THE ROOF OF THE OLYMPIC STADIUM FOR THE 2004 ATHENS OLYMPIC GAMES
from Concept to Implementation

On 21 January 2004, Dennis Oswald, Chairman of the IOC Coordination Committee for the Athens Games,[1] argued that "the construction of the roof is not necessary for the Olympic Games" and suggested abandoning it in order to have the stadium ready without a roof by August 2004. [2] It was less than two months since Santiago Calatrava, the roof's designer, had said at the construction site, "obviously, the roof will be ready on time. I would never risk my reputation if I were not sure about it."[3] The media worldwide had criticized the delays in the construction of all Olympic works and especially the delay in the roof of the stadium. The Athens Organizing Committee (ATHOC), the General Secretariat for Sports (GSS) which managed the construction of the project, and the government were fully aware that it was absolutely necessary for the stadium to be ready for the games, with or without the roof, by 13 August 2004. To be precise, the construction had to be ready two months earlier so that all the broadcasting and lighting installations as well as all the rigging for the opening ceremony could be put in place for the start of the games.

The truth is that the vision of an architectural centerpiece for the event had come rather late, in 2001. Then, the awarding of the construction contract took a long time, to follow the due process for public works. On top of that, the detail design of Calatrava had been found inadequate by the checkers, it was resubmitted to meet their concerns more than a month after the original deadline, and had to be adjusted by the contractors for structural safety, which also took valuable time. On the other hand, despite the appearance of the construction site, the ATHOC under the direction of Gianna Angelopoulos-Daskalaki was moving decisively ahead with the project and the contractors' joint venture gave assurances that they would finish on time. Yannis Pyrgiotis, Executive Director of ATHOC, recalls that it was a critical period. The Greek organizers of the Games should defy the international predictions and give an artistic dimension to the 2004 Olympics not seen since the 1992 Barcelona games. Nevertheless, there were lonely moments at the highest levels of the Greek government and ATHOC, as they were going ahead despite the odds, trusting their engineers and the contractors and believing in their vision.

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1 International Olympic Committee (IOC)
2 "Eleftherotypia," 21 January 2004.
3 "Ta NEA," 2 December 2003.

Doctor of Design candidate Andreas Georgoulias, MDesS'05, and Theodoros Patramanis, MDesS'05, prepared this case under the supervision of Professor Spiro N. Pollalis as the basis for class discussion rather than to illustrate either effective or ineffective handling of an administrative situation.

This case study was based on field studies and was sent for review to Gianna Angelopoulos-Daskalaki, Yannis Pyrgiotis, Haris Batsios, and Konstantinos Vickis (ATHOC), Thomas Stamou (General Secretariat of Sports), Vasilios Makryonitis (Prime Minister's office), Phaedon Karydakis (Karydakis Structural Engineers), Santiago Calatrava, Leonidas Kikiras (Calatrava office), Ioannis Bentourakis and Eleni Tzanou (Betaplan S.A.), Dimitrios Kallitsantsis, Manolis Stivachtakis (Aktor S.A.), Florios Glezos and Konstantinos Tsakalidis (Themeliodomi S.A.), Salvatore De Luna (Cimolai), Paul Perry (SKM Ltd), Stavros Lazaridis (No Limits S.A.) and Spyros Cavounidis (Edafos Ltd.). Most of the reviewers responded and the case would have not been possible without their contribution. Prof. Pollalis was consultant to ATHOC in the Spring 2002 to assess the engineering design submitted by Calatrava's office.

1. The organization of the Athens 2004 Olympic Games

The International Olympic Committee (IOC) is the supreme authority of the Olympic movement. It is an international nongovernmental, nonprofit organization whose primary responsibility is to supervise the organization of the summer and winter Olympic Games. The President of IOC in 2004 was Dr. Jacques Rogge from Belgium, who presided over all activities of the committee, acting as its permanent representative. IOC reviews the applications of candidate cities, and its 115 members vote to select the host city for the Olympic Games every four years. In 1996, Greece's Prime Minister Kostas Simitis appointed Mrs. Gianna Angelopoulos-Daskalaki as the President of the Athens 2004 Olympic Games Bid Committee, and in September of 1997, IOC awarded the 2004 Olympic Games to Athens. Subsequently, IOC handed over the organization of the Olympic Games to the Athens 2004 Organizing Committee (ATHOC, Οργανωτική Επιτροπή Αθήνα 2004), which was specifically formed for this occasion. The role of ATHOC was to organize the Games which were due to start on 13 August 2004, and to communicate directly with IOC. In May 2000, Angelopoulos-Daskalaki became President of ATHOC in order to steer the efforts of this administrative agency and to manage the hundreds of people working on organizing the Olympics. The key position of Executive Director in Charge of Technology and Olympic Works was given to Yannis Pyrgiotis, an experienced architect and urban planner.[4] An MIT graduate, Pyrgiotis acted as the technical consultant to Angelopoulos-Daskalaki.

2 Original Plans

Angelopoulos-Daskalaki, lawyer and former member of the Greek Parliament, headed the Athens bid for the 2004 Olympic Games. The successful outcome was largely credited to her hard work and it helped restore the pride of Greeks after failing to get the centennial 1996 Olympics. The announcement that they would host the 2004 Olympic Games was greeted with great joy by the Greek people, along with the knowledge that a lot of work had to be done. IOC required projects related to the events, such as sports venues, extensive accommodation and media facilities, but also projects that would improve the civic infrastructure.[5] The new airport was still under construction, planned for completion in 2000, and a major highway that would deal with the city's traffic issues, Attiki Odos, had not even been started. As a consequence, construction activity would greatly increase in the following years, and every project needed to be carefully examined in relation to both short- and long-term needs.

Angelopoulos-Daskalaki was withdrawn from center stage after securing the Games for Athens, but she was brought back as president of the Athens Olympic Committee (ATHOC) in 2000, when the preparations were behind schedule and Greece was facing the possibility of IOC replacing Athens as the host city for 2004. "Gianna," as she is known in Greece, quickly stepped up to the daunting task to organize the Games, oversee the construction of the venues, and have Athens ready before the deadline of the opening ceremony, which was only four years away.[6]

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[4] During operations, Pyrgiotis was appointed as Chief Technical Officer.

[5] The lack of infrastructure was one of the reasons that Athens did not win the right to host the1996 Olympics.

[6] The Olympic Games in Ancient Greece were forbidden to women athletes. In the modern Olympic Games women have gained their place as athletes, but had not assumed leadership in high positions for organizing the event. However, with the return of the Olympics to their birthplace, history was made and the Athens 2004 Olympic Games were the first Olympics with a woman in the key leadership role. Gianna Angelopoulos-Daskalaki was the first-ever woman head of a national Olympic organizing committee.

Numerous construction projects, including renovations of existing installations, were part of the preparations for the 2004 Olympics. These included 11 non-competition venues: the Olympic Village, eight media villages (of which two were private housing developments, two student housing projects, the police academy, the Ministry of Education building and two complexes of summer cottages), the IBC and the MPC, 24 competition venues including 5 projects in the OACA complex, four football venues outside Athens, the Hellenicon Complex with 6 different venues (3 different contracts), the Faliron redevelopment with two venues and the adjacent Peace and Friendship and Karaiskaki, the rowing center in Schinias, the Goudi Park which included the Modern Pentathlon Venue and the Badminton pavilion, the Equestrian Center, the Shooting Center, four more new pavilions, one in Nikaia, one in Liossia, one in Galatsi, and one in Peristeri and the Marathon race start installations. The major infrastructure projects were: the ring road around OACA, the national road extension to the coast with a number of interchanges, the Posseidonos avenue interchanges, the Pallini bypass, the Marathon Road, the Varis – Koropiou road, Kifissias Avenue interchanges, local access roads to new venues, the Suburban Railroad, the Tramway, two metro extensions plus the refurbishment of the old existing line, the major remodeling of the Port of Piraeus, four major power substations and a number of smaller urban improvement projects including the major "unification of archeological sites" in the historic center of Athens.

The construction projects were handled as 7 different groups, with one group including the constructs in the OACA area: the stadium, the velodrome, the tennis courts, the gymnasium, the Olympic swimming pool, the common areas of OACA, and the sponsor's hospitality Center.

Fig. 1. The original state of OACA sports complex and the main stadium.

The bidding documents that Athens had submitted as a candidate city had specified the Olympic Athletic Center of Athens (OACA, Ολυμπιακό Αθλητικό Κέντρο Αθηνών) as the main sports complex that would host several of the events. The main stadium of OACA, built in 1982 in accordance with all the required specifications to host Olympic Games, was nominated as the venue for the opening and closing ceremonies as well as the track-and-field events and the men's soccer final. Even though there were no initial plans for the renovation of the stadium, in 2001 the Greek government along with ATHOC decided on a major renovation of the center and the construction of a roof to cover the main stadium. This choice was driven not only by the necessity of a renovated stadium for hosting the main events of the Olympic Games and the need to have proper lighting and telecommunications, but by the intention to give an architectural centerpiece to the Games, a central node of attention, both in spatial and symbolic terms.

3 Design Process

Angelopoulos-Daskalaki swiftly understood the importance successful Olympics would have to the psyche of the Greek people and she built her modus operandi around it. Her vision was that the success of the Olympic Games, the most high-profile and costly undertaking in Greece's recent history, would give the country a boost of confidence that will show the world the transformation of a small, developing country into a modern, dynamic European state. Therefore, this effect had not only a political aspect but also a psychological parameter that had to reach the hearts and minds of people both in a mental and a visual way. From the position of president of ATHOC she understood that this could be achieved by building illustrious and impressive sports venues that would capture the spectator's eye in the short-term and still be there after the Olympics to remind the Greek people of the triumphant Athens 2004 Olympic Games. To this end, Angelopoulos-Daskalaki was instrumental in the decision of the Greek state to incorporate design excellence and signature architecture for the renovation of the main stadium.

3.1 Selection of the Architect

In March 2001, the internationally known Spanish architect Santiago Calatrava was in Greece for a series of lectures after the inauguration of an exhibition of his models and sculptures. This exhibition was held in the National Gallery in Athens and lasted from 21 March to 18 June 2001.[7] In addition, Calatrava was involved in the production of the ancient Greek tragedy *Troades,* performed by the famous Greek actress Irene Pappas, as the designer of the sets. Finally, in August of that year, Calatrava joined the committee for the selection of the design for the new Acropolis Museum of Athens, along with other Greek and international architects and engineers.[8]

Among his contacts was the Minister of Culture, Evangellos Venizelos, who said in his speech for the opening of the Calatrava exhibition in the National Gallery:

> *I am particularly happy because [Calatrava] will talk with us concerning the Olympic preparations and the Cultural Olympiad, and the monuments that these two great events must leave in the greater Athens area and in all the country.*[9]

Pyrgiotis, one of the four executive directors of ATHOC at that time, approached Calatrava through the Director of the National Gallery and started a discussion of his possible involvement

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[7] The exhibition was organized by Consorci de Museus de la Comunitat Valenciana, and Subsecretaria de Promoció Cultural de la Generalitat Valenciana. The curator of the exhibition was Professor Manuel Blanco of the Escuela Técnica Superior de Arquitectura de la Universidad Politécnica de Madrid. Among other things, the exhibition included Calatrava's famous bridges such as the Alamillo Bridge in Seville, a telecommunication tower in Barcelona, the City of Arts and Sciences in Valencia, and a train station in Zurich.

[8] The first prize was awarded finally to the proposal of Bernard Tschumi and Michalis Fotiadis, with a second prize going to Daniel Libeskind.

[9] Evangellos Venizelos, address at the inauguration of the Santiago Calatrava exhibition in the National Gallery, Athens, Greece, 21 March 2001. Cited in *Santiago Calatrava,* a catalog of Calatrava's works published by the Generalitat Valenciana in 2001 to accompany the National Gallery exhibition as well as a similar exhibition in the Tellogleio Foundation in the city of Thessaloniki, Greece, between 23 March 2001 and 31 January 2002. The exhibition in Tellogleio prominently displayed models and drawings that Calatrava had prepared for the 2004 Olympics.

with the works for the Olympic Games.[10] Pyrgiotis admired Calatrava's design genius but he was also aware of the time limitations and of problems of delivery in Calatrava's past projects. Nevertheless, he believed that he was an excellent choice for the Athens 2004 Olympic Games and he trusted ATHOC and the Greek designers and contractors to overcome issues of implementing Calatrava's design, should they occur. As Calatrava's exhibition was prolonged at the National Gallery, new models arrived from Zurich and were added to it, showing his ideas for the roof of the main stadium as well as his proposals for five additional projects in the neighborhood of the stadium.

