Three Resilient Megastructures by Pier Luigi Nervi

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December 2011

Abstract

Resilience as the ability of a structure to withstand threats and continue to function, it is normally related to durability and performance to accepted standards over time. The resilience of a structure can be threatened by poor design, changes in the public's perception of style, the potential for a change-in-use and structural attack; catastrophic events such as fire, explosion or impact are usually considered the main threats for Resilience. In the contemporary built environment Resilience is considered increasingly important; it has, in fact, become one of the major design issues, especially for large, iconic or public and prominent structures: this has not always been the case.

Following the Second World War, building designers faced the necessity to conceive projects within severe financial constraints, hence the proliferation of a low quality and limited life-span structures; buildings which were designed to be replaceable, cheap and perhaps anonymous. This was thought to be an effective answer to quickly accommodate the large number of people moving towards the urban environment partly destroyed by the WWII. These very buildings now constitute the backbone of our urban scenery and although some still function adequately, many are perfect examples of structures which exhibit a lack of resilience.

Fortunately, there were a few designers who refused this post-war tendency and attempted to design lasting structures of quality: most of them were engineers. This is not a coincidence, engineers had less to do with the issue of providing residential accommodations and more with the erection of large structures which necessitated a higher quality control on materials and technologies: Pier Luigi Nervi was one of them.

This work considers three large structures designed and built fifty years ago, in 1961, by the Italian engineer. The structures are the Bus Station at the George Washington Bridge in New York (USA); The Burgo Paper Mill in Mantua (Italy); and the Palace of Labour in Turin (Italy). All of these buildings are hybrid structures (concrete and steel), an unusual choice for Nervi that perhaps reflects the design climate at the time; These buildings reacted quite differently to the events that have occurred over the past half century. One of the key factors to achieve resilience it is considered to be the quality of the buildings, which includes their ability to perform maintenance. The lack of which for whatever reason, this paper aims to demonstrate, will inevitably result in a weak performance in terms of resilience on the long run.

Keywords Pier Luigi Nervi, Hybrid Structures, Resilience, Design process, Aesthetics.

1 Introduction

This paper discusses the design and construction, and the current state of three major pieces of work by the Italian engineer Pier Luigi Nervi. The buildings considered are the George Washington Bridge Bus Station in New York (USA); The Burgo Paper Mill in Mantua (Italy); and the Palace of Labour in Turin (Italy); all were constructed between 1961 and 1963. The scale of these buildings meant that they would later be known as 'megastructures': large functional infrastructures used by many people and designed to have a service life in excess of more ordinary constructions. These megastructures were considered at the time as a possible solution to the increasing demand for urban spaces by some of the more progressivist designers such as Archigram, Fumihiko Maki and Hans Hollein.

The three buildings were all conceived by Nervi in a relatively short period of time and at the apex of his career; he received the RIBA (Royal Institute of British Architects) and AIA (American Institute of Architects) Gold Medals respectively in 1960 and 1964 when he was considered to be one of the most influential structural designers of his era. However, they are unusual solutions for Nervi, as they make extensive use of steel, which was not his preferred material. The reasons and consequences of this choice of material are discussed in this paper. For instance, both the budget for these projects and allowable time for construction were very restrictive; arguably he was driven to use steel to enhance the speed of construction in order to satisfy the time limitation specified in the brief, a time-frame which he could not meet using only reinforced concrete and its lighter variant, ferrocement. Ferrocement is a particular kind of reinforced concrete, light and resistant, that Nervi re-invented, improved and patented in 1945 under the name of *ferro-cemento.* His success in satisfying these design parameters of economy and time was also helped by the fact that Nervi was both designer and contractor (his construction company built the majority of his designs). The ability to design and construct his own projects made his proposed solutions a rational interaction between the two processes. Nervi's capacity to look at his designs from both perspectives and the benefit he possessed from being able to control the process through design to completion of construction were invaluable. This situation facilitated the better and easier introduction of innovativeness and problem solving, massively improving the efficacy of the process. The three structures are examples of perhaps the most efficient total engineering process of their time.

This paper is based both on the most recent structural surveys [Ruggieri, 1999, Burgo, 1998, PlannING, 2011] and on repeated visits and direct observations to the structures by the authors which involved communication with the staff working in those buildings. These sources were crossed in order to determine the current state of the buildings. This was considered particularly valid as all these structures faced dramatic events during their existence, i.e. a substantial increase in volume of traffic (the Bus Station), a large fire (the Burgo Mill) and a lack of maintenance (the Palace of Labour). The exercise was set out to determine: How resilient these three structures proved to be? How their original designs influenced their time dependent performance? How their current use allows their capacity to function. And finally, what we can learn from Nervi about how to improve the flexibility and adaptability of future projects.

2 George Washington Bridge Bus Station, New York, 1961

The George Washington Bus Station, in upper Manhattan, New York, was designed by Nervi in 1961. At this point in time, after the world-wide success of his olympic structures in Rome, the Italian engineer had already received international recognition as one of the greatest structural designers of his time and he was celebrated as a fine architect too. It is worthy to note that he was awarded the RIBA Gold Medal in 1960 and in 1964, just one year after the opening of this Bus Station (17 January 1963), Nervi received the AIA Gold Medal as well.
The huge complex, whose footprint is approximately 10,000 m^2, was conceived to become the only terminal between New Jersey and New York (indeed before the completion of this building there was a series of bus terminals in the area) is, interestingly, a hybrid structure. Indeed, in order to connect the new reinforced concrete structure of the roof to the existing steel structure of the underground station Nervi used steel pins bolted at the base of the columns. One of the major issues in this kind of building is the different mechanical responses of components especially with regard to temperature. This is arguably why Nervi inserted a cross thermal joint in the roof, which can be identified by the particular shape of the column in Figure 1. In this case the hybrid structure was somehow a necessity, which characterises this particular period of Nervi's production.

Figure 1: The double steel pin at the bottom of the central column. [MC]

The internal space of the station is functionally split into three floors linked by the vertical circulation system (i.e. stairs, elevators and escalators) to facilitate the movement of the terminal users. The underground floor hosts the Underground lines (M4 and M5), the ground floor, where the passengers can find the main services (shops, ticket offices, travel information, etc.) and the upper floor which is the proper terminal, where the buses arrive, park and depart. Structurally, the Station reflects its internal layout, two huge lattice beams in reinforced concrete on the longest side of the building, one on top of the other, mark the separation between the ground and the upper floor and support the roof, which consists of 28 triangular beams. The 57 m span roof is supported centrally by a line of eight columns, also in reinforced concrete, at 20 m centres.

Figure 2: A view showing the two lattice beams and the structure of the roof. [MC]

The particular shape of the main beams supporting the roof was actually inferred from the brief which specified the need for natural light and ventilation. Nervi, using these triangular lattice beams, allowed the passage of air and light as requested. Here, the use of ferrocement for the triangular slabs was a major advantage for the construction of the roof because of its lightness and ease of assemblage. As a result of his personal reinterpretation of this material, *ferro-cemento*, Nervi was able to cover large spans using barrel vaults or domes, of which the Palazzetto dello Sport and Palaeur in Rome are the most famous examples. Indeed at the time of its completion (1960) the Palaeur's dome was the largest in the world in reinforced concrete (100m diameter).

