Computer-Aided Construction

LUCA CANEPARO
Polytechnic of Torino

INTRODUCTION

Computer-Aided Construction (CAC) is the capability of a computer system to create models of the certain aspects of the construction process with the facility to direct them into reality.

The premise of CAC is that the clear-cut separation between the competencies, know-how and responsibilities has now been turned upside down by the introduction of information technology in AEC. Designers can now model the physical specifications, the manufacture and organizational aspects of a building in a seamlessly. And they can do so rather creatively.

Every computer-aided design system used in AEC incorporates assumptions about construction. The aim of CAC is to shift from implicit assumptions towards explicit models of the construction process and to create the building according to the templates dictated by the models. From a philosophical point of view, the property of CAC is a system's evolution from being descriptive to being prescriptive.

Until the introduction of digital computers, analog models, i.e. mock-ups, structural and energy models were the main aspects of buildings modeled. Nowadays computers can model and predict the physical aspects of a building with finer tolerances than can actually be constructed (Caneparo, 1995), with detail and evidence of manufacture and organizational aspects, which otherwise can not experienced directly or defined in a direct cause-effect nexus because of complexity. But most importantly, the CAC models are dynamic-interactive: the power of computers and software allows us to understand and evaluate the interrelation of a design issue with all the aspects modeled in the system.

CAC differs from physical based simulation systems in that it has the potential to direct the model to become real, modeling technological and organizational aspects. CAC differs from CNC in that the scale of most buildings is too large to be created directly by means of NC. It is not only a matter of scale, most buildings are complex systems where several issues, architectural, technological, structural, managerial, organizational, constructive etc. interact at the same time.

CAC implements aspects common to both Product Data Management (PDM) and Enterprise Resource Planning (ERP) technologies. Basically, an ERP implementation is integrated around a unitary data model oriented to the coordination of various applications aimed to production, e.g. scheduling, planning, control (Ross, 1999) (Willcocks et al., 1997) (Cook, 1996). PDM is more focused on integration of independent applications, frequently developed by different vendors and running on diverse systems. CAC relies on a close, interactive, integration between various modeling and simulation tools (cf. CAC Implementation).

Construction is a compound process, which requires both human and machine interaction and coordination. CAC monitors this interaction, and is able to change the models in order to cope with unforeseen or random events.

Because of the number of the building typologies and of the construction system presently in use, it is impossible to define the model capabilities of CAC univocally: it requires several coexistent representations-models of the construction process, which are defined by three dimensions, respectively the physical, technological and organizational.

MODEL OF THE PHYSICAL SYSTEM

Most CAD systems are geometry-oriented, while to model the physical aspects of a building, much more information on the materials and their physical specifications, the environment and the building process is required. A shape is modeled differently depending upon the aspects considered in the design at the time. For example, the requirements in curvature, bending, torsion, angle etc. differ according to whether the shape is to the construction technology (e.g. wood, stone, iron, steel or concrete) by means of a milling, cutting, reforming, molding or casting process. To account for these requirements, CAD solid or surface models are required to integrate the geometry descriptions with the physical specifications. The modeling of the physical system is considered from the point of view of requirements, constraints and capabilities posed respectively by the design of the shape and the specifications of the material.

SHAPE-ORIENTED MODELING

Continuity or discontinuity of the surface is an effective property of several materials and manufacturing processes.

To evaluate the quality of curves, tools assign colors based on the curvature value, or render images using color and texture to simulate highlights or neon row with the capability to dynamically change the number, spacing and orientation of the lights to obtain the best surface evaluation (FreeStyle Optimizer, 1998) (NURBS Modeling, 1999).

In analytical terms the continuity can be defined as the derivative of the curve. First-derivative continuity, defined as *slope*, assures continuity of the tangent vector at vertices. In second-derivative continuity, defined as *curvature*, the slope and the derivative of the slope are continuous along the curve.

Several CAD systems implement tools to evaluate the degree of continuity. These can be post-process or interactive tools. If interactive, during modeling, wireframe, facets or normal vectors are highlighted with colors according to the derivative degree of continuity (Advanced Surface Extension, 1999) (Curvature Properties, 1999) (FreeStyle Shaper, 1998). Further analytical tools have been developed to evaluate the degree of continuity (Advanced Surface Extension, 1999) (Farin, 1988).

