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PRELIMINARY ASSESSMENT OF THE BENDING STRENGTH OF MID-NINETEENTH CENTURY OAK TIMBER

ABSTRACT

This paper deals with results of preliminary analysis to determine the bending strength of approximately 150 year old oak timber obtained from structural elements used in construction. The test procedures were those specified in the PN-EN 408 standard. The experiments involved subjecting specimens to four-point static loading using three different loading rates: 5, 7 and 10 mm/min. The specimens were sampled from full-size timber beams. The experimental data revealed that after such a long period of use the structural oak timber elements had retained high strength. The failure mode and the behaviour of the beams during tests were dependent on the location of wood defects as well as the rate of deflection gain in time.

Keywords: *laboratory testing, mechanical properties, four-point bending, element failure, old oak timber*

INTRODUCTION

Wood is an anisotropic and heterogeneous material. Anisotropy results from the relationship between the mechanical properties and the direction of analysis, relative to the axis of the original tree trunk [1]. As shown in Fig. 1, three directions of analysis were assumed:

- longitudinal – parallel to the grain (*L - longitudinal)*,
- radial – normal to the growth rings and the grain *(R - radial)*
- tangential – perpendicular to the grain and tangent to the growth rings (*T-tangential*).

The heterogeneity of the material resulting from the structural differences between early wood and late wood in the annular growth rings makes the properties dependent on the location of the point of interest. In engineering practice, this aspect is not considered and wood is treated as a homogeneous material, i.e. one for which the mechanical properties of the structural element are identical at all points.

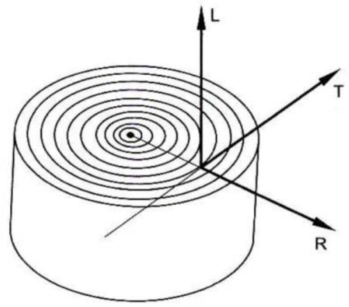


Fig. 1. Principal reference planes to describe the nature and orientation of wood: L – longitudinal (parallel to the grain), R – radial, T – tangential [2]

The mechanical properties of wood are affected by a number of factors. These include: density (the higher density, the better the mechanical properties), moisture content (the properties increase as moisture content decreases), service life, deviation of the load direction from the direction of the grain, wood temperature (the properties decrease with increasing temperature), type and location of knots (knots as inherent defects have a negative effect on the strength), load duration and the specimen dimensions (the bending strength reported for small specimens without defects was higher than that of full-size elements) [2, 3].

Recently, research in materials engineering has focused on determining a wide range of mechanical properties to characterize both the basic structural materials used in the construction industry such as steel, concrete and wood as well as state-of-the-art materials including plastics, composites and ceramics. Although much effort has been made to develop advanced models of materials to describe their damage [e.g. 4-8] and behaviour over the entire loading (deformation) range until failure [e.g. 9-11], the capacity of a structural element to resist stresses under different loading conditions is still assessed on the basis of strength. It is crucial to study the strength of materials with a long service life, i.e. those exposed to loading for several, several dozen or even several hundred years, for example, timber in historic structures still in use. Such an analysis will be described in this article.

This study aimed at assessing the bending strength of oak timber obtained from the Open-Air Museum at Tokarnia. The determination of mechanical properties of wooden structural elements after their service life has expired has been described, for instance, by Brol et al. [12] and Nowak et al. [13].

MATERIALS AND METHODS

Methodology

The bending strength of the specimens was assessed on the basis of the results of four-point bending tests, as recommended in [14]. The analysis should be performed for full-size elements and any behaviour different from that specified in this standard should be reported.

The bending strength tests were conducted at the Laboratory for the Strength of Materials of the Kielce University of Technology. The specimens had a rectangular cross-section. They were oriented in such a way as to ensure that the length of the support span of the free-free beams was equal to the 18-fold height of the cross-section (Fig. 2).

