member level, and (4) global buckling of the entire mast.

4. Optimization Study

Structural optimization problems are generally categorized into three categories based on the geometric feature they address [7]. These categories provide a framework for tackling different aspects of the optimization process:

- sizing optimization
- shape optimization
- topology optimization

The main purpose of this study is to optimize the shape of the sections composing the towers by developing novel section shapes made from extruded aluminum (sizing and shape optimization category). Therefore, the topology of the tower and special configuration of the member is the same throughout the study.

The objective function and the design variables are two crucial elements to define and solve optimization problems. The objective function represents the measure of success or quality that the optimization seeks to optimize. The objective function can be either to maximize or minimize a certain key design variable such as stiffness, strength, self-weight, etc., depending on the problem's nature. Design variables, also known as decision variables or input variables, are the parameters or factors that can be adjusted or manipulated to optimize the objective function. These variables are the adjustable components of the problem that the optimization algorithm explores to find the best combination that optimizes the objective. Design variables can include dimensions, shapes, material properties, process parameters, or any other factors that influence the system being optimized.

In this study, objective function is considered as minimizing the cost of the tower. This objective translates into minimizing the self-weight of the tower. In addition to the self-weight, other parameters such as the method of assembly, transportation costs, maintenance costs, recyclability, etc., are not yet considered in the present study. These parameters will be considered in a subsequent phase of the research project. The design variables are the dimension of the sections, shape of the section, thickness of the elements composing the section, and thickness of the stiffeners if applicable.

4.1. Proposed Extrusion Shapes

During the past 50 years, ASCE's Construction Division has witnessed the transformation of aluminum from a niche material to a widely accepted structural metal with broad utilities. The remarkable combination of its lightweight nature, corrosion resistance, and the geometrical flexibility enabled by the extrusion process has firmly established aluminum's significance for structural engineering purposes. The role of aluminum used in civil engineering structures is expected to further expand in the coming decades [5].

The utilization of aluminum material offers the advantage of extrusions, enabling a wide variety of section types that can be adapted to various structural applications. For the purpose of this study, both square hollow sections and octagonal profiles were considered. Their superior radii of gyration with comparison to angle makes them very attractive from a compressive resistance standpoint. The investigation includes optimized sections with and without stiffeners. The design variables considered in the optimization process include

the width and thickness of the section, as well as the length and thickness of the stiffeners when applicable.

Figure 4 shows the specific cross-sectional shapes selected for designing the transmission tower. Both section types are optimized with, and without the inclusion of stiffeners. The square hollow sections are described by the width of the square, d , the thickness of the square, t , and the thickness of the stiffeners, s . The octagonal sections are characterized by the overall depth of the octagonal, d , the thickness of the unreinforced parts, t_1 , the thickness of the reinforced parts, t_2 , and the thickness of the stiffeners, s . By varying the design variables, including the width, thickness, and stiffener dimensions, the optimization process aims to find the optimal combination of these parameters that will meet the desired objective function and satisfy the constraints of the problem.

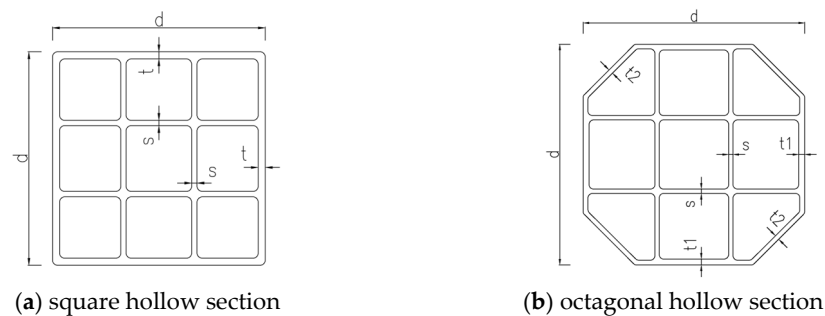


Figure 4. Shapes of the sections chosen to perform the optimization process.

