ISSN 1644-0633
www.acta.media.pl

ACTA Acta Sci. Pol. Architectura 15 (4) 2016, 153–168

INVESTIGATIONS ON TENSILE LOAD-CARRYING ABILITY OF REED STEMS

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Abstract. The investigations on mechanical properties of reed stems face numerous difficulties, because of their anisotropy, heterogeneity, shell-like structure, small lateral dimensions of stems and huge diversity of species and habitats of origination. Aware of all difficulties to cope with, the basic experiment has been conducted, that is the uni-axial tension test for reed stems, with- and without joints. The *strain-stress* relation, at tension, displayed an exponential character, showing material stiffening with the growth of strain. Test results incline to conclusion, that stem-pieces without joints are equally stiff as pieces with joints, however, they are twice as strong as the latter. It means, that joints can be perceived as fragile (in the sense: "brittle") discontinuity in structure of reed stems. The results of the test have been put through critical estimate and analysis tending to statistical modelling of the load-carrying ability of reed stems.

Key words: reed, quasi-strength, quasi-stiffness, uni-axial tension, load-carrying ability

INTRODUCTION

Reed (*Phragmites australis*) served as a building material for centuries. However, back in the days when it was used, there were no legal articles in force which would regulate the design and construction process. Constructors resorted to principles, which mainly resulted from their professional experience; part of the knowledge was handed down from generation to generation within closed associations of craftspeople. It was only the technological development (mainly the development of science) that triggered design optimisation processes. This was, however, at the time (the end of the 19^{th} and the beginning of the 20^{th} century) when new materials came to be used in the construction industry (metals, reinforced concrete, later prestressed concrete, composite materials, etc.) and it was these materials that became the main focus of interest for theoreticians researching strength of materials. In fact, mechanical properties of reed-stems still excite

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some interest among water engineers, who perceive reed stands as elastic barrier down to withstand water waves attack and reduce waves velocity [Van der Toorn and Mook 1982, Binz-Reist 1989, Ostendorp 1991, 1995a, b, Niklas 1992, Coops and Van der Velde 1996, Coops et al. 1996].

Still, traditional techniques (eg. low-processed ecological materials) have been returning to the building industry over the last several years; reed as well. This may partly result from the fact that using ecological materials is now "in vogue." Moreover, theories of using natural resources according to advanced technologies (e.g. biofibres, biocomposites) did appear [Holmes 1989, George et al. 2001, Mwaikambo 2006, Li et al. 2007, John and Anandjiwala 2008, John and Thomas 2008, Müssig 2010, Yueping et al. 2010, Wang et al. 2012]. It rises interest in properties of raw traditional building materials.

This comeback of traditional techniques should not be disregarded. As experience shows (for instance regarding wood), natural materials can be also applied when it comes to technologically advanced and complex uses, which optimally exploit material properties. Developing such technologies is a question of time. Yet, the knowledge of fundamental mechanical properties of the basic material, reed in this case [Köbbing et al. 2013], is indispensable.

The investigations on mechanical properties of reed face numerous difficulties:

1. Due to its fibrous stem structure, like other grass-type plants [Sfiligoj-Smole et al. 2004, 2005, 2013], reed is certainly an anisotropic material. It is, however, difficult to examine the difference in material properties in different directions, as there are problems with preparing suitable test pieces (small size of reed stem cross section and its annular shape). For instance, the length of a reed test piece cut out across fibre, in radial direction, may not exceed 1 mm, which makes it impossible to install the sample in a testing machine of any type.

2. Cross section through a reed stem also displays heterogeneous structure along the cross-section radius, which may be compared to the structure of wood with visible "sapwood" and "heartwood." External reed fibres are the most lignified and the stiffest; the closer to the centre the more delicate and vulnerable they become. In the case of wood, such a heterogeneity is practically synonymous with multilayered structure; wood test pieces of the size significantly exceeding the thickness of the annual ring make it possible to conduct strength tests in different directions, without isolating different material forms. In the case of reed, the change of material properties takes place on the ring wall (which is the stem cross section) at the length of less than 1 mm. There is no distinction between "sapwood" and "heartwood" here, as such, as it was in the case of wood. One might venture to say that heterogeneity here means a constant change of properties along the thickness of the stem wall.

3. The above statements incline towards giving up the term "material" with reference to reed stem. One should rather think of it as an infinite number of "materials," anisotropic materials we should add [Greenberg et al. 1989]. Only examining a reed stem as a whole can have a practical sense. In this way we can examine the properties of reed understood as a "construction" disregarding the question of material this construction is made of.

4. Reed stems are empty inside. They have a shell-like structure, which makes it difficult to install them in a testing machine. Irrespective of their structure, test-piece grips are supposed to transmit external forces triggering a certain level of stress in the test piece

cross section. These forces are transmitted at its ends, in the areas of the test piece side surface, small enough to minimise interferences in the course of stress trajectory along the test piece (according to *de Saint-Venanta's* rule). On the other hand, large forces transmitted on a small test piece area lead to local losses of sample stability (simply speaking test pieces are crushed at ends, while their fibrous structure causes further longitudinal stem cracks). Special measures need to be taken, therefore, to prevent the described phenomenon.

