Experimental verification of FE-Simulations of wood using photogrammetry

Steffen Franke  
Research Assistant

Bettina Franke  
Research Assistant

Kay-Uwe Schober  
Research Assistant

Karl Rautenstrauch  
Professor

Bauhaus-University Weimar  
Weimar, Germany

Summary

This paper presents an especially developed procedure, based on digital close range photogrammetry and image processing, which enables the measuring of the progression of deformations, cracks and deteriorations during the loading and unloading of specimens. Applying measuring marks as a narrow grid can substantially increase the significance of a test. The determined displacements of the measuring marks or other geometrical marks are easily transferable for a following numeric simulation by a FE-Program. The high degree of precision of this method of measurement in conjunction with the advantages of contact-free measurement give the opportunity to achieve a new quality in measuring deformations and the interpretation of mechanical conditions. The measuring system could be already used successfully for investigations of deformations by compression stress and of the crack behaviour by transverse tensioned areas.

1. Introduction

In the past years timber engineering has tried to evaluate the load-bearing capacity of structural members in areas of connections with mechanical connectors, openings and notches via methods of fracture mechanics. The assumption of fracture mechanics parameters leads to problems in evaluating the load-bearing safety of structural units of full and board laminated timber in loaded areas and disturbance ranges using fracture mechanics. Parameters close to reality can be gained only from experimental investigations by the determination of the crack expansion and the crack length with subsequent FE-simulation. For application of timber construction, numerous theoretical and experimental investigations, which include joints, notches and openings stressed by transverse tension, have been documented. Due to the insufficient appropriation of measured data gained by tactile position encoders in conventional measuring procedures, it is advisable to investigate the deformation behavior and crack growth with the help of photogrammetry.

Compared to common procedures, the measuring system, which was developed within a research project, enables a more exact measurement of the crack geometry for the determination of fracture mechanics parameters in the post-process. Additionally a complete picture of the local deformations is provided and the validity of the test can be increased clearly by the possibility of vary the number of discrete measuring points. This measuring system for the contactless and non-destructive determination of the displacement vectors of the measuring points consist of a high-resolution digital color camera in combination with a telecentric measuring objective.
2. Development of the Measuring System and its Application

The bases of this new measuring system are high-resolution digital cameras with especially measuring objectives. The cameras have a resolution of five million pixels (2580 x 1944) with a color CCD-Chip or a resolution of eleven million pixels (4008 x 2672) with a grey tone CCD-Chip. Both allow a picture rate of 5 images/second. The CCD-matrix camera sends a digital picture, which is transferred via the frame grabber to the PC. With the help of various software the information’s of the digital image can be read out for processing, further analysis routines or storing on disk. Based on pure 2D-measurement, using telecentric-measuring objectives (see figure 1), the specimens can move slightly depth wise without creating a distortion on the measuring results. The existing objectives have magnification scales to 1/3. According to this it is possible to examine measuring areas up to about 70*110 mm. Objectives with a smaller magnification provide a better clearness in the measuring field but they create fewer pixels in the figure of the marks and thus a higher uncertainty of measurement. Based on 3D-measurement, using at least two cameras with measuring objectives (see figure 3 and 4), it is possible to measure areas up to 100 cm.

![Fig. 1: Measuring arrangement (sketch)-2D](image1)

![Fig. 2: Camera with objective and lights](image2)

![Fig. 3: Photogrammetric stereo model-3D](image3)

![Fig. 4: Measuring arrangement for 3D-tests](image4)