3.2 Commission of Design Contract

Calatrava had started working on the project since mid summer and he signed the contract in October 2001 for a direct commission for the design of works at OACA, so that the games would have a high aesthetic dimension and the "signature" of an international architect. This was a political choice, a choice to directly select this particular architect based on his portfolio of past work, but without holding an international competition, something that is allowable by the European Directives as an extraordinary procedure for projects of artistic nature. This action on the part of the Greek government stirred up controversy in architectural and media circles of Greece.[11] The government's response claimed that the project fell under the category of projects of purely artistic nature, unique and original; therefore the selection of the architect was excluded from the European Union regulations regarding the award of public supply contracts (92/50/EC). Nevertheless, all other contracts were subject to the European Union regulations.

Fig. 2. 3D images of the initial design of Santiago Calatrava for the aesthetic unification of OACA.

3.3 The Architect's Vision

Santiago Calatrava studied architecture in Valencia and did his doctoral work at the ETH-Zurich with Professor Christian Menn, the Swiss bridge designer. In an ingenious way, Calatrava combines architecture with the art of sculpture and the science of structural engineering. Large-scale steel structures with enormous strength, like the skeletons of animals or rainbows, appear to defy the laws of gravity and attract the attention of laymen. Calatrava's designs balance levitation and action, shape and movement, and structural excess.

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[10] Pyrgiotis had been approached earlier by European architects proposing roofs for the stadium but, as he said, "We did not follow up because the roof was not a necessary piece for hosting the games and we were not impressed by the proposed designs."

[11] Rem Koolhaas was in Greece about that time to give a lecture for the Greek Institute of Architects. When a reporter commented on Calatrava's involvement in many projects in Greece, Koolhaas responded: "This confirms my theory. Calatrava is the appropriate man. He knows exactly what to do when there is no luxury of time." *Eleftherotypia,* 6 September 2001, <http://www.enet.gr>.

3.4 Design Proposal

Calatrava's design included the construction of a roof for the main stadium; a similar but smaller-scale structure for the covering of the Velodrome; and general landscaping works, such as a steel arcade named Agora, a steel kinetic structure known as the Wall of Nations, entrance canopies, and the Olympic Icon, a 100-meter-high vertical element in the form of a knitting needle intended as a landmark.[12] The scope of the design in the short term was to satisfy all the functional needs necessary for the harmonious operation of such a complex scheme. These requirements included the distinct and secure circulation of public, athletes, journalists, and VIPs; accessibility for people with special needs; and the compliance of the project with ecological requirements. In the long run, the entire project aimed at leaving an important heritage to the city of Athens and its citizens. OACA would not just be a sum of athletic fields but would be further evolved into a major urban center of athletics and culture, with a capacity for continuous operation with cultural shows, concerts, and exhibitions.

Calatrava argues that he drew from both the classical and Byzantine traditions of Greek culture. According to him, the arches and vaults are associated with the Byzantine style, and the architect considered this style suitable for spanning vary large spaces, such as the Olympic Stadium. "However," he noted, "the sequence of the [civic] space in plan is very classical, with the central axes, Agora, Plaza of the Nations, and stoa-like entrance plazas." Calatrava argues that he drew from the Mediterranean style in the landscaping and in his choice of materials. "So I would say," he concluded, "that the plan is classical, the elevations are Byzantine, and the spirit is Mediterranean."[13]

Fig. 3. Zubi Zuri pedestrian bridge, Bilbao, Spain (Calatrava, 1992).

The covering of the Olympic stadium for the 2004 Olympic Games became the architectural centerpiece of Calatrava's proposals. The design consisted of a set of double arches bearing the weight of 42,000 m^2 of coverage and spanning a distance of 304m.[14] The proposed design of OACA's roof was reminiscent of an earlier work of Calatrava in Bilbao, Spain. The Zubi Zuri (white bridge) pedestrian bridge is a few hundred meters upstream from the Guggenheim

[12] The landmark 100 m high element was not built. When it was abandoned, a 30 m cauldron was proposed by Calatrava. The final design of the cauldron was completed by the engineers of the contractors. The Wall of Nations was initially suspended and was not included in the original construction budgets but finally it was built.

[13] *Architecture Week,* 20 October 2004, p. D1.2.

[14] The structure was reduced to 24,000m^2 during design development in an effort to reduce stresses.

Museum; its structural system consists of an arch for the vertical loads, a glass deck supported on transverse beams, and a torsion cylindrical beam that holds those transverse beams (Fig. 3). Two oversized bridges, like that in Bilbao, facing each other, constituted the proposal for the stadium's roof. Similarly, the Agora was reminiscent of his work in Valencia and Toronto, and the Wall of the Nations was a vertical version of Calatrava's wave sculpture.

Calatrava likes to work with big spans and arch forms. The arch forms are appropriate for big spans because of their structural efficiency. Steel arches are placed along the long dimension of the stadium, not along the shorter side, as they should be for structural reasons. By placing them along the long side, which is more than 300 m long, the arches coincide with the athletes' jumps and also vividly provide the sense of scale and the shape of rainbows. Calatrava's own explanation is that his choice, like in the Sydney Olympic Stadium, is for aesthetic and symbolic reasons, because the track and field athletes make their efforts along the long dimension (long jump, 100-meter race, hammer throw, shot put, discus, triple jump) and their direction should match the arches' direction. The steel arches are big in order to have the necessary strength but slender compared with their span and their height, resulting in large deformations under the expected loads.

Fig. 4. The athlete's jump in harmony with the arch's shape and position along the long dimension of the stadium.

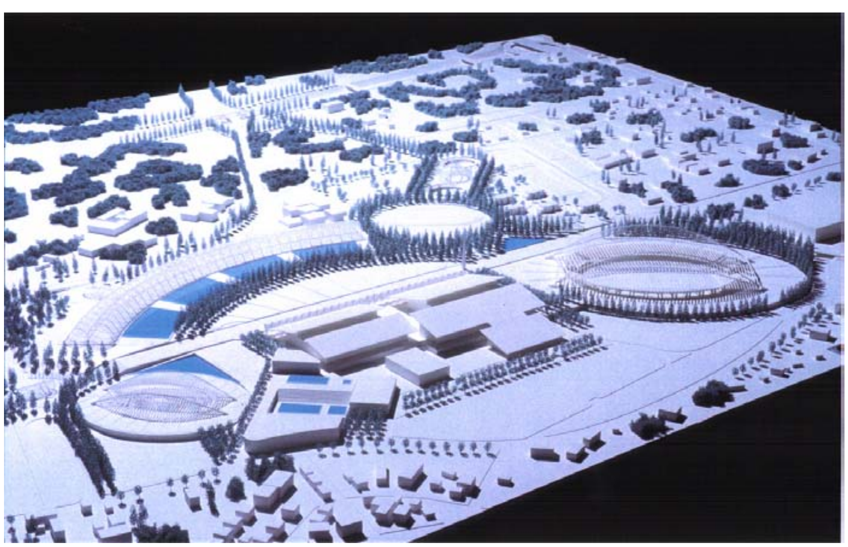

Fig. 5. Model of the initial design of Santiago Calatrava for the aesthetic unification of OACA, exhibited at the National Gallery in Athens.

Calatrava did not want a lattice arch because it would look like an industrial structure. He chose the pipe arch to give an airy form and aesthetic look even though it would have to be heavier. The final decision pertained to the choice of the cross-section of the pipe. Calatrava chose the circular section instead of orthogonal section to have the same stiffness in both axes.

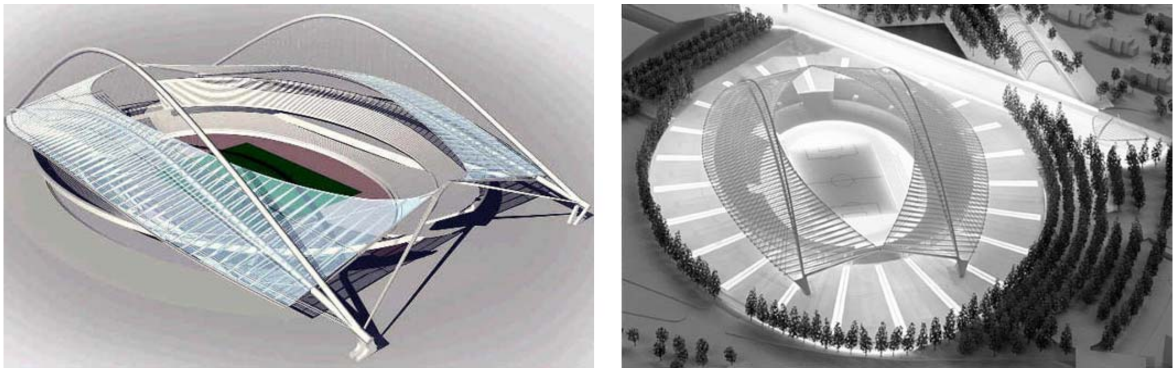

Fig. 6. 3D computer model and physical model of Calatrava's proposal for the Olympic Stadium.

3.5 Team Formation

ATHOC commissioned the design contract on behalf of the government to the Calatrava office in Zurich. Calatrava's office was the architect of record[15] and during the design phase they did not have an office in Greece. The Zurich office was the primary point of contact and assumed the responsibility of stamping all the submitted drawings. At the time and during the project, Calatrava's office was a relatively small size architectural firm for this kind of endeavor, with an even smaller engineering section.

ATHOC requested the Calatrava office to cooperate, for the purpose of the design, with a design firm based in Athens. Calatrava selected to work with the architectural office BETAPLAN S.A., which subsequently was responsible for the rest of the local design team. Betaplan, being the sole subcontractor of the Calatrava office in Greece, undertook a support role during the execution of the study for the coordination and communication with the authorities and getting the relevant permits needed for the project, had the overall responsibility for the Greek collaborating consultants: KANON MELETITIKI S.A. (Civil Engineers), LDK Consultants S.A. and KION MELETITIKI S.A. (M&E Engineers), DIM. SOTIROPOULOS & ASSOCIATES S.A. (Hydraulic Engineers), DENCO Ltd (Traffic Engineers), TOPIODOMI S.A. (Landscape Architects) and provided parts of the overall design that were assigned to it (i.e., assistance in the design of Pavilions, of the surrounding grounds and the interior refurbishment of the Velodrome). Consistent with previous Calatrava projects elsewhere, Betaplan was not responsible for the design of the main elements of Calatrava's scheme and its contribution of Betaplan in the design consisted primarily of printing the drawings that Calatrava's office sent them from Zurich in *.plt format, and communicating them to the controlling agencies.

ATHOC also contracted its own surveyors and EDAFOS, Ltd, as its geotechnical engineers for the initial soil investigation (soil borings), soil evaluation and recommendations regarding the foundations.

[15] Architect of record: the architect who stamps the drawings and is responsible for the architectural work under the law.

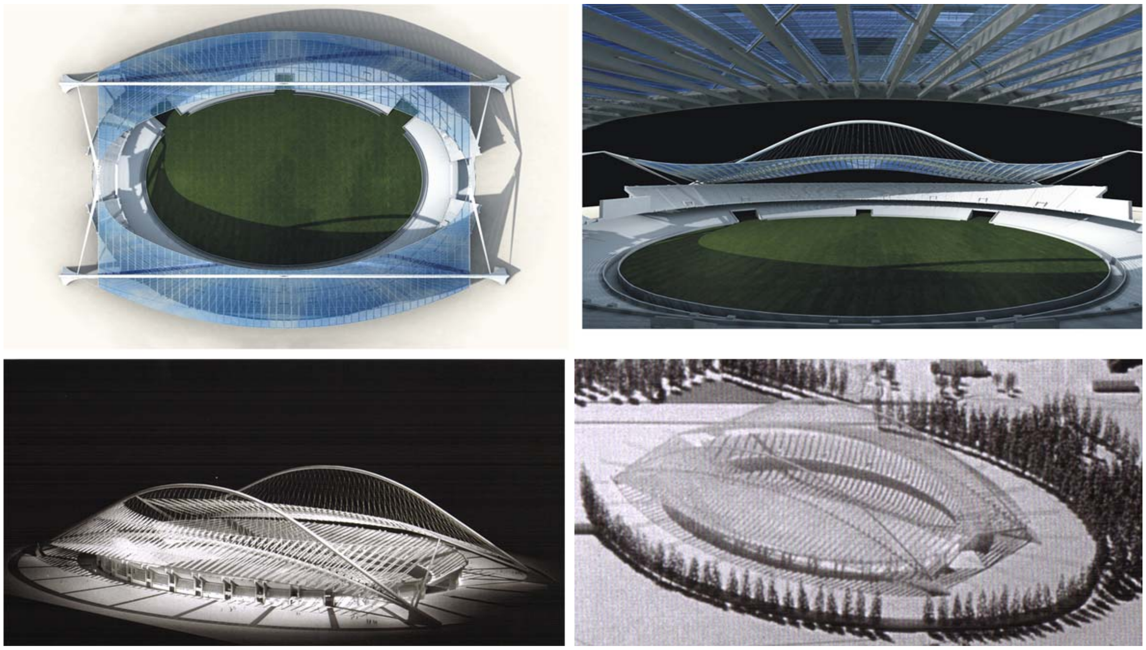

Fig. 6. Top left: Panoramic view. Top right: Interior view.
Bottom left: Perspective of the model. Bottom right: Model with landscaping.

