Free-form Ceramics

Design and Production of Complex Architectural Forms with Ceramic Elements

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This paper describes a studio experiment developed with the aim of exploring the design and fabrication of complex architectural forms using ceramic elements. History has examples of double-sided curved forms built in ceramics. Such examples would not fulfill contemporary functional and aesthetic principles, neither would they be feasible or cost-effective considering current construction standards. There are recent examples of such forms built in other materials. These examples are difficult to emulate when ceramics is concerned, as they imply the fabrication of unique parts and sophisticated assembly techniques. Creating a double-curved surface in ceramics thus seems a difficult task. There are, however, advantages to such a formulation of design problems. They prompt the questioning of traditional wisdom, the rejection of accepted types, and the raising of interesting questions. What are the design strategies that should be followed when creating ceramic free-forms? What is the design media required to design them? And what are the techniques needed to fabricate and construct them? These are the questions investigated in the design project pursued jointly by students at an American and a Portuguese school, in collaboration with a professional research center and a ceramics factory. The students tested various possibilities, and in the process learned about state-of-art design and production techniques. The final projects are very expressive of their investigations and include a twisted glass tunnel, large-scale ceramic 'bubbles,' a rotated-tile wall, and a load-bearing wall system.

Keywords: *Design education: rapid prototyping; remote collaboration; ceramics; innovation; free-form architecture.*

Introduction

This paper describes work developed within the context of an architectural design studio with the aim of exploring the design and fabrication of complex forms using ceramic elements. The studio is aimed at the exploration of advanced computer aided design and production techniques within a university-industry collaboration context. The goal of the studio is to solve complex design problems and to develop innovative construction and production solutions. It has the format of a remote collaborative project open to senior students in architecture and structural, mechanical, and computer engineering from at least two universities, and it foresees the participation of industry consultants. One of the participating universities is the university where the studio is held, Instituto Superior Técnico (IST), and the other can be a national or a foreign university. In the academic year in which the research described in this paper evolved, the foreign university was the Massachusetts Institute of Technology (MIT), U.S.A., and the industry participants where the Portuguese Center for Ceramics and Glass Technology (CTCV) and the RECER ceramics factory.

The described project is the third project undertaken between IST and MIT. The first, The Lisbon Charrette, was undertaken in the fall of 1997 and it addressed the design of housing for teleworkers in an old section of Lisbon. (Duarte et al 1999) The second, The Glass Chair, took place in the spring of 1999 and it addressed the design and fabrication of a glass chair. (Heitor and Duarte 2001, and Duarte et al 2002) The latter was the first project to involve industry participants as a way of providing students with a design problem within a „real world“ context. The Free-form Ceramics project evolved in the academic year of 2002/03 and it was the first to evolve within the new IST Program in Architecture, as the previous took place within engineering programs. IST is the engineering school of the Technical University of Lisbon and the new Program in Architecture was created within the school in 1998 with the aim of forming architects with technology-oriented profiles, in sharp contrast with the beaux-art tradition prevalent at the school of architecture. The studio was offered in the 5th and final year of the program as a synthesis class in which they could integrate and expand the expertise acquired during the program while designing a building. Students in the class became the first architects to get the diploma through the new program.

Problem

The studio evolved during two semesters. In the first, it took the format of a research collaborative studio between IST and MIT, whose students were in charge of acting as consultants to IST students in issues concerning the design and production of free-forms. During the second semester, the studio was devoted to the development of ceramic prototypes in collaboration with CTCV and RECER. The studio addressed both urban and building design problems, although the focus was mainly on the latter. The task was to design a technology-based cultural center that included free-forms built with ceramic elements on a site in Cascais, a town in the neighborhood of Lisbon, near the Atlantic Ocean.

From the urban design viewpoint, design teams were asked to consider the historical development of the site, as well as urban accessibilities and transportation, morphology, and functional uses. The character of the site, located near the main town entrance should also inform the design process. It required the insertion of a large-scale public building into the urban fabric, and the study of its relationship with the town and the ocean.

