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CINEMATIC VISUALIZATION OF FAILURE MECHANISMS IN TIMBER STRUCTURES

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ABSTRACT: The objective of the project presented was to visualize typical failure mechanisms in timber by using highly developed media technology, e.g a high-speed camera to show brittle failure mechanisms. In some cases, the film recordings were combined with contact-free measurements and finite-element analysis to better visualize the stress distribution in the test specimen.

KEYWORDS: timber, education, failure mechanisms, cinematic visualization, high-speed camera, contact-free measurement

1 INTRODUCTION

Education of engineering students has shifted from frontal teaching on a chalkboard to more interactive teaching methods, utilizing the benefits of new media. Still, many timber education programmes resort exclusively to text, diagrams and sometimes photos to illustrate the anisotropic behaviour of timber in different loading conditions.
The objective of this project, which was carried out in cooperation with the "Zimmerer Kompetenzzentrum Kassel", was to support the theoretical education in timber structures by new media technology, cinematically visualizing failure mechanisms which are typical for timber structures.
By visualizing the different failure mechanisms of structural timber elements, the students shall be stimulated and supported to develop knowledge and sentiment towards a material conform design. Examples of this are:
(1) failure mechanisms which give signal in advance (e.g. compression perpendicular to grain) in contrast to failures which occur without pre-notice (e.g. tension parallel to grain failure in bottom chords of trusses).
(2) correct dimensioning of connections (slender dowel-type fasteners)
(3) tension perpendicular to grain stresses (e.g. in connections or at notches) and possible reinforcement methods.

When planning this project, two main objectives had to be followed:
(1) to initiate the desired failure by tests typical for the respective failure mode and
(2) to adapt the configuration of the experiment to best visualize the failure mechanism itself.
For the case of ductile failure mechanisms, a standard video-camera could be used which was interfaced with the load-slip curve, emitted by the testing equipment. In some cases, the film recordings were combined with contact-free measurements and finite-element analysis to better visualize the stress distribution in the specimen.
In all experiments in which brittle failure mechanisms should be displayed, a high-speed camera was used to exemplary show fracture mechanisms, e.g. the origin of fracture onset.

2 PRELIMINARY WORK

2.1 CHOICE OF FAILURE MECHANISMS AND CONFIGURATION OF THE EXPERIMENT

Before the experiments could be planned, a code and literature review was carried out to receive information on possible configurations for the experiments which would induce the desired failure mechanism. Comparable projects were found [1] but they primarily covered failure mechanisms in concrete and steel. Hence, the experiments were planned according to the related code, if the objective of visualizability could be met. In some cases the configuration of the experiment

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was slightly adapted but still realized following the main concepts of related code. The relevant codes are listed in Tables 1-4, given below.
If a failure mechanism was not covered by a code (e.g. wood-to-wood connections), or if the standardized configuration of the experiment did not adhere to the objective of visualizing the failure mechanism (e.g. experiments on dowel-type connections), it was tried to realize these experiments as close to the real "built-in" situation as possible, e.g. as given in design codes EN 1995-1-1:2004 [2] or DIN 1052:2008-12 [3].

2.2 CHOICE OF RECORDING TECHNIQUE

2.2.1 Standard Video Camera and Photographies

For the case of ductile failure mechanisms, a standard video-camera could be used which was interfaced with the load-slip curve, emitted by the testing equipment. The camera used was a Panasonic High Definition Camcorder HDC-HS300 with a resolution of 6.2 Megapixel. In some cases, the film recordings were combined with contact-free measurements and finite-element analysis to better visualize the stress distribution in the specimen. For documentation purposes, photographies of the configuration of the experiment and the specimen before and after failure were taken with a standard photo camera (Canon PowerShot S5 IS, 8 Megapixel, 12x optical zoom). During post-production it was sometimes decided to extract additional photographies from the film material.

2.2.2 High-Speed Camera

In all experiments in which brittle failure mechanisms should be displayed, a high-speed camera was used to exemplary show fracture mechanisms, e.g. the origin of fracture onset. The camera system used was a Typhoon HD4 (frame rate: 1000 to 40000, frame size: 188x176 to 1280x720). For bending tests, the minimal frame rate was used while the maximum frame rate was e.g. used for tests inducing tension perpendicular to grain failure.
Since such systems are sensible, expensive and rather complex to apply, it was decided to rent the system, including the operator, on a daily basis. This implied that all experiments anticipated for high-speed recording had to be planned and timed very accurately. This includes spotlights since high-speed cameras require very good and bright illumination.
Due to the large amount of pictures produced per second and the limited space of random access memory available, the system is designed to overwrite the least recent images, leaving a film of a few seconds. This implies that the system has to be timely halted after failure of the specimen which was not always obvious in some experiments. Another challenge was given by the size of fracture onset, limiting the size of the image section to be recorded. Since the location of failure can not always be predicted very accurately (e.g. in bending tests), the camera position and image section had to be based on the authors most educated guess.

