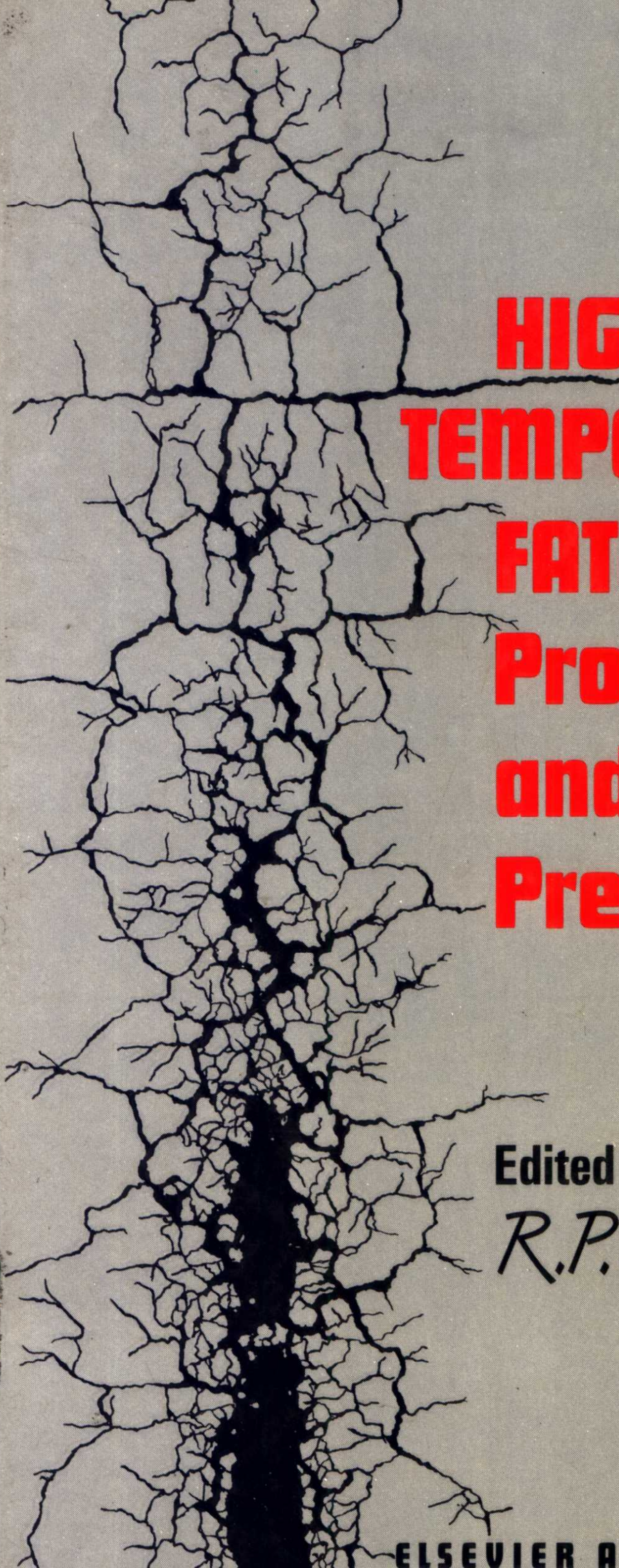

HIGH TEMPERATURE FATIGUE: Properties and Prediction

Edited by

R.P. Skelton

ELSEVIER APPLIED SCIENCE

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Preface

About 35 years ago, thermal fatigue was identified as an important phenomenon which limited the lifetime of high temperature plant. In the intervening years many investigations have been carried out, primarily to give guidance on likely endurance (especially in the presence of time-dependent deformation) but latterly, with the introduction of sophisticated testing machines, to provide knowledge of the underlying mechanisms of failure.

A previous edited book (*Fatigue at High Temperature*, Elsevier Applied Science Publishers, 1983) summarised the state-of-the-art of high temperature fatigue testing and examined the factors influencing life, such as stress state, environment and microstructural effects. It also considered, in some detail, cyclic crack growth as a more rigorous approach to life limitation.

