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IN-SITU ASSESSMENT OF STRUCTURAL TIMBER USING SELECTED WAVE-BASED NDT METHODS

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ABSTRACT

This paper reports on a research, carried out in collaboration between the University of Trento DIMS and the CNR Institute IVALSA. The research was aimed at evaluating the potentiality of a multi-sensor approach, based on the use of different wave-based NDT methods, for on-site assessment of structural timber.

Experiments were carried out on softwood samples, both in laboratory, on a dismantled beam, and on site, on the timbers of the porch's roof in St. Lorenzo church (Tenno, Italy).

For the mechanical characterization of structural timber, combination of stress-wave velocity measurement and density prediction models from PLS analysis of FT-NIR spectra is proposed.

Preliminary model generated for a single sample of Scots Pine showed a good correlation between predicted and measured values of local density.

IR thermography and stress-wave time of flight tomography were used in combination, with the intention to couple information of subsurface and internal heterogeneities, respectively. Areas of abnormal velocity values in tomograms were examined taking account of external indicators in the thermography maps. The techniques adopted are suitable to investigate large portions of the timber elements. This made it possible to limit the number of local NIR spectroscopy analysis to investigate chemical and physical local changes, and assess the nature of the detected heterogeneities.

Keywords: *Timber structure assessment, IR- NDT, SW- NDT, Multi-sensor approach*

1. INTRODUCTION

On site evaluation of mechanical and physical properties of building materials, in load-bearing structures in service, is propaedeutic at the safety assessments as well as at the definition of possible intervention strategies.

Because mechanical properties of timber are affected by defects, as well as by decay and damages (which can alter the original resistant cross-section), these qualitative parameters are also important in the estimation of global member properties.

Most of semi-destructive testing techniques are "mechanical", either measuring the local resistance of the material against the action of specific probes [1-3] or directly measuring local properties of extracted samples [4-5].

Wave-based techniques are non-destructive methods analysing the response of the material to wave fields of different nature.

Two different kinds of waves can be utilized in the wave-based NDT evaluation of timber, they are elastic waves (or called stress waves) and electromagnetic waves (i.e. X-rays, gamma rays, ultraviolet rays, visible light, infrared, microwaves).

One of the most intriguing ways of utilizing wave propagation phenomena into the tested material is nondestructive imaging the wood structure [6]. According to the penetration depth of the wave field, imaging techniques make it possible to analyze either subsurface features or internal heterogeneities of the wood material.

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Among the methods, which provide a map of wood surface properties distribution, thermal imaging has been proposed, by different authors, especially for imaging of defects [7-8] and moisture content distribution [9].

For introspective analysis on site, stress-waves parameters are mainly used, utilizing either scanning [10] or tomographic techniques [11-12].

The time of flight (ToF) or the corresponding calculated velocity is the most common stress wave parameter used during timber investigations.

Stress-wave ToF measurement is a well-established technique for prediction of elasticity properties of the material (i.e. modulus of elasticity in bending). Nevertheless, predictions can be subject to many sources of error including accurate measurements of the member density [13].

Density can be measured directly from small samples extracted from the investigated timber. Due to the variability within the element, a number of samples need to be extracted to infer global parameters, thus increasing the invasiveness of the test.

Emerging electromagnetic methods can be used, as an alternative of direct measurement of core-samples, for the estimation of the physic-chemical structures of wood.

FT-NIR technique is relatively young, and, recently, it has shown promise for various applications in wood and paper industry [14]. NIR spectroscopy analyses the vibrational characteristics of particular parts of molecules on a measured surface, when excited by the energy of infrared light. Vibrational characteristics of materials depend on the molecular structure, chemical composition and physical properties of the surface measured [15]. The technique gives local estimates, but thanks to its non-destructive nature and speed of measurement, global parameters can be inferred through adequate sampling.

In this paper, an inspection methodology, based on the use of selected wave-based NDT techniques, is proposed. The effectiveness of the approach is discussed, from the analysis of preliminary experimental results.

2. WAVE-BASED METHODOLOGY FOR ASSESSMENT OF TIMBER STRUCTURES

2.1. Preliminary analysis

For the assessment of structural timber in service, species identification and moisture content (MC) measurement and mapping are preliminary analyses to be performed.

