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REHABILITATION OF AN HISTORICAL THEATRE IN ITALY

Abstract - Roberto Tomasi, Maria Ivana Pezzo & Maurizio Piazza - Rehabilitation of an historical theatre in Italy.

Rehabilitation interventions on historical building with peculiar end-uses, such as, for example, theatres, raise problems not easily solvable, especially when different architectural and structural functions must be ensured. The rehabilitation of the historical theatre R. Zandonai, built during the 18th century in Rovereto (Italy), is a good example of how to cope with this kind of problems and to try to solve them. The will of the Rovereto municipality to rehabilitate the theatre, in order to suit the modern scenic requirements, involved the need to heighten the fly tower of about 6 meter. The deep structural modification and the reference to different design loads, led to verify the resulting structures, according to the rules and standards currently in force in Italy, among them the new Italian seismic law (O.P.C.M. 3431). Moreover the local Department for the Cultural Heritage Protection bound the maintenance of the existing masonry walls. During a national research campaign on historical timber and masonry structures, the Authors proposed to the local Administration a structural solution for the fly tower, conceived and designed with the purpose both to satisfy the severe requirements of the new Italian seismic code, and to be a reversible structure, therefore respectful to the original historical building.

Key words: Dendrochonology, Theatre, Seismic analysis, Timber structures, Cultural Heritage.

Riassunto - Roberto Tomasi, Maria Ivana Pezzo & Maurizio Piazza - Intervento di riabilitazione di un teatro storico in Italia.

Gli interventi di ristrutturazione di edifici storici con destinazioni d'uso particolari, quali, ad esempio, i teatri, pongono delle problematiche di non facile soluzione, specialmente nei casi in cui è necessario garantire all'edificio diverse funzionalità di tipo architettonico, impiantistico e strutturale. Un esempio di come tale problematica è stata affrontata e risolta è il teatro roveretano Riccardo Zandonai sorto a partire dal 1700 prospiciente all'attuale corso Bettini. La volontà del comune di Rovereto di ristrutturare e riadattare il teatro a più moderne esigenze sceniche, ha comportato la necessità di sopraelevare di circa 6 m il vano della torre scenica. La profonda modifica strutturale imposta dall'amministrazione, e l'utilizzo di differenti valori dei carichi di progetto, ha comportato l'obbligo di adeguamento sismico della nuova struttura in accordo con le normative sismiche nazionali di recente introduzione (O.P.C.M. 3274 e norme successive). L'individuazione di una possibile soluzione strutturale è risultata ancora più complicata dalla richiesta di mantenimento delle murature storiche della torre scenica da parte della Soprintendenza per i Beni Architettonici. Nell'ambito di un progetto nazionale di ricerca sul comportamento delle storiche in zona sismica, attualmente in corso presso l'Università degli Studi di Trento, gli Autori hanno ipotizzato e posto all'attenzione dell'amministrazione comunale un possibile intervento di adeguamento sismico della torre scenica, volto sia a garantire il soddisfacimento dei più severi livelli di sicurezza richiesti dalla normativa nel caso di sopraelevazione degli edifici, sia ad assicurare, per quanto possibile, la possibilità di una completa reversibilità dell'intervento. Viste le scarse caratteristiche meccaniche offerte dalla muratura esistente, la tipologia di intervento, al fine di garantire l'adeguamento sismico, ha previsto l'inserimento di una struttura metallica con fondazioni autonome con la duplice funzione di assorbire i carichi orizzontali da sisma agenti sulla torre scenica e di sostenere i nuovi carichi della sopraelevazione, della nuova copertura e di tutti gli impianti scenici.

Parole chiave: Dendrocronologia, Teatro, Analisi sismica, Strutture di legno, Patrimonio culturale.