The aim of the present volume (which in style and format follows exactly the same lines as its predecessor) is once again to pursue the desire to translate detailed laboratory knowledge into engineering design and assessment. There is, for example, a need to consider the limitations of the laboratory specimen and its relationship with engineering features. Many design procedures still rely on a simple endurance approach based on failure of a smooth specimen, and this is taken to indicate crack initiation in the component. In this volume, therefore, crack propagation is covered only incidentally, emphasis being placed instead on basic cyclic stress–strain properties, non-isothermal behaviour, metallography, failure criteria and the need for agreed testing procedures.

As was the case for the previous volume, I have approached authors who are known to each other, and who were appraised of the individual contributions. My only intervention as editor has been to supply cross references in order to forge the separate chapters into a unit whole. However, when all the contributions had been received, I realised that a rounding-off chapter (7) was required. This I attempted myself; it contains a minimum number of references, and it is hoped that it will perhaps be useful in setting the scene for those relatively new to the subject of high temperature fatigue.

The plan of the book is as follows. The introductory chapter arose almost by accident, when the author was surprised to learn that the earliest reference to non-linear deformation behaviour was in a paper dated 1729 (and written in Latin!). A separate interest in the background to constant strain testing and, indeed, the history of mechanical testing in general led to several lines of enquiry and, ultimately, to Chapter 1. The next chapter, in a more orthodox vein, looks in some detail at a topic which, in papers on high strain fatigue, has always seemed to take second place to the endurance results, namely, cyclic stress–strain behaviour. This information is of course vital to the stress analyst who has to process it before arriving at an appropriate strain range on the endurance curves. Another question often asked is: how far do isothermal laboratory tests reflect the situation in service where temperatures vary throughout the cycle? It is hoped that Chapter 3 provides at least some of the answers.

From the microstructural point of view it is known that high temperature fatigue wrings many changes in the substructure. These are summarised in Chapter 4, and the author states the role metallography has to play in the overall strategy of lifetime assessment. In Chapter 5 the background to high temperature design codes is discussed and a possible way forward suggested which takes the metallurgy of failure mechanisms into account. Finally, in Chapter 6 we see that having come of age, high temperature high strain fatigue may be required to obey certain standards in order to achieve full respectability.

As was the case in the earlier volume, the materials dealt with are, of necessity, those of interest to the power generating industry, that is, the low-alloy ferritic and austenitic steels. The higher-alloyed ferritic (9Cr–12Cr) steels are currently under active consideration although, at the time of writing, relatively little fatigue data exist. However, superalloys are treated to some extent, and Chapter 4 includes a section on Ti and Al alloys of interest to the aircraft/automotive industries respectively.

It will become clear that the cyclic stress–strain relation (expressed, for example, as the Ramberg–Osgood law) permeates much of the book. Indeed, it is one medium through which engineers, metallurgists, experimentalists and materials scientists usefully communicate: so that as well as providing the final endurance data upon which lifetime assessment of components is based, the experimentalist can, if so desired, become involved along the way, for example in finite element or other simplified analyses.

The editor bears responsibility for the overall choice of topics. Inevitably, many of the contributions were solicited from colleagues within his own industry, and so in fields where there is continued healthy debate, the views expressed are personal and not necessarily those of the CEGB. I would like to thank my fellow authors for their ready acceptance to write a chapter, despite other commitments. Once again, regarding my own work, I wish to thank the CEGB for providing typing and drawing facilities. It is finally hoped that the combined information in this and the earlier volume will be helpful to the engineering and metallurgical fraternity who are responsible for designing and assessing the lifetimes of structures operating at high temperature.

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1

Historical Introduction: Stresses, Strains and Material Behaviour

R. P. SKELTON

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SUMMARY

'For from all tempers he could service draw
The worth of each, with its alloy, he knew;
And, as the confident of nature, saw
How she complections did divide and brew.'

JOHN DRYDEN (1631–1700)

In this short introduction it is shown how adequate prediction of material properties could not be made until accurate methods were available for measuring displacements, and hence strains, on suitable specimens. Over the years, laboratory testpiece sizes have shrunk dramatically, because the sensitivity of measuring techniques has increased many fold. This fact, combined with modern knowledge of microstructural events, should lead to an improvement in our ability to predict materials behaviour and hence the lifetime of components in service.