2.3 CONTACT-FREE MEASUREMENT SYSTEM

For contact-free measurement, the ARAMIS^{TM} system for optical 3D deformation analysis, manufactured by GOM-Optical Measuring Techniques was employed. The system is based on evaluating a stochastic or regular pattern, which is applied to the specimen's surface. During the experiment, synchronised stereo images of the pattern are recorded at different load stages using CCD cameras, placed in front of the specimen at preset angles.
A high-capacity processor automatically calculates the data sets from the cameras into 3D coordinates, 3D displacements, rotations and in-plane strains, using image correlation and photogrammetric evaluation procedures. The results file can be displayed in reports, containing e.g. a 3D visualization of the specimen during the experiment in combination with the load and displacement signal from the testing machine.
During the experiments, which were chosen for contact-free measurement, the cameras were triggered with a frequency of 2 Hz, also logging the analogue signal readings of applied load from the testing machine
Clear and uniform illumination is crucial for these measurement systems. Since the complexity of illumination and accuracy of camera calibration needed is increasing with increasing specimen size, whilst accuracy of results is decreasing, this system is more applicable for small specimen than for larger specimen as e.g. beams in bending. Another drawback is that the system has to be calibrated anew with each change of configuration of the experiment, meaning it is more valuable for test series of identical specimen.

2.4 TENTATIVE EXPERIMENTS

Since standardized configurations do not exist for all anticipated experiments or given configurations would not result in visible failure, some experiments had to be newly designed for this specific purpose. In these cases, the design of the configuration of the experiment was carried out by the authors and civil engineering students at TUM within the scope of their Bachelor Theses. After the specimens were produced, tentative experiments were carried out to see if the anticipated configuration resulted in the failure mechanism aimed for or if other strength or stiffness properties would influence failure. The experiments were also needed to optimize the cinematic presentation, including camera angle, aperture, distances and uniform illumination. This was especially important for experiments in conjunction with a high-speed camera since its availability results in substantial costs, restricting its use to a short timeframe.

3 FAILURE MECHANISMS SELECTED

The following failure mechanisms which can occur in structural timber elements were selected for visualization by compliant experiments.

3.1 EXPERIMENTS TO DETERMINE STRENGTH AND STIFFNESS PROPERTIES OF SOLID TIMBER

The experiments to determine strength and stiffness properties of solid timber (see Table 1) were rather straightforward, since standardized configurations and test procedures exist for all properties aimed for. Nevertheless, tentative experiments showed that specimen had to be slightly modified, (e.g. tapered) in some cases, either to guarantee failure in anticipated mechanism or due to the size of clamping devices.

Table 1: *Experiments to determine Strength and Stiffness Properties of Solid Timber*

Experiment / Failure Mechanism	According to (resp. following the main concepts of)
Tensile Strength in Grain Direction (including effect of finger joints)	DIN 52188:1979 [4]
Tensile Strength Perpendicular to Grain Direction	EN 302-3:2004 [5]
Compressive Strength parallel to Grain Direction (including effect of knots)	EN 408:2003 [6]
Compressive Strength Perpendicular to Grain Direction	EN 408:2003 [6]
Bending Strength (including effect of knots)	EN 408:2003 [6]
Shear Strength (shear test and four-point bending test on I-beam)	EN 408:2003 [6]
Modulus of Elasticity (Deflection)	EN 408:2003 [6]

3.2 EXPERIMENTS AFFILIATED TO OTHER STRENGTH OR STIFFNESS RELATED FAILURE MECHANISMS

For these experiments, affiliated to other timber strength or stiffness related failure mechanisms (see Table 2), no standardized test setup could be found. Therefore, these experiments were designed to reproduce the real "built-in" situation as close as possible. Although intensive tentative experiments were carried out, the stability case "Euler 1" could not be reproduced. Vibration experiments were carried out as to determine the natural frequency of timber beams in different system configurations (single-span beam, cantilevered beam).

