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Structural Design with Reclaimed Materials: an Elastic Gridshell out of Skis

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Abstract

This paper presents the design and construction of a 36m^2 gridshell, the rigidity of which is achieved through the bending of an initially flat grid of 210 reclaimed skis. The generated waste for its production is near zero as it is mostly built from discarded material. Its construction process is such that it can be disassembled and reassembled multiple times without scaffolding and by means of traditional tools only. After a brief introduction on the need for reducing embodied carbon and waste in structures through reuse, the paper sets up the constraints that have driven the definition of the pavilion, the main one being the extension of the lifetime of high-performance sport equipment by reclaiming their intrinsic mechanical properties. The paper then details the encountered unusual aspects in the design process and how they have been overcome – *i.e.* sporadic material supply, categorization of mechanical properties, physical alteration of these properties, and uncertainties in the numerical modelling of both the structural analysis and the construction process. Eventually, we conclude that reclaimed skis as a material have the potential to be as good as conventional timber when designing elastic gridshells. A series of future directions for this emerging field of research are also laid out.

Keywords: conceptual design, form finding, gridshell, active-bending structures, material reuse, design for disassembly, skis.

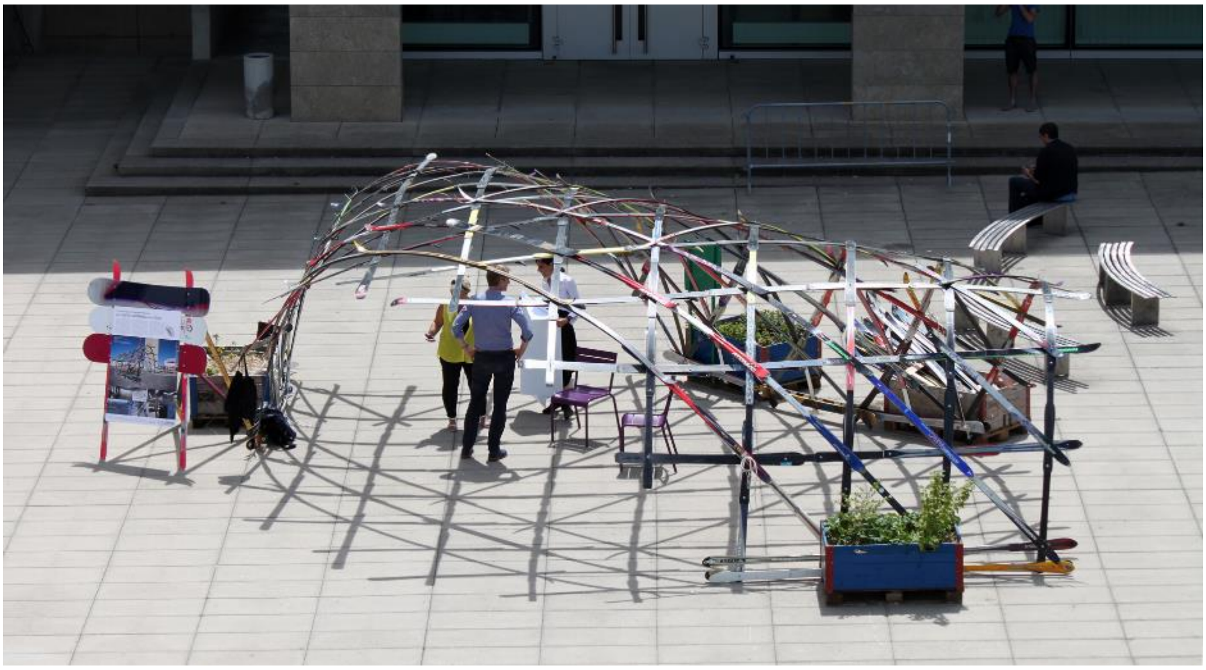


Figure 1. Third installation of the ski pavilion, EPFL, Lausanne, Switzerland.

1. Introduction: reusing components for structural purposes

To drastically reduce embodied carbon and waste production is a big challenge in the construction industry and especially in the structural design practice.

On the one hand, the manufacture, the construction, and the end-of-life of load-bearing systems is responsible for about three quarters of the embodied energy in office buildings (Kaethner & Burridge, [17]). A share that plays an increasing role in the overall energetic impact of buildings since past and current efforts have reduced the need for operational energy – *i.e.* heating, cooling, lighting, air-conditioning and electric appliances – to a minimum (Hoxha et al., [15]). On the other hand, the construction and demolition industry is responsible for the major part of waste production in terms of volume and weight (EU, [7]). Superfluous waste production in the building industry threatens earth's eco-system regarding material exhaustion and pollution, and runs counter to the rational use of energy and workforce.

