MECHANICAL PERFORMANCE OF WOOD CONSTRUCTION MATERIALS

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Abstract: The paper aims to illustrate the relevant use of infrared thermography as a non-destructive, non-contact and real time technique (a) to observe the progressive damage process and failure mechanism of wood, and (b) to detect the occurrence of intrinsic dissipation localization. The investigated parameter is the heat generation due to intrinsic dissipation caused by inelasticity. Thanks to the thermomechanical coupling, this useful technique provides a very convenient tool to detect mechanical phenomena depicting wood damage and failure. It allows a measure of the limit of a progressive damaging process under load beyond which the wood material is destroyed.

Introduction: Damage and failure behavior of wood in tensile, compressive or shear loading is an important consideration in connection with designs or regulations of wooden structures subjected to high allowable working stresses or in cases where the dead loads form a smaller part of the total load capacity. In such a situation, failure of the construction material may occur at stresses below its static strength. Accurate knowledge should therefore be obtained of the mechanical behavior of wood subjected to various loadings. As with other materials in response to these problems, diverse damage analysis methodologies have been developed in recent years, which isolate the factors affecting crack initiation and growth, and enable the prediction of their cumulative effect on the mechanical performance of structural components. They are based on (1) the formulation of analytical models for damage crack and growth, and (2) the acquisition of supporting baseline data and validation of such models by means of a comprehensive testing procedure.

The present paper proposes the use of infrared thermography as a non-destructive, non-contact and real time technique to examine the mechanisms of damage and the processes of failure of wood. The aim of this study is to illustrate the onset of damage process, stress concentration and heat dissipation localization in loaded zones. In addition, this technique can be used as a non-destructive method for inspection and evaluation of stress concentration in wood construction and engineering.

Wood is a natural product of biological origin [2-3]. It is a very variable and heterogeneous material. Its mechanical properties are affected by the presence of knots, checks, shakes, splits, slope of grain, reaction wood and decay, etc., and anisotropy. Stress concentrations occur because the knot interrupts wood fibers. Checks, shakes and splits all constitute separations of wood fibers. Slope of grain has a marked effect on the structural capacity of a wood member. Reaction wood or abnormal wood is hard and brittle, and its presence denotes an unbalanced structure in the wood. Decay is a disintegration of the wood, caused by the action of fungi. These damages are generally very difficult to quantitatively evaluate.

When the span becomes long or when the loads become large, the use of sawn lumber may become impractical. In these circumstances and possibly for architectural reasons, structural glued-laminated timber or glulam can be used. Glulam members are fabricated from relatively thin laminations of wood. These laminations can be glued together and spliced in such a way to produce wood members. Glues are capable of producing joints that have horizontal shear capabilities in excess of the capacity of the wood itself.

The efficient use of materials and the long length of many glulam members require that effective end splices be developed in a given lamination. Butt joints are poor splices. They are considered ineffective in transmitting both tension and compression. Finger joints are poor splices and are considered ineffective in transmitting both tension and compression. Finger joints can produce high strength joints when the fingers have relatively flat slopes. With scarfed joints, the flatter the slope of the joint, the greater the strength of the connection.

Veneer is the thin sheet of wood obtained from the peeler log. When veneer is used in the construction of plywood, it becomes a ply. The cross-laminated pieces of wood in a plywood panel are known as layers. Layers are often simply an individual ply, but they can consist of more than one ply. It is the cross laminating that provides plywood with its unique strength characteristics. It provides increased dimensional stability over wood that is not cross-laminated. Cracking and splitting are reduced, and fasteners, such as nails and staples, can be placed close to the edge without a reduction in load capacity. A connector or fastener is a mechanical device (nails, bolts, screws, etc.) or mechanical assembly (bolted shear plates, nailed metal truss plates, etc.), a glue or an adhesive used to hold together two or more pieces of wood or wood based products.