Table 2: *Experiments to visualize other Strength and/or Stiffness related Failure Mechanisms*

Experiment / Failure Mechanism	According to (resp. following the main concepts of)
Effect of end Notches (square shaped, round and tapered)	DIN 1052:2008 [3]
Effect of Holes (round and rectangular) near supports and at mid-span	DIN 1052:2008 [3]
Stability – Flexural Buckling (Euler 2, 3 and 4)	-
Stability – Lateral Torsional Buckling on single-span Beam	-
Serviceability Limit States – Vibrations on single span Beam and cantilevered Beam	-

3.3 EXPERIMENTS ON WOOD-TO-WOOD CONNECTIONS

The cooperation with the "Zimmerer Kompetenzzentrum Kassel" resulted in an elaborate demonstration of failure mechanisms in wood-to-wood connections (see Table 3), since this institution is highly involved in the education of German master carpenters. Since no standardized test setups were found for these connection types, the experiments were designed to reproduce the real "built-in" situation as close as possible.

Table 3: *Experiments on Wood-to-Wood Connections*

Experiment / Failure Mechanism	According to (resp. following the main concepts of)
Butt Joints – Discrete and Continuous Supports (Load at Edge and Centred Load)	EN 1995-1-1:2004 +A1:2008 [2]
Step Joints	DIN 1052:2008-12 [3]
Mortise and Tenon Joints	DIN 1052:2008-12 [3]
Scarf Joints	-
Dovetail Connection	-

3.4 EXPERIMENTS ON CONNECTIONS WITH DOWEL-TYPE FASTENERS

The experiments on connections with dowel-type fasteners (see Table 4) were not carried out according to related codes (e.g. EN 383:2007 [7], EN 409:1993 [8], EN 26891:1991 [9]), since the objective of visualization of the failure mechanism could not be reached with the specifications given in these codes. Instead, the connections were realized such that the failure mechanism aimed for was accomplished as accurately as possible. This included the combination of timber members with different density and the variation of fastener slenderness to induce e.g. embedment failure of wood or yielding failure of the fasteners. Since the visualization of load transfer in dowel-type connections is rather challenging, the connections were produced as partly open along the connection width, in some cases fixed by transparent acrylic glass.

Table 4: *Experiments on Connections with Dowel-Type Fasteners*

Experiment / Failure Mechanism	According to (resp. following the main concepts of)
Embedment Strength (in and perpendicular to grain Direction)	EN 1995-1-1:2004 +A1:2008 [2]
Yielding of the Fastener	EN 1995-1-1:2004 +A1:2008 [2]
Influence of Fastener Spacing (Splitting), incl. Reinforcement by Screws	EN 1995-1-1:2004 +A1:2008 [2]
Rope Effect (Bolted Connection)	-
Tension Perpendicular to Grain in Joints	DIN 1052:2008 [3]
Axially loaded Screws - withdrawal capacity of threaded part - pull-through strength of screw head - tension strength of screw	-

4 PRESENTATION OF SELECTED EXPERIMENTS

Due to the static manner of a paper it is not possible to show the effect of a filmed experiment. This can only be demonstrated during the presentation of the paper at WCTE 2010. Therefore it was decided to only include a selection of experiments featuring failure mechanisms which are representable on photographies. For these experiments, a short description of the configuration of the experiment in combination with drawings of the setup and photographies of the failed specimen are included. The visualization by means of contact-free measurement shall be exemplified as well.

4.1 EXPERIMENTS TO DETERMINE STRENGTH AND STIFFNESS RELATED PROPERTIES OF SOLID TIMBER

4.1.1 Tension Strength parallel to the Grain – Effect of Finger Joint

Failure in tension parallel to the grain was tested and shown on a tapered tension member which was held by two clamping devices of the testing machine (Figure 1).

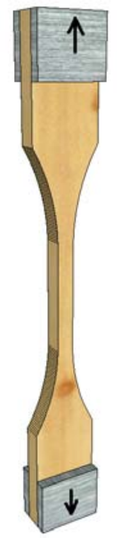

Figure 1: *Specimen and Configuration of Experiment for Failure in Tension parallel to the Grain*

Figure 2 shows the failure mechanism including the effect of the finger joint, tension failure parallel to the grain at areas of local weakening (tips of the finger joint).

