SHATIS'17
4th International Conference on
Structural Health Assessment of Timber Structures
20-22 September 2017 Istanbul, Turkey

LOAD-BEARING CAPACITY OF HISTORIC TIMBER WITH FOCUS ON THE WOOD CORROSION

Wolfgang Rug[1], **Gunter Linke**[2]

[1] University for Sustainable Development Eberswalde, Germany, wolfgang.rug@hnee.de

[2] Ingenieurbüro Rug GmbH, Wittenberge, Germany, linke@holzbau-statik.de

Keywords: Wood corrosion, Destructive testing, Non-destructive testing, Ultrasound

Abstract. *The accurate assessment of exiting timber structures is substantial for a substance-friendly redevelopment. The first measurement is the exact determination of the timber members' properties. Visual methods are providing only insufficient reliable results. Therefore, the combination of visual and non-destructive/semi destructive methods is required. The use of ndt/sdt methods allows determining the material properties and their variation. The present study deals with preliminary investigations of the ultrasonic method concerning their applicability for the determination of the load-bearing capacity of timber with special focus on the influence of chemically-aggressive media. Subject of the study were timber members (spruce, glulam & solid wood) which served 98 years in a salt warehouse. The timber was visibly affected by wood corrosion. To evaluate the applicability of the ultrasonic method comparative tests have been carried out (ultrasonic measurements, determination of the density and flexural test according EN 408). The test results revealed a relatively weak correlation between the ultrasonic speed and the other properties. However, it must be considered that the ultrasonic speed has been measured in the unaffected core of the specimen. The strength and stiffness was clearly reduced due to the wood corrosion in the peripheral cross section. The strength and stiffness of the undamaged core can be determined sufficiently accurate with the ultrasonic method. Based on these results a recommendation for the application of the ultrasonic method in timber structures with wood corrosion can be provided. The ultrasonic method is used to determine the strength and stiffness of the unaffected core. Additionally, the density can be determined by core-drilling. The thickness of the corrosion layer should be determined with the dynstat method which has been verified in previous studies. With a sufficient sample and the evaluation of the material properties variation the stability of the construction can be accurately evaluated.*

1 INTRODUCTION

The invention of the glued laminated timber by Otto Hetzer in 1906 allowed the building wide-spanning constructions [1-4]. Amongst others this innovative construction method was used to erect halls in the fertilizer and potassium salt industry, which is proven until today by several preserved buildings (see also www.otto-hetzer.de).

However, this field of application subjects the timber to particular environmental conditions [5]. The production processes as well as stored substances are releasing chemically-aggressive media, which can cause irreversible structural modifications of the wooden members. The modification of the wood due to chemically-aggressive media is not taken into consideration in the static calculations according the currently valid version of the Eurocode 5 [6]. Some suggestions concerning this problem are listed in [5].

Though, the knowledge of the degree of the modification is a significant requirement for static calculations concerning the load bearing capacity especially in the course of redevelopment or reconstruction.

2 WOOD CORROSION

Timber has a natural chemical balance. This makes timber highly resistant against chemically-aggressive media. If the correct environmental conditions are present, the wooden members will be subjected to corrosion [5].

The wood corrosion is a structural damage beginning on the surface, which is caused by chemical and physical reactions. These reactions are caused in particular by strong acidic and strong alkaline media (pH ≤ 2 respectively pH ≥ 11). If the corrosion is caused by salts, the cell structure is destroyed by crystallization processes. The lignin and the hemicelluloses are degradated due to hydrolytic splitting.

Several studies on timber constructions under influence of chemically-aggressive media have shown that the destructive mechanism is dependent on the type of the impacting media [5]. The level of the destruction depends on the several aspects. These aspects could also be called a corrosion system, which is depicted in Figure 1.