5. It is commonly known that, in nature, living organisms always reveal a high level of diversity. Plants, as research objects, are highly "heterogeneous." The examination of mechanical properties of reed will always refer to the particular set of test pieces of the particular origin. Also, statistical modelling will refer to the particular group of test pieces of the same origin.

MATERIALS AND METHODS

The easies test to conduct is the uni-axial tension test for reed stems. For that purpose, a set of 75 test pieces was selected so that a part of them contained joints, while a part of them did not. Thus, 30 test pieces, originating from the same plantation, constituted group "A"; 45 test pieces, each with a joint half-way along its length, constituted group "B". The origin of the test pieces from group "A" was different than group "B". However, both plantations are situated on the territory of fish ponds in Krakow (Balicka street), about 300 m distant from each other, where reed is growing in (typical for this species) swampy meadow, with clayey subsoil. Material for tests under consideration have been harvested in winter (January), in both groups. Test pieces have been cut-off from bottom part of original stems, so, we can assume that investigated pieces, among both groups, represent the same degree of maturity. The lengths of test pieces in both groups were not identical, due to the variety of reed stems available for research, obtained on the plantation. Perimeter of particular pieces, necessary for further calculations, have been established on the basis of stem's outer diameter meant as mean of five measured (by electronic slide calliper) values, in representative places along the test piece. Typical measured values of stem diameter varies in interval 5.29–6.76 mm among group "A" and 4.32–8.49 mm in group "B".

Each test piece was prepared for the tests-both its ends were strengthened with a chemo-hardening resin (Fig. 1), in the following way:

Fig. 1. Strengthened end of a test piece (chemo–hardening resin is visible inside destructed stem)

1. At a certain depth at both stem ends, falling out fibres and other loose parts were removed from stem interiors.

2. Cleared stem ends were clogged with cotton wool leaving the stem end empty at the length of about 5 cm (the cotton wool clog acted as if a vessel bottom).

3. An empty stem end, as if the vessel, was filled up with chemo-hardening resin and was left for 24 hours to harden.

4. Afterwards, (if necessary) the excess of the resin was removed from the stem end.

5. The second stem end was filled up in the same way.

The activities described above were conducted with particular care so as not to disturb the reed structure. The resin applied in this procedure was of appropriate stiffness and did not change volume in the course of hardening. As a result, formations similar to "stoppers" were obtained at each end of the examined test piece. The samples were installed in the testing machine with self-locking test-piece grips.

RESULTS

Tensile tests were conducted in Hounsfield's extensometer (Fig. 2), with the strain velocity of 0.002 s^{-1} (tensile behaviour is a function of strain rate [Greenberg et al. 1989, Vincent 2012, Hartzberg et al. 2012], but this aspect is off the scope of our interest).

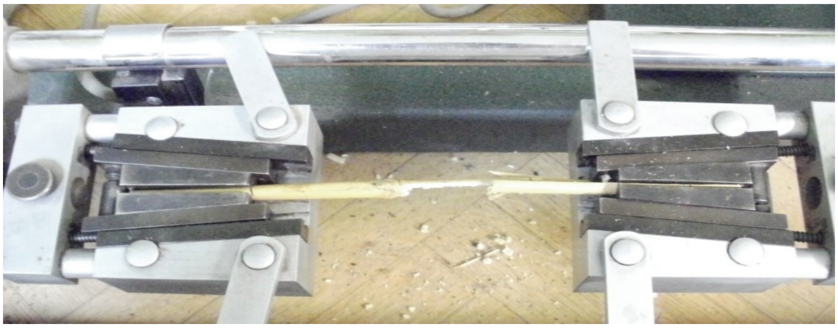

Fig. 2. Hounsfield's extensometer with a failed test piece

Conducted tests made it possible to register relations between the tensile force and a strain of the test piece, until failure. By strain, here denoted as ε we understand unit elongation, that is actual increase in length with reference to the initial span of the test piece (clear span) between the grips holding the test piece in the testing machine. In fact, also the fragment of the test piece held by the grip undergoes tension (to a certain level), despite friction of the test piece against grip sides. However, resolving this issue requires separate deliberations, both theoretical and experimental, and it is not the subject of this article.

Regarding the difficulties with identifying the material of reed stems (see Introduction, pp. 2 and 3), a problem appeared with describing internal forces in the "material" during the pure tensile test. This is usually done through normal stress (the value of the tensile force across a unit of surface of the test-piece cross section), expressed in Pascals [$N \cdot m^{-2}$]. Such stress can be referred to as "the density of longitudinal force on the surface of the test-piece cross section".

