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RELIABILITY OF THE THERMAL TREATED TIMBER AND WOOD-BASED MATERIALS IN HIGH TEMPERATURES

NIEZAWODNOŚĆ KONSTRUKCYJNA DREWNA MODYFIKOWANEGO TERMICZNIE I MATERIAŁÓW DREWNOPOCHODNYCH W PODWYŻSZONYCH TEMPERATURACH*

Existing wood and wood-based materials have had several drawbacks limiting their use, which in consequence resulted in replacing them by other materials. The most significant problems were limitations regarding maximum dimensions of the components cross – section and capabilities of manufacturing of the large-scale components. Durability and flammability of surfaces were the limiting factors as well. Nowadays, thermally treated wood and wood composites are more and more commonly used in the engineering constructions, such as: glued laminated timber (GL), laminated veneer lumber (LVL) and thermally treated timber (TT). The timber undergoes a process of thermal degradation. In high temperatures timber structure is subject to simultaneous influence in the form of forces and thermal impacts. These factors influence stress distribution in the wood structure and limit its load capacity, reflecting structure decohesion. The aim of the presented studies was to determine impact of increased temperatures on strength of the wood materials and wood-based composites. Additionally, based on the results of the strength studies, analysis of the probability of survival in high temperatures was performed. Samples used in the static bending strength studies were made of the laminated veneer lumber – LVL, glued laminated pine timber – GL, and thermally treated – TT and non-treated spruce timber - NTT. The samples were in a cuboidal shape with dimensions of 20x20x300 mm. The evaluation of bending strength was performed by means of the universal strength device - FPZ 100/1 (VEB Thuringer Industriewerk Rauenstein, Germany). Fire temperatures conditions were simulated by blowing hot air (GHG 650 LCE). The studies were conducted in the following temperature ranges: 20, 50, 100, 150, 200 and 230°C. Based on the obtained results a reliability analysis was performed. For the analysis a two-parameter Weibull distribution was applied. In case of materials with laminated structure – LVL and GL, an increase in standard deviation of the results of bending strength in the successive temperature ranges has been observed. Higher values of shape parameter c of Weibull distribution have been demonstrated for TT spruce timber (the highest c = 5.58) and NTT (the highest c = 3.31).

***Keywords**: Fire temperatures, thermally treated timber (TT), glued laminated timber (GL), laminated veneer lumber (LVL), reliability, bending strength.*

Dotychczasowe materiały drewniane i drewnopochodne miały wiele wad ograniczających ich zastosowanie, co prowadziło do zastępowania ich innymi. Największy problem stanowiły ograniczenia, co do maksymalnych wymiarów przekroju elementów oraz możliwości wykonywania elementów o znacznych rozpiętościach, również trwałość powierzchni a także łatwopalność ograniczały zastosowanie. Obecnie w konstrukcjach inżynierskich coraz częściej wykorzystuje się drewno modyfikowane termicznie oraz materiały drewnopochodne m.in. drewno klejone warstwowo (GL), drewno fornirowane warstwowe (LVL) oraz drewno modyfikowana termicznie (TT). Drewno jest materiałem ulegającym termicznej degradacji. W warunkach oddziaływania wysokich temperatur konstrukcja drewniana jest poddana jednoczesnym wymuszeniom w formie sił oraz oddziaływaniom termicznym. Oddziaływanie tych dwóch czynników wpływa na rozkład naprężeń w strukturze drewna oraz ogranicza nośność konstrukcji, powodując de kohezję struktury. Celem prezentowanych badań było określenie wpływu podwyższonych temperatur na wytrzymałość materiałów drewnianych i drewnopochodnych. Ponadto, na podstawie wyników badań wytrzymałości przeprowadzono analizę prawdopodobieństwa przetrwania w podwyższonych temperaturach. Próbki do badań wytrzymałości na zginanie statyczne zostały wykonane z drewna fornirowego warstwowego – LVL, drewna sosny pospolitej klejonego warstwowo – GL oraz drewna świerkowego poddanego – TT i niepoddanego modyfikacji termicznej – NTT, w formie prostopadłościanów o wymiarach 20x20x300mm. Oceny wytrzymałości na zginanie dokonano na uniwersalnej maszynie wytrzymałościowej FPZ 100/1 (VEB Thuringer Industriewerk Rauenstein, Germany). Temperatury środowiska pożaru symulowano za pomocą nawiewu gorącego powietrza (GHG 650 LCE). Oceny dokonywano w zakresach temperatur: 20, 50, 100, 150, 200, 230°C. Uzyskane wyniki posłużyły ocenie niezawodności. W analizie wykorzystano dwuparametrowy rozkład Weibulla. W przypadku materiałów o strukturze laminowanej – LVL i GL zaobserwowano wzrost odchylenia standardowego wytrzymałości na zginanie w kolejnych zakresach temperatur. Wyższe wartości parametru kształtu c Rozkładu Weibulla zostały wykazane dla świerku TT (najwyższe c = 5.58) i NTT(najwyższe c = 3.31).