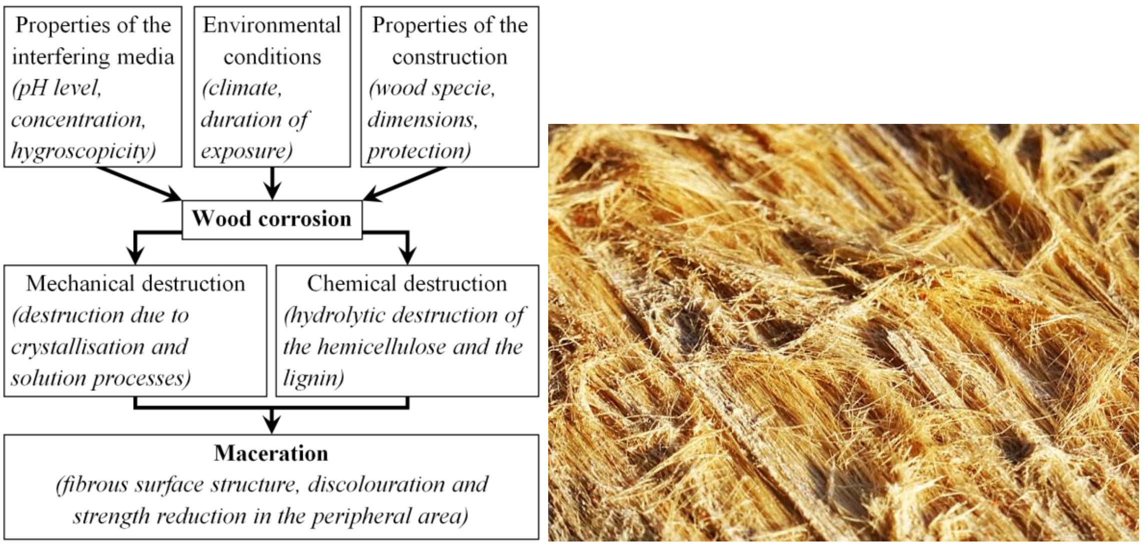

Figure 1: wood corrosion; left: schematic depiction; right: maceration on the surface

The studies carried out so far have shown that the alteration respectively destruction of the wood structure is limited to the cross-section near the surface. This destruction is visible by a greyish-brown discolouration and a fibrous surface structure. In some cases, the separation of whole strips of wood along the annual ring limits was observed. Furthermore, the peripherical cross-section shows a reduction of the strength. In the inner cross-section, there is no such strength reduction.

Glued laminated timber has a higher resistance concerning the wood corrosion if large, compact members are used and no large shrinkage cracks are appearing. Furthermore, the type of glue significantly influences the resistance against chemically-aggressive media.

3 SUBJECT AND AIM OF THE STUDY

The effect of the salts on the load bearing capacity of the historic timber and glued laminated timber has been examined in a number of studies [7-10]. The focus laid on the extent of the corrosion layer [7], the remaining strength of the historic casein glued joints [8] as well as the load-bearing capacity of solid timber and glulam members [9, 10]. The latter is outlined in the following.

The studies were divided in the determination of the material properties, which are required for strength grading – density, bending strength and modulus of elasticity – according EN 408 [13] as well as non-destructive ultrasonic measurements. The results should be used as a basis for future investigations concerning the structural stability of existing glued laminated timber constructions which are additionally stressed by chemically-aggressive media.

The study’s subject was a warehouse erected in 1912 by the use of the HETZER-construction method. The load-bearing structure of the warehouse consisted of eleven parabolic trusses made from glued laminated timber according to the patent DRP. 197773 [4]. The trusses (wood species: spruce) had a double-T cross-section (see Figure 2). After the demolition of the ware house in April 2010 several parts of the construction have been transferred to the University of Applied Sciences, Eberswalde/ Germany (HNE Eberswalde) to carry out technical studies on the wooden members.

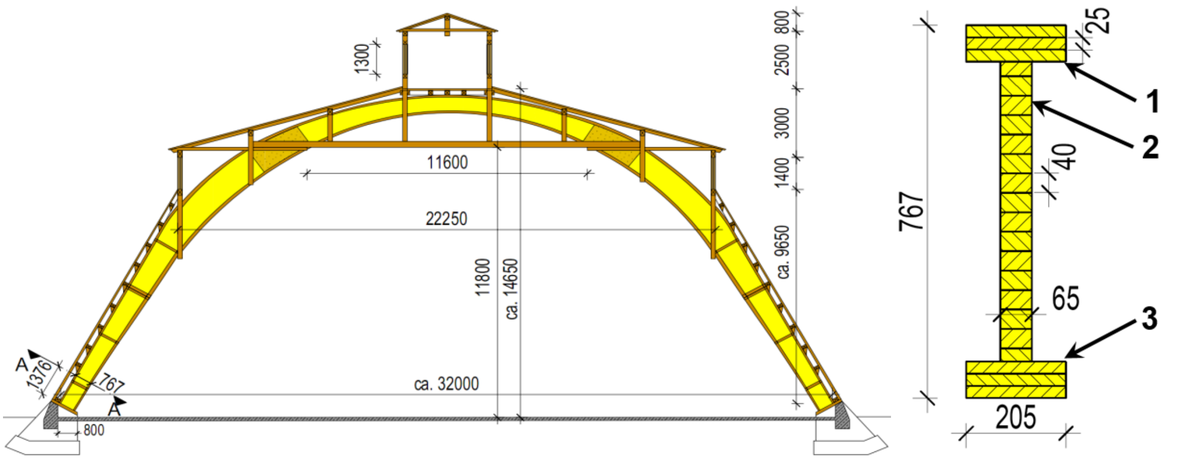

Figure 2: left: view on the truss construction; right: sectional view A-A – 1: top chord; 2: web; 3: bottom chord (all dimensions in mm)

The material had clearly visible marks of corrosion. The surface was greyish-brown discoloured and fibrous. The discolouration reached a depth of 20-25mm from the surface. Furthermore, the already mentioned separation of wooden strips could also be found. The Figure 3 shows the macroscopic appearance of the sample material exemplarily.

