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Structural health assessment of a historical building by using in situ stress wave NDT: a case study in Iran

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TECHNOLOGY OF FOREST PRODUCTS

ABSTRACT

Background: Many historical buildings in Iran need to be protected. In many of these buildings, wood is used as a structural element in features such as beam, pile, roof and floor systems. For this purpose, the architectural features of a historical building located in Gorgan (Northern part of Iran) and characterisation of faults, in addition to identification of wood species were conducted. Stress wave non-destructive testing (NDT) was used and wave speed (WS) was measured in tested members to evaluate the decay situation of major wooden beams of building frames and roof truss. After obtaining data related to WS, time of wave transition (TWT) was calculated and compared with control time. Structural elements were characterized in comparison with control time and classified according to decay severity.

Results: The results showed that local hardwood species were used for construction of this building. Furthermore, in some parts of the building, there were severely defected structures, thus highlighting the importance of safety. Moreover, WS strongly depended on the types of faults.

Conclusion: Due to high relative humidity of climate, wood structures are exposed to faults in the northern region of Iran. However, their general appearance is adequate and acceptable. For better decision making, the TWT should be accompanied by more investigation into the types of defects.

Keywords: Historical building, Non-destructive Testing, Stress wave, Structural health assessment, Testing of materials, Timber structures

HIGHLIGHTS

Stress wave method was employed for assessment of wood members in a historical building in Iran.
The times of wave transition in wood members were compared with the control value.
Identification of wood species of building were conducted.
Stress wave speed strongly depended on the types of faults.

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INTRODUCTION

There are many historical buildings in Iran whose protection is important from the cultural and tourism points of view. Wood is an important structural element in most of these buildings as it is used in the construction of beams, pile, roof and floor systems (Branco and Guerreiro, 2011; Madhoushi, 2016, Imanian et al. 2019). Although these historical buildings survived previous severe earthquakes, they are still in appropriate and acceptable conditions. This is as a result of the nature of wood materials used as loading structural member which could absorb and dissipate the energy of earthquakes (D'Ayala and Tsai, 2008; Li et al., 2015; Madhoushi and Ansell, 2008; Parisi and Piazza, 2015; Vieux-Champagne et al., 2014). Loading structural members ensure that earthquakes do not result in serious failure while the brick and crobe parts in shear walls have been damaged and failed (Elmenshawi et al., 2010; Simões et al., 2014; Vieux-Champagne et al., 2014). It should be noted that despite the survival of historical buildings under previous seismic loading, they have been exposed to ruin and destruction due to several geographical and environmental reasons (Bosiljkov et al., 2010; Phillips and Stein, 2013; Yung and Chan, 2012). For this reason, the evaluation and preservation of wooden parts of traditional buildings are critical and important when there is a serious and scientific plan for their repair and rehabilitation (Cruz et al., 2015; Nowak et al., 2013).

For repair and rehabilitation purposes, some damages cannot be seen during visual inspections. Therefore, in order to evaluate internal defects, employing a quick, efficient and economical method is necessary (Avrami, 2016; Branco and Guerreiro, 2011; Vicente et al., 2011).

Health assessments of wood buildings may be conducted with several non-destructive testing (NDT) methods, including X-ray (Yokoyama et al., 2009), FT-Raman spectroscopy (Moosavinejad et al. 2019), pilodyn and resistograph (Branco et al., 2010; Calderoni et al., 2010), stress wave (Ross et al., 2006) and ultrasonic (Cabaleiro et al., 2017) methods. All these methods may be capable of determining the density and internal conditions of wooden beam structures; however, each has its advantages and disadvantages. Among these methods, the stress wave method has more potential to determine the Young's modulus of elasticity (Kloiber et al., 2015; Yamasaki and Sasaki, 2010) and thus provides more valid results. The stress wave method is a more commercial (Dackermann et al., 2014; Ross et al., 2005) and helpful tool for the in situ investigation of buildings as it exhibits low possible errors in comparison with other methods. Despite the longer time required for its use, it is simple and easy to use; without need for any special arrangement.

Although health assessment of wooden buildings using stress wave NDT has been reported by numerous researches, it is difficult to find any clear protocol and guideline/manual among these studies (Riggio et al., 2014). In other words, stress wave NDT is the same for all studies, but the method and strategy for evaluation and also relevant calculations vary from one study to another. Hence, presenting a global or local standard protocol is required for these types of studies.

