Chapter 8
Assessment of Equipment Using Infrared Thermography in Sports

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Abstract Sporting equipment is increasingly faced with practical problems related to thermal phenomena, irreversible and dissipative processes, inducing aging, damage, degradation, fatigue and failure of the materials and structures under loading service. This text aims to illustrate the use of infrared thermography as a non-destructive, non-contact, real-time and easy to use technique in order to detect, observe and evaluate the evolution of temperature changes caused by the diverse physical processes occurring in sports engineering.

8.1 Introduction

Sports engineering covers various research themes in design and production, materials and sport, biomechanics, instrumentation, modelling, mechanics, motion analysis, dynamics, strength of materials, sports and leisure facilities. In all these areas, thermal aspects should not be ignored because they help identify different product attributes for better competitive sports performance, style, comfort, safety and enjoyment [1]. New technologies have made sports faster and more powerful, and they have also improved the performance, enjoyment, safety and the overall wellbeing of athletes [2]. This leads to an increasing requirement for appropriate testing (1) to ensure product integrity and reliability, (2) to avoid malfunctioning and failure, (3) to aid in better product design, (4) to control manufacturing processes, and (5) to strive for the highest standards in quality and safety.

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J.I. Priego Quesada (ed.), *Application of Infrared Thermography in Sports Science*, Biological and Medical Physics, Biomedical Engineering,
DOI 10.1007/978-3-319-47410-6_8

8.1.1 Objective

Mechanical engineering deals with various types of materials and structural components. The study of thermal phenomena to identify product attributes follows a well-known process: *thermal phenomena are identified and theoretical models are obtained intuitively from experience*. These must subsequently be *validated*: their predictions concerning the application are compared with relevant experimental results. An approach based on temperature change measurement provides a better understanding of the mechanical behaviour of sporting goods, equipment and accessories. It allows the detection of physical phenomena which can lead to damage, and it leads to new ideas for the improvement of sporting goods and related products. This non-destructive testing technique can effectively evaluate the mechanical performance of sporting goods merchandise in compliance with international standards, or depending upon the requirements of the athletes.

8.1.2 Method

The thermal effects due to thermomechanical coupling in solids have been identified within the general framework of the thermodynamics of irreversible processes based on internal variables. This chapter aims to illustrate the use of infrared thermography as a non-destructive, real-time and noncontact technique to detect, to observe and to evaluate the evolution of temperature changes caused by the diverse processes of irreversible physical phenomena. The results obtained highlight the advantages of differential infrared thermography.

An active thermographic system with external thermal stimulation is scanned from a single side access. When temperature variations occur on the observed surface, the infrared camera records all data for spatial visualization of temperature distribution and temporal separation of the heat images thanks to advanced image processing techniques applied to the thermal response. The thermal data processing consists simply of an image subtraction function between two stages of loading. This technique minimises the thermal noise in real environments and thus facilitates the detection, discrimination and interpretation of the diverse thermal phenomena involved in these non-linear coupled thermomechanical effects. Stress and strain concentrations in loaded materials and structural components occur and result in localized forces that are sufficient to promote plasticity and/or inelasticity. In addition to traditional techniques of mechanical strength evaluation, the technique provides a ready evaluation of (1) a threshold or limit of acceptable damage under service loading beyond which the material will be rapidly destroyed, or (2) fatigue resistance under repeated and cyclic excitations or dynamic solicitations. Finally this approach suggests various potential applications of the thermal scanning technique in diverse sports engineering domains: localisation of dissipative phenomena and rapid evaluation of fatigue limit, non-destructive testing using thermal conduction phenomena and detection of heat sources in sports equipment.

8.2 Principles of Infrared Thermography Testing

Thermomechanical coupling effects have traditionally been neglected in thermal stress analyses. The temperature field and the deformation induced by thermal dilation and mechanical loads were solved separately. However, this effect may become significant when mass inertia is not negligible, due to the flux of heat generated through the boundary of the body, or if the material is loaded beyond its stable reversible limit. The relevance of coupled thermomechanical analysis has been demonstrated for a variety of problems of mechanical engineering, such as fault analysis, damping of stress wave propagation, deformation localisation after bifurcation and strength softening of material due to the heat generated by repeated plastic deformations. Internal energy dissipation has been recognised by a number of well-known scientists [3–5]. Carrying out experiments on the cyclic twisting of cylindrical bars, Dillon [6] identified the work done to the system by plastic deformation as the major contribution to the heat effect, and proposed an internal dissipation rate **Đ** related to the plastic strain rate. The thermal effect due to thermomechanical coupling at the tip of a moving crack has been investigated within the framework of thermodynamics, taking into account stress and strain singularities [7]. The heat generated due to plastic deformation causes a large local temperature increase which is expected to affect the selection of failure modes during dynamic fracture and thus to influence the fracture toughness of the material. Well-developed empirical theories of plastic deformation in metals allowed engineers to predict successfully the behaviour of a variety of structures and machine elements loaded beyond the elastic limit for design purposes. 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 and without in any way influencing the actual surface temperature of the objects viewed. A consistent theoretical framework is necessary in order to correctly interpret the thermal images. When restricting the analysis to perfectly viscoelastic-plastic material, this leads to the following coupled thermomechanical equation:

$$\rho C_v \theta_{,t} = \rho r + \operatorname{div}(k \operatorname{grad} \theta) - \left(\beta : D : E^{e}_{,t}\right)\theta + S : E^{I}_{,t} \tag{8.1}$$

Equation 8.1. Thermomechanical equation. Where ρ ($\mathrm{kg\ m^{-3}}$) is unit mass; C_v ($\mathrm{J\ kg^{-1}\ K^{-1}}$) = specific heat at constant deformation; C ($\mathrm{J\ m^{-3}\ K^{-1}}$) = ρ C_v the volumetric heat capacity of the material (the energy required to raise the temperature of unit volume by 1 °C or 1 K); r = the heat sources; div ($\mathrm{m^{-3}}$) = the divergence operator; k (W m^{-1} K^{-1}) = thermal conductivity; grad (m^{-1}) = the gradient operator; θ (K) = the absolute temperature; β (K^{-1}) = the coefficient of the thermal expansion matrix; D (N m^{-2}) = fourth-order elasticity tensor; $E^e{}_{,t}$ (s^{-1}) = the time derivative of the elastic strain tensor; S (N m^{-2}) = second Piola–Kirchhoff stress tensor; ':' the tensorial contracted product operator; and finally $E^I{}_{,t}$ (s^{-1}) = the time derivative of the irreversible strain tensor

Since the underlying physical processes are highly diversified, the modelling is approached from a purely phenomenological point of view. Such an approach can be useful in the interpretation of the energetics of the thermoelastic-plastic behaviour. The classical theory of rate-independent isotropic or kinematical hardening plasticity is considered to be an adequate basis for such modelling as it offers the simplest constitutive model for elastic behaviour of the material while still allowing consistent inclusion of two-way thermomechanical coupling effects.