Introduction

Historical information

The construction of the Council Theatre «Riccardo Zandonai» in Rovereto (the first theatre to be built in the region of Trentino), began in 1783, according to the design of the Italian architect Filippo Maccari. In 1870-1871 the body against the main avenue was built, endowed with a foyer, a salon and the beautiful façade, still maintained; after 1892-1893, thanks to the donation of an adjacent area made by a private citizen, the stage was enlarged up to the present dimension. After the damage caused by the 1st world war, the Theatre was newly restored; recently the Rovereto municipality deliberated to refurbish the building in order to have a «full flying height» for the satisfaction of the modern setting needs. For this reason the Authors have been required to evaluate the possibility to heighten the fly tower up to 6 meter.

The fly tower: the masonry walls

A classical theatre, such as «teatro Zandonai», as well the modern theatres, is mainly composed by the *auditorium* (the part accommodating the audience during the performance), and the *stage*, on which performances happen. The part of the building where the stage is located, known as «fly tower», is usually composed by four high masonry walls around the stage, whose extension allow to «fly up» the scenery until is out of sight of the audience (for this reason, it is no possible to place any horizontal diaphragms against the walls, except for the grid, i.e the support structure, close to the top of the fly tower, on which the

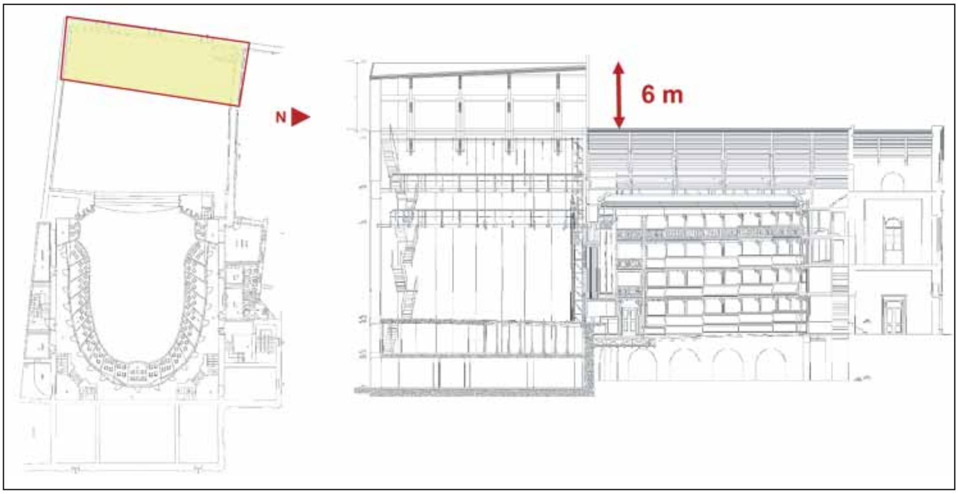

Fig. 1 - The floor plan of «Teatro Zandonai» (the 18th century enlargement is highlighted) and the original project for the heightening of fly tower.

pulleys of the flying system are supported). The wall between the stage and the audience has a big opening, the picture frame through which the audience sees the play (proscenium arch). The ideal fly tower should be more than twice the height of the proscenium arch: in this case, it is identified as a «full flying height» fly tower.

The structural typology of the fly tower is characterized by high walls, with some openings and without horizontal ties, with the exception of the wooden roofing with the support structure of the flying system (grid): from a structural point of view it can be seen like a «masonry tube», in which a significant opening is provided by the proscenium arch. Therefore the seismic resistance of the fly tower can be a critical problem for the designers.

The fly tower: the roof and the grid system

The structural typology used for the roof is the queen-post timber truss illustrated in Figure 3. In this typical configuration the compression top chord and two vertical posts form a central «square» to reduced the bending moment of the upper rafters (instead of the diagonal struts typical of the king-post truss). In this way it is possible to have more space under the roof for the scenery equipment. The secondary timber beams, which are supported by the lower chord of the truss, form the grid of the theatre.