The aim of this study was to undertake the in situ evaluation of structural wood member in a historical building (Reza-Nejad) in Gorgan, Northern Iran using stress wave non-destructive testing (NDT). The Reza-Nejad was built approximately 80 years ago. This study is the second one after that conducted by (Madhoushi, 2016) on the use of non-destructive testing (NDT) for the investigation and health assessment of historical wooden buildings in Iran.

MATERIAL AND METHODS

Architectural and structural features

The architectural and structural features of building were visually investigated and detected followed by the drawing of general plans from different geographical views. In accordance with recommendations from previous studies and also the Cultural Heritage Organization (CHO) of Iran, several high quality photos of the building were taken from the building (Fig. 1a), in addition to various plans and profiles drawn with the use of AutoCAD software. Then each of the photographs taken from the main entrance was labelled by a distinct ID code as: A) for East plan, B) for North plan, C1) for West plan ground floor, C2) for West first floor, D) for South plan and, TB) for Truss of B section (Fig. 1b).

Faults and wood species identification

All wooden parts of the building were visually investigated. Type and location of observed defects were marked with distinct codes on drawn plans. Also, wood types used in construction were identified in the laboratory at macroscopic and microscopic levels (Parsapajouh, 1988). The moisture content of all the tested parts were measured by means of a portable electrical moisture meter.

Stress wave measurement

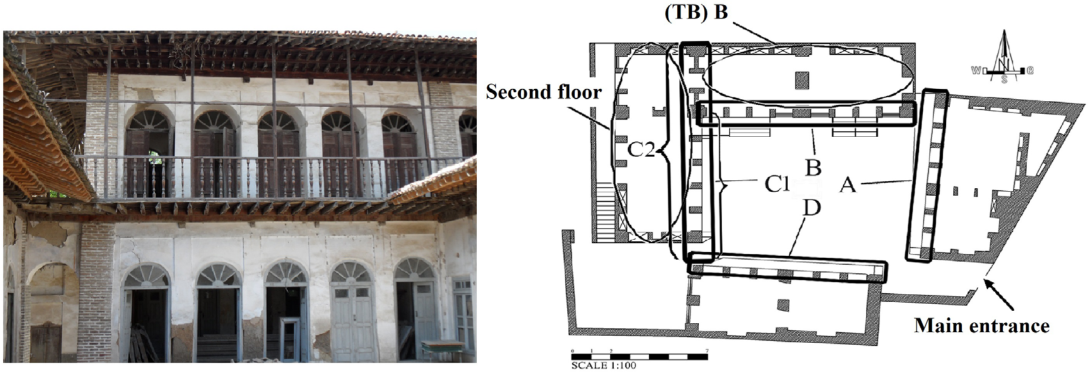
The main wooden beams of the building frame and roof truss were evaluated by stress wave NDT instrument (IML) and the wave speed (WS) was measured longitudinally (and perpendicular to grain for some rare members of truss). For this purpose, each member was tested and scanned at every 50 cm distance to obtain the best results (Fig. 2).

After obtaining data relevant to WS, time of wave transition (TWT) was calculated and compared with baseline (control) time, according to the following equation (Eq. 1) as suggested by (Ross, 2015), Where, $T_{baseline}$ is the control time (µs), WTD is the sensors distance (m).

If the time of wave in samples is lower than the baseline, it implies that the sample should be considered a sound member. Conversely, if the TWT is higher than the baseline, it means that the sample should be considered a defective member. In addition, the level of defect in each section of members was calculated using Eq. 2 (Ross, 2015) in order to distinguish and classify the wooden parts by severity of defect, where, T is the calculated time (µs).

