Bundesanstalt für Materialforschung und -prüfung

Bundesamt für Bauwesen und Raumordnung

Summary Report

for the Research Project

High-precision texture recognition of timber structures using 3D-ultrasound

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January 2013

BAM-Number 8.2 Vh 4454

Funded by The Federal institute for Research on Building, Urban Affairs and Spatial Development (BBSR) has funded the scientific report. (reference number: SF – 10.08.18.7-10.5 / II 3–F20-09-1-220)
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1 Introduction and Motivation

Under consideration of the anisotropic acoustic properties of the timber, the funded research developed the basics for an ultrasonic imaging method for timber structures and paved the way to application in practice. Improving the testability without external intervention contributes to sustain a durable stability of timber structures and thus to increase the competitiveness of the timber industry.

It seems reasonable to increasingly use timber as a building material. This results from the sustainability of timber as a renewable resource, its natural role as carbon storage and the positive energy balance when comparing the primary energy content of renewable energy sources (stored in wood and recyclable (grey) energy).

Repeated failure cases of timber components, e.g. caused by not regarding structural timber protection, results in an increasing requirement for testing existing timber structures. This applies to both, regular safety monitoring of the durability of the construction and the quality assurance during the construction process.

The research project applies a 3-dimensional (3D) reconstruction algorithm, which is new for timber structures and further developed for application to the anisotropic structure of timber aiming at high resolution imaging of internal reflectors Thus, the presently available methods for timber structures are essential complements, since now a highly precision 3D image can be achieved (resolution: 20 mm and better). The research intends to support the construction of high quality timber structures and to monitor this quality at reasonable intervals to reach a high durability.

2 Systematic Proceeding

A major role in the assessment of timber structures made of modern timber components such as glue-laminated (glulam) trusses, duo and trio beams play insufficient bond, cracks from load, cracks at fastener or voids.

Aim of the project is the detailed investigation of non-destructive evaluation of timber components with a new 3D imaging ultrasonic echo method. The newly developed 3D method takes into account the anisotropic structure of timber. The image sections and projections are calculated from ultrasonic imaging data. The measurements are performed on specimens and on components from practice.

It is important for non-destructive testing (NDT) data that the error can be clearly distinguished from reflector indications, such as tree branches and shrinkage cracks, nowadays available methods usually allow only an indirect indication of suspected sites. The accurate identification and location must be confirmed with minor destructive methods.

The newly developed processing [1] for the analysis of ultrasonic echo measurements of timber components is gradually used for 3D structural analysis and further developed [2]. Essential for a

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good test result is the knowledge of the elastic constants of the component [3] based on the three dimensions (see explanation footnote[3]). During the work, especially at this point turned out that the solution of this task needs significantly more basics to be investigated about the sound propagation in wood components than originally thought.

The measurements on the specimen timber and the timber components were carried out with a scanning system. In this, the shear waves probes has been modified so that a 1x1 dual-element probe (transmitter - receiver) was used. The linear-array "MIRA" [4] is commercially available. The Synthetic Aperture Focussing Technique (SAFT)-analysis software was specially adapted to the needs of the University of Kassel and further developed [1]. Additional studies were conducted with the commercially available A1220 that was working in the same manor as linear array. It also operated with shear waves transducers.

3 Results of the measurements

The progress of the research and analysis program development is demonstrated in the following few examples:

3.1 Measurements on the pine specimen x1124

According to various studies on specimens without defects, an L-shaped defect (dimensions: 7.5 cm x 4.3 cm) was milled in the pine specimens X1124 (dimensions 49.5 cm x 30.1 cm x 14.5 cm) as shown in Fig. 1. The wood specimens were glued together from timber blocks. The measurements using an automated scanner were carried out with a transversal wave sensor with radial wave propagation direction R (radial) with a polarization in direction L (lengthwise or axial)[3]. The measurement grid was 5 mm.