According to standard [16], wood species can be identified through either macroscopic or microscopic analysis of anatomical features. However according to [17] and [18] it is possible to perform wood species discrimination applying near infrared spectroscopy. Approaches to use FT-NIR spectroscopy as a non-destructive technique for species identification were also previously investigated by the authors [19]. It has to be mention that effective discrimination is possible only when proper constructed spectral databases are available.

The choice of the most appropriate method, for MC measurement, depends on several factors: first of all, on the target measurement (i.e. average MC, surface MC, MC distribution, maximum MC), e.g. to map the areas at the risk of fungal attacks or for correction of NDT parameters.

For the indirect estimation of local MC values, the electric resistance method is generally used [20]. This is coupled, in the methodology proposed, with the passive IR-thermography for preliminary mapping of moist areas.

2.2. Defects-decay characterization

Determination of the presence, extent, position and nature of defects and decay is a prerequisite for visual strength grading of timber members. Information about internal damage is required for determination of the effective resistant cross section of the element [21].

In the methodology proposed, IR thermography is used in combination with ultrasonic ToF tomography, to collect information of subsurface and internal heterogeneities, respectively.

After preliminary mapping of crucial zones through IR thermography (e.g. moist areas, where wood is already rotted or vulnerable to biotic attack), selected areas can be further analysed.

Remote sensing through IR thermovision is a fast inspection technique, particularly appropriate to analyse timber structures, such as large roofs, in areas with difficult accessibility.

Conversely, SW-ToF tomography requires access to, at least, two opposite faces of the element to be inspected. Moreover, perfect contact between the element surface and the sensors is necessary to allow adequate coupling. ToF acquisition process can be speeded up, utilizing a multi-channel device.

The tomographic analysis has the advantage to be completely non-invasive, thus allowing introspective investigation of large portions of the timber element. Once most decayed/damaged areas are highlighted in tomograms, local tests can be carried out on selected points to obtain higher resolution information [12].

Not only extent and position, but also nature of defects and decay must be known to adequately assess timber in service.

IR methods can provide useful information also about the nature of strength affecting features.

Active thermography is adopted, in the methodology proposed, to analyse the nature of visible or subsurface defects; in the case of knots, for instance, distinguishing sound knots from loose and decayed ones.

FT-NIR spectroscopy is then applied on selected samples, to determine the nature of decaying factors (e.g. wet rot, dry rot, etc.), thus helping the conservator in the choice of the most appropriate remedial action.

2.3. Estimation of mechanical-physical properties

Estimation of mechanical properties of wood is the most cumbersome task during on-site inspection of timber structures. Given the imperfect correlation between most NDT parameters and inferred mechanical properties, the most appropriate approach seems to be the combination of different NDT and SDT results [22].

In the methodology presented here, estimation of MoE (E_{dyn}), through correlation with stress-wave velocity and density values predicted from FT-NIR spectra, is proposed, as one of the possible NDT methods to be used for the mechanical characterization of timber elements on site.

In particular, the paper stresses the potentiality of the FT-NIR spectrometry, for non-destructive estimation of density: density parameters can be used directly as grade-determining property, as well as to improve prediction of E_{dyn}.

3. MATERIALS AND METHODS

3.1. Introduction

Tests were performed both on site, on a timber construction in the medieval St. Lorenzo church (Trentino, North Italy), and in laboratory, on some wooden samples collected from dismantled beams.

A complete series of tests (active-passive IR thermography, SW-ToF tomography, FT-NIR spectrometry, SW-ToF measurements, bending test, direct weigthing) were carried out on a single beam, in laboratory. Some tests were then repeated, on samples extracted from the investigated element, in order to isolate clear wood portions and evaluate properties of defects.

3.2. Stress-wave

3.2.1. Stress-wave time-of-flight (SW-ToF)

Data from stress-waves ToF were collected for prediction of the dynamic modulus of elasticity (E_{dyn}) of the material. A series of tests were carried out on a single beam of Scots Pine (*Pinus sylvestris* L.), from a dismissed structure, that was first tested as a whole element and, then, on clear wood portions.

According to the concept introduced by Riberholt and Madsen [23], timber members can be considered as heterogeneous elements composed of clear wood and weak wood zones (defects).

The clear wood zones' properties define the so-called basic properties of the element.