4.2. Classical Method of Optimization

Step 0: Begin the optimization process;

Step 1: Implement the geometry of the tower into SAP2000, and model guy wires;

Step 2: Assign initial sections to the structural members in the first iteration. For subsequent iterations, assign updated properties obtained from the Matlab design optimization code;

Step 3: Analyze the tower under the HQ load cases in SAP2000;

Step 4: Export the internal forces in the members obtained from the SAP2000 analysis to Matlab;

Step 5: Run the design optimization code in Matlab;

Step 6: If global convergence is not reached, export the new member sections to SAP2000 and repeat Step 2. If global convergence is reached, perform Step 7;

Step 7: End the optimization process.

Global convergence refers to the situation where all member sections from the previous iteration are the same as the current iteration.

4.3. Comparison between the Optimized Aluminum Extrusions and the Steel Angles Designs

4.3.1. Aluminum Square Hollow Structural Extrusions with and without Internal Stiffeners

The HQ guyed tower was redesigned using the same geometry and considering extruded aluminum square hollow sections (SHS) for all mast members. The design was performed considering two scenarios: (1) SHS without internal stiffeners for the legs, and (2) SHS with internal stiffeners for the legs. Diagonal members are unstiffened SHS in both scenarios. Table 4 presents the results of the last optimization iteration for a design scenario using stiffeners, where C_f is the factored compressive force demand, and T_f is the factored tensile force demand. The maximum force demands refer to the maximum member forces obtained from the SAP2000 model analyzed under 126 design load cases provided by HQ. C_r is the factored compressive resistance, and T_r is the tensile factored resistance of the members. The last column of the table presents the factored demand-to-resistance ratios.

Table 4. Results of the last iteration of optimization process using SHS with stiffeners.

Member	Optimized Sections	s * (mm)	C _f (kN)	T _f (kN)	C _r (kN)	T _r (kN)	C _f /C _r (%)	T _f /T _r (%)
F1	SHS120 × 120 × 4	3	−502.4	197.1	507.0	683.4	98.9%	28.8%
F2	SHS115 × 115 × 4	3	−445.4	121.0	465.9	653.2	95.6%	18.5%
F3	SHS115 × 115 × 4	2	−393.6	48.5	417.2	565.1	94.3%	8.6%
F1T	SHS40 × 40 × 3.5	-	−28.6	29.5	31.8	110.4	89.9%	26.7%
F1L	SHS40 × 40 × 3.5	-	−27.7	20.8	28.9	95.9	96.1%	21.7%
F2T	SHS40 × 40 × 3	-	−26.4	25.2	28.9	95.9	91.4%	26.2%
F2L	SHS40 × 40 × 2.5	-	−21.0	20.3	24.7	81.0	85.0%	25.1%
F3T	SHS40 × 40 × 2.5	-	−24.2	23.2	24.7	81.0	97.8%	28.6%
F3L	SHS40 × 40 × 2.5	-	−20.8	19.8	24.7	81.0	84.4%	24.5%

* s presents the thickness of the stiffeners.

Table 5 compares aluminum SHS with the HQ's design using steel angles from a mass per unit length (kg/m) and cost per unit length (CAD/m) perspective, where the price of aluminum per unit mass considered is 7.00 CAD/kg, and the price of steel per unit mass considered is 3.70 CAD/kg. Both prices per unit mass are based on the market prices including alloying and shape fabrication supplied by local distributors during the first quarter of 2023.

Table 5. Comparison between aluminum SHS and steel angle members in the critical section of the mast (Section 4, Figure 1).