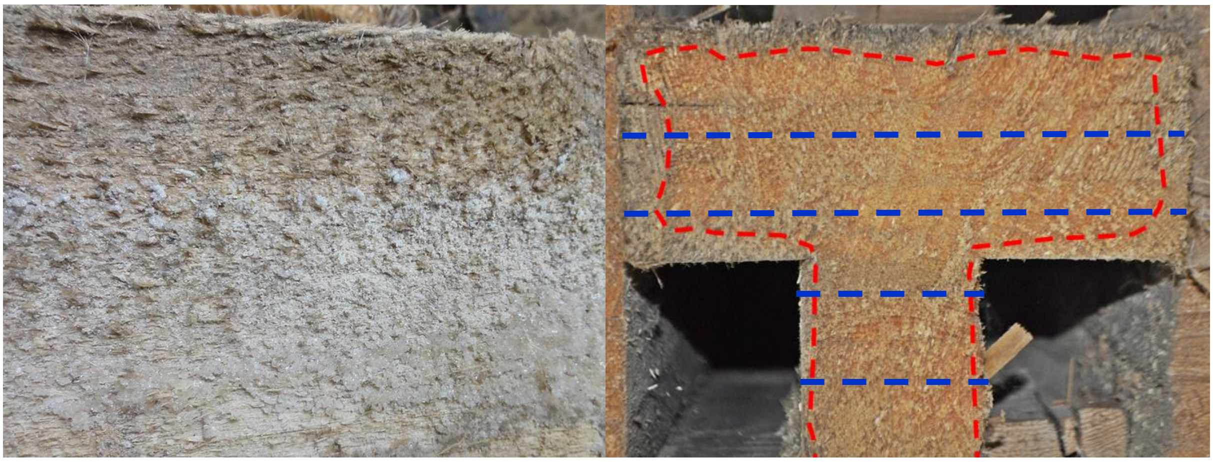

Figure 3: left: fibrous surface structure and greyish discolouration as well as salt deposits on the surface; right: sectional view on a chord and the web (the borders of the discolouration are marked in red, the glued joints are marked blue)

4 RESEARCH METHODOLOGY

4.1 Sampling

The material tests have been conducted on large scale specimen. Therefore, forty specimens were cut from the solid timber and glulam members who were salvaged after the demolition of the construction. Table 1 gives an overview on the amount and the dimensions of the examined specimen.

Table 1: dimensions of the examined specimen

Sample series	Sample size	dimensions b/h/ℓ [mm]	remarks
Solid timber	10	104/134/2376	
	30	86/176/2910	
glulam	10	65/141/2300	min. 3 lamellas per specimen
	30	63/100/1605	min. 3 lamellas per specimen

4.2 Determination of material properties according to EN 408

The main part of the comparative study was the determination of the material properties which are required for the classification according to EN 338 [11] (strength classes for solid timber) respectively EN 14080 [12] (strength classes for glued laminated timber). For this purpose the properties listed below are required to assign the samples to one of the strength classes in accordance with EN 338:2010 [11], article 6.2.2 as well as EN 14080:2013 [12], article 5.1.6.3:

1. characteristic value of the density ρ_k
2. characteristic value of the bending strength $f_{m,k}$
3. mean value of the modulus of elasticity parallel to the fibre direction $E_{0,mean}$

The bending strength as well as the modulus of elasticity was determined with the test method described in EN 408:2012 [13], articles 10 and 19. This test method is also known as 4-point bending test. This means that the specimen is placed on two supports while the test load is applied on two points on the top surface of the specimen (see Figure 4).

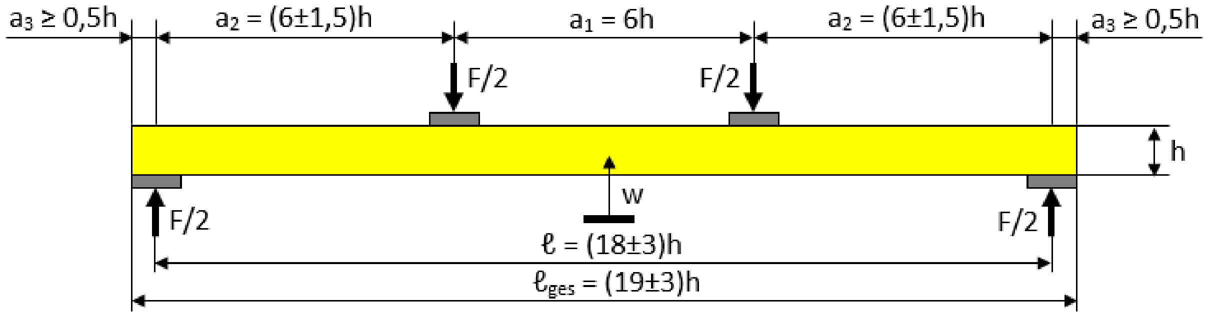

Figure 4: Test setup for the 4-point bending test according to EN 408:2012 [13], articles 10 and 19