When using internal state variables that describe structural changes of material, the right-hand side member will be completed by other terms representing the cross-coupling effects [8]. These effects influence the evolution of temperature through the second-order terms when compared with the internal dissipation term. Their contribution to internal heating during the adiabatic process is small and so they are sometimes neglected.

This coupled thermomechanical equation suggests the potential applications of the infrared scanning technique in diverse engineering domains: detection of heat sources, nondestructive testing using thermal conduction phenomena, elastic stress measurements and localisation of dissipative phenomena. Thus the detected temperature change, resulting from four quite different phenomena, must be correctly discriminated by particular test conditions and/or specific data reduction. This is the main difficulty when interpreting the thermal images obtained from experiments under the usual conditions.

8.2.1 Thermal Phenomena

The first term on the right-hand side of the coupled thermomechanical equation is related to the existence of heat sources or heat sinks in the scanning field. The surface heat patterns displayed on the scanned specimen may result from either external heating, referred to in the literature as passive heating, where local differences in thermal conductivity cause variations on isothermal patterns, or from internally generated heat, referred to as active heating.

8.2.2 Thermal Conduction

The second term on the right-hand side of the coupled thermomechanical equation governs heat transference by thermal conduction, in which the heat passes through the material to make the temperature uniform within the specimen. The second-order tensorial nature of the thermal conductivity K may sometimes be used for the detection of anisotropy of heavily loaded materials. It could also be used to discriminate different thermal phenomena generated by different dissipative mechanisms within the tested object due to their delay in conduction [9].

8.2.3 Thermoelasticity

The third term on the right-hand side of the coupled thermomechanical equation illustrates the thermoelastic coupling effect. Within the elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy, causing it to change temperature. Provided adiabatic conditions are maintained, the relationship between the change in the sum of principal stresses and the corresponding temperature change is linear and independent of loading frequency. It is the reversible portion of the mechanical energy generated; this thermoelastic coupling term may be significant in cases of isentropic loading.

8.2.4 Intrinsic Dissipation

The last term on the right-hand side of the coupled thermomechanical equation defines the energy dissipation generated by viscosity and/or plasticity. Internal energy dissipation has been recognised by many scientists, and the work done to the system by plastic deformation has been identified as the major contribution to heat effect. In thermoelastic-plasticity, it is generally accepted that not all mechanical work produced by the plastic deformation can be converted to the thermal energy in the solid. A portion of the work is believed to have been spent in the change of material microscopic structure. The work done, in plastic deformation per unit volume, can be evaluated by integrating the material stress–strain curve. This internal dissipation term constitutes a significant part of the non-linear coupled thermomechanical analysis. The quantification of this intrinsic dissipation for engineering materials is an extremely difficult task without infrared thermography. The infrared thermographic technique is mainly concerned with differences in temperature (or thermal gradients) that exist in a material rather than the absolute value of temperature. The work, reported in this chapter, considers intrinsic dissipation to be the most accurate indicator of damage manifestation. It highlights the advantages of the infrared thermographic technique, used for the detection and discrimination of this non-linear coupled thermomechanical effect within the framework of a consistent theoretical background. Several applications have been proposed for materials testing in sports equipment [10–12].

8.3 Infrared Thermography Applications to Sporting Equipment

Diverse and various applications of the infrared thermography technique to sporting equipment are based on each or in conjunction with several terms of the right-hand side of the above coupled thermomechanical equation.

8.3.1 Infrared Thermography Screening of Heat Rise in Racing Cars

Thermal imaging has been used by tire makers for product development, both for racing and passenger cars. The air pressure inside the tires supports the weight of the vehicle. Since air is a gas, it expands when heated and contracts when cooled.

According to the classical gas law $Pv = rT$—where P ($N\ m^{-2}$) is the pressure; v (m^{-3}) is the volume; r ($=287\ J\ kg^{-1}\ K^{-1}$) is the gas constant and T (K) is the temperature—temperature measurement is related to tire pressure that has to be checked to assure that the influences of time, changes in ambient temperature or a small tread puncture have not caused it to change. The tire pressure recommended in the tire information list is the vehicle's recommended cold tire inflation pressure. Some racing teams at all levels of the Formula One racing use thermal cameras to control the tires to make sure they are always running adequate tires with the right air pressure for the conditions so they have just the right contact patch.

Racing tires are substantially different from those on a passenger car:

- Race car tires are much wider—up to 12 in (30.48 cm) wide in the front and 16 in (40.64 cm) wide in the rear, whereas the typical passenger car tire is 7–9 in (17.78–22.86 cm) wide.
- Racing tires may be completely smooth to maximize the amount of rubber touching the track surface.
- The rubber on the face of the tires is extremely soft. It is more like a soft rubber eraser than anything else, and very unlike the hard rubber found in passenger car tires.

In addition, racing tires get very hot due to tread flex and friction generated by rotational speed and by cornering and braking. The higher the load and the higher the speed, the hotter the tire will get. The heat though, will not be evenly distributed. One tire may run hotter than the others, or one area of the contact patch may be hotter than another. If the technician can accurately measure tire temperatures and observe how those readings are distributed across the tire, he can adjust tire pressures and suspension to achieve improved performance.

To determine the temperature of racing car tires, it is vital that the driver uses the most robust and reliable thermometers on the market. Infrared thermometers run on thermal, or infrared energy, which is light with a long wavelength that makes it invisible to the human eye. It is the part of the electromagnetic spectrum that is perceived as heat. Unlike visible light, in the infrared world, everything with a temperature above absolute zero emits heat, even very cold objects like ice. The higher the object's temperature, the greater the IR radiation emitted. Infrared thermography allows us to see what our eyes cannot.

When taking race tire temperatures, it is important to keep the tires as close to operating temperature as possible. Therefore, the pilot must run two to three hot laps to heat the tires and get into the pits quickly. Temperature readings are taken as soon as possible, since the tread surface cools rapidly.

Maintaining sufficient air pressure is required if the tires are to provide all of the handling, traction and durability of which they are capable, but excessive pressures lead to irregular wear. "Cupping", or too much wear in the center of the tread, is a sign of overpressure. Too much wear to the shoulders of the tire is a sign of too little pressure. Combined with cold-stiffened rubber, the loss of pressure can sometimes cause tires to spring otherwise unexplainable leaks. Low pressure may progressively damage the tire, particularly the sidewall of the tire as it starts to fold over. Air pressure maintenance is actually one of the most important repeating maintenance items on the car. Proper air pressure maintenance leads to better gas mileage, avoids irregular wear and extends the life of the tires by thousands of kilometres. Due to the importance of tire pressure has on vehicle safety and efficiency, a tire-pressure monitoring system (TPM) is becoming increasingly adopted for passenger vehicles. It is an electronic system designed to monitor the air pressure inside the pneumatic tires on various types of vehicles. It warns the driver that at least one or more tires are significantly under-inflated, possibly creating unsafe driving conditions.

