Engineering Structures 49 (2013) 743–755

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Structural assessment of a modern heritage building

Stefano Sorace [a,*], Gloria Terenzi [b]

[a] Department of Civil Engineering and Architecture, University of Udine, Via delle Scienze 206, 33100 Udine, Italy
[b] Department of Civil and Environmental Engineering, University of Florence, Via S. Marta 3, 50139 Florence, Italy

ARTICLE INFO

Article history:
Received 23 January 2012
Revised 16 November 2012
Accepted 3 December 2012
Available online 30 January 2013

Keywords:
Structural assessment
Seismic assessment
Modern architectural heritage
Steel structures
R/C structures
Glazed façades
Linear analysis
Non-linear analysis
Seismic retrofit

ABSTRACT

A structural assessment study on "Palazzo del Lavoro" in Turin, a masterpiece by Pier Luigi Nervi, was carried out within a National Research Project dedicated to the analysis of modern heritage architecture in Italy. Based on the original design documentation collected through records, a complete finite element model of the building was generated. The study included detailed models of the main structural members, represented by monumental reinforced concrete columns, a mushroom-type steel roof and reinforced concrete ribbed gallery slabs, and the main non-structural systems, constituted by continuous gallery-to-roof glazed façades. The results of the linear and non-linear analyses developed by these models, aimed at fully understanding the original design concept of the various members, as well as at evaluating their current static and seismic safety conditions, are reported in this paper. The non-linear computations include a buckling analysis of the slender steel beams constituting the roof, and an "integral" seismic pushover analysis of the monumental columns. The results of the analyses highlight safe conditions and good performance objectives in general, but for some important exceptions. Indeed, the roof beams failed to pass the verifications on global and local panel flexural–torsional buckling, and some cantilever beams of the gallery floors showed poor shear resistance. Retrofit hypotheses are also formulated for these elements, so as to help the entire structure to comply with the requirements of the new Italian Technical Standards.

1. Introduction

Growing attention is currently being devoted to the study of modern architectural heritage, and particularly to the edifices built from the aftermath of the Second World War until the late 1960s. Indeed, that was a very prolific period for architecture and structural engineering, which produced significant theoretical and technical advancements in both fields. As a consequence, a global enhancement of the construction industry was reached, and a great number of exemplary masterpiece structures were designed and erected worldwide. This important stock of buildings is now over 50 years old, and may require important structural maintenance, repair and/or rehabilitation interventions. In view of this, careful evaluation and verification analysis strategies are needed to check the actual safety conditions of these skilled engineering works, and to plan possible retrofit solutions. At the same time, the development of assessment analyses of these outstanding buildings offers a profitable chance to improve the knowledge on the characteristics of their constituting materials, structural details and construction work procedures, as well as on the calculation methods originally adopted for their design. Moreover, these analyses can provide a better understanding of the original conception of the structures enquired, and evaluations about the attainment of the theoretical and technical objectives targeted in their design, which was carried out without the help of computer software. As a consequence, new contributions to the critical interpretation of the activity of the master structural designers of the 20th century can be derived, which are of potential interest also to researchers working in the field of history of modern architecture, as well as to scholars and engineers working in the field of structural assessment and rehabilitation.

An Italian masterpiece belonging to this stock named "Palazzo del Lavoro" in Turin, designed by the world-famous structural engineer Pier Luigi Nervi, is examined in this paper. The building, an external and an internal views of which in its current conditions are shown in Fig. 1, constituted the most important exhibition hall erected for the celebrations held in Turin for the first centenary of the Unity of Italy, back in 1961. The structure was designed in 1959 and completed by spring 1961, after 16 months only. This represented a really challenging enterprise, which can still arouse admiration, especially when the short construction times are compared to the imposing size of the building—160 × 160 m × m in plan—and considering the strict architectural and functional constraints imposed on the design, among which the 40 m-long free spans

* Corresponding author. Tel.: +39 432 558050; fax: +39 432 558052.
E-mail addresses: stefano.sorace@uniud.it (S. Sorace), terenzi@dicea.unifi.it (G. Terenzi).

0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.12.012

Fig. 1. External and internal views of the building in its current conditions.

required between each vertical structural element. The solution devised by Nervi consisted in a mesh of 16 reinforced concrete (R/C) monumental columns with variable sections along the height (that is, 20 m from ground to the base of the roof), constituting the most prominent example of Nervi's principle of "uniform resistance" [1] applied to vertical members in his works. Each column supports a steel mushroom-type roof panel with 16 radial beams spanning from the center. The panels are mutually separated by a 2 m-wide joint covered by a glass skylight. This solution, illustrated in the roof plan in Fig. 2, confers a suggestive monumental look to the building.