One can identify five strategies to address this double issue: reduce (the amount of resources needed), repair, reuse (or redistribute), recycle (through mechanical and chemical transformations), and restitute (to the ecological context). Circular economy is the wise application of all these strategies (EU, [7]). Although a critical component of circular economy, the reuse approach is today seldom addressed when it comes to designing structural systems. Reuse means changing the location and/or the function of an element without significantly altering its physical features. Almost every recent implementation of reuse in the building industry concerns components that are not load-bearing – *e.g.* the envelope, and the indoor and outdoor finishes (Chopin & Delon, [6]). This wasn't the case prior to the industrial revolution (Barnes, [4]). Today, rare demonstrative examples of reuse for structural purposes can be found in the work of Jean Prouvé (Chopin, [6]), Arrow Architecture & Engineering (Aubry, [3]), SSD Architecture [24], and Arup [2]. The academic world recently embraced the topic too, both in the field of design for disassembly – see for instance Paduart *et al.* [23] and Durmisevic [11] – and in the field of design from reclaimed material – see Baverel *et al.* [5].

The pavilion presented in this paper (Figure 1 and Figure 2) reclaims abandoned sport equipment for new structural purposes. Sport equipment falls in the category of high-tech products that are rapidly obsolete for purely external (understand fashion) reasons. Therefore, it usually generates a continuous and large flow of wasted resource that is hardly recoverable. In particular, elastic and resistant products such as skis, fishing rods, and pole vaults, are generally made from different performing layers, including fibre reinforced polymers, glue, foam, etc., which meet customer's expectations in terms of performances but also head these products towards an inglorious end-of-life. Not only the material and the energy needed for its fabrication is wasted, but also the technology and the mechanical behaviour embedded in it. This paper shows an application that benefits from the embedded qualities of such products while extending their life span and therefore reducing the need for new manufacture. It also proves that some sport products are well suited for new large-scale structural purposes.

To design with reclaimed material is not straightforward and implies a complete redefinition of the conventional structural design process. The properties of the elements of the system (*i.e.* lengths, cross-sectional areas and inertia, modulus of elasticity, strengths) do not result from computations but are a given. The global geometry of the structural system is not a given, but the end result. This pavilion acts both as a methodological case-study for design and construction of a load-bearing system from dismissed engineered products and as a protocol set up to manage unclassified waste.

This paper first introduces the set of design constraints that led to the choice of an elastic gridshell and then to the choice of skis (Section 2). The methodology of the design process (Section 3) and of the construction/deconstruction process is then given. Key unconventional methods are highlighted throughout the text. The environmental impact of the pavilion is discussed in Section 4.

Figure 2. The ski pavilion: second assembly in the courtyard of the Blue Factory, Fribourg CH, on the left; fourth assembly in *La Sucrière* for the "Biennale Architecture Lyon" FR, June 2017, on the right. From left to right, three ballasts replace the connecting ropes and constrain the position of the three ground edges.

2. Project overview

The typology of the structure, an elastic gridshell, was initially set as a design constraint. A pavilion made of reclaimed sport equipment suitable for bending involves the idea that such components should have been locally sourced. Though it could have been possible using fishing rods or pole vaults, the large availability of discarded skis in Switzerland became the starting point for further reflections, along with the intention of speeding up the construction and further reconstructions through a fast assembly and disassembly process.

2.1. Elastic gridshell typology

Strained gridshells are widely acknowledged as lightweight, appropriate, eco-friendly, simple construction, available to cover large spans and complex structural forms by means of small components. Scaffolding can be reduced, depending on the size of the structure, and transportation of straight components (whose prefabrication is potentially identical for all the elements) is easier than curved ones. The geometrical stiffness of an elastic gridshell can also allow different parameters of variation such as: the number of layers, as in the *Mannheim Multihalle* (Happold & Liddell, [14]), or the span between nodes, as in the *Downland Museum*, or the material quality, as in *Toledo I* (Pone *et al.*, [22]) where the more elastic laths were primarily placed where the radius was minimum.

There are no precedents in the design and construction of an elastic gridshell out of reclaimed material. However, a geodesic dome of 54 skis can be found in Baverel, [5]. Besides, it seems that bending active gridshells out of reclaimed components have good potential in the development of a new generation of bending-active structures because they are forgiving architecture, able to incorporate high tolerance variations of sizes and behaviours.