Wood frame buildings consist of several components such as walls, floors and roofs joined by intercomponent connections. The performance of wood frame buildings is influenced by the behavior of the individual components and their connections. Therefore an understanding of the behavior of the different structural components and connections is essential to accurately predict the performance of a housing unit under different types of loading. Wood frame buildings perform well under gravity loads. Considerable damage, however, has been observed in such structures under severe and moderate earthquakes and major hurricanes. Experiments are therefore required to verify and refine the numerical tools. The end result promises improved design standards that enable buildings to resist the expected earthquake and wind loads without significant damage or collapse.

Damage and failure may thus be viewed as a micro structural process through the activation and growth of one preexisting flaws or of a site of weakness, or through the coalescence of a system of interacting small defects and growing micro cracks. Macroscopically it occurs a localization of intrinsic dissipation before a visible failure. The stress level, corresponding to the activation of the defects, is related to the defect size and connected with the encompassing microstructure.

Non-destructive and non-contact tests are thus needed to define wood and wood product properties (1) to establish strength, (2) to optimize design values and (3) to insure quality control.

Infrared thermography is a convenient technique for producing heat images from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact or in any way influencing the actual surface temperature of the objects viewed. It is successfully used as an experimental method for detection of plastic deformation during crack propagation of steel plate under monotonous loading or as a laboratory technique for investigating damage or failure mechanisms occurring in engineering materials. The work, reported in this paper, considers the intrinsic dissipation as a highly sensitive and accurate indicator of damage manifestation and assumes that intrinsic dissipation and damage present the same evolution under fatigue loading up to failure.

In the framework of thermodynamics of irreversible processes, the development of thermo-elastic-visco-plasticity equations leads to the coupled thermomechanical equation [6]:

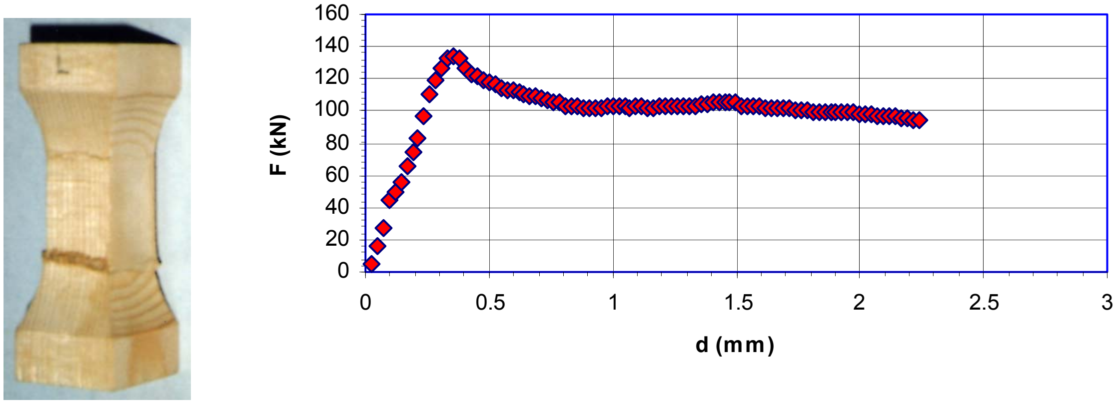
$$\rho C_v \dot{T} = r_o + K \nabla^2 T - \left(\beta : D : \dot{E}^e\right) T + S : \dot{E}^I \qquad (1)$$

where ρ denotes the mass unit in the reference configuration, C_v the specific heat at constant deformation, T the absolute temperature, r_o the heat supply, K the thermal conductivity, ∇^2 the Laplacian operator, β the coefficient of the thermal expansion matrix, D the fourth-order elasticity tensor, E^e the elastic strain tensor, S the second Piola-Kirchhoff stress tensor and E^I the inelastic strain tensor. The superposed dot stands for the material time derivative. The volumetric heat capacity of the material $C = \rho C_v$ is the energy required to raise the temperature of a unit volume by 1°Celsius (or Kelvin degree).

