COST Action FP1101 Assessment, reinforcement and monitoring of timber structures

State of the Art Report
WG 1 / TG 2

COMBINE USE OF NDT/SDT METHODS FOR ASSESSMENT OF STRUCTURAL TIMBER MEMBERS

Editors:
José Saporiti Machado and Mariapaola Riggio

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Screw withdrawal resistances for reliability-based evaluation of timber in existing structures

Nobuyoshi Yamaguchi

Abstract

Screw withdrawal measurement is a semi-destructive testing method, which are used in detailed inspections of existing timber structures. Screw withdrawal measurements had used wood-screws for probes; the method using metric-screw type probes with short-threads has been developed. The new screw withdrawal measurements are able to estimate physical/mechanical properties of timber such as their densities and shear strengths. Distribution of properties along the timber depths is also obtained from coaxial multiple withdrawal resistance measurements. Estimated properties from these screw withdrawals are applied for the evaluation of degradation of timber structures. Benchmark method, nominal value method and structural calculation method are proposed for the evaluation. The benchmark method and nominal value method use integrity indexes of components and joints of timber structures. Properties estimated from these screw withdrawals are also used in structural calculations of existing timber structures. These indexes and results of structural calculations are applied for the evaluation of existing timber structures. Physical/mechanical properties estimated from these screw withdrawals are able to apply for reliability-based evaluation of existing timber structures.

Introduction

Scales of Inspection Objects

Timber structures use many structural timbers and other materials. The components have joints connecting them to the others. Integrity of structures is dominat-

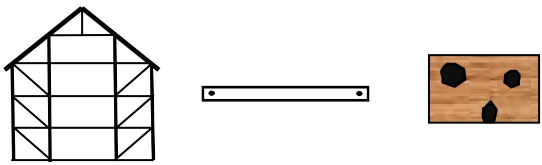


Fig. 1 Scale of Inspection Objects

ed by the integrity of their components and joints. Most of joints use fasteners such as pins, nails, bolts and metal plates, etc. Interface of these timbers and metal hardware tend to accumulate water or humidity between them, these wet/humid interfaces between them accelerate degradation of timber and fasteners. The performance of these components and joints are dominated by the integrity of their materials. **Fig.1** illustrates scale of inspection objects from structures to their materials. Integrity of structures is dominated by the integrity of their materials consequently.

Homogeneous and Inhomogeneous Degradation of Components

Homogeneous degradation of timber causes global degradation of components by weathering, aging and fungus, etc. Inhomogeneous degradation of timber causes partial degradation of components by fungus, insects, etc. Dense degradation of timber caused defects on the surface and inside of the components, and make effective cross-sectional areas of them reduced consequently. Strengths of the components are reduced by both of decrement of the cross-sectional areas and degraded stress capacity(strength) of the residual cross-sectional area of them.

Global Inspection for Screening

A flowchart of inspection and evaluation from phase 1 to 5 is proposed in **Fig.2**. In Phase 1, document and drawings on object structures, information on climate and environment and fungus/insects information around the structure are required to be accumulated as possible. Those are generally provided from owners and users of the object structures. Probable degradation areas of timber structures might be known by the people in surrounding communities empirically. Document and drawings of the structures are the bases of global inspection in Phase 2. Timber structures are composed of thousands of components; detailed inspections for all of components are not cost effective. Positions of detailed inspection are to be minimized. Screening of structures which identify the detailed inspection areas is effective to minimize the number of detailed inspections. Basic non-destructive testing methods as visual, sounding, knife test, small core sampling and others are applied for the structures. These basic inspections provide clues of probable degradation areas of the structures. Modern non-destructive testing are available such as X-ray, bore-scopes, etc [1,2]. These tests provide visual information of timbers behind finishing. Contact type non-destructive testing is able to provide visual information of components such as GPR, ultra-sound reflection tools, etc. Some semi-destructive testing is also used such as needle penetration, pin pushing, etc. Combined usage of information from owners, empirical knowledge in communities, non/semi-destructive testing will realize cost effective inspections. Global inspection will result tentative map of detailed inspection positions of the structures. Information obtained from Phase 1 and Phase 2 would be the bases for cost effective inspections.