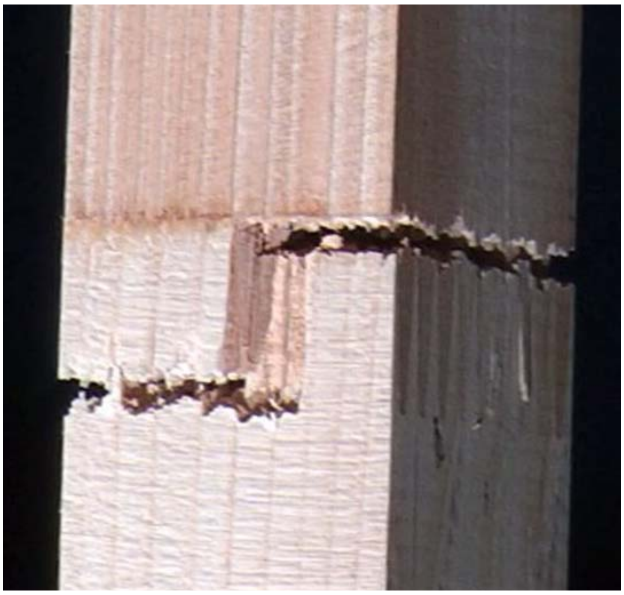

Figure 2: *Detail of Specimen failing in Tension parallel to the Grain at the Tips of the Finger Joint*

4.1.2 Compressive Strength parallel to the Grain

Failure in compression parallel to the grain was tested and shown on a tapered stud column (Figure 3).

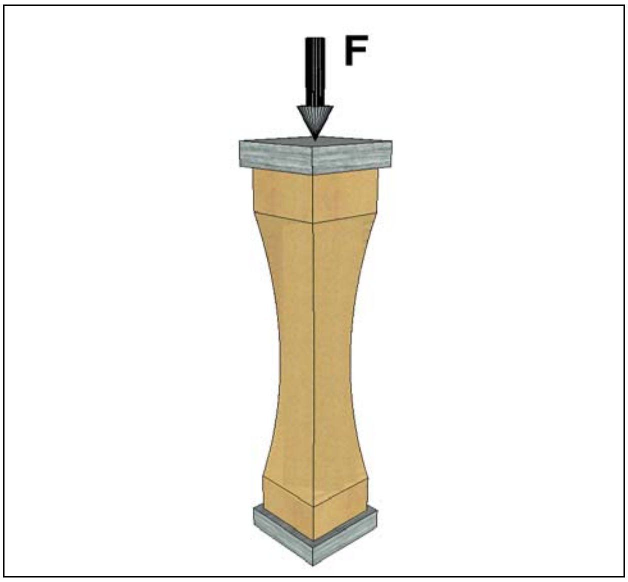

Figure 3: Specimen and Configuration of Experiment for Failure in Compression parallel to the Grain

Figure 4 shows that the anticipated failure mechanism, local buckling of a row of fibres, could well be demonstrated.

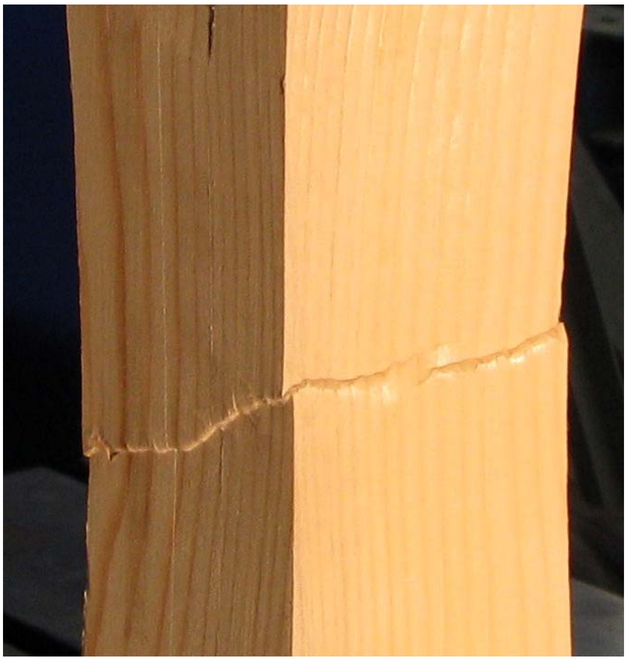

Figure 4: Detail of Specimen failing in Compression parallel to the Grain

4.1.3 Bending Strength

The bending strength was determined by a four-point bending test, the configuration is displayed in Figure 5. This experiment was filmed with a high-speed camera.