This equation shows the potential applications and various uses of the infrared scanning technique in engineering problems [4-5-7-8-9-10-11-12]. Temperature changes result from four distinct physical phenomena: heat source, conduction effect, reversible thermo-elastic coupling and intrinsic dissipation.

A scanning camera is used, which is analogous to a television camera [1]. It uses an infrared detector in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real time thermal image in a color and monochrome video system. Response times are shorter than 1 μs. Temperature differences in the heat patterns are discernible instantly and represented by several distinct hues. The quantity of energy W ($W.m^{-2}.\mu m^{-1}$), emitted as infrared radiation, is a function of the temperature and emissivity of the specimen. The higher the temperature, the more important the emitted energy. Differences of radiated energy correspond to differences of temperature. Since the received radiation has a non-linear relationship to the object's temperature, and can be affected by atmosphere damping and includes reflected radiation from object's surroundings, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the object's temperature can then be calculated with a sensitivity of 0.1℃ at 20℃. The infrared scanner unit converts electromagnetic thermal energy radiated from the tested specimen into electronic video signals. These signals are amplified and transmitted via an interconnecting cable to a display monitor where the signals are further amplified and the resultant image is displayed on the screen.

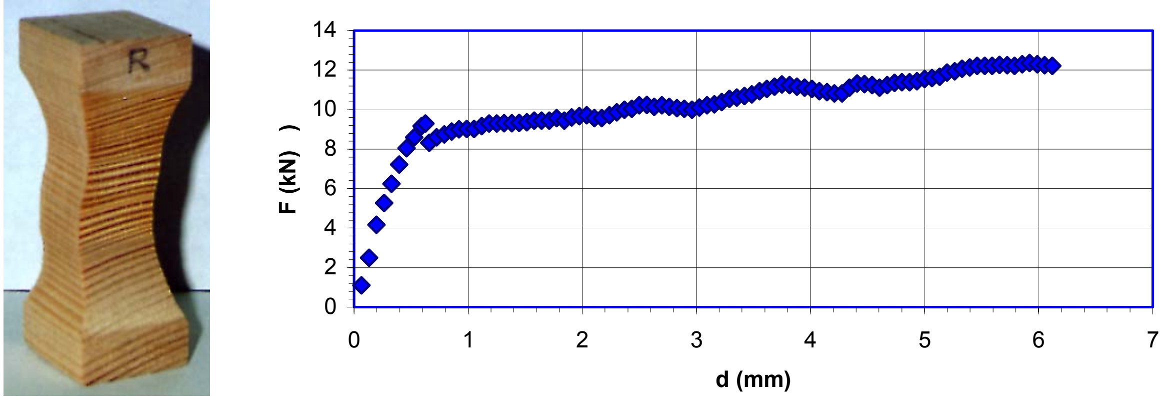
Results: Three series of monotonic unconfined compression tests have been conducted on square specimens of pinewood, prepared along its three anisotropy directions (longitudinal **L**, radial **R** and transverse **T**). The corresponding compressive force F (kN) versus axial displacement d (mm) curves are respectively presented in Figures 1, 2 and 3. The wood specimens were especially designed (cross section $S_0 = 256\ mm^2$, $h_0 = 20\ mm$) with enlarged ends to prevent from sliding, bending or premature buckling, caused by heterogeneity, bad alignment of compression loading, or others significant end effects.



Longitudinal

Compression versus displacement curve (L specimen)