Fig. 2 - The southern wall of the fly tower (note in the lower part free of plasterwork the discontinuity between the 18th century and 17th century walls); the western wall of the fly tower (note the openings in the wall, besides the three big arches not in view, in the lower part under the stage).

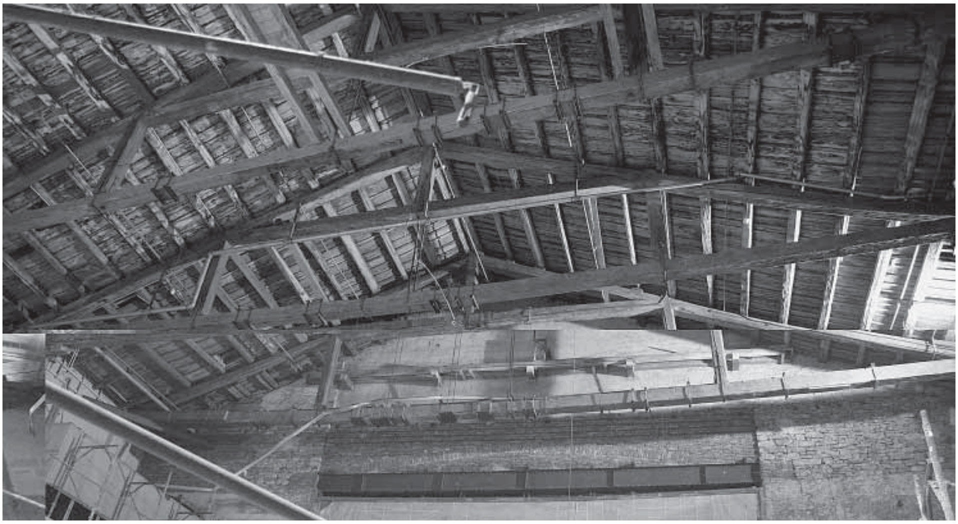

Fig. 3 - The queen-post timber truss.

The refurbishment requirement of the fly tower

In order to have a «full flying height» fly tower suitable to a modern organization of the stage, the municipality of Rovereto required to increase the fly tower of 6 meters, preserving the existing masonry walls.

Taking into account the state of conservation of the fly tower, determined through a thorough preliminary survey on masonry and timber structures, and considering the need to accomplish the high safety level required for seismic zone, the Authors suggested a structural solution respectful to the original historical building. Is worth noting that, in case of heightening of existing building, the Italian Standard requires the safety level of new constructions.

Survey of the masonry walls and timber structures of the fly tower

A preliminary survey of masonry walls has been performed, in order to evaluate the capacity of existing structures to resist to an increase of vertical and horizontal loads (wind and seismic action). In different zones of the walls the plasterwork has been taken out, to permit a visual examination: in the northern and southern walls the lack of ties between the 17th century and the 18th century masonry has been revealed. For this reason, some preliminary tests on the masonry walls have been suggested by the Authors, in order to obtain fundamental knowledge on the mechanical characteristics of existing structures.

Furthermore a dendochronology analysis has been performed on timber elements of the roof structure in order to collocate in time the last intervention on fly tower. The dating of the roof is essential to validate the consistency of the historical frame carried out through an archive research.

Diagnostic analysis of the masonry walls

Some flat jack tests performed at the foundation level of the perimetrical walls of the fly tower have clearly demonstrated the inadequate mechanical properties of the masonry, with low stiffness and strength values in the northern and southern walls, and a high stress level in the western wall, for the presence of three big arches at the ground level (Fig. 1 and Fig. 2).

In Table 1 the main results of the experimental tests performed on masonry are reported.

	Stress level	Young's modulus	Elastic threshold	Strength
	σ (MPa)	E (MPa)	σ_y (MPa)	σ_R (MPa)a
Northern wall	0,05÷0,09	309÷813	1÷1,2	1,6÷2,20
Western wall	0,09÷2,09	72÷8650	0,2÷2,2	0,80÷2,20
Southern wall	0,04÷0,63	122÷4000	0,6÷1,4	0,8÷1,2

Tab. 1 : Mechanical properties of masonry of the fly tower (minimum and maximum values).

