



## Re-use of wind turbine steel towers for pedestrian bridges

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### Abstract

Steel towers used for wind turbines are being decommissioned after relatively short service lives of around 25 years. This abbreviated lifespan is partially due to fatigue loading, although the steel itself may still be safe for normal loads. FORSBERGS and Dissing+Weitling Architecture are investigating the potential for reusing these towers as the primary structure for pedestrian bridges. The focus of these investigations lies in the structural design of a new bridge, constrained by the existing geometry of the steel tower. One approach involves longitudinally splitting a tower into two half-pipe structures that could serve as bridge spans. This study encompasses an assessment of the CO<sub>2</sub> aspect, comparing the overall carbon footprint resulting from a conventional decommissioning of a steel tower with that of repurposing it for a bridge. The proposed concept could potentially apply to narrow pedestrian or bicycle bridges, or utilise side-by-side half-pipes for multipurpose use.

**Keywords:** steel towers; wind turbines; pedestrian bridges; architecture.

### 1 Introduction

The design of a steel bridge should adhere to specified standards, such as Eurocode 3 [1]. Similarly, fabrication and construction must comply with applicable standards, like EN 1090-2 [2]. Whether constructing a new steel bridge or repurposing steel from a wind turbine tower, the design and construction requirements remain largely consistent.

Over 25 years of supporting a wind turbine, the steel structure has largely exhausted its dedicated fatigue life. However, in the case of a pedestrian bridge with minimal design loads throughout its lifespan, fatigue considerations will not govern the design. While the steel structure might be considered worn out for use in a wind turbine, it remains virtually new for a pedestrian bridge.

The imposed geometric constraints could potentially result in an aesthetically displeasing appearance of the bridge, a concern addressed within this article. A recommended practice for structural engineers is to optimize structures based on specific constraints. Developing a structure to serve multiple purposes seldomly results in an excellent technical solution. Figures 1 and 2 depict the possibility of using a portion of the wind turbine tower by slicing it, resulting in shallow end sections while maintaining a full middle section. Several other purposes and ideas are briefly outlined here.

The debate over the carbon footprint of producing one ton of steel construction persists. As per [3], the global average in 2021 stands at 1.9 tons of CO<sub>2</sub> emissions per ton of crude steel. For simplicity, an additional 0.2 tons are considered for cutting, bending, welding, transportation, and installation.



Thus, the total carbon footprint for a new steel bridge amounts to 2.1 tons of CO<sub>2</sub> per ton of steel structure.

The average for crude steel includes the typical use of scrap steel. The carbon emissions for crude steel made solely from scrap amount to 0.7 tons [3]. As outlined in [4], the CO<sub>2</sub> savings achieved by using entirely scrap steel amount to 1.5 tons per ton of steel, aligning with the above statistic.

Estimating the bridge's construction from reused steel tower components, combined with new steel parts as needed, results in an estimated 1.3 ton of CO<sub>2</sub> per ton of steel, marking a 37% reduction compared to a completely new bridge. However, while the tower bridge lacks some structural optimization, the CO<sub>2</sub> savings are approx. 21%.

Another consideration involves the missed opportunity for CO<sub>2</sub> savings since the tower steel isn't intended for remelting but rather used as-is in the new bridge. A fair argument arises: the

utilization of old tower steel in constructing a new bridge reduces the global steel demand by one unit. Consequently, this reduction in demand for new steel offsets the demand for scrap steel by an equal unit, thereby balancing out these two effects.

## 2 Wind turbine tower

### 2.1 Geometrical aspects

Wind turbines are known for their tall and slender steel structures with circular cross-sections that gradually decrease from the base towards the top of the tower (Figure 3). For transportation purposes, the diameter is typically constrained by headroom clearances under bridges, usually with a maximum diameter of 4.2 metres at the base and 3.3 metres at the top. The structure lacks fixed inner obstacles; for instance, stairs or platforms may be held in place solely by magnets to preserve the fatigue class of the primary steel structure.