Because of their versatility, infrared thermometers are also used to detect sources of heat that affect the driver, locate dead engine cylinders, or read the temperature of bearings, brakes or the track.

In race cars, non-contact temperature measurement is useful for screening heat sources generated by brakes/sealed wheel bearings, engine components, exhaust systems, tires, cooling systems, compact heat exchangers [13] and particularly engine overheating. Most engines are designed to operate within a temperature range of about 90–105 °C. A relatively constant operating temperature is essential for proper emissions control, good fuel economy and performance. But problems can arise that cause the engine to run hotter than normal, resulting in engine overheating.

8.3.2 Quality Screening of Clay Tennis Court After Wetting

The conduction term of the thermomechanical equation governs the heat transfer by the thermal conduction and radiation at the surface in which the heat passes through the material leading to a uniform structure temperature. The second-order tensorial nature of the thermal conductivity k may be used for the detection of anisotropy in heavily loaded materials.

Variations in thermal conductivity may arise because of local inhomogeneities or flaws in the material. When an unsteady state exists, the thermal behaviour is governed not only by its thermal conductivity but also by its heat capacity. The ratio of these two properties is termed the thermal diffusivity $\alpha = k/C$ ($m^2\ s^{-1}$), which becomes the governing parameter in such a state. A high value of the thermal diffusivity implies a capability for rapid and considerable changes in temperature. It is important to bear in mind that two materials may have very dissimilar thermal conductivities but, at the same time, they may have very similar diffusivities.

The French Tennis Open uses clay courts, which are generally more common in Continental Europe. Although less costly to construct than other types of tennis courts, their maintenance costs are high as the surface must be rolled to preserve flatness. No court surface varies in the height of the ball's bounce as much as clay court. On cold, wet clay, the ball bounces quite low; on dry, hot clay, it bounces quite high.

Clay courts are considered "slow", because the balls bounce relatively high and more slowly, making it more difficult for a player to deliver an unreturnable shot. Clay courts heavily favour baseliners who are consistent and have a strong defensive game, which allow players such as Rafael Nadal, Björn Borg, Chris Evert, and Justine Henin to be successful at the French Open. Clay court players use topspin to trouble their opponents. Movement on gravel courts is very different from movement on any other surface. Playing on clay often involves the ability to slide into the ball during the stroke, as opposed to running and stopping like on a hard or grass court. Clay courts are unique in that the ball bounce leaves an impression in the ground, which can help determine whether a shot was in or out. The properties of the surface influence the style of play and affect the quality of performance.

Critics of red clay courts point to the constant need to wet them down, with problems of renewing the surface if it dries out. The water content is a key characteristics and it must be balanced. The temperature of a bare wet soil surface could be measured with a narrow bandpass infrared radiation thermometer [14]. In this case, infrared thermography readily provides a rapid control of the uniformity of the temperature of the playing surface that is related to the mechanical resistance of the clay court surface.

8.3.3 Thermoelastic Coupling in Sport Equipment Testing

Experience shows thermoelasticity to be a common type of behaviour. It is characterized by *reversibility* of the material response to the excitation it undergoes. Thermoelastic behaviour is modelled by assuming that current values of the temperature and strain tensor in the material element are sufficient to define its physical state. The free energy arises as the *thermodynamic potential*, a function of the current values of the temperature and strain tensor. The stress tensor is obtained by differentiating with respect to the strain tensor. In an isotropic material undergoing small perturbations, linear thermoelasticity is characterized by *two* elastic constants and *one* thermal expansion coefficient. Elastic and thermal strains can be uncoupled as follows: total strain = elastic strain + thermal strain. In practice, the thermoelastic equilibrium problem is solved by using the superposition principle. The problem consists of adding together the solutions: (a) of the isothermal problem with excitations and (b) of the purely thermal problem.

Check-experiment of energy restitution on soccer ball

High-level matches deserve a soccer ball that respond with accuracy and a soft touch. In the past, many soccer balls made by different manufactures varied in quality when used in matches. Now soccer balls with the organization's official approval logo imprinted on them, adhere to a higher standard of quality and are more consistent in how they perform during matches. Testing procedures for the balls submitted for these designations are designed to simulate match conditions: (1) *Circumference test* for a well-balance response in play; (2) *Sphericity test* which ensures the ball's in-flight stability; (3) *Rebound test* to make sure that the ball bounces in a predictable manner; (4) *Water absorption test* which ensures a limited increase in weight; (5) *Weight test* which ensures a consistent playing response when the ball is struck; (6) *Loss of Pressure test* in order to remain playable; and finally (7) *Shape and Size Retention test* which ensures that the footballs last, even in the most challenging situations for a better playing performance. Manufacturers have to submit seven balls if they are applying for "FIFA Inspected" status, and ten samples if they seek the "FIFA Approved" label.

The manufacturer of the 1998 World Cup soccer ball (Fig. 8.1a) claimed that the Tricolore soccer ball is faster and more accurate than any other soccer ball. It contains hollow acryl-nitryl micro beads of 70 μm in diameter, pressurised at 14 MPa. They are then highly compressible and capable to restitute a great amount of the kicking energy.

Figure 8.1b depicts a check-experiment on the soccer ball kicked by a steel ball. The elasticity of the collision between soccer ball and steel ball is given by a measure of how much bounce there is, or in other words, how much of the kinetic energy of the colliding objects before the collision remains as kinetic energy of the objects after the collision. With an inelastic collision, some kinetic energy is transformed into deformation of the material, heat, sound, and other forms of energy, and is therefore unavailable as motion. A perfectly elastic collision has a

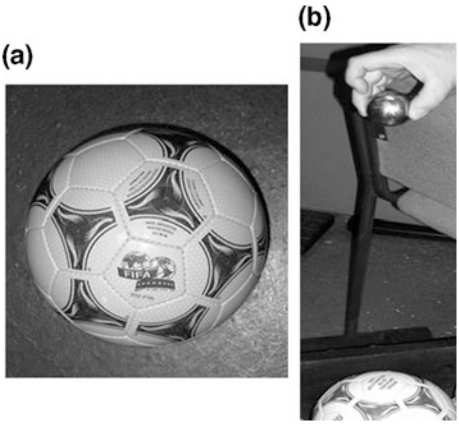


Fig. 8.1 **a** The Tricolore soccer ball used underglass print technology with a thin layer of syntactic foam. **b** Check experiment of energy restitution on a soccer ball

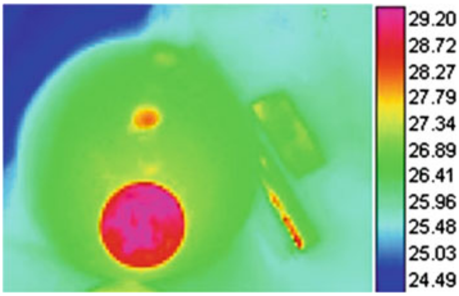


Fig. 8.2 The kicked soccer ball is the large circle at 26.5 °C. The steel ball striker is the medium size circle at 30 °C. A very localized hot zone at nearly 28 °C is due to the increased pressure in the pressurised micro beads (temperature scale is given in degrees Celsius)

coefficient of restitution of 1 (ratio of the differences in velocities before and after the collision). A thermal image (Fig. 8.2) shows the kicked soccer ball (green circle), the steel ball striker (red circle) and an extremely localised hot zone (small red zone) due to increased pressure in the pressurised micro beads. The pressurised micro beads store elastically the kicking energy according to the equation $p\,v = R\,T$ and $h = c_p\,T$. In case of perfect gas with gas constant R and heat capacity c_p, the variables are pressure p, specific volume v, temperature T and specific enthalpy h.

