NON-DESTRUCTIVE DETECTION OF LONGITUDINAL CRACKS IN GLULAM BEAMS

ZERSTÖRUNGSFREIE MESSUNG VON LÄNGSRISSEN IN BRETTSCHICHTHOLZ-TRÄGERN

DÉTECTION NON DESTRUCTIVE DES FISSURES LONGITUDINALES DANS LES POUTRES DE BOIS LAMELLÉ COLLÉ

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SUMMARY

The paper reports on the detection and length characterisation of longitudinal cracks in glued laminated timber (glulam) beams by means of ultrasound (US) pulse transmission method. In the preliminary study one large glulam beam with a crack starting at one end-grain face and ending at about one third of total beam length has been evaluated. For the transmission measurements US pulses have been applied to the narrow faces of the beam, thus propagating parallel to cross-sectional depth perpendicular to fibre. The beam has been scanned by a transmitter / receiver pair of US transducers shifted along the longitudinal beam axis. The recorded full US wave signals were evaluated for three different scalar parameters being "time of flight", "peak-to-peak amplitude" and "first amplitude". The comparison of the visual inspection with the US parameters, showing significantly different scatter ranges, yielded a satisfactory agreement with respect to the determination of crack length. The NDT crack detection based on the parameter "time of flight" was also satisfactory when the crack extended only over a part of the beam width, i. e. not being visually detectable from one of both side faces. The latter can be very important for in-situ inspection of beams in buildings with assumed or partial cracks.

ZUSAMMENFASSUNG

Der Aufsatz berichtet über den Nachweis und die Längenmessung von longitudinalen Rissen in Brettschichtholz (BSH) -Trägern mittels der Methode der Durchschallung mit Ultraschallpulsen. In der orientierenden Studie wurde ein großer Brettschichtholzträger mit einem Riss untersucht, wobei der Riss von einer Hirnholzfläche ausging und innerhalb des ersten Drittels der Trägerlänge endete. Für die Transmissionsmessungen wurden Ultraschallpulse auf die Schmalseiten der Träger aufgebracht, so dass diese sich parallel zur Querschnittshöhe und damit rechtwinklig zur Faserrichtung ausbreiteten. Der Träger wurde mit einem Ultraschall Geber / Empfänger-Paar in Richtung der Trägerachse abgerastert. Die aufgezeichneten vollständigen Ultraschallsignale wurden hinsichtlich dreier verschiedener skalarer Parameter ausgewertet: Signal-Laufzeit, Signalstärke und erste Amplitude. Der Vergleich der visuellen Charakterisierung mit den Ultraschallparametern, die jeweils deutlich unterschiedliche Streubreiten aufwiesen, ergab eine zufriedenstellende Übereinstimmung hinsichtlich der Bestimmung der Risslänge. Die zerstörungsfreie Risserkennung auf Grundlage des Parameters "Signal-Laufzeit" war auch dort noch zufriedenstellend, wo sich der Riss nur über einen Teil der Querschnittsbreite erstreckte, also auf einer der beiden Seitenflächen schon nicht mehr sichtbar war. Letzteres kann für die in-situ Beurteilung von Trägern in realen Bauwerken mit vermuteten oder teilweise vorhandenen Rissen sehr wichtig sein.

RÉSUMÉ

L’article traite de la détection et de la caractérisation des fissures longitudinales dans les poutres en bois lamellé collé, au moyen d’une méthode de transmission des impulsions ultrasons. Lors de travaux préliminaires, une poutre présentant une fissure commençant à l’une des extrémités et s’étendant jusqu’au tiers de la longueur totale a été étudiée. Les impulsions d’ultrasons sont appliquées sur les deux faces les plus étroites de la poutre et se propagent parallèlement à sa section, c’est à dire perpendiculairement aux fibres du bois. Les capteurs ultrasons (émetteur et transmetteur) balaient alors la poutre suivant son axe longitudinal. Le signal enregistré fournit trois paramètres différents: le temps de propagation du signal, son amplitude pic à pic et sa première amplitude. La comparaison entre les indications obtenues par la méthode des ultrasons et l'évaluation visuelle sont en accord quant à la détermination de la longueur de la fissure. La détection basée sur le seul paramètre « durée de propagation » est également satisfaisante lorsque la fissure ne s'étend que sur une partie de l'épaisseur, c'est à dire lorsqu'elle ne traverse pas la poutre de part en part. Ce dernier cas est très intéressant pour l'inspection in-situ des constructions présentant des fissures ou des risques de fissure.

KEYWORDS: non-destructive testing, ultrasound, pulse transmission, crack in glulam beams, scalar ultrasound parameters

1. INTRODUCTION

Non-destructive evaluation of the state of integrity resp. of defects or partial damages in structural building elements generally represents an important issue. The capability of NDT based reliable assessment of components enhances the acceptance of building systems or materials, may affect safety factors and enables assessment of upgrading or rehabilitation works. Timber and glulam beams despite all positive aspects are prone to longitudinal cracks generally resulting from interaction of poor constructive detailing and unaccounted climatic stresses. Longitudinal cracks primarily occur at i) support areas due to interaction of shear stresses and climate and ii) at notches, holes and in apex areas of curved / tapered beams due to tension stresses perpendicular to grain bound to undue load actions and / or often climate stresses. Finally, iii) longitudinal cracks can occur from poor glue lines generally bound to trespass of open / closed curing times of the adhesives.

The reliable assessment of the extent of damage and of the result of the repair works represent the two equally important aspects of the NDT assessment of damaged or upgraded construction elements. In many cases a visual inspection of the beams is very costly or almost impossible. Today reliable NDT tools for employment in the sketched area are missing for lumber / glulam beams being contrary to constructions with some other important building materials. The reason for this NDT lag consists i.a. in the anisotropy, inhomogeneity and the high damping characteristics of the natural material wood.