Although this is a 'service-building', whose principal aims are to facilitate the transit of passengers, the Italian engineer treated it with the same attention to detail as his other, more iconic, projects. He carefully designed many components, the central column for example: this is Nervi's signature in this building. Indeed, instead of having an anonymous central pillar replicated seven times, Nervi shaped the form of the structural element in order to have a 90° rotation from its base to its top. Such a formal solution for the vertical supports, obtained through variable horizontal sections of the column itself is geometrically described as a portion of a hyperbolic paraboloid. Such form was probably suggested both by the direction of the bus traffic and by the attempt to minimise the area of the columns in the bus track on one hand, and to create a suitable connection between the roof structure and the column itself on the other. A similar treatment was already anticipated by the Italian engineer in the 'piloties' for the UNESCO building in Paris (1953) and in the internal angled columns of the Palaeur (1960).

Figure 3: The variation in the profile of the central column. [MC]

According to the authors' visits performed in April 2008 and related research within the archive of the NY Port Authority and personal communications with the relevant staff, the George Washington Bridge Bus Station has been working flawlessly for fifty years and all the major structures and elements are in an excellent state of repair. In 2010, more than five million passengers on 300,000 bus trips passed through the terminal bus movements, making of this the busiest bus terminal in the USA and one of the busiest in the World. On a typical weekday, there are approximately 18,000 people completing 1,000 bus movements [NY Port Authority, 2010].

When Pier Luigi Nervi designed this bus station in 1961, the population of New York City was 7,781,984 and in 2010 it was 8,175,133 [NY Census, 2010], more than 375,000 more inhabitants. These numbers are important as they illustrate how Nervi's infrastructure has coped with such an increment in users. This is arguably due to the rational design of the station both in terms of internal design (the logic separation of floors according to their function) and the generous size of the structural grid, which allowed its smooth functioning despite the dramatic increase of users.

It is interesting to compare Nervi's building with the iconic Saarinen's TWA terminal in the JFK New York airport. Both were designed in the same year (1961) and opened within a few months of each other. However, while the bus station is still in use after 50 years, the air terminal, following management problems in the 1990s essentially related to security control issues, closed in 2001. In fact addressing these issues would have resulted in major alterations of the internal space. Although the design of the TWA Terminal certainly set a new spatial and aesthetic benchmark for similar buildings and the comparison with Nervi's infrastructure is, typologically, not totally stringent, still the responsiveness and ability to adapt to changes, or in other words the functional resilience, proved to be less effective in the project of the architect (Saarinen) compared to the George Washington Bridge Bus Station designed by the engineer Nervi.

During the 1980s the external area of the bus station was subjected to vandalism and sometimes used as a shelter by homeless people. This resulted in a 'seedy aura' of the complex [The New York Times, 2008]. However in October 2008, the NY Port Authority agreed a 152M$ plan to renovate the Bus Station. An initial layout has been provided by PA Associates (Figure 4) to increase the retail potential of the building. The project fully respects the original structure of the Italian engineer and limits any redesign to the internal spaces according to the contemporary needs. The capacity of a building to adapt while keeping its own identity is another sign of the resilience of Nervi's design.

Figure 4: Two images of the renovation scheme. [PA Courtesy of PA Associates, New York]

Figure 5: The Palace of Labour in 1961, Turin. [MAXXI]

3 Palace of Labour, Turin, 1961

On the first of May 1961 two important events in contemporary Italian history occurred. These were the Labour Day, an international public holiday celebrated to remind all of the importance of the struggles of the working class, and on the same day in 1961, the Italian Republic celebrated its first Centenary. On July 1959 the Italian Parliament, by means of a special organising commission - *Italia 61* - approved a series of cultural events organised across Italy to celebrate the Centenary. This included a national competition between a dozen leading design practices for a large exhibition hall to be constructed in Turin, the city in which the Unity of Italy was first conceived, and its first Capital.
The competition brief was particularly strict:

- A detailed project, complete with structural calculations, had to be submitted before 7 October 1960.
- The main section of the Exhibition *Italia 61* was to be hosted in the main hall, however this internal space had to allow further uses.
- The plan of the building had to be symmetrical.
- The opening day was fixed as 1 May 1961.

The brief indicated that the covered area should be approximately 25,000 m^2. The difficulties were clear, the task was to find a compromise between the political value of a building commemorating the Centenary of the Republic and its function afterwards and, perhaps above all, the feasibility of constructing it in such a short time. The roof and its supporting structure were the main concerns. Initially, Nervi's practice was tempted to design a dome over a circular plan but he then realised that this solution would take too much construction time. Other possible solutions considered were either a vaulted structure or a continuous flat roof. All three options faced the same drawback of requiring excessive construction time. After some weeks, a suitable design had not yet emerged and Pier Luigi Nervi was at the point of withdrawing from the project, when his son Antonio, propounded a daring idea: instead of having one big roof, why not design a series of smaller, independent ones to cover the whole area? This new approach would simplify the roof design but more importantly, permitted the organisation of the building site as a 'work in progress' [Nervi, 1960],[Nervi, 1961]. In this way finishing works could begin in the areas where major structural work was already complete while the latter could begin in new areas. A strictly accurate time-plan for each construction stage was essential to win the competition. The large covering was planned to consist of sixteen square plates (38×38 m) supported by a 25 m high central column. The connection between the plate and the pilaster was provided by a steel capital to which the 20 beams (composed by welded components) are bolted (see Figure 6). Four perimeter beams would then stabilise the cantilevered elements. Between each plate a 2.5 m wide glass strip panel was inserted to provide natural light.

Figure 6: Detail of the bolted connection capital-beams. [MC]

This initial layout was subsequently transformed into a detailed design in which materials, technology and site management had to be planned with absolute precision. The whole construction process of the huge structure could be reduced into the systematic construction and subsequent juxtaposition of sixteen identical structural elements: one pillar surmounted by one square plate: the 'mushrooms', nick-named by Nervi's office. The simple 'mushroom' idea presented two major problems: the construction system for

