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MODAL IDENTIFICATION AND MODEL UPDATING OF AN INNOVATIVE AUTOMATIC SELF-SUPPORTING TIMBER WAREHOUSE: THE CASE STUDY OF ROTHOBLAAS HEADQUARTERS EXPANSION

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ABSTRACT: Automatic Self-Supporting Timber Warehouse (ASSTW) is an innovative and sustainable structural system with a modal response strongly influenced by both the actual mechanical behaviour of structural elements and the load conditions. The structural analysis of ASSTW is typically carried out using numerical models calibrated referring to codified materials and connection properties. The reliability of the numerical simulations, used in the design phase, can be verified through modal identification on-site tests that also allow for a subsequent model update. This paper reports the main results of the modal identification on-site campaign, conducted by CIRI-EC laboratory of University of Bologna, of the new Rotho Blaas S.r.l. ASSTW in two different load conditions: unloaded warehouse with only the mass of the structural elements and partially loaded warehouse with eccentric mass. The subsequent model update phase is presented carrying out the most significant mechanical parameters to grasp the actual modal response of the structure.

KEYWORDS: Modal identification, Model updating, Self-Supporting Wooden warehouse, Timber structures.

1 INTRODUCTION

In recent years the use of wooden structural systems is increasingly widespread also for special building types typically made only of steel. Automatic self-supporting warehouse is a structural typology that can be profitably built using engineered wood-based products (EWP) allowing to optimize at the meantime: costs, sustainability aspects, aesthetic value and structural efficiency. This is due to the improved performances of the EWP and connection systems and to the use of advanced structural analysis and design methods [1].

Design of an Automatic Self-Supporting Timber Warehouse (ASSTW) can be developed in accordance with the current standard for the static and seismic actions [2,3] and for the fire safety [4].

The structural analysis of a ASSTW can be profitably carried out using numerical models calibrated referring to codified materials and connection properties [5]. Numerical models must be able to faithfully reproduce the static and dynamic response of structural systems characterized by significant plan dimensions and height. Modal identification on-site test represents a robust strategy for defining the actual building response and for the verification of the reliability of numerical simulations and for the subsequent model updating [6].

In this work, the case study of Rotho Blaas headquarters expansion, depicted in Figure 1, is used to describe both the innovative construction solution for ASSTW and the modal identification on-site tests adopted for the definition of modal response and for the model updating. Rotho Blaas ASSTW is one of the tallest wood warehouses in Europe, but also among the first to be fully automated, using conveyers, lifts and sliding shelving to speed and simplify the process (Figure 1-b).

Figure 1: *View of Rotho Blaas ASSTW: a) external view, b) internal view with automatic lifting system.*

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2 DESCRIPTION OF ASSTW CASE STUDY

The ASSTW consists of a multifunctional timber skeleton: the shelving is part of the constructive system of the building together with the roofing and plugging elements. The shelves, which transfer the weights of the stored goods to the ground, also act as a load-bearing structure for the warehouse itself.

The Rotho Blaas ASSTW case study is schematically represented in Figure 2 and consists of three distinct volumes as follows:

- a main volume (1), to be used as an automatic warehouse, measuring 75 x 40 meters and 21 meters high;
- secondary volume (2), which will contain the goods entrance;
- an accessory volume (3), which will connect the new warehouse with the current one (4).

In the following the focus will be only on the main body of ASSTW (1).