***Słowa kluczowe**: Temperatury pożarowe, drewno klejone warstwowo (GL), drewno fornirowane warstwowe (LVL), drewno modyfikowane termicznie (TT), niezawodność, wytrzymałość na zginanie.*

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

1 Introduction

Wood next to the stone and soil, is the oldest building material used by humans, and still one of the main raw materials applied in the engineering constructions. Increasing demands concerning the constructions result in necessity of improvement of mechanical – functional wood properties. Undoubtedly, new technologies of production of wood and wood- based structural components, as well as new types of bolts, contribute to the development of the constructions made of these materials. The wood is a flammable material undergoing thermal degradation. In the fire conditions a wooden structure is subject to the simultaneous influence in the form of forces and thermal impacts. Simultaneous interactions of these two factors influence stress distribution in the timber structure and cause a reduction of the load capacity of the construction. High temperatures occurring during the fire cause decohesion of the structure. The observable strength reduction of the timber, takes place already at temperatures above 65ºC [40]. At a micro-structural level the wood is a non-homogeneous cell composite, composed of cellulose, hemicellulose, lignin and other minor constituents [44].Cellulose is the largest part of volume of the timber. It consists of the long carbon chains, which are crucial for its strength. The hemicellulose consisting of branched amorphous polymers fills in the gap between the cellulose and lignin in the timber structure. The lignin is an amorphous polymer responsible for cohesion of timber structure, and it is a "bonding" factor [20]. Degradation of the dried cellulose occurs at temperature of about 300ºC, while degradation of hemicellulose occurs in the temperature range of 150 to 200ºC. Additionally, decomposition of the lignin, determining the cohesiveness of timber structure, takes place in the range between 220 and 250ºC [3, 17], while dehydration of lignin occurs at 200ºC. Construction timber has advantageous physical and technological properties, such as high strength and low deadweight. Till now, there have been some drawbacks due to limitations connected with maximum dimensions of the components cross-sections and manufacturing abilities of the large scale components. Nowadays, a woodworking technology, development of the treatment methods, shaping of such type of materials as well as their aesthetic properties, favor production of this kind of constructions. Possibilities of application of the special agents protecting wooden structures against a negative impact of the environmental conditions are being continuously developed, resulting in larger applications range of timber materials [8]. An application of water-resistant adhesives based on the synthetic resins together with a simple method of longitudinal joining by means of wedge joints, turned out to be especially important. It enabled much faster building method with the use of glued structural components with dimensions larger than the natural input product [25]. Joining of the wooden components by means of steel rod connectors gives more possibilities in the wood construction design and enables their local renovation with preservation of the overall structure [11]. Due to necessity to obtain high aesthetics of the interiors, in the public utility buildings wood and wood-based structures of large span are applied. In the buildings with compartments with high humidity (swimming halls), the timber proves to be a very advantageous constructional material. One of the most interesting large – scale constructions based on the timber materials is a sports hall in Hamar – "The Viking Ship" – 260 m long, 96 m wide, and 35 m high [38], or footbridge in Sromowce Niżne, which length and width together with ground ramps are 149.95 m and 3.5 m, respectively [5].

New types of timber are getting more and more popular, due to both strength as well as fire parameters, which have not been used in Europe till now. The timber from tropical countries is an alternative for the domestic brands and certainly its further investigations are to be continued [26]. In order to fulfill requirements of the modern architecture, where the most important is a freedom in the implementation of the architectural concepts, high fire resistance, necessity to obtain large structural spans, low maintenance, costs reduction and chemical resistance, the most commonly used materials are wood and wood-based composites, such as: glued timber (GL), laminated veneer lumber (LVL) and thermally modified timber (TT). However, it should be noticed that the above materials perform different functions in the constructions. The glued laminated timber composites (GL) are used in single family houses and apartment houses, as well as large-scale buildings such as production halls, market halls, sports halls, swimming pools or footbridges and bridges. The most commonly used type of timber for the production of glued components in Poland is pine or spruce, and rarely larch. A main adhesive used to produce this type of timber is a melamine adhesive, which is resistant to water and fire impact. The alternative solution is resorcinol adhesive, which is especially resistant to humidity. Both types of adhesives do not release any harmful substances, even during the fire [30]. The results of investigations have revealed that behaviour of GL in the conditions of higher temperatures strongly depends on the adhesive behaviour that bonds individual layers of the component [13]. The comparative studies of different types of timber, conducted with the use of conical calorimeter measuring heat release rate, have indicated that the charring rate of the glued timber samples decreases with the increase of timber density [42]. On the basis of specific bending strength a glued timber was divided into 5 classes: from GL24 to GL40. Grading of the sawn wood was carried out according to the standard requirements, based on the visual evaluation (for GL24 and GL28) and mechanically for the higher classes (GL32 and GL36). Due to such method of grading the classes GL24 and GL28 are the most available. The laminated glued timber after providing appropriate conditions such as chamfered edges and planed surface is resistant to fire. According to the guidelines of the Institute of Building, this type of components with a width below 12cm, are classified as low flame spread materials. The components with the width above 12cm or below 12cm with additional fire-proofing agent are classified as fire retardants. Fire resistance of the glued timber in a range of R15 to R60 can be achieved at the design stage by the proper statistical analysis and proper selection of the cross-sections.

