COMPUTER-INTEGRATED CONSTRUCTION OF TIMBER STRUCTURE

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ABSTRACT: The paper presents the integrated information system supporting design, manufactory and construction of a large glued laminated timber structure in Aosta, Italy. Design, the structure was completely computer modelled with in-house developed software, which considered both torsion and curvature constraints of timber. Manufactory, 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. Construction, to manage and verify the process onsite RF Ethernet LAN was established to allow bi-directional online communication between total station, radio frequency identification and the information system.

KEYWORDS: computer-integrated construction, project modelling, glued laminated timber, computer numeric control, distributed collaboration, concurrent design.

1. PROTECTIVE STRUCTURE

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 1, 2). 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. 90º degrees torsioned.

2. INTEGRATED INFORMATION SYSTEM

The motorway was to be inaugurated, so there was less than a year ahead to complete the design, the timber machining and the construction of the structure. Due to the tight schedule the customer was especially motivated to implement a computer-integrated information system with the aim to develop the project concurrently.

The commitment of the information system was the dynamic integration of three concurrent models of the project, respectively:

1. the modelling of the structure,
2. the modelling of the manufactory,
3. the modelling of the onsite construction.

At the heart of the system is a three tiers-architecture (Figure 3). Pertinent to each model are the applications, which the firms and companies participating to the project (cf. 7.) were using, e.g. CAD, CAE, FEA, CAM, shop and onsite scheduling, inventory control etc.

Figure 1, 2. Early computer renderings used to obtain the contract.

The front-end tier was implemented by means of Microsoft's Component Object Model (COM), which seamlessly integrated at-runtime the capabilities of the applications.
Further interoperability between applications, also not supporting COM specifications, was pursued by product and process model STEP and IFC standards (International Alliance for Interoperability, 1996). These standards defined the semantic on which the applications collaborated via the middle and back-end tiers.
The middle tier is the project server, which stored the application data as projects.
The back-end tier is the client/server distributed object oriented database. Microsoft's Distributed Component Object Model (DCOM) allowed objects residing in distributed applications to collaborate in a unified way by means of acknowledge protocols and specifications.
Standard semantic definitions with DCOM interoperability created a dynamic data model: the models, new data structures or requirements to the models could be changed at run-time

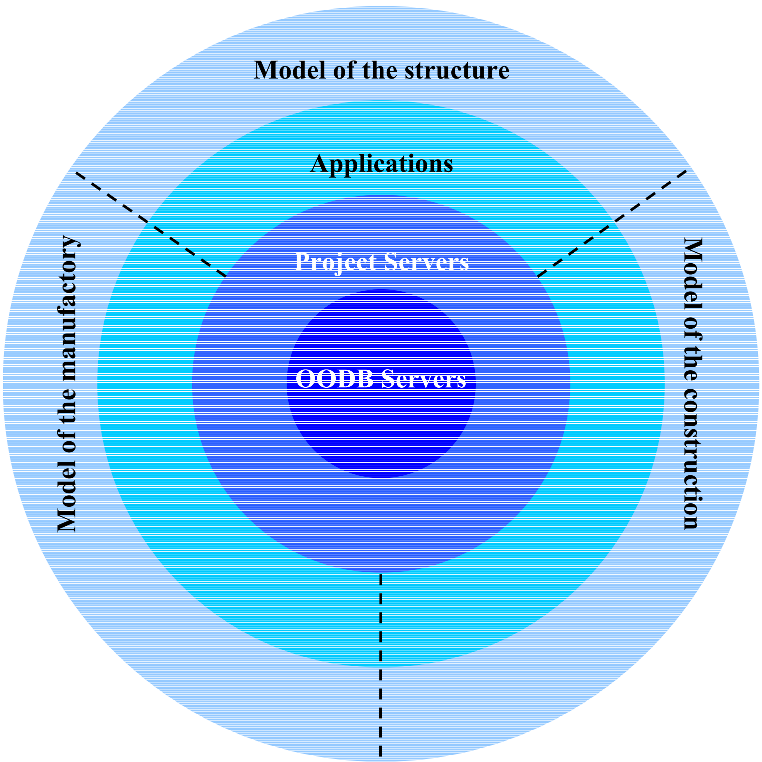

Figure 3. The three-tier architecture of the integrated information system

during the project.