1.1. BACKGROUND

1.1.1. Specimens

The present-day high strain fatigue test in direct stressing at elevated temperature is descended from a long line of experiments in mechanical testing. This goes back a hundred years or so in terms of high temperature [1], but in terms of uniaxiality began with the tensile tests on iron wires conducted by Leonardo da Vinci (1452–1519) [2]. The first known fatigue test (on mining chain) was actually conducted in 1829 [3] and, in briefly tracing the development of the sophisticated strain-controlled experiment of today, it is of course necessary to realise, first, that not all fatigue tests have been conducted on simple specimens and, secondly, that deformation modes are not necessarily uniaxial. Indeed, the theory of elasticity has its origins in the study of a bending beam and the correct placing of the neutral axis [2], and both the bending and torsion modes were able to give measurable deflections long before accurate means were available to record the corresponding parameters in direct loading.

In the following discussions it will be helpful to have the definitions below.

(i) A *specimen test* employs a piece of the material in question whose gauge length and uniform cross section (usually circular) are specified. It is assumed, not always correctly, that mechanical properties are uniform over the gauge. On this definition of a specimen, anisotropic welds and heat-affected zones, for example, or (pedantically) any testpiece containing a crack are excluded; so too are testpieces where extensometry cannot be mounted directly on the gauge. However, the gauge length may be allowed to reduce to zero, as is the case with an hourglass specimen.

(ii) Any test assembly not conforming to the above is thus a *structure* which can be of varying complexity. A *features test* may highlight the crack initiation properties of a weld or stress concentrator in a simple geometry (see Chapter 7). A fatigue test may be conducted on a *subassembly* or indeed even the whole *component*. It will be seen later that specimen and component testing are not alternatives but are complementary in any analysis of failure.

1.1.2. Disciplines

In the history of technology, there are many accounts of the design and construction of bridges, machinery and so forth, but relatively few on the strength of their materials of construction and the method of testing [2, 4–6]. The ultimate aim in traditional engineering design is one of 'optimisation in loads for use of least material' and the achievement of that aim over the years has involved the combined contributions of empirical testing, elasticity, plasticity and time-dependent deformation theories, and the efforts of metallurgists in identifying the elements responsible for producing strong alloys. Further, once the structure has been designed, the 'engineer' (who will be identified later) is faced with the task of predicting how long it will last, especially in high temperature environments. In examining the background of the modern fatigue test this short review will keep in mind:

(i) The concept of small specimen testing.
(ii) The development of simple stress–strain laws for predicting strength and fracture properties.
(iii) The observation of time-dependent mechanical deformation and its use in predicting future behaviour.

The engineering stress analyst and the materials scientist are both concerned with mechanical properties, principally materials behaviour under external stress. The former deals directly with external properties while his colleague attempts to explain observed behaviour in terms of internal microstructural effects. With regard to *internal stresses*, a stress analyst would have to deal, for example, with long-range residual stresses arising from welding or thermal transients, whereas a materials scientist calculates (say) forces between dislocations or back-stresses generated during creep. One of the main tasks of materials studies for high temperature applications is to derive relations estimating the failure time of the material, and hence of the component, which are of practical use and which are based securely on the microstructural behaviour of the alloy concerned. 'Materials Science' is officially about 50 years old and, as McLean has pointed out [7], has had a fairly rapid development largely because the scientific laws on which it is founded were readily available from other disciplines.

Despite these considerations, there have been isolated investigations in the past [2] which strangely anticipate this new Science. Thus, between 1720 and 1722, we find Réamur conducting tests on wires to check their heat treatment and also measuring hardness by indentation. In a paper of 1784, Coulomb showed that heat treatment (annealing) affected the limit of elasticity but did not alter the basic elastic properties of metals. Small deflections were supposed not to disturb the molecular arrangement, but beyond the elastic limit permanent sliding occurred as the material hardened, causing an increase in the 'cohesive forces'. During torsional oscillations, more damping occurred with the onset of plasticity. Young in 1807 had given an explanation of ductility, brittleness and toughness in terms of 'cohesive powers' and had provided an estimate of the molecular size as $\sim 2{\cdot}5 \times 10^{-10}$ in (10^{-9} mm) [2]. Much earlier, Hooke had made a no less remarkable speculation [8]: 'the particles therefore that compose all bodies... owe the greatest part of their sensible or potential extension to a vibrative motion'. He proposed a basic frequency of one million pulses per second which decreased in extension and increased during compression.