Nowadays, laminated veneer lumber is used in many ways, starting from the ceiling beams, and bridge engineering, ending with window and door components [28]. Thanks to a laminar structure of the composite, constructional components based on LVL are very rigid, have a high resistance to fire and aesthetic appearance. Such components due to their homogeneity have an excellent dimensional stability, and nowadays they are available in a wide range of dimensions [29]. The adhesive resins bonding wood layers have a significant influence on the composite properties by decreasing adsorption of humidity, reducing impact of the acidic environment, and reducing curb weight [15]. Most often for the production of glued veneers phenol-formaldehyde adhesives are applied, while for bonding the external veneers melamine adhesives can be used as well [39]. In LVL composites the layers of the cut veneers of about 3–4 mm (most often 3.2mm) are applied [8]. The physical-mechanical parameters of LVL composite are mostly dependent on the type of the trees, from which the material originates, the type of adhesive, as well as a thickness of particular layers [1, 16]. Veneer layers in one structural component can be made of different species of wood. It has been studied and found that the sequence of the particular veneer layers made of different wood species influences the bending strength and modulus of elasticity [7]. A quality of timber used for the composite production and veneer species plays a significant role as well [37]. During a fairly long LVL composites strength studies [36], slightly higher LVL composite strength (a few percents) made of I class quality veneer comparing to II and III class veneers has been demonstrated. Number of knots and their location in the material structure [41], as well as consistency of the fibers direction with the direction of the force vector, have been proved to have an impact on the strength [33].

Thermal treatment of the timber is one of the new technologies aiming at improvement of its properties. A thermally treated timber (TT) is widely used also in Poland. Most of the thermally treated timbers available on the market are the exotic types. Thermally treated domestic timber such as spruce timber can become an alternative for the exotic timber in the longer time horizon. Modification of the timber structure improves some of its physical – mechanical properties, mostly hardness and wear resistance [21], it also improves dimensional stability of the timber components and its biological resistance, as well as reduces the amount of moisture absorbed by the wood [18, 27]. The improvement of this property occurs as a result of chemical composition, mainly due to degradation of hemicellulose [14]. This process also improves resistance to the aggressive environment and wood decay, and what is important from the aesthetic point of view – enables obtaining dark decorative colour [19]. Timber thermal treatment is usually performed in a range of temperatures between 160 and 280ºC [12], while exposure time depends on the size of the treated timber components as well as their humidity, and ranges between 15 and 24 hours. It is known that thermal treatment of timber in some cases, conducted at the specific temperatures and exposure times can lead to the reduction of the ultimate wood strength.

On the basis of the obtained results from the conducted strength studies, a reliability analysis of the above mentioned wood-based composites and thermally treated timber in high temperatures was performed. In case of static structures a reliability evaluation is possible based on the probability of not exceeding of the limit state of the load capacity or failure of the construction [24]. Probability of failure or in other words probability of not survival can be determined based on the distribution of the random variable of material strength and distribution of this variable as a function of temperature in which the object is present. The above assumption brings reliability of the construction to the strength reliability and its components. The strength reliability specifies in both a synthetic and correct way, the essence of all studies and strength investigations as well as their final purpose [2]. In this case failure is equal to probability of not survival of the engineering object or its component, while reliability is a probability of survival. The crucial issue in the construction reliability analysis is a level of reliability analysis. The analysis can be conducted in a scope of deterministic static-strength evaluations and probabilistic safety evaluation of the constructions. Three levels of the analysis can be distinguished: point level – more strictly, level of the construction material particle, section level – cross-section of the construction component, object level – structural building layout. This paper presents the analysis performed on the first level, based on the results of the ultimate strength studies conducted in high temperatures conditions.

2. Materials and methods

2.1. Studied material

Samples for static bending strength investigations were in a shape of cuboids with dimensions of 20x20x300 mm, according to PN-72-/C-04907 standard [45]. In the studies four types of samples were used: glued timber composite (GL), composite of laminated veneer lumber (LVL), treated spruce sawn (TT) and non-treated spruce sawn (NTT). In order to obtain GL samples a melamine adhesive and pine sawn were used. The samples were made by combining two components of identical dimensions to obtain a standard sample as described above. The ultimate strength of the studied material was at the level of GL28 class. Material used for LVL sample originated from the manufacturers of such materials. The standard samples were made of seven layers of spruce veneer of the equal thickness and the same direction of fibres. The fibres direction in all studied samples was consistent with the long axis of the sample. Before starting investigations the samples had been stored at 20°C for a period of 6 months, after this time humidity of the samples was about 8%.