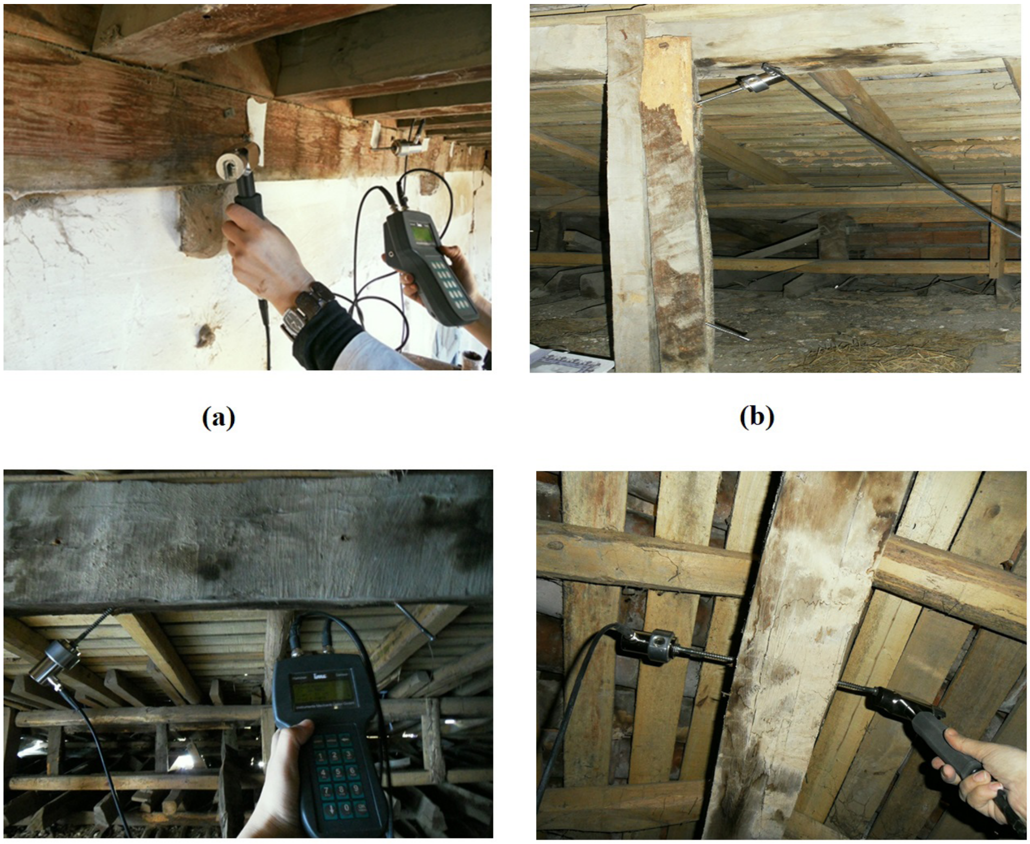
$$T_{baseline} = 1300 \times WTD \qquad [1]$$

$$Defect(\%) = \frac{T - T_{baseline}}{T_{baseline}} \times 100 \qquad [2]$$



(a) (b)

Fig. 1 a) A view of the building, b) Plan of the building.



(a) (b)

(c) (d)

Fig. 2 WS measurement in a) wood beam, b), c) and d) truss.

RESULTS

Architectural and structural characteristics

The house has a floor area of 675 m^2 and is currently under repair. This structure is a one-storey building, excluding the western part (ID code C1 and C2) which is a two-storey building with steps between the floors (Fig. 1a).

In this building, there is evidence of Islamic art (like the dome shaped window). Due to their special design, there is weak ventilation which in turns provides a more humid environment inside the building. The structures are rectangular and solid wood was utilized for the construction of loading structural members, such as beams, rafters, roofs, and floors in association with other traditional and masonry construction methods. The doors and windows are completely wooden and well preserved.

The average moisture content was measured in members was between 8 and 11%; however, in truss it was 1-2% more due to low ventilation.

Source of faults

The causes of faults were determined as weathering, fungus and insect attacks, surface and deep cracks on wooden members (Fig. 3). The color of the wood surface changed to dark brown and grey because of the action of various agents. Distinguishing faults were conducted separately at each 50 cm length in parts A, B, C1, C2, D and TB. Tab.1 shows a summary of the types and total percentages of faults in the all parts of investigated members.

Wood species

Microscopic identification of samples showed that the load bearing wooden parts of the building were made of hardwood species native to the northern region of Iran including oak (*Quercus castaneaefolia*), lime tree (*Tilia begonifolia*), acer (*Acer insigne*), and beech (*Fagus orientalis*). Fig. 4 and 5 show the microscopical sample for transverse and tangential sections, respectively. The location of wood species in the building is shown in Fig.6 and Tab. 2.