Shape-oriented modeling system, integrating tools to analyze and represent the continuity of a shape, provides the designer coexisting point of views on aesthetic, structural, and constructive aspects. From an aesthetic point of view, these tools aid to pursue either stability or instability of the form. They are an analytical aid to the visual evaluation, which in certain designs can demonstrate difficult or partial. From a structural point of view, they show curvature extrema or points where the bend changes suddenly, e.g. flat spots or saddle points. They provide a qualitative-visual aid to interpret continuity in torsion and curvature along the form. In the view of construction, these tools prevent even small discontinuities, e.g. inflections, which certain material-technology requires specific procedure.

MATERIAL-ORIENTED MODELING

In Material-Oriented Modeling (MOM) as the designer refines the models, i.e. outlines the materials and the loads conditions associated to the shape, the computer system refines the simulation of the behavior of the form. It is not a post-simulation, where the designer passes the model to an analytical tool, e.g. Finite Elements Analysis (FEA). It can be much more interactive, because the simulation tool uses the same model of the CAD system, without a meshing process (Atluri et al., 1998) (Belytschko et al., 1996). Furthermore the meshless analysis proves up to order of magnitude faster than P- and H-element solvers of FEA.

For example, if the designer assigns to a shape the specifications of a metal material, the system visualizes areas inside and outside the elastic range of deformation. The visualization can be in stop colors -red, yellow and green- to allow designers addressing first-level analysis in an intuitive way during the modeling process. Green means that the designer can proceed. Yellow signals that further cautions are required, e.g. more detailed design, analysis or the interaction with a specialist. Red means that it is necessary to rethink the design.

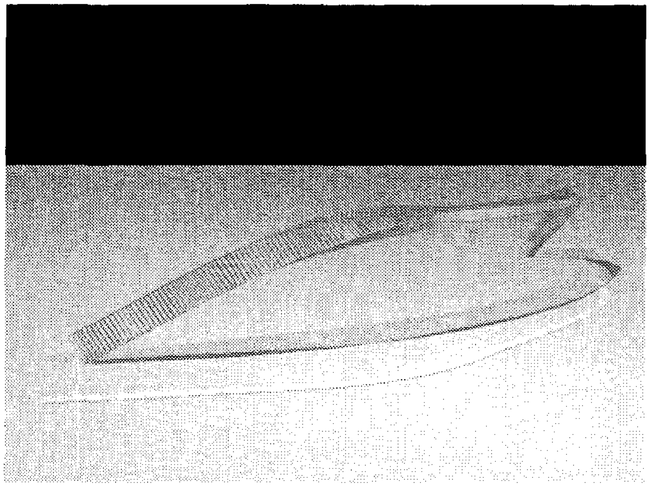

Figure 1. Material-Oriented Modeling.

As the designer interacts with the shape, the loads, or details the materials properties in a hierarchy of materials models to yield the desired one (Eberhardt, et al., 1985) (Kaljevic et al., 1997) (U.S. Congressional Board, 1988), the system updates the simulation and visualization. A more detailed description allows the system to enlarge the range of confidence of the model towards more precise representation (Fig. 1).

MOM is not conceived to substitute FEA, which provides a higher level of detail and accuracy. Even though the MOM can provide a measure of expected error and confidence on the simulation, its purpose is to lead towards an intuitive understanding and appreciation of static and dynamic interaction between the building and its environment early during design. Simplifying the model preparation, the meshless analysis is also useful in problems with changing domains, such as crack propagation, where FEA experiences difficulties in following the changing domain.

MODEL OF THE CONSTRUCTION TECHNOLOGY

The Model of the Construction Technology (MOCT) is seamlessly integrated with MOM, of which it constitutes a further level of detail. The designer directs the form more precisely towards a construction technology, and benefits from the integration of MOCT with MOM in that s/he acquires direct control of the process, which is not only descriptive, drafting-based, but becomes prescriptive as well. It turns into descriptive, because NC manufacturing allows the form to be created with little or no further human mediated intervention. This certainly challenges the capabilities and know-how of the designer, who acquires both greater control and responsibility. Without doubt several human mediated interventions along the building process amplify the possibility of misunderstanding, whereas they give an opportunity to refine-correct the execution of the design. In NC manufacturing an error or unforeseen aspect can propagate along all the process quickly, hence the relevance of modeling the building consistently increases.