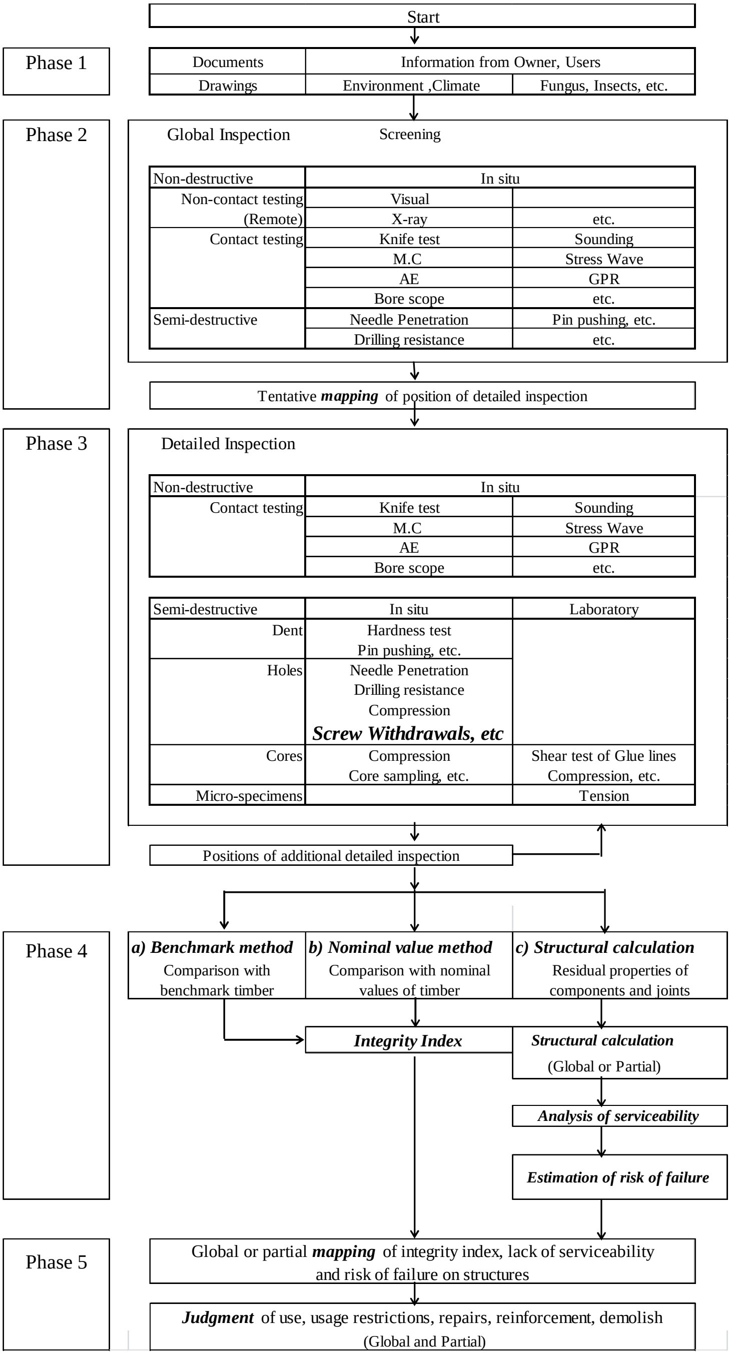


Fig. 2 Inspection and Evaluation of Timber in Existing Timber Structure

Detailed Inspections

In phase 3, detailed inspections are applied for the components and joints of structures. Physical/mechanical properties of components and joints are obtained from non/semi-destructive testing in situ and laboratories [1,3]. Non-destructive testing such as stress wave, acoustic emission (AE) tools will be available to obtain physical/mechanical properties. Semi-destructive testing such as pin pushing, needle penetration and drilling resistances will assist to estimate properties of timber. New semi-destructive testing measuring force-deformation relationship along the depths of timber is also proposed [4]. Results of detailed inspections may require additional inspection positions other than the tentative inspection positions derived from the global inspection. Physical/mechanical properties obtained from detailed inspections will be used in Phase 4.

Screw withdrawal measurements for detailed inspections

Screw withdrawal measurement is one of semi-destructive testing methods. Screw withdrawals were examined from 1980's for inspection method of timber [5,6]. Screw withdrawal measurements are one of methods which leave scars in timber as other testing methods of needle penetration, pin pushing, drilling resistance and small core sampling, etc. Screw withdrawal measurements had used wood-screws, lag-screws and nails as probes. New screw withdrawal measurements method using metric-screw type probes with short-threads have been proposed [7]. Screw withdrawals are able to provide specific densities and shear strengths of timber. Screw withdrawals also provide distribution of them along the depths in timber [7].