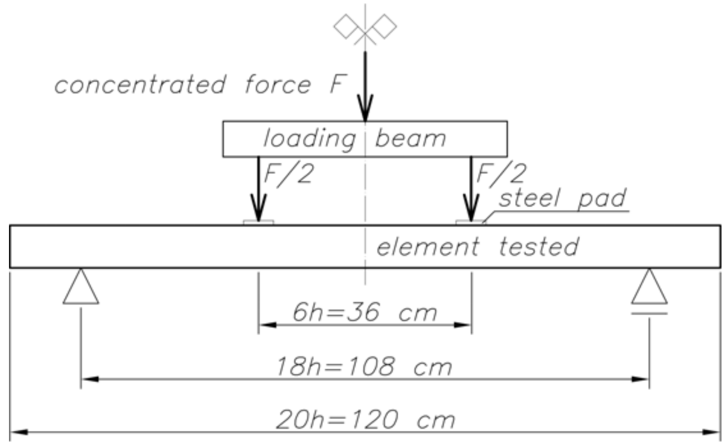


Fig. 2. Diagram of the static test setup

The elements were loaded symmetrically with two concentrated forces applied at a distance equal to the six-fold height of the cross-section from the support axes with the loading rates assumed as follows:

– 1.0 cm/min – for beam BD1,
– 0.5 cm/min – for beam BD2,
– 0.7 cm/min – for beams BD3-6.

The relationships between the support displacement and the test time reported for the different elements are illustrated in Fig. 3.

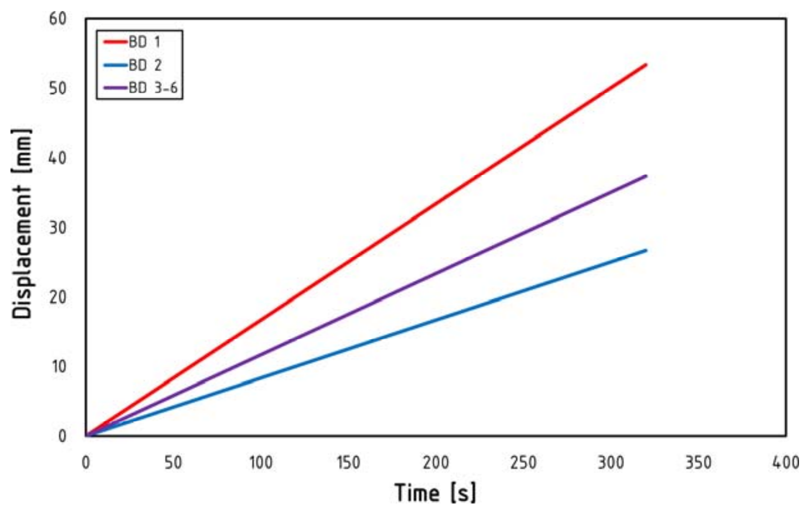


Fig. 3. Support displacement versus test time

The four-point bending tests were carried out using an MTS-151 hydraulic universal testing machine with a measurement accuracy of 1%. The concentrated force supplied by an actuator was split by means of a cross-tie made from a steel I-section into two component forces. Because of the dimensions and orientation of the cross-section, no lateral supports were used to prevent beam torsion; in order to distribute the load over a larger area guide plates were employed to stop excessive indentation of the beam. During the tests, the load was applied perpendicular to the growth rings. Figure 4 shows a view of the test setup.

The tests involved continuous measurement of the loading force F, test time T, deflection in the centre of the beam monitored with induction gauges at the extreme upper fibres under compression w and displacement at the points where loads were applied.

After the static tests, the moisture content of all the specimens was measured using a TANEL WRD-100 tester according to the procedure recommended by the manufacturer.

