

Aluminium domes of the Enel plant in Civitavecchia, Italy

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Two aluminium domes have been erected within the thermo-electrical power plant of the Italian Electrical Department (ENEL) in Torreveldaliga Nord near Civitavecchia, Italy. The two reticular space structures are shaped as geodetical domes (with 144 m diameter and 50 m high) made of aluminium alloy tubes and stainless spherical nodes, according to the MERO system. The two domes are the largest built in Europe and for sure one of the largest in the World. Their function is for coal storage, according to the requirements of the thermo-electrical power plant. The aluminium alloy 6082 T6 has been selected in order to obtain both a mechanical strength comparable with structural steel and a corrosion resistance compatible with the aggressive environment, since the plant is located close to the Tirreno sea coast. The design of the domes has been done following Eurocode 9, also considering the "design assisted by test" approach. In fact, a series of tests has been planned in order to qualify the structural behaviour of each material, component and substructure. The global behaviour has been analysed by means of sophisticated numerical models and wind tunnel tests. The wind load effect is more severe than the earthquake for this type of structure, which is partly due to the lightness of the structural material.

During erection, very comprehensive quality control and qualification tests have been planned. The final proof tests on the whole structure, both static and dynamic, confirmed that the satisfactory behaviour of the domes is in good agreement with the numerical prediction. This challenging application demonstrates once again that aluminium alloys are excellent structural materials with a strength-to-weight ratio more than twice that of steel. In addition, the good corrosion resistance allows avoiding any protective coating. Considerable economical advantages have been obtained for the structure itself, the foundation dimensions and, last but not least, the maintenance cost. The two aluminium domes represent a clear example of an aluminium solution that can compete with a steel solution.

Keywords: Dome, space truss, large span, aluminium, coal storage, power plant

1 Design requirements

The transformation into coal of the thermal power plant of ENEL (Italian Electrical Department) in North Torrevaldaliga, near Civitavecchia, required a complete change for the transporting and storing systems, as the fuel from liquid (oil) is passed to solid (coal). The prevention of dispersion of dust into the environment resulted in a total confinement of the system for handling coal from the harbour discharge up to the boilers (Fig. 1).



Figure 1. Transport and storage system for coal

It was decided to cover the storage areas with two geodesic domes (Fig. 2) to comply with the following requirements [1]:

- Size and planimetric dimensions for a capacity of 300,000 t
- Characteristics of machinery for handling and storage
- Visual environmental impact
- Structural feasibility

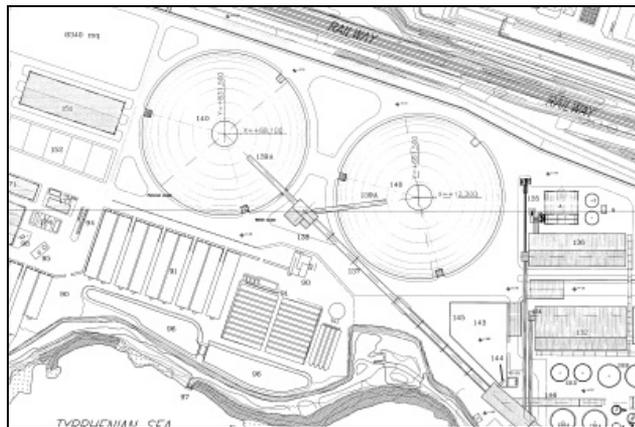


Figure 2. Location of the two domes

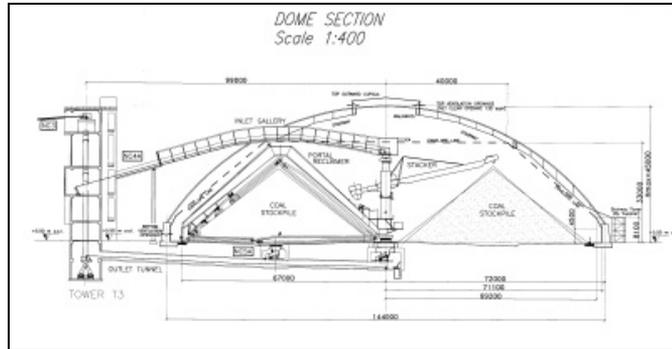


Figure 3. Cross-section of one of the two domes

These requirements resulted in the following dimensions for each dome (Figures 2 and 3):

- Diameter 144 m
- Maximum height 50 m
- Covered area 15,000 m²
- Roofing surface 21,000 m²
- Covered volume 450,000 m³
- Storage capacity 150,000 ton

Aluminium alloys have been selected as structural material, in order to obtain both an appropriate mechanical strength and a suitable corrosion resistance, compatible with the aggressive environment, since the plant is located close to the Tirreno sea coast.