WS, TWT and faults

Tab. 2 shows the average WS for main beams and truss. The WS and the TWT in wood beam and truss are shown in Fig. 7, 8, 9 and 10, for each sample. The results indicated a low WS, mostly at the two ends of members, where insects' holes and decayed parts were most visible.

Furthermore, the results revealed that the WS is higher in sound members as compared with decayed ones. In addition, in members exposed to insects' attacks, humidity penetration and tensions caused by loading, more severe destruction was observed than in other members. More severe destructions were also observed in parts that were exposed to regional wind.

TWT in all studied members in comparison with control time are shown in Fig. 11. Deeper investigation of those parts in which the TWT were higher than the baseline showed that the defects were mostly color changes and large cracks and/or knots. In other words, large cracks and knows were dominant defects in these areas. However, with lower TWT, the dominant defects were mainly color changes.

DISUSSION

The building has identical architectural characteristics which are somehow similar to other typical historical buildings in Gorgan (Madhoushi, 2016). Solid wood, of hardwood species native to Iran, was extensively utilized for the construction of

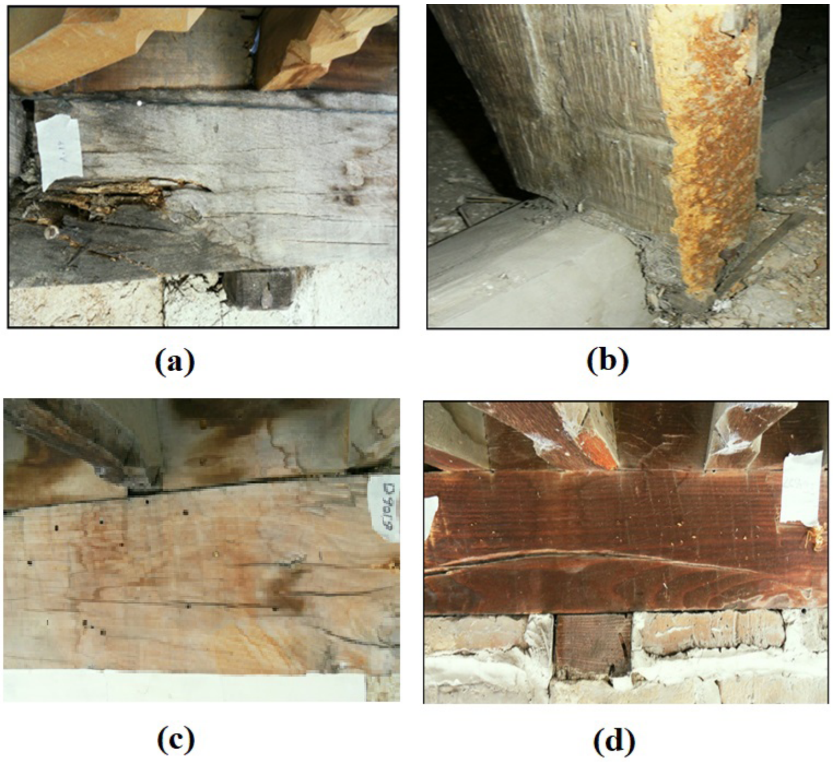


Fig. 3 Source of faults in wood members as a) weathering, b) fungus c) insect and d) cracks.

Tab. 1 Types and percentages of faults in wooden members.

Section	Types of defects (%)				
	Insect holes	Change of color to grey	Mold	Change of color to dark brown	Check and split
Eastern part (A)	37.5	31.2	37.5	12.5	50
Northern part (B)	69.5	43.4	48	21.7	60
Western part, ground floor (C1)	12.5	43.7	0	62.5	0
Western part, first floor (C2)	0	0	0	0	4
Southern part (D)	90.9	13.6	0	0	50
Truss	70	0	60	100	50