3.6 Duration of Design and Budget

The design of the stadium's roof began officially in October 2001, following the signing of the contract with the Calatrava office, and finished a little more than four months later in early 2002. According to Greek technical legislation, every design after the feasibility study is divided into three phases: preliminary (προμελέτη), final (οριστική μελέτη), and detail design (μελέτη εφαρμογής). The preliminary design was submitted 40 days after the signing of the contract, the final design was submitted 20 days later, and the detail design 44 days after the submission of the final design. The entire project was called Aesthetic Unification of the Athens Olympic Sport Complex and included everything that was designed by Calatrava and the local offices. In a press conference Minister Venizelos revealed that the total cost of the aesthetic unification and functional improvements of the complex of OACA would be 235€ million, with the aesthetic unification alone being 126€ million.[16] The Calatrava team, Venizelos stated, received a design fee of 12€ million, of which 72% came from Greek public funds and 28% from ATHOC. Venizelos added that "the fee is significantly lower" than it would have been if it had come under Greek legislation for public works, in which the design fee is a percentage of the final budget. The minister referred to both architectural and engineering fees and did not specify the exact amount.[17]

All the Olympic projects were publicly funded, except for the Olympic Village and the two media villages. The OACA project was financed with funds from the Public Investments program. The European Investment Bank had originally expressed interest in participating, as it had before in the New Athens Airport, but the Greek government gave a negative response, mainly in order not to increase the public debt. The Olympic projects could not be funded

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[16] This cost did not cover the new athletic facilities, like the Velodrome and the swimming center. Furthermore, the numbers presented reflect the overall improvements, not just the roof of the stadium.

[17] *TA NEA,* 15 January 2002, <http://ta-nea.dolnet.gr>. See also *Eleftherotypia,* 31 January 2002.

through the European Union development funds for the reason that this program does not support sports complexes and housing. As a consequence, the budget of the Olympic stadium was of major political importance and every change was subject to media scrutiny.

4 The Checkers

After the design was commissioned to Calatrava, ATHOC commissioned GIBB Hellas SA, as the checkers of the design. According to the European legislation, the checkers verify the engineering aspects of the design to assure the owner that the design meets the applicable codes and can be built safely. GIBB Hellas SA hired the Greek structural design office of Phaedon Karydakis to carry the checking. In addition, and at the intervention of Calatrava, Victor Segovia was hired as a second checker. Segovia, a Spanish structural engineer based in Madrid, had worked with Calatrava in the past.

The checkers made two trips in Zurich, to gather information on the design.[18] The first trip was after they were hired and the second trip in late November 2002, a week before the final design was due. Both trips were unsuccessful in gathering information. During these visits, there were general discussion and presentations of a large number of artistic sketches, but no structural design. The design was delivered to the checking team, after it was submitted to the client. So there was a very limited time to review, to run independent analysis and comment. This made ATHOC quite nervous. As the Olympic Games were considered by many as being delayed beyond hope, the designer of the singular iconic structure of the Games was not assisting the checker team as had promised.

On January 31, 2002, Calatrava delivered the detailed design (μελέτη εφαρμογής) to ATHOC that was given to the checkers. Karydakis and Segovia had serious objections on the validity of that design and issued 25 points that needed to be addressed. Calatrava resubmitted a revised version of the detailed design in early March responding to those objections. As in the past when a design was made available to them, Karydakis and Segovia met in Athens with the engineer of Calatrava's Zurich office for 2 days, studied the design for a week, the maximum time that ATHOC could afford them to spend on the project, and met again in Athens to write the checker's report. This time Karydakis and Segovia confirmed that the design addressed their concerns but they did not verify the design since the results of the wind tunnel tests were not available yet.[19]

5 Bidding Phase

5.1 Transition of Authority

After the submission of the detailed design, there was a transition of authority from ATHOC to the General Secretariat for Sport (GSS, Γενική Γραμματεία Αθλητισμού), which is a division of the Ministry of Culture. By legislation, ATHOC could not commission construction works related to public property, such as the sports complex of OACA. Thus, GSS became the owner of the OACA project, and its Special Agency of Public Projects/Athletic Olympic Projects-Facilities (SAPP/AOPF, Ειδική Υπηρεσία Δημοσίων Έργων/Αθλητικών Ολυμπιακών Έργων-

[18] Interview with Phaedon Karydakis, September, 2005.

[19] The final report of the checking team was issued much later, in September 2002, when the wind tunnel tests were received from Toronto.

Εγκαταστάσεων) assumed the supervision of the construction of the project. According to the Greek legislation for public works, GSS was equally responsible with the contractor for both quantities and quality. The new organizational structure included BUNG GmbH, an engineering company from Germany, as technical consultant, and Calatrava as a special consultant for GSS. Upon appointed special consultant for GSS, Calatrava opened an office in Athens. The office was based on a trailer in the construction site, and was represented by Leonidas Kikiras,[20] who was appointed head of that office.

At that time, the Greek authorities, both ATHOC and GSS, pressed with time and satisfied with Calatrava's visual aspects of the design, knew that the only way was to proceed with selecting the contractor who would assist in resolving the technical problems. So, the GSS proceeded to the bidding process for the award of the construction contract with an unverified structural design. Although the risk was high, there was no alternative.

During the execution of the detail design of the project, ATHOC and GSS decided to split the contract into two separate parts in order to hedge the risk due to time constraints and budget size. The entire project budget was 407€ million. Phase I included the entire aesthetic unification of OACA, with a budget of 180€ million for construction and 20€ million for the opening ceremony. Specifically, the stadium roof had a budget of 100€ million, with 97€ million for the steel structure and 3€ million for the covering (Appendix B).

5.2 Award of Construction Contract

The bidding documents took from April to June to be finalized, and the project bid lasted another four months until October 2002.[21] The bidding documents required each participant to select a highly qualified and experienced subcontractor for the steel works. The bidding process consisted of two phases of an international public competition. In the first phase, five joint ventures were prequalified among those that responded to the expression of interest. The two criteria for the selection of the joint ventures to qualify to the second phase were technical capability and financial solvency. In phase two, the five selected joint ventures were asked to submit their bids on predetermined quantities, based on unit prices. The criterion for the final selection of the contractor was the lowest bid.

In September 2002, the contract was finally awarded to the joint venture (JV) of three Greek construction companies, Aktor S.A., Athina S.A., and Themeliodomi S.A. teamed with the Italian company Cimolai (www.cimolai.com) as the steel subcontractor. Cimolai had worked before with Aktor in the construction of the main hangar for the New Athens International Airport. The JV signed the contract with GSS in November 2002, and hired a total of 15 subcontractors for the OACA roof.

[20] Prior to joining Calatrava's office, Kikiras, a civil engineer, had been the chief executive of Attiko Metro S.A., the company that operates the subway system of Athens. At the time of negotiating the commission for the Olympic Games, Attiko Metro awarded to Calatrava a pedestrian bridge over Mesogeion Avenue that was built shortly after.

[21] Betaplan prepared the bidding documents for ATHOC.

6 Design Adjustment Phase

6.1 Joint Venture's Verification of Design

Under Greek legislation concerning construction procedures, it is the responsibility of the contractor to verify the feasibility of the design. The contracting JV hired the British consulting firm Sinclair Knight Merz (SKM, www.skmconsulting.com) to analyze the structure and check the design submitted by Calatrava. SKM concluded that the design was not sound. In certain load combinations, the structure would fail. Thus, the preparation of the shop drawings was delayed until the structure was redesigned, and consequently the start of the construction was delayed.

At that time, in September 2002, the wind tunnel tests were made available and the design checking team, under GIBB Hellas SA, run their final checks, to conclude on the inadequacy of the structure. Furthermore, two firms examined the design in detail to propose alterations for the construction. SKM was employed by the contractor, and BUNG was employed by GSS. BUNG, in this phase, checked the structural design of the stadium roof, submitted either by Calatrava or by the JV. Several Greek engineers, including Dr. Ermopoulos, professor of steel structures at the National Technical University of Athens, and Dr. Angelopoulos, practicing engineer in Germany specializing in computer modeling and simulation of structures, worked for BUNG. Vassilios Makryonitis, the technical counselor of the Prime Minister was closely watching the project's developments to have his own understanding of the situation.

The results of these studies showed that structural elements should be stiffened and, specifically, that the cross-section of the main arches should be increased. A reason for the inefficiency of the structure is that the foundations do not provide horizontal support to the arches. So, the arch action depends on a horizontal thrust provided by the "tying" elements, the torsion arch and a series of cables. However, such a tie is not provided by direct cable elements that could connect the two foundations, to make a proper "tied arch." So, there is some bending involved that makes the whole system behave more like a "tied beam," according to Karydakis. Calatrava had attempted to introduce horizontal thrust to the arch with inclined piles at the foundations in an effort to keep the original sizes of the tubes and thus the weight of the structure at their early figures. However, such a design generated high thermal and seismic stresses.

Thus, the remaining option was to increase the size and weight of the structure. The original sizes of the tubes in the Calatrava's design were 2.50m for the arch tube and 3.00m for the torsion tube. Both independent studies asked for an increase, though without agreeing on how much. The consultant of the client (BUNG) proposed a moderate increase, whereas the consultant of the contracting JV (SKM) wanted a bigger safety margin and a greater diameter. Due to the tight time limits, a decision had to be taken. The extreme time pressure, though, also had a positive effect; all the parties knew that the only way to complete the project was to act as a team. There had to be trust, and compromises had to be made by all the actors for the project to go on. So, even though the final cost would rise, a decision was taken to follow the recommendation of the consultant of the contractor to 3.20m for the arch tube and 3.60m for the torsion tube. The thickness of the arch's pipe stayed the same and ranged from 50 to 100 mm in the most stressed sections. The total weight of the arches increased approximately 30%, with a proportional cost increase.[22] There could be no compromise in safety, and the increase in the

[22] The steel cost was 3.60 €/kg.

budget could not be compared to the possibility of a serious structural failure.[23] Calatrava did not object to the change in the size of the arches and his firm signed the new drawings. He stated that they were adaptations of the design and not changes, although he had delivered the detail design to the contractors.

Calculations by SKM show that the displacements perpendicular to each arch plane range from 0.80 to 1.0 m as a result of wind and earthquake loads. Nevertheless, a model of the system was tested in an aerodynamic tunnel, which showed that the roof could withstand wind speeds exceeding 120 km/h.[24] During that phase, there were engineering suggestions to keep the smaller arch diameter, and thus keep the cost down, while improving the behavior of the structure by increasing the stiffness perpendicular to the planes of the arches, a weakness of Calatrava's design. However, such interventions would have altered the aesthetics of the roof. The contractor respected the architect's concept for the shape of the roof, and since all the required tests confirmed the structure's stability after the 30% increase in diameter, they dismissed the suggestions of the engineers. The roof is truly an ethereal structure with acceptable oscillations and displacements of the system.[25]

6.2 Series of Design and Construction Issues

This period was a time for "really strong nerves" and lasted for five months, until May of 2003.[26] For some important decisions, the final choice was escalated to the inter-ministry committee overseeing the entire Olympic program. The negotiations between the parties, including the Calatrava team, were tough, and all the changes had to be done before the beginning of the construction. The team spirit had to be combined with the different points of view of the parties concerning decisions that would affect all of them. The increase of the diameter of the arches was one issue. The final material used to cover the stadium was another. In Calatrava's original study submitted in January 2002, glass was specified in the architectural documents, but in the structural design the weight used for the calculations was half the weight of the specified glass. So, with the structural efficiency of the whole project at stake, a decision was taken to replace the glass covering with polycarbonate panels, a compromise on aesthetics but a great gain for the total weight of the structure. Finally, a very important issue that had to be resolved was the opening ceremony.

One of the problems was that the original designs had all the equipment for the opening ceremony attached to the roof, including a set of steel wires – the spider web – from which a lot of the sets would be suspended. This would imply a considerable load and forces perpendicular to the level of the arches, in the direction where the structure was weakest. With the clock running, the parties involved did not want to hear about extra problems, so the decision was taken to construct 6 large and 24 secondary pylons around the stadium, independent of the stadium roof, to bear the spider web. The opening ceremony, though, created a series of other

[23] Other designs submitted by Calatrava have had to be reanalyzed and redesigned by the contractors, including the Alamillo Bridge in Seville, Spain. See S. N. Pollalis, What Is a Bridge (MIT Press, 1996).

[24] The wind tunnel test took place in London University, Ontario, Canada.

