SPATIAL STRUCTURES FOR AN ELEVATED CONFERENCE BUILDING

Gian Carlo Giuliani - Consulting Structural Engineer
5, via Gioberti 20123 Milano Italy
phone: intnl.+2+4699020 fax: intnl.+2+436478 E mail: redesco@iol.it

1. ABSTRACT

The building is given a character by in sight structures which are composed of huge pitched trusses supporting three dimensional trussed decks for the floor and the roof.
The elevated position, the span and the bearing location, which implies a big overhanging of the building, required the design of a structure having a remarkable three dimensional behavior.
The optimization of the assembly operations and the shape elegance were obtained by using welded members and pin connections for the trusses and pre-assembled plates with bolted skew struts and ties for the decks.

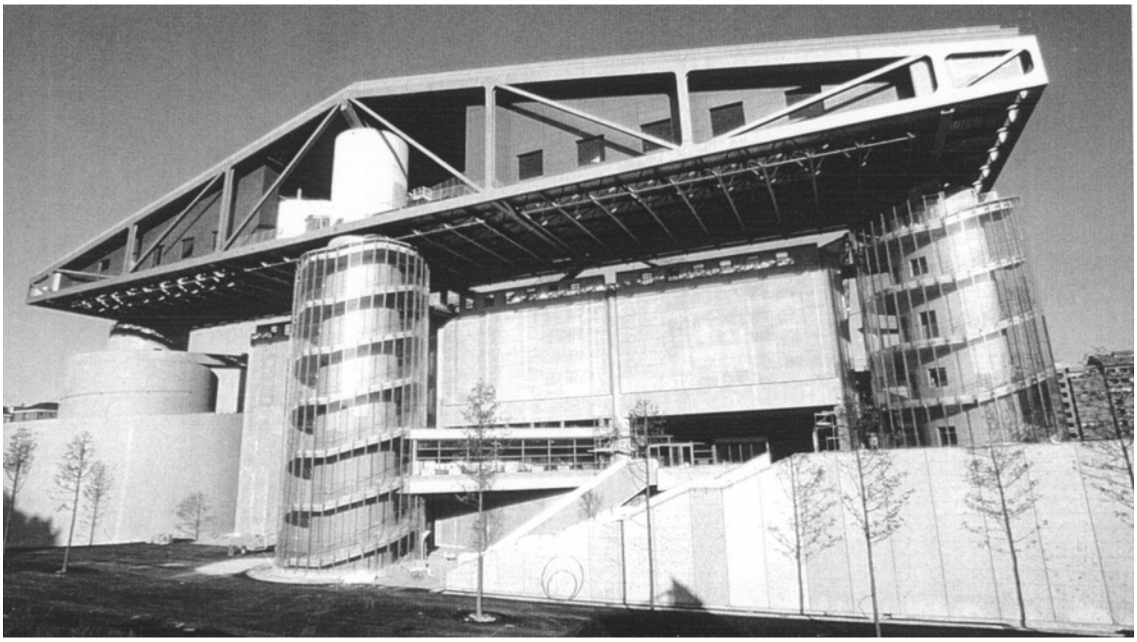

fig.01 overall view

2. STRUCTURAL CONCEPTS

Although the structural concepts are based on the interaction of giant trusses with two space decks, in architectural terms, the reference to the classic idea of a temple is quite evident, being based on massive concrete shafts supporting the extraordinarily slender upper truss in an unusual interpretation (fig.01).
The tympanum is in perfect agreement with the high technology which is a distinctive feature of the whole project of the extension of Milano’s fair. It is, in particular, the outcome of a structural awareness which can restore some craftsmanlike features in the member assembly which is emphasized by the component that has always distinguished and mercilessy selected metal structural work: the joints.