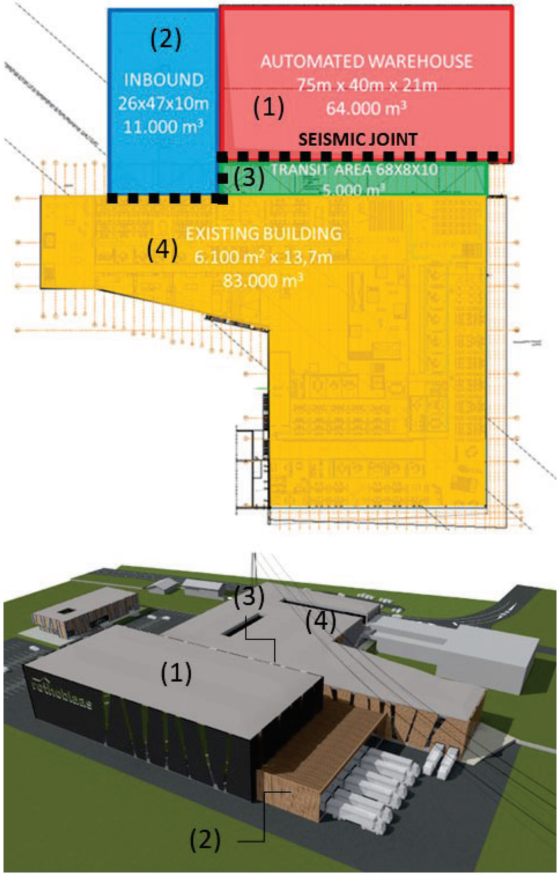

Figure 2: 3D scheme of the Rotho Blaas ASSTW

3 MULTI-CRITERIA DESIGN

The architectural and compositional design recall the choices made for the existing buildings, which are characterized by large windows and a significant presence of timber, used both for structures and for flooring and coverings. Fire safety requirements, however, have imposed different solutions for the automatic warehouse which is almost entirely covered in aluminium, while the current sloping windows will be replaced by high-quality three-dimensional coatings made of larch strips, recalling the internal timber structures (Figure 3).

Figure 3: External prospect of Rotho Blaas ASSTW

As regard the structural layout, the Rotho Blaas ASSTW has a wooden skeleton (Glulam shelves and beams) enclosed by a CLT skin (roof and perimetral walls). More in details, the ASSTW is braced with two independent systems in the two directions (Figure 4).

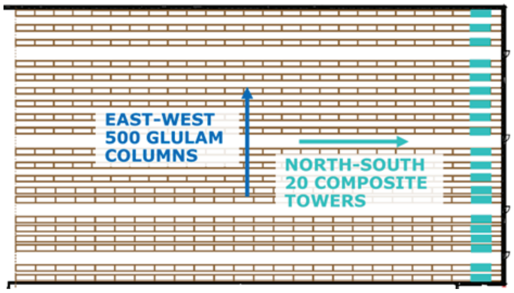

Figure 4: Scheme of the bracing system for the north-south and East-West directions

In the north-south direction (long side) twenty bracing towers consisting of a composite box section in LVL and glulam have been used (Figure 5). All the shelving is connected to the bracing towers in order to transfer the seismic forces onto them.

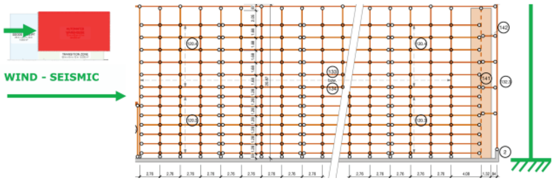

Figure 5: Scheme of north-south bracing system.

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The composite box towers are embedded in the foundation by means of plates pre-inserted in the poured concrete (Figure 6).

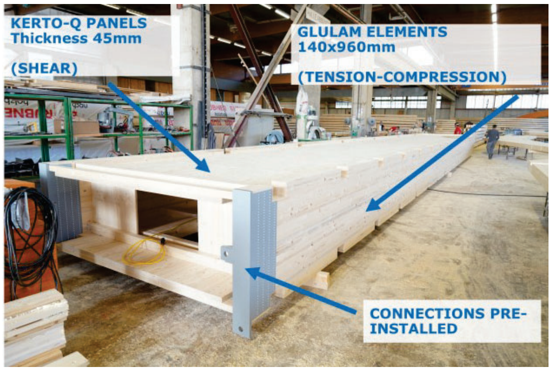


Figure 6: *View of the precast composite bracing tower during the manufacturing phase.*

In the east-west direction, the bracing system is constituted by the shelving itself (Figure 7), with the five hundred cantilevers interlocked at the base and connected to each other only at the roof (Figure 8). The roof is constituted by a framework of glulam beams and CLT panels, which create a limitedly deformable diaphragm.