1.2. MECHANICAL BEHAVIOUR AND THE STRESS–STRAIN LAWS

Early tests on the strength of materials were concerned solely with establishing the load to cause failure of a given specimen or structure, and observing the point at which fracture took place. No means were available for measuring the displacements which occurred and, excepting experiments on wires, compression and bending tests on fairly rigid solids preceded those in tension because of difficulties arising with gripping. The numerical law of elasticity for a slender wire was published by Hooke in 1678 [8], but it was not until the nineteenth century that stress–strain laws were established which included a contribution from plasticity. These have been reviewed by Osgood [9].

1.2.1. Ultimate Tensile Strength

It should be noted that early investigators did not possess the concept of stress as force divided by an area, and so the breaking loads observed were specific to the testpiece under examination. Further, the quality of material could confuse the results in unexpected ways: da Vinci's experiments showed that, for the same load, longer wires broke but shorter wires of the same cross section did not. Nowadays we would argue [10] that the longer wire had a greater probability of containing defects, and it is remarkable that specimen-to-specimen scatter must have been apparent to da Vinci, who urged that the test should be repeated several times to check the results [2]. Galileo (1564–1642) gave some indication of the ultimate strength of copper [2] and realised that the strength of a column was proportional to its cross-sectional area and not to its length.

Mersenne (1588–1648) performed experiments on vibrating wires of musical instruments to determine the effect of tension and other parameters upon pitch [11], but he was also interested in their breaking point [12]. This is an early example of a specimen and component test actually coinciding. Mariotte (1620–1684) was able to state that fracture occurs at a certain limit of elongation [2]. His dumb-bell-shaped tensile specimens (of wood) are a clear precursor of the modern short test specimen. Much later, Vicat in 1834 reported [13] the fracture behaviour of iron wires used in the cable of suspension bridges. The diameter was unspecified but the testpiece, although not machined, must clearly be regarded as a *specimen test*.

1.2.2. Elastic Laws

The justly celebrated law of Robert Hooke (1635–1702) that '... the Rule or Law of Nature in every springing body is, that the force of power thereof to restore itself to its natural position is always proportionate to the distance or space it is removed therefrom...' [8] was a landmark in the difficult birth of elasticity which has been admirably traced elsewhere [2, 6, 7]. Hooke realised that the material was internally stretched in due proportion down to a fine scale, but his law could equally well apply to a structure. Not until 1807 did Thomas Young conceive that the ratio of stress (σ) to strain (ε) (as we now know them) characterised a material property as measured in a specimen. Young arrived at this result [14] by

TABLE 1
SIGNIFICANT EVENTS IN ELASTICITY STUDIES

Investigator	*Date(s)*	*Comments*
da Vinci	1452–1519	Columns: strength varies directly as some ratio of cross section
Galileo	1564–1642	Strength $\propto$ cross-sectional area
Mariotte	1620–1684	Elongation $\propto$ force
Hooke	1678	'Ut tensio, sic vis'
Jacob Bernoulli	1654–1705	Curvature of elastic beam at a point $\propto$ bending moment there
Euler	1707–1783	Introduced an 'elastic constant' in bending beam theory
Coulomb	1773	Concept of shear stress
Young	1807	Modulus—a material property
Cauchy	1822	Concept of stress and strain at a point
Navier	1826	Modern definition of E
Poisson	1830	Poisson's ratio

considering the original height of a steel column that would halve its length under its own weight (1500 miles!). The practical definition of Young's modulus E was provided in 1826 by Navier [2]:

$$E = \sigma/\varepsilon \tag{1}$$

Table 1 lists in chronological order the concepts ultimately responsible for eqn (1). Poisson's ratio was not discovered until some years later. Young was uncertain about lateral dimensional changes and it is doubtful whether they could have been detected at that time.

1.2.3. Elastic–Plastic Laws

1.2.3.1. Measurements in Tension

Hooke was concerned with the nature of the elastic restoring force [8], and he did not record evidence of permanent set although the sensitivity of his tests on 40 ft (12·2 m) wires would have been adequate. The first indication that tension might be proportional to the load raised to some power was that of Bulfinger in 1729 [15] who considered the equilibrium of the tension fibres in a bent beam. A similar non-uniform relation was also derived by Riccati in 1731 [16]. This author also refers to some earlier experiments of s'Gravesande (1688–1742) [17], in which the original specimen length was not restored after the application of large loads (elasticity having been 'given up').