The test load is applied with a constant velocity which is adjusted in a manner that the rupture of the specimen occurs after t = (300±120)s. During the tests the test load was measured with a digital load cell. The deflection in the middle of the specimen's span width was measured with two incremental position sensors.

The bending tests have been accompanied by the determination of the density according to EN 408:2012 [13], article 7 and the moisture content according to EN 13183-1:2002 [14].

4.3 Ultrasonic time-of-flight measurements

In advance of the bending tests ultrasonic time-of-flight measurements have been carried out on the specimen. The ultrasonic time-of-flight measurement is a non-destructive test method for the reliable determination of the physical and mechanical properties of timber members. The advantage of this test method is that it can be applied on timber members in existing constructions with relatively small. The knowledge of the limiting parameters is a necessary requirement for the reliable application.

Several studies concerning the application of the ultrasonic time-of-flight measurement for the strength grading of timber have been published in the last decades. The majority of these studies were carried out on new timber. There are only few studies regarding the application of this test method for the determination of material properties of old timber in existing constructions. Furthermore, these studies had a limited sample size and were object-related. Extensive systematically studies are still lacking until today (see [15]). This is particularly valid for timber members which were exposed to chemically-aggressive media.

The ultrasonic velocity of the sample material has been determined using the Sylvatest Trio (CBT CBS, Lausanne/CH, see Figure 5).

Figure 5: ultrasound measuring instrument Sylvatest Trio (CBT CBS, Lausanne/CH); left: measuring apparatus; right: measuring cables with transmitting and receiving probe

The time-of-flight of the ultrasonic impulse was measured directly (the probes were placed on both ends parallel to the grain) and indirectly (the probes were placed on one surface in an angle of 30° to the grain) in the longitudinal direction of the specimen (see Figure 6).

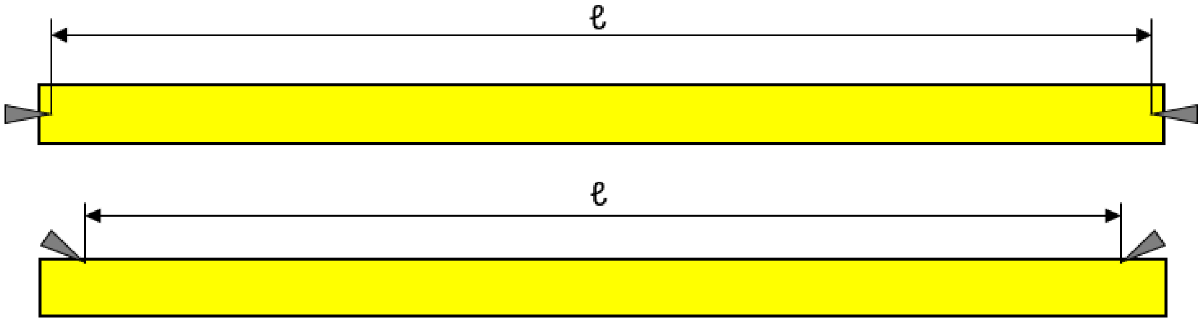

Figure 6: measuring setup; top: direct longitudinal measurement; bottom indirect longitudinal measurement

The environmental climate as well as the moisture content was determined in addition to the time-of-flight measurements and to interpret respectively to adjust the measured ultrasonic velocity. The environmental climate was determined with a digital thermo hygrometer (GANN Hydromette BlueLine Compact). The moisture content estimated by measuring the electrical resistance according to EN 13183-2:2002 [16] using the GANN Hydromette HT 85 with insulated electrodes (t = 45mm). The measured ultrasonic velocity has then been adjusted to reference conditions of ω = 12% (see equation (1)) and υ = 20°C (see equation (2)) with the empiric equations given in [17].

$$v_{12} = v_{\varpi} + 29 \cdot (\varpi - 12) \quad (\text{für } \varpi \leq 32\%) \tag{1}$$

where: v_{12} … ultrasonic velocity for ω = 12%; v_{ω} … ultrasonic velocity for $\omega \neq$ 12%; ω … moisture content

$$v_{20} = v_{\upsilon} \Big/ \left[1 - 0{,}0008 \cdot (\upsilon - 20)\right] \quad (\text{für } \varpi = 12\%) \tag{2}$$

where: v_{20} … ultrasonic velocity for υ = 20°C; v_{υ} … ultrasonic velocity for $\upsilon \neq$ 20°C; υ … temperature

5 RESULTS & DISKUSSION

5.1 Failure behaviour

Usually only bending failures have to be expected in a 4-point bending test since the central part where the test load is applied is free of shear stress due to the test setup. The maximum of the shear stress is located at the supports. There, a shear failure can appear when the specimen has relatively low shear strength.