Because elasticity is to a greater degree determined by average properties than by local weak spots, the ultrasonic method was applied to obtain a prediction of the E_{dyn} in clear wood zones, which is then assumed as the basic stiffness of the member [24].

Ultrasonic wave velocities were measured using a multi-channel device, also used for tomographic acquisition. A source of 55 kHz was utilized for emitting signals.

For the estimation of the dynamic modulus of elasticity E_{dyn}, longitudinal measures were made for the total of the samples, with the transducers placed at the ends of the element (propagation parallel to the grain). Because the direct method is often impossible to apply on timber members in service, a series of indirect readings were made on the entire beam.

For determination of the (elasto)dynamic modulus (N/mm^2), Equation (1), for prismatic, homogeneous and isotropic elements, with a section width smaller than the stress wavelength, was used:

$$E_{dyn} = \rho V^2 \tag{1}$$

where V is the propagation velocity of the longitudinal stress waves (m/s) and ρ is the density of the specimen (kg/m^3).

3.2.2. Stress-wave ToF Tomography

SW-TOF transmission tomography uses velocity values of the transmitted waves as contrast-producing parameter.

Stress-waves were generated at 55 KHz by a piezoelectric transducer and recorded by receivers placed at a pre-set distance (2-3 cm), depending on the geometry of the investigated section and the designed spatial resolution. Transducers were connected to a portable multi-channel device (TDAS 16 – Boviar s.r.l.).

Tomography profiles were acquired along longitudinal segments of beams, in direct transmission mode, i.e. pairing energization points and receivers on opposite sides of the timber. Assuming a linear propagation of the pulse waves, maximal inclination of transmitted waves (i.e. reciprocal position of transmitter and receiver) was pre-determined, in order to avoid outliers due to propagation along the fibers.

Transversal sections were also analyzed and measuring points were defined, in order to mitigate effects of transversal anisotropy (between radial and tangential directions) in wave propagation.

Data were processed, from the array geometry and the travel times of the first arrivals, using commercial software Tomotool© , which gives optimized solution from different inversion algorithms (ART – algebraic reconstruction technique, SIRT – simultaneous iterative reconstructive technique, LSQ – least squares and SVD – singular value decomposition) [25].

In a preliminary experimental campaign [11], the capability of the tomographic method to characterize biotic decay and natural occurring defects was evaluated, testing timber structural elements from dismantled historical structures.

The method was then applied on site, on the porch roof of the S. Lorenzo church.

3.3. IR

3.3.1. IR Thermography

The passive heating procedure was used for thermographic imaging of moist areas, while, for defects characterization, an active heating procedure, utilizing as heat source two infrared lamps, 250 W and 276 W respectively, was adopted.

Surface temperature of wood in transient depends on the thermal conductivity (λ) of the material, defined as the thermal energy Q per unit time t which flows through a thickness s of a substance with a surface area A under a steady-state temperature difference ($\tau_2 - \tau_1$), as in Equation 2.

$$\lambda = Q\,s\,/At(\tau_2 - \tau_1) \tag{2}$$

Because thermal conductivity varies with density, active thermography was utilized to highlight heterogeneities due to the different density of clear wood and detected features. A FLIR, model T200, thermovision camera was used to produce thermal maps, after giving inputs on ambient temperature, relative humidity, distance to target area, and a relevant emissivity of target surfaces. IR images were analysed by using ThermaCAM QuickReport 1.1 software. Infrared images of the subject areas were taken in segments together with their visible light photographs.

3.3.2. FT-NIR spectrometry

Even though portable NIR spectrometers allow on-site measurements, in this study, spectra were measured from extracted samples, by using FT-NIR spectrometer VECTOR 22-N (Bruker Optics GmbH) installed in the Wood Quality Laboratory of IVALSA/CNR. The measured spectral range was between 4000 cm^{-1} and 12000 cm^{-1} with a resolution of 8 cm^{-1}, which are standard conditions for such measurements. Each spectrum has been computed as an average of 25 internal scans in order to increase the signal-to-noise ratio. Tree separate measurements were performed on each sample. All measurements were performed in climatic chamber (20ºC and 65% RH) to minimize influence of temperature and humidity of environment. OPUS 6.5 and National Instruments LabView 8.5 software packages have been used for signal processing and data analyses. Derivatives were calculated according to the Savitzky-Golay algorithm. For the mathematical management of the spectra and then for the evaluation of the results, Principal Component Analysis (PCA) and Partial Least Squares (PLS) were applied. PCA allows the discrimination of the samples of different degradation levels. Partial

Least Squares (PLS) regression algorithms are frequently applied for computation of regression models linking near infrared spectra and reference values. In this particular case PLS was used to prepare models for density prediction.