In a paper otherwise concerned with the correct placing of the neutral axis in a beam, Hodgkinson in 1822 [18] subjected a 7 ft (2·13 m) iron wire weighing 2 dwts. 17 grs. (5·12 g) to ever-increasing loads and noted a permanent set of 0·03 in (0·76 mm). His tabulated results are shown in Fig. 1 in terms of strain. Taking the density of wrought iron as $7{\cdot}7 \times 10^3\ \mathrm{kg\ m^{-3}}$, the cross-sectional area of the wire is calculated to be $0{\cdot}31\ \mathrm{mm}^2$ and so, assuming elastic unloading, eqn (1) predicts a value $E = 1{\cdot}66 \times 10^5$ MPa from this early data of Hodgkinson.

In 1827 Lagerhjelm stated [4] that if C be the extension of a bar at the elastic limit and Δ the extension when it breaks, then the product $C\sqrt{\Delta}$ is a constant and, further, that permanent set produces an increase in volume. A similar deformation law was produced several years later by Gerstner [2, 4], who also reported strain hardening, deduced from experiments in loading and unloading. Some of these early relations are of questionable validity but they do indicate that attempts were being made to measure deviations from Hooke's law.

Stress–strain formulae for elastic–plastic deformation derived since 1830 have been surveyed by Osgood [9], who included his own relation:

$$\varepsilon_t = \frac{\sigma}{E} + \left(\frac{\sigma}{A}\right)^{1/\beta} \tag{2}$$

where ε_t is total strain, σ is the stress, and A and β are constants. It is one of the few expressions which recognises that elastic deformation continues to act beyond yield, a point appreciated by Young [14]. In eqn (2) a plot of

$$\log\left(\varepsilon_t - \frac{\sigma}{E}\right)$$

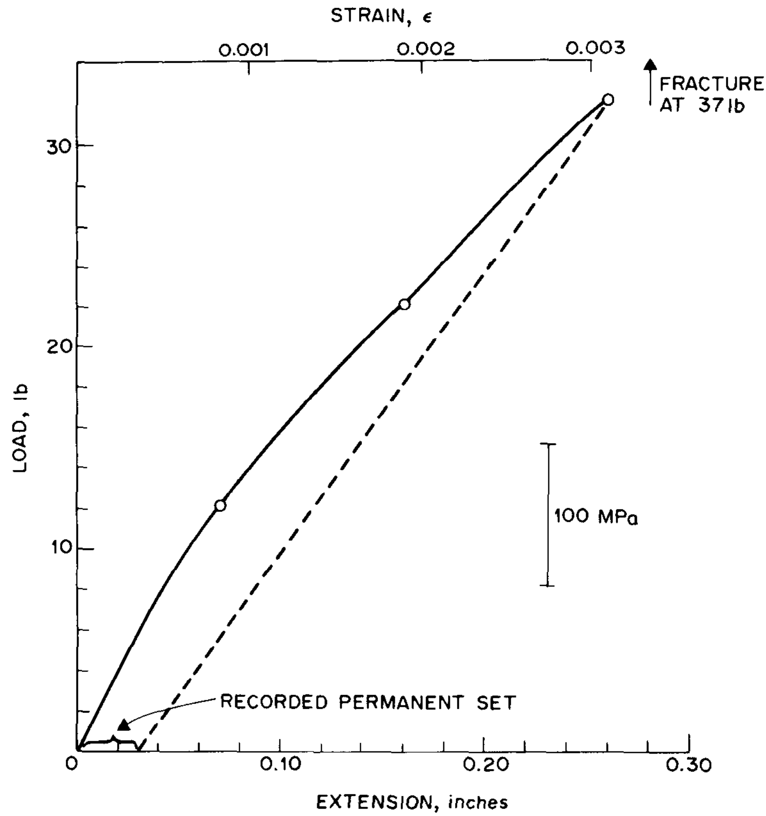

FIG. 1. Hodgkinson [18] gave sufficient information for a calculation of Young's modulus, a parameter not in use at the time.

i.e. the plastic strain, against log σ gives a straight-line fit for most metals and alloys. This formula is examined extensively for fatigue deformation in Chapter 2.