[25] In the case of the Alamillo Bridge in Seville, although Dragados, the contractor, had raised some questions regarding the form of the bridge, in the end they were sensitive to Calatrava's proposed shape and proceeded only with the structural details. See Pollalis, S.N., *What is a Bridge?*, MIT Press, 1999.

[26] Haris Batsios, the ATHOC project manager for the OACA complex. Interview taken in Athens, 3 January 2005.

issues and conflicts. First of all, it was an independent contract, with ATHOC as the commissioning party. Second, it totally interfered with the construction of the stadium roof because both had to happen in the same location and the available space was limited. The third and most important issue was that the opening ceremony had to be able to take place, whether or not the stadium roof was finished. ATHOC, facing the time pressure and the still cloudy situation of the OACA roof, developed a contingency plan.

6.3 Project Delivery Method

Because of the limited available time, fast-track construction was chosen as the project delivery method. The steel works subcontractor Cimolai had an engineering subsidiary, Studio Romano S.A. that specialized in preparation of shop drawings of complex steel structures. But the JV could not wait for all the shop drawings to be finished and started the procedures for the preparation of the basic parts of the roof. Essential materials for the construction of the structure such as the steel sheets that would be used for the creation of the tubular arches had already been ordered from steel factories in Germany. The subcontractor for the installation of the polycarbonate panels covering the roof was Gallop from Cyprus. These panels were manufactured in Israel and then sent to Bayer A.G. in Germany for final treatment.[27] Finally, the panels arrived in Greece in sizes of 5 m x 1 m, where they would be cut on site to the exact dimensions. It should be noted that for a project of such technical specifications that required specialized manufacturing processes of raw materials, the procurement and logistics were also of considerable importance. Issues such as weather and means of transport were very important and had to be planned in advance because the time frame did not allow for a mistake or a second chance.

7 Construction

7.1 Dimensions and Materials

In May 2003 the construction of the roof began. The team had only 14 months to complete the project before the opening ceremony of the games. It is a structure with a maximum height of 72 m and a clear span of 304 m. It has a weight of 19,000 tons, including the electrical and mechanical equipment. The upper arch (arch tube) has a diameter of 3.20 m, and the lower arch (torsion tube) has a diameter of 3.60 m. The torsion tube accommodates the entire necessary infrastructure as well as access for maintenance personnel. The four piers holding all the weight of the structure have footprints of 20 m x 16 m; they are founded on 32 to 48 bored 1.5 m diameter piles per pier and go to a depth of 31 m. For the covering of a total surface of 24,000 m^2, 5,000 polycarbonate sheets were used, with a thickness of 16 mm. The panels absorb 45% of

[27] The exact material is a solid, highly transparent plastic sheet of Makrolon® polycarbonate from Bayer Material Science AG. The sheets weigh 14.4 kg/m^2. Had they been made of glass, the elements would have weighed more than twice as much. A special additive in the plastic keeps the spectators cool despite the summer heat. This additive reflects the majority of the radiant heat from natural sunlight, but still allows the visible part of the light to pass through. As a result, the air mass in the stadium does not heat up as much. Another advantage of the plastic sheets, which have additionally been given a scratchproof finish, is their machinability. They can be sawed, drilled, and cut without problems. See <http://www.bayermaterialscience.com>.

the incoming solar radiation and heat. These polycarbonate panels are supported by steel girders with a maximum length of over 25 m, and 10,000 m of steel wire suspend the entire system.[28]

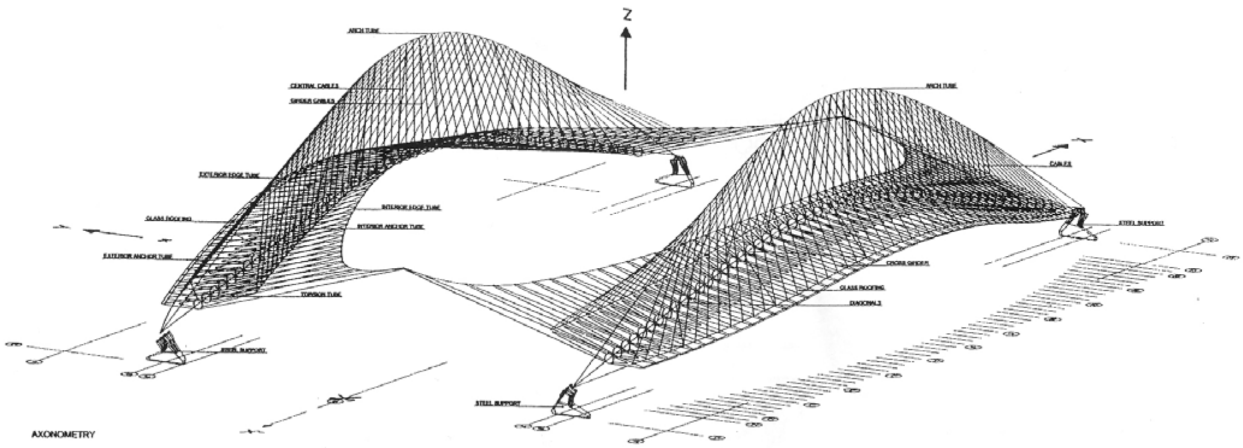

Fig. 8. Axonometric of the structure for the covering of the Olympic Stadium.

7.2 Deep foundations

The foundations of the stadium room constitute an important element of the entire system because of the wide span and the large loads of the arches. With approximately 10 m of the top soil a backfill and the rest of the soil with a generally of good strength, it was decided to use piers on bored piles to support the structure. A concern was the seismicity in Athens, and earthquake was the critical load case which determined the final cross-sections and the size of the foundation in general.

The subsoil mainly consists of layers of red-colored stiff clay. Most of the boreholes that were drilled to research the subsoil came across this layer, which is predominant in the area of the project. Furthermore, there were lignite layers of lower shear resistance and there was a fear that there were tunnels for the exploration of lignite in the area, although none had been encountered in the soil borings. The lignite deposits had been systematically exploited in the past, and there were reports about the existence of unmapped mining tunnels for the extraction of coal in the greater area of the project until 1950. When the lignite tunnels were not used anymore, they may have been partially back filled with clayey silty sand with organic material. The lignite layers and tunnels had been discovered for the first time in early 1980s, during the design and construction of the nearby SELETE school. Senior employees of the GSS remembered their existence and had clearly warned the areas to avoid for foundations. Nevertheless that information was not properly archived.

During the construction of the bored piles and from supplementary soil investigations in January 2004, the contractor found that in the piles' toe level and in certain areas, the soil profile was different from what was found during the soil investigation when it was initially assessed for the design of the piles. The JV and Edafos, the foundation consulting firm, discovered the existence of weak layers of backfill down to a depth of 25 m, with most of the problems reported at the southeastern pier. The discovered weak soils were not considered to be the part of lignite tunnels but rather they were seen as backfills on an old riverbed.

[28] The roof girders' shape is evidence of Calatrava's inspiration in the skeletons of bird and humans. They resemble the wings of birds.

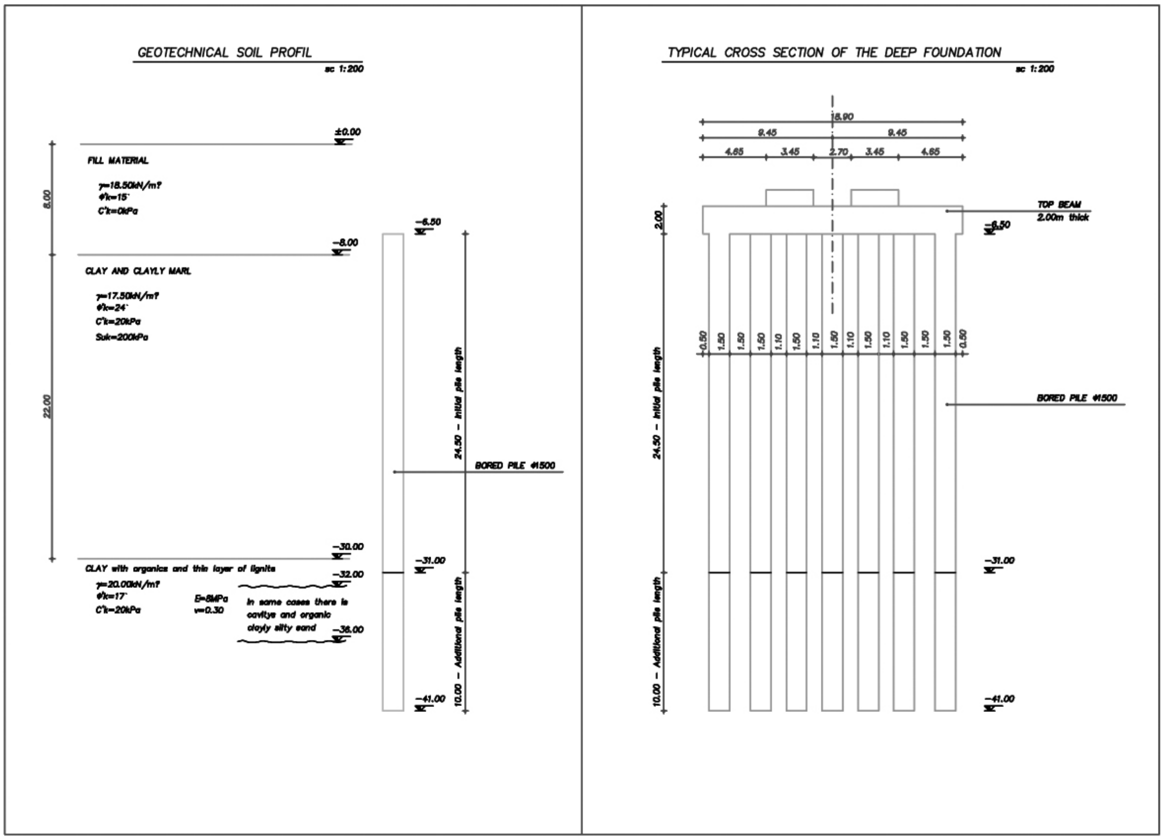

Fig.9. Diagram of the foundation method and the soil issues.

This created particular worries that affected the entire progress of the project and its schedule, given the very limited available time for its completion. The project manager paid specific attention to this episode because it spawned a crisis in the project and upset a lot all the actors involved. They feared that the piles might meet pockets of soft soil layers that would reduce the bearing capacity of the piles. Immediately an alarm sounded for all the project's participants. It is always understood that there is some uncertainty about a site's soil profile and the characteristics of the various layers, as well as that the engineer does not have direct information on the soil's condition at great depths. Therefore, the engineer depends on the results of the soil investigation; their completeness, however, is often questioned.

The participants of the project as well as expert scientists from both the foundation consultants and the foundation contractors discussed the situation at length, and, after a new series of geotechnical tests, it was decided that the design of the foundation had to be adjusted.[29] "They drilled the entire area," Dr. Tsakalidis, Director of the Design Department for Special Geotechnical Works at Themeliodomi, commented on this new comprehensive set of boreholes at the southeast pier location. In record time all the relevant data were evaluated; a decision had to be taken so that no valuable time would be lost. Themeliodomi, the contractor with a specialization in foundations, in cooperation with Edafos, its consultant engineering firm in foundations, assessed all the new geotechnical information. When hired by ATHOC at the initial stage, Spyros Cavounidis, geotechnical engineer and CEO of Edafos, had suggested to have additional borings at the very same place that the bored piles would be constructed with the

[29] Some of the geotechnical drilling tests went to a depth of 95 m. In addition, geophysical surveys that measure the speed of seismic waves were carried out to determine weak zones.

borings going at least 5 m lower than the toe of each pile. The contracting JV weighed the situation and assumed a leadership initiative that the rest of the actors involved did not question. The CEO of Aktor as the highest-ranking officer of the JV and the CEO of Themeliodomi made the recommendation and GSS approved, taking the risk to proceed according to the new geotechnical information. The orders for the construction of the piles were based on the new information and called for the additional piles and for increasing the length of the piles, with some piles designed to be 10 m longer than the original design.

Fig. 10. Excavation and foundation of the support piers.

The foundation works for the arches' four support piers included bored piles to a depth of 30 m. The piers included groups of bored piles, ranging from 32 to 48 per pier, with a pile diameter of 1500 mm. Themeliodomi was responsible for the construction of three piers, and Aktor built the fourth.

The extra cost of the construction of additional piles and the greater depth was calculated based on the length of pile in meters; a separate cost was the weight of the extra steel used for the reinforcement cages. The additional budget for the foundations was approved by GSS.

The redesign of the foundations of the piers did not prolong the duration of the project. For such a serious and delicate issue that created so many worries, the contractors, project managers, and consultants gave a direct and substantial solution that allowed for the smooth continuation of the project within the breathlessly tight schedule and without creating other side effects. Meanwhile, the secondary foundations of the supporting pylons for the erection of the arches were being prepared to expedite the construction.