The contrast and the consistently distributed lighting of the entire image field decide about the results of measurement. Since the applied software requires a grey tone picture for the optical determination of the coordinates of the measuring points, the measuring field is lighted by infrared light for the use of the color CCD-camera or for the use of the grey tone CCD-camera lighted by normal cold light. The used transfer marks can vary in diameter from 0.6 to 3.0 mm. So far strains between points with a grid distance of about 5-10 mm could be determined by this procedure. Grid distance up to 1 mm is also possible. Another advantage of this way to mark the specimens compared to penetrating marks, such as pins or drawing pins, is, that no interference or even destruction of the structure occurs.
During the test the coupling of the force signal and the other measuring signals of conventional measuring technology and the picture sequence is necessary for the later evaluation of the results. Under real test conditions it is presently possible to measure with a frequency of up to 4 Hz. The determination of the coordinates of the applied measuring points is carried out by software with automatic measuring procedures. With these procedures, a touching uncertainty of 1/5 to 1/10 pixel for a single point can be regarded as surely attainable. The attainable reproducibility of the photogrammetric touching of the measuring marks with the developed system depends on the applied objective and shows a standard deviation of 0.5 µm.

3. Experimental Investigations

3.1 Examination of Kink Band for Compression Tests with Timber

3.1.1 Longitudinal Compression

Excellent and new insights could be obtained in first test series for the determination of strain-dependent strength behaviour in the area of plastic deformations, caused by the formation of a kink band. When the displacements of selected measuring points are measured, the formation and development of the kink band can be registered exactly by the introduced system. Strains and also the modulus of elasticity may be determined for each area by applying the measuring grid. Also a more exact material behaviour in the area of the kink band and contact area between the load plate and the specimen could be determined. In so far performed experimental investigations this was only possible in a much wider area or over the complete length of the specimen. That caused that the determination of the parameters for the descriptions of the strength behaviour was subject to certain errors and wrong assumptions.

Figure 5 shows a specimen with the measuring area in the deformed state, the load-time-diagram and compression-time-diagram. The load is introduced at the entire cross section by a steel plate (see in the top of the figures). The way (blue curve) was increased up to 7 mm continuously. The load (red curve) achieves the maximum after 100 s. The first 30 s include the slip of the groove between the steel plate and the wood specimen. This is also observable in comparison with figure 6.

![Fig. 5: Compression test: deformed specimen, load-time-diagram (red) and compression-time-diagram (blue)](image)

Figure 6 visualize the deformed measuring areas and the associated determined compressions compared to the unloaded state at t₁=30 s, t₂=100 s and t₃=300 s. Section 1 includes the slip of the groove with compressions of nearly 500 µm. The sections 2 to 8 have elastic deformations only. The formation of the kink band starts in the section 10 after 100 seconds (middle picture), when the maximum load is reached. At 300 seconds the kink band extends first into section 11 then into section 9 and 12 and the compressive strains get up to more than 2.5 mm.
3.1.2 Radial and Tangential Compression

The strain dependent strength behaviour by compression perpendicularly to the grain decides the construction reaction of classical carpenter’s connections essentially. The characteristic compressive strengths perpendicularly and parallel to the grain are available for the design. The more convenient structural behaviour during load on partial areas is considered by using effective compression load areas in method for design. For a numeric transformation of classical carpenter’s connections it is necessary to investigate the strength behaviour caused by compression stress and the effective area of load on partial area more exactly.

It was possible to determine first parameters of the description of the strength behaviour caused by compression stress perpendicular to the grain in test series with specimens under full and partial load area and radial, tangential or diagonal annual ring. In areas of plastic deformations it was possible to measure the strains about the complete specimen using a constant applied measuring grid at the surface of the specimen (q.v. chapter 3.1.1). In the next step it was possible to determine the modules of elasticity in discrete areas and the compression strength perpendicular to the grain as well as the radial strain coefficient for each test specimen. Furthermore different load bearing performances in the transition area between partial load area and unloaded area could be observed (q.v. Fig. 9). Using the photogrammetric measuring system it is possible to carry out investigations more exactly and to specify the effective compression area in a next step for the design method.
3.2 Investigation of Fracture Mechanics at Transverse Tensioned Areas

3.2.1 General

In timber constructions the usage of fracture mechanics increases. That demands a new approach using experimental tests and the determination of different parameters of the material wood. The described photogrammetric measuring system is the base for experimental investigations to determine fracture mechanics parameters to estimate the load bearing capacity for components with tension perpendicular to the grain, for example end notched beams or beams with holes. The limit between stable or instable crack growth is interesting for the evaluation of the load bearing performance using fracture mechanics. One method is based on the numerical determination of crack resistance curves. These curves allow determining the limit between the stable and unstable crack growth with the critical fracture energy. At first this method was used and tested at investigations with fracture mode I, then it was applied to investigations of notched beams with mixed mode.

