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COMPUTER-AIDED DESIGN AND CONSTRUCTION OF GLUED LAMINATED TIMBER STRUCTURE

Luca Caneparo

Design Network Lab, Dipartimento di Progettazione architettonica, Politecnico di Torino, v.le Mattioli 39, 10125 Torino, Italy, e-mail caneparo@polito.it

Abstract: The paper presents the computer-aided design and construction of a large glued laminated timber structure in Aosta, Italy. The structure was completely computer modelled with in-house developed software, which considers both torsion and curvature constraints of timber. Further proprietary software was used to develop, on a plane, the shape of each timber layer without torsion and curvature. The profiles were converted into CNC instructions to cut the timber leaves. To assemble the leaves on-site a temporary iron scaffolding was constructed. To manage and verify this process, the site manager used the coordinates from the CAD model, converted into the digital format compatible with the total station.

Keywords: computer-aided construction, glued laminated timber structure, computer numeric control cut.

1. PROTECTIVE STRUCTURE

In 1992 close to Aosta, Italy, it was decided to build a protective structure at the intersection between the motorway Turin-Courmayeur and the cableway to Pila.

The structure protects vehicles on the motorway from the eventuality of a falling cabin or, more likely, from objects and blocks of snow, which might fall down from the cableway above it.

Four arcs span the motorway and sustain a grid of security glass over the four ways lanes. Each arc measures 48 metres, and is curved, along the main axis, to magnify the impression of entrance, driving along the motorway (Figure 1a, 1b). The location of the structure, close to the city centre of Aosta, could even acquire the significance of gateway - entrance to the city. The architectural design communicating this symbolic meaning.

The dimensions of the structure are constrained by, on the lower side, the maximum shape of the vehicles on the motorway and, on the upper side, by security clearance of the cableway. To meet with these constraints, the two arcs crossing the cableway are torsioned along their axes, so that in the middle they are horizontal, i.e. 90° degrees torsioned.

The motorway was to be inaugurated in autumn '93, so there was a year to complete the structure starting from scratch, with two sketches.

An attempt was made to work concurrently, as far as possible, and so the overall project was divided into three parallel sub-projects:

- Modelling the structure,
- Cutting the timber leaves,
- Assembling the timber leaves.

2. MODELLING THE STRUCTURE

The computer model was the core of the project because it served as the reference for the different groups working on each sub-project.

The modelling of the timber beams posed several constraints. First, the shape of every section, perpendicular to the barycentric axis, had to be rectangular. Second, the curvature and torsion of the beams had to accomplish the elastic bending of the single timber leaves, which composed the global beam by means of the juxtaposition of the laminated glue.

Several modelling approaches were tried (spline, B-spline, nurbs), although they weren't sufficient to achieve the form needed, because it was not a free form in space, but a timber structure: a form where both the design and the construction issues meet [1, 2, 3, 4].

In principle it was possible to model the shape of the beams by means of a B-spline polynomial, placing and adjusting the control point in space. This

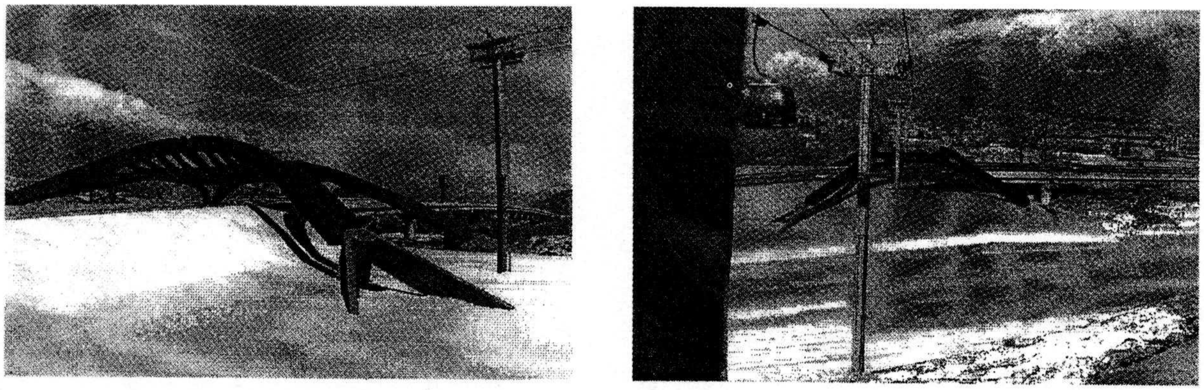

Figure 1a, 1b. Early computer renderings used to obtain the contract.

process was certainly handy, because "fair" shapes required few control points but placing them was challenging.