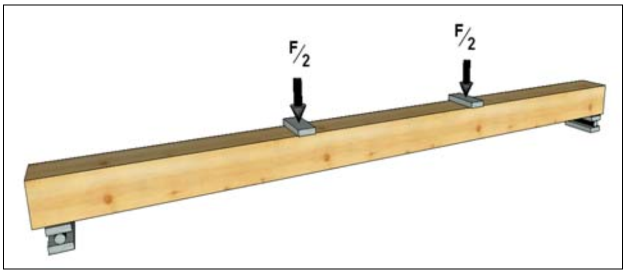

Figure 5: Specimen and Configuration of Experiment for Failure in Bending

The detail shows the typical failure of a timber member in bending, triggered by failure in tension parallel to the grain in the tension zone of the member (see Figure 6).

Figure 6: Detail of Specimen failing in Bending (Tension failure parallel to Grain)

4.1.4 Modulus of Elasticity (Deflection Test)

This experiment was selected to exemplary show the application of contact-free measurement technique to measure deflection of a beam in bending (see Figure 7). The configuration of the experiment complied with the configuration shown in Figure 5 except that the member side was coated with a white primer, followed by the application of a stochastic pattern realized by black dots (see Chapter 2.3)

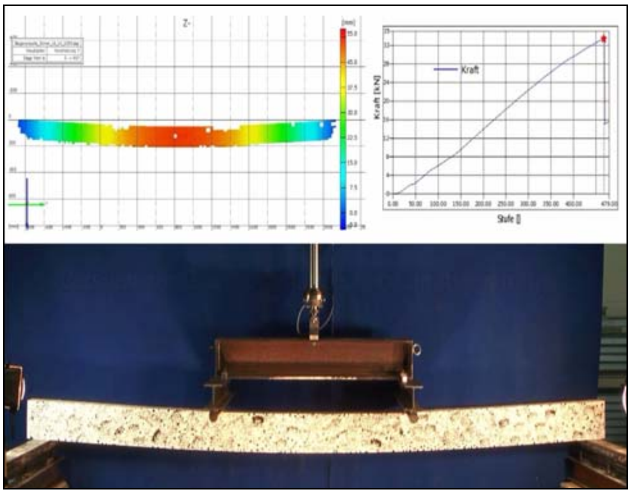

Figure 7: Excerpts of Report from contact-free Measurement System (Display of Deflection, Load-Slip Curve and Member in Bending with Stochastic Pattern)

4.2 EXPERIMENTS AFFILIATED TO OTHER STRENGTH OR STIFFNESS RELATED FAILURE MECHANISMS

4.2.1 Effect of rounded End Notch

The effect of a rounded end notch on a beam in bending was tested and shown by a three-point bending test as illustrated in Figure 8.

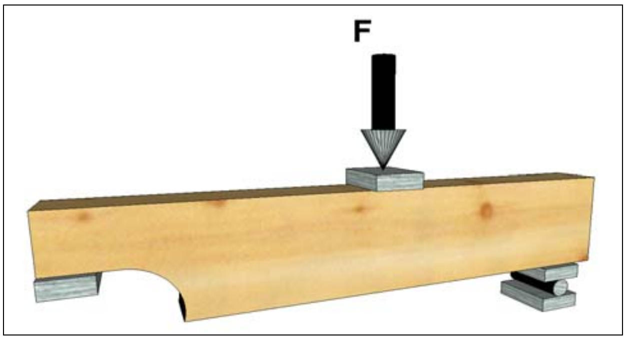

Figure 8: *Specimen with rounded End-Notch in three-point Bending Test*

The failure occurred in the middle of the rounded part (~40°), followed by a crack propagation along the grain as shown in Figure 9. This figure was extracted from the high-speed film. The necessity of illumination is clearly visible.

Figure 9: *Detail of Timber Member fractured at rounded End- Notch (marked by circle)*

4.2.2 Effect of rounded Hole at Mid-Span

The experiment to exemplify the effect of a rounded hole at mid-span of a member in bending complied with the test configuration given in Figure 8.
Figure 10, which was extracted from the high-speed film shows that the crack onset from the upper edges of the hole occurred at the same time as failure in tension in grain direction due to exceeded bending stresses.

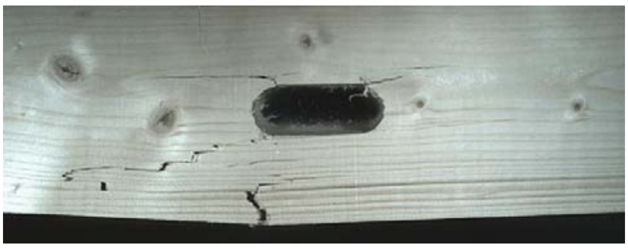

Figure 10: *Detail of failed Timber Member in Bending with rounded Hole at Mid-Span*

4.2.3 Failure in flexural Buckling – Euler 3

Stability failure, e.g. Euler case 3 was shown on very slender timber columns. Depending on the bearing situation, these were either put between the clamps of the testing machine or placed on the head of a small steel bolt to realize a pinned connection. The configuration of the experiment as well as the deformation figure at failure is given in Figure 11.