			Aluminum (SHS)	Steel (Angle)	Aluminum/Steel
Scenario 1: Members without stiffeners	Leg member F1	Mass (kg/m)	7.5	18.4	41%
	SHS145 × 145 × 5				
	L127 × 127 × 9.5	Price (CAD/m)	52.8	68.2	77%
	Diagonal F1T	Mass (kg/m)	1.19	4.1	29%
	SHS40 × 40 × 3				
	L64 × 51 × 4.8	Price (CAD/m)	8.3	15.2	55%
	Total mast	Mass (kg)	863	2204	39%
		Price (CAD)	6042	8157	74%
Scenario 2: Members with stiffeners	Leg member F1	Mass (kg/m)	8.5	18.4	46%
	SHS120 × 120 × 4_s3				
	L127 × 127 × 9.5	Price (CAD/m)	59.8	68.2	88%
	Diagonal F1T	Mass (kg/m)	1.3	4.1	33%
	SHS40 × 40 × 3.5				
	L64 × 51 × 4.8	Price (CAD/m)	9.1	15.2	63%
	Total mast	Mass (kg)	990	2204	45%
		Price (CAD)	6931	8157	85%

The scenario using unstiffened leg member yielded to 145 mm SHS leg members with a thickness of 5 mm. The SHS legs are much lighter than the benchmark tower with a mass ratio of 41%. The related aluminum-to-steel price ratio is 77%, which indicates that the price of the aluminum leg members is less than its steel counterpart. The scenario using stiffened leg member yielded to 120 mm SHS leg members with a wall thickness of 5 mm, and 3 mm thick stiffeners. The stiffened SHS legs are also much lighter than the benchmark tower with a mass ratio of 46%. The related aluminum-to-steel price ratio is 88%, meaning that the price of aluminum stiffened legs is also less than its steel counterpart.

The scenario using unstiffened leg member yielded to 40 mm SHS diagonal members with a thickness of 3 mm. The SHS diagonals are lighter than the benchmark tower with a mass ratio of 29%. The related aluminum-to-steel price ratio is 55%, which indicates that the price of the aluminum diagonals is almost half of its steel counterpart. The scenario using stiffened leg member yielded to 40 mm SHS diagonals with a wall thickness of 3.5 mm. The diagonals are also much lighter than the benchmark tower with a mass ratio of

33%. The related aluminum-to-steel price ratio is 63%, meaning that the price of aluminum of the diagonals for the stiffened legs scenario is also less than its steel counterpart.

Both designs using aluminum yielded much lighter designs with mass ratios ranging between 41% and 46% for the legs in scenarios 1 and 2, respectively, and 29% and 33% for the diagonals for scenarios 1 and 2, respectively. Both aluminum designs also yielded cheaper designs with price ratios ranging between 77% and 88% for the legs in scenarios 1 and 2, respectively, and 55% and 63% for the diagonals for scenarios 1 and 2, respectively. Scenario 1 using unstiffened leg members is more efficient from a purely cost-based decision. However, the scenario where leg members are stiffened is more advantageous from a robustness point of view because the stiffeners strengthen the members locally, making them less prone to local damages during transportation and construction. In addition, internal leg stiffeners are also favorable, making our new type of connection more robust. This new connection will be the subject of future publications.

Overall, the total mass of the mast considering the legs and diagonals yields an aluminum to steel mass ratios of 39% for the unstiffened leg case, and 45% for the stiffened leg case. The corresponding aluminum-to-steel price ratios are 74% and 85%, for the unstiffened and stiffened legs, respectively.

4.3.2. Aluminum Octagonal Hollow Structural Extrusions vs. Steel Angles

An optimized design of the tower was also performed considering octagonal hollow sections (OHS) considering the same scenarios as in the case of the SHS legs, i.e., (1) with and (2) without internal stiffeners for the legs. Table 6 presents the results of the last optimization iteration for a design scenario using stiffeners. In both cases, unstiffened SHS were considered for the diagonals.

Table 6. Results of the last iteration of optimization process using OHS with stiffeners.