From the building design viewpoint, students were asked to think of the way technology could change the concept of a building devoted to culture. Namely, they had to consider how technology could influence traditional art forms or originate new ones, affect the relationship of architecture with the other arts, and change the patterns of interaction with the public.

From the production viewpoint, students had to test the possibility of designing and building complex forms with ceramic elements, solving the architectural, structural, and production issues involved. Moreover, they explored the use of tools such as advanced geometric modeling, rapid prototyping, and virtual reality in the generation of digital, virtual, and physical models. These models would later be used in the conceptual design stage to explore design solutions, and in the construction detailing stage, to produce the information required for fabricating the components and constructing the building.

From the design process viewpoint, students had to develop a set of procedures and protocols that permitted the formation of geographically distributed, multidisciplinary design teams. Despite the fact that in the last decades, information systems greatly expanded the opportunities for remote collaboration, they remain scarcely applied by architectural firms, in part because they are not well understood. Design teams had to think of ways in which existing technologies could be integrated into design studios and contribute to change the social and professional dynamics of design activity.

The program thus included parallel explorations at the urban fabric macro-scale, and at the building components micro-scale, focusing on the process – both of design and construction – as a means to bring together those two dimensions. A series of exercises led to the final design:

1. Tool learning:
a) Remote collaboration: form teams with two elements from IST and three elements from MIT. Software: Picturetel, Netmeeting, ICQ;
b) Geometric modeling: model a 3D free-form surface that you might include in the design of the building. Software: Autocad, 3D Studio, Rhino, and Catia;
c) Virtual reality: model the surface conceived in the previous exercise considering constructability and navegability aspects. Software: EON Studio;
d) Rapid prototyping: make a physical model of the surface conceived in b). Processes: milling, stereolithography, FDM.

2. From urban design to the conceptual design of the building:
a) Site: analyze the site considering aspects such as history, accessibilities, transportation, and functional uses;
b) Program: develop the program for the building indicating the spaces and its areas;
c) Concept: sketch the building and its insertion into the urban fabric;
d) Preliminary design: design the building at the 1/200 scale.

3. From the prototype to the construction design:
a) Development of a prototype in collaboration with CTCV and RECER;
b) Development of the licensing and construction design projects, considering the 1/100, 1/50, 1/20, 1/5 e 1/2 scales.

Due to space limitations, this paper is focused on the description of the free-form aspects of the project.

Participants

As mentioned above, two schools, a research center, and a factory participated in the problem. Students were organized in four teams of five students each, being two from IST and three from MIT. In the first semester, students at IST were in charge of setting the architectural program, defining the urban design, and designing the building. They also had to provide the specifications of the free-form building system and to collaborate with their MIT colleagues in its development. Students at MIT concentrated on the development of the building system according to the specifications provided by IST students. In the second semester, IST team members had to refine the building system in collaboration with CTCV and RECER. The role of CTCV was to assist the students in the product development process while mediating their dialogue with RECER, which had to build mockups of the projects.

IST students were assisted by a team of research assistants in charge of helping them in issues such as advanced geometric modeling, collaborative technologies, rapid prototyping, virtual reality, and structural analysis. In addition they benefited from the support of teachers in structures and construction who became part of the project's team. Architects from the professional practice were asked to participate in the reviews to comment on the urban and architectural quality of the design work.

The fact that design teams had both to respond to manufacturing, structural and construction constraints while being judged on the architectural quality, put pressure on them not to compromise such a quality to solve the technical aspects.