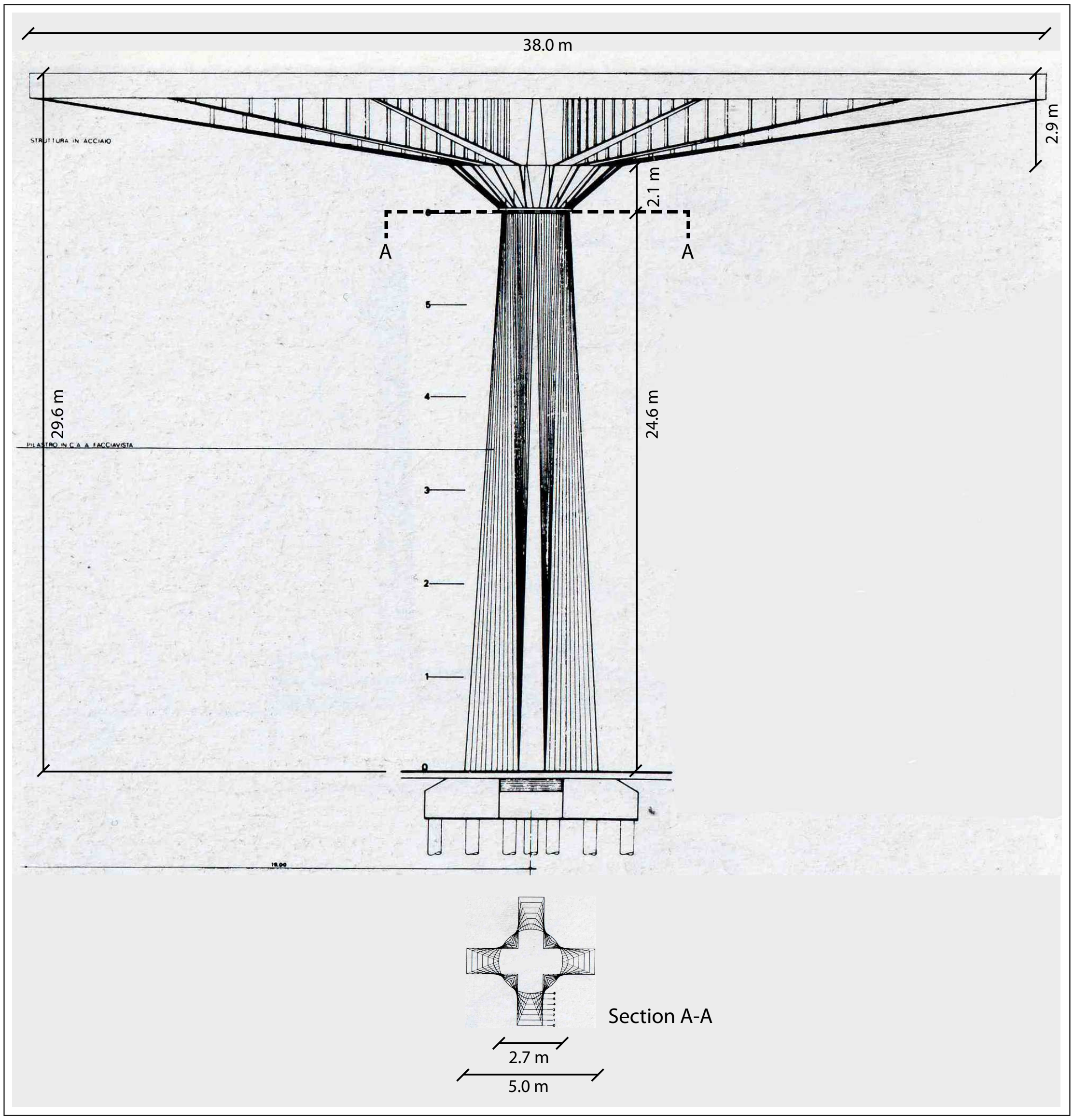


Figure 7: The elevation and section of the column. [CSAC-MC]

the erection of the huge pillars and the structure and material for the plates.
Nervi and his team realised that to construct the horizontal element, the 'capital' of the mushroom in reinforced concrete would take too long, especially considering the complication of two cold winters. Hence, for the first time in Nervi's career at such a scale, steel was preferred to reinforced concrete. After planning the initial scheme, the detailed design of the structure was given to a firm which specialised in steel construction, the Badoni Company from Lecco, which worked under the supervision of the steel engineer, Gino Covre. Nervi met Covre for the first time on the occasion of the 1940 competition for a monumental arch at the EUR district in Rome when the two engineers designed the structures for the reinforced concrete (Nervi) and the steel (Covre) version of the arch. It is worthy to note that both Antonio Badoni and Gino Covre were involved also in the Burgo Paper Mill.

The construction of the columns in exposed reinforced concrete presented various issues. The main one was that it was crucial to have perfect vertical alignment of the columns, especially at the top where the steel capital was to be placed. This is very difficult to achieve with normal timber forms. Even more importantly, it was difficult to provide a continuous surface between the cruciform base and the circular top of the columns. As there would be no time for corrections the columns had to be constructed perfectly from the very beginning. Finally, the forms for the columns had to be accurately placed by a crane and it had to have its own stability. The final solution was to build a single steel framework, composed of six components bolted together which could be dismantled, with which to erect all sixteen columns; a huge 'machine'. The concrete was to be poured in three different stages, each one every two components. The giant steel framework was also constructed by Badoni and costed 10 million ITL (120.500 EUR (Dec. 2010)).

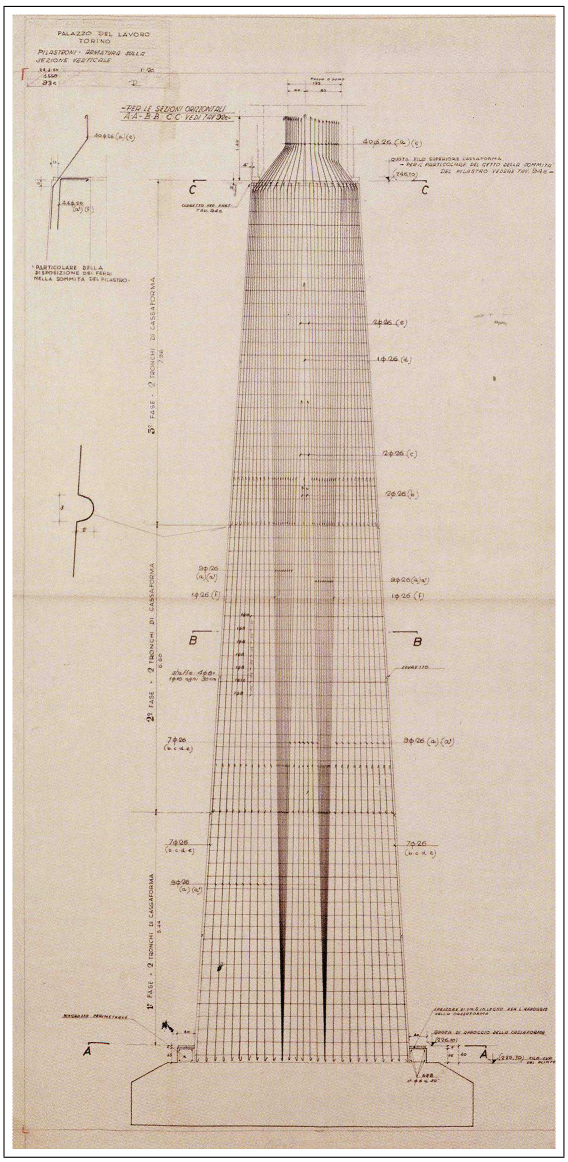


Figure 8: The reinforcement of the 25m column. [CSAC]

On 20 October 1959 the panel concluded the examination of all the entries declaring that the only 'fully satisfying' project was Nervi's. Foundations were excavated on 1 February 1960. The final building was to be a square of 167 m per side with an internal height of 25 m. In July 1960, the machine for the construction of the columns started to work. The six pieces in which the tall column was made, were marked by a 2 cm timber groove to avoid possible irregular separation between two consecutive pours. The complete cycle for the erection of one column was achieved in ten days. When a column was finished, the whole steel form was dismantled and its internal timber skin, formed by 12 cm wide timber strips, was taken out, polished and re-installed within the machine, ready for another cycle. This process, repeated for all columns, allowed the finishing work to start where the structure was already complete. It is important to note that internally the columns permit the passage of the rain ducts and a manhole is provided for their structural inspection and maintenance. On the 30 October 1959, after only four months, the construction of the sixteen mushroom-shaped columns was completed.