Thermal treatment of the pine samples (TT) was performed in three stages, as shown in the first figure (Fig.1). First stage consisted in a placement of the samples in the drier and heating to 100°C for 30 minutes. Next, temperature was raised successively to 120°C for 60 minutes. During that time a process of drying of the timber took place, humidity decreased to around zero.

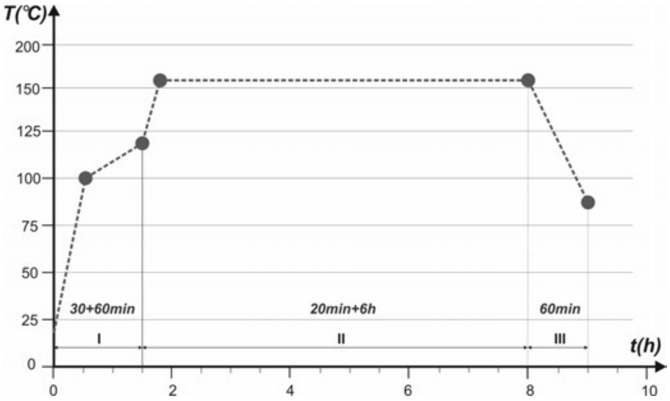

Fig. 1. Process of thermal timber treatment [authors' work]

The second stage consisted in the extensive heating. This phase had a significant impact on the final effect of the treatment. At this stage the temperature was raised to 160°C in 20 minutes and samples were stored in such temperature for 6 hours. The third stage included cooling and conditioning. At this stage temperature in the drier was reduced to 80-90°C, which lasted for 60 minutes. The samples were gradually cooled down. Afterwards they were wrapped in aluminium foil.

The same spruce sawn was used for both thermally treated (TT) and non-treated samples (NTT).

Investigations were performed on the group of 204 samples (66 - LVL, 54 – GL, 42 – NTT and 42 – TT), in equal quantities in each group, specified by the temperature level.

2.2. Strength investigations

Strength tests have been carried out by the three-point bending method. Strength investigations were conducted with the use of universal resistance device FPZ 100/1 (VEB Thuringer Industriewerk Rauenstein, Germany), which enabled static loading and maintaining it in a vertical position at the specified level. The maximum static force produced by the device was 100 kN. The device had four velocity ranges of traverse. During the studies I/III traverse velocity range was used, corresponding to velocities range of 0.021÷0.84 mm/min. The traverse velocity range was established by a potentiometer placed in a centre of velocities range.

In order to determine the bending strength a following equation was applied:

$$R_{bw} = \frac{3P_{\max} \cdot l}{2b \cdot h^2} \tag{1}$$

where:

P_{max} – force breaking the sample [N]
l – sample length [mm]
b – sample width [mm]
h – sample height [mm]

Strength investigations were carried out in high temperatures until sample failure.

2.3. Simulation of fire temperatures

Before the main strength studies, some preliminary studies were conducted in order to determine temperature ranges for the experiment and exposure times up to the temperature equalization in the whole sample volume. During the preliminary studies some openings were made in the samples, in which thermocouples, type K, were placed to measure temperature in the geometric centre of each sample. A heating time was determined as the time after which the temperature foreseen in the schedule was measured with the thermocouple.

As the initial the ambient temperature of 20°C was assumed. The limit temperature was 230°C, which is close to ignition temperature of the wood surface. Additionally, the studies were conducted for the following temperature ranges: 50°C, 100°C, 150°C and 200°C.

During the main studies temperature was measured at the surface of the sample by means of two thermocouples being in contact with a side surface of the sample. Loading of the sample was performed after reaching a specified temperature value and maintaining it for a period of time established during the preliminary studies. Value of the breaking force and temperature were recorded in a real time. Temperature increase in a chamber was obtained by blowing with hot air (GHG 650 LCE, Bosch, Germany). Temperature range at the outlet of the nozzle was 50-560°C, and a hot air flux was adjustable in a range between 250 and 500 l/min.

2.4. Reliability analysis

Reliability analysis was performed based on the results obtained during a three-point bending strength test. In highest temperature the reliability was analysed on the basis of Weibull model.

For the analysis a two-parameter Weibull distribution was applied. Weibull cumulative distribution function (with positive σ_0, c, and σ_u parameters), is described by the following relationship [22]:

$$P_f = 1 - \exp\left[-V\left(\frac{\sigma - \sigma_u}{\sigma_0}\right)^c\right] \tag{2}$$

where:

σ – breaking load,
σ_0 – scale parameter,
c – shape parameter,
σ_u –location parameter,
e – constant (e = 2.71828...),
V – sample volume.