The design of the skis pavilion draws on the recursive relationship between form-finding, construction methods, and material performances. The form-finding process commenced, following the tradition of Frei Otto, with a physical model, scale 1:10, out of timber sticks. This first result has been combined with a two-step real-time physics simulation engine: 1) a first dynamic relaxation performed through the *Gridshell Form-Finding Tool* "GFFT", described in Pone *et al.* [22], of a two-layer flat lattice, to achieve a first doubly-curved shape; and 2) a further digital simulation of the construction process, aimed at fulfilling the construction and structural requirements (see chapter 3.2).

Given the relatively small span of the pavilion, two orthogonal layers of skis were chosen. For larger structures, where the bending rigidity of a two-layer grid would not be sufficient, it is usually necessary to double the layers, that means increasing the inertia, as well as the material cost. The first simulation was run with a span between nodes of 50 cm; the result was a too high initial bending stress condition where breakages of the laths is likely to happen. Decreasing the grid density to 90 cm span between the nodes (which decreases self-weight, working time, number of components) was considered a safe degree of tolerance. In a traditional elastic gridshell, the stress generated by the forming process may determine the cross-sectional size. In this case, the cross section is given and is variable ski by ski, making the span between nodes and the number of layers, the actual variables. An additional variable was introduced thanks to the varying nature of the skis (that is their varying bending strength, Figure 4) and the varying geometrical stiffness of the gridshell. Compensation of stiffness was obtained by allocating skis of higher bending strength where the shell presents lower geometrical stiffness, *i.e.* smaller curvature.

A diagonal bracing system (acting as struts or ties), triangulating the square grid geometry, is set to ensure in-plane shear strength, as well as tightening the connection bolts to reach the final rigidity. Untightening the bolts during the bending phase, allowed the required cylindrical hinge-like kinematics. Additional rigidity was introduced while overlapping the bracing skis forming a same diagonal line.

2.2. Reclaimed skis

The environmental footprint in terms of global warming potential for the treatment of 1 kg of wasted skis is approximately 2.27kg CO2-eq (Luthe *et al.*, [21]). Such amount of carbon dioxide is equivalent to the emission of the same quantity of gasses during the process of production of 12 kg of concrete or 7 kg of timber. This comparison highlights the importance of extending the lifespan of discarded skis.

The industrial interests into the ski business and the need for safety regulations to prevent failures or injuries for the users, has led to the definition of ISO standards (De Gobbi & Petrone, [10]). Still, the design of the structural behaviour of the skis remains an object of research (Jentschura & Fahrbach, [16]). Carving skis mechanical properties fulfil high demands because the strongest forces act on the thinnest portion of the ski; yet, they must be rigid enough to avoid vibrations of the shovel and tail and, at the same time, elastic enough to absorb the strong lateral forces exerted during turns. All these characteristics play a key role in the determination of skis performance and in the way their second-life can be projected for structural purposes.

The aptness of skis in the field of bending-active structures, was first suggested by their physical characteristics in comparison to the material selection chart compiled by Ashby [1]. Along the main axis, skis have a high breaking strain and low modulus of elasticity combined with a low moment of inertia. Along the two transverse directions, skis have high flexural rigidity. Moreover, skis present a non-brittle behaviour. The choice for skis was also suggested by the recognised potential of fibre reinforced polymers as recommended material – except for their high cost – for bending-active structures (Lienhard *et al*. [20]).

Their high performances, despite use and age, have been confirmed during the construction of the pavilion and are substantial especially if compared to other elastic materials such as timber and bamboo. Thousands of skis are discarded every year in Switzerland alone. To retrieve parts of the embedded technology in those skis is not only opportunistic but also prevents other resources to be use instead.

3. Design and construction process

Compared to conventional structural design processes, this one is flipped over because a number of decisions were a consequence of – not a cause leading to – the quantities, geometries, and mechanical properties of the elements. The inherent variability related to the use of reclaimed skis is here overcome by ensuring load-path redundancy and high factors of safety regarding bending stresses and bending curvature. The following can be considered as a protocol for the use of reclaimed materials for structural purposes.

3.1. Inventory of locally sourced material

Once the bindings were removed, a specific inventory of the collected skis (see Acknowledgments) has been set to survey their geometrical characteristics and their bending resistance. The measured parameters are: the total length of the ski; the length of the ski before the shovel; the maximum tip width before the shovel; the position of the waist; the waist; and the tip, tail and waist thicknesses. These data were then used with Grasshopper® to model each ski onto the construction drawings as well as to inform the jointing system, the push up system, the bracing, and the boundaries.