Timber Department of Otto-Graf-Institute being deeply involved in the assessment / expertises of damages, repair proposals and technical approval of rehabilitation works has started to focus on active NDT methods about a year ago. This paper gives some preliminary results of one of the on-going projects. It is reported on the detection and length characterisation of longitudinal cracks in glued laminated timber (glulam) by means of ultrasound (US) pulse transmission method. The US method has been chosen due to its sensitivity to impedance changes at discrete boundaries. Former literature known attempts in this field [KLINGSCH, 1991; KIMURA ET AL 1991] dealt with artificial defects, being rather thick saw cuts of defined length parallel to beam axis and over full cross-sectional width. The results and the practical relevance of the exclusive focus on such slots / cracks has been discussed controversially in the involved engineering community. In the investigation reported here a fully practice relevant crack resp. cracked beam was investigated.

2. EXPERIMENTAL SET-UP

The investigated specimen represented a part cut from a large beam with a round hole loaded until failure in bending, compare Fig. 1a. The beam had failed with two large cracks initiated at the hole periphery by high local stresses perpendicular to grain. The crack propagation was then driven by both, shear and tension stresses perpendicular to grain.

The investigated NDT specimen (Fig. 1b) showed an open crack over full width b at end grain face Y closer to the former hole location and no visible crack at the opposite end grain face Z. Thus, despite disputable accuracy of visual inspection the crack must end within the specimen as the latter consisted of one massive piece.

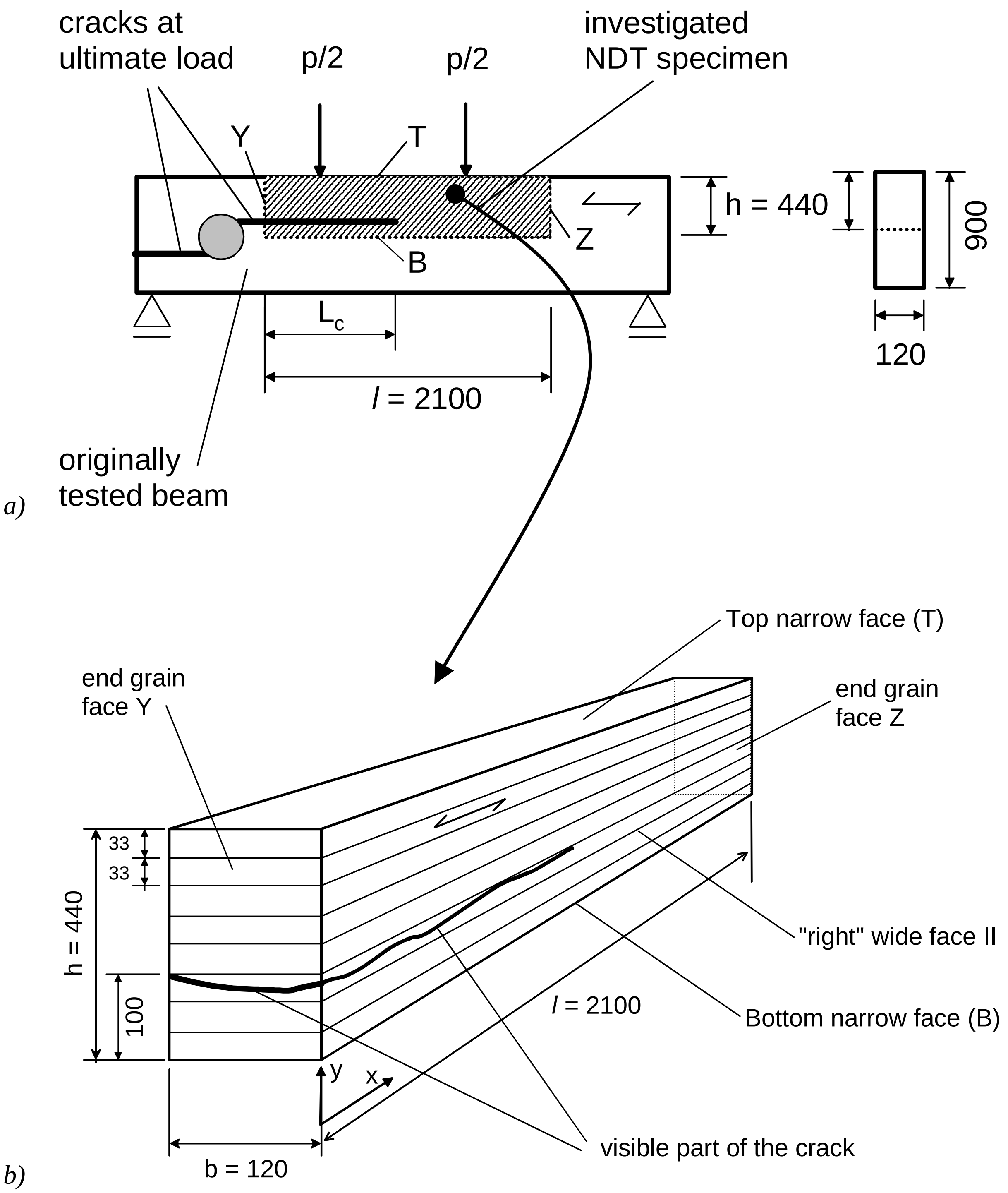
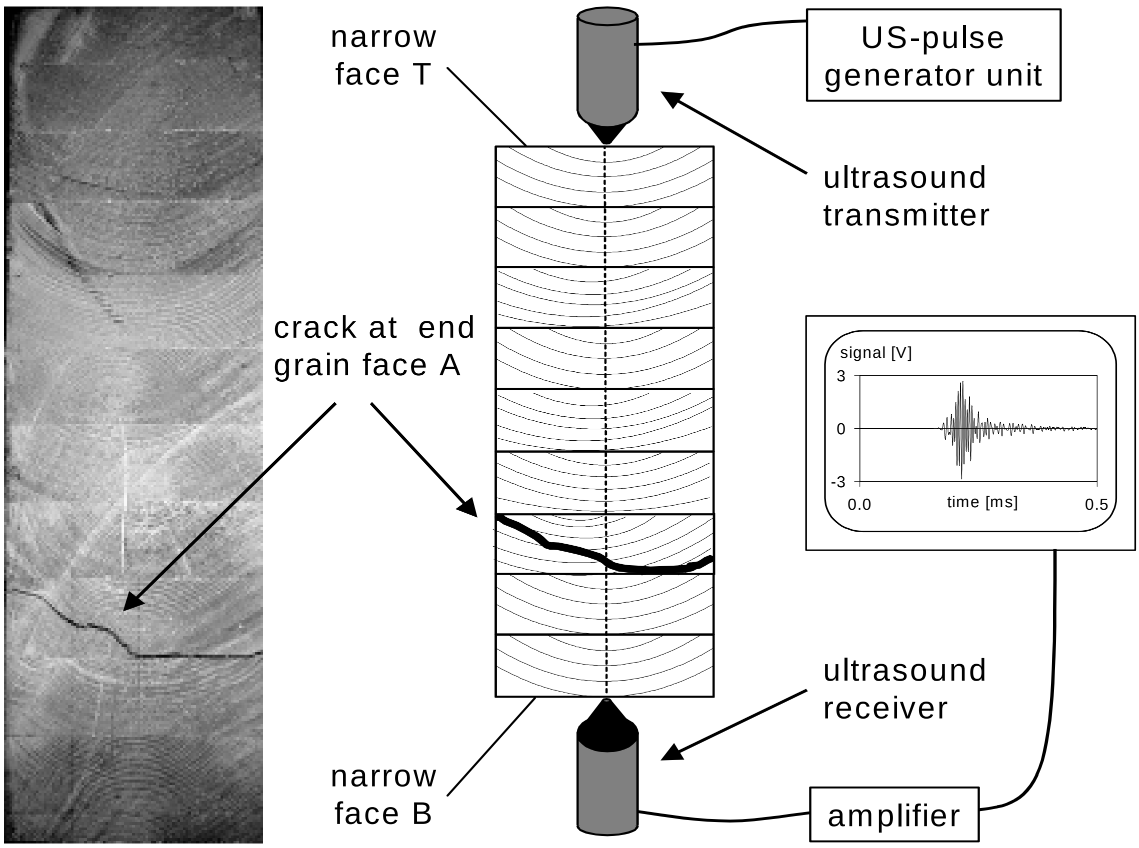