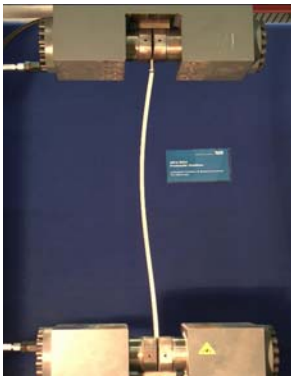

Figure 11: *Configuration of Experiment and failure of Timber Column in flexural Buckling (Euler case 3)*

4.2.4 Serviceability Limit States – Vibrations of Single Span Timber Beam

The dynamic response of a single span timber beam (timber lamella) was measured by two one-axial accelerometers, placed at mid span and in ¼ of the span as shown in Figure 12. The member was accelerated by an impulse load (hammer).

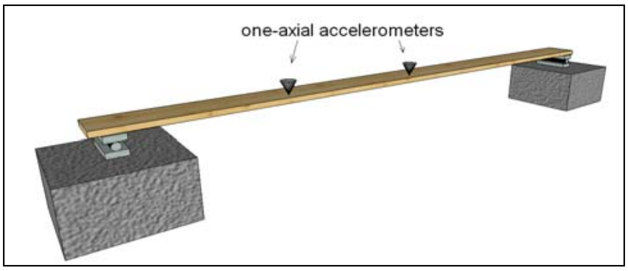

Figure 12: *Configuration of Experiment for Vibration Test on single span Timber Beam*

The output of the vibrometer in form of an oscillation curve (see Figure 13) was filmed, followed by a picture of the computed natural frequency.

Figure 13: *Vibration test on single span Timber Team (lamella) and Oscillation Curves*

4.3 PRESENTATION OF SELECTED EXPERIMENTS ON WOOD-TO-WOOD CONNECTIONS

4.3.1 Compressive Strength perpendicular to the Grain – Butt Joint on discrete Support

Failure in compression perpendicular to the grain of a member on a discrete support was tested and shown on two butt-jointed rectangular timber pieces, as illustrated in Figure 14.

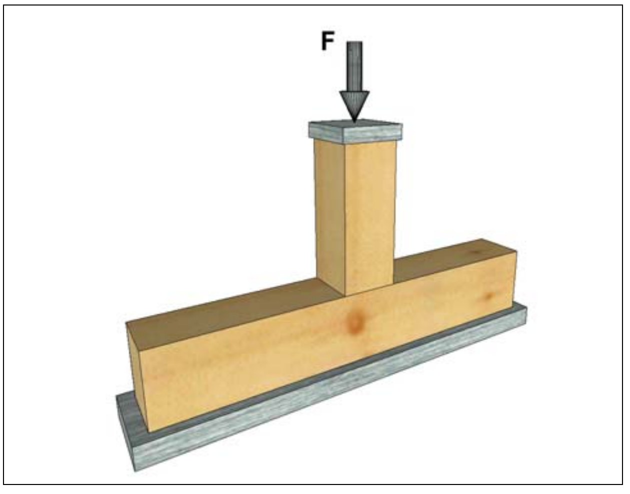

Figure 14: *Specimen and Configuration of Experiment for Failure in Compression perpendicular to the Grain (Butt-jointed Members on Discrete Support)*

Figure 15 shows a detail of the member failing due to local compression of the fibres. The rope effect between the loaded and the unloaded part of the fibres can be seen as well.

Figure 15: *Detail of Specimen failing in Compression perpendicular to the Grain*

4.3.2 Step Joints – Failure in Compression at an Angle α to the Grain

The reproduction of a typical step joint in an experimental configuration was a little bit more challenging, since one member had to be supported and fixed at an angle of 45°. The configuration of the experiment is shown in Figure 16.