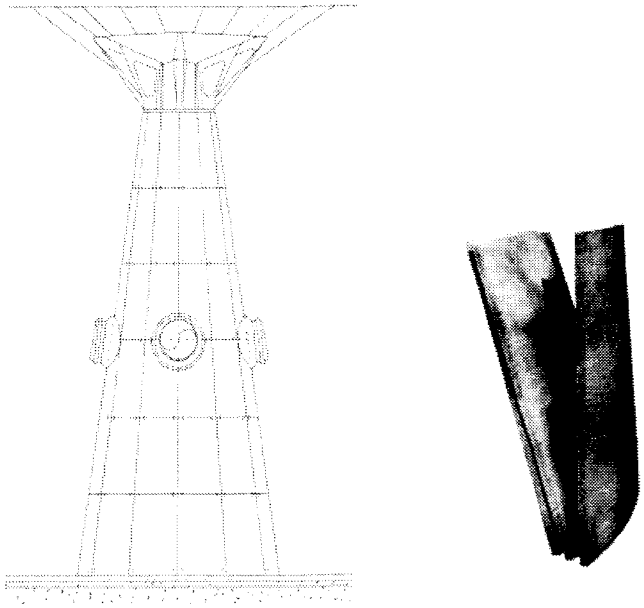

Figure 2. CNC cutting of granite slabs. Kuala Lumpur Airport.

CAC integration opens the capability to model the building parts "as-constructed" precisely by means of quantitative and qualitative-visual evaluation before any manufacturing process really takes place. Because in the building trade no unique construction technology exists, but several different ones are feasible, the paper briefly introduces three: tooling, forming and casting-molding.

TOOLING OF STONE, WOOD, PLASTIC, AND METAL

Tool refers to the manufacturing process where a computer-controlled machine moves the tool and/or the object along a programmed path. Machines and tools exist to cut-remove a wide range of materials: stone, wood, plastic, metal etc. The machines are usually grouped according to the movement they can impress to the tool-part: from two axes up to five.

The capabilities of tool manufacturing are becoming much more widely available to the designer with the integration of CAM systems with material specifications such as strength, density, texture and finish, sometimes inherited from MOM (Material Data System, 1999) (Figure 2).

The software is increasingly able to profit the integration of the geometry and material descriptions to automatically recognize and optimize paths, directions, movements, speed, tangency, roughing, finishing and eventually change of the tool (Catia MFG, 1998) (Generative Machining, 1999) (Expert Machinist, 1999) (Vericut, 1999).

Closer integration of MOM with MOCT provides the designer with tools to highlight differences between the "as-machined" vs. the modeled object, before the NC data are transferred to the factory floor. The in-process simulation can quantify the accuracy of the "as-machined" part considering aspects relating form (e.g. gouges, clashes, under- or over-cuts), the material and the tool path. False color visualizations highlight dimensional variance due to the tooling and any material remaining. Realistic CG animation of the tool path is useful for evaluating quality, optimization strategies, roughing options, surface finishing, tolerances and possible collisions of the tool (ESPRIT, 2000) (NC Machining, 1999) (Vericut, 1999) (VirtualNC, 1999).

To minimize the waste of valuable materials, the software can automatically define the optimal assignment of the parts to be manufactured to the raw blocks. This option can demonstrate cost effective especially with a great number of parts or in the case of blocks of irregular shape, e.g. wood, stone.

FORMING OF METAL, GLASS, WOOD, AND POLYMER

A process of application of loads-forces and/or heating can reform several materials (e.g. metal, glass, wood and polymer).

The importance of the close integration of MOM with MOCT (cf. A Case Project) lies in the assistance to the designer in modeling shapes coherent with both the physical and manufacturing reality. Material-Oriented Modeling of curved or multi-curved surfaces considers texture, elastic or plastic constraints of the material. Since the constraints of the material are satisfied during the design process, the software can automatically develop the designed surface in the plane, before applying bend and torsion. The profile of the curve in the plane is manufactured either as a whole or parts by means of NC (cf. Tooling). The software interprets the material and bend parameters as NC instructions for the machine, which forms the overall object or each part to the calculated curvature (see Fig. 3).