Communication tools

The remote collaborative process encompassed presentation sessions involving all the participants, and informal working sessions among team members. The five presentation sessions were scheduled at the outset and they occurred at the beginning of the project, and at the end of each working phase. The working sessions were booked at the pace and convenience of the design teams. ICOM, an Internet-based videoconference system under development at MIT was used for most of the sessions. ICOM functioned 24 hours a day, allowing permanent visual and sound contact between the classrooms at IST and MIT, and it was crucial for developing a virtual shared space including the two schools. However, because sound and image quality were not the best at the peaks of Internet usage, ICOM was coupled with Netmeeting—a Web-based videoconference application with camera, voice, chat, whiteboard, and application sharing features. When video and audio transmission was bad students used a combination of whiteboard and chat. E-mails were used extensively for summarizing live sessions and for asynchronous communication when teams could not afford synchronous communication. Some teams used an Internet connection at home to work with their teammates, to avoid going to school after hours as sometimes required by the time difference or by the extensive usage of ICOM during the day.

Tools and Processes

Parallel to the traditional studio design work and to the acquisition of knowledge concerning ceramic manufacturing techniques, students were engaged in learning various tools for drawing, modeling, and rapid prototyping. Combining solid modeling with rapid prototyping had a significant impact on the students working method and it proved to be an important tool for design investigation.

In addition to traditional design media for sketching, students used Autocad 2000 for accurate 2D and 3D modeling, 3D studio for producing photo-realistic images, Rhino for modeling complex forms, and SAP 2000 for structural analysis at IST. Catia was also used for parametric form modeling at MIT. The idea was to create a parametric modeling system for designing ceramic surfaces. Once a parametric system encoded a given free-form concept, it could be used to manipulate the form and easily adapt it to new aesthetic or functional needs. EON Reality, a virtual reality desktop package, was used for visualizing and assessing complex forms at IST. The rapid prototyping facilities were different on both sides. A three-dimensional printer (FDM by Stratasys), a laser-cutter (X-Class by universal), and a water-jet cutter were available at the MIT Department of Architecture. A 5-axes milling machine and a stereolithography machine were available at the IST Laboratory for Advanced Production Technologies. Physical models were often exchanged across the Atlantic, and when IST students and teachers went on a field trip to MIT.

Students also developed large-scale partial mockups of their designs using ceramics when they wanted to test the process, or substitute materials when they wanted to test the discrete parts and their assemblage into the final shape. Various ceramics production processes were available at the factory and at CTCV, including tile pressing and brick extrusion processes, and students were asked to work within the constraints of the available systems. Collaboration with industry partners allowed for the development of a truly research environment between students, faculty, and industrial partners, and fostered a continuous process throughout the project that culminated with the fabrication of a few ceramic prototypes. Within this research environment, it was soon discovered that one of the main difficulties in linking students' projects to available manufacture techniques was the mismatch between these technologies and free-form designs. Many of the current ceramic production processes are geared towards a standardized production line that mainly produces construction elements, such as wall and slab bricks, tiles, and cladding elements. Despite the quality of these products and the sophistication of their production technology, there is room for investment in systems that could permit the fabrication of innovative free-form architectural ceramic elements.

At the end, a real prototype of one of the students' designs was developed at the ceramics factory in collaboration with CTCV, using wet clay pressing and double firing processes. However, it was determined that industrial production of that specific part should proceed using ceramics powder pressing and single firing processes.

Results: studio projects

Free-form is not a new concept and architecture history is rich in examples of its use, particularly during the Baroque period. The term free-form refers to use of double curved surfaces and to architecture in which issues of form-making play a major role in the design of buildings. Nowadays, with the possibility of using high-end software tools, the opportunity for manipulating form is greater as these new tools bring increased formal freedom. However, such a freedom implies a renewed discussion about the role of form in architectural design. Thus, while developing the four studio projects briefly described in this section, the students engaged in a discussion on the feasibility and validity of developing free-forms in architecture. Their projects differ in the extent to which free-form elements were incorporated in the architectural solution, and in the scale of their application.