The state of conservation of the masonry was inadequate for the existing walls to support the lateral and vertical load due to the modern scenic require-

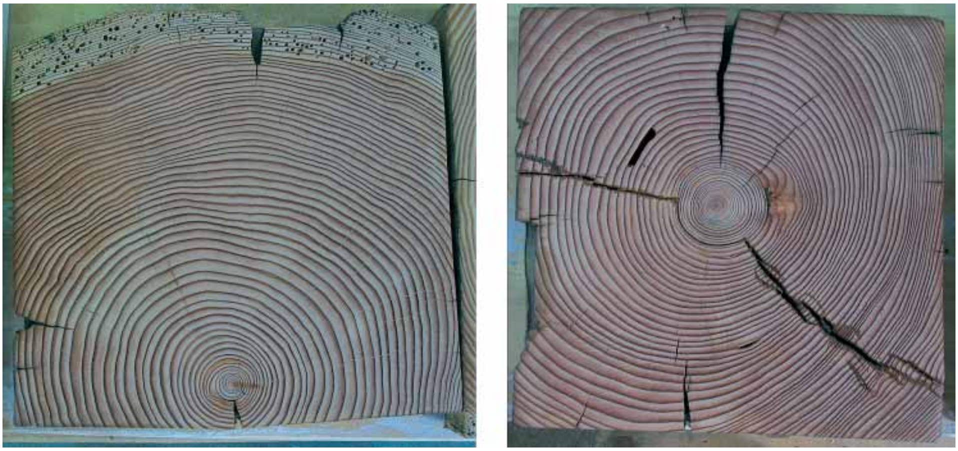

Fig. 4 - Wooden slice ZAN 1 and ZAN 5 of timber truss. The wood specie is Larch, which is traditionally considered durable (the insects attack is limited to the sapwood).

ments. In fact, the low values of mechanical properties, to be ascribed mainly to the insufficient quality of the mortar, determine the inadequacy of the original masonry to accept higher loads.

Dendochronology analysis on timber structures

In the course of the refurbishment of the stage tower of the Theater Zandonai of Rovereto the third truss from the proscenium arch (see Figg. 1, 2 and 3) was dismantled and delivered to the Materials and Structural Testing Laboratory of University of Trento, in order to carry out a series of studies. From this truss 6 slices were withdrawn and prepared by the technical assistant Alfredo Pojer: the surface of the specimens has been adequately smoothed to make visible the ring sequence.

Afterward the samples were submitted to Laboratory of Dendrochronology of the Museo Civico di Rovereto for the determination of the wooden species and for the dating. For the dendrochronological study the program TSAP (Time Series Analysis and Presentation) has been used. The measuring and the dating were made by Dr. Maria Ivana Pezzo, while the determination of the species was carried out by the Dr. Stefano Marconi.

Description of the samples

ZAN - 1 (A)

Slice from the lower chord of the truss

Rings = 74
Species = larch (*Larix decidua* Miller)
Dating of the last measurable ring = **1903**
Observations:
The sample presents a ring sequence that includes the pith and 18 rings of sapwood. The sample is in excellent conditions and the insects attack is limited to the sapwood.

ZAN - 2 (B)
Slice from the bracket of the truss
Rings = 60
Species = larch (*Larix decidua* Miller)
Dating of the last measurable ring = **1896**
Observations:
The sample presents a ring sequence that includes the pith and 12 rings of sapwood.
The sample is in excellent conditions and the attack of insects is limited to the sapwood.