7.3 Erection of the Steel Structure

The steel structure of the roof was erected in two parts, left and right of the stadium and at a distance of 70 m from the final position, by using five main and ten secondary steel towers on each side. The reason for this construction methodology was that the existing seats of the stadium could not support the weight of the steel towers.

At the insistence of Calatrava, all connections of the steel structure should be welded and bolt connections could not be visible for pure aesthetic reasons. The larger tubes that were accessible through their interiors were aligned and held in place with bolted interior flanges that were not visible from the outside. Then the pieces were welded together, with the welding taking the bulk of the stresses. In situ welding is generally avoided and when necessary it is subject to rigid specifications and requires experienced welders as excessive heat fro the welding could damage the steel in the vicinity of the connections. The OACA roof, with 100 mm thick steel elements subject to torsion and bending, posed challenges for quality welding that Cimolai and Studio Romano were willing to assume.[30]

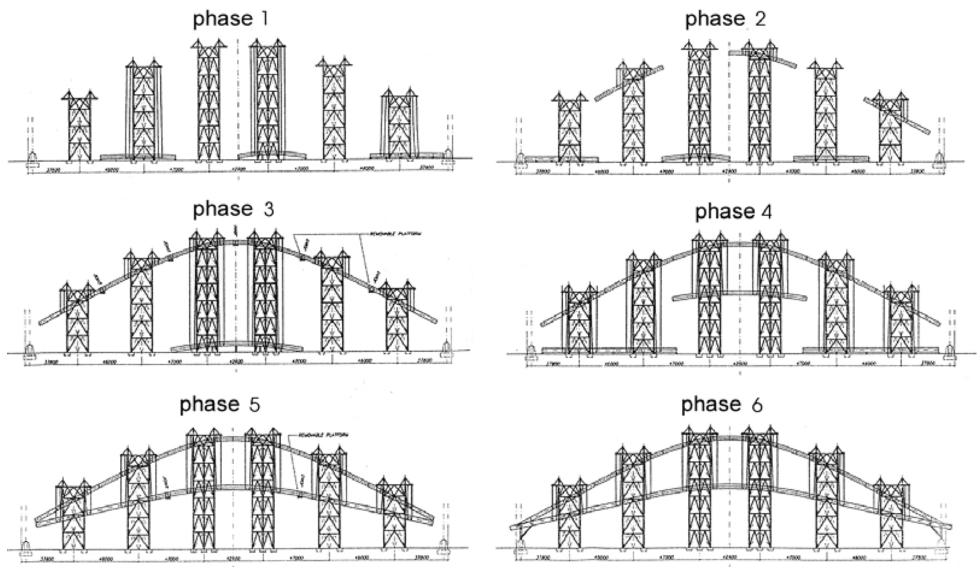

Fig. 11. The erection phases of the arches on the supporting steel towers.

The construction began with the foundation works for both the temporary steel pylons and the permanent piers where the arches would finally rest. The base of each pylon was made of reinforced concrete to a depth of 2.50 m, lying on concrete piles to a depth of 25 m. The separate parts of the arches arrived in Athens by ship from Italy in several phases, with 62 parts for the upper arch tube and 40 for the lower torsion tube. They were assembled to their final curvature on the ground on top of small concrete towers and then they were lifted in parts in a procedure that was divided into six phases. Furthermore, renovation work was simultaneously taking place inside the stadium.

During phase 1, the parts of the upper arch tube that were to be positioned directly on the erection towers were assembled on the ground. In phase 2, these parts were placed on the towers and the in-between parts of approximately 55 m length were simultaneously assembled on the ground. In phase 3, the in-between parts were hoisted up to their final position by special jacks and connected with bolts inside the tube to form the entire arch. In phase 4 the lower torsion tube was assembled on the ground in three large parts, welded, and then the central part was lifted. In phase 5, the left and right parts were lifted and welded to the middle one so that the lower arch was one continuous piece. Finally, during phase 6 the end pieces, where the upper and lower arches connect, were erected and assembled. The different methods of assembly were chosen because the torsion tube bears more of the weight of the structure and torsion forces from the girders. At the same time, the construction of the abutments where the edges of the double arches finish was completed in Italy. They were put in place after the completion of the arches.

[30] On November 9, 2005, SKAI radio (100.3 FM) and the newspaper Kathimerini (www.kathimerini.gr) revealed that in March 2004, GSS had appointed German maritime and construction safety firm Germanischer Lloyd AG (www.gl-group.com/)) to inspect the 17,000-ton roof. The report, made public, refers to improper welding conditions, misalignments of the components of the main structural elements, and calls for repairs. The report does not raise issues of safety, but asks for regular inspections.

Fig. 12. Steel pylons supporting the structure. Suspension with steel wires and installation of girders.

Fig. 13. View of the arches from inside the stadium.

Subsequently, the procedure for the suspension of the lower arch with steel wires of a 100 mm diameter began. In parallel, the installation of the main (girders) and secondary (perlins) beams was taking place. The girders were placed in pairs and the perlins were used to connect the system in the horizontal level and to create the supporting frame for the covering panels. About

30% of the covering, which was made of aluminum frames and polycarbonate bluish translucent panels, was installed before the arches were slid into their final position. The next stage was the installation at the inner edge of the roof of the suspended catwalk for the control of the M&E equipment.

7.4 Project Management

During that phase everybody was working in extreme rhythms. The construction contract for the opening ceremony was also awarded to the JV, which subsequently hired EREVNA Ltd for the architectural design, AKTER Ltd for the M&E design and Phaedon Karydakis for the structural analysis, for the design of the project, as well as, to provide technical support during its construction. In addition to the design of the structures for the opening and closing ceremonies, these Greek offices were commissioned by the JV the design concerning the necessary additional structures for the reconstruction of the athletic grounds of the Olympic Stadium so as to comply with Olympic Games Regulations and the requirements of ATHOC. Calatrava was special consultant for GSS and BUNG supervised the construction on behalf of GSS and performed structure quality work for GSS. ATHOC, although not contractually involved in the construction of the roof, had a coordinating role assigned by the government. Also had direct control of the opening ceremony and was responsible for the coordination of all the issues of the games. The JV had been commissioned to construct both the roof and the ceremony structures, while EREVNA Ltd in conjunction with Phaedon Karydakis and AKTER Ltd prepared the shop drawings for the ceremony, under the control of the GSS and the JV. To handle the multiple contracts and the limited time, ATHOC decided to organize weekly meetings where all the issues of coordination, conflict, and change orders would be solved.

These meetings took place at noon every Thursday with the participation of all the players involved: GSS and ATHOC; BUNG; Interpraxis; the JV; people from the Athens office of Calatrava; EREVNA Ltd; representatives from the Athens Olympic

Fig. 14. Panoramic view of the construction.

Broadcasting and the ceremonies production company Jack Morton; and finally the sponsors, Mondo, Panasonic and Swatch. About 35 people were at those meetings, expressing strong interest and team spirit. A lot of contractual interfaces were dealt with, without going deeply into technical details, which were left to the contracting JV. Also, there was a mechanism for escalating the conflicts that a decision could not be easily made. Such conflicts were sent to the inter-ministry supervising committee. Haris Batsios, coordinator of these meetings, said in his interview that "*the success was based on this organizational scheme. I believe this wholeheartedly*."

Moreover, every 15th of the month there was a meeting with the deputy Minister of Culture, Nassos Alevras, and every 10 days representatives from the International Olympic Committee visited Athens to check the progress of the work. With time pressing, IOC started to express doubts, highlighted by the remarks of Oswald that the construction of the roof should be abandoned.[31] The position of the team was very sensitive. The media worldwide started to criticize the delays in the construction and the sliding process. Everybody wanted to see the roof in its final position. In addition to all that, in March of 2004 there was a transition in the governing party following national elections. Thankfully, this change did not affect the team spirit of the players.[32]

7.5 The Contingency Plan

At ATHOC's initiative and in consultation with the contractors, a contingency plan was developed as a response to the anxiety created by the soil findings of January 2004 and delays in the sliding schedule. The contingency plan called for an independent structure to support all the equipment, sets, and wiring required for the opening ceremony. The JV asked Karydakis for a proposal, who suggested the scheme of 6 main and 24 secondary pylons, anchored on counter weights, on the perimeter of the stadium. This scheme was approved and the design and production of the spider web (spidernet) proceeded in parallel.[33]

Even with the spider web suspended from the independent pylons, there were hundreds of cameras and lights attached to the inner edge of the stadium roof, and all the wiring passed through the lower arches. In the worst-case scenario in which the stadium roof was not in place at the necessary time, a contingency plan had all these taken care of so that the opening ceremony could go on. However, the quality of lighting and broadcasting would be superior if lights and cameras were positioned on the roof and the contingency plan was a suboptimal alternative. One very important aspect of this plan was time. If during the assembly of the roof something went wrong, if there was for example a minor failure, there might be no time to go back, delay a little bit, fix it, and continue. So, in the schedule for the roof construction, milestones had been defined at certain stages; if they were missed, the project would stop and the contingency plan would come into play. The last milestone was in the middle of February of 2004, six months before the opening ceremony. For obvious reasons, the contingency plan was kept secret from the public and also from the contracting JV.

The contracting JV was aware of all these concerns and different scenarios and knew that faith in the completion of the project was the only way forward. Florios Glezos, a member of the management of the contracting JV said "This is an architectural project of high aesthetics. It is a project that had to be finished when it was finished; there was no possibility, for any reason, of a time extension."[34]

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[31] *Eleftherotypia,* 21 January 2005.

[32] After the March 2004 elections, the new government appointed Mrs. Fanny Palli-Petralia to the position of Alternate Minister of Culture, with the portfolio of coordinating Olympic Preparation. Minister Petralia was already aware of the construction details and the deadlines for the completion of the Olympic venues and double shifts went into place at the request of the JV, and the progress of the works was checked on by the Minister herself on a weekly basis.

[33] The construction of the pylons was completed before the sliding of the arches, and the spider web was placed shortly after.

[34] From the interview taken in Athens, 5 January 2005.

All projects —a highway or a building—can have a time extension for certain reasons. This particular project could have no time extensions beyond the specified date when it had to be finished. Even though the JV believed they could do it, there were also stress, pressure, and doubt. Another factor is that this is a monumental project, not a project that you can easily repair or change. In a highway, you can improve or change the asphalt if something has gone wrong. In a building project you can change something if it is not working out. This was a project where such things could not happen; it had to be built the way it was built, and constructed as its design commanded.

7.6 Sliding of the Arches

With the time getting very close to the opening of the games, in April 2004, the construction of the roof reached its final stage: the sliding of the arches to their permanent position. During construction, careful measures of the exact curvature of the arches were taken and the computer model done earlier in Germany by BUNG was updated by Dr. Angelopoulos. After the completion of the steel structure, the temporary auxiliary towers were gradually dismantled, until the total release of the main structure. This was a very crucial point for all the teams, because they wanted to verify one thing. With the release of the structure, the arches would bear all the weight, and normally they would have deformation. The computer model had calculated this deformation, and the actual one, compared with the calculated, would verify (or not) the accuracy of the assumptions made and the validity of the computer simulation. To the great pleasure and relief of all, the actual and the calculated deformation were equal. So, in a meeting with the managing directors, the consulting teams, and Calatrava himself, the decision was taken to start the sliding.

Fig. 15. The sliding beams.

For the purpose of the sliding, the JV constructed two concrete sliding beams (7 m x 5 m x 70 m) at each side, and on top of them were positioned hydraulic jacks, rails, Teflon, plates for sliding, and propulsion. The two sliding beams were also founded on piles due to the substantial weight they would have to carry. The jacks slid the roof in steps, each step taking 5 minutes. The sliding process took 3 days per side in total. The sliding of the west arch started on 11 May 2004 and the sliding of the east arch on 3 June 2004. During the sliding, the JV and BUNG for GSS were constantly performing checks on the curvature and the relative displacement of the abutments. In the case of a slightly faster movement in one abutment than in the other, the geometry of the arches might alter, leading to plastic deformations, something that would affect the behavior of the static model. The entire system was designed to have elastic deformations to withstand wind pressure and seismic forces, so it could move but it would always return to its initial form.