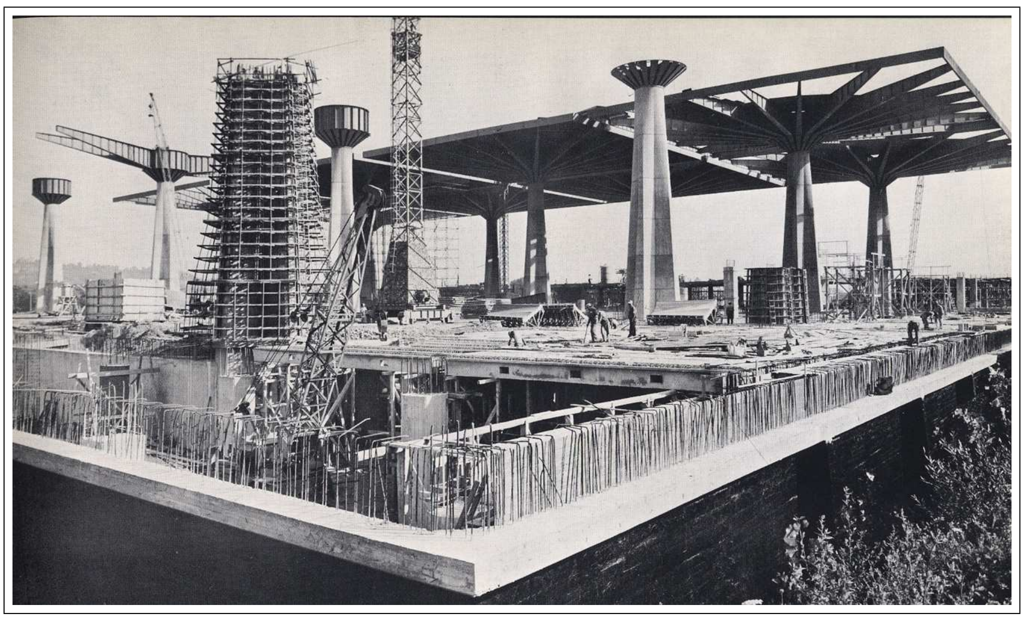


Figure 9: The Palace of Labour, in construction. [MAXXI]

At the same time the mezzanine floor, at the perimeter of the building, was finished. A system of movable forms in *ferro-cemento* was employed to quickly build the structure of the floors, 'signed' by Nervi by his isostatic intrados (Figure 11). The isostatic lines are, in this case, the strain-lines of the bending moment present in the rectangular slab supported at its corner by four column. Nervi placed the reinforcement bars along these lines achieving at the same time an elegant and, to some extent, structurally correct solution. Indeed, this solution would be more correct without the presence of the ribs as the isostatics are coplanar to the slab and, moreover, the presence of the ribs changes the overall geometry of the building element (the slab) and hence the way that strains flow within it.

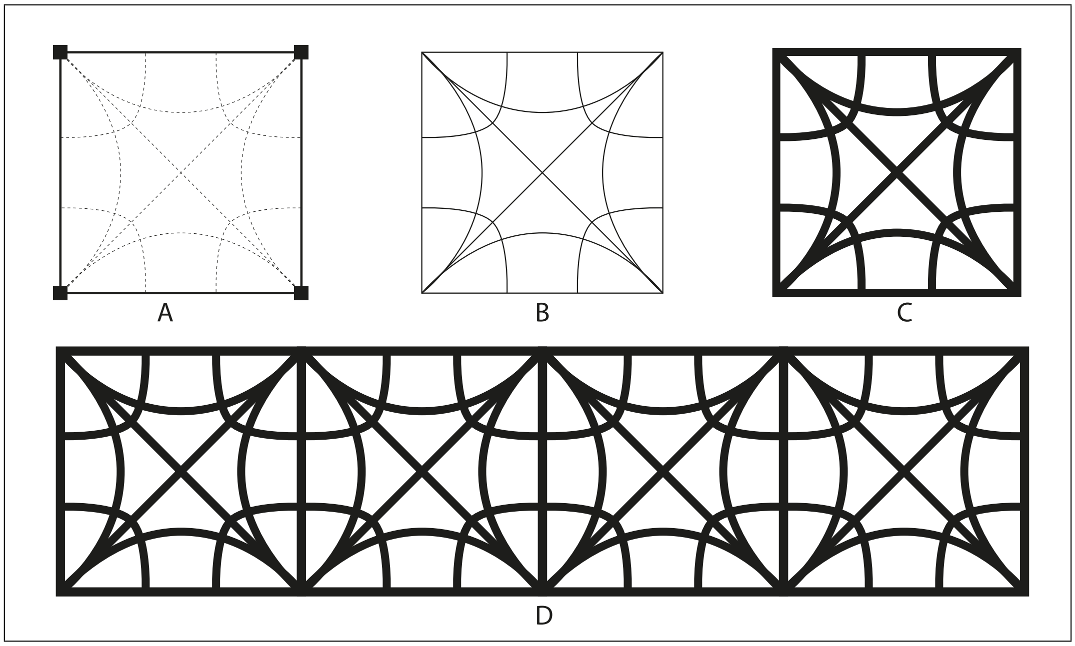


Figure 10: From the isostatics diagram (A) to the reinforcement lines (B) to the definition of a ribbed slab (C) and to the final ceiling pattern (D). [MC]

Figure 11: The Palace of Labour, the isostatic floor. [MAXXI]

The glass skin of the building was assembled and the whole building was ready for the exhibition organised by the architect Gió Ponti in January 1961 as planned. Ponti and Nervi, colleagues and friends, had previously worked together during the design of the Pirelli building in Milan, in 1956 (the *Pirellone*, with its 127m, is still the tallest building in Italy). The great hall was received with controversial comments. Many critics attacked Nervi's new direction towards gigantic structures and the scant attention to architecture. In particular, Bruno Zevi criticised the 'anonymous glass envelope' [Zevi, 1961]. Moreover, in addition to the negative comments of some critics, Nervi's design was fiercely contested by some other competitors for instance, the architects C. Mollino, C. Bordogna and the structural engineer S. Musmeci who presented a formal complaint to the panel as the building did not provide a second floor as requested by the brief. However, other critics admired Nervi's achievement: in a postcard sent by Le Corbusier to Nervi from the Palace of Labour the Swiss Architect described the venue as a '*magnifique palais*' [Cresciani, 2009]. The Palace of Labour in Turin demonstrated Nervi's ability to master the construction of a large building within strict conditions. However, it also demonstrated his limitations as a pure designer of space. Indeed, it can be argued that to limit the whole design of a monument to the nation by the mere planning of its construction methods and the technologies involved, although ingenious, may diminish the significance of the architecture in its tridimensional and symbolic aspects. Furthermore, the decision not to build a second floor has complicated the chances to use this building after the celebration of the centenary. On this occasion, Nervi seemed to be more concerned about the definition and realisation of the components rather than the overall final product. However, considering the close deadline and the overall aesthetic finishes that Nervi provided to the gigantic structure, this was clearly an acceptable compromise for the judging panel.