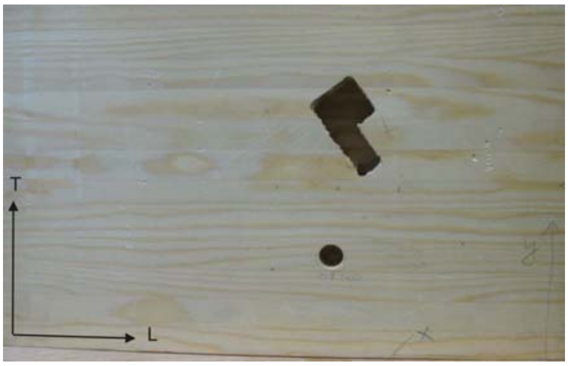


Fig. 1 Large pine wood specimens (specimen X1124) with L-shaped defect (back side)

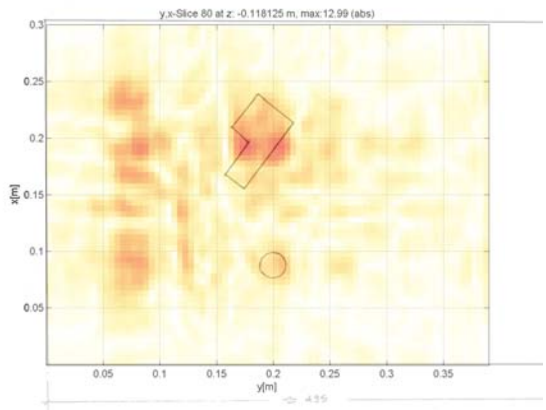


Fig. 2 Surface-parallel section (C-scan, time slice) of a 3D SAFT reconstruction, depth z = 118 mm with marked defects location

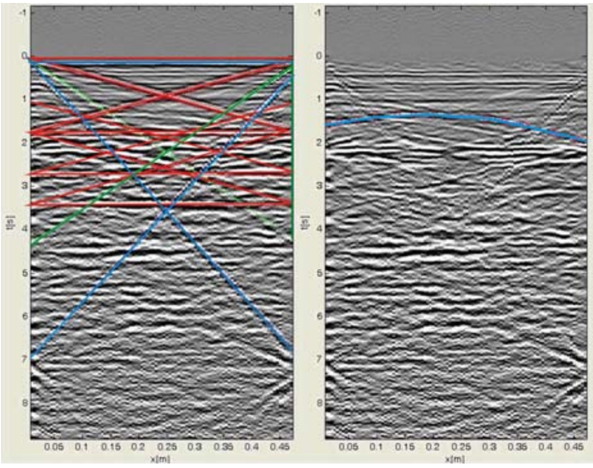
Fig. 2 shows a surface-parallel section (C-scan) of the SAFT-reconstruction. There, the position of the defects with the reconstruction result is matched. The void is not clearly visible and could not be distinguished from defect indications without prior knowledge.

The ultrasonic data show many surface waves, which are reflected at the specimen´s edges (see B-Scan/ line scan on the left in Fig. 3). This has a disturbing effect on the SAFT reconstruction, but it

[3] R = radial, L= lengthwise or axial, T = tangential, directions indicated refer to the growth direction of the tree

can be filtered out using the inter-saft-processing. As we can see in Fig. 3 the hyperbola of the lower reflector is clearer in the right line-scan, after filtering off the surface waves.

As shown in the upper image in Fig. 4, shear-waves with the polarization in L-direction exit an additional surface wave in L-direction. In the volume a oblique running head wave similar to a plane wave develops, which is aligned to the (slower) shear wave. The head weave connects the slow quasi-transversal wave qT1 and the fast quasi-longitudinal wave qL. It follows now experimentally the polar diagram in Fig. 4 bottom. By applying the hyperbolic function, the waves qL and qP2 are combined.



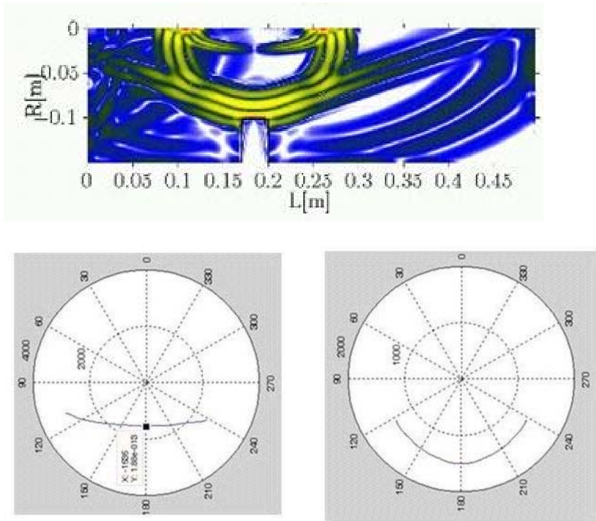


Fig. 3 Evaluation of the measurement of pine wood: Identification and suppression of surface waves (left), identification of the hyperbola of the lower reflector (right)