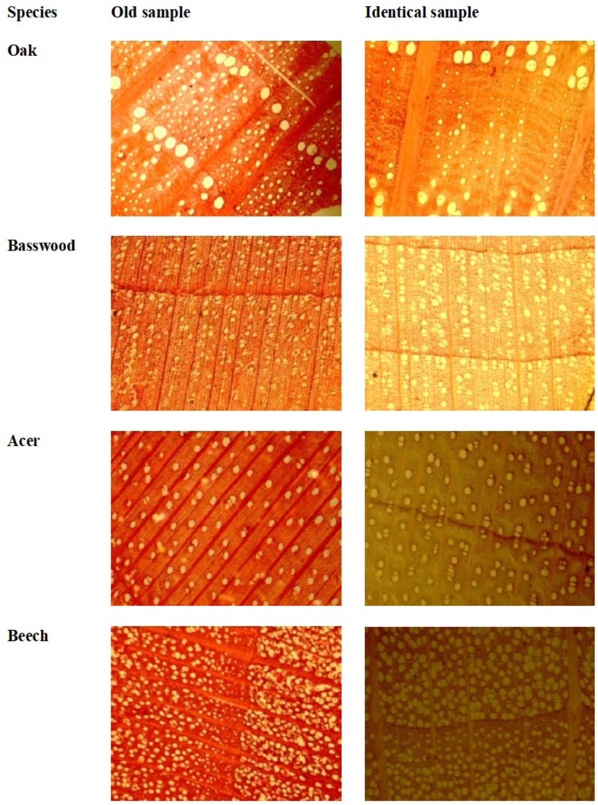


Fig. 4 Microscopical samples of old wood compared with typical ones in cross section.

Fig. 5 Microscopical samples of old wood compared with typical ones in tangential section.

Tab. 2 Position of wood samples in building, and average of WS and TWT.

Position	Species	WS (m/s)	TWT (μs)
Eastern part (A)	Oak	2708 (±944)	432.59
Northern part (B)	Oak	2146 (±1033)	780.06
Western part, ground floor (C1)	Oak, Acer	3695 (±577)	278.26
Western part , first floor (C2)	Acer	3848 (±305)	261.44
Southern part (D)	Beech, Basswood	1848 (±1264)	950.23
Truss	Oak	2952 (±637)	671.33

loading structural members in association with other masonry construction methods. Besides inherent defects in the wooden parts, such as knots and spiral grain, different faults were observed as weathering, fungus and insect attacks mainly in parts A and B of buildings, which is consistent with (Cruz et al., 2015).

The results of this study is in agreement with previous ones by (Dackermann et al.; 2014, Ross, 2015); which indicated that stress wave passes more rapidly through intact samples than decayed. This difference was used as a key to distinguish sound parts from defected ones. Moreover, the results indicated that the parts affected by moisture penetration and extensive loading exhibited more severe decays and faults compared to other parts and thus showed more destruction (Riggio et al., 2014). This finding should be considered for *in situ* investigation of timber buildings.

Moreover, the finding revealed that the WS wave should be considered and compared with the types of defects of area, especially with cracks and knots as Fig. 12 shows. This figure demonstrates these findings as a general pattern. These findings were not reported by previous investigations, as WS has majorly been used as an indicator and method of identification of defects without types of faults.

With regards to defect percentages, in general, member D showed severe and critical decayed parts in some sections, for example: 87, 174, 384 and 424%.. Other members showed lower defect percentages.

CONCLUSIONS

Due to high relative humidity of climate, wood structures are exposed to faults in the northern region of Iran. However, their general appearance is adequate and acceptable. Wooden parts of the studied house suffered color alteration as well as fungus and insect attacks. TWT in wooden parts is dependent on the defect amount, thus, stress wave would move faster in healthy wooden parts than in destroyed ones. In some parts, there were severe defective members which are very critical from a safety point of view. The results indicated that for better decision making, the TWT should be accompanied by more investigation into the types of defect, especially in those parts where TWT are higher than control time.