The tested sample material has shown inconsistent failure behaviour. The solid timber specimen failed mainly due to bending stress. Only five out of forty specimens have shown combined failure behaviour (see Figure 7).

Figure 7: exemplary illustration of a combined failure – sample series „solid timber“; left: bending failure between the support and the load application; right: shear failure along the growth rings on the support of the same specimen

Twenty of the forty tested glulam specimen failed due to bending stress. The other twenty specimens failed due to shear stress or showed a combined shear and bending failure behaviour (see Figure 8).

Figure 9: exemplary illustration of a combined failure – sample series „glulam“; left: bending failure in the centre of the specimen; right: combined failure with a bending failure beneath the load application and a shear failure along the glued joint

Generally, the sample material has shown typical fracture behaviour for macerated timber. The fractures were short-fibred and brittle. In some cases, wooden strips broke loose along the growth rings.

5.2 Density, bending strength and modulus of elasticity

The test result had to be adjusted due to a moisture content of $\omega \neq 12\%$. The adjustment was carried out according to EN 384:2010 [18], article 5.3.4.2 as listed below:

- Density: reduction by 0,5% per %-point moisture content above $\omega = 12\%$; increase by 0,5% per %-point moisture content below $\omega = 12\%$
- Bending strength: no adjustment needed
- Modulus of elasticity: reduction by 1,0% per %-point moisture content below $\omega = 12\%$; increase by 1,0 % per %-point moisture content above $\omega = 12\%$

After the adjustment to a reference moisture content of $\omega = 12\%$ the test results have been examined concerning statistical outliers according to the GRUBBS test. In the result no statistical outliers have been found.

The results of the statistical analysis of the adjusted physical and mechanical properties are listed in the tables 2 & 3.

Table 2: results of the statistical analysis of the density, bending strength and modulus of elasticity – sample series „solid timber“

	Density ρ [kg/m³]	Bending strength f_m [N/mm²]	Modulus of Elasticity E_m [N/mm²]
Quantity	40	40	40
Minimum	348,8	18,7	6009,1
Mean value	421,9	38,7	11225,4
Maximum	508,8	67,8	20614,8
Standard deviation	33,1	12,1	2836,6
Variation coefficient	7,8%	31,3%	25,3%
Characteristic value	379,6	19,2	11903,0

Table 3: results of the statistical analysis of the density, bending strength and modulus of elasticity – sample series „glulam“

	Density ρ [kg/m³]	Bending strength f_m [N/mm²]	Modulus of Elasticity E_m [N/mm²]
Quantity	40	40	40
Minimum	376,5	9,8	6143,4
Mean value	458,7	42,1	8919,4
Maximum	567,4	66,4	12104,6
Standard deviation	48,0	12,4	1426,1
Variation coefficient	10,5%	29,4%	16,0%
Characteristic value	377,6	19,1	6519,6

The statistical distribution of the material properties bending strength and modulus of elasticity are exemplary shown in figure 10.