In authors opinion, such the attitude is misleading when referred to reed, as well as other grass-type materials, due to stems heterogeneity. Here, internal forces should rather be defined through "force density along the perimeter of the test piece," expressed in N·m^{-1}. These are not stresses in the strict meaning of the term, they can therefore be called quasi-stresses. In the figure captions they were marked with the Greek symbol σ. In this way, heterogeneity of the material in radial direction in the sample cross section does not lead to erroneous interpretation of the term σ. For in the circular cross section of the sample, quasi-stress understood in this way expresses the share of the sector (in the geometric sense as circular sector) of the cross section in transmitting the longitudinal force compared to the entire cross section, while sectors of the same width are after all comparable. It would be difficult here to interpret stress understood in the traditional way, since material heterogeneity means that a unit of cross section surface participates in the transmission of the longitudinal force depending on the material stiffness, therefore depending on where this surface is situated in the cross section (we are talking here, obviously, of a surface small enough to avoid the question of averaging, from a technical point of view). It is impossible to describe the state of stress with one number, for a heterogeneous material (even in the case of pure tension); unfortunately many authors pretend to do so [Coops and Van der Velde 1996, Baets de et al. 2008].

The relations between the tensile force and unit elongation of the test piece, obtained in the tests, are illustrated in Figure 3 to Figure 4. The presented graphs refer to only a few test pieces from each of the analysed groups (A and B) which were representative in terms of the relationship of ε versus σ. Thus, in Figure 3:

1. Test piece No. 25 represents an example of a stem characterised by high stiffness and average strength (σ_{max} = 72.98 kN·m^{-1} with ε = 0.111; that is with mean stiffness amounting to E_{mean} = 657.5 kN·m^{-1}; within the group "A" the top value of σ_{max} was equal to 101.09 kN·m^{-1}).

2. Test piece No. 7 represents an example of a stem characterised by low stiffness and average strength (σ_{max} = 76.13 kN·m^{-1} with ε = 0.278; with mean stiffness

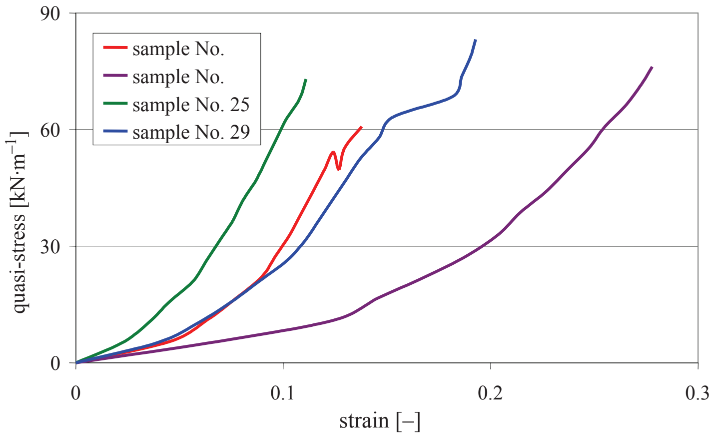

Fig. 3. Stress-strain relationship for a few representative test pieces without joints (group "A")

E_{mean} = 273.8 kN·m^{-1}). The stiffness of this test piece is lower from the one of test piece No. 25 by 2.4. Nevertheless, this test piece is slightly stronger.

3. Test piece No. 6 is an example of a stem with relatively high stiffness and average strength (σ_{max} = 60.79 kN·m^{-1}), which lost a part of its stiffness during the tensile test (after reaching the value of instant stiffness E_{inst} = 1068.8 kN·m^{-1} – see Fig. 4), which was probably caused by breaking the stiffest fibres. Nevertheless, it recovered the ability of transmitting stress through a redistribution of internal forces (more vulnerable but stronger fibres took over the transmitting role). The highest value for instant stiffness for this test piece equals E_{inst} = 2004.0 kN·m^{-1}, while the mean value is E_{mean} = 440.5 kN·m^{-1}.

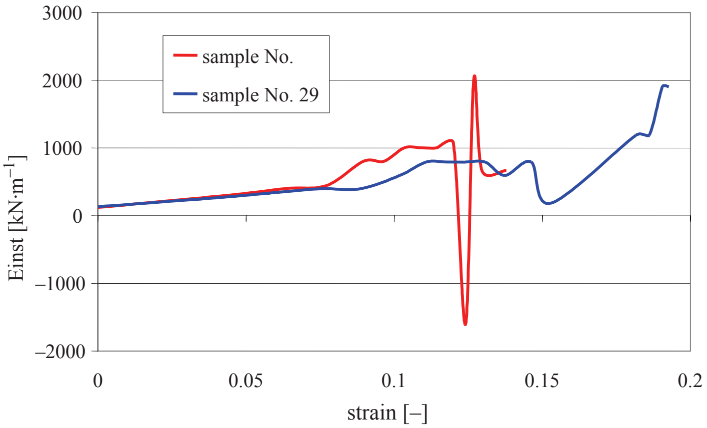

Fig. 4. E_{inst} vs. ε relationship for a few test pieces without joints (group "A")

4. Test piece No. 29 represents the few cases, which in the course of the tensile test, after reaching a certain level of σ, partly lost their stiffness, while after reaching further strains regained and multiplied it (in the case of the sample No.6 mentioned before, this process proceeded very violently, with temporal decreases in quasi-strain; in this case the loss of stiffness was smooth and slow – see Fig. 4). It is worth noting that the final fragment of the graph for the test piece No. 29 is almost vertical (high stiffness). The highest instant stiffness value for this sample equals E_{inst} = 1901.6 kN·m^{-1} while the mean value amounts to E_{mean} = 431.1 kN·m^{-1}.