In the analyzed case P_f is a probability of failure of the sample made of wood or wood-based composite. Value of the probability contains in a set between 0 and 1. In case when the load at which probability of failure equals 0 is known (in the presented analysis it is the highest known breaking load at 20ºC), the probability can be calculated from the following relationship:

$$P_f = \left(\frac{n}{N^* + 1}\right) \tag{3}$$

where:

N - total number of samples,*
n – set of the ranked samples.

In case a sample size – sample volume V is constant in all subgroups of population determined by the successive temperature ranges, it can be omitted in the calculations [10, 35].

Assumption of the location parameter $\sigma_u = 0$ reduces Weibull distribution to the two-parameter distribution. The above assumption brings failure probability range to the beginning, to the known highest breaking load value. Under these assumptions the equation takes the following form:

$$1 - P_f = 1 - \left(1 - \exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^c\right]\right) \tag{4}$$

The above equation can be simplified by using the logarithm to the form of $y = ax + b$ by:

$$\ln\left[\ln\left(\frac{1}{P_s}\right)\right] = c\ln(\sigma) - c\ln(\sigma_0) \tag{5}$$

where:

P_s – survival probability (equals 1 – Pf).

An intersection of Y axis depends on $-c\ln(\sigma_0)$, a slope of the curve is a shape parameter of Weibull distribution - c. Sample size has an influence on the determination coefficient R^2, which decides on the quality of prediction of the Weibull distribution parameters [31]. Thus, the higher it is the better selection quality of the shape parameter (R^2 values are shown in Figure 2).

3. Results of the studies

Descriptive statistics of the bending strength results are shown in table 1.

Logarithmic distribution of non-failure wood samples probability in high temperatures is shown in Figure 2.

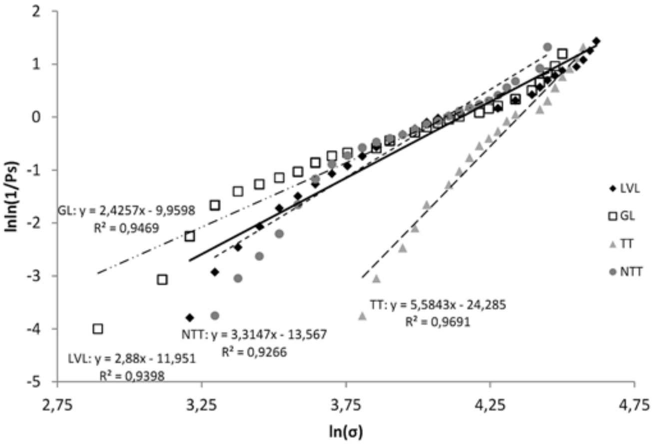

Fig. 2. Logarithmic distribution of failure probability as a function of bending strength of the sample in high temperatures

4. Results and discussion

Studies on the bending strength of wood indicate that humidity and temperature of timber applications significantly influence on mechanical strength of wood [23,43]. The decrease of wood humidity improves mechanical properties, while the temperature increase aggravates these properties. The presented results show that high temperatures influence on the strength decrease. In case of thermally treated spruce timber (TT), reduction of the bending strength at 230ºC was 42.21%, while in case of non-treated timber (NTT) it was 58.19%, in relation to the one obtained at 20 ºC. Wood-based composites LVL and GL at 230 ºC maintained 33.32% and 28.57% of the strength obtained at 20ºC, respectively. A similar level of a residual value at 230 ºC was obtained in studies presented in an article [20]. In the article, the results were determined from compression forces parallel to grain, what may indicate on s similar process of these properties degradation.

Regarding natural material, the observed strength of NTT was lower in all temperature ranges, however value of bending strengths

Table 1. Descriptive statistics of the bending strength results

Temp. [°C]	Bendig strength R_{bw} [MPa]								
	N	Average	Min	Max	Std. dev.	Coaf. of var.. %	Residual strength %	Strength degradation intensity [MPa/ °C]	σ_0 [MPa]
LVL									
20	11	90,82	81,00	101,25	7,13	7,86	100,00	-	58
50	11	77,52	72,00	87,75	5,54	7,15	85,36	0,44	
100	11	55,02	45,00	63,00	5,07	9,21	60,58	0,45	
150	11	47,05	38,25	54,00	4,32	9,19	51,81	0,16	
200	11	38,45	31,50	45,00	4,55	11,83	42,34	0,17	
230	11	30,27	24,75	36,00	4,19	13,85	33,33	0,27	
GL									
20	9	85,75	81,00	90,00	3,81	4,44	100,00	-	62
50	9	75,75	67,50	85,50	6,16	8,13	88,34	0,33	
100	9	56,75	49,50	69,75	7,01	12,34	66,18	0,38	
150	9	46,50	36,00	58,50	7,79	16,76	54,23	0,21	
200	9	32,00	24,75	38,25	5,00	15,63	37,32	0,29	
230	9	24,50	18,00	29,25	3,27	13,34	28,57	0,25	
NTT									
20	7	79,71	72,00	85,50	5,33	6,69	100,00	-	60
50	7	67,50	60,75	74,25	4,86	7,20	84,68	0,41	
100	7	53,68	45,00	60,75	5,42	10,10	67,34	0,28	
150	7	49,50	38,25	83,25	15,91	32,14	62,10	0,08	
200	7	38,57	33,75	42,75	3,54	9,18	48,39	0,22	
230	7	33,11	27,00	38,25	4,05	12,23	41,54	0,18	
TT									
20	7	89,68	83,25	96,75	4,93	5,50	100,00	-	76
50	7	87,43	83,25	92,25	3,03	3,46	97,49	0,08	
100	7	72,64	67,50	76,50	3,11	4,27	81,00	0,30	
150	7	67,18	63,00	72,00	3,54	5,27	74,91	0,11	
200	7	61,07	56,25	67,50	3,99	6,53	68,10	0,12	
230	7	51,75	45,00	56,25	4,31	8,33	57,71	0,31	