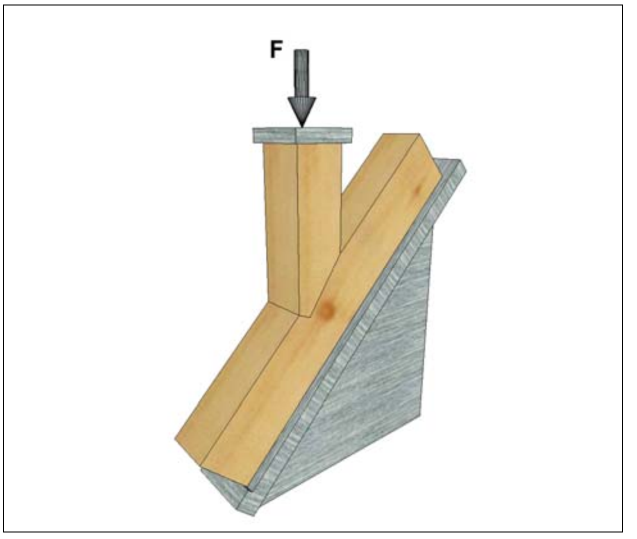

Figure 16: *Specimen and Configuration of Experiment for Step Joints (Failure in Compression at an Angle α to the grain)*

The failure mechanism of a step joint, failure in compression at an angle α to the grain is illustrated in Figure 17.

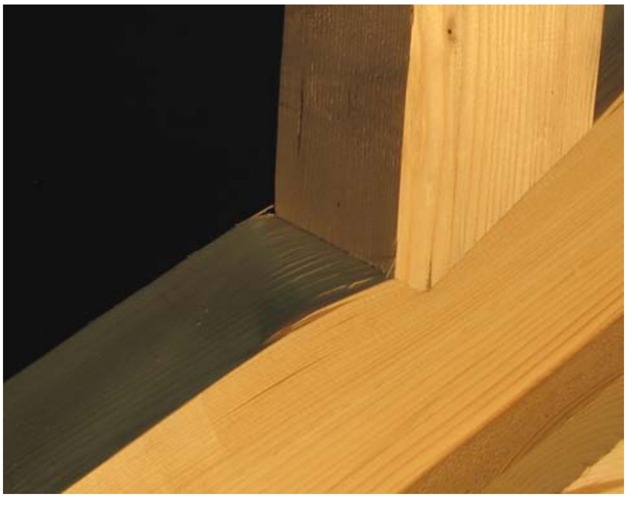

Figure 17: *Detail of Step Joint failing in Compression at an Angle α to the grain*

4.3.3 Dovetail Connections – Failure in Tension perpendicular to the Grain

Nowadays, the dovetail connection is mostly used for secondary beam – main beam connections in residential buildings. Therefore, the configuration of the experiment was designed to reproduce that connection type (see Figure 18)

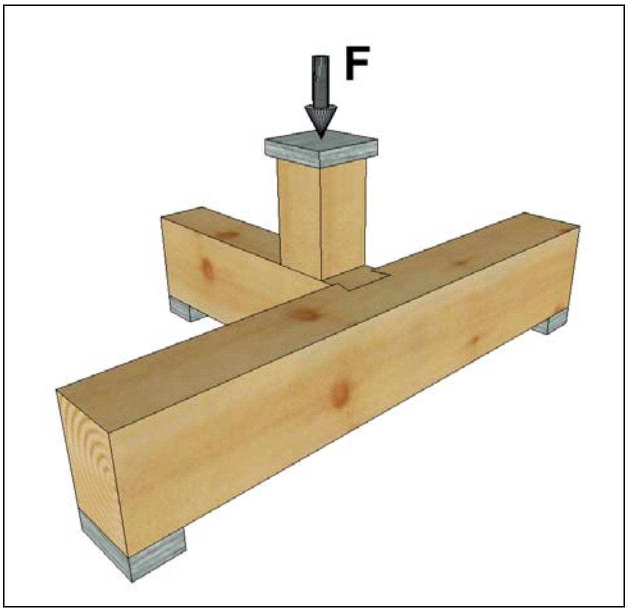

Figure 18: *Specimen and Configuration of Experiment for Dovetail Connection*

The failure of the dovetail connection, failure in tension perpendicular to the grain in the main beam is shown in Figure 19.

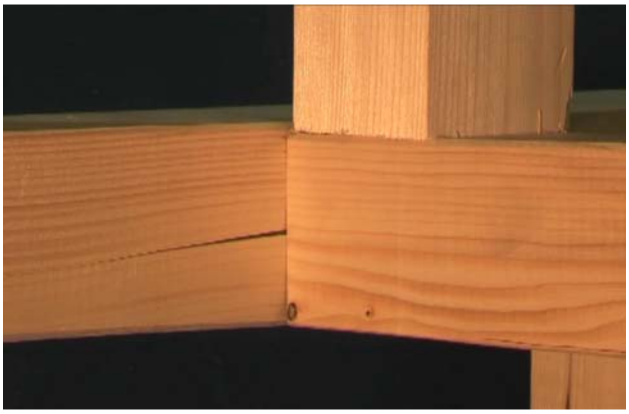

Figure 19: *Detail of Dovetail Connection failing in Tension perpendicular to the Grain in the Main Beam*