CASTING OF CONCRETE—MOLDING OF METAL AND PLASTIC

In principle any material with a fluid state can be used for a casting/injection process during which it acquires the shape of the mold. In the case of material with quick solidification, high cohesion, relevant retraction or objects with thin parts, the designer can significantly benefit from a design system integrating the shape requirements with those of the casting/injection process and the characteristics of the material.

The flow analysis is becoming an integral aspect of the design process since it can suggest modification to the shape and to the parameters to fill the mold, e.g. pressure, vibration, temperature, points of injection (MPI/Flow, 1999) (Moldflow, 1999) (Powerflow, 1999).

The art of casting/injecting relies also on the art of mold making. It is important -apart from the other general characteristics of a good mold- that there should be no dielock parts, which will cause problems during the extraction of the object. Shape-evaluation tools are integrated in the system to visualize dielock conditions from a defined pull direction during design. To evaluate the surface specifications of a mold, e.g. roughing, finishing and tolerances, designers can benefit from NC simulation (cf. Tooling), before the mold is manufactured.

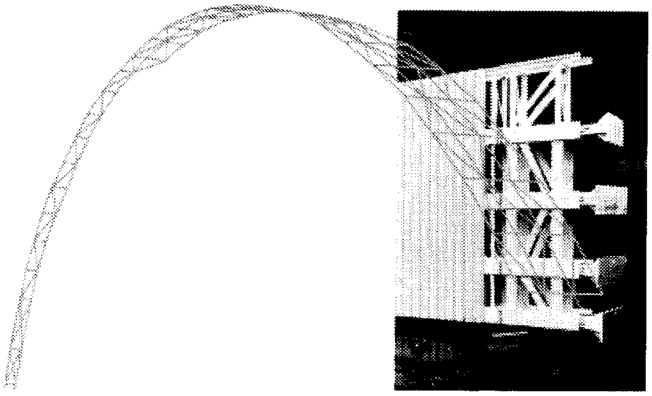

Figure 3. CNC bending of T beams, Courmayeur Tunnel.

In the case of formworks, for example for casting concrete (Hanna et al., 1990), the designer can use forming technologies (cf. Forming) to create the mold, including multi-curved surfaces, from the computer model.

MODEL OF THE CONSTRUCTION ORGANIZATION

Since most buildings are simply too large to be manufactured as a single piece, the construction process has to deal with a widely distributed organization, which concludes sometime at the construction-site.

The paper does not explicitly consider highly automated processes, where NC machines and robots integration play a primary role in both manufactory and on-site construction (Proceedings of the Seventh Symposium on Construction Robotics in Japan, 1998). Conversely it deals with the ongoing spreading of NC technologies in industries manufacturing materials and components for the construction trade. Present investments in CAD/CAM and NC technologies will multiply their benefits if they extend behind the AEC firms, design offices and factory floor (MOM and MOCT) towards the whole construction process.

While MOM and MOCT deal with the physical and manufacturing aspects of the construction process, the Model of the Construction Organization (MCO) is oriented to the modeling of the managerial aspects of the project. Organizational modeling is "the process of configuring an organizational structure to accomplish a given high-level task while attempting to satisfy stated performance objectives. An organization includes people supported by information-processing and communication tools." (Kunz et al., 1998).

The background of MCO dates back to Weber's theory and successive development by Simon (1976) (March et al., 1958) and Galbraith (1997). Galbraith (1997) and Levitt (1994) (Kunz et al., 1998) information processing approaches to organization lead the way to model and simulate work processes.

The Workflow Process Definition Language (WPDL) and IDEF3 are two promising languages for representing work processes. The WPDL (Hollingsworth, 1995) was developed by the Workflow Management Coalition, a non-profit international organization of workflow vendors, users and analysts, founded in 1993. IDEF3 was developed by the U.S. Air Force to standardize a technique for stating requirements (Mayer et al., 1992). IDEF3 compared with WPDL has a more detailed representation of the work, since it explicitly represents the individuals, machines and resources participating to the process.