4. ANALYSIS OF EXPERIMENTAL RESULTS

Preliminary experimental results are discussed in this section, to highlight the potentiality of the multi-sensor approach proposed for on-site assessment of timber structures.

4.1. IR Thermography

Figure 1 shows IR thermograms of some beams in the investigated porch roof.

Areas of lower surface temperature are clearly distinguishable, at the beam ends, where water stagnation occurred, at the interface with the façade wall, as also confirmed by thermograms of the inner façade (Fig. 2).

MC measurement with the resistance meter gave values ranging from 16 to 22% in the moist areas, thus confirming that the fiber saturation point was reached in some locations.

Fig. 1 Thermography of a beam end (S. Lorenzo, Tenno)

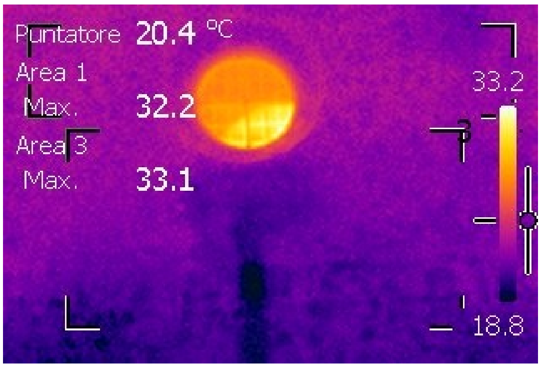

Fig. 2 Thermography of the inner wall

Figure 3 shows the image of a beam with knots inspected with passive thermography. Average surface temperature of a decayed knot is similar to that of cavities and checks (21°C), whereas, temperature of sound knots on the same surface is higher (22°C).

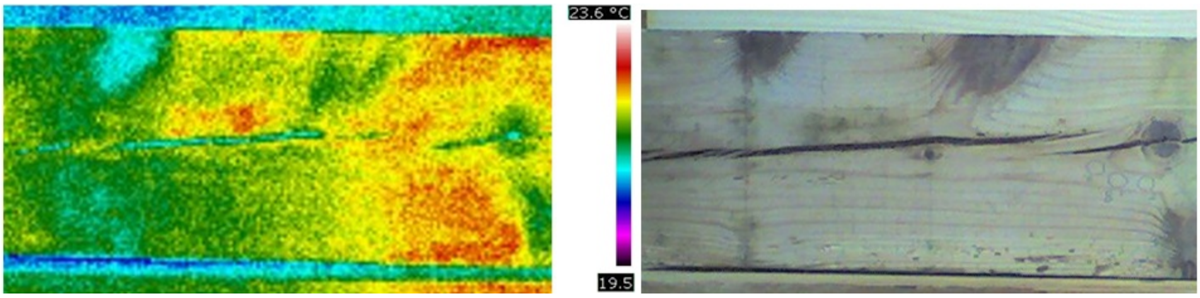

Fig. 3 Passive thermography (left) and photography (right) of a wood element with defects

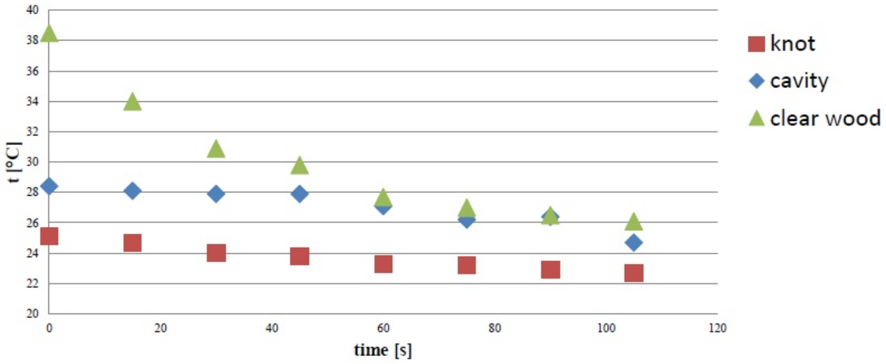

Fig. 4 Temperature variation of different wood features

To observe the thermal behaviour of different wood material features, the active method was applied and comparison of temperature variation during cooling is reported, (Fig. 4). For this purpose, the wood surface was previously heated 60 sec. long with IR lamps 250 W at a distance of 50 cm.
From the curve of the temperature variation, low conductivity of the defective zone is observed.