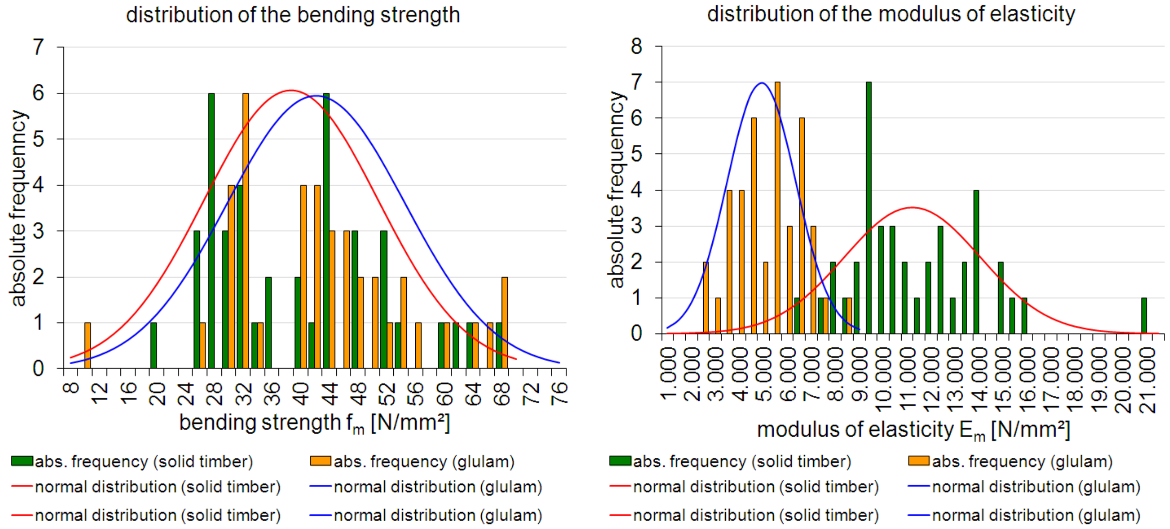

Figure 10: distribution of the bending strength and the modulus of elasticity

The evaluation of the test results is carried out as a comparison with the material properties of solid timber and glulam timber according to EN 338:2010 [11] and EN 14080:2013 [12]. The characteristic values of the tested sample material’s properties were determined according to EN 384:2010 [18] (solid timber) as well as EN 14358:2007 [19] (glulam). The characteristic values are listed in table 2 & 3.

To assign the sample material to a certain strength class according to EN 338:2010 [11], article 6.2.2 respectively EN 14080:2013 [12], article 5.1.6.3.2 the characteristic values of the density ρ_k and the bending strength $f_{m,k}$ as well as the mean value of the modulus of elasticity $E_{0,mean}$ at least have to equal the characteristic and mean values of the corresponding strength class. In the case of solid timber the mean value of the modulus of elasticity has to equal at least 95% of the modulus of elasticity of a certain strength class.

The tested solid timber specimen can be assigned to the strength class C18 according to EN 338:2010 [11]. The characteristic bending strength is decisive for this assignment. Considering the characteristic density and the mean value of the modulus of elasticity an assignment to the strength class C30 are possible (see table 4).

Table 4: comparison between the characteristic values of the tested sample material (sample series „solid timber") and the characteristic values of solid timber of the strength classes C18, C24, C27 and C30 according to EN 338:2010 [11]

	solid timber	C18	C24	C27	C30
Density ρ_k [kg/m³]	379,6	320	350	370	**380**
Bending strength $f_{m,k}$ [N/mm²]	19,2	**18**	24	27	30
Modulus of elasticity $E_{0,mean}$ [N/mm²] (95% of the modulus of elasticity)	11903	9000 (8550)	11000 (10450)	11500 (10925)	**12000** **(11400)**

The tested glulam specimen cannot be assigned to a strength class according to EN 14080:2013 [12]. The characteristic bending strength as well as the mean value of the modulus of elasticity is decisive for this assignment. Considering the characteristic density an assignment to the strength class GL22h is possible (see table 5).

Table 5: comparison between the characteristic values of the tested sample material (sample series „glulam") and the characteristic values of homogeneous glulam of the strength classes GL20h, GL22h and GL24h according to EN 14080:2013 [12]

	glulam	GL 20h	GL 22h	GL 24h
Density ρ_k [kg/m³]	377,6	340	**370**	370
Bending strength $f_{m,k}$ [N/mm²]	19,1	20	22	27
Modulus of elasticity $E_{0,mean}$ [N/mm²]	6519,6	8400	11000	11500

The fact that the tested glulam specimen could not be assigned to a strength class of modern days homogeneous glued laminated timber according EN 14080:2013 [12] illustrates the necessity of a closer inspection of historic glulam constructions to exactly asses the material properties in the course of redevelopment or reconstruction projects.

5.3 Ultrasonic time-of-flight measurements

The comparative ultrasonic time-of-flight measurements have been evaluated with a linear regression analysis between the results of the time-of-flight measurements and the physical-mechanical material properties density, bending strength and modulus of elasticity. The correlation coefficients as well as the regression equations are listed below in table 6.

The correlation and regression analysis revealed that the relation between the measured ultrasonic velocity and the physical-mechanical properties of the sample material are partially very weak. Especially the relation between the ultrasonic velocity and the density of the solid timber specimen (directly & indirectly measured) and the glulam specimen (indirectly measured). The remaining correlation coefficients have a value between r = 0,147-0,470 which is a medial value at best.