One aim of modeling construction organizations is the analysis, namely the understanding of the specific way they perform the work, their strong and weak points. After comes the capability to simulate scenarios, i.e. designing different structures of the organization to evaluate the benefits in terms of time, quality and cost (Kunz et al., 1998) (Butler et al., 1999).

A further aim of modeling a construction organization, either an existing or planned one, is its operative implementation in a PDM or ERP system. Research issues are open to system integration of modeling the relations between the actors, the tasks and the resources of construction processes and the relevant product model schemas (Junge et al., 1997). At present there is a lack of integration between implementation independent languages, such as WPDL and IDEF3, and proprietary models-languages used in ERP systems (AcceleratedSAP, 1999) (BaanWise and Dynamic Enterprise Modeling, 1999) (FastForward, 1999).

MODEL OF CONSTRUCTION MATERIALS MANAGEMENT

The Model of Construction Materials Management (CMM) serves to represent and therefore optimize the flow of materials and components during the construction process. The CMM belongs to the organizational, management and production activities, from the raw materials to the components, from the sources through the work processes to the site. The role of CMM in the computer aided construction process is particularly important, because it shifts building tasks and processes from the construction site to manufactory: CAC tends to produce value-added components, which are to assembled onsite.

A crucial aspect of CAC is the coherence of the models with the construction process along the different phases and aspects. Before spread of the digital computer, organization and management models had hardly been considered as subject of experimentation: they were more a subject of validation by means of statistical observations. MCO and CMM models can be validated and increase their effectiveness through continuous monitoring of the construction process in order to map its progress and unforeseen or unpredictable events. For researchers the monitoring provides data to refine the models and systems, while it offers the construction industry working tools to improve the total quality management, to reduce the time cycle and to optimize the use of resources. Effective monitoring technologies to be integrated with CAC are as follows.

Total station instruments are habitually used on-site to locate and survey precisely. They are interfacable to computer systems 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 manually identify and then locate each object.

Barcode is a robust technology widely used. It is based on a labeling system to be attached to each item to identify it univocally. It requires an untrained operator to point a laser hand-held device to automatically read the label. It requires both line of sight and proximity between the reader and the label. Barcode technology makes it possible to identify objects throughout the construction process, from the factory to the construction-site, but surveying of the items is provided only indirectly either by a fixed reading station or by the operator measuring with further technologies.

Radio frequency identification (RFID) 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 (Fig. 4). 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 etc. At the construction-site or later during the building maintenance, it can store information of tasks completed, in progress or scheduled.

An ongoing research project (Caneparo, 1999) aims to develop a new generation of transponders with the capability to continuously monitor certain physical and chemical parameters of the construction; while a network of fixed stations manage communication across a local area, e.g. the construction-site, with the capability to query the transponders in real time and locate them with a resolution up to the scale of centimeters.

A CASE PROJECT

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 glue laminated timber 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 meters, and is curved, along the main axis. The two arcs crossing the cableway are torsioned along their axes, so that in the middle they are horizontal, i.e. 90 degrees torsioned (Fig. 5).

CAC IMPLEMENTATION

The motorway was to be inaugurated, so there was less than a year ahead to complete the structure, starting from design. Due to the tight schedule the customer was especially motivated to implement a CAC system with the aim to develop the project concurrently.

Seamless integration between MOM, MOCT, MCO and CMM was pursued embedding the applications within a modeling kernel or, when this was unfeasible, by means of Microsoft's Component Object Model (COM), which seamlessly integrated at-runtime the interchange protocols of the component applications. 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. The semantic interoperability between applications, not embedded in the modeling kernel, was pursued by STEP or IFC standards (ISO, 1994) (IAI, 1996) (IAI, 1998). These standards defined the semantic on which the applications collaborated via DCOM. STEP and IFC semantic definitions with DCOM interoperability defined a dynamic data model: the modeled objects, new data structures or requirements to the models could be changed at run-time during the project.