Project #1 emphasizes design research by proposing a double skin twisted tunnel, which would be produced with translucent ceramics. (Fig. 1) The form of the tunnel was produced by translating a rectangle along a curved path while rotating it at the same time so that it was vertical at the beginning and horizontal at the end. This process of generating the form was conceptually tied to a decrease in the speed of public transportation between the start and ending points of the path. In the process of developing their project, the students realized that it was not feasible to use translucent ceramics because the amount of lighting required would originate extremely high temperatures. As a result, they decided to use glass, which technically is still a ceramic material. The problem then became one of decomposing the tunnel into discrete elements by a process of unfolding. Initial attempts showed that such an unfolding resulted in too many different

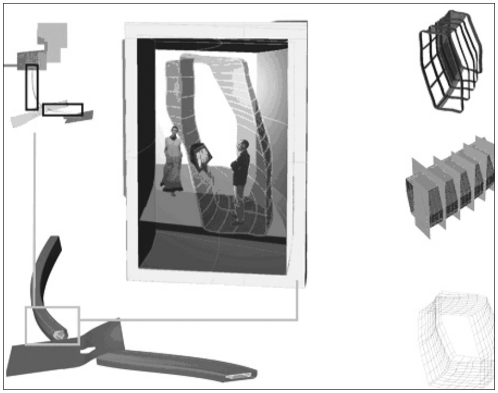


Figure 1
Project #1 by Joana Couto, Mariana Pedroso, Jen Seely, Gonçalo Soares, and Eric Orozco.

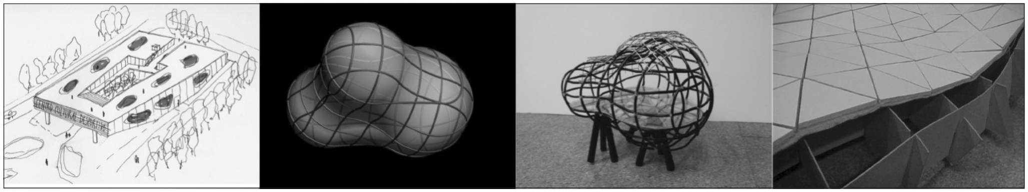


Figure 2
Project #2 by Inês Pinto, PaulaSilva, Xin Tian, Eddie Can, and Keneth Namkung.

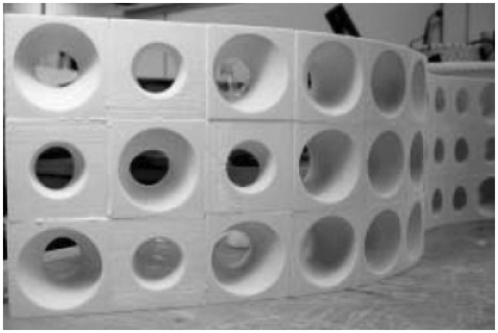
parts, making fabrication and assembly cumbersome. The observation that the dimensional differences among many of the parts were very small, led students to classify the parts into classes of almost identical parts. The idea was that such differences could be absorbed by the joints among them. The parts were held together in place by a connective part attached to a steel frame. Budget restrictions prevented students from building the final mockup.

Project #2 explores the idea of a flexible skin consisting of simple flat ceramic triangles that adapt to the shape of various free-form 'bubbles.' The building was to be devoted to art based on high performance sports and the form of the bubbles was inspired on human organs. The bubbles were exhibition rooms that would acquire different shapes in different parts of the building in response to different functional needs. (Fig. 2) This ambitious project went through several stages of development. In the beginning, all the bubbles had different shapes that were generated by manipulating a parametric model. Soon, students realized that having too many different shapes made design and construction too complicated and they decided to have only one bubble shape that was positioned in different ways inside the building causing it to look different. Then they changed the shape of the bubble so that it could be generated by the intersection of three spheres. Using ruled primitive shapes, made it easier to triangulate the compound shape. The structure of the bubbles consisted of vertical and horizontal steel profiles obtained by intersecting the bubble shape with parallel planes. The resulting cage was supported on three tripods, one for each sphere. A mesh was attached to this cage to bridge the spans among the profiles. A textile was then attached to the mesh and the ceramic triangles were glued to the textile.