In the connections of the trusses to the transverse beams and the of latter ones to concrete supports there is a reappearance of the commonly lost inclination for an unreserved loyalty to the theoretic structural scheme, for the ideal constraint, for the "pure hinge"; such an inclination necessarily involves a design sensibility which transfer engine concepts in the structural idea.
The bearing position does not allow for laying the main trusses along the straight connecting lines so that the structural scheme appears to be complicated and its feasibility can be reached only if the space behavior is taken into account (fig.02 - 03).

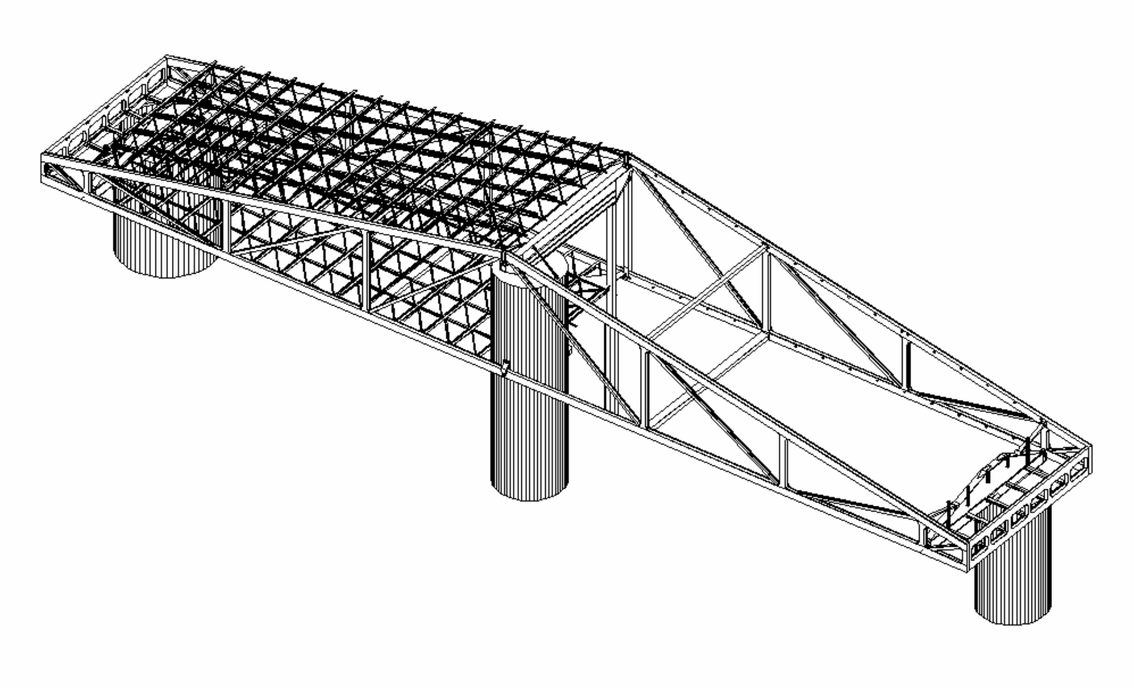

fig.02 structural scheme

Close to the ends, transverse cantilever beams (fig.04), anchored to the lower concrete walls, support the main trusses which lay parallel to, but outside of, the facades; in the middle section another transverse beam supports the main trusses with short overhanging and bears on the shaft of a central staircase and on a steel extension of a prestressed concrete column of the exhibition building.

fig. 03 spatial layout of the structure fig.04 cantilevers

The free length of the aforesaid member is reduced by an horizontal truss beam, anchored to the staircase and therefore restraining the top of the prestressed concrete column; the top of this structure is used as a pedestrian connection between the parking and the elevator and the stair.

The lower chords of the main trusses are supported by the stair case on the northern side and by a tie hanging from the middle beam on the parking side. The ends of the trusses are connected by two Vierendeel like beams.

The level 28.50 m floor and the roof are supported by a two way space truss fitted with struts and ties which lay in a 45 degrees skew directions with respect to the longitudinal and transversal chord members; by this arrangement the structure results in a space deck which features an high stiffness and is integrated into the general resisting system.