4.2. Stress-wave ToF Tomography

The map of velocities in tomograms is represented by a 256 levels of grey diagram, where the white level corresponds to the maximum velocity, and the black level corresponds to the minimum velocity.
Capability of SW-ToF tomography to detect sound knots, even of little size, into the wood has been highlighted by the authors from previous researches [11]. As can be observed in Fig. 5, their presence is associated with very high velocity zones in tomograms. Detection of loose knots through tomographic inspection is less accurate, because local discontinuities cause stress waves to deviate from their original path, thus resulting in artefact in the tomograms (e.g. knot at the upper corner on the right in Fig. 5).

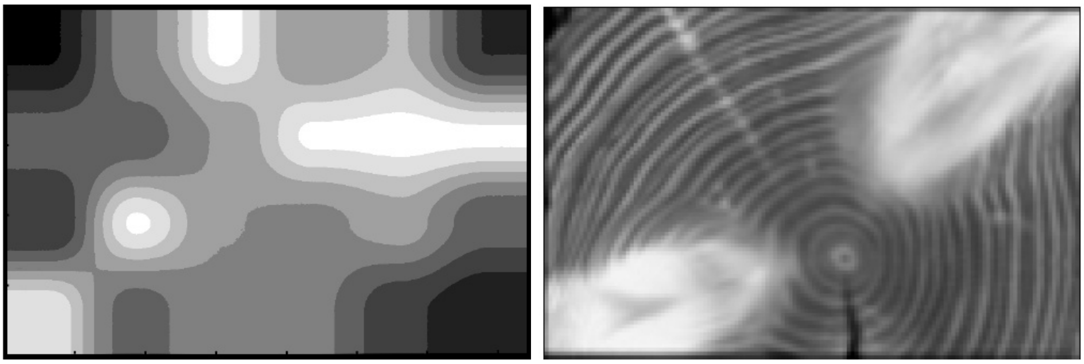

Fig. 5 Comparison between SW-ToF tomography of a knotty section (left) and real position of knots (right)

Tomographic inspection on site, at the S.Lorenzo church, confirmed preliminary outcomes from thermographic scanning. As it can be seen in Figure 6, very low velocity values (< 700 m/s), which clearly indicate bad mechanical quality and degradation of the material, were found in velocity maps acquired on transversal slices of the beams close to the façade wall. An internal sound wood portion is also distinguishable, but its extension could not be estimated by means of the tomography, due to low resolution of the analysis (> 10 mm).

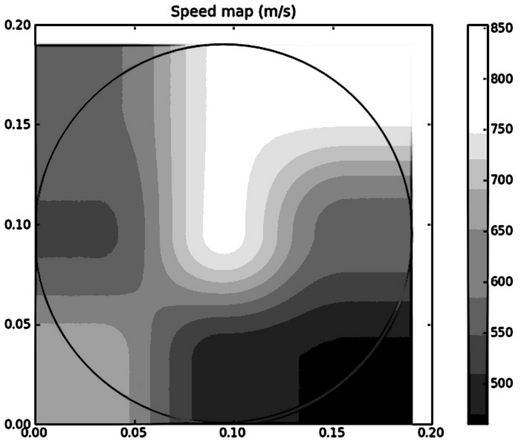

Fig. 6 Tomography of a transversal section of a beam with decay (S.Lorenzo church, Tenno)

4.3. FT-NIR measurement

FT-NIR has been previously reported as a fast and reliable technique to investigate and estimate chemical and physical changes to assess fungal degradation [26]. In the research reported, FT-NIR was selected for estimation of the wood condition and degradation stage of the beams in S. Lorenzo church. Comparing spectroscopic results with enzymatic activity of fungi it can be concluded that degradation is most probably caused by nonselective white-rot fungi. Such fungi could remove most of lignin, hemicellulose and some cellulose, since different type of hydrolyzing enzymes destroy cell wall components and relies them as a small molecules [27].