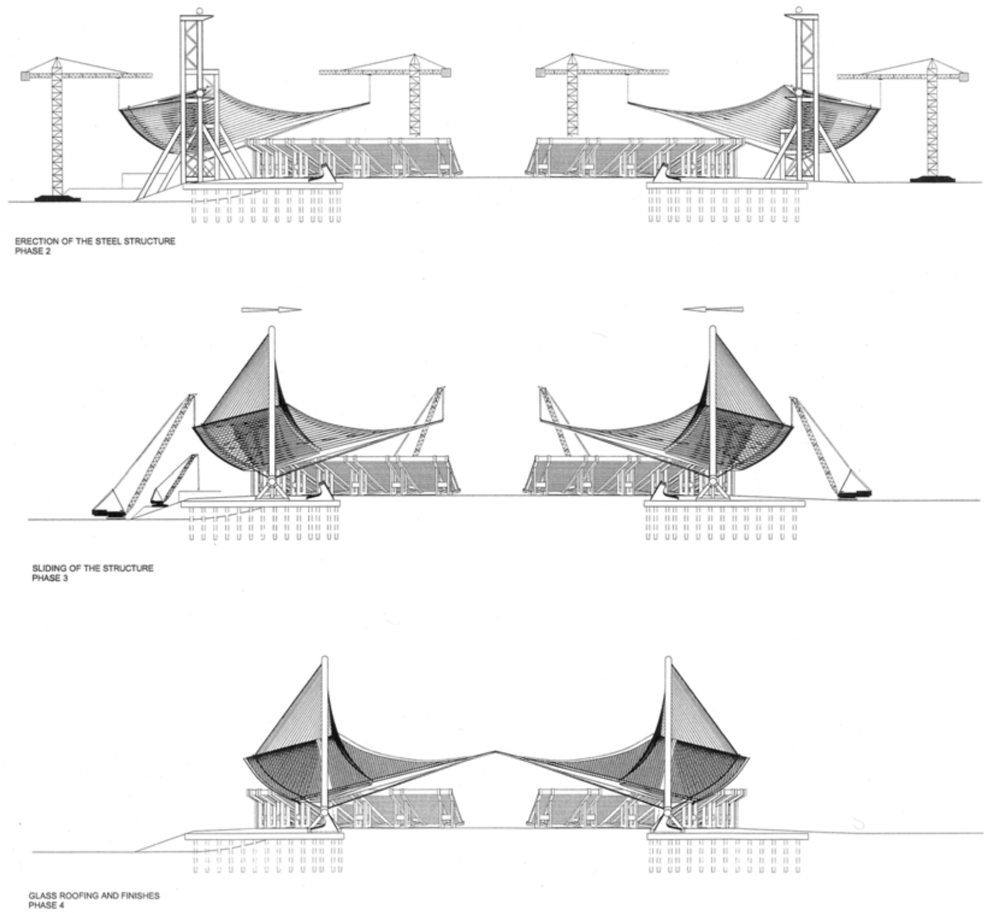


Fig. 16. The construction and sliding phases.

The fact that the roof was sliding with 30% of the covering already placed increased the risks of permanent deformations due to wind pressure. When the steel structure reached its final position, the two north abutments were fixed on the piers whereas the south ones were connected in a way to allow minor movements in the longitudinal axis due to thermal systole and diastole. Finally, the two main nodes, the points where the two facing arches met each other, were connected, and the structural system was stabilized.

An additional complexity of the sliding was the blocking of the auxiliary tunnels of the stadium. The tunnels were used for cables connecting the stadium with the Athens Olympic Broadcasting (AOB) and the temporary structure for sliding the roof had blocked with solid concrete some of those tunnels. As a result, testing was not possible until the sliding was complete and the tunnels were restored.

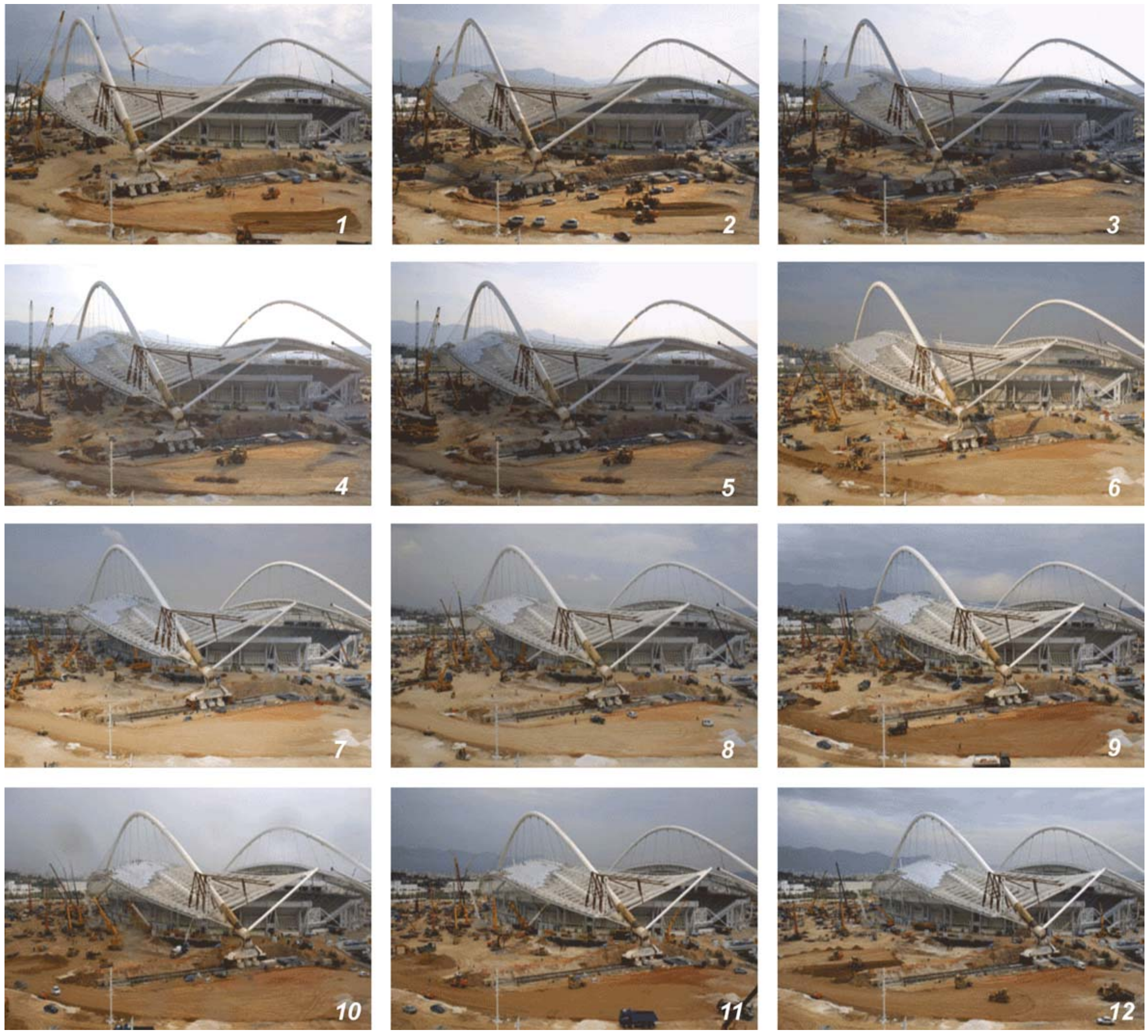


Fig. 17. Sliding sequence of the east arch.

7.7 Safety and Security of Construction

The roof covering required a great deal of work to be performed at heights up to 78 m above the ground. Therefore the responsibility for the implementation and supervision of worker safety called for sophisticated expertise in the field of heights safety. No Limits S.A. was the subcontractor for heights safety systems at the OACA stadium roof project. No Limits personnel included rock climbers and mountain hikers with vast experience who are holders of climbing and mountain guiding diplomas, and professional electricians and welders with professional diplomas as heights safety specialists; a total of twenty-three people. There had been fatal casualties in similar projects in the past. Many predicted fatal accidents at the OACA construction site, and special simulation models for this kind of project forecast seven deaths. In an interview, the technical director of the company noted: “We undertook great responsibilities.”[35]

[35] Interview with Stavros Lazaridis, technical director and heights safety specialist, No Limits S.A., 12 January 2005, Thessaloniki, Greece.

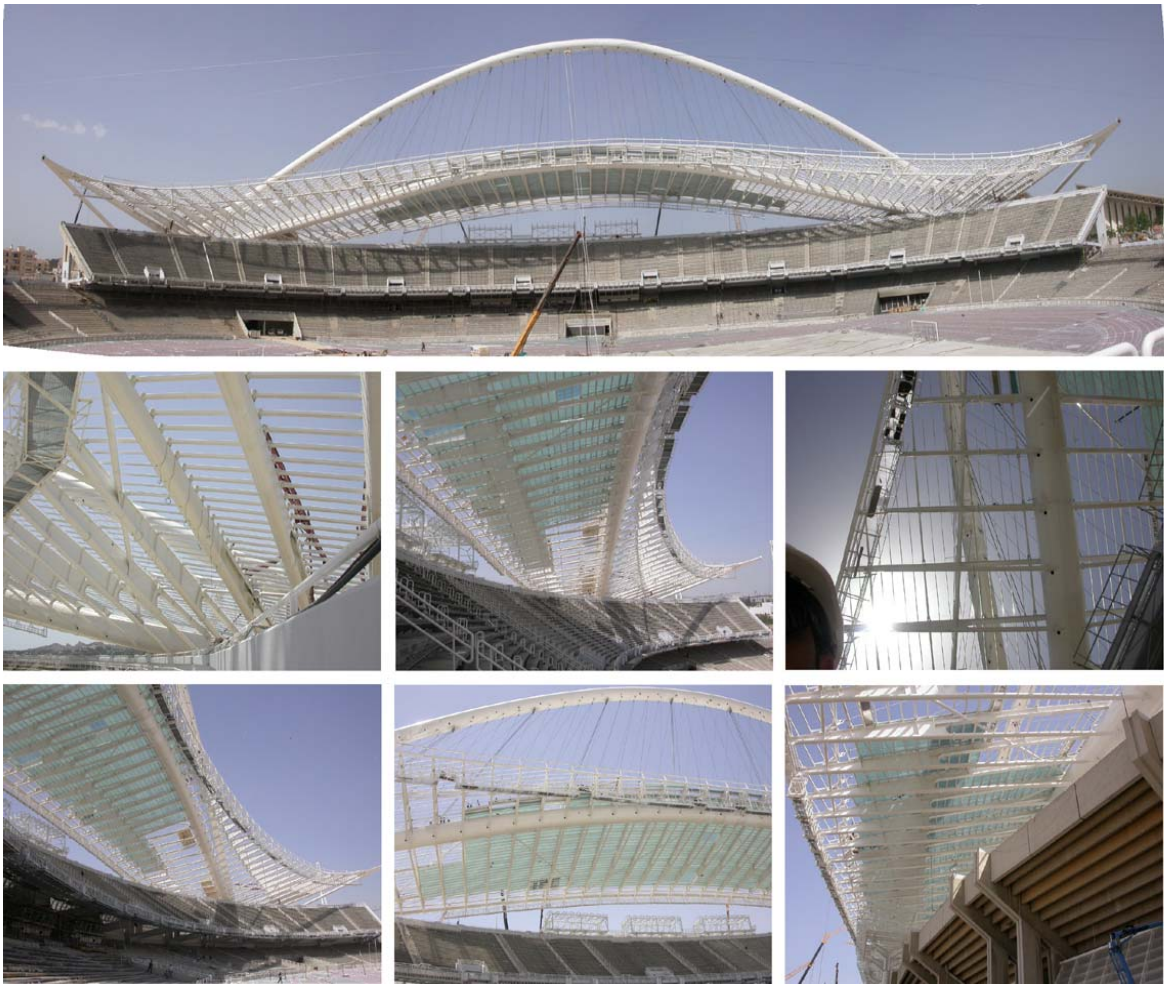


Fig. 18. Installation of girders, perlins, and polycarbonates.

Fig. 17. No Limits staff working at extreme heights on the OACA stadium roof.

The main tasks of No Limits analytically included:

- The development and supervision of a heights safety system for the technicians working at heights.
- The supply of the equipment to the workers who performed tasks at heights.
- The installation of the lights at OACA as well as the ballast light transformers (separate subcontract).

- The installation of all the sound speakers (separate subcontract).
- The installation of all the electrical shafts and cable trays (separate subcontract).
- The installation of the special lights for the architectural and artistic lighting of the stadium.
- The installation of several secondary polycarbonate panels until the subcontractor for the roof covering became at ease with working at heights and the system was set in motion.
- The development and supervision of a heights safety system for the Velodrome.

In addition, No Limits installed a security system for Jack Morton personnel who organized and covered the opening ceremony from very elevated positions on top of the arches, and trained and supervised photographers assigned to take pictures and video of the games from the roof.

Fig. 20. Steel wires and safety belts protect the workers when working on top of the arches.