While these two projects focus on interior architectural aspects, the following two focus more on the structural aspects of building form. The work of the Uruguayan engineer and architect Eladio Dieste (Anderson, 2004) was a major source of inspiration in these projects due to his innovative use of ceramics as structural material. Project #3 proposes an integrated building system where free-form ceramics act both as structural façade elements and as interior cladding panels. (Fig. 3) Such a system uses a single structural ceramic element that acquires a variety of additional functions (ventilation, lighting, flower pot) to create a membrane that mediates between the interior and the exterior of the building while function as a landscape element. The problem the students had to face was how to support such elements. The initial idea was that they would function as large, hollow bricks put together using mortar to form self-supported surfaces. Structural analysis, however, revealed that the surfaces needed reinforcement with concrete nervures like a two-way waffle slab. The students disliked the solution and considered another concept that consisted in using three-dimensional tiles placed in different positions to create an optical illusion, as in Vasarelli paintings, so that the observer perceived a flat surface as a free-form. The tiles had the shape of a bent volcano placed in rotated positions on a flat, square base. The challenge was how to make the different tiles in an economic way. The solution was to use a single mold to produce a tile with a round base, which would be rotated and cut into a square base before being fired to produce the different tiles. The volcanoes were hollow and could be used for lighting and ventilation. This project was selected for developing a full mockup because of its economic attractiveness and aesthetic appealing.

Project #4 applied ceramics as a structural element for exterior façades. A wavy ceramic form constitutes the wall. It was generated by offsetting a surface to create a volume with ducts that are used to insert tension reinforcement. (Fig. 4) The deformation of the wavy wall volume was parametrically controlled in Rhino, and mock-ups of different variations were developed using clay, Rockite and ceramics. The design team followed a post-rational approach to the free-form problem by first exploring the architectural solution and developing the free-form, and then decomposing it into manufacturable ceramic components. The solution was to build the curved walls exclusively out of flat ceramic elements, as they are easier to produce in a standard ceramics industrial facility. In the architecture project developed, the free-form walls were curved only in the vertical direction, as they were rectilinear between the wavy vertical guidelines that marked the inflexion points in the layout. Wall sections were thus formed by 'rule-based' surfaces generated by superimposing, offsetting, and rotating strait lines. The system also had the possibility of creating surfaces curved in the horizontal direction, but the students opted for not exploring that capacity in their architectural design.

The final system was constituted by six different pieces. The curved interlocking endings of two of the pieces allow for the rotations in plan. The vertical curves are made possible by slightly offsetting and rotating the pieces within limits set by the structural analysis in SAP 2000. Structural analysis also showed that the walls needed to be reinforced



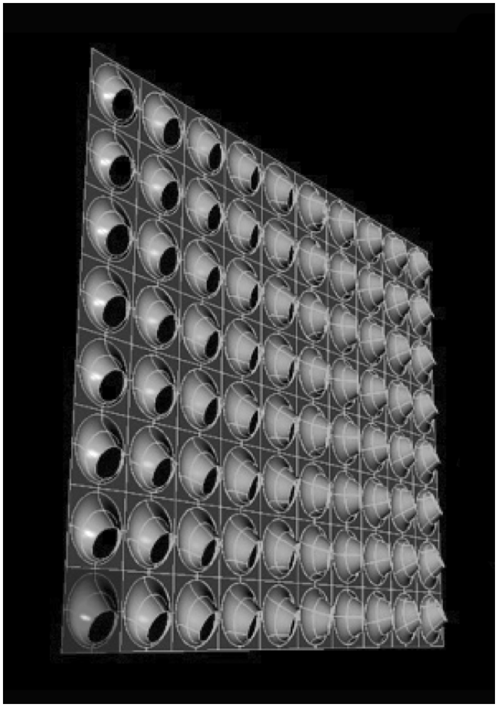


Figure 3
Project #3 by Silvia Preto, Mitjia Novak, Christine Gaspar, Andrew Marcus, and Rori Dajao.