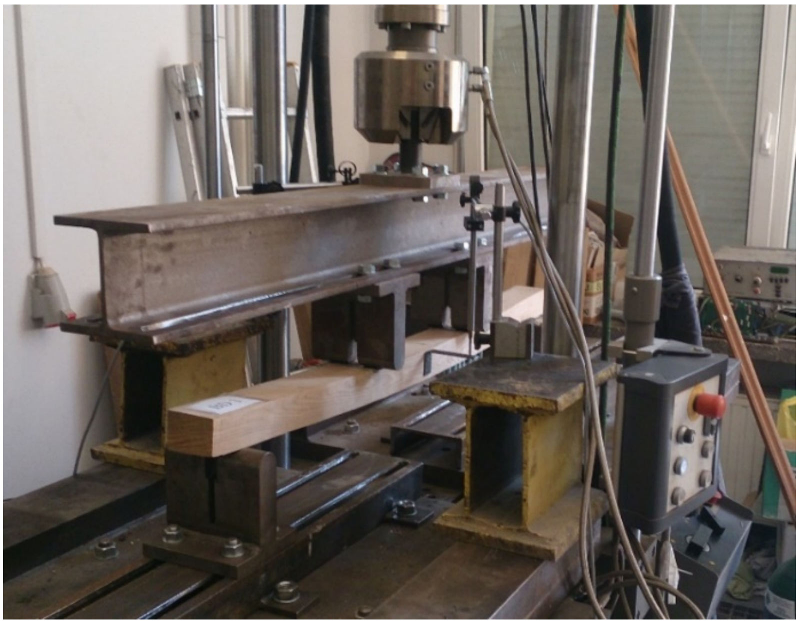


Fig. 4. Setup for static loads

The bending strength was determined on the basis of the experimental data. It was calculated from the following equation [14]:

$$f_m = \frac{aF_{\max}}{2W} \qquad (1)$$

where: a – distance between the point at which the concentrated force was applied and the nearest support [in millimetres],
F_{max} – maximum force [in Newtons],
W – section modulus [in cubic millimetres].

Methodical guidelines

Since wood is an anisotropic material and the study of the old oakwood was preliminary in nature focusing on one property only, further investigations are necessary.

- A larger number of specimens should be tested to obtain more accurate predictions of the bending strength.
- Elements with a moisture content of 12% should be analysed so that the values obtained can be compared with the experimental values presented in this paper as well as the theoretical data to discuss the relationship between strength and moisture content.

Material

The beam-shaped specimens to be tested were cut from two wooden beams with dimensions $b \times h \times L$ = 22×34×3700 cm provided by the Open-Air Museum at Tokarnia. The beams had been part of the building outer walls, which means that during operation they had been subjected to compression. The condition of the elements was assessed as good.

Twenty-four elements with nominal properties $b \times h \times L$ = 8×6×120 cm were obtained. The preliminary tests were conducted on a set of six beam elements, which were randomly selected to achieve a representative sample. Despite their small dimensions, the specimens used in the tests were not free from material defects affecting the load-carrying capacity. Unlike specimens without wood defects recommended by the respective Polish standards, the specimens containing wood defects objectively reflect real beams. The basic physical properties and geometry of the specimens prepared for the tests as well as their visual inspection are provided in Table 1.

Table 1. *Properties of the oak specimens*

Beam	Nominal dimensions $b \times h \times L$ [m]	*Mass [kg]	**Density [kg/m^3]	Visual inspection of the specimens
BD 1	0.08×0.06×1.20	4.177	725.17	Knot in the near-support zone
BD 2		4.159	722.05	Element in good condition; visible longitudinal crack.
BD 3		4.063	705.38	Element in good condition; visible longitudinal crack.
BD 4		4.039	701.22	Element in good condition; knot in the middle of the span within the compressed zone.
BD 5		4.290	744.79	Element in good condition; longitudinal crack in the compressed zone.
BD 6		4.149	720.31	Element in good condition; knot above the support; signs of insect activity.
* Mass measured for each specimen after the strength test ** Density determined as the ratio of the mass of the whole specimen to its volume (refers to density at 19-20% moisture content)				

The elements had a uniform hue and a characteristic acidic smell.

RESULTS AND DISCUSSION

Bending strength

The results of the four-point bending tests are shown in Table 2. The behaviour of the different oak beams is illustrated by the load-time and load-deflection curves (Figs. 5 and 6, respectively). Table 2 provides the values of the failure load, the maximum bending moment and the maximum stress corresponding to the bending strength of the particular beams recorded during the four-point bending tests.