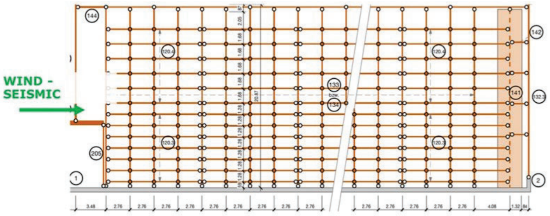


Figure 7: *Scheme of east-west bracing system.*

Figure 8: *Detail of the Glulam cantilever during the manufacturing phase.*

The main critical point of these structures is the deformability towards wind actions, which must be limited in order to allow the machines functionality. In fact, due to operational requirements, the project includes a displacement at the top (at a height of 20 meters) of only 19 millimetres in the east-west direction and 12 in the north-south direction (Figure 9).

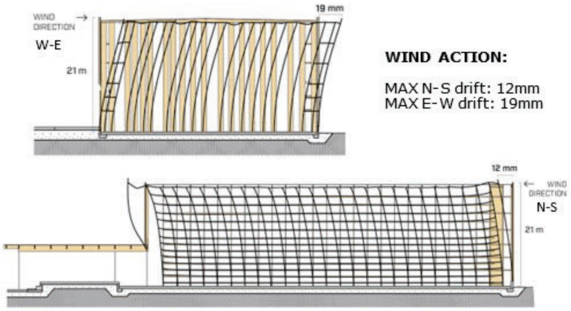


Figure 9: *Deformed shape and max drift of the ASSTW under the horizontal wind action in W-E and N-S directions.*

The ASSTW, is located in northern Italy, in an area classified as low seismic hazard. However, given the height of the building and the isostatic construction system, the seismic design was particularly challenging. Therefore, a non-dissipative design was chosen, with a structure factor of 1.5 according to EN 1998-1 [3]. Since the building adheres to the existing building, it was necessary to create a seismic joint to decouple the dynamic behaviour between old and new structures (Figure 2).

Regarding to the fire safety, a R30 resistance for all the structures of the warehouse was adopted. It is worth nothing that, it is relatively easy to achieve the R30 requirement with properly designed timber structures. The R30 requirement also shifted the design of connections to solutions without exposed plates, using innovative timber-based materials instead of steel plates. Solutions with intumescent coatings to protect the steel were adopted where this was deemed unfeasible.

A further relevant aspect of warehouse design concerns the in-situ construction phases. In particular, the installation must ensure the stability of the structural system by exploiting the bracing elements of the system itself. Figure 10 shows some explanatory photos of the assembly sequence.

Figure 10: *In situ assembly phases – photo gallery.*

4 ON-SITE MODAL IDENTIFICATION

Goals of the on-site modal identification are:

- Characterization of the modal response of the warehouse in the initial post-construction configuration in order to verify over time, by means of periodic repetition of the dynamic tests, any changes in the modal response and any system performance decay.

- Validation of the FE numerical model used for the seismic design and subsequent model updating for refined analyses to predict the warehouse response under different mass distribution.
- Identification of the interaction between the contiguous buildings and the stiffening effect of the external facade system.

On site modal identification tests were conducted by CIRI-EC laboratory of University of Bologna.

The modal identification on-site tests were performed installing 12 accelerometers (acc.1-12 in Figure 11) to measure the absolute accelerations of the structure along the longitudinal and transversal direction. Signal acquisitions were carried out when the ASSTW was subject to natural vibrations induced by wind or external vibrations [6].