Fig. 1a,b: Original location and dimensions of the employed NDT specimen.
a) larger cracked beam from which the NDT specimen was cut out after failure of the beam
b) view and dimensions of partially cracked NDT specimen

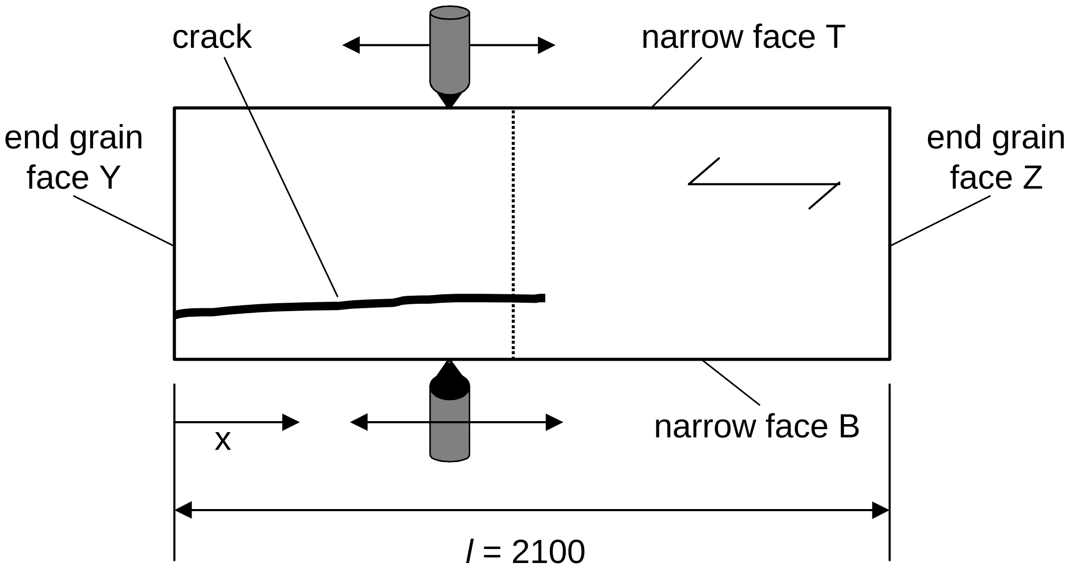
The dimensions of the block were (width b × depth h × length *l*): 120 mm × 440 mm × 2100 mm. Starting at end-grain face Y and proceeding in the longitudinal (x-) beam direction, the crack is visible at both side-faces I and II for the major part of the crack length (compare chap. 4).

The ultrasonic NDT evaluation / assessment of the crack (length) was throughout performed by means of a pair of piezoelectric (US) transducers. Transmitter and receiver were positioned oppositely at mid-width of the narrow faces T and B of the beam specimen and aligned parallel to depth. Starting at the end-grain face Y with the opened crack the transducer pair was moved along beam length l with increments of $\Delta x = 50$ mm towards the end grain face Z. At each position an ultrasonic pulse synthesized by a generator unit was put to the specimen by the piezoelectric transmitter. Figure 2 shows a schematic representation of the experimental set-up. The fixation of the transmitter and of the receiver differed. The transmitter was throughout fixed to the surface by a hot melt adhesive also serving as coupling agent. Contrary, the receiver was not glued to but applied to the surface by hand pressure without using any kind of coupling agent.

At each location x a number of 25 repetitive measurements were performed in order to enable noise reduction. As the crack was not centred in the middle of the cross-sectional depth but much closer (~70 mm) to narrow face B it was questioned whether there might be an influence if the transmitter is at a closer or more remote distance to the crack. Therefore two test series S1 and S2 were performed with the transmitter first being at narrow side T and then at narrow side B.



a)



b)

Fig. 2a,b: Schematic representation of the experimental set-up

3. NDT EQUIPMENT

The generator unit (USG 20, Geotron Electronics), originally optimised for NDT of concrete, produced high voltage pulses with main frequencies between 20 kHz and 350 kHz. The duration of a single pulse was less than 1 ms.