MATERIAL-ORIENTED MODEL

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

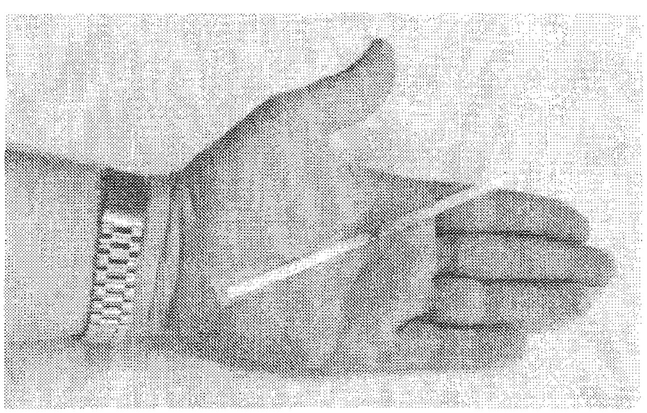

Figure 4. A radio frequency identification transponder.

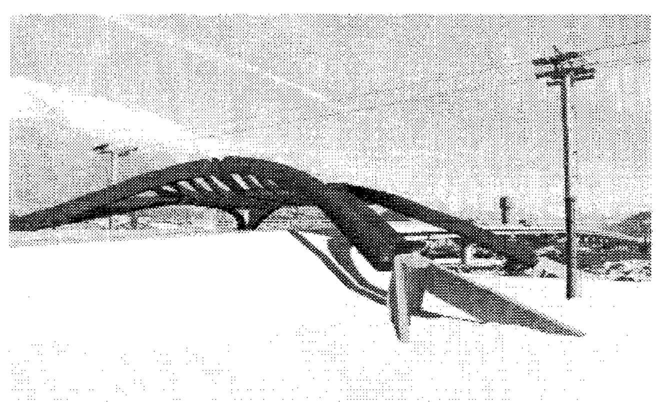

Figure 5. Early computer rendering used to obtain the contract.

MOM aided the design team in modeling the shapes of the four arcs according to the constraints of the composite construction material, glulam timber. MOM fulfilled bend and torsion constraints of glulam along all the four arcs as well as the single timber leaves since design inception. In view of the assembly process, MOM made the designer attentive to even small discontinuities in the bend, e.g. inflections, which could generate additional stresses inside the timber.

MODEL OF TIMBER CONSTRUCTION

MOCT made it possible to develop each modeled layer of timber in the plane, including the multi-curved torsioned beams. Figure 6 illustrates half of one 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 visualize and verify the patching procedure.

The software enabled the design team to analyze and visualize the exact shape of each timber leaf when flat; i.e. before torsioning and bending it to assemble the beam in space. This was especially useful in the early design phase, when the capability to exactly simulate the profile of all the timber layers suggested the possibility of unifying the profiles. The possibility of cutting and assembling a unified layer of timber instead of 16 slightly different ones for each arc was considered cost effective.

The profiles of each timber layer, developed on a plane, were converted in NC instructions to cut them (cf. Tooling and Forming).

The NC instructions, scaled 1 to 20, were used to cut scaled Masonite leaves. Using glue the scaled leaves were assembled to build the mock-up of the four beams and the central grid. The mock-up was the effective demonstration of the feasibility of the CAC methodology, that is the coherence between the models, the software and the physical reality.

MODELS OF CONSTRUCTION ORGANIZATION AND MATERIAL MANAGEMENT

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

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

Each timber leaf was uniquely identified using an RFID transponder. In the factory and at the construction-site mobile wireless communication were established by means of RF Ethernet technology (Proxim, 1999) with the CAC system connected via ISDN lines. An operator with a handheld station could read/write data to/from the transponder and the CAC system directly. This allowed tracking each part along all the construction process: from manufactory to the onsite assembling.

Assembling on-site required a scaffolding to supply a temporary support for the layering and stacking of the timber

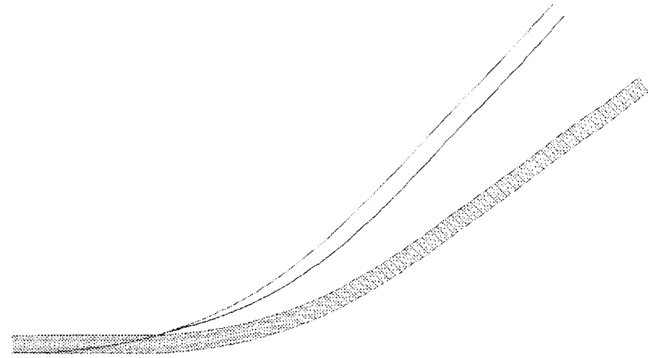

Figure 6. The edges of the base layer in the torsioned beam and developed in the plane.

leaves with glue and screws. To exactly shape the temporary scaffolding, the site manager used a total station to position the upper level of the scaffolding, which directly supported the timber layers. RF Ethernet supported online bi-directional communication between the total station and the CAC models.