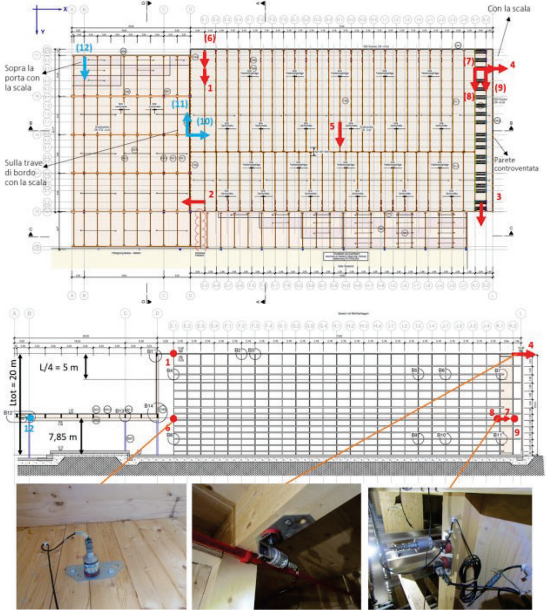


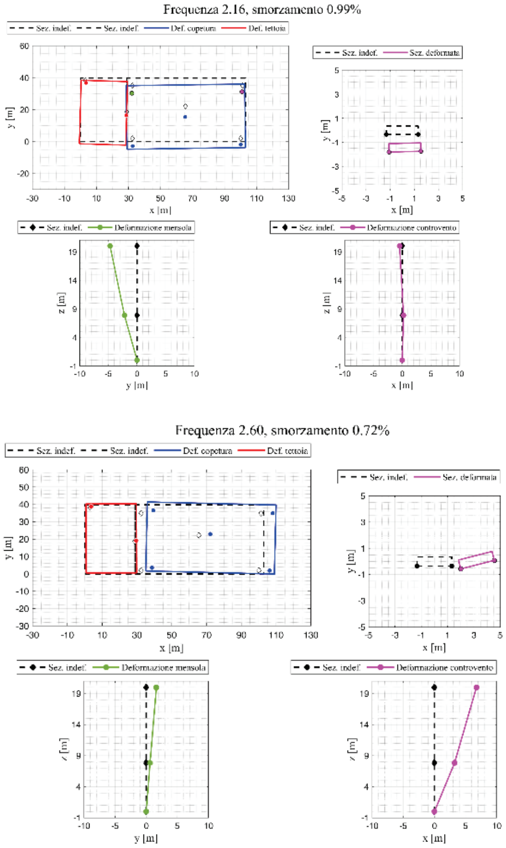
Figure 11: *Plan view and longitudianl section of the structural timber skeleton with indicated the localization of accelerometers employed for the modal identification.*

Two different load conditions were investigated: unloaded warehouse with only the mass of the structural elements and partially loaded warehouse with eccentric mass.

The Enhanced Frequency Domain Decomposition (EFDD) method [7,8] was used to process the on-site acceleration acquisitions obtaining an estimation of eigen frequencies and modal deformations of the Rotho Blaas ASSTW. The method derived from the on-site acceleration acquisition the power spectral density and subsequently the vibration eigenfrequency and modal deformed shape.

Results of modal identification are depicted, in terms of deformed shapes associated to the two principal eigen frequencies, in Figure 12 for the unloaded configuration and in Figure 13 for the partially loaded warehouse with eccentric mass.

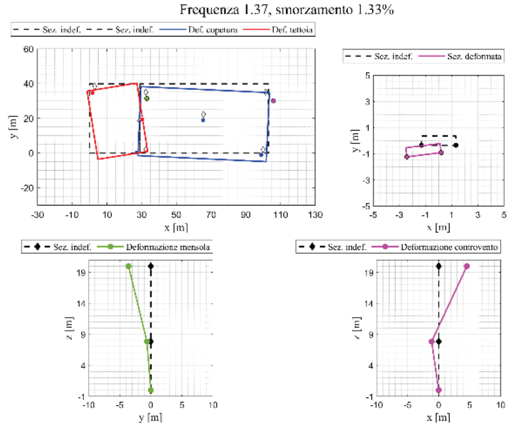
Results demonstrate that the additional eccentric mass induces a variation in the principal eigen frequency and correspondent modal shapes. In detail it was observed a reduction of 1st eigen frequency value and modification of the modal response from translational to torsional. Moreover, a reduction of 2nd eigen frequency value was observed without significant modification of the modal response (translational in longitudinal direction).