of TT and NTT at normal temperature (20ºC) were similar. It seems possible that thermal wood modification improves strength reliability. The decrease of humidity, in a technological process of thermal wood modification, results in polymers (cellulose) degradation [20]. This polymers significantly influence on mechanical strength of wood [4, 34]. According to Schaffer [32], lignin, located at the exterior of wood fibers, also influences on wood strength. The lignin structure may start to change at 55°C.

Together with temperature increase an increase of the coefficient of variability of the bending strength results have been observed, while in case of LVL and GL the increase was larger. This is not unfavourable since it significantly reduces abilities of precise evaluation of the construction condition and prediction of the hazard level at the point, where the temperatures of construction components are lower than their ignition temperature.

The strength degradation intensity of studied materials was higher in a first two temperature ranges (tab.1). Different connection has been shown only in case of TT materials, for which the decrease of strength was slight in a first range. It may be the result of thermal wood modification, which influences on transition of cellulose and hemicellulose vitrification. Additionally, it is indicated that transition of cellulose structure during thermal modification, under proper conditions, influences on rigidity improvement and other physical and mechanical wood properties [4].

A presented method of reliability analysis of the material is insufficient to evaluate reliability of the construction. The method does not include different functions performed by components made of the studied materials in the construction. It enables only a comparative reliability analysis of the materials. This method can be in a way referred to the first level of the construction reliability analysis, concerning one component of the construction. It means that the presented analysis, based on the simple three-point bending strength test, does not take into account a redistribution of forces to the other construction components as well as other methods of loading performance. In the reliability analysis, in case of the whole construction sections, which usually are serial sets of components, the analysis is performed for a so called “the weakest element”. The reliability of the whole section being a serial arrangement, in the simplest concept is a product of reliability of its components [24]. A serial model can be applied also to the evaluation of the safety and reliability of the construction components statistically indeterminable, if redistribution of the internal forces is not allowed and statistical calculation methods are applied – stresses in all critical cross-sections of the construction are calculated and compared with the material strength [24].

A limiting factor of the presented analysis is concluding only based on the ultimate strength of the samples without the loading history. Moreover, as well known, a long-term strength of timber is much lower than the ultimate one. According to [6] after 10 years of operating it represents only about 60% of the ultimate strength, and after 50 years – about 50%.

In the presented publication survival probability (no failure) was analysed in two different ways. First the analysis as a function of strength (Fig. 2) was performed, without dividing into successive temperature ranges and using all available strength results from the successive temperature ranges. It enabled application of two-parameter Weibull distribution and obtaining shape and scale distribution parameters. Next, the analysis as a function of temperature of simulated fire conditions (Fig. 3) was performed. The aim of such procedure was to obtain a single reliability distribution, continuous in the successive temperature ranges, for each of the materials instead of having many distributions for the successive temperature ranges. Applicability of the latter ones is much lower.

Based on the logarithmic distribution of failure probability in the temperature field, the higher values of shape parameter *c* of Weibull distribution have been obtained in case of spruce timber TT (the highest value c = 5.58) and NTT (the highest value c = 3.31). The lower value of scale parameter of Weibull distribution indicates a larger scatter of the obtained results. The reason for the lower values of shape parameters for LVL (c = 2,88) and GL (c = 2,43) is most probably a laminar structure of composites.

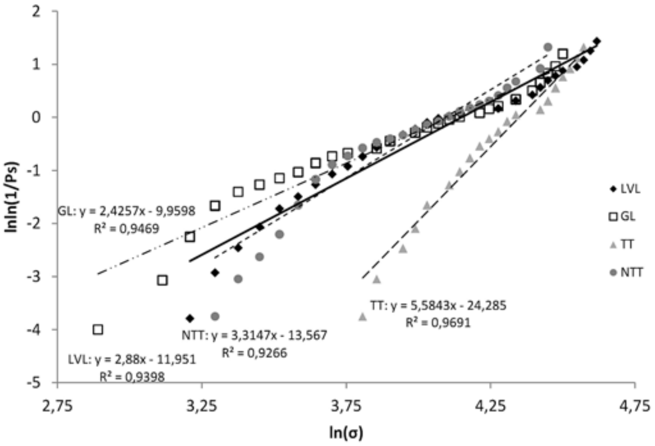

Fig. 3.