Table 2. *Test results*

Beam	Deflection* [mm]	Maximum concentrated force F_{max} [N]	Maximum bending moment [kNm]	Bending strength [MPa]
BD 1	32.19	16021.66	2.88	60.08
BD 2	37.52	17581.06	3.16	65.93
BD 3	34.37	18770.80	3.38	70.39
BD 4	34.53	18960.97	3.41	71.10
BD 5	32.61	20408.82	3.67	76.53
BD 6	29.11	19895.15	3.58	74.61
*Values reported at a maximum concentrated force measured from the assumed initial load of 250 N				

The results also include deflection and time to failure, both measured from the moment an initial load of 250 N was applied until failure occurred.

The moisture content of the specimens tested ranged from 19% to 20%.

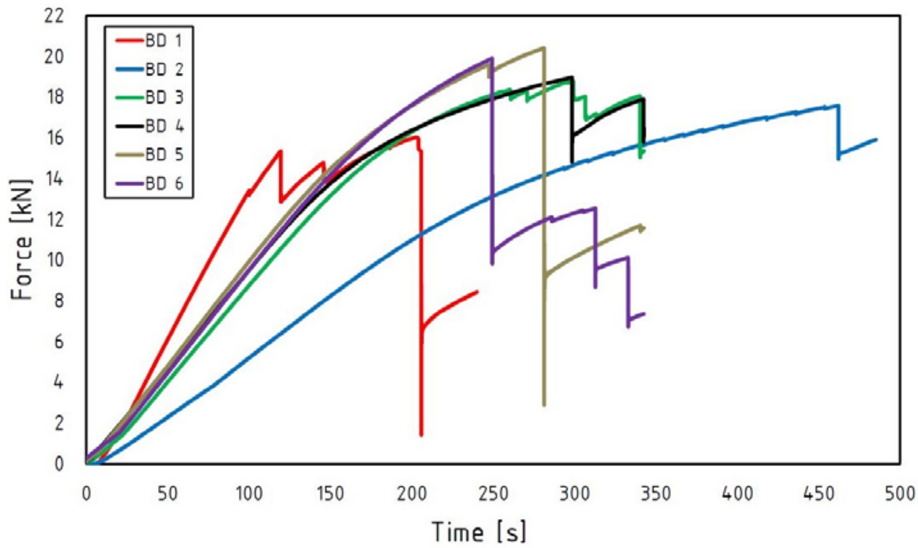


Fig. 5. Force-time curves obtained for the different beams

Figure 5 shows the relationship between the loading rate and the time to failure. As can be seen, the time to failure decreases with increasing loading rate, while there is no significant difference in the maximum deflection between the specimens.

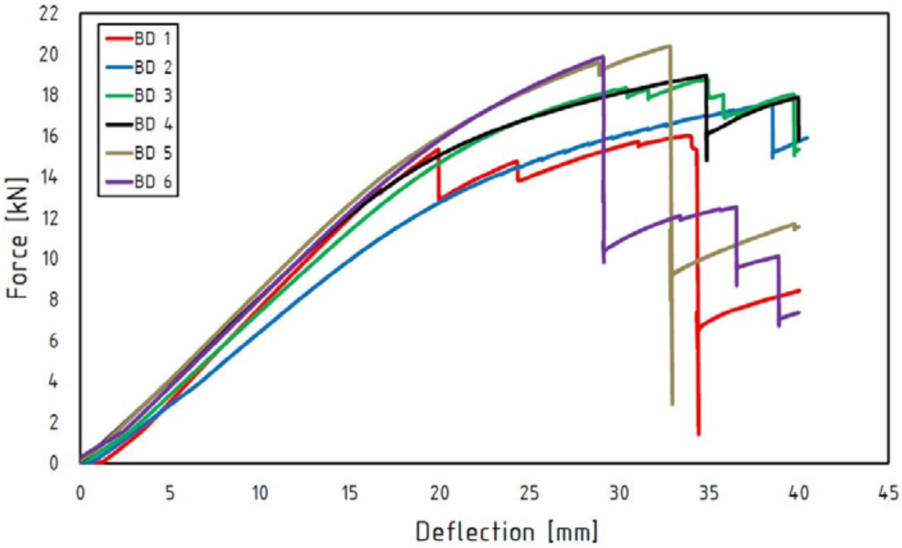


Fig. 6. Force versus deflection curves obtained for the different beams

The statistical analysis of the experimental data was divided into two stages. First, the results obtained for all the beam specimens were analysed and then the elements for which the loading rate was 7 mm/min were evaluated (Table 3). The investigations involved determining the basic parameters of variation as well as the parameters of distribution for the preliminary results (Table 2).