"We abided by all the European heights safety specifications, which are close to the American ones," said the technical director of the company. The safety system covered 157 workers of various specialties such as workers for the installation of the polycarbonate panels, the roof's TV/audio equipment, the stadium lights, as well as electricians and painters at heights ranging from 50 m to 78 m. No Limits used static safety ropes to create temporary lifelines: the worker's waist and back are harnessed from steel wires so he can walk on top of the arch, with no danger of falling if he should lose his balance.[36] It should be noted that nobody was to be authorized to work on the arches unless he had previously gone through a three-hour safety seminar on the use of the equipment.

Furthermore, an organized rescue team was always on site and maintained open communication with all the workers and crews working on the roof and arches. This rescue team was comprised of four people, all experts with special kits ready to step in when somebody who was working suspended was in trouble.

Overall, No Limits installed 11,500 m of static safety ropes and 2,700 m of steel wire, used 2,300 m of dynamic safety ropes, and spent 1,000 hours on the supervision of the work at

[36] All the ropes used for safety purposes were put in special cases for protection against mold or erosion.

heights. Despite the intense construction schedule and hectic working pace, the company managed to do an impeccable job, with not even a minor accident.[37]

8 The Final Stage

After the sliding of the arches to their final position on 5 June 2004, the project managers of ATHOC, GSS and the JV felt that the most intricate phase of the project was over. According to Minister Petralia, "We are going ahead, defying the odds and the pessimistic predictions. We created a national monument of civil pride and public involvement by mobilizing human resources and know-how".

Fig. 21. Spider web and installation of M&E along with the placement of the polycarbonate panels**.**

The roof's construction had been in the limelight among the Greek public and especially the international community. The world media had spent considerable time covering the project since its beginning and repeatedly criticized the delays; most of their reporting predicted a failure to deliver the roof on time. The timely placement of the roof in its ultimate location soothed the IOC, which had expressed several concerns about the feasibility and schedule of the project.[38]

Fig. 22. Preparations for the opening ceremony.

[37] According to the project managers of ATHOC, "These guys were terrific."

[38] In an interview in the Spanish newspaper *El Mundo*, Oswald said that if the project was not going to be finished on time, it would be better to cancel its construction. *TA NEA,* 11 August 2003.

Fig. 23. The completed stadium of OACA, with the independent pylons for the opening ceremony and lights.

With this anxiety behind them, ATHOC, GSS and the contractors now focused their attention and energy on finishing the work that related to the interior of the stadium, such as the replacement of the seats, the construction of a mechanism for the elevation of an artificial pond beneath the stadium's field as a part of the opening ceremony; the assembly of the spider web on the already completed pylons; the installation of M&E equipment on the roof; the installation of lights; and the construction of the Olympic cauldron, the construction of the synthetic track by MONDO, its protective covering to build the lake and the track on which rolled the ceremony procession, the installation and wiring of the power generators (8MW) for the ceremonies, the timing and scoring equipment and the two scoreboards by SWATCH, the reclining Panasonic video board (support structures and reclining mechanism by the JV), the full scale athletic test event that included the transport and assembly of the turf on palettes that was being grown in a field near the airport, its removal and its reassembly after the ceremony, the two full scale test events for the opening ceremony. All these had to be very carefully and accurately planned in a highly disciplined manner that involved a large number of contractors and their crews with different habits and cultural attitudes that had to adjust their habits and demands to a common schedule. The site "belonged" to the JV which undertook the responsibility to "host" all these different crews, adjusting their own schedule and undertaking all the insurance risks. At the same time, however, the subcontractors continued with the installation of the bulk of the polycarbonate panels for the roof's covering. In addition, security systems were installed and counterterrorist drills had to be planned and carried out simultaneously with the other work in progress.[39] All this was carefully supervised by ATHOC.

[39] Security for the Olympic Games had evolved over the years – and especially after the terrorist attacks of 11 September 2001 in New York – into a major issue for Greece's preparation to host the games. The final cost of security was estimated to be 1€ billion.

Fig. 24. The completed stadium of OACA, showing the torsion pipe and the arch on the west side of the stadium.

9 Conclusions

The JV successfully delivered the project in time for the opening ceremony on 13 August 2004, although there had been numerous doubts and disbelief from Cassandras who questioned whether it could be done. The project was built in just 13 months, even though the Greek construction industry was not particularly experienced in projects of such distinctiveness. After the opening ceremony, all the parties involved received the sincere and enthusiastic congratulations of the international community for the impeccable and impressive execution of the event.

Dimitrios Kallitsantsis, CEO of Aktor S.A. and leader of the contracting joint venture, has been honored by ENR as one of the top twenty-five newsmakers for construction industry accomplishments in 2004. In him, the international construction world recognized the engineers, architects, project managers, and the construction industry of Greece for their energy, hard work, commitment, and innovation to successfully complete the erection of the roof just in time for the 2004 Olympic Games amidst political pressure, international media criticism, and a breathless schedule. The perseverance and creativity of the Greek contractors and project managers of the Athens Organizing Committee resulted in a signature Olympic stadium that became the global emblem for the 2004 Athens Olympic Games.

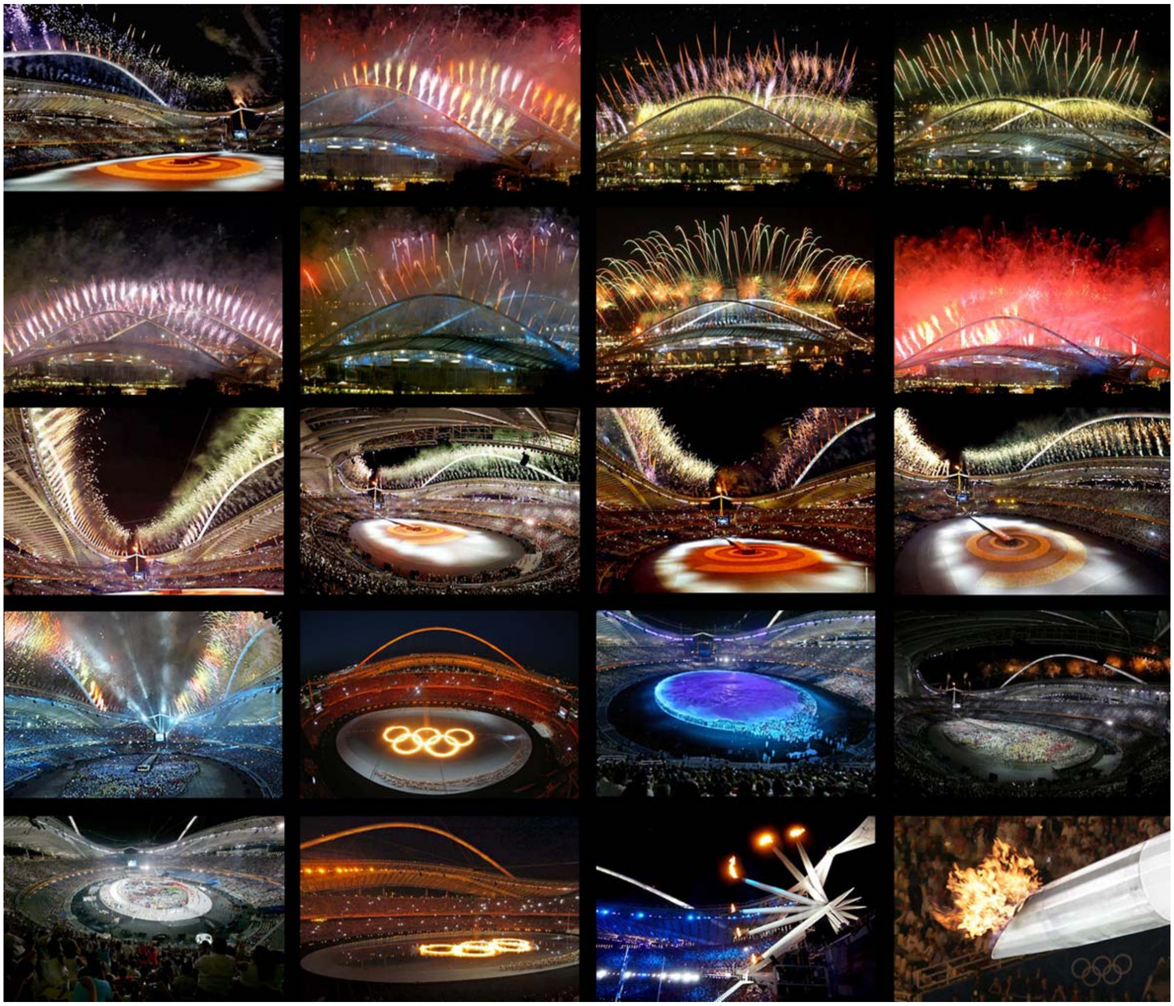
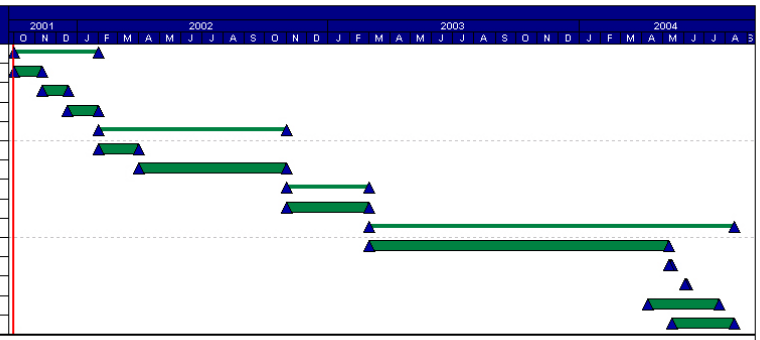


Fig. 25. The glorious opening ceremony for the Athens 2004 Olympic Games with the roof as an emblematic icon of human accomplishment and artistry.

APPENDIX A: PROJECT TIMELINE

Original study	6 months	October 2001 – April 2002
Bidding documents	2 months	April 2002 – June 2002
Project bid	4 months	June 2002 – October 2002
Signing of contract with JV (Aktor – Athina - Themeliodomi):		November 2002
Design adjustment/ shop drawings	5 months	December 2002 – April 2003
Construction of project	13 months	May 2003 – June 2004

Description	Early Start	Early Finish
design	**10/01/01**	**01/31/02**
concept design	10/01/01	11/11/01
final design	11/12/01	12/18/01
detailed design	12/18/01	01/31/02
bidding	**02/01/02**	**11/01/02**
bidding documents	02/01/02	03/30/02
bidding phase	04/01/02	11/01/02
design adjustment	**11/02/02**	**03/01/03**
design adjustment	11/02/02	03/01/03
construction	**03/02/03**	**08/13/04**
metal structure erection	03/02/03	05/10/04
sliding of west arch	05/11/04	05/14/04
sliding of east arch	06/03/04	06/04/04
coverage panels installation	04/10/04	07/21/04
opening ceremony works	05/15/04	08/13/04



APPENDIX B: PROJECT BUDGET

Roof steel structure	97€ million
Roof polycarbonate panels	3€ million
Velodrome roof and renovation	25€ million
Agora (steel arcade)	5€ million
Civil works (concrete foundations, etc.)	40€ million
Stadium common domain (landscaping and site)	10€ million
Total budget	180€ million
Final cost*	256,205,333€
(NEA, 12 July 2004 from Technical Services, Ministry of Culture)	
Total cost of all Olympic construction	1,655,365,872€
OACA as a percentage of total construction	15.5%

* the final cost includes the Wall of the Nations, not included in the original estimate.

EXHIBIT A: MASTER PLAN OF OACA[*]

EXHIBIT B: AERIAL IMAGE OF OACA

[*] The Monument was not built; the 30 m cauldron is at side of the stadium near the agora.