The phenomenon of stiffness loss and recovery at the higher strain level (the mentioned test pieces No. 6 and 29 are only examples here) can be caused by two possible mechanisms:

1. It is possible that the most resistant fibres are as if "dormant" since the stem contains a small number of fibres made of a very stiff material, which take the greater part of the tensile force; there are, however, a few of these and they are damaged after losing their load-carrying ability, after which the more vulnerable fibres take over the tension effects. As a result, the test piece can withstand larger strain and reach higher load-carrying ability [Greenberg 1989, Kabla and Mahadevan 2007, Giesa et al. 2012].

2. We cannot also rule out the fact, that a certain part of fibres undergoes tensile prestress, still before the initiation of the laboratory tensile test. During the test itself, they

undergo failure earlier than other fibres, because tension effects sum up with pre-stresses and these fibres (earlier than others) deplete their load-carrying ability. This, however, does not lead to the failure of the entire test piece. Thus, pre-stresses probably concern a small number of fibres. Pre-stresses can be brought about by botanic factors (for example: cracking tree bark in the vegetation season, cracking fruit – this is due internal material pressures); there may be also external reasons (stresses during wood seasoning also cause cracks).

Figure 5 illustrates the results of the tensile test for a few examples:

1. Test piece No. 20 is an example of a stem characterized by high stiffness and strength (σ_{max} = 119.84 kN·m^{-1} with ε = 0.102; the highest achieved σ in the group "B" is σ_{max} = 157.557 kN·m^{-1}). The highest value for instant stiffness for this test piece is E_{inst} = 1999.34 kN·m^{-1} while the mean value equals E_{mean} = 1174.9 kN·m^{-1}.

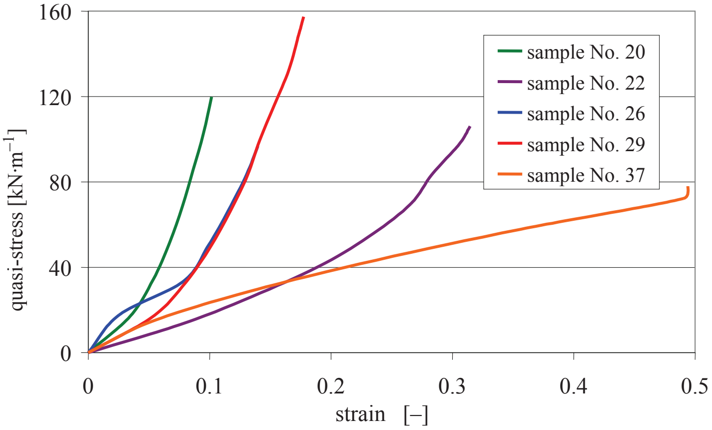

Fig. 5. Stress-strain relationship for a few representative test pieces with joints (group "B")

2. Test piece No. 29 is an example of a stem characterized by high stiffness and strength (σ_{max} = 157.557 kN·m^{-1} with ε = 0.177 which yields E_{mean} = 890.2 kN·m^{-1}; it is the highest strength obtained in the group "B"). For this test piece, the highest value of E_{inst} = 2053.969 kN·m^{-1}.

3. Test piece No. 26 exemplifies the cases, which in the course of the tensile test, after achieving a certain σ level, partly lost their stiffness and regained it after achieving larger strain. This situation is analogous to the test pieces No. 6 and 29 from group "A" described earlier. The achieved strength level is medium while the stiffness level is high (σ_{max} = 96.77 kN·m^{-1} with ε = 0.14 which yields E_{mean} = 691.21 kN·m^{-1}; the highest value of E_{inst} = 1432.127 kN·m^{-1}).

4. Test piece No. 37 represents one of the few cases, when the test piece lost its stiffness in the course of the entire test (in Fig. 4 the curve strain-quasi stress is convex upward) and just before failure, it suddenly strengthened reaching E_{inst} = 1678.5 kN·m^{-1} while E_{mean} = 157.9 kN·m^{-1}. The test piece reached σ_{max} = 78.02 kN·m^{-1}, which means small strength.

SOME CRITICAL REMARKS

Strengthening the ends of test pieces made it possible to install particular reed stems in self-locking grips of the extensometer. The following analysis has been conducted in order to resolve the question of test piece grip efficacy and the influence of test piece slip in the grips on the correctness of conducted measurements of tensile load-carrying ability of reed stems. If we assumed that during the test, a slip of test pieces took place or that the grip proved ineffective, we should expect that these phenomena would exert greater influence on shorter than longer test pieces. For example, a slip within the grips would have to cause decrease in the initial test piece stiffness $E_{min,}$ which would be more significant for shorter test pieces, due to smaller initial length. Since the grips of the extensometer are self-locking (a wedge effect) we can assume that the slip speed should decrease as the tensile force grows. This is confirmed by the strain vs. quasi-stress relation*:* if the slip kept pace with the tensile force this relation would have a linear character. Therefore, slip velocity should be the lowest when test piece stiffness reaches the highest value. The E_{max}/E_{min} relation for short test pieces should be larger than for long test pieces. For both groups of test pieces, “A” and “B,” the relationship between the length of test pieces versus E_{min} and E_{max}/E_{min} has been presented in the figures below (Fig. 6 to Fig. 9); in all cases, under consideration, empirical values of correlation coefficient r_{emp} and their critical values r(5%*,* n-2), assuming significance level at 5%, have been calculated. Hence, among data from Figure 6 – r_{emp} = 0.1878, r(5%, 28) = 0.3739. Respectively, for data in Figure 7 – r_{emp} = 0.2722, r(5%, 28) = 0.3739. For data in Figure 8 – r_{emp} = –0.0317, r(5%, 43) = 0.3008 and for data in Figure 9 – r_{emp} = 0.3784, r(5%, 43) = 0.3008. Only in one of presented figures $|r_{emp}| > r(5\%, n\text{-}2)$, which means, that in most of cases, strength of linear relationship between variables is small.