3. MODELLING THE STRUCTURE

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 were not 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 (Casal, 1998) (Krasojevic, 1995) (Haller, 1998) (Ranta-Maunus and Ristimaki, 1991).

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 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 (Mortenson, 1985) (Taylor, 1992).

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” (Farin, 1988):

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

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 (Derron, 1975) (Zienckiewicz and Taylor, 1991), 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 manufactory and assembly processes (cf. 4. and 5.), 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 (1964 and 1974).

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. 7.).

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 other two beams had 90th degree torsion along their axes: they started vertical, became 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 4).

Seamless integration of CAD with FEA allowed the structural engineer to contribute to the design process throughout, for instance proposing and calculating sections of the beams during the design process. The section adopted was 70 cm base by 180 cm high.

4. MODELLING THE MANUFACTORY

To construct the structure consistent with the CAD model, 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.

Several methods were conceived and experimented to develop three-dimensional timber shapes in a plane without torsion and curvature. 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.

In-house developed software implemented this algorithm. The software made it possible to represent each layer of timber as if it were flat. Figure 5 illustrates half of the torsioned beam: 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

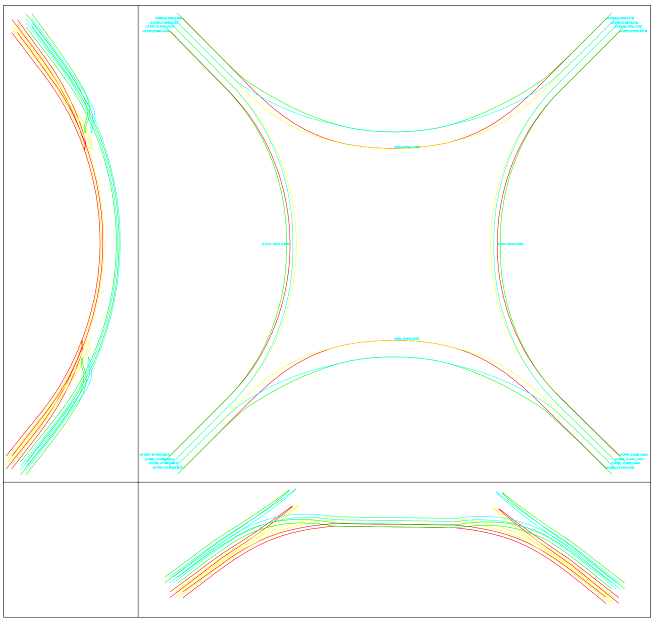

Figure 4. Plan and elevations of the beams.

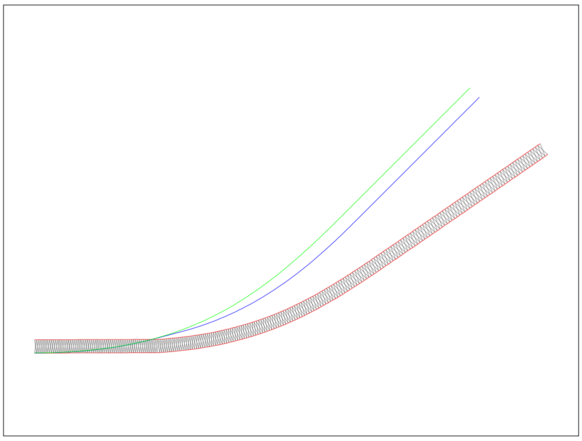
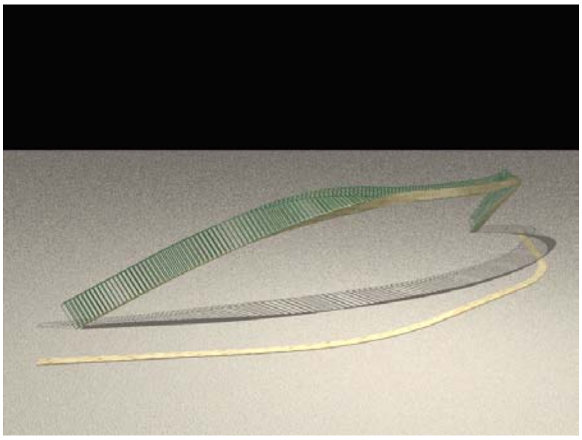