3.2.2 Experimental Investigation at SENB-Beams with Mode I

The investigations in fracture mode I, tension perpendicular to the grain, were carried out by using SENB-beams. The SENB-beam is specified in the Draft Standard [11], which is designed by the CIB-W18 for wood. First of all the median fracture energy was determined according to the draft standard. The next step was to reproduce the experimental determined load deformation curve by using numerical simulation of the photogrammetric measured crack length. Using this numerical simulation of the test and the path-independent line integral, which describes the energy release rate of simultaneous crack growth, the crack resistance curve could be determined. The curve of the
released energy related to the crack growth enables the determination of the critical energy release rate and the characterization of the crack growth in the post critical range. Fig. 9 shows exemplary the developed crack resistance (red curve) curve for one test with tension at the RL-plane. Additionally to this the levels of the median fracture energy and of the critical fracture energy are displayed.

3.2.3 Experimental Investigations of end notched Beams under Mixed Mode (Mode I and II)

The load situation in areas of end notched beams is characterized by a combined stress in mode I (tension perpendicular to the grain) and mode II (shear). Based on the procedure for pure fracture mode the introduced algorithm (q.v. chapter 3.2.2) was used to determine fracture mechanics parameters. For the estimation of the shear influence of principal tension stressed connections, as end notched beams, the existing critical fracture energy can be determined by separating the existing fracture modes by using the continuous determined crack length and the numerical determined J-integral. It was detected that the progression of the released energy of the fracture mode I decrease with increasing residual height of the beam. For the fracture mode II with combined stresses the energy level is relative constant. This statement is a basis to reassess the design approaches, which considers critically a constant energy release rate. Furthermore the photogrammetric determination of deformation vectors of the measuring points allow the determination of strains perpendicularly to the grain in a differential small distance. This enables a quite accurate determination of the area stressed by transverse tension. The determined strain progressions depend on the load of studies of notches, which are exemplary displayed in figure 11. Based on these the length of the area stressed by transverse tension can be defined to be 30 mm.
3.3 Cross Connections with Single Fastener

Empirically developed concepts, based on fracture mechanics, are specified in standards for calculation of transverse connections. The observance of minimum geometrical values, e.g. edge distances and spacing, is important to prevent brittle failure in form of splitting or cracking. Investigations for connections with single dowels were carried out for the stress analysis of transverse connections with mechanical fasteners. The load was continuously increased up to the failure. The maximum load in the tests averaged 9 kN. With the photogrammetric measuring system it was possible to investigate the crack appearance, the crack growth and the strain progression at first test with transverse connections with mechanical fasteners. The developed crack resistance curves show clearly a non-linear fracture mechanical behaviour.

![Cross Connection: sample with a single mechanical fastener, calculated crack resistance curves](image)

**Fig. 14:** Cross Connection: sample with a single mechanical fastener, calculated crack resistance curves

4. Conclusions

Our approach of a photogrammetric measuring system for experimental investigations of stress in timber engineering enables a more complex measurement of the load bearing performance of specimens than conventional measuring techniques. The crack behaviour and the strain behaviour during loading can be determined with specimens with realistic dimensions. Multi axial strain states can be determined easily.

In the future many problems will be analyzed with FE-simulations. Therefore the specification and the knowledge of initial parameters are required. The measuring system can contribute to discuss the bearing performance of differential ranges and the material behaviour of wood. First steps for the usage in the field of fracture investigations could be presented and should contribute to carry out experimental investigations in a more efficient way.

5. References


[8] Ballerini, M., Bezzi, R. 2001. Numerical LEFM analyses for the evaluation of failure loads of beams loaded perpendicular-to-grain by single-dowel connections. CIB-W18 Conference, paper 34-7-6, Venice, Italy