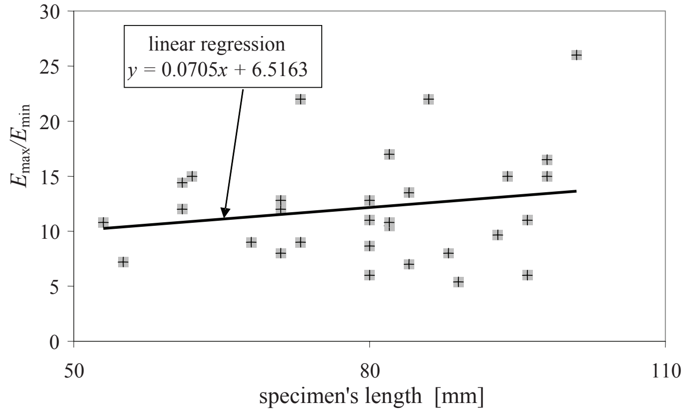

Fig. 6. E_{max}/E_{min} relationship versus test piece’s length and its linear regression for the group of test pieces without joints (group “A”)

Regression lines in these figures point towards the growth of E_{min} and E_{max}/E_{min} with the increase in test piece’s length (except for Fig. 8), which contradicts the assumed hypothesis concerning the slip results [Mańczak and Nahorski 1983, Bendat and

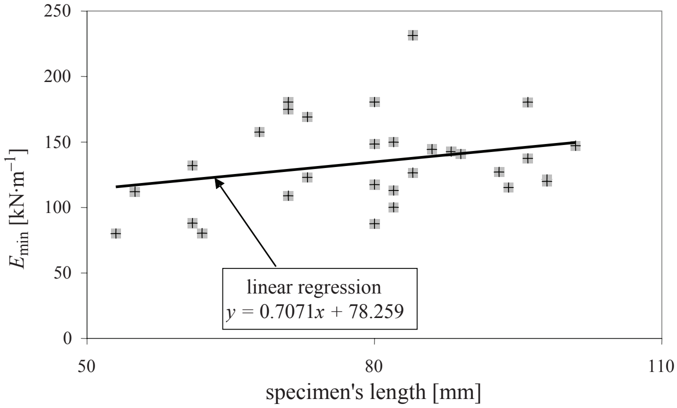

Fig. 7. E_{min} vs. test piece's length and it's linear regression for the group of test pieces without joints (group "A")

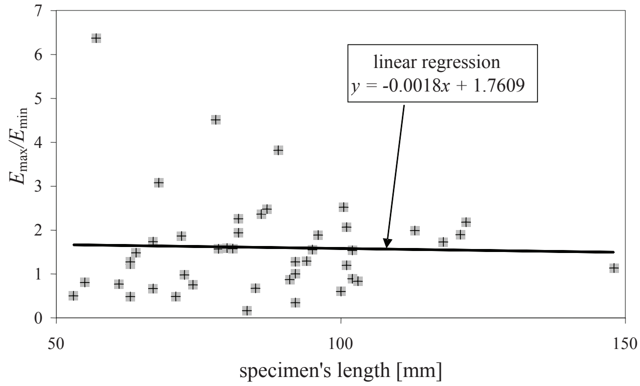

Fig. 8. E_{max}/E_{min} relationship vs. *test piece's length* and its linear regression for the group of test pieces with joints (group "B")

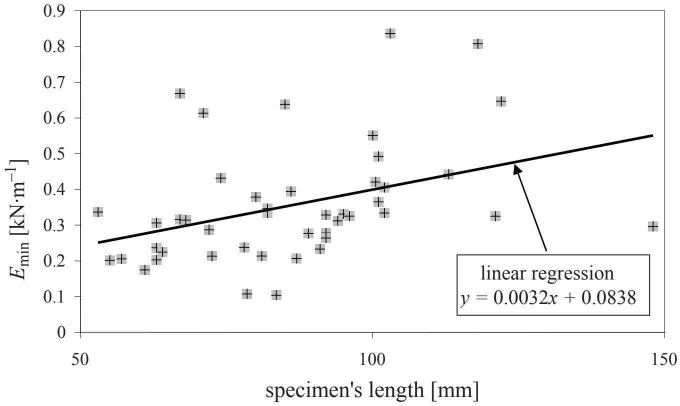

Fig. 9. E_{min} vs. test piece's length and its linear regression for the group of test pieces with joints (group "B")

Piersol 2010, Montgomery 2013]. However, measurement results in all graphs are very scattered and the course of the regression line is not very credible. In order to improve result credibility, the method of "bootstrap statistics" throughout resampling of data, has been used. The "bootstrap" is a procedure that involves choosing random samples with replacement from data set and analyzing each sample the same way. Sampling with replacement means that every sample is returned to the data set after sampling. So a particular data point from the original set of data could appear many times in succeeding "bootstrap" samples. The number of elements in each "bootstrap" sample equals the number of elements in the original data set.