Judgement

After the detailed inspection in Phase 3, three evaluation methods of benchmark method, nominal value method and structural calculation method are prepared in Phase 4. Physical/mechanical properties obtained from detailed inspections are compared to the reference values in benchmark method and nominal value method. The benchmark method and nominal value method use relative comparison between residual properties and initial/original properties of timber. Estimated residual mechanical properties are also used in structural calculations.

Benchmark method

Benchmark timber is need in benchmark method. Benchmark timber is the reference selected from the same species as the object timber. The benchmark timber is required to have average properties of the object timber species. The same testing method should be applied for the measurement of properties of the object timber and the benchmark timber. Integrity index I_{BS} of benchmark method is given from **Equation (1)**. Index I_B is ratio of measured properties of the object timber and the benchmark timber, which is defined in **Equation (2).** P_r and P_B are measured properties of the object timber and the benchmark timber. Index I_S correspond to the decrement of cross-sectional areas by inhomogeneous degradation is defined in **Equation (3)**, where A_r is residual cross-sectional areas of the object timbers, and A_o is original/initial cross-sectional areas of them. Integrity of the object timber is evaluated by the integrity index I_{BS}. In case of screw withdrawal resistance measurements, index properties are withdrawal resistances both of the object timber and the benchmark timber for the same directions to the grain. Benchmark method is available for non/semi-destructive testing methods, especially for the case that nominal values of physical/mechanical properties are not listed in wood handbooks, etc.

$$I_{BS} = I_B \times I_S \tag{1}$$

$$I_B = \frac{P_r}{P_B} \tag{2}$$

$$I_S = \frac{A_r}{A_o} \tag{3}$$

Nominal value method

In case benchmark timber is difficult to prepare, nominal value method will be alternative of benchmark method. Reference for the comparison is nominal properties of the object timber species. These nominal properties are generally the average or the lower limit (5 percentile) values listed in wood handbooks, etc [8,9]. Integrity index I_{NS} of nominal value method is given from **Equation (4)**. Index I_N is ratio of the properties estimated from the object timber and nominal properties of them, which is defined in **Equation (5).** P_r is estimated properties of the object timber. P_N is nominal properties of the object timber species. Nominal value method requires less measurement works than those by benchmark method, however, need nominal properties of the object timber species. In case of screw withdrawal measurements, densities or shear strengths parallel to the grain are used for the index properties, because both of nominal values are listed in wood handbooks. Although shear strengths perpendicular to the grain is obtained from measured withdrawal resistances, the shear strengths parallel to the grain is not directly obtained from withdrawal resistances. Estimation of shear strength parallel to the grain is required in screw withdrawal measurements.

$$I_{NS} = I_N \times I_S \tag{4}$$

$$I_N = \frac{P_r}{P_N} \tag{5}$$

Structural calculation method

The other method is structural calculation. Structural calculations are applied for object structures or part of them. Structures are required to resist actual and design loads in principle. One of the methods to evaluate integrity level of existing structures is to calculate structural safety of existing structures with their residual properties against their actual and design loads. Structural calculations result stress level of components, safety level of joints, deformation of components and displacement of structures. These deformation and displacement are used for serviceability analysis of the structures. Stress level of the components and joists are used for risk analysis of failure of the structures. Structural calculations need principal mechanical property of components and joints of the object structure. Screw withdrawal measurements provide only densities and shear strengths of timber. MOR and MOE of timber are estimated from screw withdrawal resistances with velocities of stress waves. Compression of timber is also correlated with screw withdrawal resistances. Expedient inspection methods should be used for mechanical property estimation of structural components and joints. In order to estimate required mechanical properties, screw withdrawal measurements would be used with other inspection methods.

Mapping and judgement

Detailed inspections provide physical/mechanical properties of timber. These properties are used for integrity indexes of benchmark and nominal value methods. Integrity indexes, serviceability rank and risk of failure of the structures are mapped on the drawings and included in the inspection reports. Judgment for the future of the object structure is made such as use, usage restrictions, repairs, reinforcements and demolish of all or part of the structure. Value of the structures and cost of repairs and reinforcements of them are also considered for the judgements.