These data characterize the largest couple of geodetic aluminium domes in Europe and one of the largest in the World (Fig. 4).

The perimetral base of each dome is supported by 48 reinforced concrete columns of about 6.0 m high and a spacing of 9.85 m, founded on a continuous circular beam. The base drum design includes natural ventilation grids and allows vehicle access for maintenance of the machinery.

2 Choice of structural materials

The choice of materials has been dictated primarily to minimize the costs of maintenance and monitoring of structures of such large dimensions, in relation to a design life set at 50 years. In addition, aluminium alloys have an intrinsic reliability in terms of corrosion resistance, which is the prerogative of the material, to be used for both principal and



Figure 4. External view of one of the twin domes

secondary structures. The success of the use of aluminium alloys as structural material in the field of so-called civil construction is a phenomenon that is increasingly acknowledged [2, 3]. The concrete possibilities of competition with steel are based on the rational exploitation of the special prerequisites of these "new" materials [4]. Aluminium alloys are a large family of materials, whose mechanical properties completely cover those of the ordinary mild steels. The corrosion resistance allows avoiding any protection even in particularly aggressive environments. The specific weight, one third compared to steel, provides all the advantages related to lightness. The manufacturing process by extrusion offers the designer the opportunity to "draw" the shapes of cross-sections in a suitable way in order to optimize the static performance with the functional requirements, without being blocked by the standardized commercial forms [5]. By simplifying, one can say that aluminium alloys can provide an economical solution, and therefore a competitive solution, in all those applications which can exploit at least one of these properties: corrosion resistance, lightness and originality of the cross-section [6].

Due to the development of the research activity carried out within the European Convention for Constructional Steelwork, the first European codification for aluminium alloy structures of was published in 1978 (European Recommendations for the Design of Aluminium Alloy of Structures). The first Italian code (UNI 8634) was developed on this

basis in 1985. In the early 90 ' structural aluminium applications were introduced in the framework of Eurocodes. Eurocode 9 "Design of Aluminium Structures " reached the EN stage in 2007. It is composed by 5 parts [7]:

- Part 1.1: General rules
- Part 1.2: Resistance to fire
- Part 1.3: Structures susceptible to fatigue
- Part 1.4: Cold formed sheeting
- Part 1.5: Shells

In the specific case of reticular domes situated near the sea, and intended to contain huge masses of coal, the choice of a steel structure would have been quite critical. The advantage of not hindering the production due to maintenance during the years in the highly aggressive environment has strongly promoted the choice of aluminium alloys: in particular, the 6000 series alloys (type 6082 T6) for tubular struts of the domes, which has a mechanical strength comparable to that of steel Fe 430 and also a good resistance to corrosion in a marine atmosphere. The 3000 series alloys has been selected for cladding sheeting, which requires less resistance. It also has been decided that the nodes of the reticular structure are made of stainless steel.

The choice of all materials was also supported by a series of tests, like salt spray 1000 hours NSS (UNI-EN 9223/9227), which also allowed to check the electrical compatibility at the points of contact between stainless steel and aluminium. The results of laboratory tests have confirmed the design assumptions:

- No protection for the internal structures, considered as a moderately aggressive marine-industrial environment;
- Anodizing of 20µm for secondary structures (grids and staircases) placed outside, considered as an aggressive marine-industrial environment;
- Physical separation at the contact points of between stainless steel and aluminium.

The design of the aluminium alloy structures of the two reticular geodetic domes was made according to the Eurocodes. One can certainly say that this is the first major aluminium structure designed with the Eurocode 9, not only in Italy.