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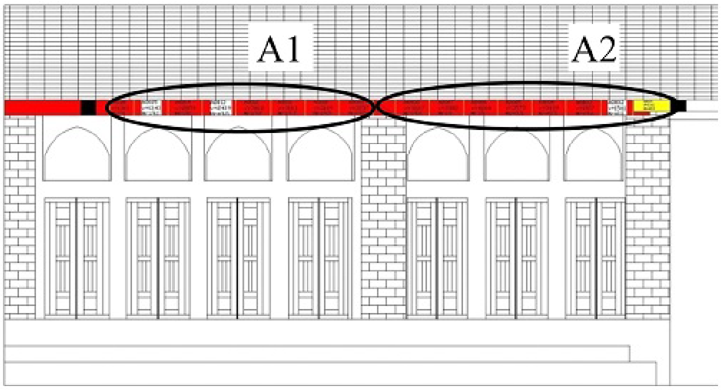
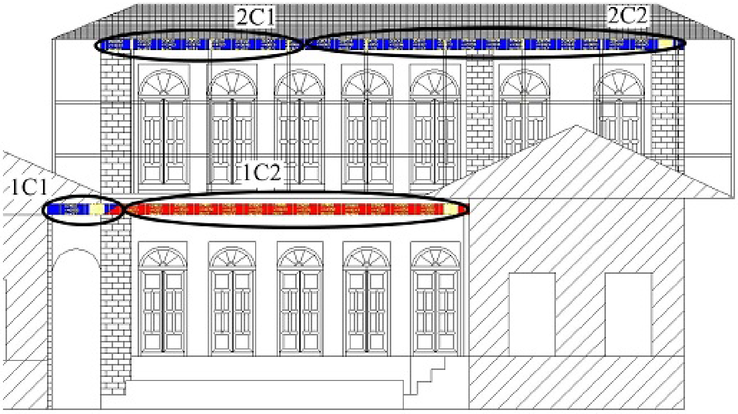


(a) Section A-A East,

🟥 **Oak,** 🟨 **Basswood**

(b) Section B-B North,

🟥 **Oak**



(c) Section C-C West,

🟥 **Oak,** 🟦 **Acer**

(d) Section D-D South,

🟨 **Basswood,** 🟪 **Beech**

Fig. 6 Main plans of four sections of buildings and wood beams in a) A, b) B, c) C, and d) D (see Fig. 1 for more details).

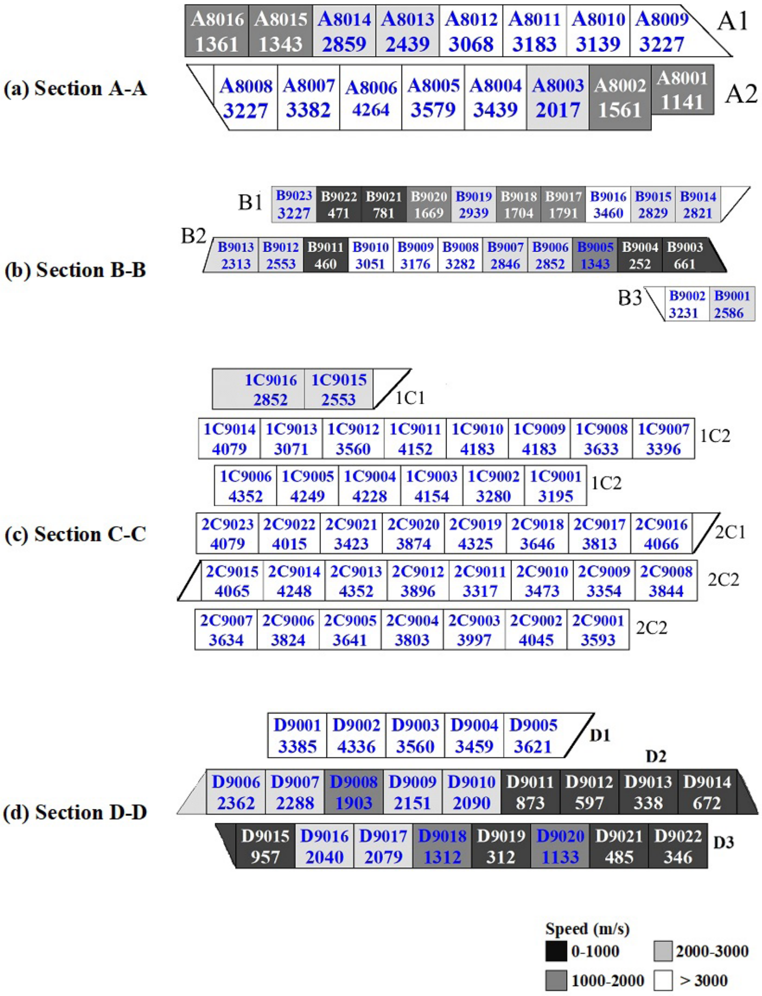


Fig. 7 WS in wood beam a) A, b) B, c) C, and d) D (see Fig. 6 for more details).