During the construction process the positioning of each timber leaf was mapped in real-time into the CAC system. The surveying process was speeded up by the integration of total station and RFID technologies: the rodman identified a part by means of the handheld RFID station and then positioned the prism twice, respectively in correspondence with the lower-left and upper-right corners of the leaf, allowing the total station to get two measures and communicate them to the CAC system.

CONCLUSIONS

As considered earlier in the case study, CAC was experimented during the design and construction of an infrastructure. CAC was shown effective in accomplishing the schedules and deadlines of the project. The integration of the different models reduced the overall time requested by the cycle of designing-manufacturing-transporting-assembling, and improved accuracy, and reduced tolerances. While the integrated design and management of the project suggested several possible optimizations, such as the unification of the profiles (cf. Model of Timber Construction).

The real-time monitoring improved the project development towards a continuous process covering the whole models and aspects, beyond manufactory and construction, towards full interplay of information from designing to assembling and throughout competences and responsibilities. It made each model and phase of the project 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 (Fig. 7) 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.

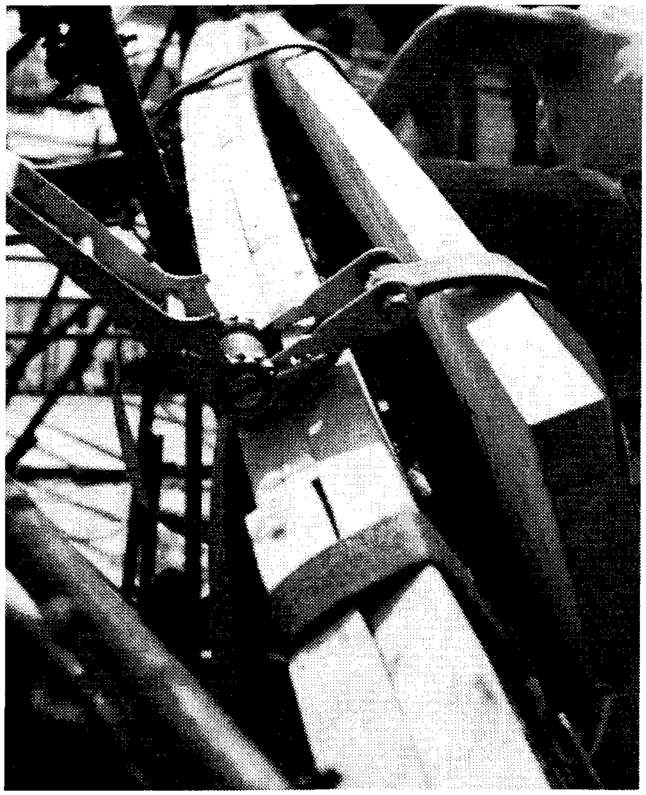

Figure 7. Stacking process of a timber leaf.

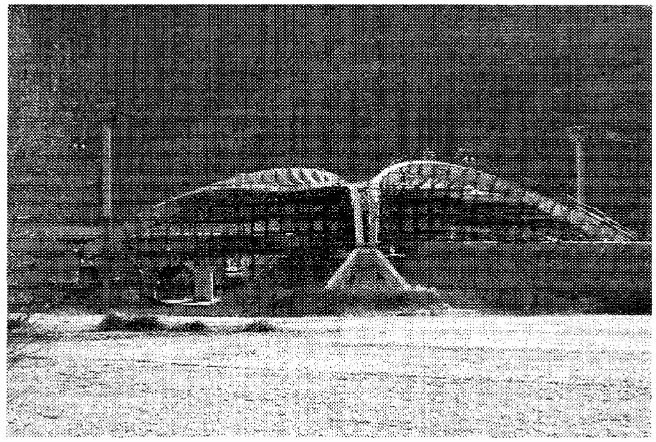

Figure 8. The structure completed with the temporary scaffolding still up.

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