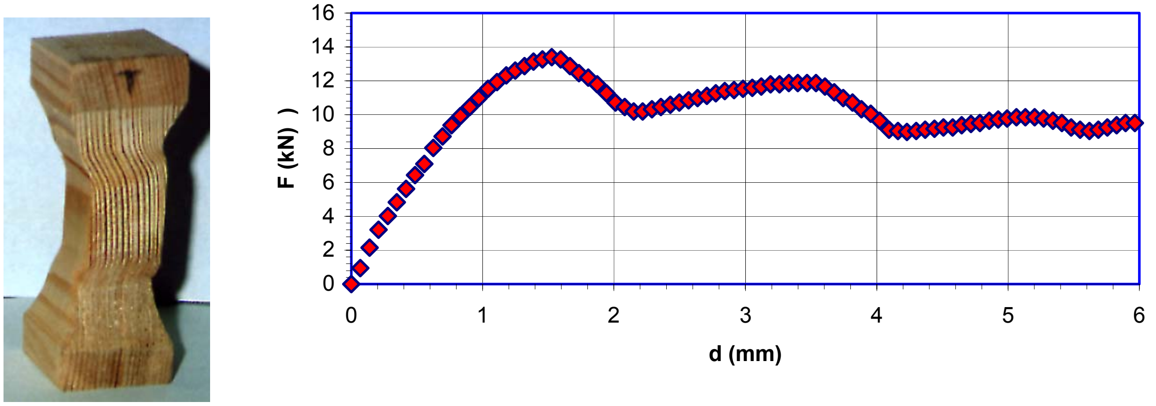
Figure 1: Mechanical response of pine wood specimen in the longitudinal direction.



Radial

Compression versus displacement curve (R specimen)

Figure 2: Mechanical response of pine wood specimen in the radial direction.



Transverse

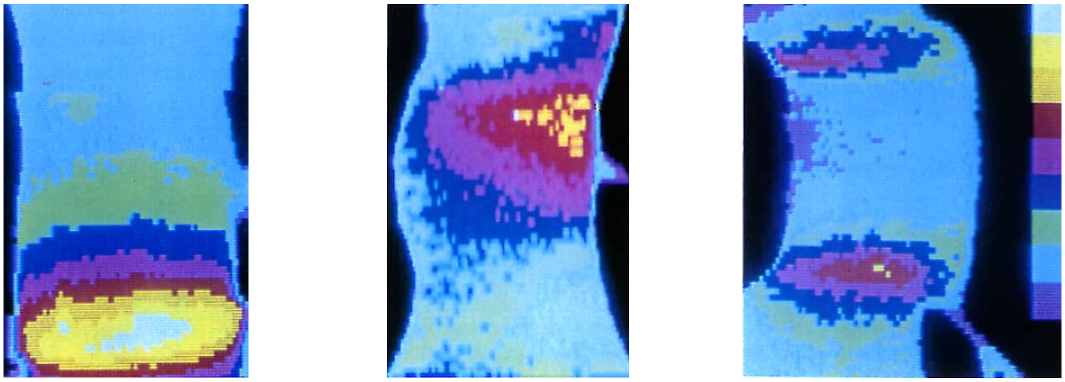
Compression versus displacement curve (T specimen)

Figure 3: Mechanical response of pine wood specimen in the transverse direction.

The Agema SW-782 infrared scanner, incorporating a high-temperature filter and equipped with a real time system Discon (Digital Infrared System for Coloration) converting thermal images into a ten-color isotherm display, was used to record the bulk of the heat emission data. That device displays a ten-color calibrated surface-temperature picture of the specimen. Each color hue corresponds to 0.2 °C. Infrared thermography readily depicts intrinsic dissipation localization announcing quite different mechanisms of damage preceding wood failure, according to the three directions of wood anisotropy.

When pinewood undergoes compressive loading, the infrared thermographic technique readily evidences the influence of anisotropy (Figure 4).

- The L specimen fails by local crushing of the fibers at ends and subsequently a vertical splitting.
- In the R specimen, crushing of the hollow wood fibers in the spring or early wood regions of some growth rings can often be seen.
- The T specimen fails in an unsymmetric mode because of the finite growth ring diameter, often with two plastic hinges.



Longitudinal Radial Tranverse

Figure 4. Localization of intrinsic dissipation in wood specimens as a function of their anisotropy directions (each color hue corresponds to 0.2 °C).