ZAN - 3 (C)
Slice from the king post of the truss
Rings = 55
Species = larch (*Larix decidua* Miller)
Dating of the last measurable ring = **1895**
Observations:
The sample presents a ring sequence that includes the pith and 12 rings of sapwood. The sample presents only few short shrinkage cracks but it is suitable to be analyzed. The attack of insects is limited to the sapwood.

ZAN - 4 (D)
Slice from the king post of the truss
Rings = 65
Species = larch (*Larix decidua* Miller)
Dating of the last measurable ring = **1894**
Observations
The sample presents a moderate growth with the pith and 3 rings of sapwood.

ZAN - 5 (E)
Slice from the lower chord of the truss
Rings = 91
Species = larch (*Larix decidua* Miller)
Dating of the last measurable ring = **1866**
Observations:
The ring sequence presents a rather irregular growth; the pith is present, the outside rings are missed.

ZAN - 6 (F)
Slice from the bracket of the truss
Rings = 84
Species = larch (*Larix decidua* Miller)
Dating of the measurable ring = **1894**
Observations
The sample presents a ring sequence that includes the pith and 11 rings of sapwood.

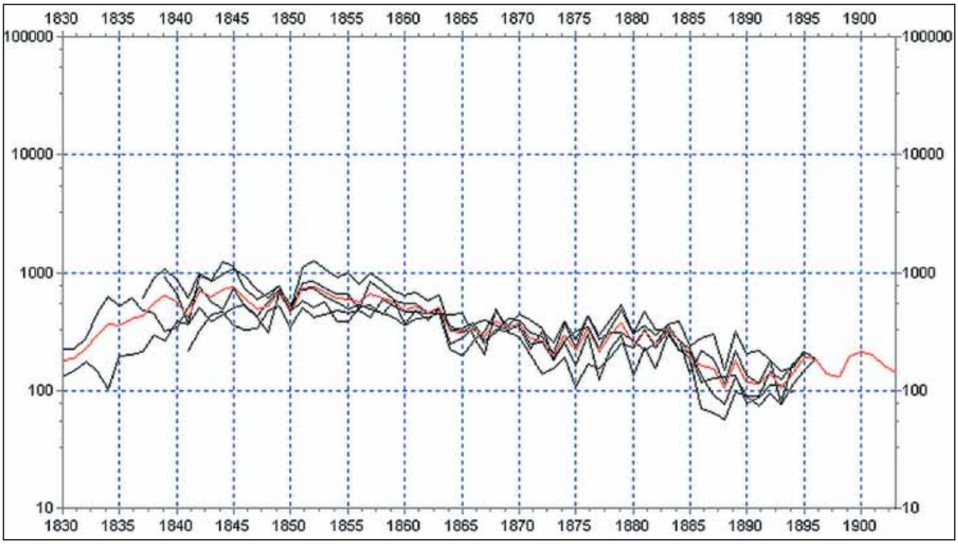

Fig. 5 - Graphs of the wooden samples with the years of the first and the last preserved ring.

Dating

The samples from the truss of the Theater Zandonai of Rovereto supplied a clear indication of the *terminus post quem* to date the construction and the arrangement of the same truss. With 6 champions a short chronology of 74 years was built whose last ring goes back to 1903. The date is consistent with historical frame previously described.

The samples are from plants of a same species: larch (*Larix decidua Miller*). Except for the sample ZAN-5, all the other samples present rings of sapwood. This is to indicate the fact that the beams were used few years after having been cut.

Analysis of the global stability of the fly tower

A very important aspect for the structural rehabilitation of the theatre R. Zandonai is the analysis of the structural performance of the fly tower under lateral loads, like wind and seismic actions. In fact, in order to better understand the behaviour of the structure, it is not sufficient to analyze the strength of the masonry walls (*local stability*); the evaluation of the structural resistance under horizontal loads (*global stability*) is a very important and complicated aspect and it implies that the building should behave like a three-dimensional wall-box with very good connections between the different structural elements.