3 The structural system

The MERO system has been selected for the reticular scheme of the geodetic domes. In particular, the reticular structure is composed of aluminium tubular bars (alloy 6082 T6), connected to the nodes by means of bolts. Both nodes and bolts are made of stainless steel, 1.4462 and A4-80, respectively. Figure 5 shows the bar-to-node connection; the conical terminal is welded at the end of each bar.

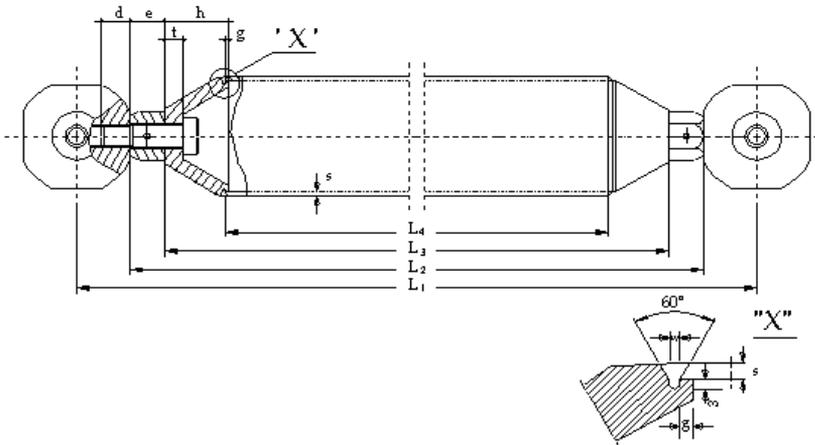


Figure 5. The bar-to-node connection of the MERO system

The problem of galvanic corrosion, which can occur in the contact between different materials like aluminium and steel, has been avoided by applying a fibre-glass washer at the node contact point and painting the screw with Dracomet. The combination of bars and nodes was chosen such that a double layer spherical surface has been composed (Fig. 6).

4 Design assisted by testing

The definition of loading conditions was a delicate operation preliminary to the design process. Particular attention has been given to the behaviour of the dome as a result of wind action, which is a crucial issue for this type of structures, illustrated by the dramatic collapse of some similar domes in Taiwan a few years ago. The assumption of the wind load is depending on the following factors:

- Environmental off-shore conditions
(Zone 3, roughness class D, exposure category 1, return period of 1000 years);

- Reference differential wind speed
(27 m/s in the execution phase, 31.5 m/s in use);
- Anemometer analysis of the site;
- Wind tunnel tests for comparison with the loads given by codes
- According to the code, the first two points conservatively correspond to offshore facilities.

The third point can be further highlighted as follows:

- Design peak speed $V_p = 60.4$ m/s, constant over the whole area
- Maximum peak speed recorded in situ (period 1971-2005) $V_p = 46$ m/s

Wind tunnel tests have been performed with a physical model (Figure 7), which is representative of the influence area of the installation (about 300 m radius). The instrumentation consists of 112 pressure cells on the outer surface and 16 inside.

The results have shown a significant contribution of the drag force transverse to the wind direction (Figure 8), produced by the "Venturi" effect, due to the interference between the two domes which are very close to each other.

Comparison of the experimental values to the global forces provided by the Eurocode EC1 (EN-1991) has shown that the code overestimates the lifting force, while underestimating the drag force (table 1). The design has taken into account both sources, by maximizing values and by emphasizing the eccentricity in the loading combination.

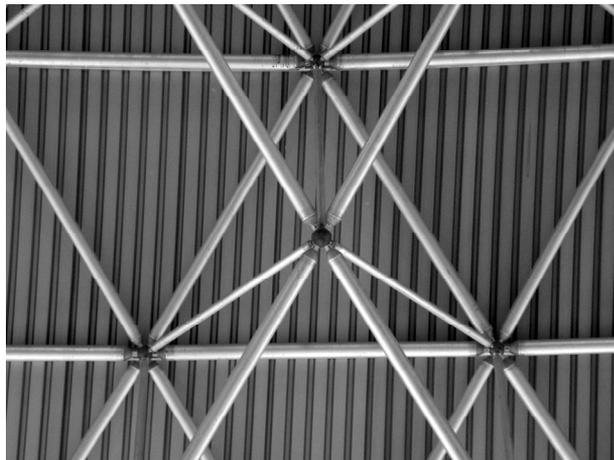


Figure 6. The reticular space structure

Table 1: Wind loading determined analytically and experimentally

	Eurocode 1	W.T. test
Lift	18,000 kN	0 - 5,300 kN
Total drag	1,700 kN	0 - 3,400 kN