Fig. 4 Imact waves generated by the excitation polarization TL in pine wood (according to the model)
bottom: polar plot of the velocities in the L- (left) and T-direction (right)

If the calculated velocity profile is considered in the reconstruction calculation, the reconstructed L-shaped defect is displayed as shown in Fig. 5. Here, the position and shape of the defect is clearly visible in the image.

Fig. 5 shows additionally to the reconstruction result of the defect, the 3D representation of the simulation result, too. The planes yx (in Fig. 5, top left), zx (in Fig. 5 bottom left), zy (in Fig. 5, bottom right) as well as the 3-D overall view (in Fig. 5, top right) can be seen. The possibility of a 3-D representation of the reconstructed results of timber components is an important result of the project.

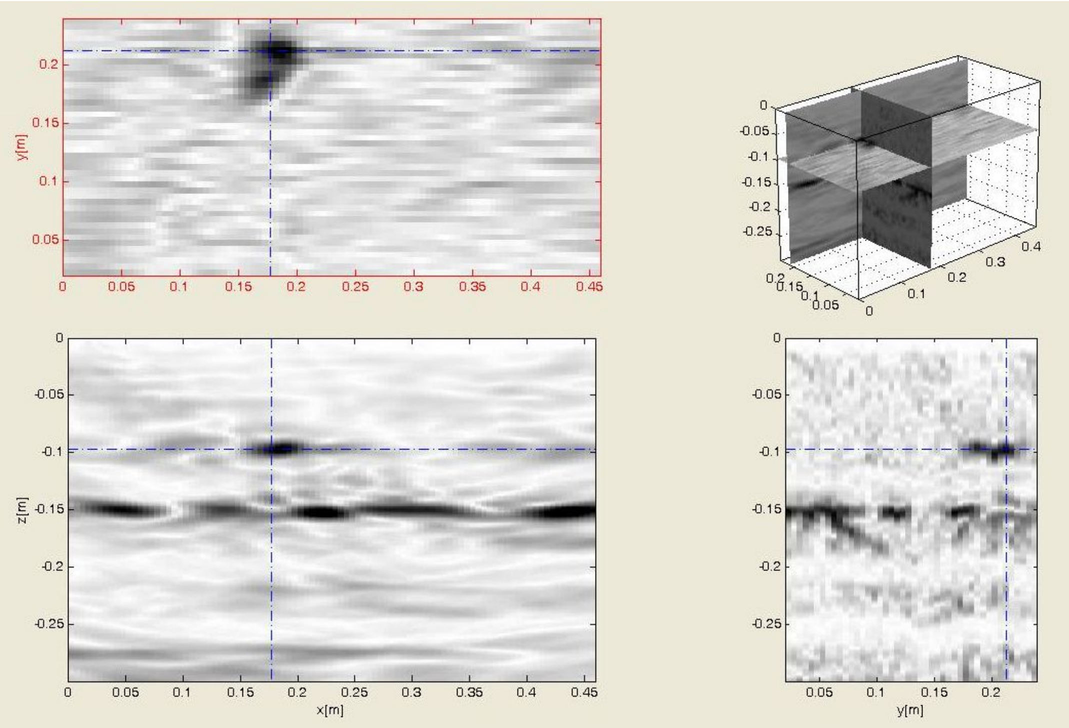


Fig. 5 Pine X1124: Result of the reconstruction bill with experimentally determined velocity profile.

3.2 Measurements on the spruce specimen F245

Further investigations were carried out on the spruce specimen F245.