To take into account the heterogeneous nature of the collected set of skis, a series of non-destructive bending tests have been performed on each ski (Figure 3). Each ski is supported in two points at 1m distance, the vertical load is applied at mid-span. The outcome is a load-displacement relationship (Figure 4), a value that has been used to allocate the skis on the flat lattice while compensating local lack of geometric flexibility of the shell with higher material rigidity of the skis (see Section 2.1). Thanks to this simplified measurement a computation of the cross-sectional area and of the stress values was avoided, which would have been otherwise highly time-consuming given the variable sections of each pair of skis and the composite nature of the material. Except for three pairs of skis, no plastic deformation has been noticed during the tests. Out of the 350 collected skis, 210 were used in the pavilion.

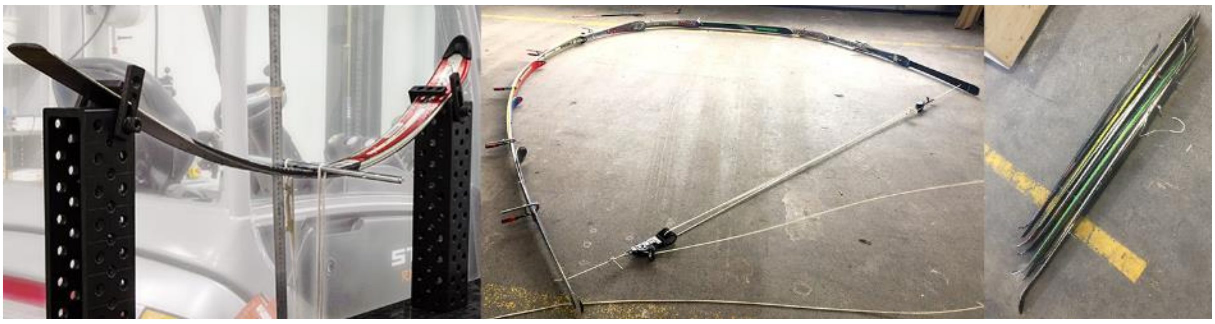


Figure 3. Bending stiffness tests on a ski (left) and on a nominal arch (centre). Folded arch (right).

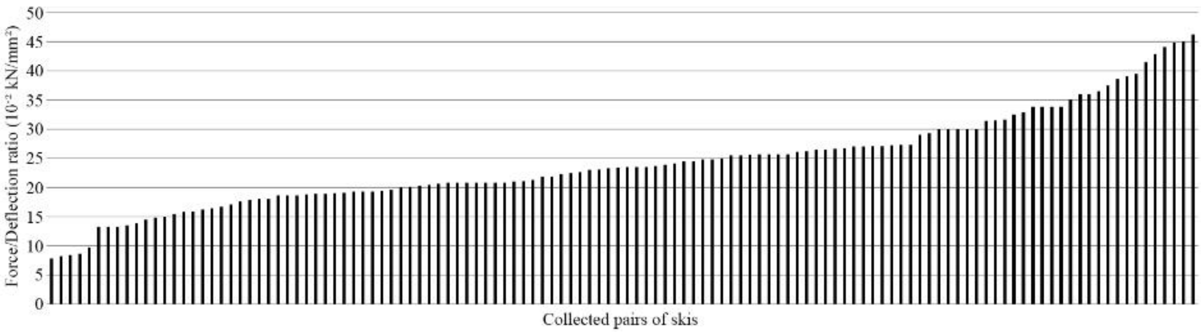


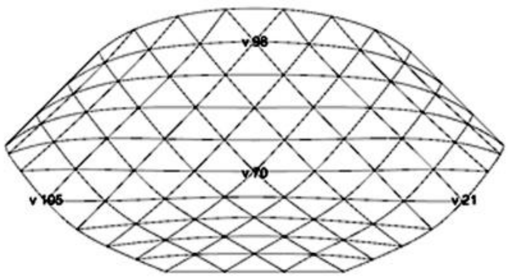
Figure 4. Heterogeneous distribution of the stiffness of the collected skis. Skis for children, free-style and cross-country are mostly on the left of the table; full steel professional and army skis are on the far right.

3.2. Form-finding and structural analysis

The simulation of the bending process which was required to determine the final gridshell shape, was carried out by adopting the numerical framework described in D'Amico *et al.*, [9]: a co-rotational finite element formulation (Crisfield, [8]) is employed for each beam-element, whilst the solution of static equilibrium is iteratively sought by using an explicit integration scheme (4^{th} order Runge-Kutta method). The adopted numerical scheme is an implementation, with 6 degrees of freedom (DoF) per node, of the dynamic relaxation scheme, which is usually implemented by only considering 3 DoF per node. The kinematic of the nodal connections between the actively bent members was modelled by using the cylindrical hinge joint as described in D'Amico *et al.*, [9]. Zero-length axial springs were used to simulate the system of horizontal and vertical cables pulling the grid into shape. The variable cross-section of each ski was modelled assuming an average constant value for the numerical model of 1x8 cm, whilst an approximate value of 10^8kN/m^2 was set for the elastic modulus.