Table 3. *Statistical analysis of the experimental data*

Parameter	Arithmetic mean	Standard deviation	Coefficient of variation
Results for specimens BD1 – BD6			
Bending strength	69.77 MPa	5.48 MPa	7.85
Maximum bending moment	3.35 kNm	0.26 kNm	7.87
Failure load	18606 N	1460 N	7.85
Deflection*	33.39 mm	2.57 mm	7.70
Results for specimens BD3 – BD6 (at a loading rate of 7 mm/min)			
Bending strength	73.16 MPa	2.52 MPa	3.44
Maximum bending moment	3.51 kNm	0.12 kNm	3.41
Failure load	19508 N	671 N	3.44
Deflection*	32.66 mm	2.18 mm	6.68
*Values measured from an initial load of 250 N until failure			

The class of the bending strength of the oakwood studied was determined according to the PN-EN 384:2004 standard. The correction factors were used in the analysis because of the small number of specimens tested and their dimensions.

The characteristic strength was calculated from the following equation [15]:

$$f_k = f_{05} \cdot k_s \cdot k_v \qquad (2)$$

where: f_{05} – the value of 5% of quantile [in megapascals],

k_s – correction factor corresponding to the number and size of the specimens,

k_v – correction factor corresponding to machine sorting.

The value of f_{05} was calculated from the formula [15]:

$$f_{05} = f_r \tag{3}$$

where: f_r – value corresponding to 5% of quantile of the ranged testing results [in megapascals].

Because of the small number of specimens tested, a 5% quantile was calculated from the following equation [12]:

$$f_{05} = f_{mean} - t_a \cdot s \tag{4}$$

where: f_{mean} – mean strength [in megapascals],
t_a – statistical ratio for the normal distribution corresponding to a probability of 95% [unitless],
s – standard deviation [in megapascals].

Since the specimens studied were less than 150 mm in height, the correction factor was calculated to adjust the characteristic value according to the following equation [15]:

$$k_h = \left(\frac{150}{h}\right)^{0.2} \tag{5}$$

where: h – specimen height [in millimetres].

Table 4. *Strength properties of the timber tested*

	Mean strength [MPa]	Correction factor k_s [-]	Correction factor k_v [-]	Correction factor k_h [-]	Characteristic strength f_k [MPa]
Results for specimens BD1 – BD6					
Bending strength	69.77	-	1.00	1.20	49.94
Bending strength	69.77	0.77	1.00	1.20	38.45
Results for specimens BD3 – BD6 (at a loading rate of 7 mm/min)					
Bending strength	73.16	-	1.00	1.20	56.99
Bending strength	73.16	0.77	1.00	1.20	43.88

The data provided in Table 4 reveal that the oak timber obtained from the Open Air Musem at Tokarnia had good bending strength. The strength class was ranked in accordance with [16] applying the correction factor k_s (because of the number of specimens tested and their dimensions). The results were as follows:

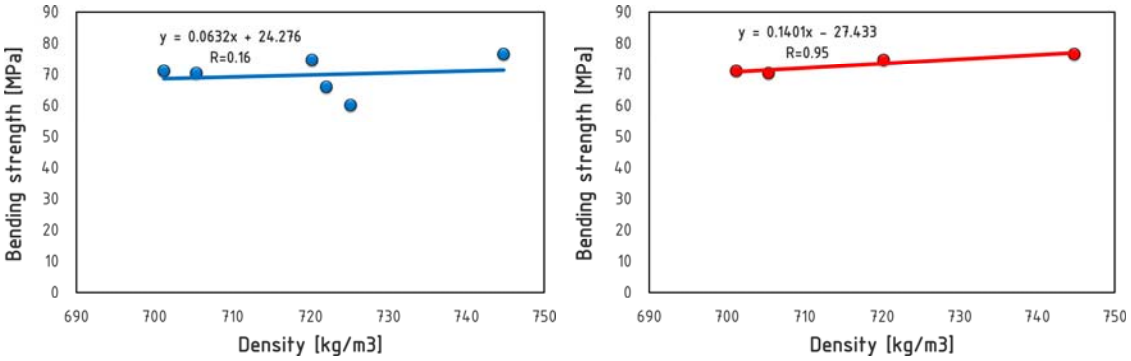
- class D35 for all the specimens,
- class D40 for specimens BD3-BD6.