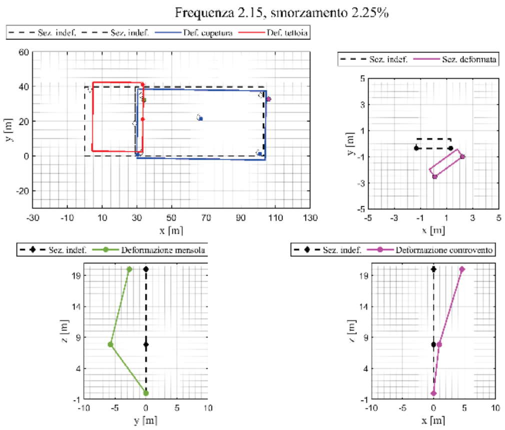
a)

b)

Figure 12: *Unloaded configuration - deformed shape associated to the: a) 1st mode; b) 2nd mode.*



a)



b)

Figure 13: *Partially loaded configuration - deformed shape associated to the: a) 1st mode; b) 2nd mode.*

5 MODEL UPDATING

The modal analyses of the ASSTW, in the different loading configuration, was carried out implementing a detailed Finite Element Model (FEM) considering both the main bracing elements and the stiffening contribution provided by the external massive walls made of CLT panels. The shelves were modelled as cantilever beam elements as well as the bracing towers while plate elements were used for the CLT outer skin panel and for the roof diaphragm. (Figure 14).

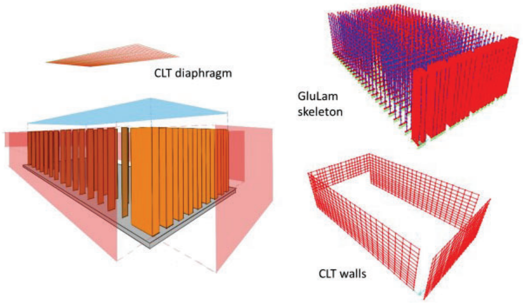
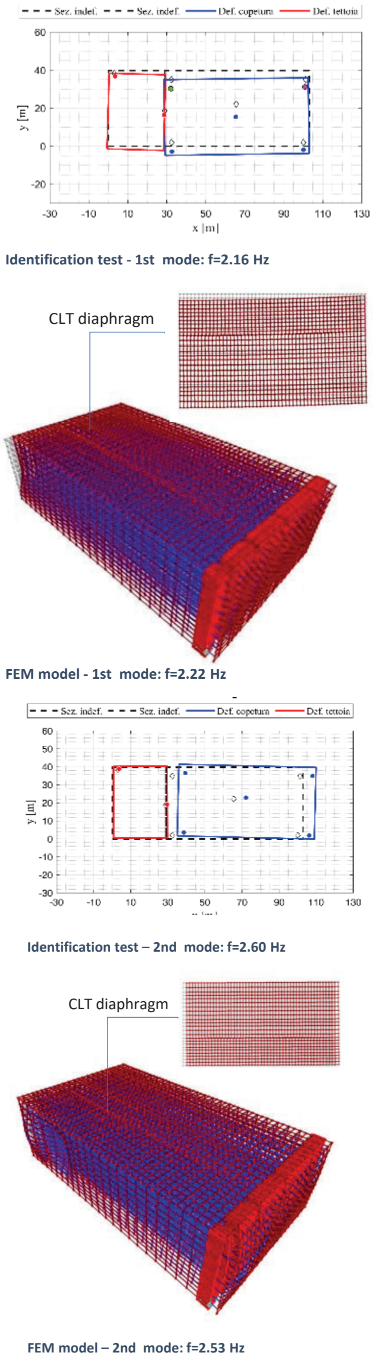


Figure 14: *Scheme of FE model components used for the model updating.*

Different modelling approaches [9] were used to predict the actual response of the warehouse: considering rigid or semi-rigid connections of the shelves and bracing tower; rigid or deformable diaphragm; considering all CLT walls, north and east wall, and no walls [10].