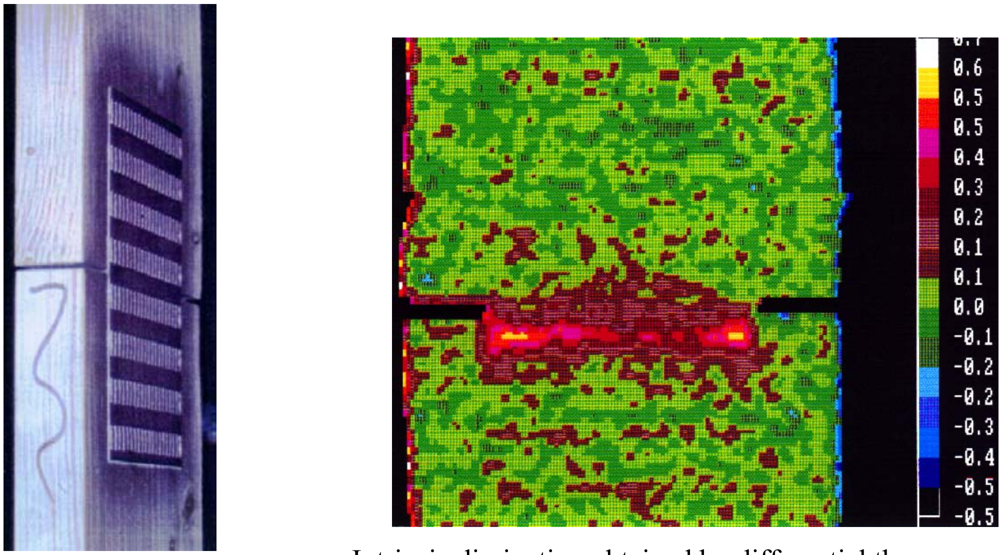
In several architectural applications there is a need for the development of high-ductility connections for braced-frame systems and energy-dissipating connections for anti-seismic applications. Metal-plate-connected wood trusses are widely used in residential construction (Figure 5) and continue to be increasingly used in agricultural and other commercial construction. A reason for the widespread use and continued growth of applications for wood trusses concerns the efficiency and effectiveness of punched-metal-plate connectors. Extensive engineering design services support the almost unlimited variety of components that can be assembled with plates and dimension lumber.

Figure 5. Metal-plate-connected wood trusses.

Current design procedures are based upon simplified assumptions of connection behavior and have proven to be quite adequate for truss applications in light-frame redundant assemblies. The increased use of metal plate connected trusses, in applications involving longer spans with fewer redundancies, suggests that a more thorough understanding of the behavior of metal plate connections would be beneficial for upgrading design procedures. As infrared thermographic scanning offers new information on metal plate connection behavior, refinement of design procedures can be made as needed and new, more effective, and specialized truss-plate configurations can be contemplated.

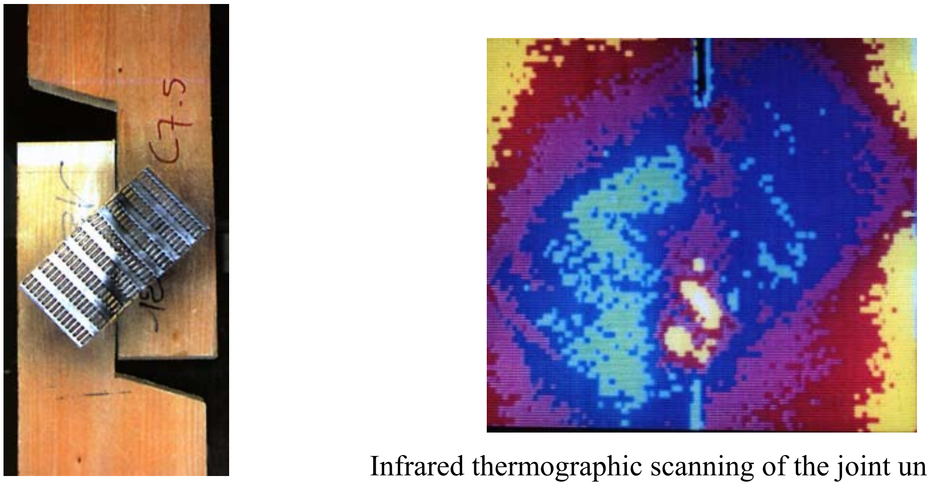
Although the actual configuration of metal connector plates varies widely among manufacturers, the plates generally consist of galvanized sheet steel of 14 to 20 gages with teeth of 1/4 to 3/4 in. (6.4 to 19.0 mm) punched in a regular pattern across the plate. The long side of the punched rectangular holes defines the major axis of the plate. The plates are pressed into the wood members on each side of a joint, and the teeth act as nails in transferring load from the wood member into the steel plate and into the adjacent wood member.