The experiment evidenced:

- a very localised heat change decreasing rapidly (Fig. 8.3),
- several consecutive experiments at the same location confirm that the heat increase remains very localised and no accumulation of temperature changes occurs on the soccer ball. This fact demonstrates that dissipative behaviour is negligible.

A fast soccer ball kick has been recorded 129 km/h (80.1 mph) in Madrid, Spain on 29 October 2001. It was achieved by Francisco Javier Galan Màrin at the studios of *El Show de los Récords*. However, according to the Guinness Book of Records

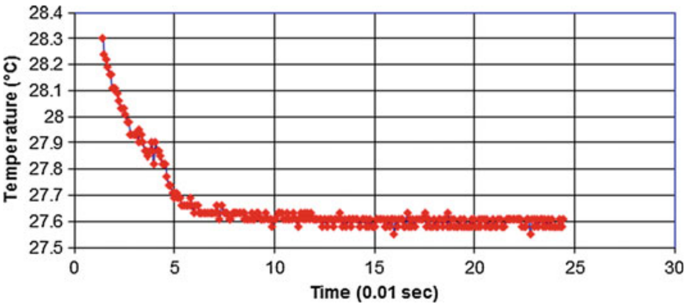


Fig. 8.3 Evolution of temperature versus time during impact

Ronny Heberson shook the goal with an incredible 132 mph for Sporting Lisbon against Naval in 2006. The ball travels so fast that it becomes almost imposible to see during the flight of the ball towards the goal. Top professional players are exploiting the chaotic flight and speed of modern balls used in today's matches. A change of external structure called the PSC structure (Power, Swerve and Control) can give outfield players the advantage. Goosebump-like shapes on the surface layer give the ball more power and swerve.

In addition when the soccer ball offers a high coefficient of restitution with negligible deformation, the soccer player can precisely kick it slightly off center, causing it to rotate around a given axis. When the ball travels, air moves over the ball according to the location of kicking impact and generates the Magnus effect. Different spins can cause different effects on the ball generating different flight paths of the ball. With a backspin on a ball, the air will go faster over the ball with more pressure underneath. This will cause the ball to rise and travel farther.

Design testing of a light sport airplane

Ultralight aviation is the flying of lightweight, 1 or 2 seater fixed-wing aircraft. The integrity of any novel or unusual design feature having an important bearing on safety should be established by test. Design values of strength must be chosen so that no structural part is under strength as a result of material variations or load concentration, or both.

Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). The light sport aircraft wings must be tested to ensure great handling, strength under load, and flight performance across a range of airspeeds and angles of attack.

Within the linear elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy causing temperature change. Provided adiabatic conditions are maintained, the relationship between the change in the sum of principal stresses and the corresponding change in temperature is linear and independent of loading frequency [15].

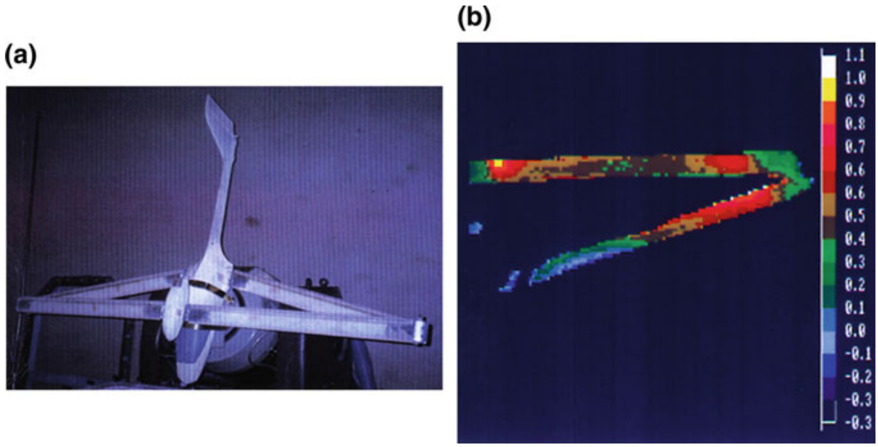


Fig. 8.4 **a** Reduced scale model of a double-winged aircraft subjected to vibratory loadings. **b** Elastic stress concentrations recorded on the test specimen during vibratory loading (temperature scale is given in degrees Celsius)

A vibratory test was performed on a reduced scale model of a double-winged aircraft (Fig. 8.4a) in order to evaluate the weakness zones around connections (i) between the two wings themselves, and (ii) between the wings and the fuselage. The double-wing design is assumed to lead to greater maneuverability. The big disadvantage of the biplane layout was that the two wings interfered with each-other aerodynamically, each reducing the lift produced by the other. This interference meant that for a given wing area the biplane produced more drag and less lift than a monoplane. This mechanical statement is supported by the hot locations on the wings caused by stress concentrations (Fig. 8.4b). High local stresses can cause objects to fail more quickly. These experimental results are used to assist in a better design of the light sport airplane prototype, minimizing stress concentrations and if posible avoiding them.

8.3.4 Damage Occurrence and Detection in Sports Materials

In materials testing in an industrial environment, thermal noise often generated by gripping systems may sometimes obscure the intrinsic dissipation of the tested specimen. This difficulty can be overcome when using thermal image subtraction or differential thermography.

Mechanical performance of tennis strings under tension

Natural gut has been regarded as the premiere tennis string since the early 1800s. It has been, and remains, the most frequently used string on the pro tour. It has better tension retention than any other material, and also is softer than any other material used for tennis strings. It provides the most energy return, meaning it is the most efficient string. It remains soft at high tensions while other materials tend to stiffen dramatically. This allows gut string to enable players to string rather tightly to improve ball control without losing much rebound efficiency (power) and without greatly increasing impact shock, which can hurt the elbow and other joints.

Damage and failure behaviour of natural gut strings and others types of synthetic tennis racket strings are an important consideration for skilled tennis players who should be highly aware of their equipment's performance relative to their personal needs and game style. Much engineering research has been conducted to determine optimal string tension (Fig. 8.5) for different size rackets made from various types of materials [16]. The effect of varying string tensions is important to skilled players wanting to improve their shot velocity and control [17]. When string is loaded, it deforms as a whole in spite of its heterogeneous characteristics and its localised defects. Stress concentrations occur and result in localised forces that are sufficient to promote plasticity and inelasticity. Failure mechanisms of string specimens subject to tensile loading are readily evidenced by infrared thermography. Gut is a natural animal fibre, manufactured from the smooth muscle portion of sheep or beef intestines through a sophisticated chemical process of washing, bleaching, twisting, drying, and refining to ensure strength and uniformity [18]. This product is designed for an optimisation of playability, comfort, hitting power and durability.