Table 6: results of the correlation and regression analysis

Sample series “solid timber”	Directly measured ultrasonic velocity v_{dir}	Indirectly measured ultrasonic velocity v_{ind}
Density ρ	$r = 0{,}010$ $\rho = 0{,}002v_{dir} + 412{,}1$	$r = 0{,}097$ $\rho = 0{,}013v_{ind} + 352{,}3$
Bending strength f_m	$r = 0{,}287$ $f_m = 0{,}017v_{dir} – 59{,}8$	$r = 0{,}441$ $f_m = 0{,}021v_{ind} – 77{,}7$
Modulus of elasticity E_m	$r = 0{,}147$ $E_m = 2{,}041v_{dir} – 600{,}2$	$r = 0{,}323$ $E_m = 3{,}583v_{ind} – 8737{,}7$
Sample series “glulam”	**Directly measured ultrasonic velocity v_{dir}**	**Indirectly measured ultrasonic velocity v_{ind}**
Density ρ	$r = 0{,}379$ $\rho = 0{,}119v_{dir} – 239{,}1$	$r = 0{,}037$ $\rho = 0{,}007v_{ind} + 415{,}4$
Bending strength f_m	$r = 0{,}374$ $f_m = 0{,}030v_{dir} – 135{,}3$	$r = 0{,}340$ $f_m = 0{,}017v_{ind} – 60{,}2$
Modulus of elasticity E_m	$r = 0{,}470$ $E_m = 4{,}409v_{dir} – 16843{,}3$	$r = 0{,}323$ $E_m = 2{,}360v_{ind} – 5025{,}6$

The reason for such weak relations can be found in the effect of the chemically-aggressive media. The alteration respectively damage of the sample material due to the chemically-aggressive media in the peripheral cross section could not be exactly measured with the ultrasonic time-of-flight measurements. In fact, the measured ultrasonic velocity represents the unaffected core of the cross section whereas the determined material properties density, bending strength and modulus of elasticity are significantly affected by the chemically-aggressive media.

Previous studies on the extent of the alteration have revealed a thickness of the so-called corrosion layer of t = 5-10mm. Such a significant reduction of the load-bearing cross section has a clear effect on the mechanical properties. The same applies for the increased density under consideration of the determined salt content of up to 13% in the peripheral cross section (see [7]).

The regression equations for the bending strength and the modulus of elasticity of the tested sample material in comparison of the regression equations for new, unaffected spruce according to [20] are exemplary shown in figure 11. It is therefore obvious that the equations which were determined for bending strength of the tested sample material are quite congruent compared to the equations in [20]. Concerning the modulus of elasticity at least a similar progression can be recognised. Therefore it can be concluded that despite the weak correlation relation the ultrasonic time-of-flight measurement is an appropriate non-destructive test method to determine the strength respectively stiffness of the unaffected core section of solid timber and glulam members which have been exposed to chemically-aggressive media.

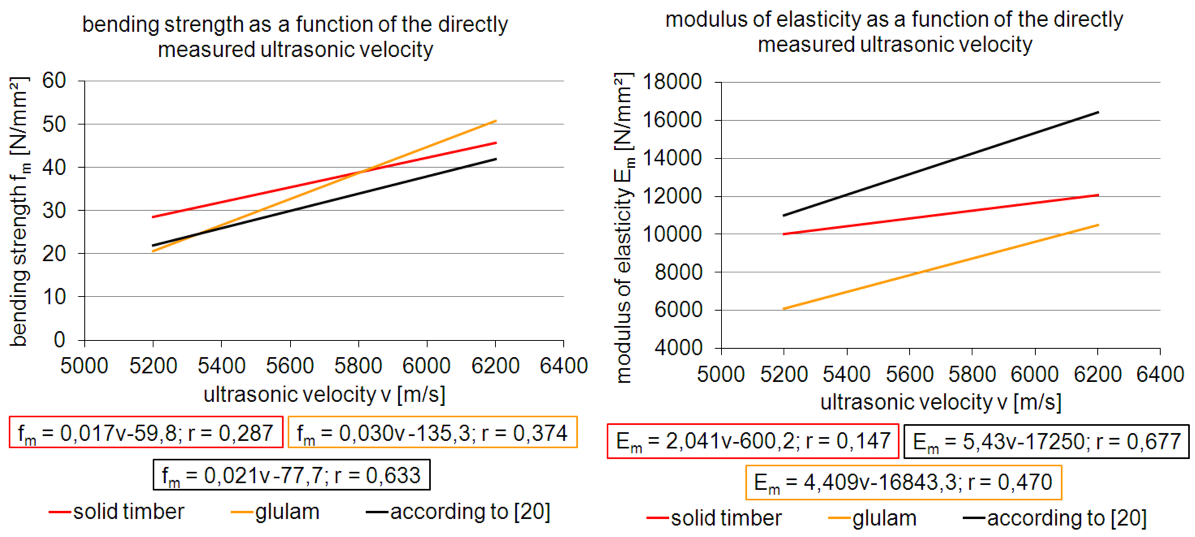

Figure 11: regression equations for the bending strength and the modulus of elasticity of the tested sample material and according to the literature [20]

6 CONCLUSIONS

The results of this study have proven the effected of chemically-aggressive media on the load-bearing capacity of solid timber and glulam which is apparent in the macroscopic alteration and destruction of the peripheral cross section as well as in the reduction of the strength and stiffness of the sample material.