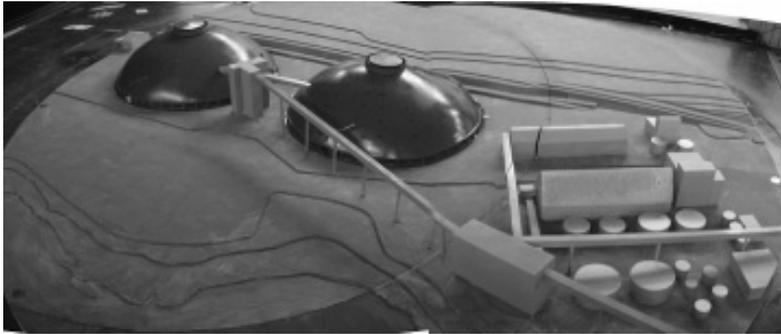


Figure 7. Wind tunnel models

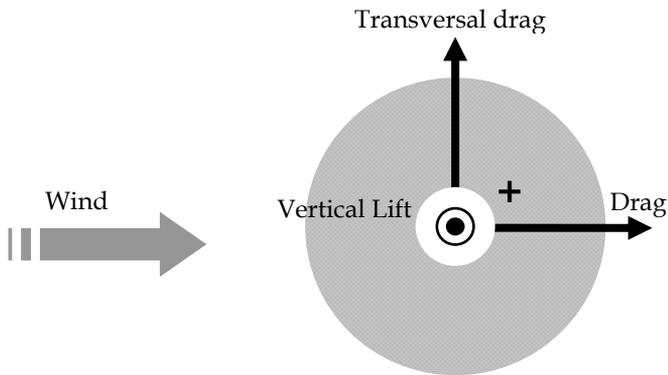


Figure 8. Wind loading components

With regard to dynamic effects, the test recordings have shown that the energetic wind component is maximum for the frequency values of the order of 0.1 Hz and it is smaller by a factor 100 for frequency values of about 1 Hz. Comparison to the 2 Hz of the first frequency of the dome shows that these values exclude the initiation of any resonance phenomenon. Moreover, the shape of the domes excludes the possibility of detachment of alternate von Karman vortices.

Finally, a series of loading tests on full-scale models have been planned during the design process in order to qualify the structural system; in particular should be mentioned.

- collapse tests on the bar-to-node connection (Figure 9a),
- a collapse test on the cladding panel-to-purlin connection,
- a loading test on a full scale substructure as a portion of the spatial structure (Figure 9b),
- Loading tests on a portion of a cladding panel.

The obtained results have confirmed the degree of safety given by the codes of practice and assumed in the design.

5 Structural analysis

Different types of action have been considered in the design process: static loads, thermal variations, foundation settlements, seismic loads and erection phases. Vertical static actions are those due to dead load and snow load, in addition to live load equal to 1.00 kN/m^2 (Figure 10a). Special mention deserves the action produced by the wind, which is considered static in nature and, on the safe side, is evaluated for a return period of 1000



Figure 9a. Bar-to-node test

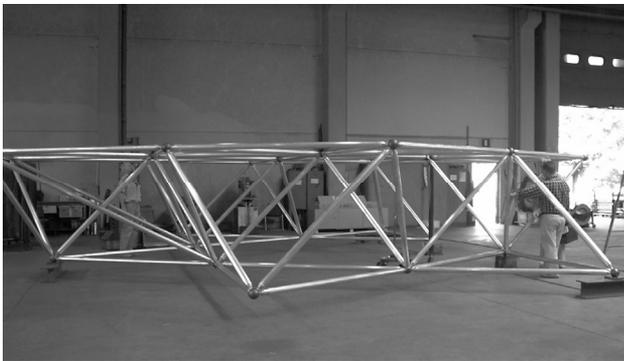


Figure 9b. Substructure test

years and for offshore structures. The wind calculation has been done by considering 8 different directions of incidence, by means of special algorithms, which produced, a mapping of pressure for each direction (Figure 10b).