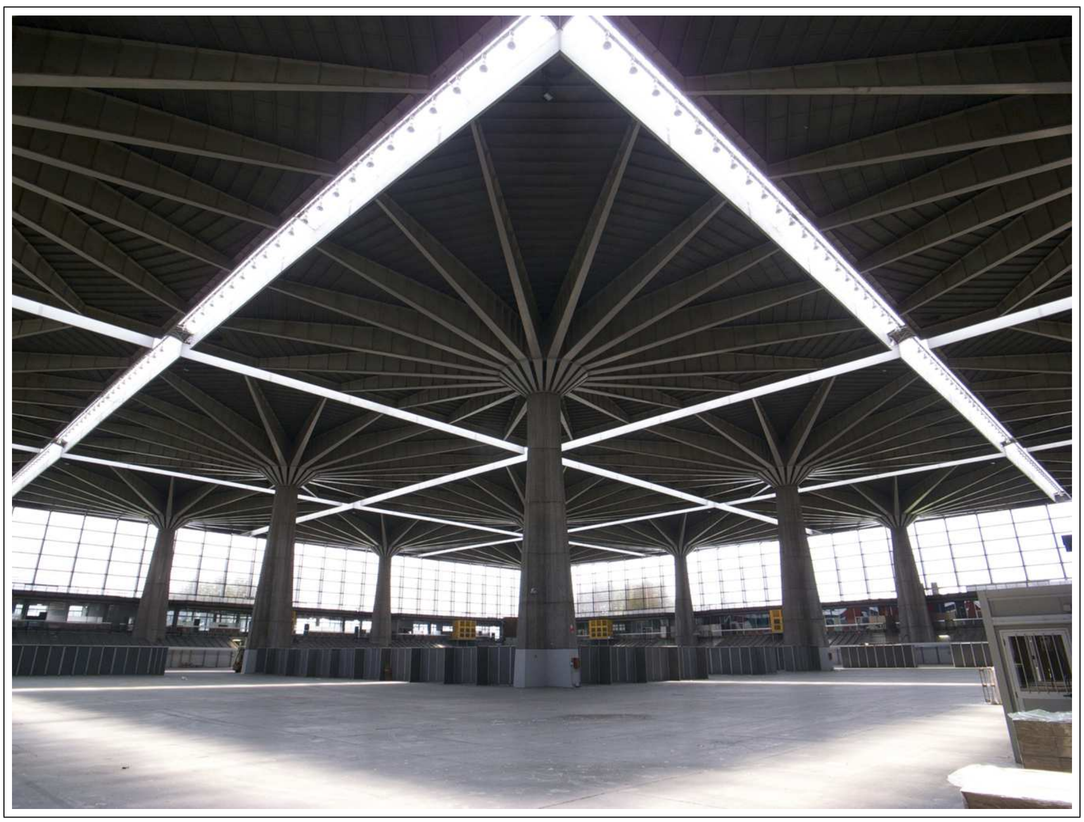


Figure 12: The Palace of Labour, the internal hall in 2008. [MC]

Designed to be one of the most prestigious monuments of *Italia 61*, the Palace is now reduced to a semi abandoned building, partly used by the Faculty of Economics of the University of Turin. Despite this, the structure is still in a 'good state both for the columns in reinforced concrete and the steel roof' [Ruggieri, 1999], the dramatic internal hall is now used merely as a storage area with restricted access.

The internal built environment is unhealthy and its maintenance is almost non-existent. Indeed evidences of animal presence are visible in several areas of the main hall and staircases. In the areas occupied by the University, the elegant and famous ribbed ceiling (Figure 11) is now hidden by a mundane false ceiling. Externally the Palace is also in poor condition. Particularly the south elevation, where there are clear signs of rusting of the steelwork of the bris-soleil and the reinforced concrete supports exhibit carbonation degradation.

The Palace of Labour, built to celebrate the Unity of Italy is, ironically, the only building designed by Nervi which appears to be totally forgotten. On one hand this depends from a fault in the design, in particular it can be argued that the lack of the second floor made the large internal hall less usable; but more importantly it is the lack of maintenance which determines its current state, and makes it even less attractive for potential users. This is a bitter counterpoint for a designer who took maintenance and therefore resilience as one of the fundaments of his design process. Nervi's buildings were designed to be used, and therefore maintained. In the lack of care, this gigantic structure has no choice but demolition.
With its fate undecided, during the recent Winter Olympic Games in 2006, hosted by the City of Turin, the whole building was wrapped in colourful panels which served both to advertise the Games and to conceal its current condition. In November 2008 a new interest in the Palace of Labour, was demonstrated by the famous commercial chain from Spain, the *Corte Inglés*, which seemed to open a possibility of imminent restoration [Il Giornale del Piemonte, 2008]. Unfortunately, no agreement was then reached.

Figure 13: The Palace of Labour, the new project, opening in 2013. [WWW Courtesy of Studio Rolla]

In July 2009 however, the Dutch company *Foruminvest* delivered a preliminary scheme which was published by the Italian print and subsequently approved by the local authorities on 22 September 2009 [La Stampa 2009]. However nothing happened. It is as recent as March 2011 the news that a new proposal has been put forward by an Italian investor (Gruppo Ponchia). The initial design delivered by Studio Rolla, still at its early stage (Figure 13), will include a new commercial centre on two storeys and a temporary exhibition area. With the foreseen cost is 135.000.000 EUR, site works should commence in early 2012. On this occasion, a full review of the structural state of the Palace has been undertaken by the Structural Consultants 'PlannING - Ingegneria e Pianificazione s.l.r.', from Bologna (Italy) and completed in November 2011. From this review an interesting and unknown fact (to the best of the authors' knowledge) emerged. In 1963, only two years after the construction, Nervi decided to dismantle the original steel roof-cover (designed by Covre, Figure 14) and to replace it with a new one in *ferrocemento*. Although it is not clear what were the reasons for Nervi to came to this decision, this had certainly consequences. PlannING engineers are inclined to consider a concern from Nervi on the torsional resistance of the roof elements after a heavy snowfall; the heavier new roof in *ferrocemento* needed the radial beams of the capital to be stiffned in their central part.

The whole process resulted in a better performance of the roof which allows it to satisfy the current legal specification for snow load (according to the NTC 2008, the 'Norme Tecniche per le Costruzioni, January 2008, 125 Kg/m^2). The survey tested the existing structures also with respect to the fire resistance and to wind loads specified in NTC 2008 to discover that Nervi, with respect to the latter, actually tested the structures with an identical combination of loads used in the current normative, fifty years later.

In essence, the structural survey performed by PlannING in 2011 reveals that all the primary structures of the Palace of Labour are in good conditions (the only major intervention would be to reinforce some of the shorter radial beams due to the possibility of local buckling for a snow load exceeding 50Kg/m^2) and can be used for the forthcoming project.

Figure 14: The Palace of Labour, the original roof in steel, removed in 1963. [Courtesy of PlannING]

Figure 15: On the roof of the Burgo Paper Mill in 1961, Mantua. [BURGO]

4 Burgo Paper Mill, Mantua, 1961

The Burgo Paper Mill represented, as did many of Nervi's works, a challenge. In 1960, The Burgo Company was about to build a factory to accommodate new machinery for transforming wood pulp into newsprint. Such a process required an overall production length of 100m. The building had therefore to be considerably longer. Furthermore, any future expansion would require additional space in order to insert an identical machine adjacent and parallel to the original; which made the design even more challenging considering the need of a central space between the two machines in order to allow personnel to work and control the process. The whole area had to be free from any vertical structural elements for at least 150 m, which meant that, after consideration of all ancillary spaces and working areas, the whole structure had to be approximately 250 m long and 30 m wide without internal columns: a gigantic, empty box.
In the first, preliminary layout, Nervi explored the option of a structure composed of two 200 m long lowered arches in reinforced concrete. The excessive stress to and cost of the foundations prompted the consideration of a flat roof solution and, indeed, Nervi opted for this. However, the horizontal roof element could not be supported by any columns within the building and therefore it had to be suspended. The flat covering of a rectangular edifice such as this, to be achieved without the use of columns, is an apposite analogy to the structure of a suspended bridge, a structure Pier Luigi Nervi had already designed but not yet built; Indeed, it is interesting to note the structural similarities between the Burgo and Nervi's proposal for the bridge over the Sicilian channel [Cresciani, 2007].