Figure 5, 6. The base layer in the torsioned beam and developed in the plane.

process.
In the early design phase the software was used to analyse each timber layer and to represent it developed on the plane: the capability to exactly simulate the profile of the timber layers suggested the possibility of unifying them. The timber manufacture company, the mandatory and customer company, the design group considered the possibility of cutting and assembling a unified profile of timber instead of 16en slightly different ones as 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 7). These data were considered during the modelling of the structure.

4.1 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 integrated information system enhanced the communication between the CAD and CAM systems: the CAM program used the profiles of the timber layers, developed on a plane, to define the cutting parameters and paths, and to generate the CNC instructions for the machine.
The cutting paths, scaled 1 to 20, were also used to generate the CNC code to machine scaled Masonite leaves. Using glue the scaled leaves were assembled to build the mock-up of the four beams and the central grid (Figure 8).

Figure 7. Two beams converging toward the bearing.

Figure 8. The 1:20 mockup of the structure.

The mock-up was the final demonstration of the feasibility of the method adopted, that is the coherence between the CAD models, the software implemented and the physical reality.

5. MODELLING THE ONSITE CONSTRUCTION

Glued 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 (cf. 3.) suggested the possibility of forming the leaves directly on-site, over the iron scaffolding, without pre-curving them in an oven. FEA (Kermani and Goh, 1994) and 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.

About thirty templates (tubular metal squares of 703180 cm) for each beam had to be precisely placed and rotated in 3D to align and support the stacking of the leaves (Figure 9).

To place, align and verify the position of the templates and the leaves total station and radio frequency identification technologies were used.

5.1 Total station

Total station instruments are habitually used on-site to locate and survey precisely. They are interfacable to computers to provide spatial coordinates in digital format. However their use is demanding and lengthy: they require a trained operator with, in certain cases, an assistant to identify each object and then position the prism manually.

Figure 9. Temporary scaffolding with the templates and the first layers of timber.

5.2 Radio frequency identification

Radio frequency identification (ID) is rapidly emerging as a promising technology because it does not require a line of sight and the proximity is extending to the range of tens of meters (Finkenzeler, 1999). It is based on either a passive or an active transponder and a fixed/mobile RF station. The mobile station is comparable in size and weight to a handheld barcode reader. When the transponder receives a signal from the station it starts a read/write communication session. The transponders have onboard read and/or write memory up to several Kb. Each transponder is identified by a unique digital code. The transponder r/w memory can be used to store information on the associated item along all the construction process. On the factory floor the memory can carry information on the manufacturing cycle as well as exceptions or peculiarities, e.g. tooling, finishing, quality etc. At the construction-site or later during the building maintenance, it can store information of tasks completed, in progress or scheduled.

5.3 Online integration

In the factory and the construction-site mobile wireless communication were established by means of RF Ethernet LAN (Proxim) connected to the Internet via ISDN lines. The RF Ethernet through the Internet provided for online bi-directional communication between the total station and the integrated information system.

The software of the total station downloaded the co-ordinates of the model from the information system through the RF Ethernet. The site manager used these coordinate to exactly shape the temporary scaffolding, to position the thirty templates, which directly supported the timber layers. To accurate locate these points, the laser beam of the total station determined 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. Some total stations incorporate an assistant light changing colour or blinking cycle to indicate if the prism has to "go" or "come" to fit the exact distance automatically.