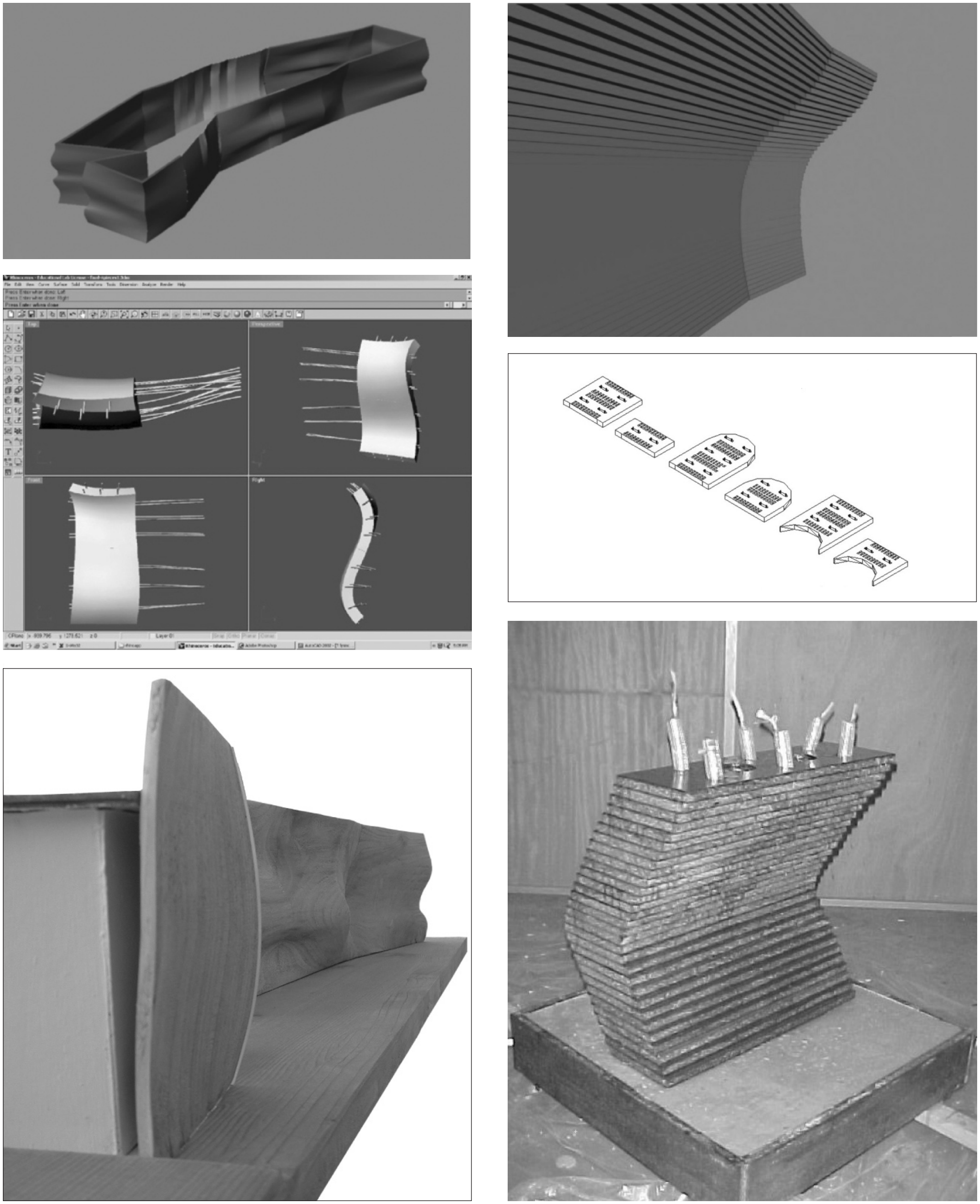


Figure 4
Project #4 by Carolina Passos, Tânia Silva, Min Cho, Michael Lehner, and Georgi Petrov.

by running a series of cables through voids created in the pieces. Other voids are carved out to reduce the weight of the pieces. As the ceramic walls only support their own weight, the buildings required an independent structure to support the remaining vertical loads. The external ceramic skin formed by the free-form walls is attached to the building by means of joints with neoprene springs due to the need to support horizontal loads.