Actions due to the foundation settlement, produced by differential distribution of coal in the two domes, have been considered. A geotechnical survey has shown that the most severe situation is both domes loaded with half-load near each other. Dynamic effects due to an earthquake have been analyzed according to the Italian regulations, which consider the site as a low seismicity area (zone 4) with $a/g = 0.05$, where a is the peak acceleration

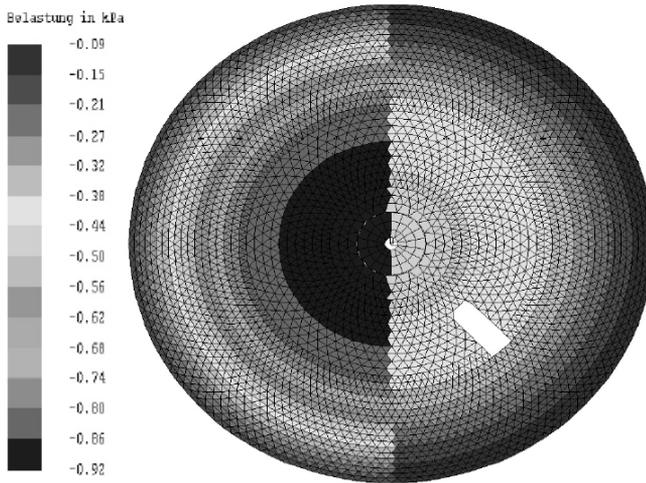


Figure 10a.
Stress distribution due to vertical loads

Left: external layer

Right: internal layer

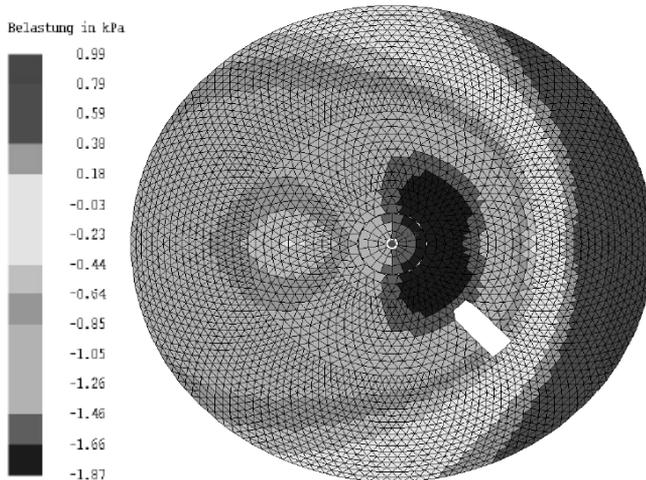


Figure 10b.
Stress distribution due to wind load

and g is the gravitational acceleration. Due to the very light dead load of the structure (approximately 0.15 kN/m^2), the seismic actions were not significant for the design. Transitory conditions during erection have been considered, when the whole structure is not yet completely supported by the columns. The analysis has been done starting from the final structural model and simulating the various stages of the erection process, in which the structural segments are progressively assembled (Figure 11), also for identifying the need for provisional supports.