Figure 1. Pedestrian bridge Option O, approach view

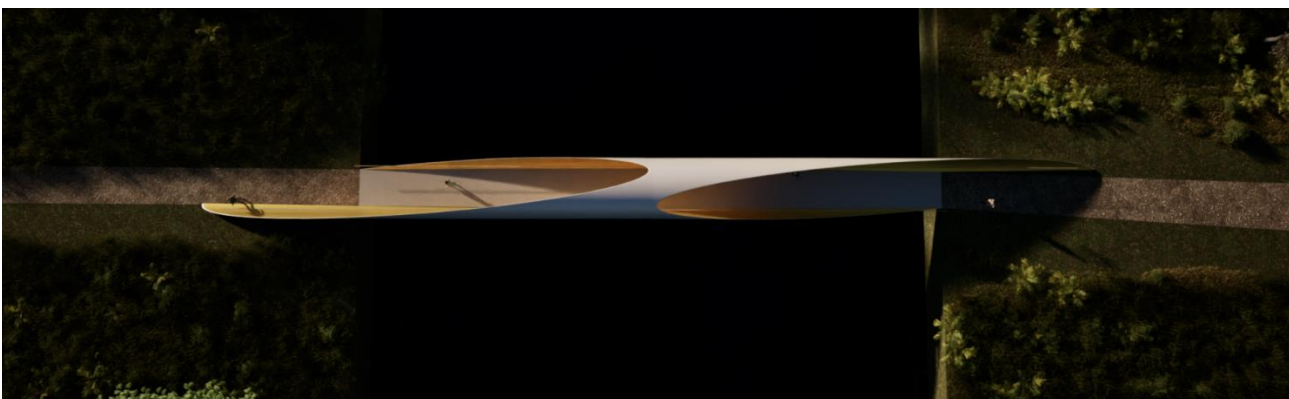


Figure 2. Pedestrian bridge Option O, top view



Figure 3. Wind turbine towers

The tower shaft arrives in segments measuring 20 to 25 metres in length and is assembled using bolted one-sided circumferential flanges. Typically, the skin plate measures 15 to 20mm, a relatively thick steel plate for pedestrian bridges. Consequently, using the tower will result in a heavier bridge compared to one that's perfectly optimized.

A horizontal cut produces a perfect circle, while a vertical cut yields a straight edge, and any cut angle in between tends to be somewhat elliptical. Despite the modest taper, these structures can still be adapted to bridge decks and other structures as depicted here. The challenges are primarily theoretical and can be resolved through practical assembly details. Aligning two parts during assembly requires matching geometry, necessitating the development of astutely chosen cutting principles. The existing bolted flange connections may also be reused.

## 2.2 Logistics

In Denmark, having approx. 6000 onshore wind turbines, the towers slated for decommissioning originate from the early stages of the wind industry, standing at heights around 50 metres. However, in the forthcoming years, the heights are expected to increase to approximately 90 metres, a common stature for a 3 MW onshore wind turbine. The yearly count of towers to be taken down might fluctuate significantly based on market conditions, resulting in non-uniform supply but rather stepwise availability. Assuming, for instance, the removal of 10 towers per year as an argument.

This scenario poses logistical challenges: how can a bridge be planned and designed if the timing and quantity of tower removals remain uncertain?

Two mitigation strategies are proposed: Firstly, the design should encompass geometry ranges, enabling it to accommodate several towers while requiring only one. Secondly, the bridge project should be locally oriented and incorporate flexibility in timing. For instance, consider a community that has had a wind turbine and its tower contributing green energy to the town for 25 years. Repurposing the very same tower for a pedestrian bridge within the same town could be an impactful narrative.

## 2.3 Removal of a tower

Additional options arise when considering the dismantling of the tower for scrap purposes, including the utilization of explosives. However, if the intention is to reuse the tower, the deconstruction process requires a sizable and costly mobile crane, necessitating its expenses to be factored into the project's total cost. The estimated cost for dismantling a tower could amount to approximately 70,000 EUR, or 2-3 times the cost of removing a tower by means of explosives. However, this is a fairly small amount compared to a total cost of a bridge, which could be 3 mill EUR.

## 3 New pedestrian bridge

New designs of pedestrian bridges based on use of the tubular steel element of the wind turbine tower are illustrated below.