"Fair" shape was an aesthetic value; nevertheless it could be also defined in analytical terms as the degree of continuity of the curve. First-derivative continuity, defined as *slope*, assured continuity of the tangent vector at vertices. In second-derivative continuity, defined as *curvature*, the slope and the derivative of the slope were continuous along the curve [5, 6].

The analytical definition of a *fair* curve can be refined further. "A curve is fair if its curvature plot is continuous and consists of only a few monotone pieces" [7]:

$$\frac{dk}{ds} = \frac{\det[\dot{x}, \dddot{x}]}{\|\dot{x}\|^4} - 3\dot{x}\ddot{x}\frac{\det[\dot{x}, \ddot{x}]}{\|\dot{x}\|^6} \qquad (1)$$

where k is the slope, s is the arc length and dots represent derivatives with respect to the given parameter u of $x(u)$.

During the design process evaluating visually a curve, which in reality spanned 48 meters, from a monitor or even a large plot turned out to be difficult. The *fair* analysis (1) of the models of the beams proved useful to evidence curvature extrema or points where the curvature changed suddenly.

From a structural point of view [8, 9], the *fair* analysis tested the continuity in torsion and curvature along the timber leaves: every point of the structure had to be inside the range of elastic deformation.

In view of the assembly process (cf. 4. Assembling the timber leaves), the *fair* analysis prevented even small discontinuities in the curvature, e.g. inflections, which could generate additional stresses inside the timber in the structure.

Once the expected shapes of the arcs and the criteria they must fulfil were outlined, a parametric modelling was adopted based on analytical generation of conic sections. Conic sections are very thoroughly studied curves and many of them, like ellipses and parabolas, were used frequently through the centuries in architecture. The pioneer of the use of conics in CAD was Coons [10, 11].

The in-house developed software to model conic sections was interfaced to the CAD system. The CAD environment offered visualisation tools suitable for interactively modelling the beams as the centre weight of the curves was manipulated. Often the modelling process involved the multidisciplinary group (cf. 5. Participants in the Project).

Satisfactory final design of the beams were achieved with a sixth degree parabola:

$$y=a_1x^6+b_1x^4+c_1x^2+d_1 \qquad (2)$$

$$z=a_2x^6+b_2x^4+c_2x^2+d_2 \qquad (3)$$

The (2) and (3) defined the shapes of all the four arcs. The difference between the shapes of the torsioned and un-torsioned beams lay in the different values of the a, b, c and d parameters: that's why the shapes of the four beams were defined "affine".

The equations (2) and (3) described the barycentric line of the four beams. The model of two beams was achieved by roto-translating the section of the beam along the barycentric line. The structural engineer calculated this section as 70 cm base by 180 cm high.

The other two beams had a 90th degree torsion along their axes: they started vertical, became

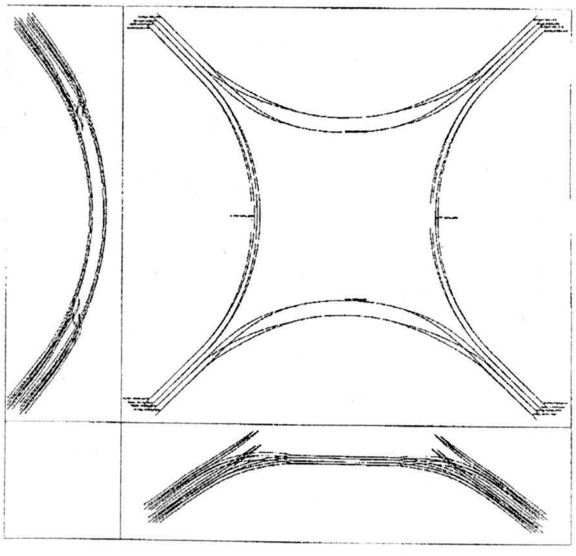

Figure 2. Plan and elevations of the beams.