The intrinsic dissipation, generated by plasticity, is considered as a highly sensitive and accurate indicator of damage manifestation. Thanks to the thermo-mechanical coupling [19], infrared thermography is used to observe the physical

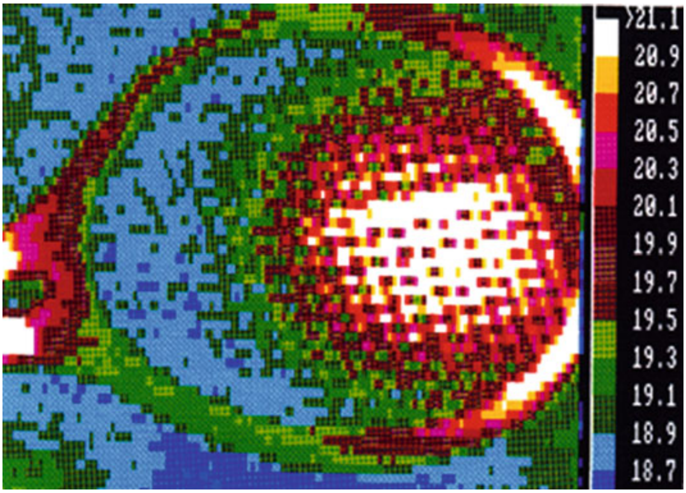


Fig. 8.5 Infrared thermography of a tennis raquet impacting the ball (temperature scale is given in degrees Celsius)

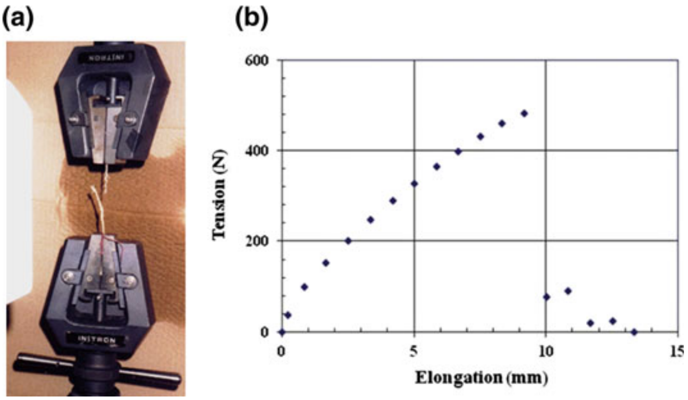


Fig. 8.6 **a** Specimen of a natural gut string subjected to tension loading. **b** Experimental elongation versus tension curve of a natural gut string specimen

processes of damage and to detect the onset and the evolution of damage and failure processes of tennis string when the specimen is subjected to increasing tensile loading (Fig. 8.6).

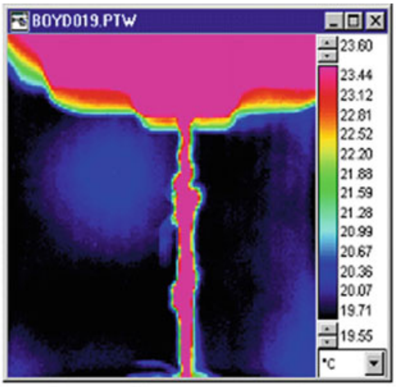
If the evolutions of damage and intrinsic dissipation are assumed identical, a thermal image processing give the intrinsic dissipation at tension T as shown in Fig. 8.7. It readily gives a measure of the material damage and locates the failure of the gut string specimen. In addition it permits a graphical evaluation of the limit of acceptable damage **LAD** that separates low and high regimes of dissipation or damage manifestation (Fig. 8.8). This tension—dissipation plot precisely defines a threshold under which natural gut provides its best mechanical performances.

Material composites have increased the diversity of design and manufacturing for sports products. There are a large variety of synthetic products including nylon, artificial gut, graphite string, oil-filled string, etc. Very specific designs are targeted to match the physical capability of each player. Can their mechanical performance be characterised in term of damage and durability? In the interaction of the ball and the strings, the kinetic energy of the ball is converted into potential energy stored in both ball and string deformation. By storing a larger fraction of the incoming energy in the strings, less is dissipated, and more is returned to the ball's rebounding kinetic energy [17]. The shock vibrations of the wrist joint are transmitted from the racket with an impulse at the impact location and several vibration mode components of the racket frame and strings [20]. The higher the string tensions the higher the vibration frequency. This fact influences the feel or comfort of the arm or hand on impact.

Dry sliding of natural gut string at nodes

In order to produce ball spin in tennis, the player must accelerate the racket head through impact to brush the backside of the ball: (a) upward for topspin, (b) downward for underspin and (c) sideways for sidespin. The resulting effect is to

Fig. 8.7 Evaluation of intrinsic dissipation of a natural gut specimen under tension by subtraction between two thermal images (temperature scale is given in degrees Celsius)



Thermal image at tension T

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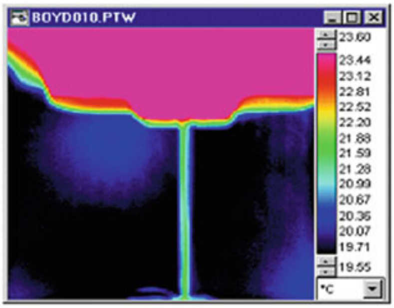

Thermal image at tension T = 0

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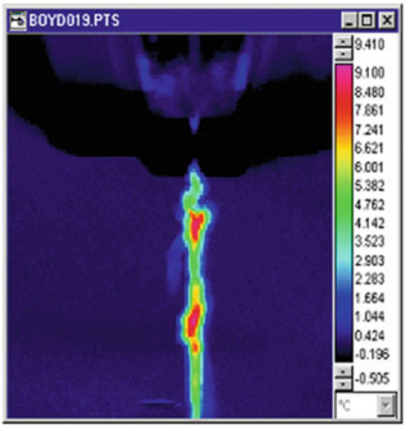


Intrinsic dissipation subject to tension T

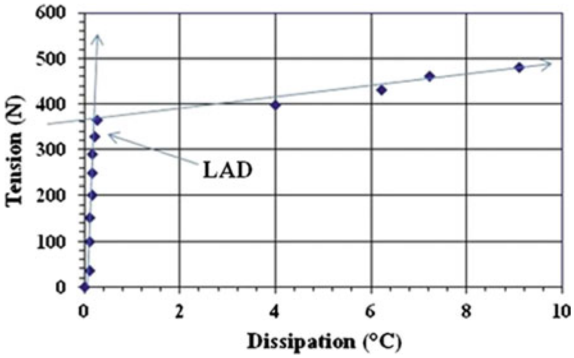


Fig. 8.8 Graphical determination of the limit of acceptable damage **LAD** of a natural gut string in tension

curl the tennis ball trajectory. When the tennis ball travels, air moves over the ball. The air will move more quickly around one side, making less pressure on that side of the ball (faster speed of air corresponds to lower pressure). On the other side of the ball, the air moves more slowly, as the spin is going directly against the flow of the air, causing there to be more pressure on that side of the ball. The ball is pushed in the direction from high pressure to low pressure, making the ball curve. Rafael Nadal uses a forehand grip which places the palm of the hand underneath the racket handle. His forehand allows the ball to clear the net with a high net clearance as he uses an upwards swing; as a result more topspin is produced.