Methodology

PROBES

Screw withdrawal measurements had used nails, wood-screws and lag-screws. Wood-screw based probes with short-threads were developed, and probes manufactured from threaded rod with metric-screws were developed[7,10]. Shape of wood-screws is not standardized internationally; however, shape of metric-screws is standardized by ISO 261 and 724. Metric-screw probes are longer and have smaller diameters of their threads than typical wood-screws; the probes are suitable for measuring withdrawal resistances in deep of timber. The short-threads clarify measuring positions in deep timber, and reduce withdrawal resistances. Coaxial multiple withdrawal resistance measurements (CMWR) using long metric-screw type probe provide distributions of withdrawals along pre-drilled holes. The metric-screw probes have outer cylindrical shear plains around the threads. In case of timber, these shear plains have shear strengths correspond to shear directions. **Fig.3** and **Fig.4** show the probes for the screw withdrawal measurements which have short-threads and are manufactured from threaded rods of ISO standard metric-screws. Diameter, pitch and length of the probe thread in **Fig.3** was 3.87mm, 0.7mm and 12.85mm respectively. The probe has double heads of conical heads on top for withdrawing and hexagonal heads below for screwing.

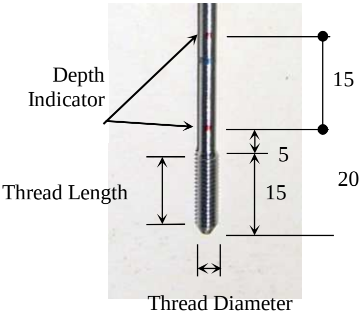


Fig 3. Short-thread of the Metric Probe

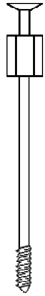


Fig.4 Metric-screw Probe with Heads for Screwing and Withdrawing

EUIPMENT

Tools for withdrawing and measuring

Two cramp types of withdrawing tools are shown. **Photo1** shows typical withdrawal tools developed by Prof. F.Divos [11]. **Photo 2** shows withdrawal tool developed for the coaxial multiple withdrawal resistant (CMWR) measurements [12]. Load-cells are installed in these tools. Peak loads are indicated on the indicators connected to the load cells. Rate of withdrawing should be constant as possible. Electric screwdrivers are able to apply constant rate of withdrawing better than that by hands.

Photo 1 Typical Withdrawal Tool

Photo 2 Withdrawal Tool for CMWR

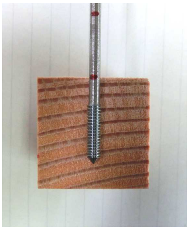
PROCEDURES

Pre-drilled holes

Wood-screws do not need pre-drilled holes, but lag-screws and metric-screw type probes need pre-drilled holes to screw them into timber. Pre-drilled holes are applied by drilling tools. These pre-drilled holes are required to be orthogonal to the surfaces of timber generally. Diameter of the pre-drilled holes used with the probes shown in **Fig.3** was 3mm.

Single Withdrawal Resistances

The probes are screwed into the pre-drilled holes by hands or electric screwdrivers, etc. Single withdrawal resistance (SWR) measurements are used for typical withdrawal measurements. The probes are screwed into timber as **Photo 3**. The probes are able to be screwed into timbers through finishing such as gypsum boards and plaster, etc. **Fig.5** shows withdrawal resistance measurements of timber behind the finishing. Multiple measurements of SWR are required to obtain reliable SWR values.



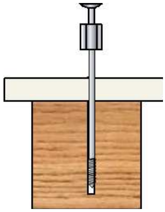


Photo 3 Single withdrawals **Fig. 5** Measurement of Timber behind Finishing

Coaxial Multiple Withdrawal Resistances

SWR is a method to measure withdrawal resistance at one depth position. In order to obtain distribution of withdrawal resistances along depth direction of timber, coaxial multiple withdrawal resistance (CMWR) measurements were developed [7,10,12]. **Fig.6** illustrates procedures of CMWR using the same pre-drilled hole. The probe in **Fig.6** equips attachment adjusting depths of the probe thread in timber. Typical procedures of CMWR are as follows. The probe is screwed into timber 20mm deep into the wood. The probe is pulled out and withdrawal-resistances are measured simultaneously by the withdrawal tools. Then the probe is removed from the hole to get rid of sawdust from the hole. The probe is then screwed in 15mm deeper than before. The probe is also pulled out and withdrawal-resistance is measured simultaneously. The probe is removed from the hole to get rid of sawdust from the hole. These procedures are repeated. Tip positions of the probes in timber will be 20, 35, 50mm depths in this case. Multiple measurements of CMWR are required to obtain reliable CMWR values.