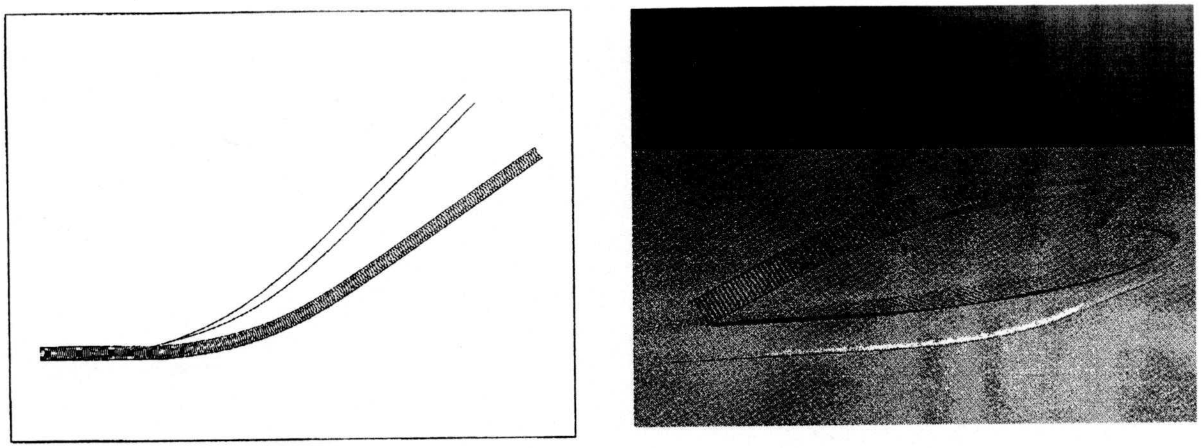

Figure 3a, 3b. The base layer in the torsioned beam and developed in the plane.

horizontal in the middle, and terminated vertical again. A uniform torsion function was applied during the roto-translation process of the section along the barycentric axes. (Figure 2)

3. CUTTING THE TIMBER LEAVES

To transform the 3D CAD model into the timber structure it was useful to know the exact shape of each timber leaf when flat; i.e. before torsioning and curving it to assemble the beam in space.

Since, at the beginning of the 90s no other studies into developing three-dimensional timber shapes in a plane without torsion and curvature were known, several methods were conceived and experimented. One showed itself to be reliable in developing shapes on a plane. This algorithm patched the surface of the timber layer into triangular faces. Because three points identify one and only one plane, the triangles are always planar.

To develop the surface on a plane, triangles of infinitesimal dimension were considered. Each triangle is rotated to coincide with the plane of the preceding triangle. The projection plane $Z=0$ is imposed on the initial triangle. The angular values of the rotation, respectively parallel and perpendicular to the timber fibres, are used to calculate the deformations according to the module of normal elasticity. The stresses in the beams were always considered inside the elastic range of timber, since the modelling process was made constantly uniform to the elastic bending and torsion range.

The software made it possible to represent each layer of timber as if it were flat. Figure 3a illustrates half of the beams with torsion. The two edges, at the base of the beam, are juxtaposed to their profiles developed in the plane. The triangles, between the two edges, were displayed to visualise and verify the patching process.

The capability to exactly simulate the profile of each timber layer suggested the possibility of unifying the profiles. The possibility of cutting and assembling a unified profile of timber instead of 16^{en} slightly different ones was considered cost effective. In the case of the unified profile, the software simulated the maximum shift from the bottom to the top layer of timber in 8 cm, along the 180 cm vertical axis of the beam (maximum tolerance 0.044%) (Figure 4).

3.1 Validation

A major concern was the validation of the analytical method and the software implemented to develop the timber layers on a plane. Initially, they were tested with simple shapes, although this did not prove the method as general, i.e. effective with complex shapes too.

The profiles of each timber layer, developed on a plane, were converted to the DXF format, and imported in MicroCAM to generate the CNC instructions to cut them.

The CNC instructions, scaled 1 to 20, were used to cut scaled Masonite leaves. Using glue the scaled leaves were assembled to build the mockup of the four beams and the central grid (Figure 5). The mockup was the final demonstration of the feasibility of the method adopted, that is the coherence between

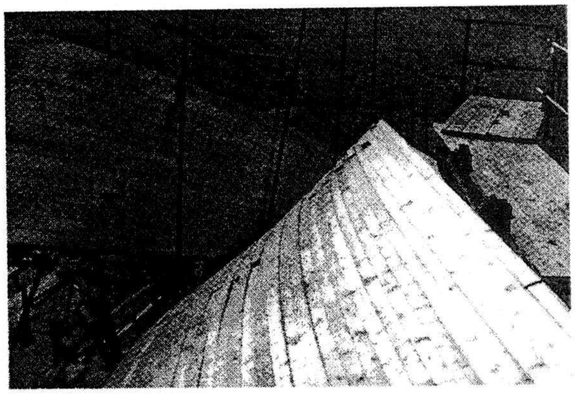

Figure 4. The torsioned and un-torsioned beams converging toward the bearing.