The space deck is integrated by transverse beams which connect the joints of the twin trusses.

The torsional stiffness of the whole structure, which is fundamental because of the lack of the bearing alignments, results from the sum of the contributes of the cantilever beams and by the “box” effect created by the main trusses and by the lower and the upper space decks; the discontinuity of the optimal tangent stresses, due to the not distributed but concentrated connections between the main trusses and the space decks, yields either an acceptable reduction of the torsional stiffness and a limited magnification of the member forces.

3. RESTRAINTS

3.1 External restraints

The restraint system is a matter of though because it has either to withstand the overturning moment and allow for the thermal strains and for the general displacements produced by the loads

The fixed points for the three displacement components of the truss upper chords are located on the transverse middle beam; the truss lower outer chords are pin connected to the stair shaft while the inner ones are fixed to an horizontal bracing truss built in the same stair shaft.

At the inner side, the cantilevering beams are anchored by a system of steel rods fitted with spherical sockets to allow for the longitudinal displacements of the two halves of the main trusses and to transfer to the lower walls axial actions only (fig.05); these tensile forces are balanced by post-tensioned bars.

The outer bearing, in the cantilever direction, is of a restrained neoprene-PTFE pot type which allows for the longitudinal and the transverse displacements of the main trusses.

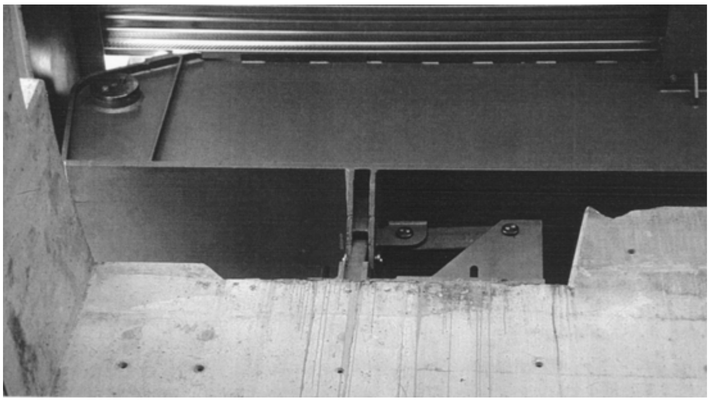

fig.05 rear anchor of the cantilever support

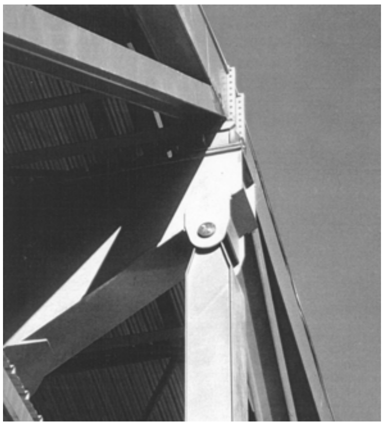

fig.06 pendulum

3.2 Internal restraints

All the structural members are mutually restrained to assure the general building stability under the load effects and to achieve the proper stiffness; because of the structural shape and of the position of the external restraints, the internal connections have to withstand actions directed along 3 axes not contained in a plane.

The upper and lower chords of the main truss are connected to the cantilevering beams in a way which avoids unrequested bending moments.

Similar connections based on pin and pendulum elements (fig.06) are located in the middle between the main truss halves and the transverse beam; the chords are continuous through the connections, thus achieving a favorable effect on the actions and of the deflections of the whole structure.

3.3 Junctions

The mutual junctions of the main structural members are based on pins in order to ease the erection and to maximize the efficiency of the connections either for structural concepts and for the reduction of the material consumption; as a matter of fact bolts and plates are no longer necessary and bending moments arising from the extension of the joint, which is needed for housing all the bolts, are eliminated.

All the structures were designed for shop manufacturing of elements to be assembled at the construction site, taking into account the requirements for the transport and for the erection.