The simulation of the forming process was primarily carried out to assess the final deformation of each member, hence checking that such curvature values were below the maximum allowed one, which was determined by preliminary experimental bending tests (as shown in Figure 3). The forming process simulation also provided an estimate for the maximum tensile force (2.19kN) of the horizontal cables, thus qualifying the use of specific ropes, through an adequate number and type of pulleys (Figure 7).

Once the simulation of the bending process was completed, 50 skis were added to the 3D model in order to triangulate the quadrangular grid. Such bracing was modelled as simple axial springs, since, for the structural analysis, their contribution is only related to increasing the in-plane stiffness of the gridshell. Also, the boundary nodes, previously pulled into position by aid of zero-length springs, were restrained against translation in the three Cartesian directions and a load of 0.4kN was applied to each node of the gridshell by increments of 0.04kN. The total load of 0.4kN per node roughly corresponds to a uniformly distributed load of 0.49kN/m^2. Load-displacement curves were derived for four representative nodes of the structure, reported in Figure 5. The rate of deformation of the structure increases non-linearly with the load. Nonetheless, buckling instability does not represent the critical issue for the described structure given the assumptions of geometric non-linearity and linear-elasticity of the material, given the results of the numerical model, and given the temporary nature of the pavilion. The buckling load, calculated at 9.41kN/m^2, assumes a linear-elastic behaviour of the skis. Reducing the span between nodes from 90cm to 70cm would reduce the maximum displacement by an increment of 1.44cm, and would increase the initial tensile force of the ropes by 2.58kN. The range of displacement magnitudes shown on Figure 5 were later confirmed with basic experimental loading on the constructed shell, which supports the need to double the layers of skis if a stiffer structure had to be designed.



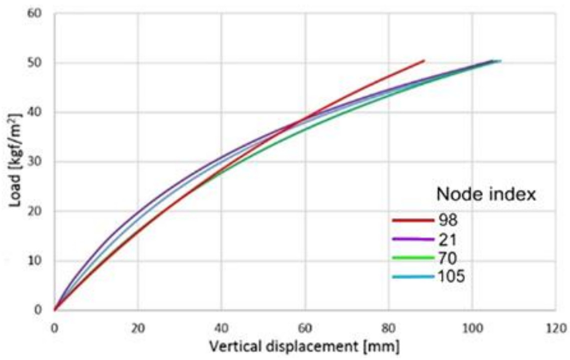


Figure 5. Reference nodes used to monitor the deformation behaviour of the gridshell during the load analysis (on the left). Nodal load-displacement curves obtained from the load analysis.

3.3. Design for Disassembly

The layout of the skis on the flat grid was designed according to the following criteria: 1) their reciprocal fitting into a simple connection made of one M8 bolt, two washers and a nut; 2) ski stiffness compensating the lack of geometric stiffness; 3) no fixed connection to the ground.

The flat grid is prefabricated into its orthogonal arches which are brought to site packed and folded like folding rulers (Figure 3, on the right); once in position they are unfolded on the ground and connected with each other. The specific positioning of a ski on an arch depends on its relative stiffness and on the way the geometry of its shovel and tail allows superimposition with other skis or connection with the rope system on the ground. The major number of used skis was characterised by an almost flat tail and a curved shovel measuring 8 to 15cm. For this reason, the first bolts (M8, 60mm) on the tail are set to

6cm from the initial point, the second and third (M8, 80 and 100mm) spacing 90cm each other, are set according to the specific sorting on the arch (Figure 6). The simply-bolted joint behaves as a pivot, allowing relative rotation between the arches. It also allows the tightening of a ring bolt to tie the boundaries with the ropes.