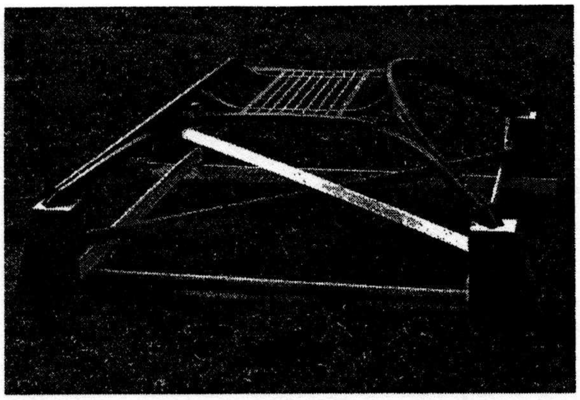

Figure 5. The 1:20 mockup of the structure.

the CAD model, the software implemented and the physical reality.

4. ASSEMBLING THE TIMBER LEAVES

Glue laminated structures are usually assembled over a special bench press in a controlled humidity and temperature environment, which assures the creation of a composite material with predefined and well known properties.

The possibility of pre-assembling in the factory four arcs of 48 m width and 10 m high and then shipping them for several kilometres to the construction site was considered unfeasible. So pre-assembling the beams was discarded in favour of assembling them on site. Assembling on site raised several problems.

A scaffolding was required to offer a temporary support for the layering and assembling of the timber leaves with the glue and screws.

Moreover, it was considered whether to pre-curve and torsion the timber leaves or not. Usually in glulam structures the timber leaves are formed to the final curvature and torsion keeping them for days in a high temperature and humid environment, i.e. oven, with applied constant or increasing bending and torsion forces. The absence in the beams of values outside elastic curvature and torsion suggested the possibility of forming the leaves directly on-site, over the iron scaffolding, without modelling them in an oven. Tests with full-scale leaves demonstrated that for 6 and 12 cm thickness of the leaves the glue and screws were sufficient to make and form the timber layers on site.

The assembling of the structure on-site required both solid and exact shaping of the temporary scaffolding. The scaffolding was required to align the stacking of the leaves, to support the weight of the timber itself as well as the adjunctive forces generated during the forming of the leaves plus the tensions due to the consolidation of the glue.

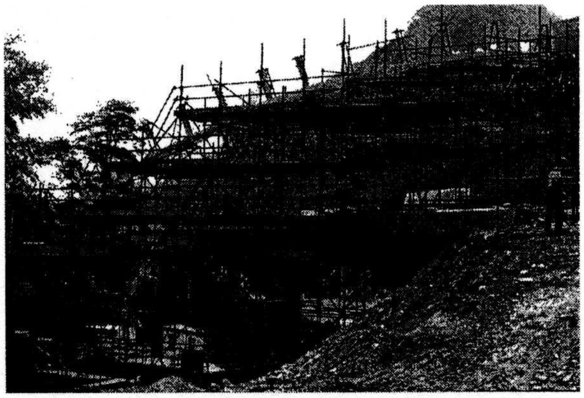

Figure 6. Temporary scaffolding with the templates and the first layers of timber.

Approximately thirty templates (tubular metal squares of 70 × 180 cm) for each beam had to be precisely placed and rotated in 3D to align and support the stacking of the leaves (Figure 6).

The co-ordinates of the base edges of each beam were discretised every 10 cm. The software of the total station downloaded the co-ordinates from the CAD through the serial interface.

The on-site accurate location of these points used the laser beam of the total station to determine the axis to position the prism. The rodman had to move the prism along the laser axis to fit the exact distance. The adjustments of the distance were based on the feedback from the surveyor at the total station. This process was simplified by the fact that the point lay at the intersection between a curve, the base edge of the beam, and the axis traced by the laser beam. So, often, only minor adjustments of the distance of the prism were required. More recent instruments incorporate an assistant light changing colour or blinking cycle to indicate if the prism has to "go" or "come" to fit the exact distance.

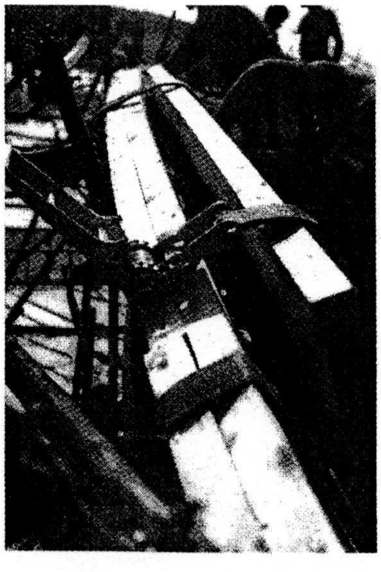

Figure 7. Stacking process of a timber leaf.