The cantilevering beam and the end Vierendeel beams were completely assembled in the shop and directly erected.

The main trusses were divided in elements, which include the vertical members with the chord junctions, and in the horizontal and skew members; the connections were achieved by means of on site fully penetrating welding on prepared edges being the arc ignition shifted on special heels.

The connections of the decks feature shop welded plates to the chords and bolted junctions for the skew members and for the secondary chords.

4. STRUCTURAL ELEMENTS

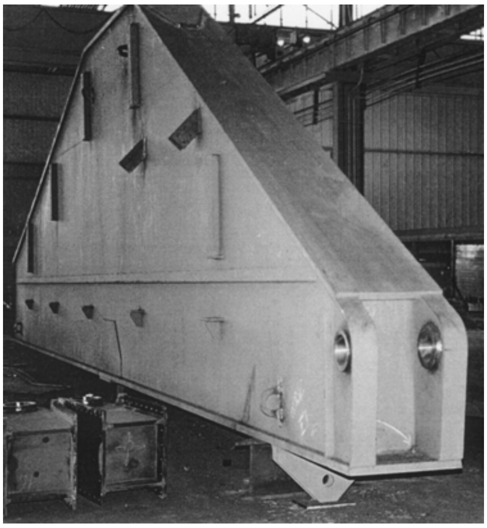

fig.07 sockets for pin connection

fig.08 box and rolled truss sections

4.1. Cantilevers

The end cantilevers are box beams featuring an horizontal flat bottom flange and an upper flange laid in trapezium profile, according to the pattern of the bending moments, thus reducing the self weight and allowing for a passage to the mechanical rooms (fig.04).

The webs are equipped with longitudinal stiffeners and the upper flange is reinforced by additional outer plates in the corners of the longitudinal profile.

In the sections where the concentrated loads and the reactions are applied, 15 mm thick transverse diaphragms provide for the stress diffusion into the webs; the thickness of the webs and of the flanges are 15 and 50 mm respectively and were defined as the result of an optimization analysis with the cost reduction objective, taking into account the incidence of the stiffeners; the maximum height of 4000 mm was determined by geometrical constraints.

The ends are equipped with machined sockets to fit with the connection pins of the trusses (fig.07).

4.2 Middle transverse beam

It is a box beam also, with parallel flanges set at the 2500 mm depth, which is tapered close to the ends to house the pins for the connections of the main trusses.

4.3 Main trusses

The huge main trusses are composed of an horizontal lower chord and of a pitched upper chord, which feature a box section with the outer dimensions of 800 by 450 mm and is composed with 25 mm thick plates; close to the joints the web connection with the vertical struts and the skew ties shows a round fillet.

The vertical struts also feature a 600 by 420 mm box section, while the skew ties, which are always under tensile stresses, are composed of rolled wide flange sections HE 400 B or M. (fig. 08)

4.4 End beams

These beams feature a Vierendeel structural scheme with all the members built with box sections and connected each other trough round fillets.

4.5 Decks

The structure is arranged in a three-dimensional way; the upper and lower chords are laid in two orthogonal directions and are connected by skew members; the center lines are arranged along the edges of a 3125 by 3125 mm square pyramid with the height of 1562.5 mm (fig.09).

The floor and the roof surfaces are composed of corrugated steel sheets and of insulating panels under precast fiber-reinforced concrete plates covered by vinyl tiles and steel panels respectively.

An interesting feature of the structure is the three-dimensional connection system which is based on plates welded to the chords and on bolted junctions, without the use of any special and costly joint (fig.10).