In this case "bootstrap statistics" has been utilized to correlation coefficient calculations, applying the 1000 times replacement procedure. The resulting sets of 1000 correlation coefficients have been grouped in 30 categories, according to their values, in equally spaced ranges of value. Each group has been labeled with the number of coefficients the group comprises. As a result, the following histograms have been charted in Figure 10 to Figure 13.

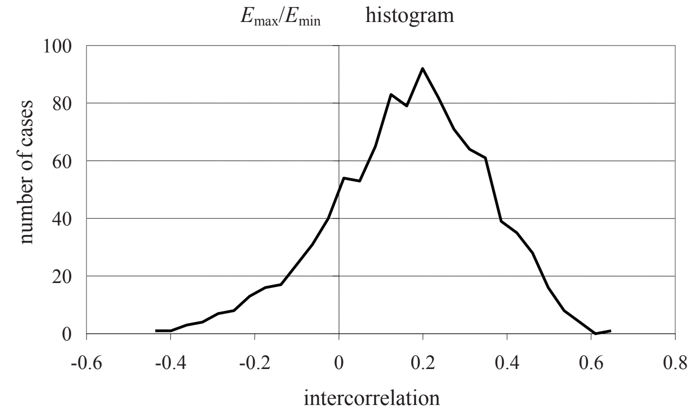

Fig. 10. Histogram of the intercorrelation of E_{max}/E_{min} vs. test piece's length after 1000× replacement of samples for the group of test pieces without joints (group "A" – see Fig. 4)

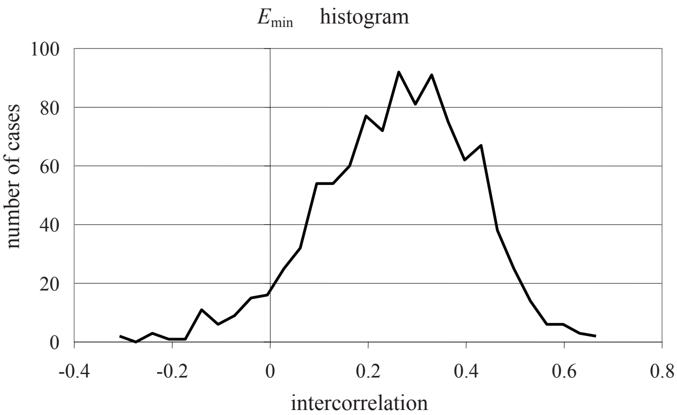

Fig. 11. Histogram of the intercorrelation of E_{min} vs. test piece's length after 1000× replacement of samples for the group of test pieces without joints (group "A" – see Fig. 5)

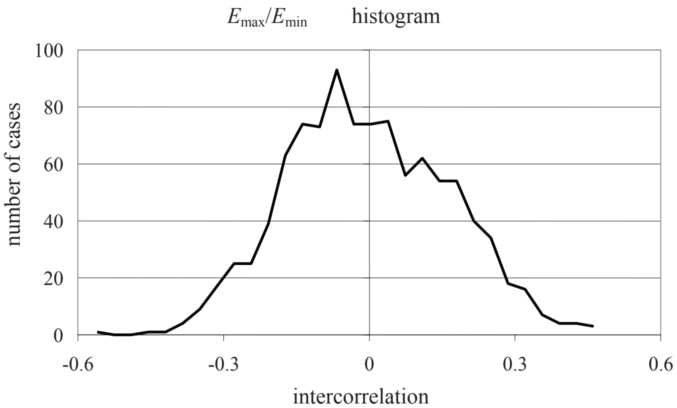

Fig. 12. Histogram of the intercorrelation of E_{max}/E_{min} vs. specimen's length after 1000× replacement of samples for the group of test pieces with joints (group "B" – see Fig. 6)

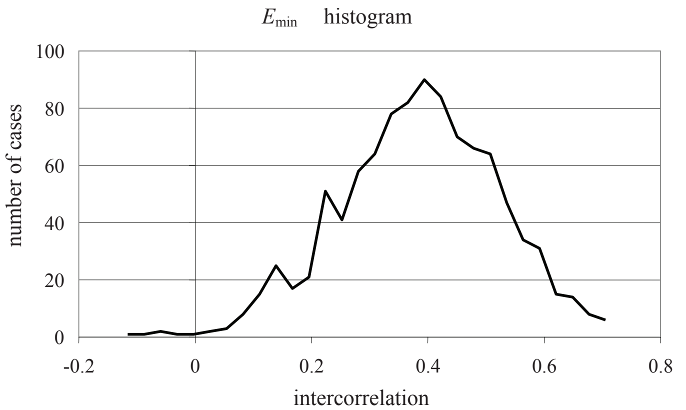

Fig. 13. Histogram of the intercorrelation of E_{min} vs. test piece's length after 1000× replacement of samples for the group of test pieces with joints (group "B" – see Fig. 7)

All four figures demonstrate a lack of correlation between the test piece's length versus E_{min} and E_{max}/E_{min} for both groups of test pieces. The position of graphs on the minus side of the correlation line means that random variables for both pairs (E_{max}/E_{min} vs. test piece's length) are selected in an entirely arbitrary way. So there is no justification for the statement that the slip of test pieces in the extensometer grips significantly influenced the course of the experiment.