Results form analyses performed considering different modelling hypothesis demonstrate that, for the unloaded configuration, the most accurate model is the one with: fixed shelves and bracing towers; all external CLT walls and deformable diaphragm. This model ensures a good correspondence between FE analyses and identification results for both eigen frequency and modal shape. A comparison between updated FEM results and on-site identification test outputs is reported in Figure 15 for the 1st and 2nd vibration modes.



a)

b)

Figure 15: *Partially loaded configuration – comparison between FEM and on-site identification results: a) 1st mode; b) 2nd mode.*

Results substantially demonstrate that for small amplitude vibration (i.e. white noise) all the structural component are activated with a very stiff behavior. ***The*** FEM was also used to investigate the effect of the external CLT walls on the global response of the systems. It was observed that considering only the transversal walls the 1st eigen frequency is reduced from 2.22Hz to 1.46Hz. Otherwise, the system without CLT walls shows a 1st eigen frequency equal to 1.41Hz.

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Comparative analyses demonstrate that external walls stiffen the system but do not modify the 1st deformed shape of the warehouse that is governed by the bracing tower. The in-plane stiffness of the roof diaphragm was also investigated. Results highlight that whit a rigid diaphragm the 1st eigen frequency is equal to 2.58 Hz and therefore greater than the reference one (deformable diaphragm - 2.22 Hz). It means that, despite the rigid panel to panel joint, the significant in plant dimension of the floor diaphragm requires a deformable modelling approach.Finally, the updated FEM was used to predict the response of the structure in different load cases: empty; 30% eccentrically loaded; 100% loaded. Figure 16 reports the results from the FE analyses.

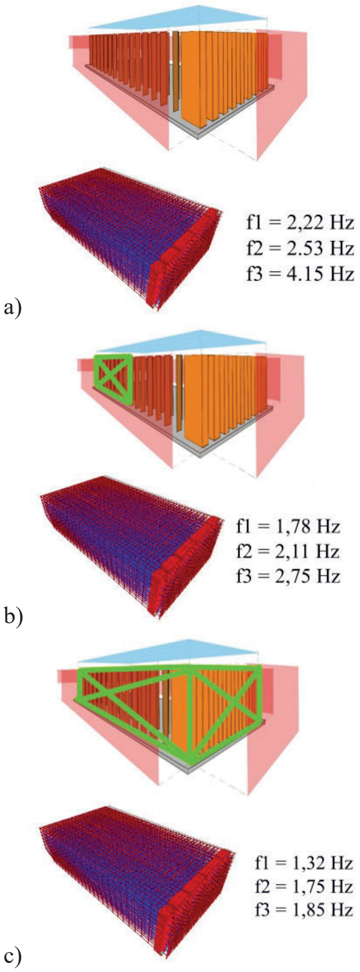

Figure 16: *principal eigen frequencies carried out with FEM analyses for different loading condition of the warehouse: a) empty; b) 30% eccentrically loaded and c) 100% loaded.*

It can be noted that for the 30% eccentrically loaded configuration, results demonstrate a good agreement with outcomes from on-site identification tests. Moreover, a significant reduction of the 1st eigenfrequency is observed for the 100% loaded configuration.

CONCLUSIONS

This work demonstrates the possibility to realize efficient and safe automatic self-supporting warehouse using EWP and high-performance connection elements. Modal response of such special timber structure can be profitably verified using on-site model identification tests. The FEM can be therefore updated using results of on-site modal identification thus providing a more reliable simulation of actual structural response at global and local level.

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