The remaining structural elements also remarkably contribute to the elegant and monumental appearance of the building. The most important elements are the R/C ribbed slabs constituting the two perimeter gallery floors. A plan of the upper floor is shown to the right of Fig. 2. The design solution for the slabs, traced out following the analytical equal-stress lines of their plate model, is also a typical feature of Nervi's style [2], and was applied to other famous structures of him. An original drawing of the formworks, specially designed to the purpose, and a view of the intrados of the slabs, with the steel roof in the background, are displayed in Fig. 3.

Among the secondary structural elements of the building, the continuous glazed façades, also visible in the images in Fig. 1, represent a much advanced technical solution for the time too, as they are an early application of the "curtain wall" concept, with remarkable global dimensions (free height equal to around 16 m, from the first gallery floor to the top, and total surface greater than 12,000 m^2).

This paper offers a synthesis of the structural and seismic assessment analyses carried out on the building, which make a part of the studies developed within a National Research Project financed by the Italian Ministry of Education, University and Research dedicated to innovative structural designs and the correlations between the leading engineering and architectural activities in Italy, during the 1950s and 1960s. The computational models generated for the analyses, as well as the verifications carried out for all members, were entirely based on the original design documentation collected through extensive record research, because field testing activities have never been developed on the building structure. However, the original documents, also including the certificates of the structural materials tested during the various stages of the construction works, are exhaustive enough to fix with certitude all input data for the numerical assessment enquiry.

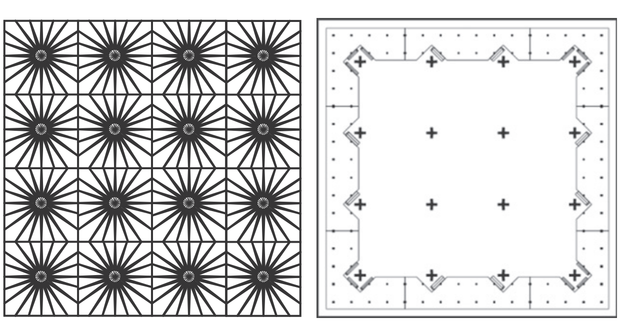

Fig. 2. Plans of the roof and the upper gallery.

The following aspects of the study are presented and discussed in the next sections: a modal analysis of the entire building; basic resistance and global/local buckling verifications of the steel roof beams, with comparisons of the results derived from the normative expressions of the critical stress of panels and the global lateral–torsional buckling resistance of beams with the corresponding finite element buckling computations; linear and non-linear seismic analyses of the R/C columns, the latter being carried out by an unconventional "integral" pushover approach, with the numerical model constituted by a full mesh of solid octahedral smeared cracking "concrete" elements with embedded steel reinforcements; the analysis and verification of the ribbed R/C gallery floors, including an evaluation of the correlation of their equal-stress line original conception to relevant finite element solutions; and the seismic analysis and evaluation of the glazed façades, developed by referring to non-structural performance limitations specially formulated to the purpose.

2. Modal analysis of the building

A modal analysis of the entire building was developed as a first step of the assessment enquiry, in order to evaluate its general dynamic characteristics [3]. The analysis was carried out by a finite element model generated by the SAP2000NL calculus program [4], where all the structural elements—mesh of light alloy profiles supporting the glazed façades and "pennon" beams constituting the vertical load bearing and bold bracing system of the façades included—were reproduced. Views of the model without the façade elements and the perimeter beams of the mushroom roof panels, and its complete layout, are shown in Fig. 4. Each monumental column is reproduced by 7 frame elements with different cross sections, as discussed in Section 4.1, and each radial beam of the roof panels by a single frame element with variable section. Ten frame elements are used to model each of the 20 steel frames constituting the circular drums situated on top of the columns, as described in detail in Section 3. The mesh of perimeter steel edge beams connecting the free extremities of the radial beams of the mushroom panels is made of 420 frame elements. In total, the assembly of the 16 R/C columns and relevant mushroom panels includes 3364 frame elements. The slabs of the two gallery floors are reproduced by a mesh of inner square and outer rectangular shell elements, with 1 m × 1 m and 1 m × 2 m sides, respectively, for a total of 12,240 elements for the two floors. The longitudinal,