The specimen Fichte245 (Fig. 6) was glued in such a way that the measurements could be made in T~z-direction and the polarization has L~x- or R~y-direction (for shear waves). The measurements were performed again with a scanning system with shear wave probes (1 transmitter x 1 receiver) at a frequency of 55 kHz and with longitudinal wave probes (1 transmitter x 1 receiver) at a frequency of 75 kHz. In the reference measurement with shear waves with the polarization in the L-direction in the B-Scan is at t = 137 µs, the echo of the back wall is visible. This reflection cannot be detected if the polarization is in the R-direction. Again, the surface waves are quite intense in these measurements. These waves severely affect the SAFT-reconstruction and must be specially processed, at best by suppressing or filtering.

Here, the results of the measurements after excitation with the polarization TT are exemplarily described, i. e. excitation by longitudinal waves. An overview of the results is shown in Fig. 8. In the SAFT-B-x~L, z~T-image is shown only the area in which lies the circular disks. The circular discs 1 to 5 are apparent here.

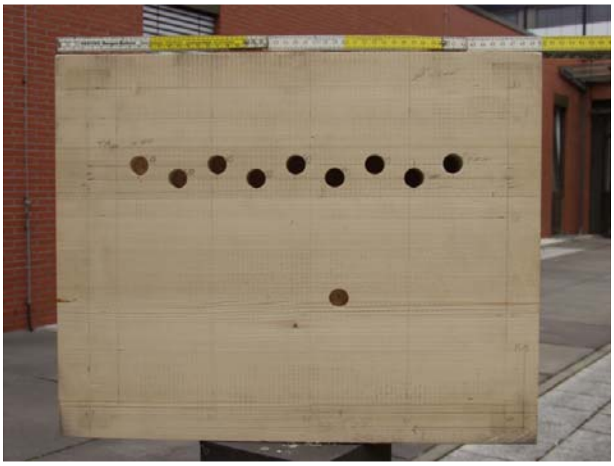


Fig. 6 Spruce specimens F245 (dimensions: 50 cm x 40 cm x 9 cm) with artificial defects on the back side.

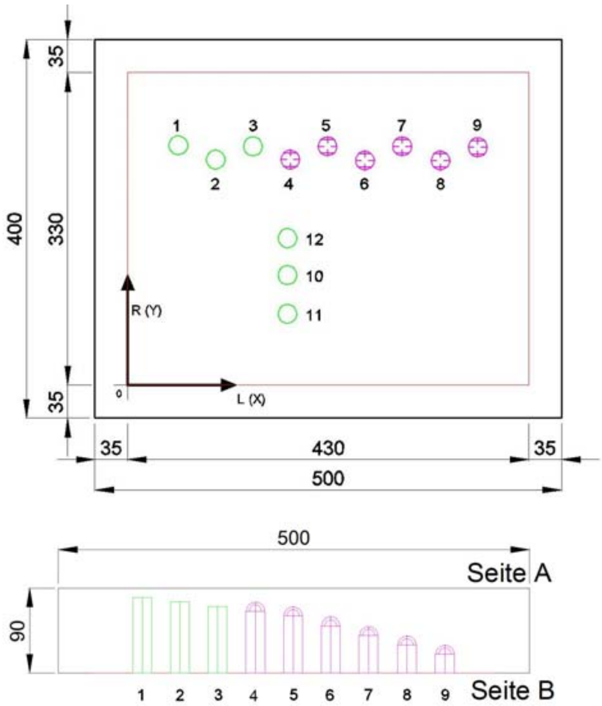


Fig. 7 Modified disc reflectors in the specimen Spruce F245 (all dimensions in mm)
Above: View of the reflectors on the measurement side A
Bottom: side view; Green: maintain original position, red: modified with hemispherical curves

Here, the results of the measurements after excitation with the polarization TT are exemplarily described, i. e. excitation by longitudinal waves. An overview of the results is shown in Fig. 8. In the SAFT-B-x~L, z~T-image is shown only the area in which lies the circular disks. The circular discs 1 to 5 are apparent here.

At z = 40 mm, a further reflection is inclined slightly upwards . On this wave front, there is a reflector, which agrees with the original x-and z-position of the arched disc 6 (254 mm, 39 mm), but in the SAFT-C image it has no equivalent. Possible causes for that are:

a) the change of symmetry of the wood cube (change the inclination of the growth rings) or

b) a deficiency in the glue joint.