Initially, Nervi's practice proposed two variations in terms of materials. The first was a building made entirely in reinforced concrete, the second combined reinforced concrete with steel elements. Both provided a flat roof suspended by means of four external supports. Again, economic considerations and concerns regarding the speed of construction ensured that the steel-concrete option prevailed over the purely reinforced concrete solution. It is worthy to note that at the beginning of the 1960s the price of steel was still higher compared to concrete, however, the convenience of using reinforced concrete also began to be less apparent as the necessary labour employed in this technology was considerably more expensive in the high wage society that Italy was becoming. This and other, more technical considerations (i.e. the reluctancy of Nervi to use prestressed concrete), might explain why, starting from this period, Nervi began to employ steel much more frequently as already seen in the Palace of Labour, in the structure analysed in this section and in the project for the Messina Bridge.
The Burgo Paper Mill solution is a straightforward project, a quality of Nervi's design approach, especially with regard to large scale buildings. It can be separated into three distinct systems (see Figure 16):

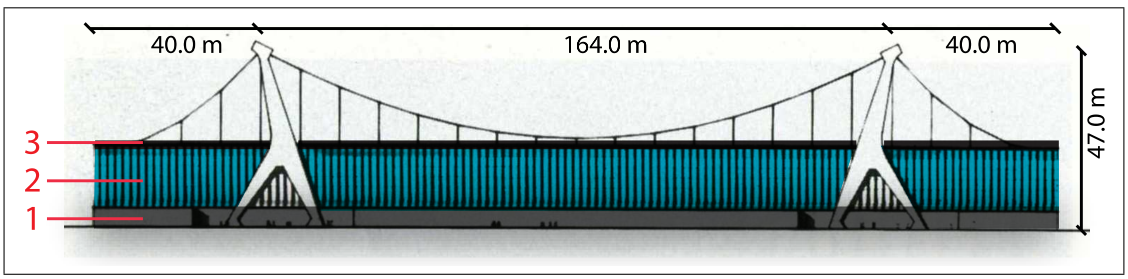


Figure 16: The Burgo Paper Mill, The main components and sizes. [MAXXI - MC]

- 1: The base - on two levels - which supports the continuous paper machine.
- 2: The steel-glass curtain walls which enclose the whole building.
- 3: The flat steel roof and its supportive, composite structure.

After establishing the construction site, the erection of the four pillars began in September 1961. The variable section of the pylons and their overall shape, as is usual in Nervi's structural elements, are suggested by the line of stresses transmitted by the suspended ceiling to the ground. The main problem for this particular case, and also a central point in Nervi's design process, was how to avoid the huge amount of carpentry required to assemble the wooden or metal cast forms for such a difficult shape and also their inevitable waste. These were typical building site issues for which Nervi proved to be an indefatigable innovator, here he applied a spectacularly simple but effective procedure. Initially, panels in reinforced concrete (7 cm thick) were carefully prefabricated in-situ at ground level. These were reinforced concrete self-supporting box moulds which were then filled according to the sequence of the large poured sections, to which they remained as an external 'skin': this solution was effective and avoided the wastage of materials. (see Figure 17).

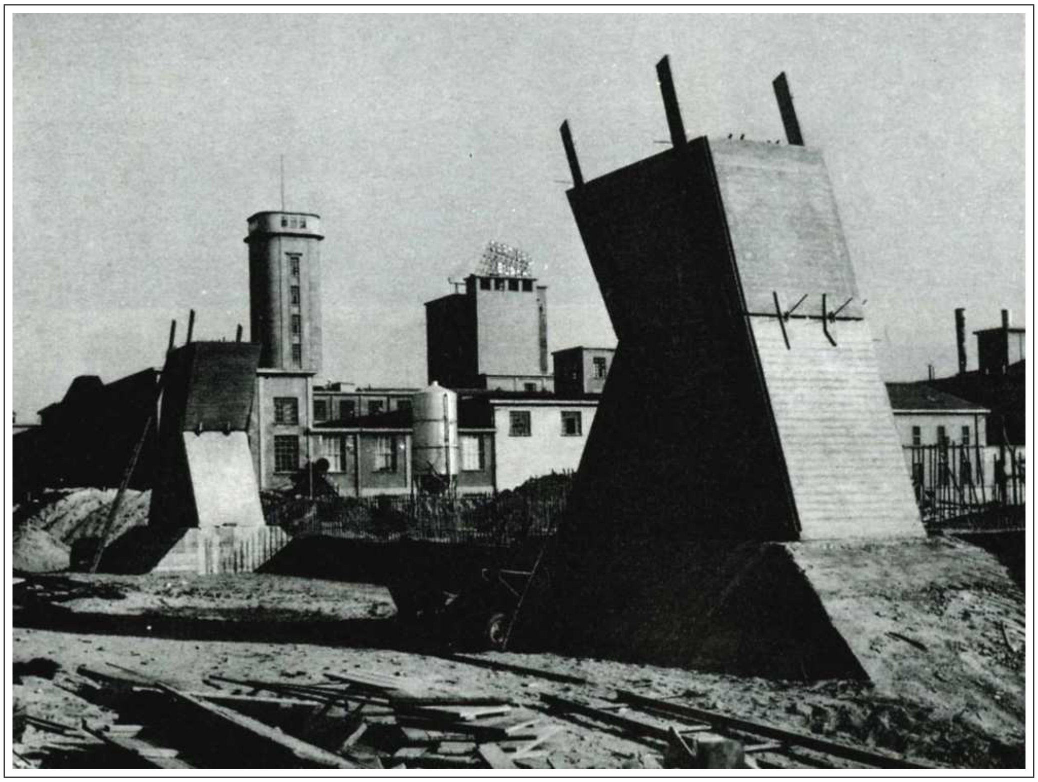
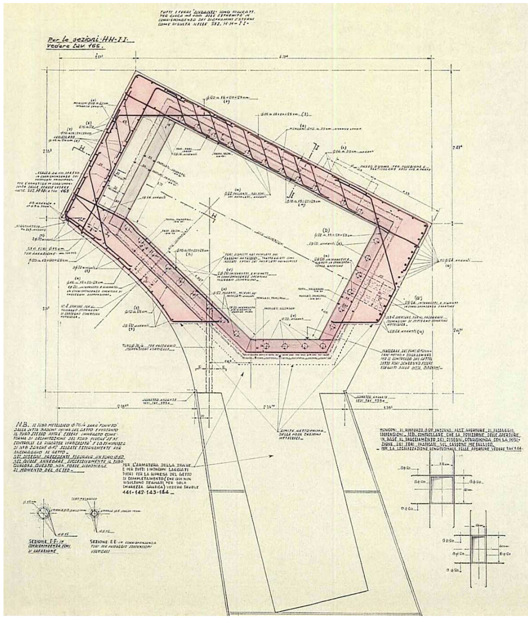


Figure 17: The Burgo Paper Mill, detail of the reinforced concrete support. [MAXXI]