The project involved the construction of a number of rapid prototyping models, together with some more conventional ones, such as a 1:500 stereolithography model of the buildings, 1:50 FDM models of different solutions for the wall, 1:10 cardboard models of the system's pieces and their possible combinations, a 1:2 wooden model of the wall system, and a 1:2 ceramic prototype developed at CTCV using a handcrafted process. Rapid prototyping techniques where also used to construct a 1:50 scale partial model of one building to study daylight issues, in the context of an Environmental Design course taught by one of the studio professors. The final ceramic elements were design to be produced using extrusion techniques, since the overall dimensions of the elements required presses that were too large to be economically viable in the Portuguese ceramics factory scenario.

Conclusions

This paper reports a collaborative teaching experiment by two universities, a professional research center and a factory with the goal of designing and making free forms out of ceramic elements using state-of-art design, production, and communication technologies to show how they can foster innovation through design.

Results revealed two different approaches to the problem. The first approach, starts by conceiving discrete pieces and then explores ways in which they can be combined to create free-forms. In the second approach, the free-forms are first created and then the task becomes one of decomposing it into parts that can be manufactured and assembled. Results also show two other categories of solutions. In the first, ceramics is used as a structural material to develop self-supporting volumes, whereas in the second it is used as a non-structural material to form cladding surfaces that are attached to an independent structure. The final designs emerged in response to aesthetic and functional requirements as much as to production and structural constraints. Students had to balance formal freedom with 3D modeling and fabrication constraints due to the need to work within the available technology. The final designs are particularly elegant outcomes of this process. The fact they led to two patent requests also shows that they have commercial value. In the end, it shows that innovation pays-off and that it could help ceramics factories to expand their business.

Acknowledgements

We thank William Mitchell and Manuel Heitor for helping to define the scope of the project, and Teresa Heitor and António Lamas for providing the institutional context. We thank Sousa Correia and Alain Thibault for the support of CTCV and RECER, respectively. We also thank Larry Sass, Axel Killian, and Carlos Barrios, the teaching team at MIT, and Filipe Coutinho, Rodrigo Correia, and Pedro Studer, the teaching assistants at IST, for their valuable contributions. We thank our colleagues Jorge Brito and Francisco Virtuoso for their support in the construction and structural aspects, and Pedro Rosa from the IST Laboratory for Advanced Production Technologies. Special thanks are due to all the students whose work is referred to in this paper, as well as to the architects who participated as critics in the various stages of the project, namely: José Beirão, Diogo Burnay, Pedro Gadanho, Manuel Mateus, Pedro Ravara, Manuel Salgado, Frederico Valsassina, and Manuel Vicente. The project was partially funded by a grant from the Luso-American Foundation (FLAD). We would like to express our gratitude

to ExperimentaDesign for including the final projects in the S-Cool exhibition, as part of the Lisbon Biennial 2003, and to the Cascais Town Hall showing the projects in the Gandarinha Cultural Center.

References

Anderson, S.: 2004, Innovation in Structural Art, Princeton Architectural Press, NY.

Duarte, J. P.; Bento, J.; and Mitchell, W. J.: 1999, Remote Collaborative Design: The Lisbon Charrette, IST Press, Lisbon.

Duarte, J. P.; Heitor, M.; and Mitchell, W. J.: 2002, The Glass Chair: Competence Building for Innovation. In Koszewsky, K. and Wrona, S. (eds) Design e-dication: Connecting the Real and the Virtual. Proceedings of the 20th eCAADe Conference , Warsaw, Poland.

Heitor, M. and Duarte, J. S.: 2001, Collaborative Design of a Glass Chair, IST Press, Lisbon.