If the correction factor k_s had been omitted in the analysis, the strength class would have been D40. For specimens BD3-BD6, the class would have been higher (D50). However, all the specimens failed at a stress higher than 50 MPa. This reveals that the elements could have been retrieved for reuse in new or old buildings as structural elements. Another important aspect is their dimensional stabilisation.

Since there is no information on the original bending strength, it is difficult to assess how much the wood strength had decreased over the years. The literature data concerning the mechanical properties of oak timber [2] suggest that, at a moisture content of 15% and a volumetric mass density of 710 kg/m^3, its bending strength is 94 MPa. This may indicate that the load-carrying capacity of the elements tested was lower than that of elements made of fresh timber.

Figure 7 shows the relationship between the bending strength and density of the specimens. Like in the statistical analysis (Table 3), two regression curves were plotted for different loading rates. In both cases, the regression curve had a positive slope, which indicated a gain in bending strength with increasing density of the specimen tested. The Pearson product-moment correlation coefficient was:

- R = 0.16: poor correlation (for elements BD1-BD6, Fig. 7a),
- R = 0.95: strong correlation (for elements BD3-BD6 at a loading rate of 7 mm/min, Fig. 7b).



a) b)

Fig. 7. Density versus bending strength: a) elements BD1-BD6; b) elements BD3-BD6

The hypothesis that the bending strength of oak timber increases with increasing density was tested using significance tests for the Pearson correlation coefficient at a significance level of 0.05. For specimens BD3-BD6 tested at the same loading rate, there is no reason to reject the hypothesis. It is evident that the correlation between the density and bending strength of the oak timber is statistically significant at a probability of 5%. This has been confirmed in the literature [2], which provides information on the correlational relationships between the density and mechanical properties of timber.

As the same level of significance was reported for all the elements, there is no reason to claim that the hypothesis is true. The hypothesis was rejected because the changes in the load applied to the elements and the presence of defects in the material affected the bending strength, which was particularly visible in the case of element BD1.

Failure

The wooden beams failed at the bottom in the central zone where the maximum bending moment occurred causing the strength of the wood to be exceeded at the extreme lower fibres (specimens BD 2-6) and in the zone where both a bending moment and a shear force were observed (specimen BD1). The failure of these specimens resulted from the loss of strength in the tension zone. However, the failure of each element occurred in steps. In the case of beams BD1, BD3 and BD5, the first drop in the loading force did not imply a maximum concentrated force. The results obtained for the other beams revealed that once the maximum load-carrying capacity was reached, the force and strengthening of the material decreased rapidly several times before failure.

The load-time curve in Fig. 6 indicates that only beam BD2 did not fail during the test (at a displacement rate of 5 mm/min for loading) in the range of time recommended by the relevant standard. The element was found to have the highest bending strength before failure.

When there was an increase in load, beam BD1 behaved in the most unpredictable manner. The strength dropped several times before failure was observed.

Figure 8 illustrates the typical failure of a beam-like element with no defects in the tension zone. The crack occurred in the pure bending zone between the points at which concentrated forces were applied.

Fig. 8. Typical failure of a beam without defects

Figure 9 shows the failure of an element with defects (specimen BD 1). A crack formed in the tension zone between a point of support and the point at which the concentrated force was applied. The crack propagated at the bottom towards one end of the beam along the grain towards the inside.