The structural typology of the fly tower results very sensitive to the effects of the seismic action, that depends on the distribution both of the masses and of the structural elements. The height and the width of the walls (15 meters in height and 19 meters in width) with the absence of any horizontal bracing, the big opening for the proscenium arch, the mass distribution concentrated only over the flying system (grid), the poor toothing-stone between perpendicular walls represent a critical problem for the seismic resistance of the fly tower. On this basis, only an innovative solution can solve the problem of the structural rehabilitation of the theatre, in which both structural, architectural and scenographichal aspects could converge.

A steel skeleton

In Fig. 6 and Fig. 7, the solution proposed by the Authors is illustrated for: i) global reinforcement of the fly tower under horizontal action, and ii) support of the additional vertical loads of the new roof and timber - grid. The supporting structure, performing like a steel skeleton for the masonry, is reversible, taking into account the possibility to dismantle it and to return to the original configuration. The vertical steel columns are more as possible respectful of the architectural plan and have their own foundations.

In the structural conception a special attention has been dedicated in order to take advantage of all the architectural elements for structural purpose. The two levels of *small balcony* around the fly towers, which are functional for the backstage operations, allow to have an horizontal bracing of the steel structure, with regard to the torsional behaviour. For the same reason the *grid*, if adequately braced, can be considered as an horizontal rigid diaphragm for the fly tower. Even the steel vertical truss-structure supporting the *fireproof safety curtain* (which can be dropped to separate the audience from the stage in case of fire), is included in the skeleton designed as an earthquake resistant structure (Fig. 7).

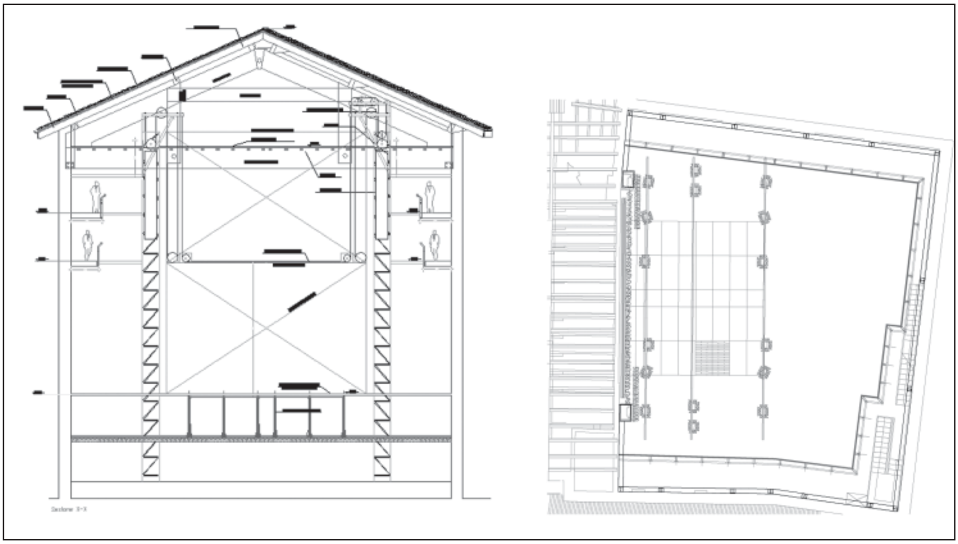

Fig. 6 - Section of the original project with the queen post timber truss and the steel vertical truss-structures (left); the floor plan of the earthquake resistance steel structure proposed by the Authors for the fly tower (right).