Once the four supports were erected, the involvement of the Antonio Badoni Company was requested in order to build and install the suspended roofing in Spring 1962. The links between the steel roof and the external supports are four suspended chains which form, in the central part, a parabolic curve. This curve is actually fragmented in a series of independent rigid steel bars jointed (bolted) every 10 m. The connection between the chain and the reinforced concrete pylons is provided by four steel boxes placed within the cross beam at the summit of the four supports (see Figure 18). At intervals of 10 m, corresponding with the joints, 92 vertical rods of 45 mm diameter support the four lattice steel beams which act as the principal structure of the roof (see Figure 15); cross-beams ensure the overall stability of the roof, which has an overall thickness of 2.1 m. The Burgo Paper Mill represents the apex in Nervi's hybrid-works. The massive use of steel became here of the greatest structural relevance. Nervi was aware of this fact and arguably this is the reason why he called Gino Covre again after their recent collaboration at the Palace of Labour in Turin. Despite the design team was the same (Nervi-Covre), the project of the Burgo Factory differs considerably from the Palace of Labour: the former is a building clearly conceived from the 'outside' whereas the latter was developed from the 'inside'. This makes the Burgo a less recognisable work of Nervi's, who was a theorist of the 'from the inside to the outside' design process. The only part in which Nervi's hand is apparent in this work is probably the storage area below the paper machine, where he returned to the one of his favourite themes: the ribbed ceiling.



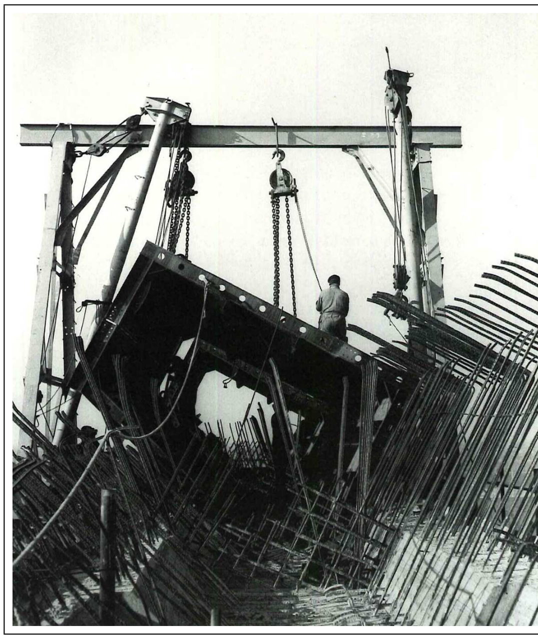


Figure 18: A cross section (in red the reinforcement around the steel box) and a photo of the positioning of the hybrid connection between the support and the chain, the steel box. [CSAC-BURGO]

Figure 19: The Burgo Paper Mill, on site. [MAXXI]

On the night of the 30 March 1974, a fire started in the Burgo Paper Mill severely damaging the continuous paper making machine. At that time Burgo produced almost the half of the Italian newspaper requirement. There were huge economic and social consequences of the fire but after the four external reinforced concrete supports and the steel roof were examined and found secure, Burgo repaired the machine and resumed production forthwith.

Figure 20: The Burgo Paper Mill after the fire in 1974. [BURGO]

Extended lead time for delivery of the glass for the external curtain-walls, forced the Eng. Martinego (Martinego was an assistant engineer at Burgo Paper Mill building site in 1963. At the time of the fire, in 1974, he had become chief engineer at Burgo's technical department). to alter Nervi's original design and opt for insulated metal panels which were locally manufactured and readily available.
These insulated panels sensibly improved the internal temperature of the factory which can raise up to 50° Celsius in Summer and enabled restoration of the factory in only 36 days. The steel supports were replaced in accordance with Nervi's original design, however the transparent glass was substituted in the south elevation by blue aluminium, which gave an improved thermal insulation and reduced solar gain. During a visit by one of the author in July 2006 the Head of HR at Burgo, stated that originally Nervi adopted the glass solution in order to create a pleasant environment for the workers who were able to 'see' their city. The so-called 'Transparent Factory' was also in the spirit of time in Italy, especially at that time of strong socialist culture.

The Burgo Paper Mill today is a wealthy company manufacturing only from recycled paper. As a company, Burgo is one of the major suppliers for some of the most important Italian newspapers such as *Il Corriere della Sera* and *Il Sole Ventiquattrore*. Its success as a company is also due to the iconic and, indeed, resilient headquarter in Mantua. The recovery from the big fire in 1974 was an evident test for the resilience of Nervi's building. The keeping of the original design (in terms of internal layout and structural components) showed how the initial project was still valuable eleven years after its completion and, indeed, judging from the current production of Burgo, still is.

Figure 21: The Burgo Paper Mill in August 2008 with the blue aluminium elements. [MC]

5 Conclusions

The George Washington Bridge Bus Station in New York, the Palace of Labour in Turin and the Burgo Paper Mill in Mantua are some of the challenging attempts to link structural and aesthetic issues within the 1960s' so-called 'Megastructures'. This trend, later developed and formalised by architects working around a new definition of urban environment such as Fumihiko Maki, Hans Hollein, Archigram, Chamberlain-Powell & Bon, Mario Fiorentino and Vittorio Gregotti, was pioneered by some engineers, traditionally employed in large buildings. One of them, perceived by many as an architect was Pier Luigi Nervi. In these three large structures the reference to the aesthetic of the *Machine* was quite apparent; all the structural joints are visible, the material are left exposed with no space for any ornament and their dimension made of them 'objects' within the urban fabric. Perhaps Nervi who met and worked with the Le Corbusier (who theorised around the concept *Machine à Habiter*) on the occasion of the project of the UNESCO headquarters in Paris in 1953, was influenced by the ideas of the Swiss Architect.
However, despite his functional and pragmatical design approach, in all of these construction is still possible to recognise the hand of Nervi. This can be seen, for example, in the shape of the columns or in the ribs of the ceilings; both were claimed to be shaped around the laws of Physics by Nervi, but his aesthetic intervention is clear. Indeed, in the case of the isostatic ribs for example, Nervi carefully selected a limited number of these isostatic lines (which are indeed a bundle of curved lines) and deliberately exposed them under the plane in which they actually flow (the slab itself). In doing this, and in many other occasions Nervi showed a clear interest for the form as such, although vaguely related to the Statics principles; examples are the variable shapes of the columns for some of his buildings, including those in the Bus Station and the Palace of Labour) Leaving aside the architectural significance of these three works, they remain perhaps Nervi's most complex challenges from a structural point of view. Moreover, as a series, these three structures are particularly interesting both because of their huge dimensions and in view of the massive use of steel for the Italian engineer famous for his reinforced concrete buildings.

The reasons for such a choice are different. In the case of the steel pins used at the base of the columns in the Bus Station in New York, this approach was taken because the steel joints allowed a certain movement due to the thermal expansion of the components of the roof. To choose to build the entire station in reinforced concrete would probably have meant to over-increase the rigidity of the system with the risk of structural cracks. The use of hybrid structures for the Italian works are motivated by time and costs issues. In the case of the Palace of Labour, this was essentially due to the strict construction time to cover an area of 25,000 m^2. Simply, a roof in reinforced concrete would have not met the deadline. Interestingly the idea to prefabricate the sixteen elements in steel was Nervi's son, Antonio. The Palace of Labour started the fruitful collaboration amongst Nervi, Gino Covre (the steel engineer) and the steel construction company Badoni. After the completion of the Palace in Turin, the same team, Nervi-Covre-Badoni, met again a few months later in the same year, 1961, for the Burgo Paper Mill in Mantua. Again

Nervi, after having discarded a preliminary project all in reinforced concrete in which the primary structure was constituted by two external lowered arches, opted for a flat steel suspended roof. The main reason was this time due to financial issues: the over-expensive foundations for the two reinforced concrete arches which were supposed to support the roof.