The ultrasonic transducers (UPG-D 3037, UPE-D 3038, Geotron Electronics) used in the experiments were piezoelectric converters with a coupling-surface of 3 mm in diameter. The transducers showed a multi-resonant frequency characteristic with main peak values between 20 and 100 kHz.

The received ultrasonic pulses have been amplified by a broadband amplifier (AM 502, Tektronix) with an amplification factor of 100 dB. The complete signals were recorded by a PC based transient recorder with 12 bit amplitude resolution and 20 MHz time resolution.

4. VISUAL CHARACTERIZATION OF THE CRACK DIMENSIONS

For correlation of the ultrasound NDT parameters with the length of the crack in longitudinal beam direction and with the crack opening, the dimensions of the crack were determined by visual inspection at both wide side faces I and II of the specimen. The crack openings were measured with a feeler gauge.

Figures 3 a and 3 c give a schematic illustration of shape, position and dimensions of the crack according to the visual characterization and feeler gauge measurements at the two wide faces I and II, while Fig. 3 b shows a top view indicating the projected crack area. According to the visual findings the crack can be divided into three different sections.

In section A ($0 \leq x \leq 53$ cm), the crack is characterized by measurable openings of 1.2 mm (x = 0) to 0.4 mm (x = 53 cm) at side face I; at side face II the respective dimensions are: 0.4 mm (x = 0) to 0.05 mm (x = 53 cm).

In section B ($53 \text{ cm} < x \leq 67$ cm) a crack-opening was only measurable at side face I with openings in the range of 0.35 mm to 0.25 mm. At side face II, the closed crack was visible as a small displacement edge within the surface.

Finally in section C ($67 \text{ cm} < x < 88.4$ cm), the crack was still measurable at side face I with openings from 0.25 mm to 0.05 mm. The end of the crack at $x = L_C = 88.4$ cm almost coincides for measurable (0.05 mm) crack opening and visual inspection. At side face II, the crack is not visible at all.

The true extension and shape of the crack front might well be somewhat ahead of $x = L_C$ what will be determined at the end of the ongoing experiments.

5. CHARACTERIZATION OF SIGNAL-PARAMETERS

Once an ultrasonic pulse is generated and applied to the narrow face of the glulam beam, it is proceeding through the specimen perpendicular to the direction of the glued lamellas, i.e. perpendicular to fibre direction and is detected by the receiver at the opposite surface.

The recorded full wave signals purged from noise by multiple pulse measuring method were so far evaluated for three different scalar parameters, being:

- “Peak-to-peak amplitude” (pp amplitude) of the signal, which represents the difference between the recorded absolute maximum and minimum of the complete signal. The parameter is correlated to the transmitted energy of the pulse. Figure 4 shows one exemplary wave signal, including the determination of the pp-amplitude.
- “Time of flight” (TOF) of the signal is defined as the time lag between the external trigger edge given by the pulse generator and the on-set, i.e. the begin of the recorded signal. The signal-parameter TOF and also the below specified parameter $|1^{st}$ a$|$ are exemplarily depicted in Fig. 5 for the signal given in Fig. 4 now presented with a close-up at the begin of the signal.
- “First amplitude” (1st a) of the signal is defined as the maximum (or minimum) amplitude of the first observable half cycle. In detail, for signal characterization, the absolute value of the first amplitude has been used.