A comparison with the normatively regulated characteristic material properties of new, unaffected solid timber and glulam clarifies this result.

The significant alteration respectively degradation of the material makes a detailed inspection of comparable existing structures in the course of redevelopment and reconstruction absolutely necessary. The particular focus has to be laid on the exact determination of the existent material properties.

The comparatively carried out ultrasonic time-of-flight measurements have shown that the damage of the material due to the effect of the chemically-aggressive media is could not be determined with this particular test method. The measured ultrasonic velocity represents the strength and stiffness of the unaffected core section.

Therefore, studies on comparable constructions should be carried out in the following manner:

- The extent of the damage – i.e. the thickness of the corrosion layer – can be precisely determined on drill cores with the help of the dynstat method
- The strength and stiffness of the unaffected core section can be measured with the ultrasonic time-of-flight measurement
- The density should be determined on drill cores as well

With a sufficient sample size the stability and load-bearing capacity of the construction can be exactly assessed and evaluated.

ACKNOWLEDGMENT

This study was financed by private donations. The authors would like to thank the donors for the generous support.

LITERATUR

[1] Rug, W. 1994. „Innovation im Holzbau – Die Hetzerbauweise (Teil 1)“. *Bautechnik* 71(4), PP: 213–219.

[2] Rug, W. 1995. „Innovation im Holzbau – Die Hetzerbauweise (Teil 2)“. *Bautechnik* 72 (4), PP: 231–241.

[3] Rug, W. 2006. „100 Jahre Hetzer-Patent“. *Bautechnik* 83(8), PP: 533–540.

[4] DRP. 197773. 1906. Gebogener Holz-Bauteil für vereinigte Dach-Pfosten und -Sparren

[5] Rug, W. and Lißner, A. 2011. “Untersuchungen zur Festigkeit und Tragfähigkeit von Holz unter dem Einfluss durch aggressive Medien“. *Bautechnik* 88(3),PP: 177–188.

[6] DIN EN 1995-1-1:2010 – Eurocode 5: Bemessung und Konstruktion von Holzbauten – Teil 1-1: Allgemeines – Allgemeine Regeln und Regeln für den Hochbau.

[7] Rug, W., Linke, G. and Lißner, A. 2016. “Studies on the wood corrosion on a historic glulam-construction”. World Congress on Timber Engineering 2016, Vienna (Austria), PP: 3048-3057

[8] Linke, G. 2016. “Study on the glued joints of historical glued laminated timber”. Young Engineers Colloquium 2016, Hamburg (Germany)

[9] Haupt, M. 2013. “Festigkeitsuntersuchungen an historischem Brettschichtholz”. Diploma thesis. University of sustainable Development, Eberswalde (Germany)

[10] Piotter, L. 2014. “Festigkeitsuntersuchungen an mazeriertem Vollholz”. Diploma thesis. University of sustainable Development, Eberswalde (Germany)

[11] DIN EN 338:2010 – Bauholz für tragende Zwecke – Festigkeitsklassen

[12] DIN EN 14080:2013 – Holzbauwerke – Brettschichtholz und Balkenschichtholz – Anforderungen

[13] DIN EN 408:2012 – Holzbauwerke – Bauholz für tragende Zwecke und Brettschichtholz – Bestimmung einiger physikalischer und mechanischer Eigenschaften

[14] DIN EN 13183-1:2002 – Feuchtegehalt eines Stückes Schnittholz – Teil 1: Bestimmung durch Darrverfahren

[15] Linke, G., Rug, W. and Pasternak, H. 2017. “Festigkeitssortierung von Bauholz in historischen Gebäuden – Bericht zum Stand der Technik”. *Bauingenieur 92* (05-2017), in preparation

[16] DIN EN 13183-2:2002 – Feuchtegehalt eines Stückes Schnittholz – Teil 2: Schätzung durch elektrisches Widerstands-Messverfahren

[17] Sandoz, J.-L. 1993. „Moisture content and temperature effect on ultrasound timber grading“. Wood Science and Technology 27 (5), PP: 373-380

[18] DIN EN 384:2010 – Bauholz für tragende Zwecke – Bestimmung charakteristischer Werte für mechanische Eigenschaften und Rohdichte

[19] DIN EN 14358:2007 – Holzbauwerke – Berechnung der 5%-Quantile für charakteristische Werte und Annahmekriterien für Proben

[20] STEIGER, R.1991. „Festigkeitssortierung von Kantholz mittels Ultraschall“. *Holz-Zentralblatt Nr. 59* (1991), PP: 985-989