### 3.1 Cross-section A – half pipe

The apparent segmentation of the tubular cross-section of the wind turbine tower into two half-pipes, as depicted in Figure 4, results in a beam-like structure capable of spanning long distances while offering maximum floor width and integrated safety railings from the outset. However, this concept tends to require a relatively high tonnage. In order to achieve the necessary beam capacity, top flanges are essential, alongside a straight horizontal floor panel. This design approach may involve a considerable amount of 'unnecessary' steel compared to a fully optimized new bridge design.

The prefabrication of the floor panel allows for welding along the two sides. Once welded to the half-pipe, it significantly enhances torsional stiffness and strength, providing crucial structural reinforcement.

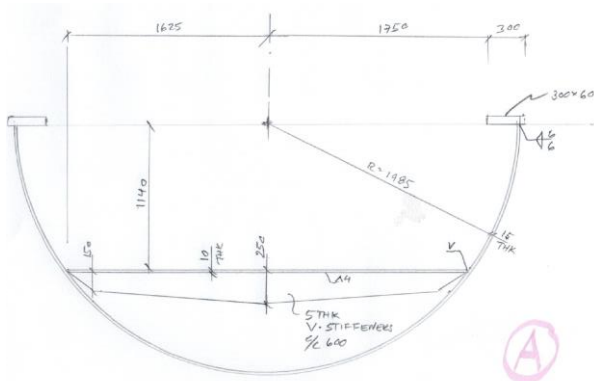


Figure 4. Cross-section A

Another option involves a composite glass-fiber sandwich deck, approximately 50mm thick [5]. However, accommodating the differential temperature expansion presents a design challenge, particularly regarding the support of such a slab along the inner sides of the steel half-pipe. The weight would be ca. 20 kg/m<sup>2</sup>.

### 3.2 Cross-section B – 1/3 pipe

The next iteration of the design, with purpose of reducing the amount of unnecessary steel is shown in Figure 5. The cross-section comprises only 1/3 of the tower circumference, resulting in a 50% reduction in tower material quantity.

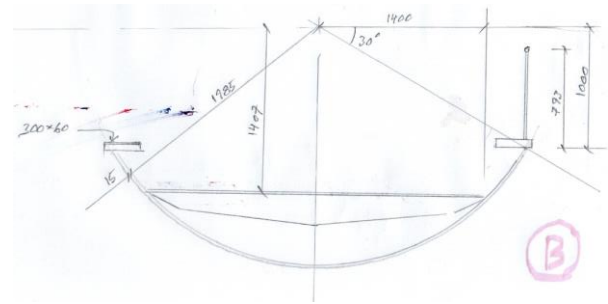


Figure 5. Cross-section B

However, this design choice comes with drawbacks such as reduced floor width and lower railing heights. Consequently, the beam structure is unable to span as extensively as Type A and requires additional handrails. By incorporating an extra handrail, it's possible to attain other advantages such as increased transparency and a lighter visual aesthetic.

### 3.3 Cross-section A and B - variants

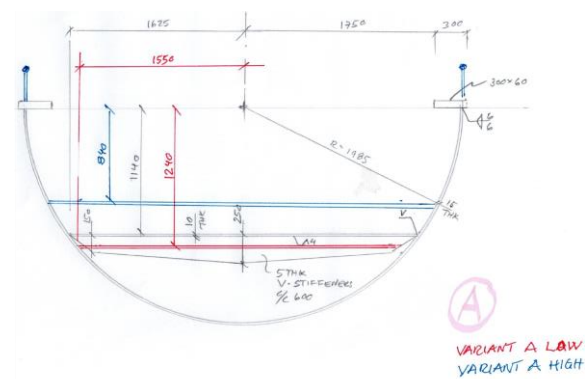


Figure 6. Cross-section A variants low and high

Both options A and B offer the possibility of elevating the floor panel along with the bridge, as illustrated in Figures 6 and 7. The panel would slightly taper in width to accommodate the larger distance at the higher level. When the deck panel is raised, the handrails must also follow suit. The primary advantage here isn't just to gain extra floor width, but also to enable seamless longitudinal bridge profiles without any abrupt changes in the connection spans. While the main structure might have a distinct kink, the walkway remains smoothly curved.

For cross-section A, there might also be a potential to lower the floor panel, as depicted in Figure 6, albeit to a limited extent.





to the girder bottom. This approach allows for the development of aesthetically pleasing supports.