STATISTICAL MODELLING

The mechanical characteristics of reed stems, obtained as a result of the tests, helped to build a simple statistical model of quasi-strength and stiffness of reed. It should be underlined that, the obtained models refer solely to the test pieces which were the subject of the experiments and should not be applied in different conditions, e.g. for different reed varieties, or for reed from different plantations. A computer programme [MATLAB 2002] has been used for a non-parametric estimation of the probability density function (pdf) [Mańczak and Nahorski 1983, Bendat and Piersol 2010, Montgomery 2013] by applying the kernel function of the following types: "normal", "box", "triangle," and "epanechinikov." The following figures (Fig. 14 to Fig. 17) illustrate the distributions of probability density of quasi-strength and quasi-stiffness of reed, obtained empirically, for test pieces from groups "A" and "B."

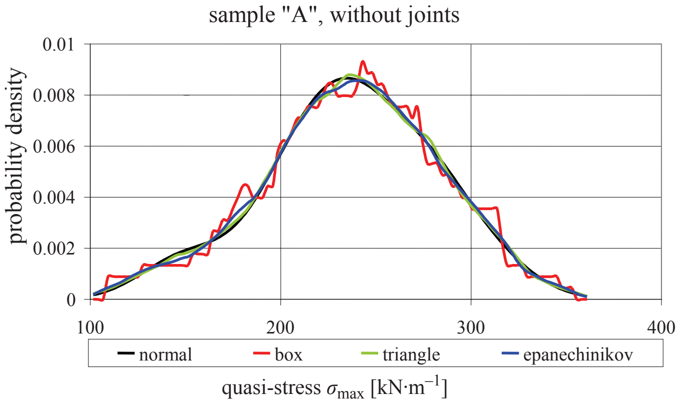

Fig. 14. Empirical probability density function pdf of quasi-strength for the group of test pieces without joints

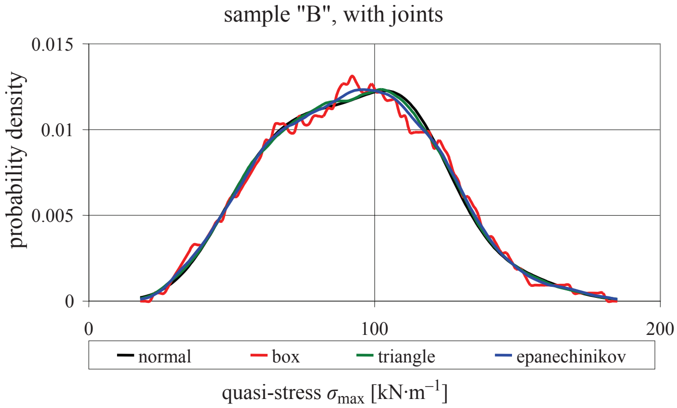

Fig. 15. Empirical probability density function of quasi-strength for the group of test pieces with joints

Probability density function of quasi-strength for the group of test pieces without joints, presented in Figure 14, can be described by mean value μ = 236.48 kN·m^{-1} and variance σ^2 = 1857.85. For the same group of test pieces, pdf of quasi-stiffness (Fig. 16) characterize: mean value μ = 1611.94 kN·m^{-1} and variance σ^2 = 464,068.35. Respectively,

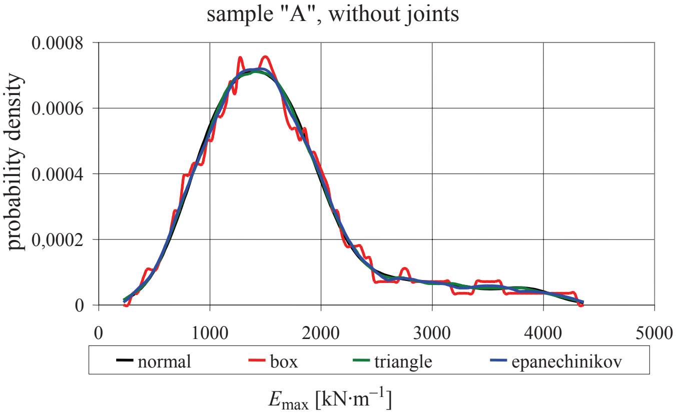

Fig. 16. Empirical probability density function of quasi-stiffness for the group of test pieces without joints