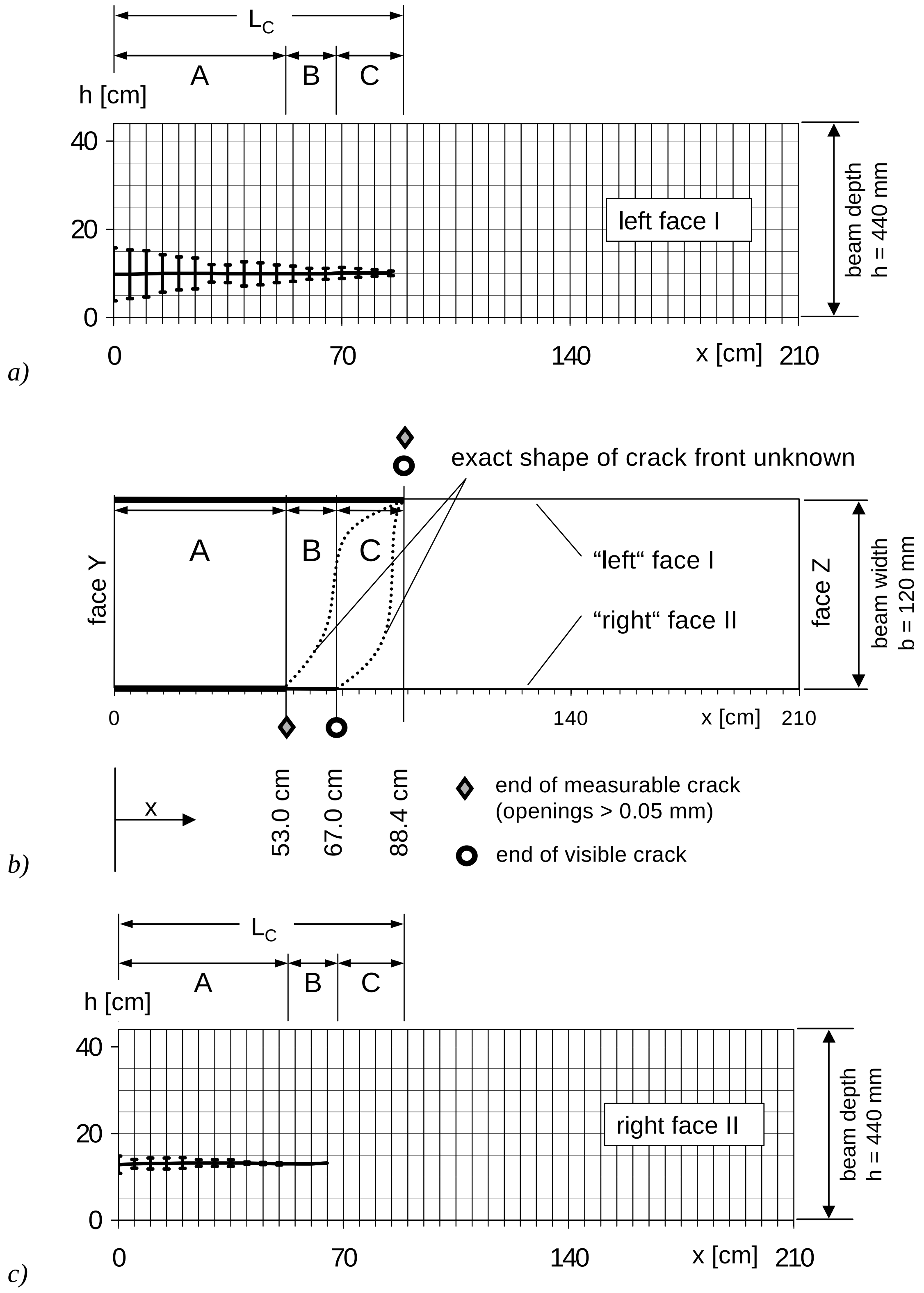


Fig. 3a-c: Schematic illustration of the appearance of the crack at different faces of the specimen. The graphs 3a) and 3c) give measured crack lengths and crack openings (100-times enlarged) at the left and right wide side faces (I and II). Fig 3b shows a projection of the crack area revealing the three crack sections A-C.

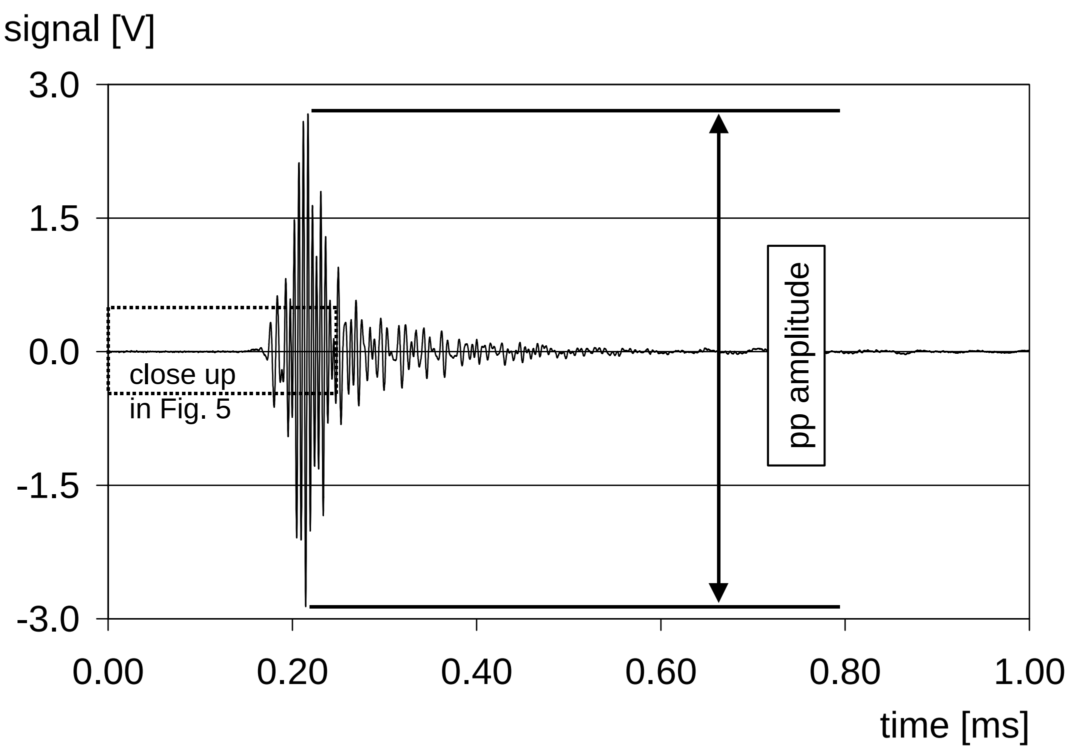


Fig. 4: Recorded signal with evaluation / definition of the "peak-to-peak amplitude" (pp amplitude)