Fig. 9. Failure of a beam with defects

CONCLUSIONS

This paper has described results of preliminary studies concerning the bending strength of approximately 150-year-old oakwood beams. The conclusions drawn from the experimental data obtained for a six-element set of specimens are as follows:

- the bending strength of the oakwood beams removed from a 150-year-old building was still high, when compared with the data specified in the PN-EN 338:2004 standard concerning the strength classes of structural timber;
- elements with higher density were reported to have better mechanical properties;
- beams characterised by higher density but containing defects are likely to fail at lower loads;
- the failure of the beams was due to a loss of load-carrying capacity at the extreme fibres under tension in the pure bending zone; the failure curve is a step-like curve,
- the rate at which an element is loaded affects its behaviour; maximum deflection occurs prior to failure;
- compared with the literature data, the test results indicate that the bending strength of the 150-year-old oak timber is smaller than that of fresh oak timber.

From the calculation results it is clear that the structural oakwood elements under study had sufficient bending strength to be retrieved for reuse in buildings.

REFERENCES

1. Kossakowski P.G.: Influence of anisotropy on the energy release rate G_I for highly orthotropic materials, Journal of Theoretical and Applied Mechanics 45(4) (2007), pp. 739-752,.
2. Stefańczyk B.: Budownictwo ogólne. Materiały i wyroby budowlane. Tom 1, Arkady, Warszawa, 2005.
3. Rudziński L.: Konstrukcje drewniane. Naprawy, wzmocnienia, przykłady obliczeń., Skrypt Politechniki Świętokrzyskiej, Kielce, 2010.
4. Mazars J.: A description of micro- and macroscale damage of concrete structures, Engineering Fracture Mechanics 25(5-6) (1986), pp. 729-737.
5. Yazdani S., Schreyer H.: Combined Plasticity and Damage Mechanics Model for Plain Concrete, Journal of Engineering Mechanics 116(7) (1990), pp. 1435-1450.
6. Bazant Z. P.: Nonlocal damage theory based on micromechanics of crack interaction, Journal of Engineering Mechanics ASCE 120(3) (1994), pp. 593–617.
7. Chaboche J. L., Lesne P. M., Maire J. F.: Continuum Damage Mechanics, Anisotropy and Damage Deactivation for Brittle Materials Like Concrete and Ceramic Composites, International Journal of Damage Mechanics 4(1) (1995), pp. 5-22.
8. Sandhaas C., Van de Kuilen J.W., Blass H.J.: Constitutive model for wood based on continuum damage mechanics, WCTE, World conference on timber engineering, Auckland, New Zealand, 15-19 July 2012, pp. 159-167.
9. Kossakowski P.G.: Microstructural failure criteria for S235JR steel subjected to spatial stress states, Archives of Civil and Mechanical Engineering 15(1) (2015), pp. 195–205.

10. Kossakowski P.G., Wciślik W., Experimental determination and application of critical void volume fraction f_c for S235JR steel subjected to multi-axial stress state, in: T. Łodygowski, J. Rakowski, P. Litewka (Eds.), Recent Advances in Computational Mechanics, CRC Press/Balkema, London, 2014, pp. 303–309.
11. Kossakowski P.G., Wciślik W.: Effect of critical void volume fraction fF on results of ductile fracture simulation for S235JR steel under multi-axial stress states, Key Engineering Materials – Fracture and Fatigue of Materials and Structures 598 (2014), pp. 113–118.
12. Brol J., Dawczyński S., Malczyk A., Adamczyk K.: Testing timber beams after 130 years of utilization, Wiadomości Konserwatorskie - Journal of Heritage Conservation nr 32 (2012), pp. 100-104.
13. Nowak T., Brol J., Jasieńko J.: Estimation of the strength parameters of wood in building structures – preliminary studies, Annals of WULS – SGGW Forestry and Wood Technology No. 83 (2013), pp. 303-306.
14. PN-EN 408:2004 Konstrukcje drewniane. Drewno konstrukcyjne i klejone warstwowo. Oznaczanie niektórych właściwości fizycznych i mechanicznych.
15. PN-EN 384:2004 Drewno konstrukcyjne. Oznaczanie wartości charakterystycznych właściwości mechanicznych i gęstości.
16. PN-EN 338:2004 Drewno konstrukcyjne. Klasy wytrzymałości.