Member	Optimized Sections	t_1 * (mm)	s (mm)	C_f (kN)	T_f (kN)	C_r (kN)	T_r (kN)	C_f/C_r (%)	T_f/T_r (%)
F1	OHS150 × 150 × 3	5	3	−499.6	199.6	500.3	773.8	99.9%	25.8%
F2	OHS150 × 150 × 3	5	2.5	−442.4	123.2	452.6	715.7	97.7%	17.2%
F3	OHS145 × 145 × 4	4	3	−390.6	50.9	417.3	692.6	93.6%	7.4%
F1T	SHS40 × 40 × 3.5	-	-	−28.7	29.4	32.7	110.4	87.9%	26.6%
F1L	SHS40 × 40 × 3	-	-	−26.5	20.7	28.9	95.9	92.0%	21.7%
F2T	SHS40 × 40 × 3	-	-	−26.4	25.1	28.9	95.9	91.5%	26.2%
F2L	SHS40 × 40 × 2.5	-	-	−21.1	20.2	24.7	81.0	85.3%	25.0%
F3T	SHS40 × 40 × 2.5	-	-	−24.1	23.1	24.7	81.0	97.7%	28.6%
F3L	SHS40 × 40 × 2.5	-	-	−20.7	19.8	24.7	81.0	84.6%	24.5%

* t_1 presents the thickness of the stiffened part.

For our OHS, the walls that are directly linked to stiffeners are intentionally designed to have a larger thickness compared to the angled sides of the structure (see Figure 4b). This strategic variation in wall thickness serves a specific purpose. By reinforcing the walls that are connected to stiffeners, the overall structural integrity and bending strength of the octagonal section are significantly enhanced.

Table 7 compares aluminum OHS with the HQ's design using steel angles. The scenario using unstiffened leg members yielded to 170 mm OHS leg members with a thickness of 7 mm. The OHS legs are much lighter than the benchmark tower, with a mass ratio of 55%. The related aluminum-to-steel price ratio is 105%, which indicates that the price of the aluminum leg members is slightly more than its steel counterpart. The scenario using stiffened leg members yielded to 150 mm OHS leg members with variable wall thicknesses between 3 and 5 mm, and 3 mm thick stiffeners. The stiffened SHS legs are also much lighter than the benchmark tower with a mass ratio of 52%. The related aluminum-to-steel price ratio is 99%, meaning that the price of aluminum stiffened legs is more or less the same as its steel counterpart.

Table 7. Comparison between aluminum OHS and steel angle members in the critical section of the mast (Section 4, Figure 1).

			Aluminum (OHS)	Steel (Angle)	Aluminum/Steel
Scenario 1: Members without stiffeners	Leg member F1	Mass (kg/m)	10.2	18.4	55%
	OHS170 × 170 × 7				
	L127 × 127 × 9.5	Price (CAD/m)	71.4	68.2	105%
	Diagonal F1T	Mass (kg/m)	1.3	4.1	32%
	SHS40 × 40 × 3.5				
	L64 × 51 × 4.8	Price (CAD/m)	9.1	15.2	60%
	Total mast	Mass (kg)	1099	2204	50%
		Price (CAD)	7694	8157	94%
Scenario 2: Members with stiffeners	Leg member F1	Mass (kg/m)	9.6	18.4	52%
	OHS150 × 150 × 3_t15_s3				
	L127 × 127 × 9.5	Price (CAD/m)	67.7	68.2	99%
	Diagonal F1T	Mass (kg/m)	1.3	4.1	33%
	SHS40 × 40 × 3.5				
	L64 × 51 × 4.8	Price (CAD/m)	9.1	15.2	63%
	Total mast	Mass (kg)	1101	2204	50%
		Price (CAD)	7712	8157	95%

Both scenarios yielded to 40 mm SHS diagonal members with a thickness of 3.5 mm. The SHS diagonals are lighter than the benchmark tower, with 32% and 33% mass ratios for the unstiffened and stiffened legs scenario, respectively. The mass ratios vary even though the diagonal members are the same in both scenarios because the depth of the OHS leg sections influences the length of the diagonals. The related aluminum-to-steel price ratio is 60% and 63%, which indicates that the price of the aluminum diagonals is much less than its steel counterpart.

Both designs using aluminum yielded much lighter designs with mass ratios ranging between 55% and 52% for the legs in scenarios 1 and 2, respectively, and 32% and 33% for the diagonals for scenarios 1 and 2, respectively. The aluminum leg design using unstiffened members proved to be slightly more costly than its steel counterpart, and the aluminum leg members with stiffeners proved to be more or less the same price as the steel legs.