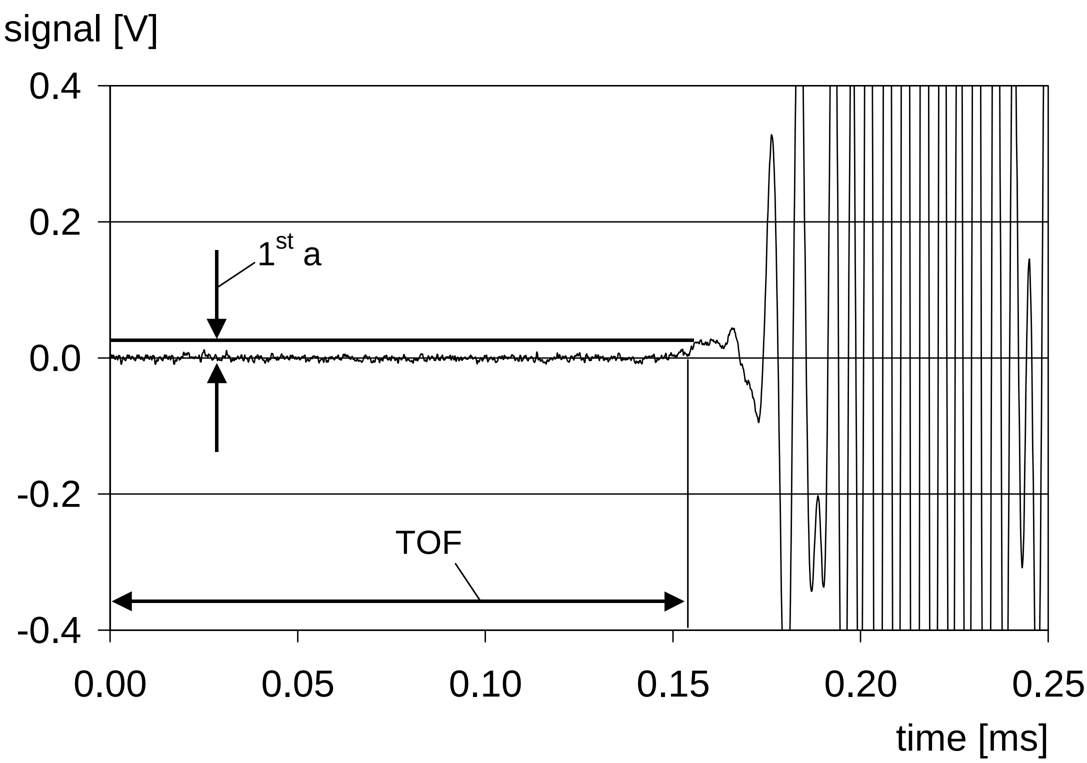


Fig. 5 Evaluation / definition of "time of flight" (TOF) and of "first amplitude" (1st a); the graph represents a close-up of the recorded ultrasound pulse given in Fig. 4

6. RESULTS OF THE ULTRASOUND MEASUREMENTS

The reproducibility of the signal parameters for repeated independent measurements at a specific location x (uncoupling and new coupling of the transducers for each measurement) differed considerably between parameter TOF on the one side and parameters pp and $|1^{st}\ a|$ on the other side. In case of TOF in average an extremely small coefficient of variation (C.O.V.) of 0.3 % was obtained whereas for the parameters pp and $|1^{st}\ a|$ the considerably higher C.O.V.'s were 21% and 24 %, respectively. For the reproducibility test a number of 10 repeated measurements have been evaluated.

The major results of the performed preliminary investigations are compiled in Figs. 6 to 8, showing the signal parameters TOF, pp and $|1^{st}\ a|$ along specimen axis x. In all graphs the results of the two test runs S1 and S2 with the alternative transmitter positions at narrow specimen sides T or B are given, and the mean value of both test runs is shown additionally. Further, the quality of the signal parameter reproducibility is indicated in all Figures by an error bar with a height of 2 times of the respective standard deviation (the error bars are not visible in Fig. 6 due to the very small C.O.V.'s). The visually determined crack length segments A, B and C are indicated in the graphs, too. Following the results are discussed in more detail.

Figure 6 specifying "time of flight (TOF)" vs. beam axis x reveals almost throughout a steep decrease of parameter TOF along crack length segments A, B and C. It should be emphasized, that the TOF decrease in the investigated case is apparently not affected by the fact that the crack is not visually detectable at surface II in crack zone C. For positions $x > L_C$ a rather constant TOF value of 253.2 ms is obtained. This gives a mean phase velocity in transverse direction to fibre of $v_{90} = 0.44 / (253.2*10^{-6}) = 1738$ m/s which is in good agreement with literature data [Buchur 1989] on phase velocities perpendicular to fibre of wood / glulam made of European spruce. A comparison of test series S1 and S2 indicates apart from one exception in the crack range A, that the TOF results are obviously not influenced by transmitter location closer resp. more far from the crack plane.