The more vertical (or horizontal) the racket swings (in either direction), the more ball spin will be produced. The amount of spin a player imparts on the ball, combined with a high stroke velocity, generates dry sliding between longitudinal and transverse strings at nodes located in the racket's effective hitting zone. Relative movements between longitudinal and transverse strings occur depending on the type of ball-racket impact. They lead to tribological phenomena, such as friction, wear, pitting and fretting fatigue.

Fretting is a major problem in optimising tennis strings. It is defined as the surface damage induced by small-amplitude oscillatory displacements between strings in contact. This damage can either be wear or crack nucleation, depending on the prescribed forces or the displacement amplitude.

Considering a contact problem, in which a moving longitudinal string (9 cm long) is in contact with a fixed transverse string (5 cm long). The two strings were initially stretched at 200 N. An electromagnetic vibrator at a frequency of 1 Hz controls the cyclic motion of the longitudinal string. Force sensors respectively measure the normal and tangential contact forces during testing (Fig. 8.9a). Infrared thermography has been used to estimate tribological parameters, such as a frictional temperature rise (Fig. 8.9b), the shape and the size of the contact area (Fig. 8.9c).

Infrared thermography readily detects heat dissipation by Coulomb friction at contact location where sliding occurs between longitudinal and transverse gut strings. The experimental data demonstrate that wear phenomena occurring in tennis rackets could become significant in long matches such as the men's final of 1988 US open Tennis Tournament Lendl versus Wilander (4 h, 54 min with several

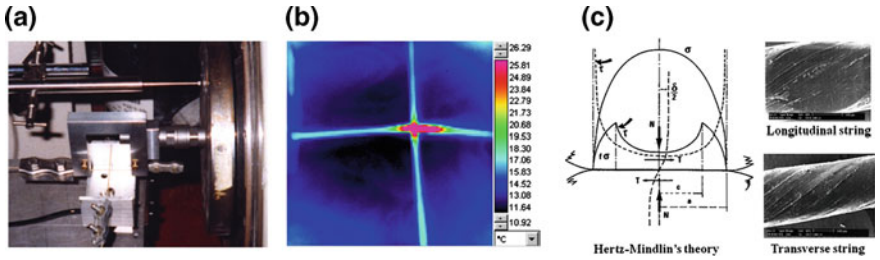
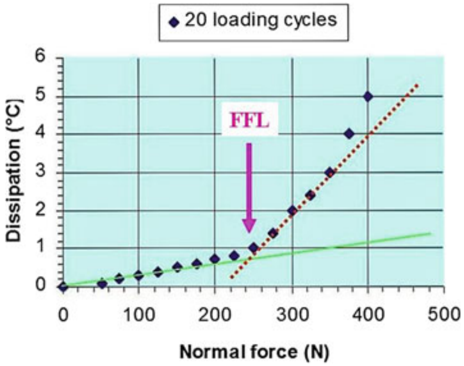


Fig. 8.9 **a** Experimental set-up for fretting fatigue testing on natural gut string at nodes. **b** Thermal image of natural gut string at nodes during fretting fatigue testing (temperature scale is given in degrees Celsius). **c** Contact between the 2 perpendicular gut strings

Fig. 8.10 Experimental determination of fretting fatigue limit (**FFL**) of a natural gut string using infrared thermography



thousands of strokes) or the men's 1st round of Wimbledon 2010 Isner versus Mahut during more than 11 h. The main parameters identified are string tension, racket stiffness, effects of spin, hitting power, etc.

These results have demonstrated that the dissipativity of tennis string material under tension or frictional loading is highly sensitive and an accurate predictor of damage. Owing to the thermomechanical coupling, infrared thermography offers the possibility of a non-destructive, non-contact testing of string degradation and damage. It provides a ready determination of a fretting fatigue limit **FFL** (Fig. 8.10), beyond which the string will fail in a long match. The opportunities offered by thermal techniques with remote operation and fast surface-scanning rates are particularly attractive for sports equipment.

8.3.5 Safety Control of Playing Surfaces

Each sport requires an individual approach to the design, installation and maintenance elements in the development of successful sport surfaces. Sports managers are often charged with providing cost effective, safe playing surfaces for athletes. The challenge is to create a uniformly dense cover (using soil, turf or synthetic materials) that provides sure footing and one that is able to tolerate and recover from the extreme wear and tear to which high-use fields are subject.

Common injuries could result from:

(a) *Heat*. Grass dissipates heat and naturally cools the environment. Heat related injuries are rare. Synthetic field can reach extremely high temperatures even at head height.
(b) *Abrasions, burns, grazes*. Natural turfgrass field is generally soft and not abrasive. Problems only arise when the ground has become bare and dry. Most synthetic fibers are relatively non-abrasive. The choice of infill is critical. Sand is more abrasive and rubber can cause friction burns if sliding.
(c) *Traction: knee and ankle sprains and muscle strains*. The choice of grass type is important for traction. Too much traction has been linked to an increased risk of severe knee injuries and too little traction to muscle strains and facial fractures. On synthetic field, footwear plays a major role in the amount of traction a player experiences.

In order to reduce the injury risk of skin burning and skin abrasion in cases of player-to-surface interaction, safe control of different playing surfaces should be done and communicated to users. A slip/skid resistance tester was used in conjunction with an infrared camera. The process is quite simple. The pendulum is released from the horizontal position by a quick release button. It swings down with uniform force each time, and the rubber slider—that simulates natural skin—at the bottom of the pendulum contacts the playing surface for a fixed length previously set by highering or lowering the height of the pivot of the pendulum (French Standard NF EN 1339). The rise of temperature detected by the infrared camera will be dependent on the friction/resistance the rubber meets on the playing surface (Fig. 8.11).

If the playing surface is abrasive, it can lead to friction burns when a player slides on the surface. However a certain amount of friction is necessary to slow the player down as he slides.

Mechanical properties of wood used as green building materials

Sport is great driver of materials technology for the designers of sports and leisure facilities using glulam timber beams, laminated timber, laminated veneer lumber (LVL), plywood, particleboard, fibreboard, thermowood. Sports structures such as multi-sport wooden halls are a particularly suitable application for wide-span glulam roofs. This is supported by the light weight of the material, combined with the ability to furnish long lengths and large cross-sections. Wooden halls are often lighter and more competitive than comparable constructions with alternative building materials. Combination of high quality wood, covered with membranes system offers great value, high durability and comfort.