Definitely the most accurate picture of the circular disks reflectors is obtained by means of the pressure waves (polarization TT) . Both, the flat bottom holes as well as the holes with additional bowing displayed reflectors 1 to 5 in the x-, y-and z-direction with a maximum deviation of 5 mm.

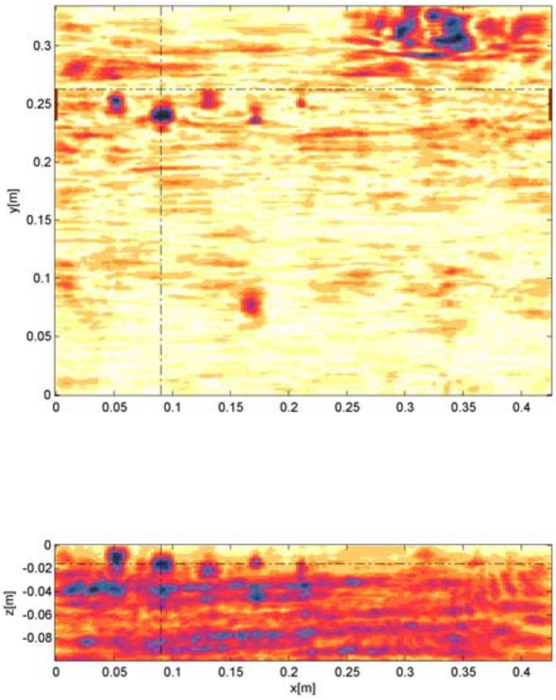


Fig. 8 Spruce F245 with modified circular disks, TT polarization, the result of 3-D SAFT reconstruction with elliptical velocity profile and 2-D reconstruction. Projection of y~R area of the circular disks (x~L, z~T).

We must notice that the deepest circular disc (No.6), which could be imaged in the spruce specimen F245 has a depth of 39 mm. Thus, this reflector is above the glue joint. So, a clear image may be prevented either by gluing or the changing of the annual ring-tilt, i.e. the change of symmetry.

3.3 Application to buildings - footbridge Fabeckstrasse

For a case study, a pedestrian bridge that was built for another project, was tested, to prove the new developed 3-D representation of the ultrasonic measurements that was so far developed and tested at the timber specimens. The wooden bridge was made of glued laminated (glulam) timber from Siberian larch.

The measurements were performed with a scanner (see Fig. 9), in which a transverse wave probe with 1 transmitter x 1 receiver was mounted in TL-polarization. For the SAFT, the velocity was adjusted with an elliptical approach, which was integrated in the evaluation program inter-saft.

In Fig. 10 the reconstructed C-scans are shown at various depth slices z = 92 mm, 106 mm and 204 mm, which corresponds to the back wall. The reconstruction was carried out with an elliptical approximation. It is visible that the spatial resolution is good in the x-direction. The reason is that for the reconstruction calculation the oblique directions of propagation have to be considered according to the angle dependence of the group velocity.

Since the reflectors are quite long in the L-direction and in the R direction, in accordance with the SAFT-B (R~y/T~z)- image, they are limited to about 30 mm, the interpretation of the reflectors assumes broken areas of single or multiple adjacent lamellae of the glulam beam. However, an unambiguous assignment of the individual vertical cracks is not possible. The reflectors can be first classified only as abnormality. A more detailed analysis will be possible only after a subsequent verification.

Fig. 9 Automated-scanning system with a commercially available A1220 interface.