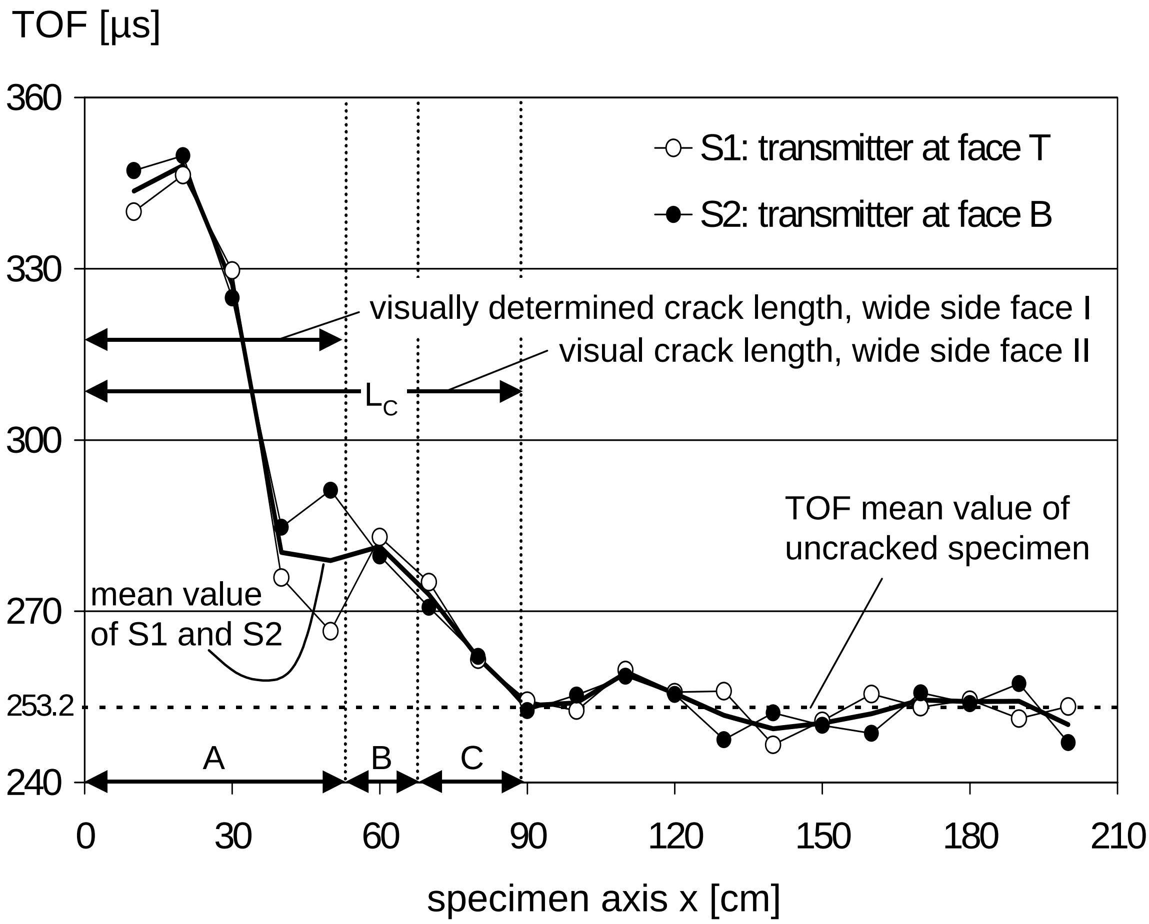


Fig. 6 Results of time of flight (TOF) measurements along the beam axis x. The x-axis gives the distance x [cm] of the transducers position to the end grain face Y. The crack was supposed, according to visual inspection, to end at x = 88.4 cm.

Figure 7 shows the “peak-to-peak amplitude” (pp amplitude) of the transmitted signals. Qualitatively a slow increase of pp-amplitude values from mid- length of segment A through to C and the increase continues to about 20 cm beyond C; into the visually uncracked part of the beam. Quantitatively high scatter of the measured data, especially in the uncracked section is observed. Exemplarily at a distance x = 160 cm from end grain face Y, certainly well ahead of the crack front, the pp-amplitudes exhibit a local minimum with values comparable to those measured within the crack at x = 70 cm (in section C). The transition from the cracked to the undamaged section is rather smooth without a clearly marked step in the pp amplitude course.

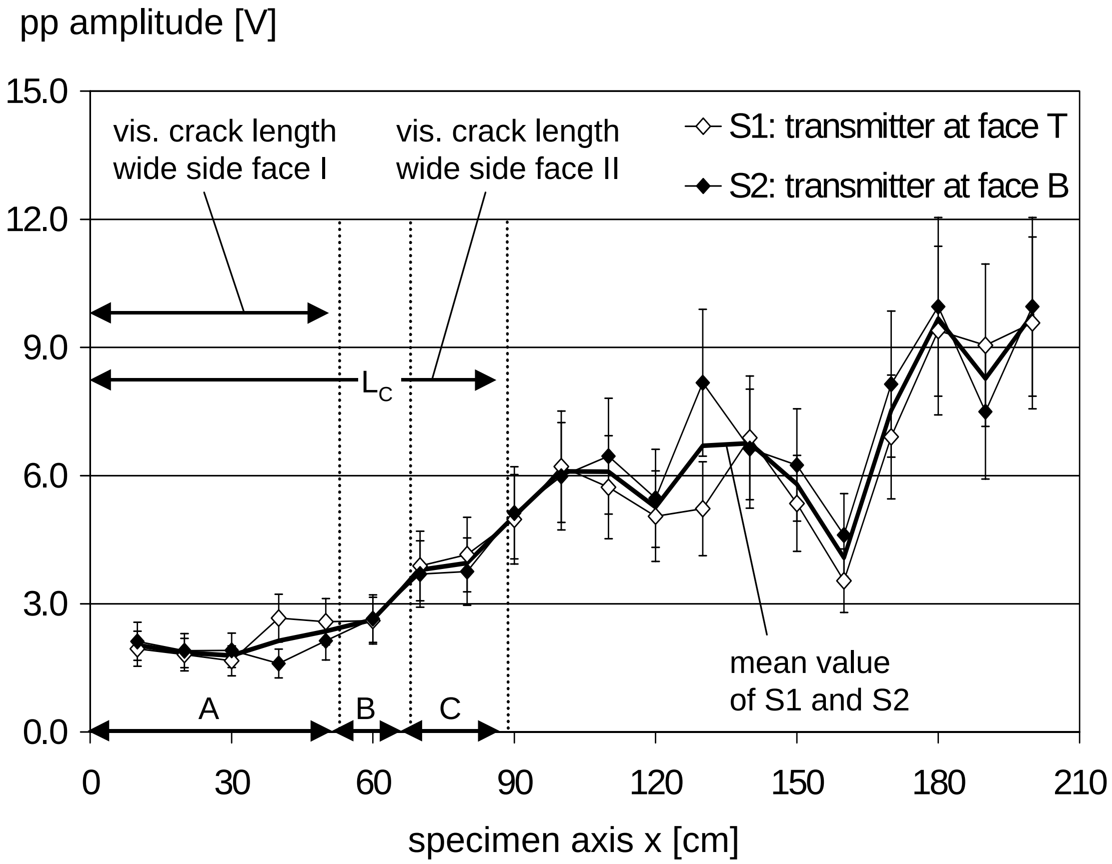


Fig. 7 Results of peak-to-peak amplitude (pp amplitude) measurements along beam axis x. The x-axis gives the distance x [cm] of the transducers position to the end grain face Y. The crack was supposed according to visual inspection to end at x = 88.4 cm.

Thus, the signal-parameter pp-amplitude does not allow a clear identification of the crack length. The relatively high uncertainty due to coupling conditions makes it even more difficult to quantitatively estimate the location of the crack tip. However, in spite of the scatter, the clearly visible trend of decreased attenuation for decreasing crack openings is not affected qualitatively.

The presented results for the behaviour of the peak-to-peak amplitude in case of cracks can be compared to the observations of [KLINGSCH, 1991], where no damping of pp amplitudes has been measured in the case of saw-cuts.

In Fig. 8 the results of $|1^{st}\ a|$ along beam axis x are shown for the two performed test series S1 and S2 together with the boundaries of the different crack sections.