### 3.8 Option B-ST - stair

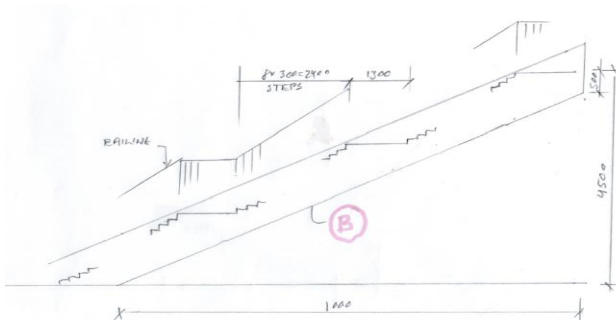


Figure 12. Elevation option B-ST – stair

A 1/3 pipe, sloping at a ratio of 1:2.5 between the bridge end and the ground, featuring stairs and resting platforms positioned between the inner sides of the pipe, can provide pedestrian access (Figure 12). However, the steel consumption for this stair construction might be viewed as extravagant compared to conventional stair constructions.

### 3.9 Option O – full section

This solution enables an impressive 70m bridge span due to the high bending capacity provided by the entire tower cross-section at the mid-span.



Figure 13. Pedestrian bridge Option O, side view



Figure 14. Pedestrian bridge Option O, interior

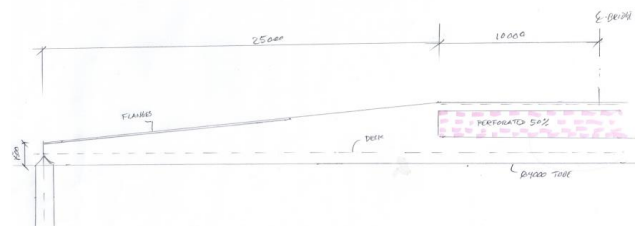


Figure 15. Option O – variant, side view

Optionally, the upper half can be perforated to introduce daylight into the interior of the pipe. The architectural renderings in Figures 1, 2, 13 and 14 depict spans of approximately 50m, while Figure 15 (sketch) presents a concept for a 70m span.

### 3.10 Option C – zig-zag variant

The concept behind this variant (Figure 16) is to showcase the limitation of the tower's straight structure, whereas a pedestrian bridge can incorporate curving elements in its design. While option C typically maintains straightness, allowing for slight kinks and smoothly curved lane strip markings might be acceptable. This type of bridge, for instance, could be ideal for crossing a harbor basin at a lower level.

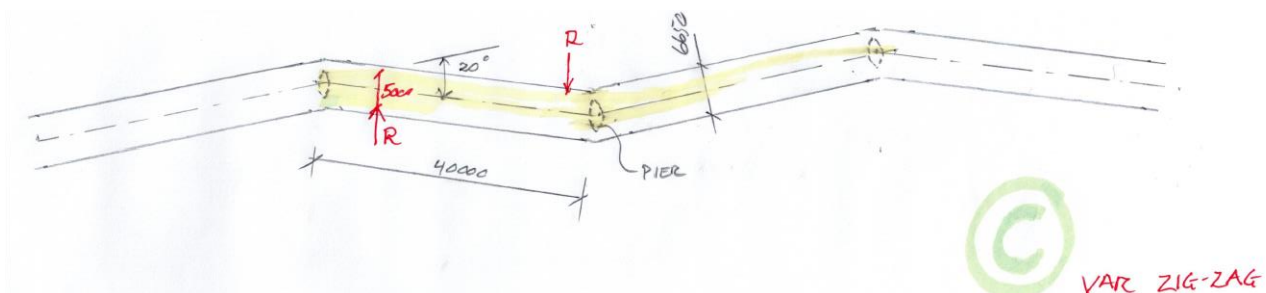


Figure 16. Plan view C – zig-zag



### 3.11 Ramps

A pedestrian bridge often spans heights of around 5 or 6 meters above ground level. Maintaining a limited slope of, let's say, a maximum of 4% requires considerable lengths of ramps (Figure 17). These ramps often consist of fill embankments, the most cost-effective solution, with slopes of 1:1.5 on either side of the pathway. This design necessitates substantial embankment widths, and in confined spaces, sheet pile walls are sometimes employed to contain the ramp's width. Instead of using new sheet pile steel for such structures, an alternative could involve cutting portions of wind turbine

towers and repurposing them as retaining wall material. Option R1 (Figure 18) illustrates full-circle tower sections filled with gravel, forming a base for prefabricated concrete slabs that create a 4% sloping pathway. With tower elements placed at, for instance, 5m c/c (center to center), air gaps are present between them, allowing cross passage.