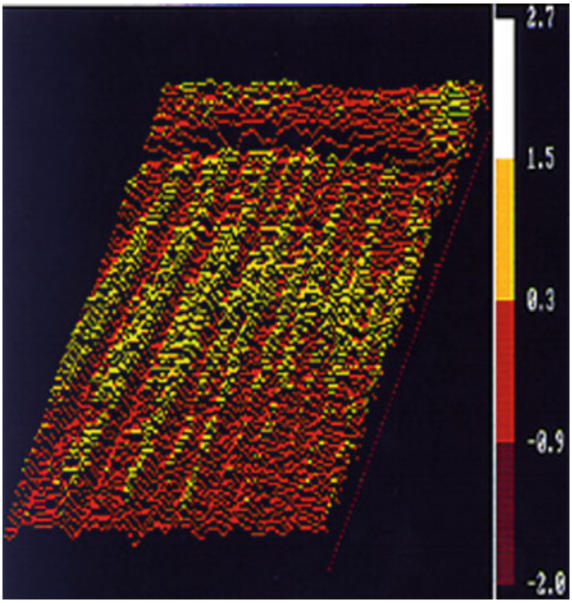


Fig. 8.11 Heat rise after skid resistance testing on a synthetic playing surface (temperature changes are given in degrees Celsius)

Wood is a natural product of biological origin [21, 22]. 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 fibres. Checks, shake and splits all constitute separations of wood fibres. 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. 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 is used to hold together two or more pieces of wood or wood based products. It is generally very difficult to quantitatively evaluate damage in these cases.

When a wood or a structural wood product is loaded, it deforms as a whole in spite of its heterogeneous characteristics and its localised defects. Stress concentrations occur and result in localised forces that are sufficient to promote plasticity. At the macroscopic level, breakdown is accompanied by both loss in stiffness and accumulation of irrecoverable deformation. At the structural level, breakdown appears as micro cracking and possibly slippage at component interfaces. Damage and failure may thus be viewed as a micro structural process through the activation and growth of one pre-existing 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 localisation 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 micro structure.

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

Infrared thermographic scanning of pine wood specimens

Pine wood is an orthotropic material; that is, it has unique and independent mechanical properties in the directions of the three mutually perpendicular axes: the longitudinal axis **L** parallel to the fibre (vertical grain), the radial axis **R** normal to the growth rings and perpendicular to the grain in the radial direction, and the tangential axis **T** perpendicular to the grain but tangent to the growth rings [23].

Three series of monotonic unconfined compression tests have been conducted on square specimens of pine wood, prepared along its three anisotropy directions. The wood specimens were especially designed with enlarged ends to prevent from sliding, bending or premature buckling, caused by heterogeneity, bad alignment of compression loading, or others significant end effects. Infrared thermography readily depicts intrinsic dissipation localisation announcing quite different mechanisms of damage preceding wood failure, according to the three directions of wood anisotropy (Fig. 8.12). The longitudinal L-specimen fails by local crushing of the fibres at ends leading subsequently to a vertical splitting (Fig. 8.13a). In the R-specimen, crushing of the hollow wood fibres in the spring or early wood regions of some growth rings can often be seen (Fig. 8.13b). The T-specimen fails in an unsymmetrical mode because of the finite growth ring diameter (Fig. 8.13c).

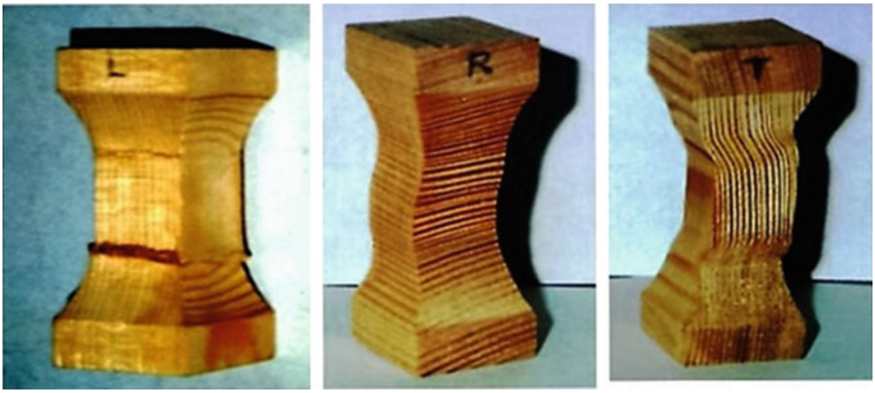


Fig. 8.12 Failure modes according to the anisotropy directions (longitudinal L, radial R and transverse T)