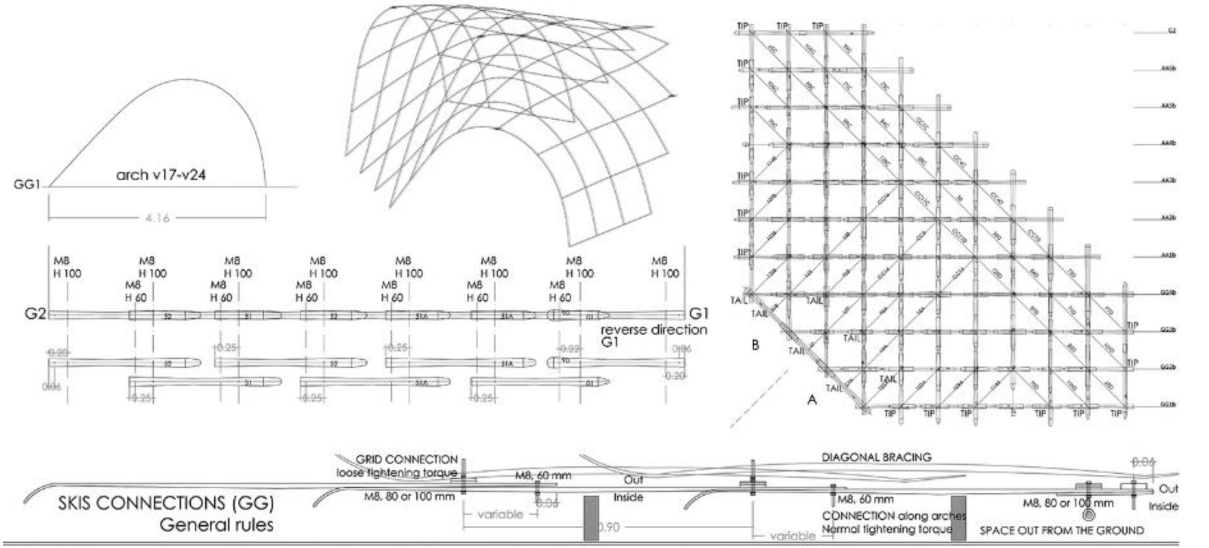


Figure 6. Ski sorting along the arch, as a consequence of the geometry stiffness of the gridshell (on the left). Bracing system (on the right). Ski assembly detail (below).

The pulling system derives from ancient tools and naval techniques in order to make it manually operable by a single person. It is made of two symmetrical blocks and tackles, each made of a threefold purchase, amplifying six times each the tension force (Figure 7). Two pulleys and blocks are fixed on the boundary EH and connected to the symmetrical boundaries AB and CD. Two stilts are used to help the central area rise and keep it in place while the set of bracing skis is being added and the bolts are being tightened. An analogue set of ropes then replaces the pulling system. The correspondence to the designed gridshell is verified through a set of reference points in the xyz space.

Figure 7. Plan view of the push-up method (on the left). Blocks and tackles (on the right).

The disassembly is achieved by flattening the shell on the ground and then removing the structural bolts while leaving in position the 60mm ones; this allows to fold each arch into a handy component by simply rotating each ski around the 60mm bolts (Figure 3, on the right). So far and after five assemblies over a period of two months, the deformation process of the skis has been proved to be elastic and hence reversible.

On average, the assembly process takes about three hours and four workers, from the unfolding of the arches to the removal of the pulling system. The disassembly is twice as fast.

4. Discussion

The built pavilion is characterised by a global high deflection which would be improper for real-world application, and even more so if cloth or cladding are to be hung. However, this lack of stiffness depends on the project and not on the material itself and is mainly due to time constraints and to a lack of knowledge prior to the experiment.

The built pavilion is made of single layers of skis – a choice that is uncommon to timber gridshells and that was followed to simplify assembly and disassembly. The authors expect that the construction of a doubly-layered gridshell of skis is feasible and will present substantially smaller deflections. Further to these considerations, the pursued goal of not connecting the structure to the ground plays a major role in the elastic deformation of the overall system. Further developments of the research project should consider evaluating the long-term behaviour of the skis under permanent stress, the variation of span between nodes, the overlapping length, the number of layers, the coverage system, and the connection to the ground.

A life-cycle assessment has been conducted both on the ski gridshell and on a speculative timber gridshell with same characteristics (64m^2 flat grid, 36m^2 footprint once shaped, 1 layer in each direction) except the span between nodes, set to 50cm instead of 90cm, Figure 8. The study period has been set to one-year and includes the following stages: production, transport to construction site, construction stage, use stage, and end of life. In the case of the skis, the production stage started from their disposal. The cumulative energy demand environmental indicator (Frischknecht *et al.*, [12]) and those proposed in CML methods (Guinée *et al.*, [13]) are evaluated using the Ecoinvent database (Kellenberger *et al.*, [18]). For the Swiss context, the cumulative energy demand, non-renewable and global warming potential indicators are most pertinent (SIA-D0236, 2011). Eventually, the cut-off method described in PAS-2050 (2011) is set to calculate the benefits of reclaimed skis as structural components.

Considering the average weight (1.5kg) and the average useful length (1.6m) of each ski, the weight of the 210-skis pavilion is 315kg, or about 5kg/m². An equivalent timber gridshell with the following characteristics: 1) larch specific weight: 800kg/m^3; 2) laths section: 2.5x5cm; 3) flat lattice made of 242m of laths; gains the total nominal weight of 484kg, 35% more than the ski one. In this evaluation, no bracing, ground connection, nor nuts and bolts have been considered.