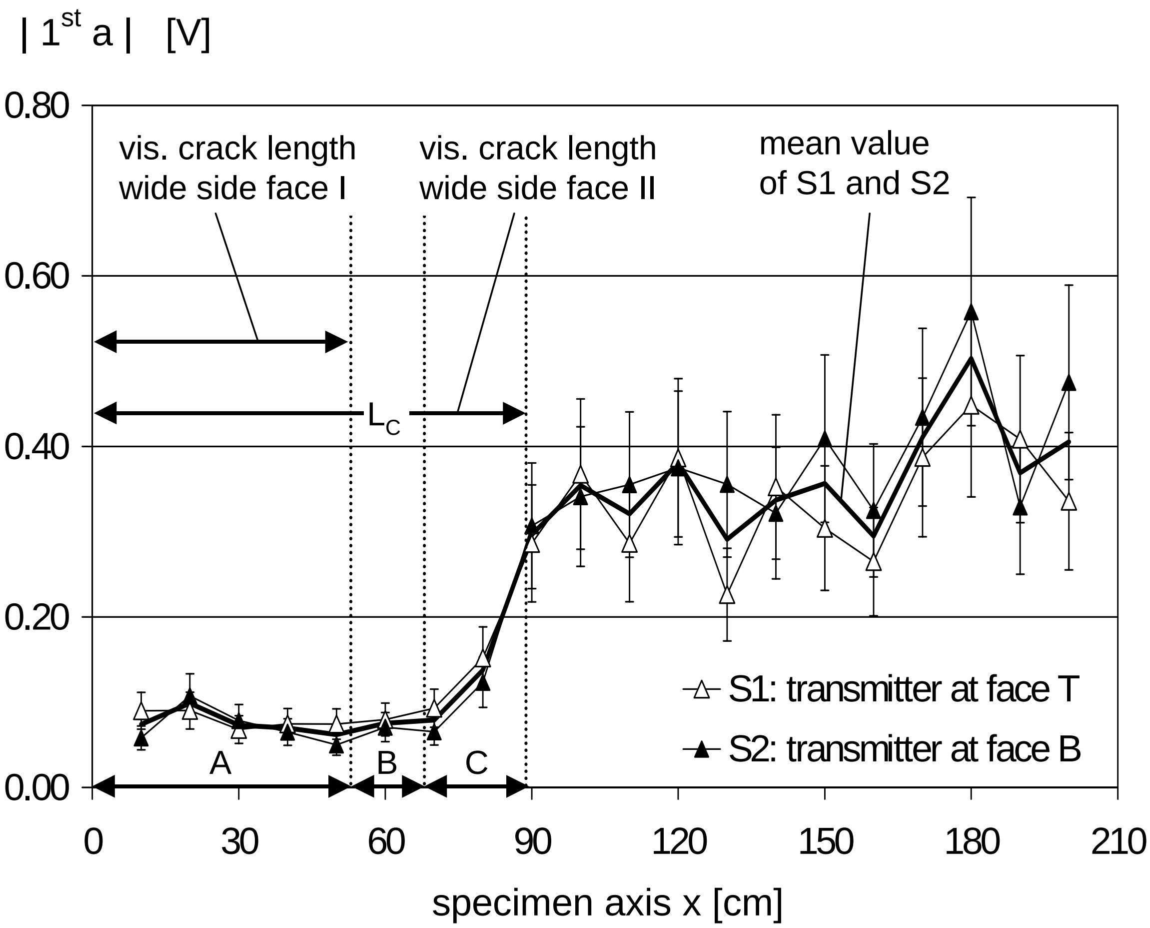


Fig. 8 Results of measurements of absolute values of the first amplitude (|1st a|) along the beam axis x. The x-axis gives the distance x [cm] of the transducers position to the end grain face Y. The crack was supposed according. to visual inspection to end at x = 88.4 cm.

The measured course of the |1st a| values can roughly be described as a step function with quite constant low values within all three sections A to C of the crack and a sharp increase at the assumed crack tip. It is interesting to note that in section C still strong damping of |1st a| is observed, while the crack is solely visible at one side face of the specimen.

Although the scatter among |1st a| values within the undamaged part of the beam is significant, the results between cracked and uncracked parts of the beam are clearly separated, which is especially true for the mean values of the two test series with interchanged transmitter / receiver conditions.

7. CONCLUSIONS

The performed preliminary study on the feasibility of crack detection in glulam beams by means of ultrasonic pulse transmission method revealed promising results.

All three evaluated scalar signal parameters, being time-of-flight (TOF), peak-to-peak-amplitude (pp-amplitude) and first amplitude ($|1^{st}\ a|$) showed significant correlations with the occurrence of the completely or partly visually detectable crack.

Both, pp-amplitude and $|1^{st}\ a|$ exhibited relatively high scatter among the values within the undamaged part of the beam accompanied by a quite poor reproducibility bound to the performed non-ideal coupling conditions. The pp-amplitude values showed a smooth transition zone from cracked to the uncracked sections of the beam. Contrary hereto the $|1^{st}\ a|$ values exhibited a pronounced step indicating the end of the crack clearly.

The TOF-results showed best reproducibility and a clear, although smooth change at the end of the crack. The different crack sections with one-sided throughout measurable crack openings respectively one sided first measurable and then visible crack opening were best represented by the course of TOF results.

For all three characteristic signal parameters, no significant differences due to interchanged positions of transmitter and receiver were observed. Thus, no detection of the location of the crack with respect to depth direction could be performed, being in good accordance with the results of [KLINGSCH, 1989, 1991].

Although feasibility of the applied NDT methods and evaluation for crack detection could be shown by the presented study, the results from only one exemplary specimen may not be generalized. Additional tests also with investigate different beam / crack configurations have to be performed to obtain a statistically more reliable data basis.

In order to improve the presented ultrasonic method for applications in real structures, the coupling problem has to be solved and the feasibility for beams with realistic heights of about 1 to 1,5 m has to be shown. Advanced signal processing techniques for the evaluation in the frequency domain (i.e. Fourierand Wavelet transforms) should be used for noise reduction, enhancement of resolution and defect sensitivity.

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