The ability of Nervi to master steel and reinforced concrete, especially in the case of the Italian buildings must be credited to the strict collaboration with Gino Covre, the structural designer, and to the Badoni Company for the realisation of the steel structures. Their structural achievement has been certified by the test of time: all these buildings are in very good condition from a structural point of view after fifty years. This resilience has been possible because of the robust but flexible design both in terms of structure and internal facilities. The attention to mechanical behaviours and formal details of structural elements (as in the case of the Bus Station), the logic behind the building technology and the appreciation for future use of their internal spaces are the key factors for their success. Furthermore, Nervi's rational and modular design allowed the possibility to perform regular maintenance within the structures (examples are the basement level to access the paper machine in the Burgo factory and the possibility to internally inspect the columns in the Palace in Turin).

When considering the reasons for their resilience, it is important to take into account the aesthetic plus-value which Nervi inserted in all his works, both in the more utilitarian works (e.g. the central column in the Bus Station, or the ribbed ceilings in the Burgo factory) and, of course in the public buildings (the gigantic cruciform column in the Palace of Labour); these were all 'signatures' of the Italian engineer, all elements which made them unmistakably Nervi's. This modifies the general evaluation of these buildings, for two reasons: On one hand the insertion of an aesthetic element within a factory or a station enriched their space and perception. Somehow it also represents the refusal of the designer to deliver 'just' a functional building composed by ordinary and standardised structural elements. On the other, because of this 'personal touch' which ultimately leads to a particular designer (in this case Nervi), these buildings are not isolated constructions but part of a series, episodes of a cycle, and therefore more valuable and worthy of maintenance (with exceptions). Their aesthetic values turned into a non-structural resilient element.

The current use of the three megastructures deserves a final consideration. Two out of the three buildings (the Bus Station in New York and the Paper Mill in Mantua) despite the heavy use and the fact that they both faced a drastic change of conditions (the huge increment of passengers for the Bus Station and the big fire of 1972 for the Paper mill) are still used daily for the same function they were designed for. The success and longevity of these three structures seem to be related to some design-factors which are summarised below.
Firstly, the continuity between the design process and the construction planning and management. This attitude came natural to Nervi, being the designer and the constructor of his works. However, even in the few cases in which he was not in charge for the construction (mostly abroad as in the case of the Bus Station in New York) he

provided a detailed and conspicuous number of drawings to the construction firm (some of the technical drawings are still visible at C.S.A.C at the University of Parma, Italy). Nervi's designs took in great consideration the constructional aspects of the building process. For example, in the Palace of Labour the glass panels between the steel roof were detailed large enough to place a tall crane during the building site. Or, as already cited in the text, the use of reinforced concrete formworks for the large support in the Burgo Paper mill (see Figure 17). The attention for the final product was for Nervi an integral part of the design process. Another reason for their success is the long span and grid-structures based design. Indeed this solution allows greater flexibility of internal use compared to buildings based on a continuos structure: the comparison presented earlier between Nervi's Bus Station and Saarinen's TWA Air Terminal inferred that this difference ultimately determined the fate of the two buildings. Indeed, to alter the (beautiful) spaces of Saarinen's Terminal is much more complex than the Nervi's Bus Station, as the recent projects seem to demonstrate.

Ironically, probably the most apparent example of grid based building designed by Nervi, the Palace of Labour, which demonstrated the capacity to multi-function, having already hosted the faculty of Economy of the Polytechnic of Turin and in recent times a temporary worship space for the Muslim community in Turin (see Figure 22) is the one which had suffered of a complete lack of interest.

Figure 22: End of Ramadan in Turin, 2009. [WWW - http://torino.blogosfere.it]

As mentioned, it is mainly due to the lack of maintenance which causes this building to be at the verge of abandonment (the lack of the mezzanine floor alone, although relevant, cannot justify the current state of this building). As a matter of fact, the Palace of Labour, despite being still structurally sound, is threatened to be demolished and is, at the time of writing, a forgotten work of Pier Luigi Nervi. Its wrapping into colourful screens on the occasion of the Winter Olympic Games in 2006 has been a dubious attempt to hide a national shame. More recently, both during the International exhibition on Nervi in Turin and in occasion of the Celebration of 150 years of Italy as a Nation in 2011, the palace was not used (surprisingly, as it would have been an appropriate site for both events: an exhibition hall designed by Nervi himself exactly 50 years ago for the centenary of Italy). The recent interest of two international companies represents a new hope for its metamorphosis, the chance to see this building functioning again in respect of both the new internal use and the old, but still, to quote Le Corbusier, *magnifique palais*.

Finally, the common element which links all the three buildings taken into consideration in this paper is their intrinsic quality. Both in terms of design and construction/materials, this is indeed a characteristics which spread across the entire production of Nervi, as an example, in 2003 the Norfolk Scope in Norfolk, Virginia - USA (opened in 1971), won the 'Test of Time Award' by the Virginia Society - American Institute of Architects - AIA.
Nervi focus on the 'total quality' was delivered through his design process from the initial concepts to the choice and quality of construction materials and even to a carefully planned building site management. In reality all the flow from initial sketches to the detailing of the components was perceived by Nervi as a continuum. The preliminary design took immediately into account the construction issues, it was not a design process divided in stages: usually, Architectural Project - Structural Design - Site Management. Especially in the Italian works where he was directly responsible for the construction (via his Company, The *Nervi & Bartoli*), the study of the construction process and the understanding of the different stages is a fascinating exercise in itself, a design in the design. Nervi's almost hand-made buildings developed a peculiar resilience to the aggression of time and unexpected events, as testified by the three works of this paper. It must be said though that these works belong to an era where although generally reinforced concrete was a cheap option compared to steel, Nervi's *Ferrocemento* and his reinforced concrete in general was of the highest quality and handled by trained builders (Nervi had a selected team of about twenty specialised builders who built almost all his works). Arguably this kind of design and build process is not repeatable these days, as the cost of specialised labour is very high and, to keep the cost contained, globalisation imposes more standardised structural solutions. The combination of all these elements: careful design, quality materials and attention to the construction process permitted to these buildings not only to age well but also to allow substantial refurbishment during the years, as the recent projects for the Bus Station and the Palace of Labour seems to indicate. This is the ultimate lesson that we can learn from Pier Luigi Nervi's: quality as the 'necessary condition' for resilience.

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CREDITS

The following structural surveys which have been used as references in this paper have been performed by the following practices:

For the **Palazzo del Lavoro**:

Studio PlannING (2011) [PLANNING]

For the **Cartiera Burgo** (all available at the Burgo Paper mill Archive [BURGO]):

Studio Arch. Galdi e Poltronieri - Studio Ing. A. Massarenti (1998)
Santino e Mario Beraud SPA (2000)
Agliardi Traslochi (2001)
Ing. C. Tottoli (2002)

The Structural surveys and related documents relative to the **George Washington Bus Terminal** have not been made available the NY Port Authority on the ground of Security issues.