5. Conclusion

The aim of this work is to determined the influence of high temperatures on the wood and wood-base materials strength. Additionally, based on experimental strength results, the analysis of survival probability in high temperatures (20–230 °C) has been carried out. Investigations were performed on the group of 204 samples (66 – LVL, 54 – GL, 42 – NTT and 42 – TT), in equal quantities in each group, specified by the temperature level. The test obtained static load and thermal treatment. The results lead to following conclusions:

High temperatures influence on the decrease of studied materials residual strength. The highest residual strength has been obtained for thermally modified wood (TT). It seems possible that the preliminary thermal treatment favor strength maintaining in high temperatures.

In case of non-treated spruce timber NTT and thermally treated TT the residual strength has been higher than in case of two wood-based composites (LVL and GL). Glued-laminated structure as a negative factor on behavior of these kind of materials under fire conditions should be considered.

The standard deviation increase of bending strength results of LVL and GL materials has been observed in following temperature ranges. There is probability that the highest unpredictability strength increase of these materials occurs in temperatures which are similar to wood ignition temperatures. It was different in case of non-treated spruce timber. The highest increase of the standard deviation of strength has been observed in 150^{o}C - in this temperature the process of hemicellulose degradation is intensive.

Based on the logarithmic distribution of failure probability in the temperature field, the higher values of shape parameter *c* of Weibull distribution have been obtained in case of spruce timber TT (the highest value c = 5.58) and NTT (the highest value c = 3.31). The lower value of scale parameter of Weibull distribution indicates a larger scatter of the obtained results. The reason for the lower values of shape parameters for LVL (c = 2,88) and GL (c = 2,43) is most probably a glued-laminated structure, which does not improve material behaviour under fire conditions.

The presented studies show that in case of non-thermal test group materials determination quotient has low values (below 0,95). It may be result of non-linear decrease of materials properties in high temperatures and increase behavior unpredictability.

References

1. Baldwin RF. Plywood and veneer-based products, manufacturing practices (Wood technology books ser). Miller Freeman. San Francisco 1995.
2. Bąk R, Burczyński T. Wytrzymałość materiałów z elementami ujęcia komputerowego. Wyd. WNT. Warszawa 2001.
3. Beall F.C, Eickner H.W. Thermal degradation of wood components. Forest Products Research Paper 1970: 130.
4. Bhuiyan RT, Hirai N, Sobue N. Changes of crystallinity in wood cellulose by heat treatment under dried and moist conditions. Wood Sci Technol 2000; 46: 431–6.
5. Biliszczuk J, Hawryszków P, Maury A, Sułkowski M, Węgrzyniak M. Kładka dla pieszych w Sromowcach Niżnych. Rekordowa konstrukcja mostowa z drewna klejonego. Nowoczesne Budownictwo Inżynieryjne 2007; 11: 36-39.
6. Bliszczuk J, Bień J, Maliszewski P. Mosty z drewna klejonego. WKŁ Warszawa 1988.
7. Burdurlu E, Kilic M, Ilce A, Uzunkavak O. The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech (Fagus orientalis L.) and lombardy poplar (Populus nigra L.). Construction and Building Materials 2007; 21: 1720–1725.
8. Caggins C.R. Timber preservation in building and construction. Construction and Building Materials 1989: 114–117.
9. Chui Y, Schneider M, Hang H. Effects of resin impregnation and process parametre on some proporties of poplar LVL. Forest products Journal 1994; 44: 74–78.
10. Davies D.G.S. The statistical approach to engineering design in ceramics. Proceedings of the British Ceramic Society 1973; 22: 429–452.
11. D Otero Chans, Estevez Cimadevila J, Martin Gutierrez E. Glued joints in hardwood timber. International Journal of Adhesion & Adhesives 2008; 28: 457–463.
12. Fengel D, Wegener G. Wood chemistry, ultrastructure, reactions. Berlin, Walter de Gruyter 1989.
13. Frangi A, Fontana M, Hugi E, Jobstl R. Experimental analysis of cross-laminated timber panels in fire. Fire Safety Journal 2009; 44: 1078–1087.
14. Gunduz G, Aydemir D, Karakas G. The effects of thermal treatment on the mechanical properties of wild Pear (Pyrus elaeagnifolia Pall.) wood and changes in physical properties. Materials and Design 2009; 30: 4391–4395.
15. Johansson C.J. Glued-in bolts. Timber engineering. STEP 1: lecture C14. Centrum Hout. Almere 1995.
16. Kamala B.S, Kumar P, Rao R.V, Sharma S.N. Performance test of laminated veneer lumber (LVL) from rubber wood for different physical and mechanical properties. Holz Roh Werkst 1999: 114–116.