4.4 PRESENTATION OF SELECTED EXPERIMENTS ON CONNECTIONS WITH DOWEL-TYPE FASTENERS

4.4.1 Embedment Strength Failure in single shear connection

To reproduce an embedment strength failure in a single shear connection, a dowel with a very low slenderness had to be used. The chosen configuration for the experiment is given in Figure 20

Figure 20: *Configuration of Experiment for Embedment Strength failure in a Single-Shear Connection*

The failure of this connection, embedment strength failure in conjunction with rotation of the dowel (Failure Mode 1a) can be observed in Figure 21.

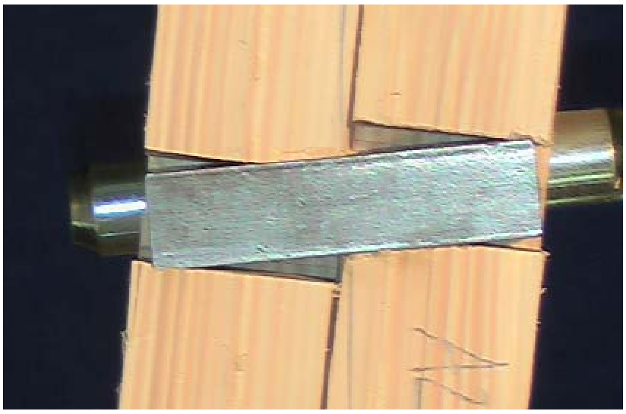

Figure 21: *Detail of Embedment Strength failure in a Single-Shear Connection*

4.4.2 Yielding Failure of Bolts in Double-Shear Connection – Rope Effect

Inversely to the connection setup in 4.4.1, very slender bolts were used to reproduce yielding failure of the bolts. Larger washers were utilized to induce a visible rope effect (see Figure 22)

Figure 22: Configuration of Experiment for Yielding Failure of Bolts in a Double-Shear Connection including the Rope Effect

Figure 23 shows the failed connection, the yielded bolt (Failure Mode 3) as well as the rope effect (indentations of washers into timber).

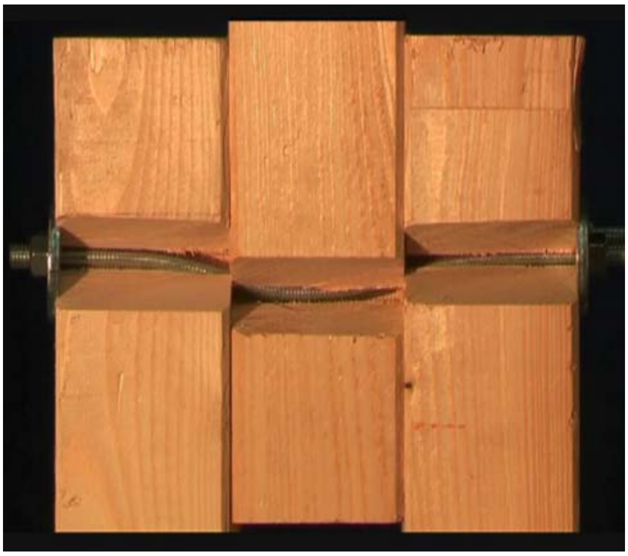

Figure 23: Detail of Failed Double-Shear Connection – Yielded Bolt and Rope Effect

5 POST-PRODUCTION AND DOCUMENTATION

During post production, each film was edited to a length of approximately one minute. Each film contains a title page followed by one picture showing the configuration of the experiment. The film of the experiment until failure forms the main part, followed by longer blends of pictures of the failed specimen, enabling the lecturer to further explain the failure mechanism.

All data was classified into a data base, comprising one folder for each failure mechanism, containing the edited film and associated photographies.

6 CONCLUSIONS

The finished films were shown to the students during the courses “Structural Design in Timber” and “Timber Engineering”, receiving very positive feedback. Feedback received included mention that it becomes much more clear what kind of material a structural engineer deals with when designing a timber structure as well as an increased interest in practical work with timber, e.g. in the Timber Testing Laboratory of the Materialprüfungsamt at the Technische Universität München. It is foreseen to extend and improve the film library on failure mechanisms in the scope of e.g. future Bachelor Theses.

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