EXHIBIT C: CHANGE ORDER FLOW – CONSTRUCTION OF THE STADIUM ROOF

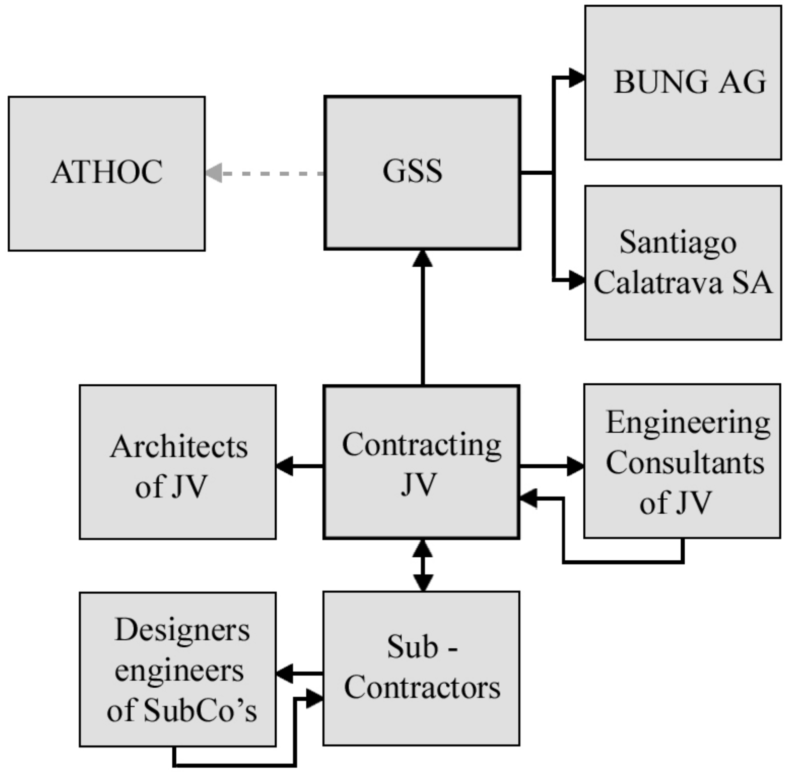


EXHIBIT D: PROJECT STRUCTURE FOR THE DESIGN OF THE STADIUM ROOF

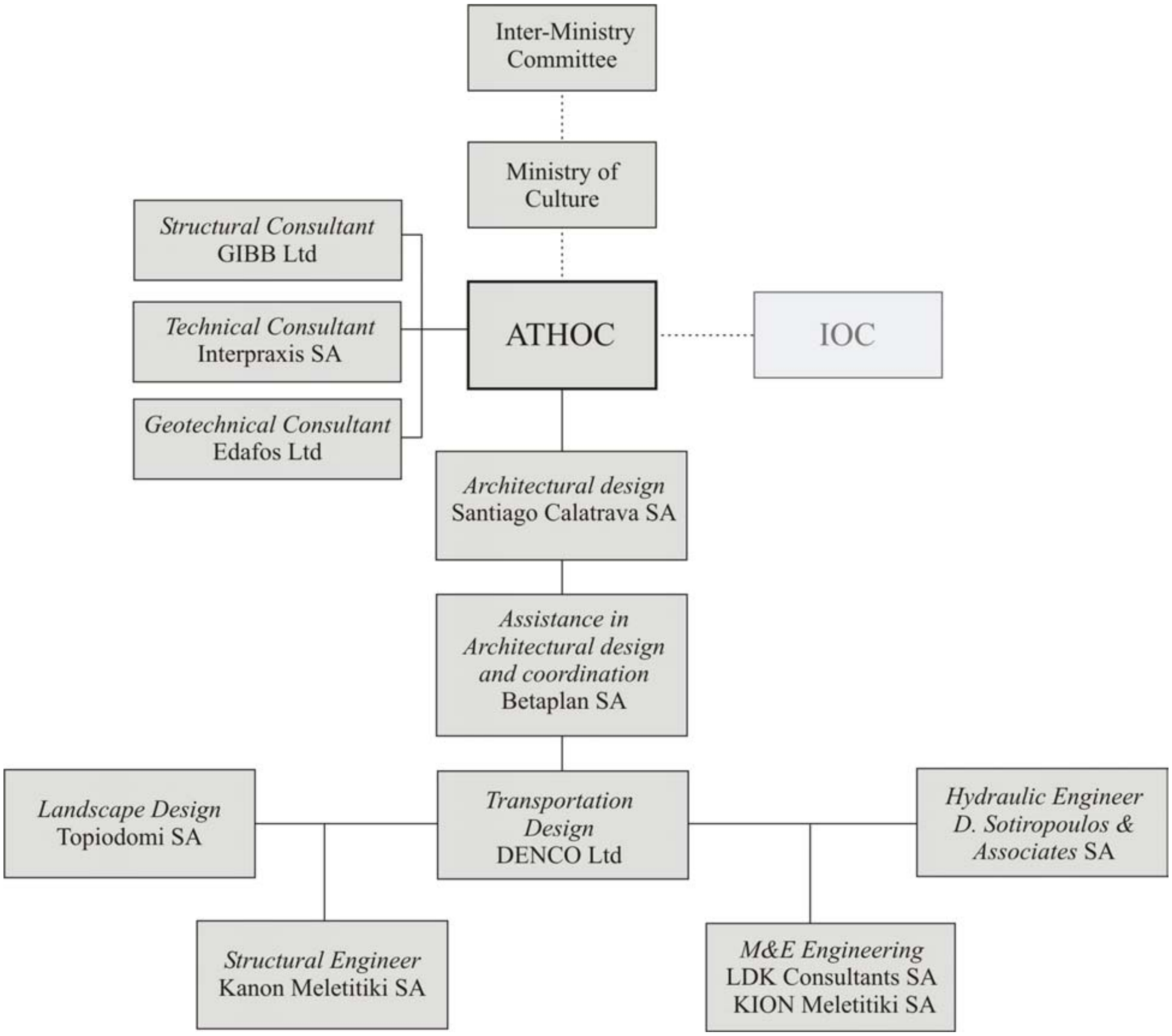


EXHIBIT E: PROJECT STRUCTURE FOR THE COORDINATION OF THE CONSTRUCTION OF THE ROOF

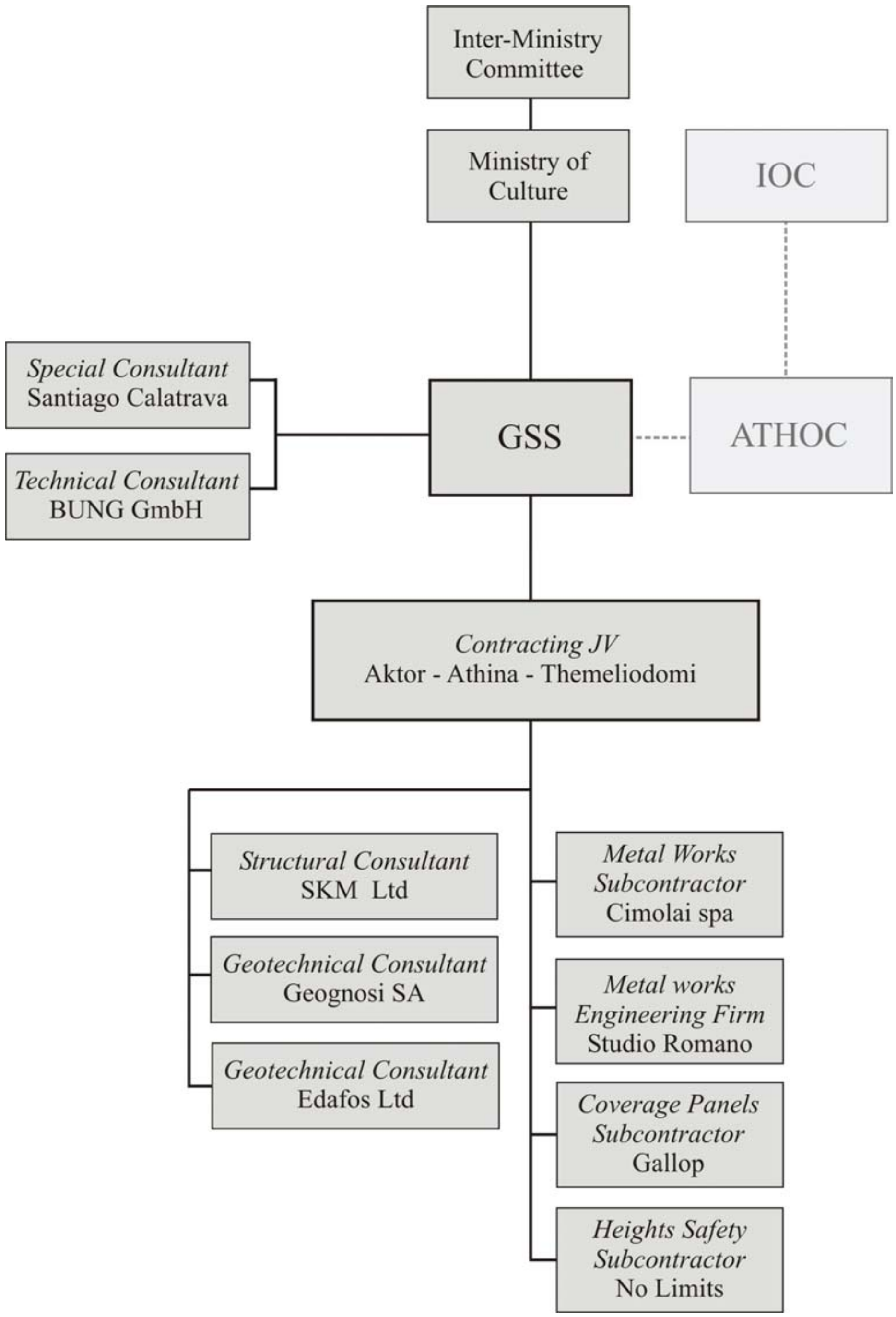
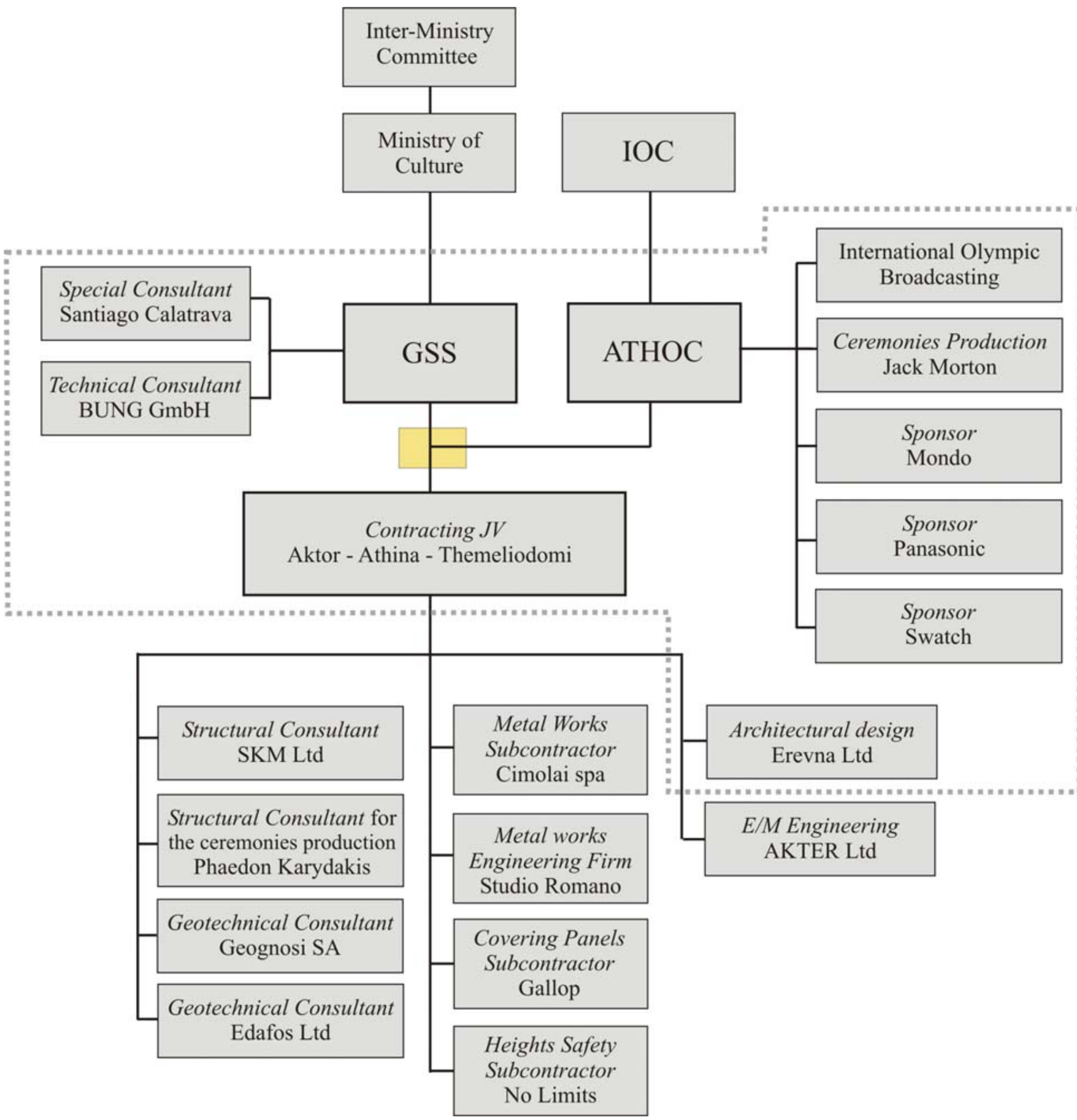


EXHIBIT F: PROJECT STRUCTURE FOR THE COORDINATION OF THE CONSTRUCTION OF THE STADIUM ROOF, THE WORKS REQUIRED FOR THE OPENING CEREMONY, AND THE OVERLAYS. SEPT 2003 – SEPT 2004[*]



* Parties in dotted line participated in the weekly coordination meetings.