17. Kamdem D.P, Pizzi A, Jermannaud A. Durability of heat-treated wood. Holz als Roh- und Werkstoff 2002; 60: 1–6.
18. Kartal S.N, Hwang W.J, Imamura Y. Combined effect of boron compounds and heat treatments on wood properties: Chemical and strength properties of wood. Journal of Materials Processing Technology 2008; 198: 234–240.
19. Korkut S, Akgul M, Dundar T. The effcts of heat treatment on some technological properties of Scots pine (Pinus sylvestris L.) wood. Bioresource Technology 2008; 99: 1861–1868.
20. Manríquez M.J, Moraes P.D. Influence of the temperature on the compression strength parallel to grain of paricá. Construction and Building Materials 2010; 24: 99–104.
21. Mazela B, Zakrzewski R, Grześkowiak W, Cofta G, Bartkowiak M. Resistance of thermally modified wood to basidiomycetes. Wood Technology 2004; 7: 253–262
22. Migdalski J. Inżynieria niezawodności. Poradnik. Wyd. ATR ZETOM. Warszawa 1992.
23. Moraes PD et al. Influence of temperature on the embedding strength. Holz Roh-Werkst 2005;63:297–302.
24. Murzewski J. Niezawodność konstrukcji inżynierskich. Wyd. Arkady. Warszawa 1989.
25. Neuhaus H.: Budownictwo drewniane, podręcznik inżyniera. Polskie Wydawnictwo Techniczne. Rzeszów 2006.
26. Njankouo J, Dotreppe J, Franssen J. Fire resistance of timbers from tropical countries and comparison of experimental charring rates with various models. Construction and Building Materials 2005; 19: 376–386.
27. Obataya E, Tanaka F, Norimoto M, Tomita B. Hygroscopicity of heat-treated wood 1. Effects of after-treatments on the hygroscopicity of heat-treated wood. Journal of Wood Science 2000; 46: 77–87.
28. Ozcifci A. Effects of scarf joints on bending strength and modulus of elasticity to laminated veneer lumber (LVL). Building and Environment 2007; 42: 1510–1514.
29. Ozcifci A, Okcu O. Impacts of some chemicals on combustion properties of impregnated laminated veneer lumber (LVL). Journal of materials processing technology 2008; 199: 1–9.
30. Przepiórka J, Żurowski P. Konstrukcyjne drewno klejone. Inżynier Budownictwa 2008; 10: 60–64.
31. Ritter JE, Bandyopadhyay N, Jakus N. Statistical reproducibility of the dynamic and static fatigue experiments. Ceramic Bulletin 1981; 60: 798–806.
32. Schaffer EL. Effect of pyrolytic temperatures on the longitudinal strength of dry douglas fir. J Test Eval 1973;1(4):319–29
33. Sei-Chang O. Applying failure criteria to the strength evaluation of 3-ply laminated veneer lumber according to grain direction by uniaxial tension test. Construction and Building Materials, 2010.
34. Sivonen H et al. Magnetic resonance studies of thermally modified wood. Holzforschung 2002;56(6):648–53.
35. Stanley P, Fessler H, Sivil AD. An engineer's approach to the prediction of failure probability in brittle components. Proceedings of the British Ceramic Society 1973; 22: 453–487
36. Strickler M.D, Pellerin RF. Tension proof loading laminated beams. Forest Prod J 1971; 21: 10–15.
37. Tichy RJ, Bodig GJ. Flexural properties of glued la pine dimension lumber. Forest Prod J 1978; 29.
38. Tomusiak A. Drewno klejone warstwowo. Materiały Budowlane 2001; 8: 92–93.
39. Uysal B. Bonding strength and dimentional stability of laminated veneer lumbers manufactured by using different adhesives after the steam test. International Journal of Adhesion & Adhesives 2005; 25: 395–403.
40. White RH, Dietenberger MA. Wood Products: Thermal Degradation and Fire. Encyclopedia of Materials: Science and Technology. Elsevier Science Ltd 2001: 9712–9716
41. Wolf R, Moddy R.C. Bending strength of vertically glued laminated beams. Forest Prod J. 1979; 30: 32–40.
42. Yang T, Wang S, Tsai M, Lin C. The charring depth and charring rate of glued laminated timber after a standard fire exposure test. Building and Environment 2009; 44: 231–236.
43. Young SA, Clancy P. Compression mechanical properties of wood at temperatures simulating simulating fire conditions. Fire Mater 2001;25: 83–93.
44. Younsi R, Kocaefe D, Poncsak S, Kocaefe Y. Computational and experimental analysis of high temperature thermal treatment of wood based on ThermoWood technology. International Communications in Heat and Mass Transfer 2010; 37: 21–28.
45. PN-72/C-04907: Środki ochrony drewna. Oznaczanie wpływu na wytrzymałość drewna.

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