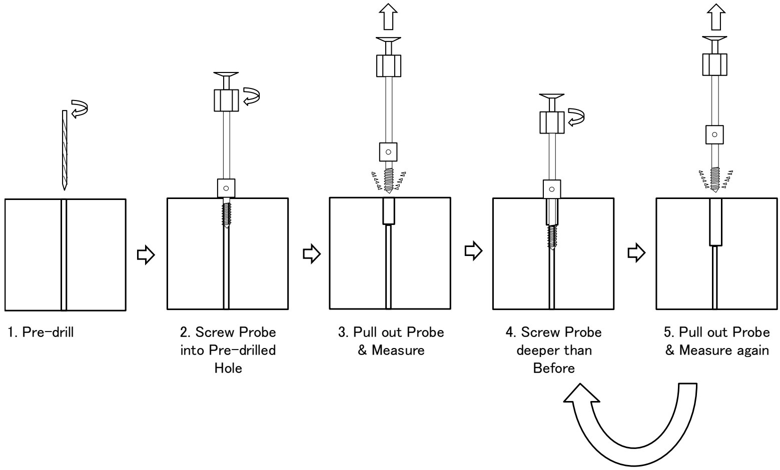


Fig. 6 Procedure of CMWR Measurement

Normalized Withdrawal Resistance (NWR)

Measured withdrawal resistances are affected by the area of outer cylindrical shear plain around the probe threads. Removing the effect of dimensions of the probe threads, measured withdrawal resistances were normalized by the outer cylindrical area of the thread. These normalized withdrawal resistance (NWR) is obtained by **Equation (6)**[12]. NWR indicates estimated shear strength of wood on the outer cylindrical shear plain shown in **Fig.7**. When the probe is screwed into the timbers from their longitudinal surfaces, direction of the estimated shear strength (NWR) will be RT-direction (radius or tangential direction = perpendicular to the grain) of timber.

$$\tau = \frac{P}{R_t \times \pi \times L_t} \tag{6}$$

τ	: Estimated shear strength (NWR)	[N/mm^2]
P	: Withdrawal resistance	[N]
R_t	: Diameter of the thread (peak to peak)	[mm]
L_t	: Length of the thread of probes	[mm]
π	: Circular Constant	

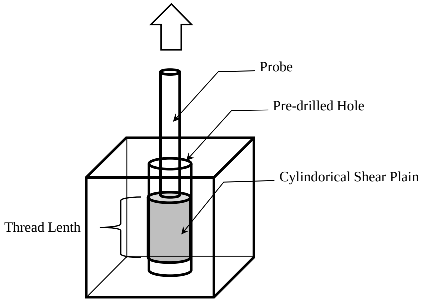


Fig.7 Cylindrical Shear Plain around Probe Thread

Application

DENSITY

Withdrawal strengths of wood-screws are correlated with densities of timber, withdrawal resistances of wood-screws are calculated using equations with density terms [8]. **Fig.8** and **Fig.9** are examples of relationship between measured densities and withdrawal strengths. **Fig.8** shows relationship between timber densities and withdrawal strengths of typical wood-screws [13]. **Fig.9** shows relationship between densities and NWR of metric-screw probes [14]. The tests in **Fig.9** used three coniferous species. NWR(–RT) in **Fig.9** means NWR for radius(R) or tangential(T) directions of timber, those are for perpendicular to the grain directions. Both figures show clear correlations between densities and withdrawals. A regression equation between densities and withdrawal strengths is proposed in **Fig.9**. A regression equation in **Fig.9** is obtained using three coniferous species totally. Withdrawal forces include the effect of thread dimensions; however, NWR exclude effects of thread dimensions.

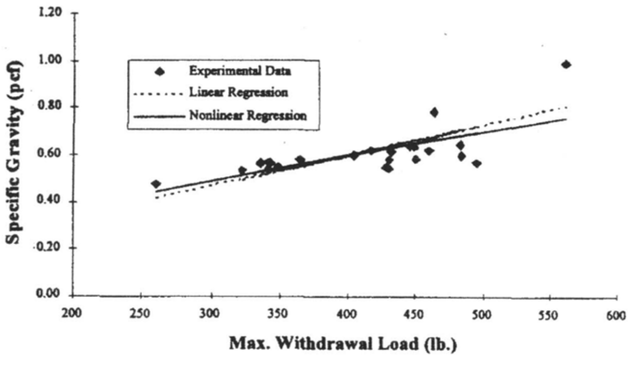


Fig. 8 Densities-Withdrawals Relationships by Wood-screws [13]