Option R2 (Figure 19) employs 1/6 shell sections joined by top-to-bottom hinges. By placing every second element upside down, the asymmetric effect of the tower taper is counterbalanced, utilizing the total circumference of tower steel efficiently. Transverse rods maintain load balance between the two sides.

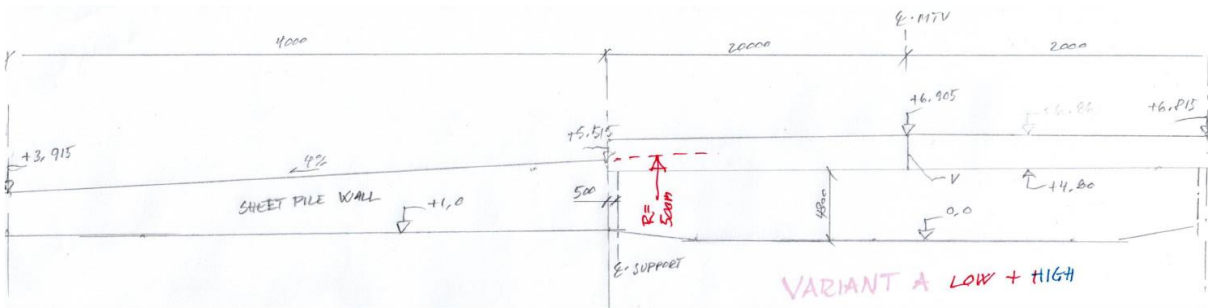


Figure 17. Elevation – bridge span with ramp

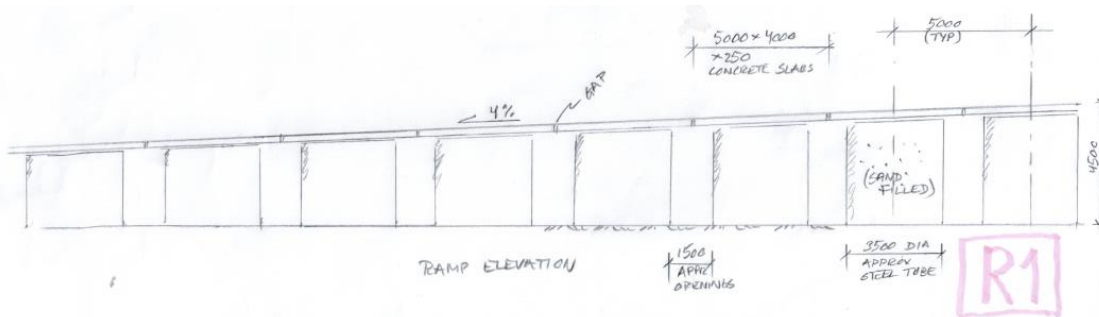


Figure 18. Ramp option R1

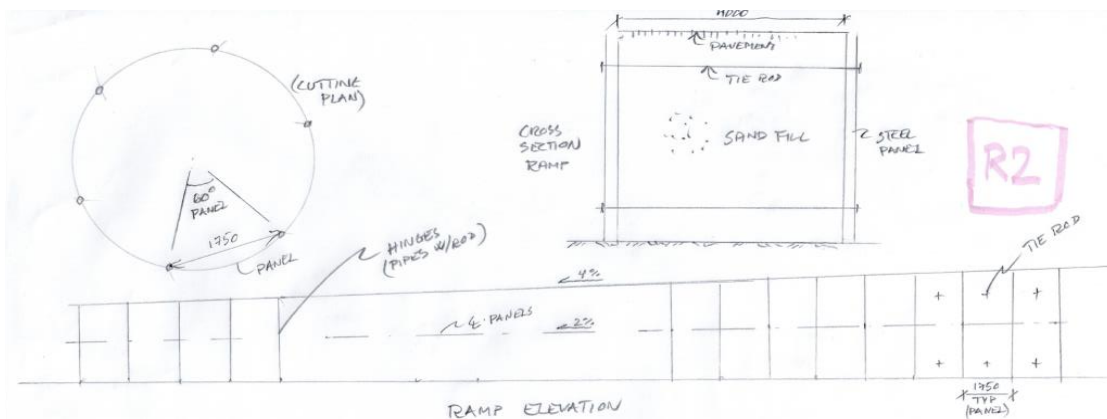


Figure 19. Ramp option R2



## 4 Embodied carbon comparison

### 4.1 Examples

The CO<sub>2</sub> emissions may be compared for the various options, some of which are shown in Figure 20.

Option	New	A	B	A <sup>GRFP</sup>	B <sup>GRFP</sup>
Weight t	40	50	40	42	32
Ratio	0/100	60/40	47/53	75/25	66/34
CO <sub>2</sub> t/t	2.10	1.32	1.49	1.13	1.22
CO <sub>2</sub> t tot	84	66	60	47	39

Figure 20. Comparison table

The weights of bridge spans have been calculated based on a 40m span and 4m width, with the ratio indicating the proportion of repurposed material to new material.

Significant reductions in CO<sub>2</sub> emissions are observed, particularly when utilising a fiberglass sandwich deck in combination with other methods.

Ramps, however, might require a substantial amount of steel compared to the aforementioned structures. Using sheet piles along both sides of the ramp could necessitate up to three times the steel of the bridge span, totaling 120 tons. Alternatively, constructing ramp confinements from wind turbine towers could result in a 10–20% increase in steel usage. Surprisingly, despite the additional steel, this alternative structure would have a minimal CO<sub>2</sub> impact, ranging only between 0.1 and 0.2 tons of CO<sub>2</sub> per ton of structure. Consequently, this approach could yield significant CO<sub>2</sub> savings.

### 4.2 Carbon emission

The carbon emissions from producing 1 ton of new crude steel are estimated at 1.9 tons (ref sec 1), while reused tower steel has no associated CO<sub>2</sub> emissions, effectively standing at 0 tons CO<sub>2</sub> per 1 ton of structure. As indicated in [6], the energy required to produce 1 ton of new steel from iron ore might be around 9 GJ, whereas utilizing scrap steel reduces this energy demand significantly to