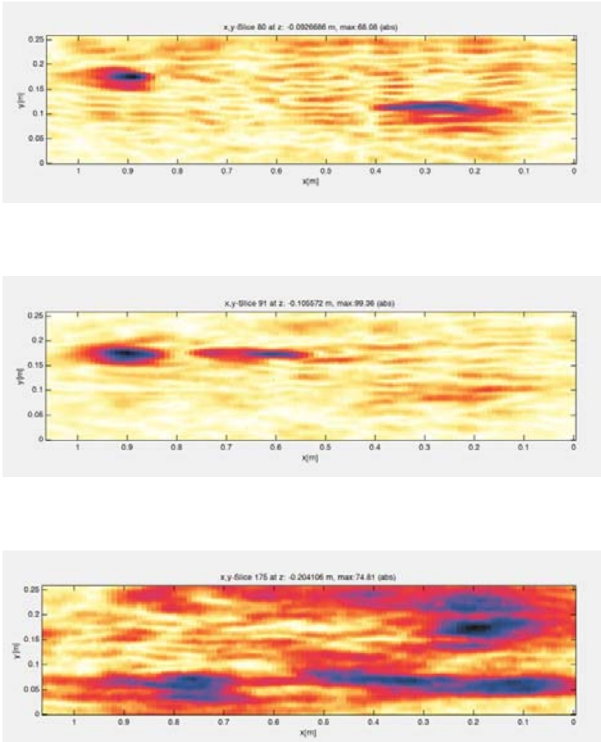
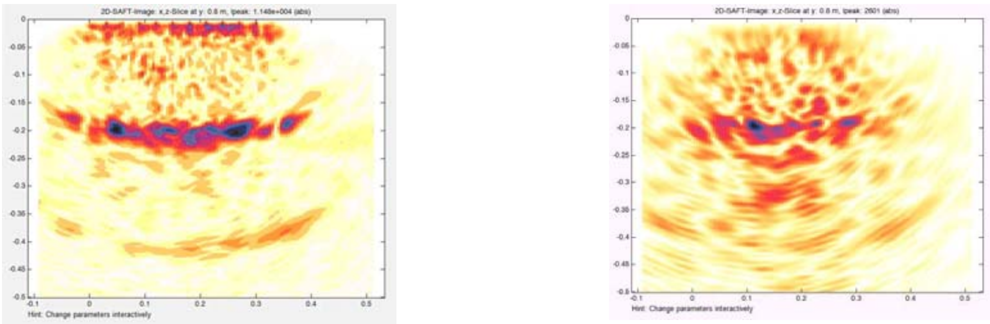


Fig. 10 Reconstructed SAFT-C-scans (x~L, y~R) in 3 different depths: 92 mm, 106 mm, 204 mm (backwall).

Further studies on the pedestrian bridge were performed using the commercially available linear array "MIRA". The measurements and the reconstruction showed a result similar to those of the scanning system with single transmitter-receiver probes.



all distances

only probe distances of 12 cm

Fig. 11 Pedestrian bridge made of glulam from Siberian larch. Measurements with the linear array.
Left: For the SAFT-reconstruction were used data sets of all 12 probe segments.
Right: for the SAFT- reconstruction were used only data sets of probe segments, which had a distance of 12 cm.

The results of the 2D data sets collected with the linear array can be additionally analysed to determine whether a cross-ultrasonic transmission through the lamellae boundaries contributes to the image of the reflectors. A specific evaluation tool in the software package inter-saft serves to solve this task. A certain distance between the transmitting and receiving probe can be chosen, which is evaluated for the reconstruction calculation.

Normally, all transmitting and receiving positions are used for the reconstruction calculation as shown in Fig. 11 left. This it means that the half of the matrix of the transmitter and receiver positions is completely selected. Depending on whether less or more different distances are selected for the reconstruction calculation, a more or less good imaging quality of the back wall echo is the obtained. The back wall echo is clearly shown even at large probes´ distances, as shown in Fig. 11 right, which is possible for a lamina with a width of 28 mm only with transverse through transmission.

The case studies on the pedestrian bridge Fabeckstrasse shows, that during the project, a possibility for the three-dimensional imaging for the ultrasonic echo technique the analysis was developed that worked for a spatially accurate representation of internal reflectors in glued laminated timber. However, a verification of the results could not be made. This will be possible after completion of the actual research work on the bridge, when the bridge has failed in a full scale destructive test.

3.4 Studies on Glulam from practice

There were also carried out tests on glulam trusses made of spruce. These were taken from a roof. However, the measurements with the scanning system do not show results that indicate internal reflectors. The echo of the back wall of the specimens was not located, too. A possible explanation for this is that the propagation of the ultrasonic waves was restricted to guided waves along the lamellae of the glulam. Or possibly cracks along the lamellae or a insufficient bonding prevent the visualization of the back wall in the image.

SAFT was applied to reconstruct the measurement data sets, obtained with the scanning system. An elliptical velocity distribution was assumed. Although some C-scans are sometimes very detailed, no reflectors can be seen that match recognizable with the actual structure of the glulam trusses.