In a truss, this connection system involves a complicated transfer of load as the metal teeth interact with wood at various grain orientations and in various loading situations. Metal plate connections exhibit a non-linear, semi-rigid load deformation response. Failure modes include the teeth pulling out of the wood, failure of the wood member within the plated region, yielding of the plate in tension or shear, and compression buckling of the plate in gaps between wood members. Typical splice joints under tension and shear loadings are respectively shown in Figures 6 and 7 with their corresponding thermal images before failure.



Intrinsic dissipation obtained by differential thermography

Figure 6. Infrared scanning of splice joint under tension loadings (each color hue corresponds to 0.05 °*C*).



Infrared thermographic scanning of the joint under shear loading

Figure 7. Infrared scanning of splice joint under tension loadings (each color hue corresponds to 0.2 *°C*).

Discussion: In accordance with the coupled thermomechanical equation (1), the analysis of thermal images consists in isolating the intrinsic dissipation from thermal noises by simply subtracting the thermal image at a reference load level from the thermal image at a higher load level. Computer assisted thermography software allowed the data reduction of the thermal images using the function subtraction of images. The resulting image showing the temperature change between two compared images, obtained under nearly identical test conditions. This image processing provides quantitative values of intrinsic dissipation that readily defines a *threshold of acceptable damage* TAD for these mending plates used for reinforcing intersections of wood or fixing damaged areas.

The Figures 8 and 9 show respectively the tension T (kN) versus displacement d (mm) of a toothed metal plate used as a fastener under tension and the corresponding tension T (kN) versus dissipation D (°C).