Overall, the total mass of the mast considering the legs and diagonals yields an aluminum-to-steel mass ratios of 50% for the unstiffened leg case, and 50% for the stiffened leg case. As in the case of the SHS legs, the scenario where leg members are stiffened is more advantageous from a robustness point of view because the stiffeners strengthen the members locally, making them less prone to local damage during transportation and construction. Internal leg stiffeners are also a feature that benefits our new prototype connection.

5. Conclusions

The primary objective of this paper is to explore innovative concepts for aluminum transmission towers, aiming to replace conventional materials like steel, concrete, or wood. Because aluminum is typically costlier than traditional materials, an optimization study is performed to reduce the tower's weight by optimizing the shape and size of extruded aluminum sections. A crucial focus of the research involves designing novel extruded section shapes made from aluminum to minimize the cost of the material while exhibiting a solid structural performance. SHS and OHS with and without internal stiffeners were considered in the optimization study. The optimization study demonstrated that it is possible to design aluminum towers that can compete with steel structures from an economic standpoint. In all cases, the mass of the aluminum members was almost half compared to steel. This can be a major advantage for projects where roads must be constructed to deliver the structural parts to the site, or when helicopters are used to bring tower sections on-site. At this point, in preliminary analysis, we neglected the updating of wind and gravity loads by taking

different sections, as the critical design loads come from the conductors. However, this will be studied in future work. The next phase of this project will focus on the design and experimental validation of the novel connection concepts envisioned for the proposed aluminum towers. An experimental validation of the tower concepts presented herein is also planned.

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References

1. Loredou-Souza, A.M.; Davenport, A.G. The influence of the design methodology in the response of transmission towers to wind loading. *J. Wind Eng. Ind. Aerodyn.* **2003**, *91*, 995–1005. [\[CrossRef\]](#)
2. Lee, P.S.; McClure, G. Elastoplastic large deformation analysis of a lattice steel tower structure and comparison with full-scale 254 tests. *J. Constr. Steel Res.* **2007**, *63*, 709–717. [\[CrossRef\]](#)
3. Mennink, J. Cross-Sectional Stability of Aluminium Extrusions: Prediction of the Actual Local Buckling Behavior. Ph.D. Thesis, Department of Structural Design, Eindhoven University of Technology, Eindhoven, The Netherlands, 2002.
4. Mennink, J.; Soetens, F.; Snijder, H. Cross-sectional stability of aluminium extrusions with arbitrary cross-sectional shapes experimental and numerical research. *Heron* **2005**, *50*, 69–92.
5. Mazzolani, F.M. Structural applications of aluminium in civil engineering. *Struct. Eng. Int.* **2006**, *16*, 280–285. [\[CrossRef\]](#)
6. Couceiro, I.; Paris, J.; Martinez, S.; Colominas, I.; Navarrina, F.; Casteleiro, M. Structural optimization of lattice steel transmission towers. *Eng. Struct.* **2016**, *117*, 274–286. [\[CrossRef\]](#)
7. Christensen, P.W.; Klabring, A. *An Introduction to Structural Optimization*; Springer: New York, NY, USA, 2009; Volume 153.
8. Spillers, W.R.; MacBain, K.M. *Structural Optimization*; Springer: New York, NY, USA, 2009.
9. Nielsen, M.G.; Stottrup-Andersen, U. Comparison of the advantages of guyed masts to self-supporting towers. In *Structures Congress 2006: Structural Engineering and Public Safety*; American Society of Civil Engineers: Reston, VA, USA, 2006; pp. 1–10. [\[CrossRef\]](#)
10. ASCE10. *Design of Latticed Steel Transmission Structures*; American Society of Civil Engineers: Reston, VA, USA, 2015.
11. CSA-S157; Strength Design in Aluminium. Canadian Standards Association: Toronto, ON, Canada, 2017.

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