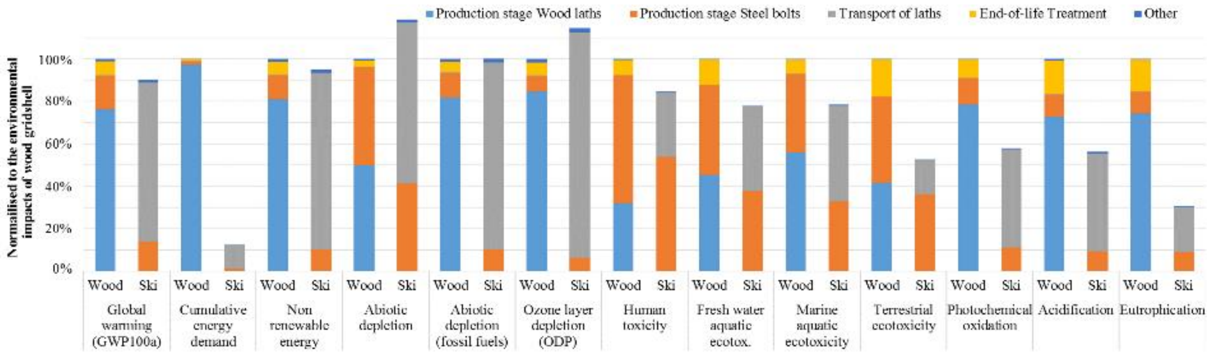


Figure 8. Environmental impacts comparison between a ski gridshell and a timber gridshell.

The comparison between the environmental impacts of the two gridshells (Figure 8) shows that:

- Transport stage can be considered as the largest contribution to the overall impacts when reusing the skis. As a result, future collections of discarded skis should not exceed a limit distance of transport.

- To reuse skis generally has a positive effect on environmental impacts, especially in terms of cumulative energy demand, non-renewable and global warming potential indicators.
- A ski gridshell shows higher impacts of abiotic depletion and ozone layer depletions.

5. Conclusions and perspectives

This paper details the design and the construction of a 36m² elastic gridshell that reclaims 210 discarded skis. The need for reusing components in structural design was first addressed. The paper then detailed: why skis are suitable for elastic gridshells; how confidence in the behaviour of such reclaimed material has been obtained thanks to basic mechanical testing and sorting; how the design process was shaped such as to compensate the lack of knowledge about the material; and how the construction details allowed for repeated rapid erection and dismantling. Finally, the need for additional study on the matter was discussed and the environmental impact of the obtained elastic gridshell in skis was compared with an equivalent timber one.

Conclusions can be drawn on two levels. Firstly, this pioneering experiment proves that reclaimed skis are a potentially very good choice when designing bending-active structures, especially regarding weight-to-performance ratio and environmental impact. Secondly, it is possible to define a design/construction protocol that provides sufficient confidence throughout the process although information on the reclaimed component, its actual material composition, its mechanical behaviour, and its history remain sparser than usually expected.

To reuse discarded components not only allows material to be saved from the landfill and the use of brand new components to be prevented; it also allows the high technology embedded in the material to be retrieved, turning a moral issue into an engineered one. Still, substantial research involving the development of new tools and design methods should be completed before this emerging approach can be scaled up to routine practice.

Acknowledgements

All skis used for the pavilion were considered waste at the time of pick-up except for three second-hand pairs used for preliminary testing. The skis either originate from the Fribourg waste collection site, from the ‘damaged skis’ unit of Scott Sport Givisiez or from the set of a performance held in Gruyères, Switzerland. Claude Alain Jacot, Charles Riedo, Dominique Corday, Alberto Pugnale and Serena Vanbutsele helped collecting these skis. The skis have been disassembled from their bindings, surveyed, and tested in the smart living lab with the collaboration of Jan Brütting and Valeria Didonna. In addition, Jacopo Orlandi, Julieta Moradei, Elena Jacobs Fernández and Alex Muresan offered their occasional help to reassemble the pavilion.

References

[1] Ashby M., *Material selection in mechanical design*, Pergamon Press LTD, Oxford, 1992, p. 45.

[2] Arup, *The Circular Building*, http://circularbuilding.arup.com, 2015.

[3] Aubry F., *Heurs et Malheurs de l’Œuvre de Victor Horta*, www.artnouveau-net.eu, 2010. See also Arrow Architecture & Engineering, *Horta Grand Café & Art Nouveau Zaal*, Antwerpen, Belgium, 2000. http://www.grandcafehorta.be/victor-horta.

[4] Barnes, S, Le métabolisme urbain, *Matières Grises*, J.Chopin & N.Delon (Eds), Editions du Pavillon de l’Arsenal, Paris, 2014.