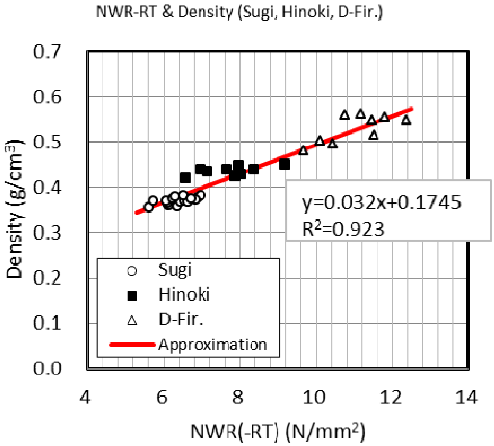


Fig.9 Densities-NWR Relationships by Metric-screws[14]

SHEAR STRENGTH

Perpendicular to grain

NWR is shear strengths on outer cylindrical plains around the threads of probes. Withdrawal measurements are applied for perpendicular to grain in general; NWRs obtained from these withdrawal measurements are for perpendicular to grain direction. Measured NWRs by withdrawal measurements are shear strength perpendicular to the grain, but it is difficult to measure shear strengths perpendicular to the grain by typical shear strength tests using chair type specimens.

Parallel to grain

Typical shear strengths of timber are those parallel to the grain. Nominal shear strengths listed in typical wood handbooks are those for parallel to the grain direction [8,9]. Nominal shear strengths are obtained from shear strength tests based on testing standards(ASTM D143, JIS Z2101). Shear testing standards uses chair type specimens which have flat shear plains, use offset distance between two loading shear plains parallel to the grain. NWR is shear strengths on cylindrical shear plains, have no offset, for perpendicular to the grain. **Fig.10** shows relationship between densities of timber and measured shear strengths(L) Sh_L parallel to the grain [14]. A regression equation between strengths(L) Sh_L and densities is proposed in **Fig.10**. A regression equation in **Fig.10** is obtained using three coniferous species totally. The specimens used for the tests of **Fig.9** and **Fig.10** were end-matched. Shear strengths(L) Sh_L are able to be calculated from NWRs of withdrawal resistances using these two regression equations shown in **Fig.9** and **Fig.10**. Regression equations in **Fig.9** and **Fig.10** are examples respectively.

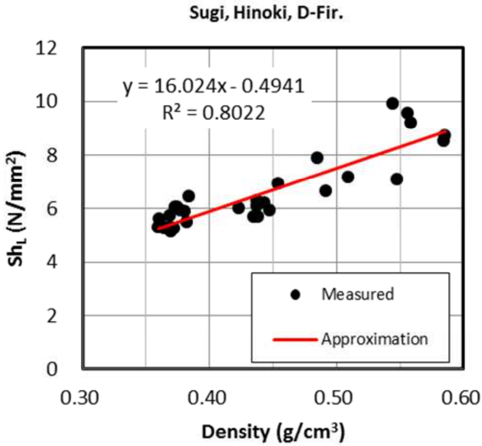


Fig. 10 Densities-Shear Strength(L) Sh_L Relationship [14]

CMWR

Fig.11 shows comparison of averaged NWRs distributed in depth direction measured by SWR and CMWR measurements. The depth direction was perpendicular to the grain. CMWR used a 105x105x105mm specimen of Douglas-fir with nine pre-drilled holes and six depth positions for CMWR measuring respectively. SWR used twenty seven 30x30x30mm specimens with a pre-drilled hole and a depth position respectively. These specimens for CMWR and SWR were cut off from the same timber. Those were also end-matched and depth-matched. NWR distribution by CMWR measurements was just about close to that by SWR measurements; distributions of NWRs for depth direction are measured by CMWR measurements [12].

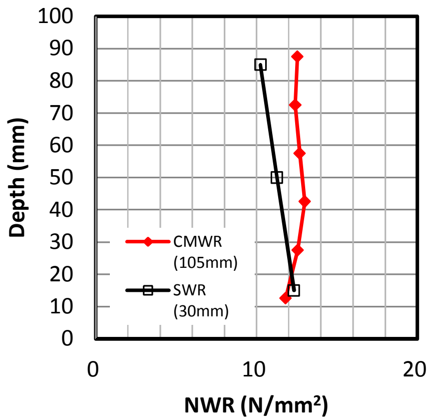


Fig.11 Distribution of NWRs by CMWR and SWR Measurements

COMPRESSION

Relationship between compression and screw withdrawal/pull-out force was studied [15]. **Fig.12** shows one of these results. The withdrawal/pull-out force values are correlated with compression strengths of timber.