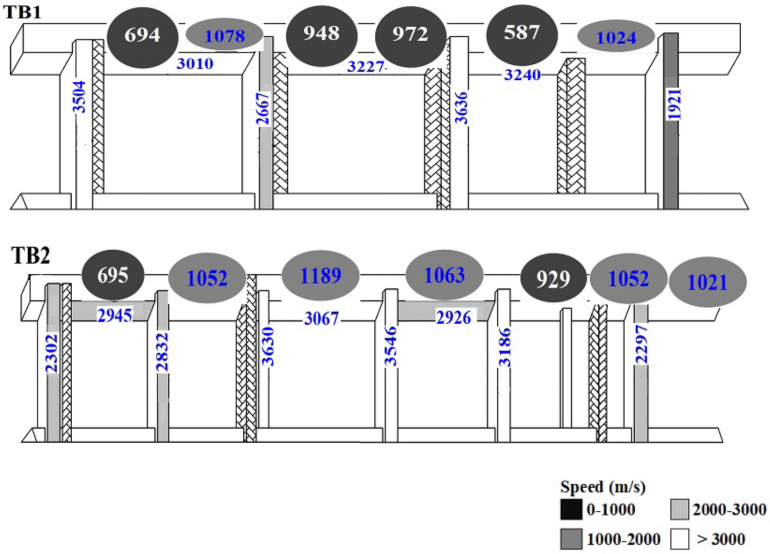


Fig. 8 WS in wood of truss (see Fig. 1 for more details)..

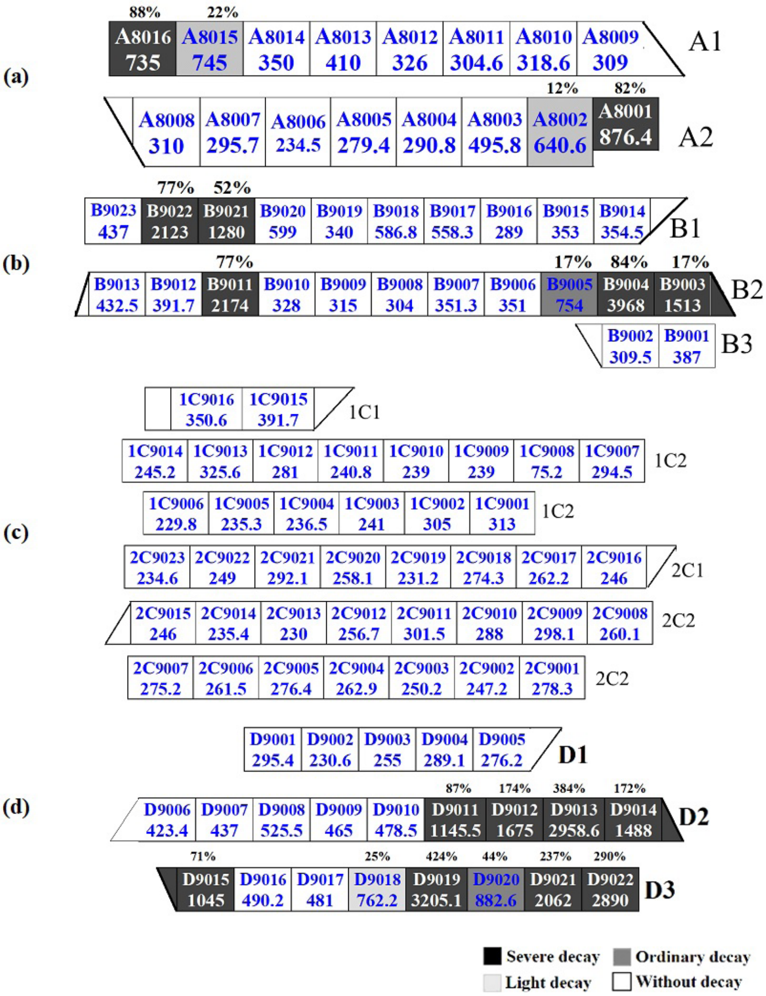


Fig. 9 TWT (μs) in wood beam a) A, b) B, c) C, and d) D (see Fig. 6 and 7 for more details).