In the analysis of the combined data set using 3-D SAFT with elliptical velocity alignment, the back wall echo was suggestively detected. The quality of the image and the number of back-scatter from the interior volume do not allow unambiguous correlation of scatterers. It is noted that the current state of evaluation methods is not sufficient to achieve useful results of a glulam regarding its design and quality.

There were additional measurements on damaged balcony structures of glulam timber, which were provided by a partner. The ultrasonic measurements were performed with the commercial hand-held A1220. The device has a transverse probe and operated at a frequency of 55 kHz.

The back wall of the balcony column element is clearly visible. The second back wall reflection was also detected. In contrast to the back wall of the defective column element was not clearly visible. Cause is the shadowing of the signal due to reflections at the damage.

Further studies on these balcony column elements will follow. After the restoration of the broken column elements from the balconies, the elements will be replaced and the deteriorated columns will be provided for the purposes on continuing studies. Since this only happens in the next few weeks, it was not possible to include these results in the report.

4 Summary and Conclusions

The approach of this research project is an further developed ultrasonic imaging method with a the frequency range between 30 and 100 kHz for non-destructive testing of timber structures. There is a similar performance as has been already achieved for concrete structures. The 2D measurements were performed with point contact probes, the imaging analysis was done of the principle of the reconstruction calculation. The results can be analyzed in a 3-D visualization program. The modelling of ultrasonic wave propagation in wood was carried out by means of **E**lastodynamic **f**inite **i**ntegration **t**echnique (EFIT) and the reconstruction calculation (3-D SAFT, **S**ynthetic **A**perture **F**ocusing **T**echnique) was developed for this purpose by the University of Kassel. Thus, the program is ready for use for ultrasonic measurements of timber components and upgraded for the practical construction tasks. The comparison of the results with the actual condition of the timber components allows an evaluation of the method for various types of wood and tasks.

Long lasting fundamental investigations on idealized specimens were required, before practical applications could be addressed as shown in the example.

The analysis, the algebraic consideration of surface waves, their suppressing or filtering in calculation is essential especially for small components. The imaging of the anisotropic material requires the consideration of propagation direction depending material specific velocities. The velocity id derived from known reflectors and the adjustment to the velocity profile for the used material.

The imaging of artificial reflectors may be achieved in many cases only when the head wave, exited by the surface wave, is considered in the volume.

In glued laminated timber from spruce, the most accurate image of flat bottom holes was achieved with the TT polarization (pressure waves in the T direction (tangential to the annual rings)). With the other polarizations TL (shear wave propagation tangential to the annual rings and polarized in the fiber direction) and TR (polarization in the radial direction), only partially achieved exact images.

The achieved knowledge in the project was successfully used for non destructive testing of a pedestrian bridge, which was constructed for research purposes. Practical hints are derived from the results of the research for an equipment concept for practical ultrasonic testing.

The project has mainly delivered results, which wave modes and with which measuring and reconstruction techniques allow precise localisation and imaging of reflectors in timber structures. Here, we have groundbreaking results of which may not yet be derived, for which specific test function this type of ultrasonic imaging has more practical applications. For this, necessarily, further systematic analyses on test specimens and structural members must be done.

5 Literature

[1] Mayer, K., Softwarepaket inter-saft zur bildgebenden Auswertung von Ultraschallechomessungen an Holzbauteilen, im Auftrag der BAM, 2008.

[2] Mayer, K., Chinta, P., Langenberg, K.-J. and M. Krause, Ultrasonic Imaging of Defects in Known Anisotropic and Inhomogeneous Structures with Fast Synthetic Aperture Methods, Proceedings of the 18th World Conference on Non-Destructive Testing, 16. - 20.04.2012, CD-ROM, 10 pages, Durban, South Africa, 2012.

[3] Bucur, V., Acoustics of Wood, 2nd Edition, Springer-Verlag, Berlin Heidelberg, Germany, 2006.

[4] Bishko, A.V., Samakrutov, A.A., Shevaldykin, V.G., Ultrasonic echo-pulse tomography of concrete using shear wave low-frequency phased antenna arrays, proceedings: 17th Wold Conference on Non-destructive Testing, 25 - 28 Oct 2008, Shanghai, China, 2008.