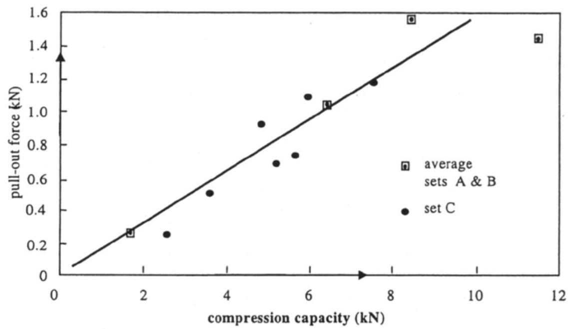


Fig.12 Compression-Pull out Force Relationship[15]

MOR

Relationship between MOR and screw withdrawal resistances is known from 1990's. F.Divos et al. proposed **Equation (7)** and **Equation (8)** which predict MOR of coniferous and hardwood species respectively. Screw withdrawal forces and velocities of stress wave are used in these equations. The applied units in these equations are: MOR[MPa], F[kN], v[km/s]. Screw withdrawal forces *F* were measured using wood-screws. Diameter and length of their threads was 4mm and 18mm. 2.7mm diameter pre-drilled hole was made in timber to accommodate screw. The results are shown in **Fig.13**. In sound wood, longitudinal transmission velocities generally fall within the range of 3.5 - 5 km/s. Screw withdrawal forces using wood-screws for transverse direction of timber generally fall with the range of 1 – 3.5 kN. These withdrawal forces are considered to be equivalent to 4.5 – 15.5 N/mm^2 of NWR. The correlation coefficient between measured and predicted MORs by **Equation (7)** and **Equation (8)** was 0.74 [1,11,16].

$$MOR = 0.809F \times v^2 + 26.8 \tag{7}$$

$$MOR = 1.258F \times v^2 + 36.9 \tag{8}$$

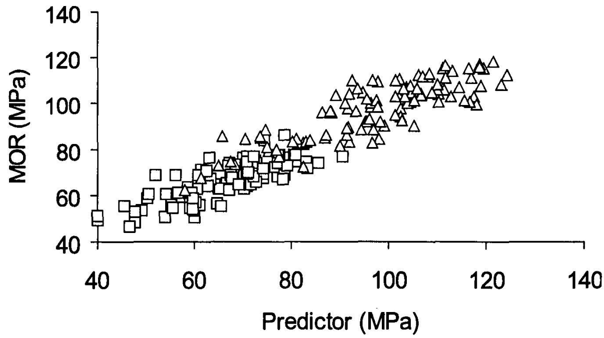


Fig.13 Measured and Predicted MOR Relationship [11]

MOE

Relationship between static MOE and screw withdrawals of timber were examined. Static MOE were correlated with dynamic MOE. Static MOE(*E)* was predicted by **Equation (9)** with regression coefficients *a* and *b*, density ρ and stress wave speed v. The densities ρ were estimated from measured screw withdrawals with their regression coefficients. Predicted MOE(*E*) was correlated with the actual static MOE [3,13].

$$E = a + b\rho v^2 \qquad (9)$$

Reliability-based Evaluation

In case that the structural performance and design loads are probabilistic, structural safety is evaluated stochastically. Reliability-based integrity analysis of existing timber structures will be realized by structural calculations using residual mechanical properties of timber obtained from detailed inspections such as screw withdrawals and others.

Further Application/Calibration of Output from Non-destructive Testing

Non-destructive testing method is expected to provide physical/mechanical properties of materials, but information obtained from non-destructive testing is limited. For example, applying screw withdrawal tests in conjunction with non-destructive testing for the same location of the same timber, relationship between non-destructive testing output and screw withdrawal resistances are obtained. Output from non-destructive testing could be calibrated by the physical/mechanical properties estimated from screw withdrawals. Calibrated output provided from non-destructive testing is more informative and useful than those without calibrations.