approximately 1.3 GJ. This highlights a substantial CO<sub>2</sub> reduction achieved by using existing steel, a well-known fact in today's context.

The carbon footprint for a fiberglass sandwich panel remains the same as for new steel, measuring 1.9 tons per 1 ton structure. However, the considerable advantage lies in its weight, as it only amounts to 1/6 of the weight of a steel deck alternative.

### 4.3 Cutting, welding, transport and installation

Cutting, executed through various techniques like plasma cutting, contributes relatively minimally to the overall CO<sub>2</sub> footprint of steel constructions. Techniques such as plasma cutting generally contribute very little due to the small amount of steel melted during the process, typically around 2mm in cut width compared to the total tonnage of steel used.

An arc cutter, for instance, operates at approximately 9 kW power and melts steel material at a rate of about 75 grams per minute [7]. Despite a notable energy loss in the process, the overall impact remains relatively small due to the limited quantity involved.

Welding, essential for bridge construction, sees a welder producing a 25 mm weld seam per minute using an aggregate power consumption of 3 kW. For a 40-ton bridge structure requiring a total weld length of 1000m, the total energy consumption sums up to 2000 kWh or 7 GJ. This energy usage, however, is significantly lower than that expended in steel production (52 – 360 GJ for 40 tons bridge structure).

Transport, inclusive of fuel use and energy for vehicle and crane manufacturing, contributes relatively minimally to the overall CO<sub>2</sub> footprint.

In this article, the combined consumption for these secondary contributors is estimated at 0.2 ton CO<sub>2</sub> per 1 ton of structure.



## 5 Architectural appraisal

### 5.1 Wind turbine towers reimaged as pedestrian/bike bridges: Aesthetic and sustainable synergy

The reuse of wind turbine towers as pedestrian and bike bridges offers a unique chance for architectural adaptation, sustainability, and aesthetics. In this discussion, we explore the options that makes readaptation not only ecologically and economically sound but also socially and aesthetically compelling.