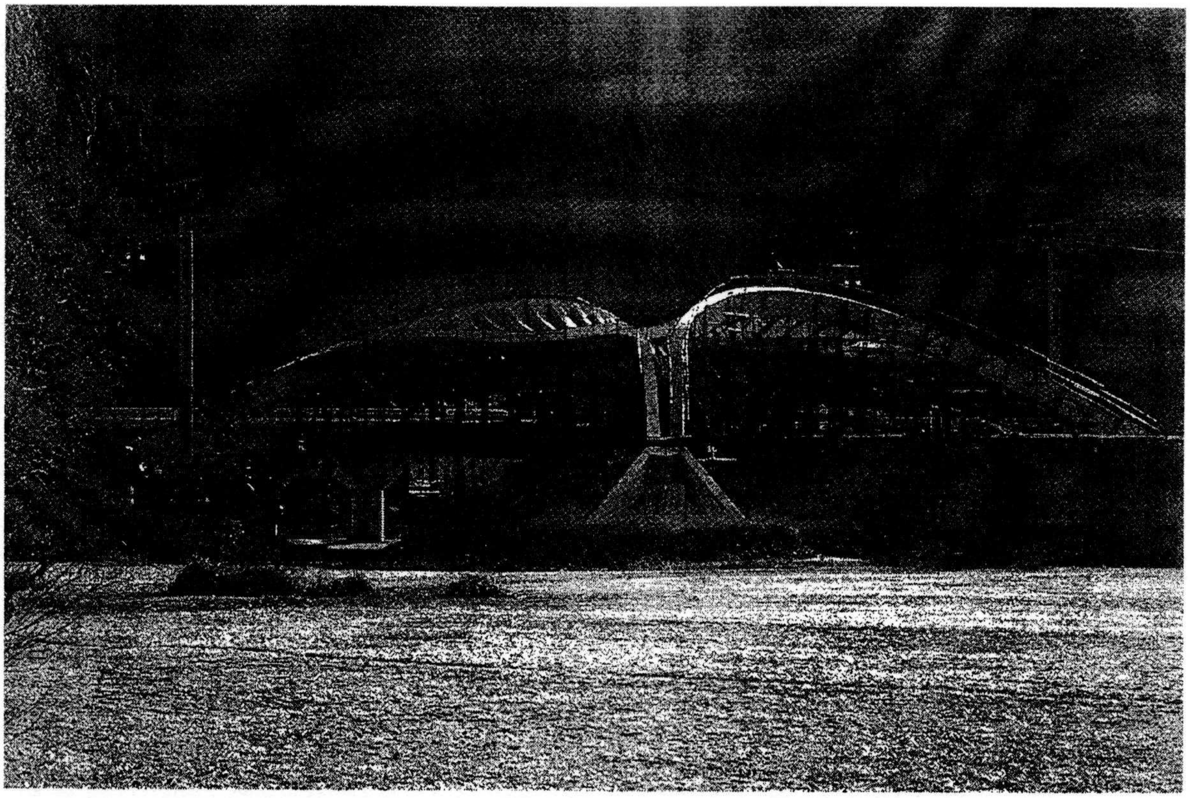

Figure 8. The structure completed with the temporary scaffolding still up.

The site manager used the total station to position the upper level of the scaffolding, which would directly support the templates and the timber layers exactly. During the construction the instrument allowed him to verify the real position of the squares and according to the measured position to calculate incidental adjustments due to, for instance, settling of the scaffolding.

The base of each beam was constituted of two timber layers, each 6 cm thick, while the further layers were 12 cm thick. The successive layers were taken in place and pressed, during the consolidation of the glue, by means of screws and temporary straps (Figure 7). As the number of staked layers increased, the beam was acquiring the definitive rigidity.

The surveying of the profiles of the constructing beams confirmed the accurate coincidence with the computer model, without consequently requiring adjustments in the layering of the timber leaves.

5. PARTICIPANTS IN THE PROJECT

The main participants in the project were: Società Autostrade Valdostane spa customer; INCISA spa mandatory; Arch. Sergio Beccarelli of Policreo architectural design; Eng. Innocente Porrone structural engineer; Arch. Luca Caneparo CAD/CAM manager; Chenevier spa timber cutting and assembling; Edilchimica Italia srl glue supplier.

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