Limitations

Screw withdrawal is one of cost effective inspection methods. But the followings are limitations of screw withdrawals. Screw withdrawals leave holes on timber. Repair of the holes may be required. Knots are often hidden in object timber. Screw withdrawals provide very large withdrawal resistances when the probe is in and around knots hidden in object timber. These withdrawals should be eliminated preventing the false estimation of timber properties. Screw withdrawal measurements are time consuming. CMWR measurements are more time consuming than SWR. In order to obtain reliable results from screw withdrawal measurements, multiple measurements of screw withdrawals are required. Screw withdrawal measurements need skills for pre-drilling and withdrawing. Lengths of drills for the pre-drilling and metric-screw probes are limited.

References

[1] Bohumil Kasal, Thomas Tannert, In Situ Assessment of Structural Timber, Springer , RILEM State of the Art Reports, Volume 7, 2010

[2] Mariapaola Riggio, Ronald W.Anthony, Francesco Augelli, Bohumil Kasal, Thomas Lechner, Wayne Muller, Thomas Tannert, In situ Assessment of Structural Timber using Non-destructive Techniques, Materials and Structures, DOI 10.1617/s11527-013-0093-6, 2014

[3] Thomas Tannert, Ronald W.Anthony, Bohumil Kasal, Michal Kloiber, Maurizio Piazza, Mariapaola Riggio, Frank Rinn, Robert Widmann, Nobuyoshi Yamaguchi, In situ Assessment of Structural Timber using Semi-destructive Techniques, Materials and Structures, DOI 10.1617/s11527-013-0094-5, 2014

[4] Kloiber, M., Drdácký, M., Tippner, J., Sebera, V.: New construction NDT device for in situ evaluation of wood by using compression stress-deformation measurements parallel to grain. In: 18th International Nondestructive Testing and Evaluation of Wood Symposium, 2013, September 24-27, Madison, Wisconsin, USA. FPL-GTR-226: pp. 585-592.

[5] Talbot, J.W. unpublished research, Pullman, WA: Washington State University, 1982

[6] Robert J. Ross, Roy F. Pellerin, Nondestructive Testing for Assessing Wood Members in Structures, General Technical Report FPL-GTR-70, Forest Products Laboratory, US Department of Agriculture (1994)
[7] Nobuyoshi Yamaguchi, Shiro Nakajima, Hirofumi Sakuma, Inspection Method of Wood Integrity Using Distribution of Resistances to Axial Withdrawals of Wood-Screw Probes, Proceedings of 15th international symposium on non-destructive testing and evaluation of wood, Duluth (2007), pp.233-241
[8] Wood Handbook, 2010 Edition, Forest Products Society, Madison, WI, USA (2011)
[9] Wood Industry Handbook, ISBN 4-621-07411-3 C3550, Forest and Forest Products Research Institute, Maruzen, Japan (2004) in Japanese
[10] Nobuyoshi Yamaguchi, Withdrawal resistances by screw-based probes for in-situ assessment of wood, Proceedings of international conference on structural health assessment of timber structures (SHATIS'11), Lisbon (2011)
[11] Ferenc Divos, Laszlo Nemeth, Laszlo Bejo, Evaluation of the Wooden Structure of a Baroque Place in Papa, Hungary, Proceedings of 11th international symposium on non-destructive testing and evaluation of wood, Washington State University, USA (1998) , pp.153-160
[12] Nobuyoshi Yamaguchi, "In situ Assessment Method of Wood using Normalized Withdrawal Resistances of Metric-screw Type Probes", Advanced Materials Research Vol.778 (2013), pp.217-224
[13] Cai, Z., Hunt, M.O. R.J. Ross, and L.A. Soltis, Screw Withdraw-al - A Means to Evaluate Densities of In-situ Wood Members, Proceedings of the 13th International Symposium on Non-destructive Testing of Wood, Forest Products Society, Madison, USA, pp.277-281, 2002
[14] Nobuyoshi Yamaguchi, Inspection Method of Integrity of Wood Components in Existing Timber Construction (Part 4) In situ Evaluation using Screw Probe Withdrawals, (in Japanese), Summaries of Technical Papers of Annual Meeting, Structure III, Architectural Institute of Japan, 2014, in Japanese, Print Pending
[15] Gilfillan, J.R., Christie, D. and S.G. Gilbert, The Residual Strength of Timber Degraded by Woodworm Infestation, Proceedings of Durability of Building Materials and Components 8(Volume One), NRC Research Press, Ottawa, Canada, pp.714-722, 1999
[16] Ferenc Divos, Evaluation of Single Members in Historical Structures, RILEM meeting, Prague, May 30. 2005