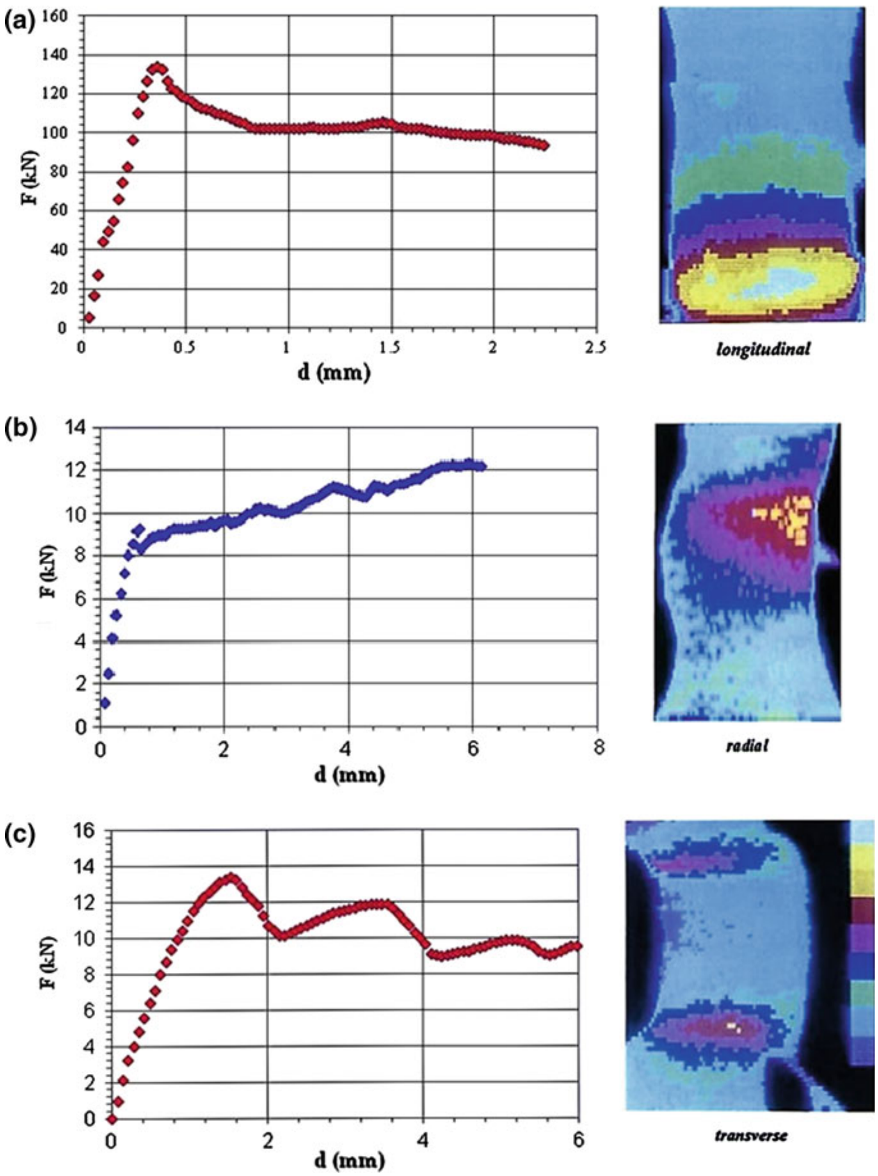


Fig. 8.13 **a** Mechanical behaviour of a clear L-specimen parallel to the grain. **b** Mechanical behaviour of a clear R-specimen perpendicular to the growth rings. **c** Mechanical behaviour of a clear T-specimen perpendicular to the grain and tangent to the growth rings

Infrared thermographic scanning of metal-plate-connected wood-splice joints

One prime advantage of wood as a structural material is the ease with which wood structural parts can be joined together with a variety of fastenings: nails, spikes, screws, volts, lag screw, drift pins, staples, and metal connectors of various types.

Metal-plate-connected wood trusses are widely used in residential construction 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. Current design procedures [24] are based upon simplified assumptions of connection behaviour 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 behaviour of metal plate connections would be beneficial for upgrading design procedures [25].

As infrared thermographic scanning offers new information on metal plate connection behaviour, refinement of design procedures can be made as needed and new, more effective, and specialised truss-plate configurations can be contemplated. Although the actual configuration of metal connector plates varies widely among manufacturers, the plates generally consist of galvanised sheet steel of 14–20 gage with teeth of 1/4–3/4 in. (6.4–19.0 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, semirigid 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 (Fig. 8.14) or shear (Fig. 8.15), and compression buckling of the plate in gaps between wood members.

With growing concerns over climate change and the pressure to reduce the carbon footprint of the built environment, building designers are increasingly being called upon to balance functionality and cost objectives with reduced environmental impact. Wood has many attributes that make it obvious choice in green building, in particular it has come from a sustainably managed resource. It grows naturally, using energy from the sun, and is the only major building material that is renewable, re-usable and sustainable. When considered over its life cycle, wood outperforms both steel and concrete in terms of embodied energy, air and water pollution, and others environmental impacts. It contributes to a building's energy efficiency and indoor air quality, and has an important role to play in the fight against climate change. The emergence of mass timber products such cross laminated timber (CLT) is allowing designers to create a broader range of low-impact sports and leisures structures.

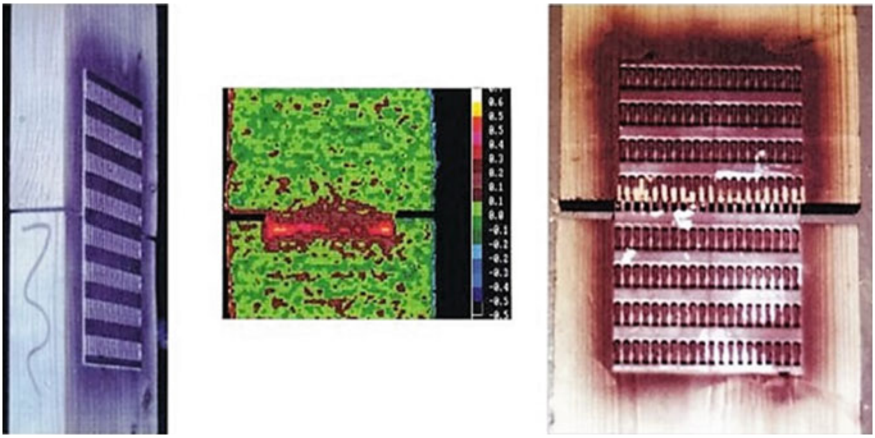
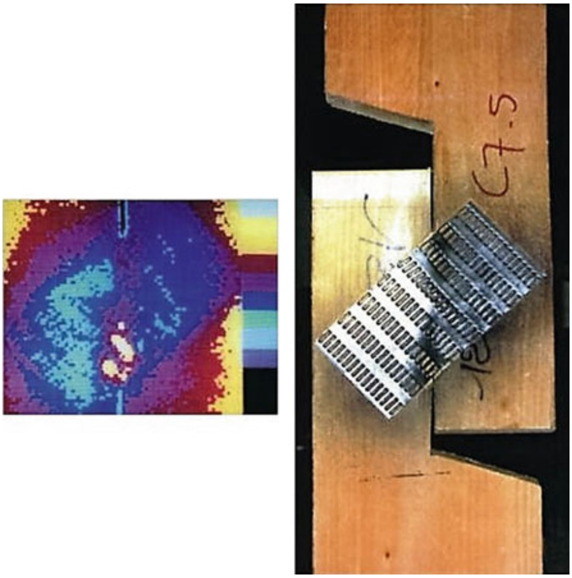


Fig. 8.14 Infrared scanning of splice joint under tension loadings (temperature changes are given in degrees Celsius)

Fig. 8.15 Infrared scanning of splice joint under shear loadings (temperature changes are given in 0.2 °C for each colour)



8.4 Conclusions

This chapter has shown that:

(a) The infrared thermography technique offers a versatile temperature tool that adapt to the most demanding needs for smart race car teams.
(b) It could be used to control the quality of clay tennis court after wetting.

(c) The thermoelastic behaviour of material optimises the design of sport prototype and

(d) The dissipativity of engineering materials or structures of sport equipment under solicitations is a highly sensitive and accurate predictor of health impacts and damage of construction materials involved in green building of leisure and sports facilities.

Thanks to the thermomechanical coupling, infrared thermography provides a non-destructive, non-contact and real-time test to observe the various phenomena generating temperature changes and the physical process of degradation based on the occurrence of its intrinsic dissipation. It thus readily provides a measure of the material damage and allows definition of a limit of acceptable damage and fatigue limit under load beyond which the material is susceptible to failure. It should be pointed out that the inelastic strain due to compressive loading provides information only on the current geometry while the internal state variables provide information on the internal state and on the micro-structural defects.

The method allows not only qualitative studies such as finding flaws, defects or weakness zones, but also quantitative analysis of the effects of flaws and defects on strength and durability of structural components. Several published results demonstrate the versatility of infrared thermography technique in various domains of application, provided that the physical phenomena are correctly interpreted in a consistent theoretical framework.

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 accurately. Subsequently it may suggest multiaxial design criteria, highly relevant for full scale testing on sport equipment.

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