Further analysis of the FT-NIR spectra was carried out, with the aim of building reliable models for density prediction. PLS models correlating the FT-NIR spectra and calculated density are already used in the preliminary classification of raw material [28]. In this work, however, an alternative model based on density of a single wooden beam was created. (Figure 7).

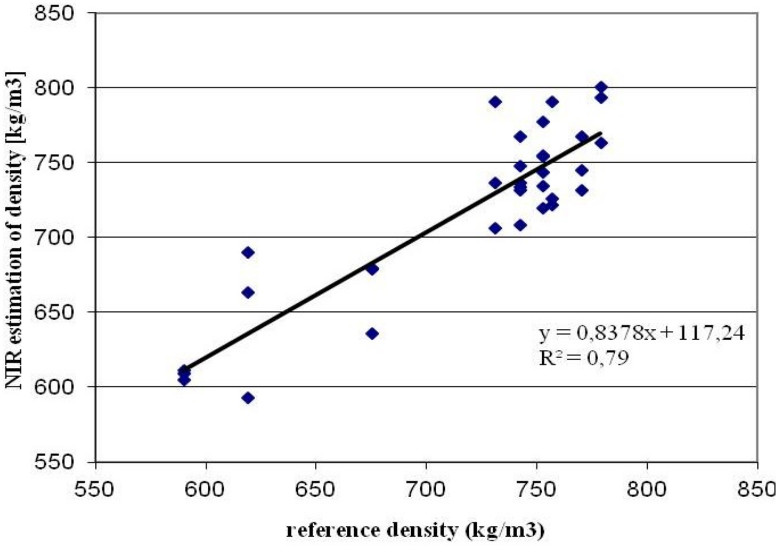

Fig. 7 Calibration model for wood density

4.4. E_{dyn} prediction

E_{dyn} values were estimated using density parameters differently determined, in order to define appropriate sampling method for IR spectrometry.

In particular, density was measured from the weight and apparent volume of the entire timber element and from clear wood portions.

Results from preliminary tests on a single timber beam show that the difference between MoE estimated from bending test and stress-waves ToF measurements is about 41%, if density is measured from the entire element, while it decreases to 29%, when density is referred to clear wood.

If results will be confirmed by further tests, this would give indication about sampling criteria for density prediction from the analysis of spectra, which should refer to clear wood areas of the structural element.

5. CONCLUSIONS

In the methodology developed for in situ assessment of structural timber members, combination of different NDT methods, based on analysis of infrared radiation and stress-waves propagation into the wood material, is proposed. The method is conceived to collect information about both basic material properties and defects/decay.

IR thermography showed a great potential as preliminary non-contact screening procedure, to select areas for introspective analysis.

Stress-wave ToF tomography, thanks to its completely non-destructive nature and the possibility to map large timber sections, can be adopted as large-scale global evaluation method, for decay and defect detection in the interior of the wood material.

NIR spectrometry demonstrated to be a versatile and promising tool for several applications. Species recognition, physical properties prediction and evaluation of degradation level are some of examples.

In particular, use of spectroscopy for the prediction of physical properties of wood is one of the most promising potential uses of this technique. However, it requires preparation of a large database of high precision reference values to build reliable, flexible and sufficiently generalized models.

Because of anisotropy and high variability of the wood material, adequate data acquisition (e.g. considering wave propagation phenomena in the different anatomic directions) and proper sample collection (taking into account the influence of macro and meso heterogeneities on measurements) are fundamental to obtain sufficiently reliable results.

Particular attention must be paid for the mechanical characterization of structural timber. Indeed empirical relationships to estimate mechanical properties can have a varying degree of correlation,

which are further reduced due to compounded correlations (e.g. SW velocity and density for E_{dyn} prediction) and indirect correlation (E_{dyn} vs static MoE, or even, bending strength).
For these reasons, a multi-sensor approach, based on integration of data from different NDT methods, is recommended, in order to calibrate results from different methods and supply correct information on element behaviour.

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