The software of the total station uploaded the surveyed coordinates to the information system through the RF Ethernet. Although the surveyor has to associate the coordinate to the appropriate item manually. To automate this process, each timber leaf was uniquely identified by an ID transponder.

On the shop floor fixed stations queried the transponders at the beginning and end of each major manufactory phase, e.g. cutting, finishing, stocking, shipping. The data to and from the transponders were communicated in real-time to the information system via the RF Ethernet.
At the construction-site fixed stations at the gate and stocking area supported online check-in and check-out of the items. The online integration of total station with ID technologies allowed tracking each part along all the construction process: from the manufactory to the onsite assembling.
Furthermore, the online integration speeded up the onsite construction. The rodman identified online a part by means of the RF handheld station and then positioned the prism twice in correspondence of two fiducial points, respectively the lower-left and upper-right corners of the leaf. The total station got the two measures and communicate them online to the information system. The information system identified the item according to the ID information, and associated the surveyed coordinates to it automatically.

6. CONSIDERATIONS

Online monitoring of the manufactory and construction processes made each phase, which previously tended to be considered in a sequential manner, really interdependent and interrelated with each other. If, for example, a leaf did not fit with the designed position, because of settling of the structure, displacements due to glue tensions during the consolidation (Figure 10) or incidental adjustments of the scaffolding, the design team could model alternate solutions and evaluate the appropriate one. In certain cases, the solutions considered were a displacement of some leaves, different glue application or reshaping of some of the leaves still in the manufactory process.
The structure was completed in time for the inauguration of the motorway.

7. 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, IT manager; Chenevier spa, timber cutting and assembling; Edilchimica Italia srl, glue supplier.

Figure 10. Stacking process of a timber leaf.

Figure 11. The structure completed with the temporary scaffolding still up.

REFERENCES

International Alliance for Interoperability. (1996). *End User Guide to Industry Foundation Classes, White Paper*, Washington DC: IAI.

Casal B. (1998). "Numerical Modeling of Wood Structures - Benefits and Drawbacks", *World Conference on Timber Engineering*, Lausanne.

Krasojevic M. (1995). "Conception des assemblages en bois assistée par ordinateur", *JCSR*, vol. 6.

Haller P. and Menzel R. (1998). "Computer Based Routine Design for Timber Structures", *World Conference on Timber Engineering*, Lausanne.

Ranta-Maunus A. and Ristimaki T. (1991). "Computer Assisted Design of Glulam Hall Structures", *ITEC 91 Conference Proceedings*, London.

Mortenson M. E. (1985). *Geometric Modelling*, New York: John Wiley.

Taylor D. L. (1992). *Computer-aided Design*, Reading MA: Addison-Wesley.

Farin G. (1988). *Curves and surfaces for computer aided geometric design: a practical guide*, Boston: Academic Press.

Derron J. (1975). "Calcul des systèmes spatiaux de barres courbes par la méthode des éléments finis", *Bulletin Technique de la Suisse Romande*, vol. 21.

Zienckiewicz O. and Taylor R. (1991). *The finite element method*, New York: McGraw-Hill.

Coons S. (1964). *Surfaces for computer aided design*, Cambridge (MA): MIT Technical Report.

Coons S. (1974). "Surface patches and B-spline curves", in R. Barnhill and R. Riesenfeld. C*omputer Aided Geometric Design*, Boston: Academic Press.

Kermani, A. and Goh, HCC. (1994). "Finite element analysis of timber joints incorporating mechanical connectors", in Topping B.H.V. and Papadrakakis M (Eds.), *Advances in Structural Engineering Computing*, Edinburgh: Civil- Comp press.
Finkenzeler K. (1999). *Radio-frequency identification fundamentals and applications*, New York: Wiley.
Proxim. RangeLAN2, http://www.proxim.com/