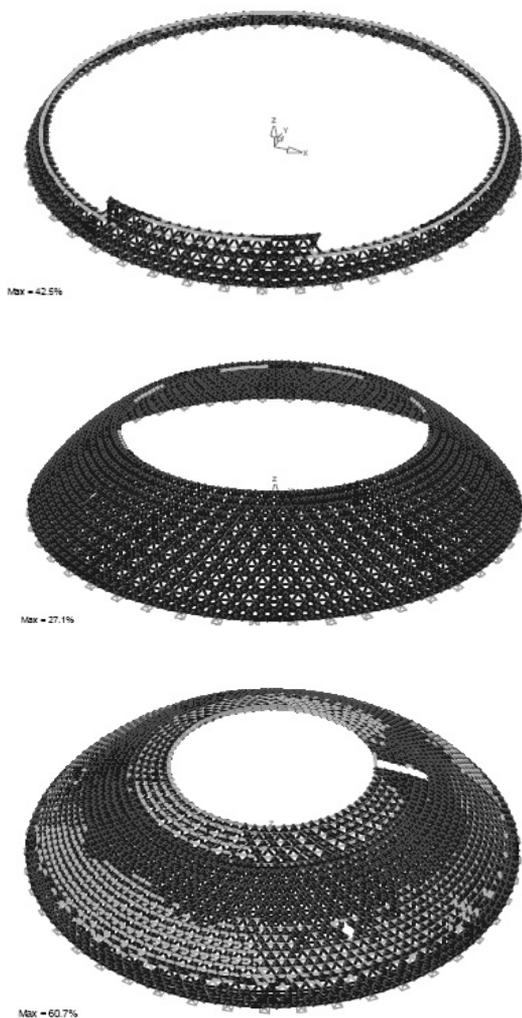


Figure 11.
Analysis of erection phases

6 Erection

The sequence of assembling the reticular structure started from the bottom ring, which is supported by the perimetral columns (Figure 12a) and proceeded up to the top (Fig. 12b). The structure of the MERO system for each dome is composed of 6,200 nodes and 25,000 bars. As soon as the reticular dome had been completed, the assembly of the purlins and the secondary structure has been done for the subsequent fixing of the corrugated aluminium sheeting. The positioning and fixing of the panels has been done from the bottom upwards (Fig. 13a, b). About 100,000 screws per dome have been installed. Several thousand points of possible attack of water as coatings, seals and singular points of anchorage have been checked and protected from storm water. When the whole structure



Figure 12a.
Erection of the first rings of one of the domes

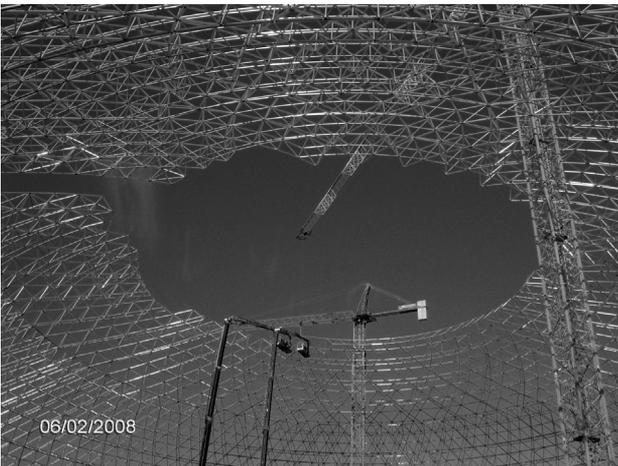


Figure 12b.
Erection of the top of one of the domes

was completed, including stair-cases, walkways, machinery and equipments, the storage of coal started inside each dome (Fig. 14a, b).

7 Conclusions

Aluminium alloys have been selected as the suitable structural material for fulfilling the fundamental prerequisites, which were assumed for design of the two domes of the thermo-electrical power plant of Torrevaldaliga (Civitavecchia, Rome), i.e. to provide large corrosion resistance without protection in aggressive environment and, as a



Figure 13a.
*Covering of the dome by
aluminium sheeting:
external view*



Figure 13b.
*Covering of the dome by
aluminium sheeting:
internal view*

consequence, to guarantee little maintenance during operation. The domes are a typical case in which there is no competition between steel and aluminium because the last material is the most convenient choice. In addition, it is noteworthy that these domes represent a significant application example of the Eurocode 9 provisions, immediately after their final version, showing their ease of application to important structures.

At the moment, the twin domes are the largest aluminium structures in Europe, probably also in the world. At the same time, they clearly express the Italian paradox that these very challenging structures have been built in a country, where aluminium alloy structures are not supported by a code of practice. It should be hopeful that this remark could be considered by the relevant authorities in order to fill this gap in the Italian regulations.



*Figure 14a.
Equipment for coal
storage inside the dome*



*Figure 14b.
Coal storage inside the
dome*

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