### 5.2 Architectural adaptation

The repurposing of wind turbine towers for use as bridges necessitates a creative process of architectural adaptation (Figure 21). These iconic structures symbolize a transition toward a more sustainable future. Architecturally, the towers are transformed, yet their geometric characteristics persist. Working with these geometric restraints can yield original solutions and the resulting framework can offer a design solution distinct from traditional bridges. An adaptation to a new reuse can therefore be a statement of innovation while preserving historical elements.

### 5.3 Aesthetic responsibility

Repurposed wind turbines should display the patina and history embedded in the reused objects. It should not be hidden away and unnecessary processed. Wind turbines, as symbols of sustainable change, bring an inherent historical significance to new structures it is repurposed as. Their characteristic geometries should be integrated into the new design, but this does however require an aesthetic responsibility from designers. Making the most of available resources and minimizing waste is worthwhile pursuit in itself, but it should still result in an elegant bridge that people in the near and far future enjoy looking at and interacting with.

### 5.4 Social sustainability

Beyond their environmental and economic merits, windmill bridges could contribute to social sustainability. An integrated solution could reflect

the values and aspirations of a community. The reuse of wind turbine towers to create mobility, connecting people and promoting biking would be a commitment to sustainable practices. A second wind for the material that already has produced green energy, now further continuing this story. That is furthermore why the history of the geometry, and its materials should not be hidden since the reuse may symbolize a transition towards a sustainable future that some community would embrace and share a sense of pride in. This pride being paramount to the longevity of the bridge.

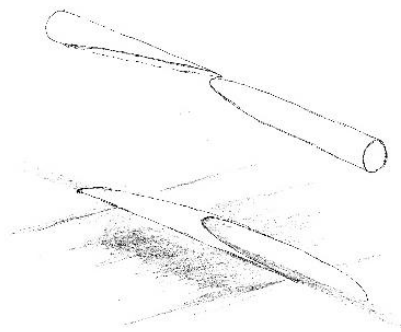


Figure 21. Pedestrian bridge Option O, dynamic shape cut from tower geometry

### 5.5 Multicultural canvas

Wind turbine bridge project could serve as a multicultural canvas where craftsmen and designers learn to adapt to a shifting paradigm, where reuse becomes an integral part of the norm. The act of repurposing these would require new skills that will produce craftsmen and designers with the skills and experiences to further push the concepts in other areas of infrastructure and the built environment.

### 5.6 In conclusion

The repurposing of wind turbine towers as pedestrian and bike bridges represents a unique blend of sustainability, architectural adaptation, and aesthetics. This endeavour could demonstrate our ability to adapt, conserve, and embody a commitment to a sustainable future. These transformed structures can become symbols of change and innovation, enriching a community both culturally and physically.



## 6 Conclusions

Various possibilities for repurposing wind turbine steel towers into new pedestrian bridges have been briefly explored and deemed technically feasible. While a detailed cost analysis in comparison to fabricating new steel structures remains pending, initial assessments suggest that costs may either be on par with or lower than those of new constructions.

Optimizing the architectural merits of a bridge using reused steel tower components is an engaging exercise, despite the inherent constraints. These constraints prompt intriguing architectural evaluations and encourage innovative solutions.

However, it's essential to note that repurposed structures may not offer the same architectural freedom as entirely new bridges. Surprisingly, our assessments so far indicate that aesthetics may not suffer as much as anticipated. The designs illustrated in this article portray potentially impressive outcomes.

The reuse of wind turbine towers could result in a noteworthy saving of up to 1 ton of CO<sub>2</sub> per 1 ton of bridge structure. Interestingly, differences in cutting, welding, transport, and installation between the two alternatives contribute relatively little to the overall CO<sub>2</sub> consumption.

Ramps leading to the bridge can also feature earth retaining structures constructed from repurposed tower parts.

The plan is to expand upon this idea, validating the preliminary estimated CO<sub>2</sub> reductions highlighted in this article. A comprehensive examination of the pros and cons concerning technical quality, economic feasibility, and carbon footprint will be conducted to substantiate the concept.

## 7 Acknowledgement

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