[5] Baverel O., Feraille A., Brocato M., “Environmentally Compatible Spatial Structures: some Concepts from the Reuse of Manufactured Goods”, *Journal of the International Association for Shell and Spatial Structures, J.IASS*, 2013, Vol.54, No.4, pp. 311-320.

[6] Chopin J., Delon N., *Matières Grises*, Editions du Pavillon de l’Arsenal, Paris, 2014.

[7] Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, *Closing the loop - An EU action plan for the Circular Economy*, European Commission, Brussels, 2015.

[8] Crisfield M.A., *Non-linear Finite Element Analysis of Solids and Structures. Volume 2: Advanced Topics.* (2nd ed.), Wiley, 1997.

[9] D'Amico B., Kermani A., Zhang H., Pugnale A., Colabella S., Pone S., Timber gridshells: Numerical simulation, design and construction of a full-scale structure, *Structures*, Vol. 3, Elsevier, 2015, 227-235.

[10]De Gobbi M., Petrone N., Structural Behaviour of Slalom Skis in Bending and Torsion, in M.Estivalet, P. Brisson, *The Engineering of Sport*, 7, 2009, Vol. 2, Springer.

[11]Durmisevic E., *Transformable Building Structures, Design for disassembly as a way to introduce sustainable engineering to building design & construction*, PhD thesis, TU Delft, 2006.

[12]Frischknecht R., Jungbluth N., Althaus H.J., Doka G., Dones R., Hischier R., Hellweg S., Humbert S., Margni M., Nemecek T. & Spielmann M., Implementation of Life Cycle Impact Assessment Methods: Data v2.0. *ecoinvent report* No. 3, Swiss centre for Life Cycle Inventories, Dübendorf, CH, 2007.

[13]Guinée J.B., Gorrée M., Heijungs R., Huppes G., Kleijn R., van Oers L., Sleeswijk A., Suh S., Udo de Haes H.A., de Bruijn H., van Duin R. & Huijbregts M.A.J, *Life Cycle Assessment: an Operational Guide to the ISO Standards*. Kluwer Academic Publishers, Dordrecht, 2002

[14]Happold E., Liddell W. I., Timber lattice roof for the Mannheim Bundesgartenschau, *The Structural Engineer*, March 1975, No. 3, Vol. 53.

[15]Hoxha E., Habert G., Lasvaux S., Chevalier J., Le Roy R., Influence of construction material uncertainties on residential building LCA reliability, *Journal of Cleaner Production*, 144, 2017, 33-47.

[16]Jentschura U. D., Fahrbach F., Physics of Skiing: The Ideal–Carving Equation and Its Applications, *Canadian Journal of Physics*, 2004, 82(4), pp. 249-261.

[17]Kaethner S. & Burridge J., Embodied CO2 of structural frames, *The Structural Engineer*, London, United Kingdom, 2012, pp. 33-40.

[18]Kellenberger D., Kunniger T. & Althaus H.J., Life Cycle Inventories of Building Products: Cement Products and Processes. *Final report ecoinvent* V2.0 No.7. EMPA Dübendorf: Swiss Centre for Life Cycle Inventories, 2007.

[19]Kotelnikova-Weiler N., et al, Materials for Actively-Bent Structures, *Journal of the International Association for Shell and Spatial Structures, J.IASS*, 2013, Vol. 28, No. 3&4.

[20]Lienhard J., Alpermann H., Gengnagel C., Knippers J., Active Bending, A Review on Structures where Bending is used as a Self-Formation Process, *Journal of the International Association for Shell and Spatial* Structures, J.*IASS*, 2013, Vol.28, No.3&4, pp. 187-196.

[21]Luthe T., Kägi T., Reger J., A systems approach to sustainable technical product design. *Journal of Industrial Ecology*, 17(4), 2013; pp. 605-617.

[22]Pone S., Colabella S., D'Amico B., Fiore A., Lancia D., Parenti B., Timber Post-formed Gridshell: Digital Form-finding / drawing and building tool, *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium, Beyond the Limits of Man*, 2013.

[23]Paduart A., Debacker W., Henrotay C., Asnong K., De Wilde W. P. & Hendrickx H., Technical detailing principles for the design of adaptable and reusable construction elements in temporary dwellings, *Waste Management and the Environment IV*, WIT Transactions on Ecology and the Environment, 2008, Vol.109, pp. 425-433.

[24]Single Speed Design Architecture, The Big Dig House, http://www.ssdarchitecture.com/2013/07/big-dig-house/ http://www.archdaily.com/24396/big-dig-house-single-speed-design, accessed March 2017.