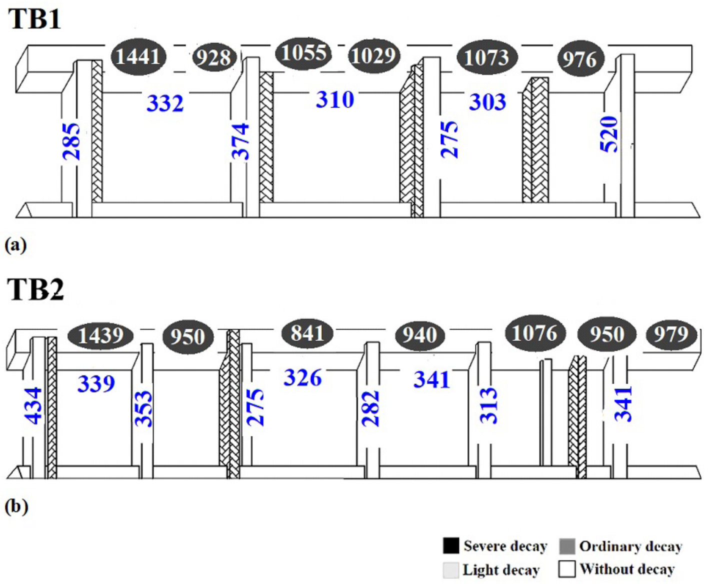


Fig. 10 TWT (μs) in wood of truss (see Fig. 8 for more details).

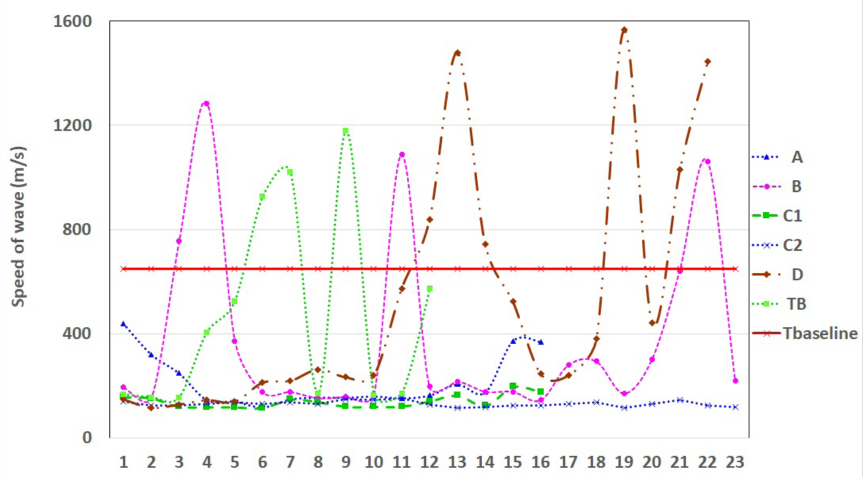


Fig. 11 TWT in all studied members in comparison with control time (baseline).

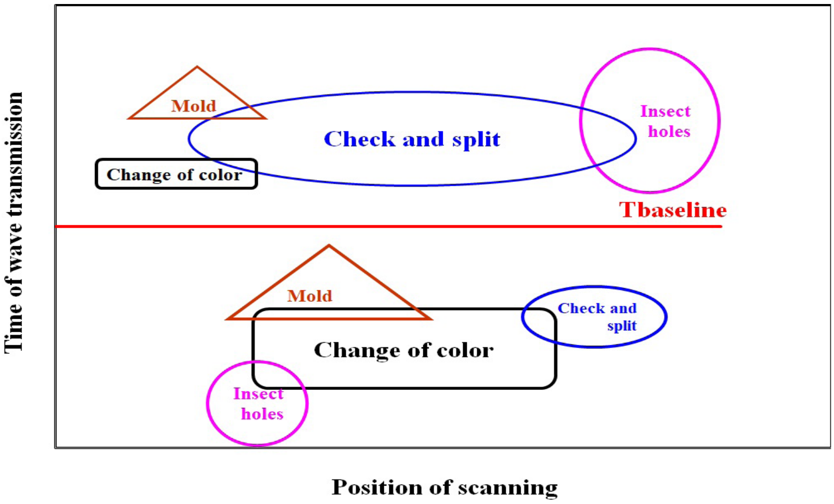


Fig. 12 Types of defects in comparison with control time (baseline).

AUTHORSHIP CONTRIBUTION

Project Idea: MM

Funding: MM

Database: MM, SE

Processing: MM, SE

Analysis: MM, SE

Writing: MM,

Review: MM, SE, AO

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