All the members are composed of coupled rolled angles; the whole structure remains in sight and, thanks to the aforesaid features, results in an elegant shape.

fig.09 space deck

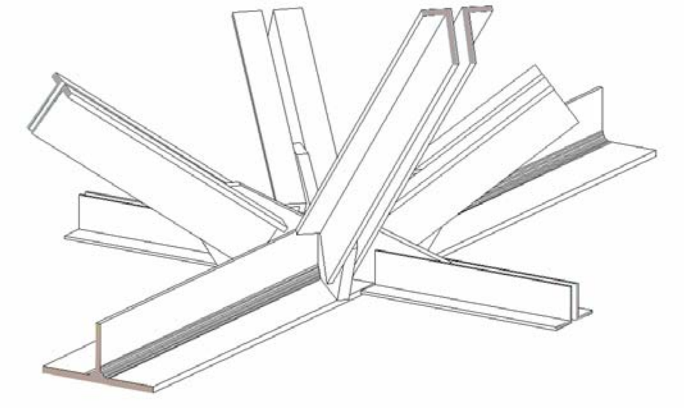

fig.10 welded spatial joint

5. MATERIALS

The structural shapes and the plates which compose the box sections are of the Fe430C grade; the pins for the connections of the structural elements are obtained by machining of C40 steel bars.

The swinging bearings, which are subjected to displacements during all the structure life, are equipped with spherical sockets lined with sintered bronze and PTFE.

All the welds, either prepared in the shop and at the construction site, were done according the pre-heating procedures, design definition of the thickness and of the number of the beads, ignition heels, grindings and ultrasonic and radiographic controls.

All the bolts used for the deck connections are of the 8.8 grade, and were tightened by compressed air driven tools, calibrated to the prescribed torque.

6. ASSEMBLY AND ERECTION

The construction of a structure with overall dimensions of a 108 m length, a 20 m width and a 12 m depth, located in a construction at a soffit height of 28, fitted by hinge-like mutual connections and with coupling tolerances of only tenths of mm, required an absolutely special attention to manufacturing, while programming activities related to the construction in the workshop and on site.

The organization of work emphasized the need for solving the following main problems in the correct way:

a) global construction feasibility of joints required by the final design and planning of realization sequences of the truss welded joints
b) planning of realization sequences of joints between trusses and transversal connection beams (hinged joints)
c) planning of realization sequences of joints welded on site
d) planning of sequences for erection
e) the achievement of a proper accessibility to the various components of the element being examined
f) the simplification of the welding procedure employed
g) the simplification of the non-destructive control method employed
h) the limitation of deformation consequent to joint welding

6.1 Tolerances

The fulfilling of the prescribed tolerances and thus the correct organization of the subsequent activities on site, most certainly was the problem of greatest importance.

Erecting elements of such a considerable size and slenderness, through hinge-type constraints either mutual with concrete shafts, at a height between 28 and 40 m from ground, could absolutely not allow for any inaccuracy in workshop processes which would be added to those produced during the realization of joints on site.

On the other hand, the effects of a joint welding on the dimensional features of the elements involved, especially if rather thin, are most obvious.

Programming a simple pre-assembly in the workshop was not to be considered a solution, as it would “only” produce an awareness in advance of the deviation which were obtained in any case.

The only actual solution consisted in completing the parts intended to be coupled while ensuring that their assembly stages were performed simultaneously; therefore the sequence was performed in the following order:

a) separate composition (assembly) of each of the two elements
b) coupling of the elements by means of the intended constraint
c) manufacturing of approximately 80% of the total welding operations
d) release of the elements to complete welding activities
e) pre-assembly and final dimensional assessment

The implementation of the described method made it possible to solve brilliantly the deformation problems related to the shrinkage to which welded joints are subjected, thus achieving the respect of the imposed tolerances.

6.2 Transport and erection

The tolerance problem was necessarily related to the study of the method of transport from the workshop to the building site and then to hoisting and erecting procedure.

In consideration of the features of the selected hoisting means (crane truck with max. carrying capacity of 5000 kN, assisted by two auxiliary crane trucks with a max. carrying capacity of 1500 and 1000 kN respectively) and of the number and way of realizing the in situ joints, two couples of semi-trusses, without the central part of the lower stringer, were assembled on site at the ground level.