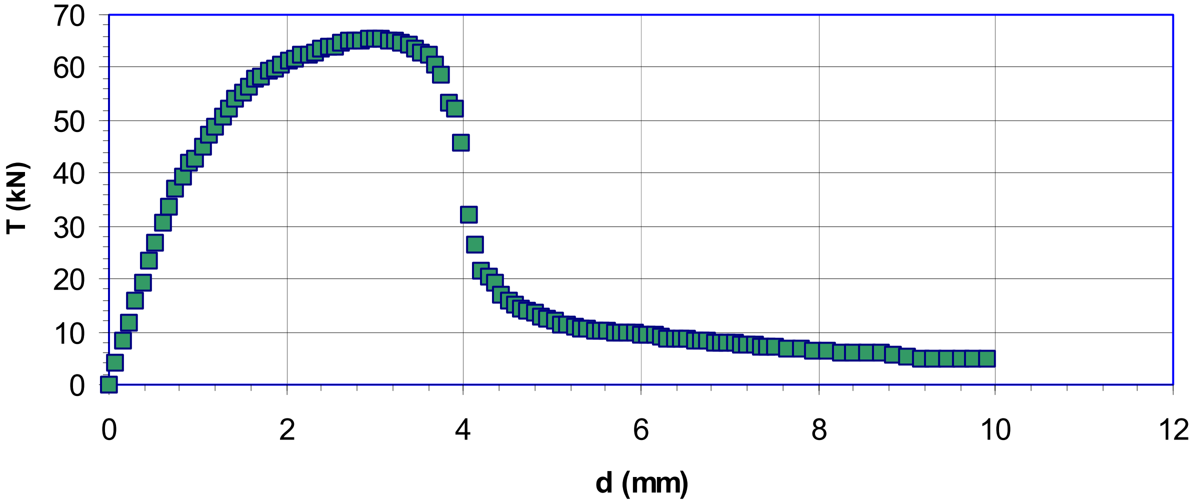


Figure 8. Mechanical response of a metal-wood fastener under tension

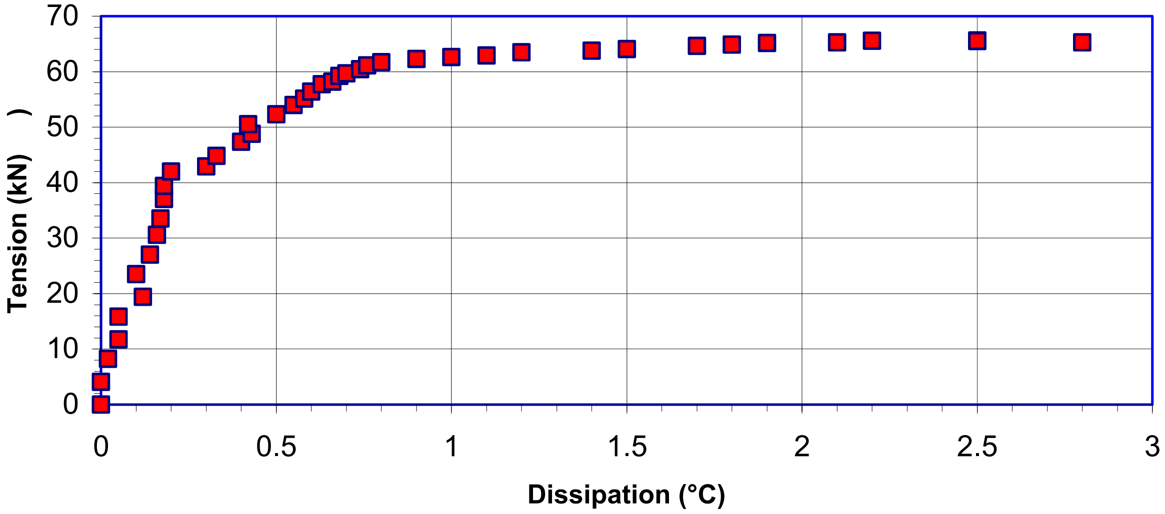


Figure 9. Dissipation of a metal-wood fastener under tension

Conclusions: This work has demonstrated that the *dissipativity* of wooden construction materials under loading is the most sensitive and accurate *manifestation of damage*. Owing to the thermomechanical coupling, infrared thermography provides a non-destructive, non-contact and real time test to observe the physical process of wood degradation and to detect the occurrence of intrinsic dissipation. Thus it readily gives a measure of the material damage and permits to evaluate the limit of a progressive damaging process under load beyond which the material is susceptible to failure. It is of particular interest that the method allows not only qualitative work such as finding flaws, defects or weakness zones, but also quantitative analysis of the effects of flaws and defects on strength and durability of wood structural components. This useful and promising technique offers accurate illustration of crack initiation, the onset of its unstable propagation through the material and/or flaw coalescence when increasing irreversible microcracking is generated by cyclic loading. The main interest of this energy approach is to unify microscopic and macroscopic test data. The parameter *intrinsic dissipation* under consideration is a scalar quantity, easy to evaluate with accuracy. Subsequently it may suggest multiaxial design criteria, highly relevant for full scale testing on engineering structures. Infrared thermography is an attractive and relatively unexplored technique for the non-destructive evaluation of failure in industrial materials and structures. The main advantages of this technique are speed and non-contact operation. Signal processing techniques might be efficiently used to extract more quantitative information. Significant developments are expected soon, capitalizing on the recent progress in computing power and image-processing techniques. The opportunities offered by thermal techniques with remote operation and fast surface-scanning rates are particularly attractive for on-line applications.

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