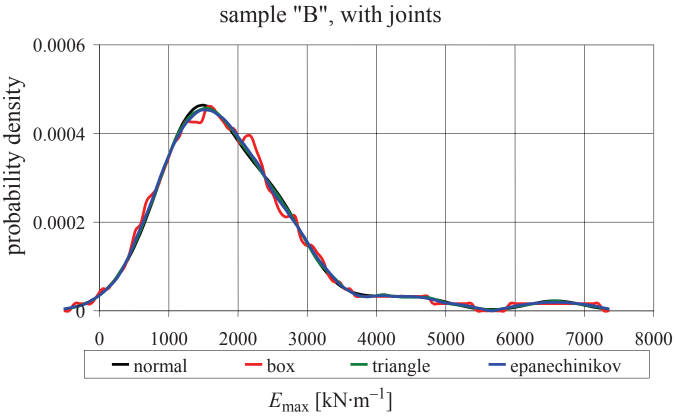

Fig. 17. Empirical probability density function pdf of quasi-stiffness for the group of test pieces with joints

pdf of quasi-strength for the group of test pieces with joints, presented in Figure 15, describe: mean value μ = 92.65 kN·m^{-1} and variance σ^2 = 709.08. For the same group of test pieces, pdf of quasi-stiffness (Fig. 17) characterize: mean value μ = 1961.04 kN·m^{-1}; variance σ^2 = 1273,262.39.

Among the kernel functions applied for the procedure of the pdf function estimation, only the "box" function yields an unsmooth distribution. The remaining functions are smooth and similar to each other, enough to make them practically undistinguishable (from a technical point of view). By analysing the shape of the obtained pdf curves, we can conclude that the distributions of quasi-strength resemble the Gaussian distribution, while the distributions of quasi-stiffness – the Weibull one. The verification of probabilistic hypotheses is not, however, the subject of this study.

CONCLUSIONS

1. Strengthening the ends of reed test pieces with the help of chemo-hardening resin makes it possible to conduct a pure tensile test (in testing machines with self-locking grips) in a satisfactorily accurate way.

2. Anisotropic and heterogeneous specificity of reed stems and the annular shape of their cross sections justifies why the status of internal forces at uni-axial tension is described through quasi-stress, understood as the resultant of cross-section forces on sector of a test piece's perimeter, expressed as $N \cdot m^{-1}$. By analogy, the physical relation between strain and quasi-stress should be understood as quasi-stiffness.

3. The strain vs. quasi-stress relation, at uni-axial reed tension, displays an exponential character, showing material stiffening with the growth of strain.

4. Some test pieces, during the tensile test, sustained a temporary loss of stiffness, regaining it afterwards, which points towards complex distribution mechanisms regarding internal forces in the fibrous structure of the reed "material" .

5. Test results incline to conclusion, that stem-pieces without joints are equally (from technical viewpoint) stiff as pieces with joints, however, they are twice as strong as the latter. It means, that joints can be perceived as fragile (in the sense: "brittle") discontinuity in structure of reed stems; test pieces of both groups ("A" and "B"), however, are of different origination, so, this conclusion should be verified.

6. Relatively small statistical sample made it possible to build a simple statistical model of the experiment, which encourages further investigations on testing probabilistic hypotheses in studies of this type.

7. Distributions of strength and stiffness probability of reed stems, obtained as a result of the computer estimation with the use of the "normal," "triangle," and "epanechinikov" kernels functions are undistinguishable from a technical viewpoint.

8. Empirically obtained probability density functions (in non-parametric estimation procedure) of quasi-strength resemble the Gaussian distribution (in both groups of test pieces), while the distributions of quasi-stiffness – the Weibull one.

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BADANIE NOŚNOŚCI ŁODYG TRZCINY NA ROZCIĄGANIE

Streszczenie. Badania wytrzymałościowe trzciny napotykają szereg trudności z powodu powłokowej struktury łodyg, ich anizotropii, niejednorodności, małych wymiarów przekroju oraz dużych rozrzutów w wynikach z powodu specyficzności użytych próbek. Mając świadomość wszystkich tych trudności, w niniejszej pracy przedstawiono wyniki prostego eksperymentu, polegającego na osiowym rozciąganiu próbek łodyg trzciny z kolankami i bez. Związek między odkształceniem a naprężeniem w czasie testu przybierał charakter wykładniczy, co wskazuje na tendencję do usztywniania się łodyg wraz ze wzrostem odkształceń. Wyniki testu skłaniają do wniosku, że części łodygi bez kolanek są tak samo sztywne jak z kolankami, są jednak dwukrotnie od nich wytrzymalsze. Prawdziwość takiego wniosku oznaczałaby, że kolanka stanowią niepodatne, kruche osłabienie łodyg. Wyniki przeprowadzonego testu poddano krytycznej ocenie, a przeprowadzone dodatkowe analizy pozwoliły na budowę prostego modelu probabilistycznego dla przeprowadzonego eksperymentu.

Słowa kluczowe: trzcina, quasi-naprężenie, quasi-sztywność, rozciąganie osiowe, nośność na rozciąganie

Accepted for print: 28.11.2016

For citation: Kowalski, W. (2016). Investigations on tensile load-carrying ability of reed stems. Acta Sci. Pol. Architectura, 15 (4), 153–168.