During ground assembly operations and subsequent welding, a particularly accurate topographic control was performed, either before the edge coupling and after the relevant deformations.

The exact positioning of the ridge and of the intermediate connecting beams at the constraint points on the concrete shafts was clearly of fundamental importance. Such a preciseness was achieved by overcoming two kinds of problems:

a) the compensation of the different performance tolerances of the concrete column casting operations and of the manufacture of the metal beams
b) the positioning, with precision to the millimeter, in a point approximately 10 m from the constraint point, cantilevered for approx. 8 m, at a height of approx. 28 m, of the hinge of a beam approx. 3.8 m deep.

The erection started with the steel column-horizontal bracing system of the middle section, followed by the transverse ridge and end beams and finally by the main truss halves and the Vierendeel beams.

The lengths of the intermediate parts of the lower chords were adjusted according to a survey effected after the erection of the main truss halves.

The stability of the structures during the erection was obtained by means of specially designed connection members.

The assembly of the decks was performed at ground level by means of bolts in order to build units having a two moduli width and the length corresponding to the distance of the main truss chords; the erection was performed by the tower crane already operating at the site.

7. SECONDARY STRUCTURES

Inside the main structures, secondary load resisting units are necessary to bear the facades and the roof of the central hall which lies at a lower level under the pitches in order to obtain a more harmonic ratio of the dimensions of the inner space and to give the trusses a transparency below the ridge.

The northern facade middle section is shaped according to a cylindrical surface which mirrors the circular reinforced concrete stair shaft; the vertical structure bears on a box beam which is superimposed to the deck elements, being its top restrained by the beams and the bracings of the secondary roof, which transfer the horizontal forces to a couple of vertical trusses resisting the shear forces.

The facades are composed of outer aluminum panels, insulation and plaster drywalls (fig.11/12).

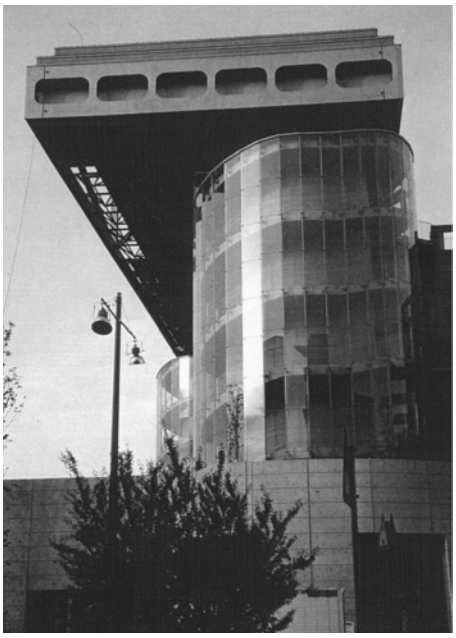

fig.11 side view

fig.12 view from the road level

8. MASS OF THE STRUCTURES

The mass of the structures results from the following items:

end transverse box beams	kg	95.000
middle box beam	kg	35.000
Vierendeel beams	kg	28.000
main trusses	kg	310.000
lower space deck	kg	140.000
upper space deck	kg	120.000
secondary structures	kg	90.000
facade structures	kg	42.000
Total	kg	860.000

9. CREDITS

The consultants who prepared the complete integrated design according to the functional requirements of the Direction of the Project for Requalification and Development of the Milano Fair, are:

Mario Bellini Associated for the architectural design

Redesco srl (G.C and M.E.Giuliani for the structural design and specifications, C.Carini for the structural modeling, G.Valentini for the design of the machined components)

Intertecno srl for the mechanical design

SPI for the quantity survey and for the civil work specifications

As the result of an international tender, the “turn key” construction works were conferred to a joint venture composed of: CMC / Recchi / Maltauro / Frabboni / CGC / Italtel Telesis / Kone.

The steel structures were built and erected by MAEG.