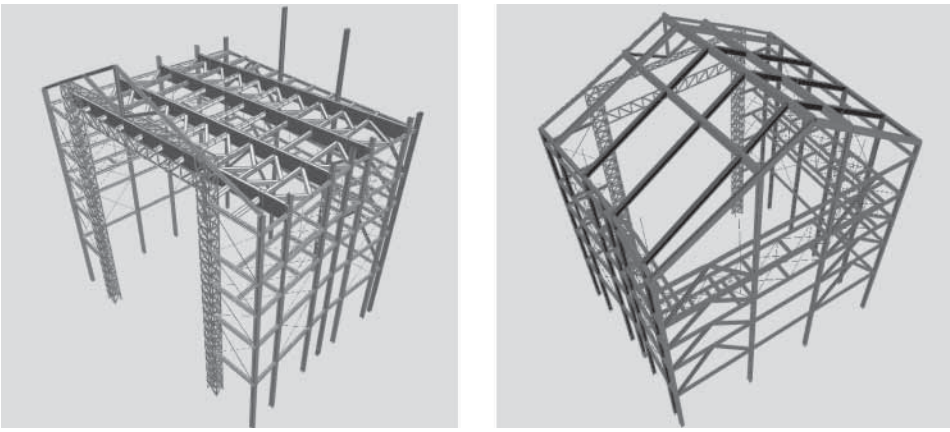

Fig. 7 - Three dimensional views of the earthquake resistant structure with the grid timber structures (left) and the roof timber structures (right).

Structural solutions for the roof and for the grid

The original project aimed to maintain the queen post truss geometry for the roof, following the conservative restoration principles. Unfortunately the high level of the loads and the particular geometry of the joint between the rafter and the tie beam (see Figure 6 left) cause a state of stress inconsistent with the truss geometry. Therefore a solution has been proposed in order to separate the roof structure from the grid structures (see Figure 7 right).

Masonry reinforcement

Due to the poor quality of the masonry, the Authors suggested to execute masonry reinforcement interventions, in order to consolidate the existing walls. Some reinforcement techniques have been proposed, such as mortar injection for the lowest levels of the walls and polymers mesh reinforced plasterwork.

Design and verification of the structure under seismic actions

The design forces acting on the structural members under static and seismic load combinations have been obtained by means of a multimodal dynamic analysis with response spectrum, assuming the structure as non-dissipative (behavior factor *q* equal to 1,5).

All the structural elements (steel skeleton, the two levels of small balcony around the fly towers, the timber grid, the masonry walls) have been implemented in the numerical finite elements model developed with the non-linear SAP2000 code, considering the mechanical and geometrical properties of the steel, timber and masonry structures. The boundary conditions adopted for the model took into account the actual interactions between steel and masonry structures and between the fly tower and the other structural parts of the theater.

The structure has been designed and verified in such a way that the No-collapse requirement (ULS) and Damage limitation requirement (SLS) are met, with an adequate degree of reliability. The structure as a whole has been checked to ensure that both overturning and sliding stability have been taken into account. Moreover, it has been verified that both the foundation elements and the foundation soil are able to resist the new actions without significant permanent deformations. All structural elements, including connections and the relevant non-structural elements, have been designed in order to satisfy the Italian standard (O.P.C.M. 3431, 2005) and Eurocode documents (EC3, 2005; EC5, 2004 and EC8; 2004).

Conclusions

In order to reach the request of Municipality of Rovereto, an earthquake resistant structure has been designed with the purpose to refurbish the fly tower of the historical theatre R. Zandonai, in order to suit it to modern scenic requirements. The typology of the fly tower, from a structural point of view, can be seen like a «masonry tube», endowed with significant openings, and therefore unsuitable to adequately perform under seismic actions.

The preliminary tests on masonry walls demonstrated the poor mechanical properties of the material, and consequently the impossibility to support the lateral loads due to seismic actions and vertical loads given by the modern scenic requirements. On this basis an innovative solution has been proposed, consisting in a steel skeleton that should provide a global reinforcement of the fly tower.

A finite element three-dimensional (3D) model, implemented through the non-linear SAP2000 code, has been developed, where all the structural elements have been considered, also taking into account the experimental evidences for the mechanical properties of the material. All the structural elements have been designed and verified in order to satisfy the requirements given in Italian and European standards.

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