By the end of the first quarter of the nineteenth century, investigators were also aware that the elastic modulus appeared to be relatively insensitive to alloying, heat treatment and plastic deformation.

1.2.3.2. Measurements in Compression

Early theories of strength supposed that solids were incompressible. In any case, given the likelihood of buckling, it is improbable that uniaxial

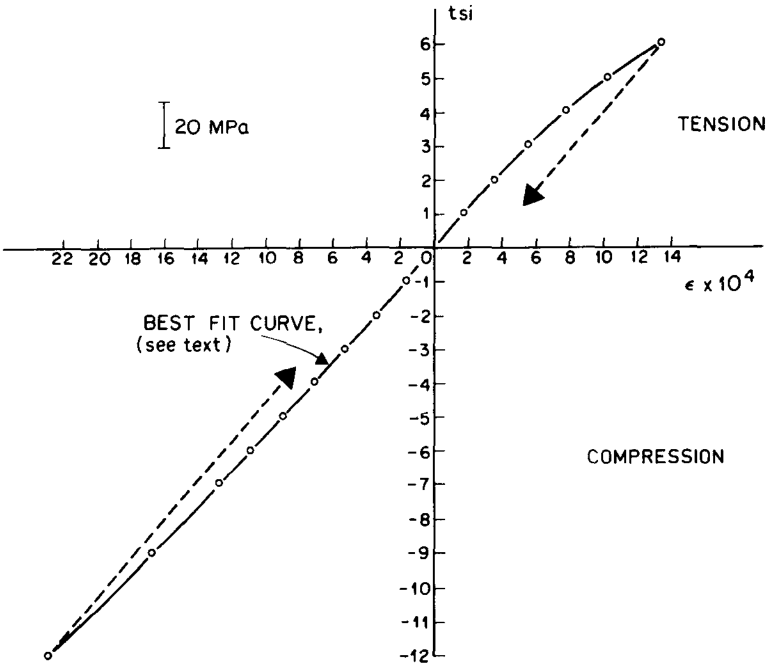

FIG. 2. Only by testing very long bars could Hodgkinson obtain measurable strains in compression.

specimens could have been made long enough for realistic measurements to have been taken. In considering bending, Parent (1666–1716) supposed that elastic properties in tension differed from their counterparts in compression. It was again left to Hodgkinson in about 1840 to determine a stress–strain curve for 10 ft (3 m) long bars of cast iron [19]. His results, quoted by Unwin [5, 20] are plotted in Fig. 2 together with the relation deduced by Hodgkinson:

for tension: $\sigma = 6220\varepsilon - 1\,298\,000\varepsilon^2$
for compression: $\sigma = 5773\varepsilon - 233\,500\varepsilon^2$

where σ is expressed in tons/sq. in.

If desired, Fig. 2 may be regarded as a forerunner of a single-cycle hysteresis loop: gauge lengths in the meantime have tended to become somewhat shorter!

1.3. EXPERIMENT AND DESIGN

Some of the investigations listed in Table 1, for example, were undertaken as a scientific study of the properties of solids. A history of the testing of the materials of construction would no doubt begin with the work of Musschenbroek (1692–1761), who invented a tensile lever machine for deforming small samples [2]. By this time (~1729) the idea that the properties of a small specimen could reflect those of larger structures seems to have been firmly implanted, despite the unavailability of the stress concept. Apparently Buffon, who tested iron bars and was a contemporary of Musschenbroek, felt that small specimens (of wood) were unrepresentative and preferred to test beams up to 28 ft (8·5 m) long [2].

With the invention of the screw cutting lathe in 1797 leading to ease of specimen manufacture and better surface finish, the way was clear for more accurate experimentation and reproducibility of results. Once the difference between elastic limit and ultimate tensile strength was appreciated, a more rational approach to design could then be made, as Navier was urging in 1826 [2]. The traditional method of avoiding failure in service was to multiply known breaking loads (latterly stresses) in laboratory tests by a factor of safety. Starting with a factor of one tenth in 'prehistory' [7] the joint requirements of avoiding cumbersome appearances and of using materials more economically reduced this to one half of the elastic limit (Poncelet), and then to one third of the UTS (Telford) [2]. Where dynamic action was involved, the breaking weight was to be divided by 'six times the live load added to three times the dead load' [5]. In 1858 the Board of Trade actually adopted an absolute value of 5 tons in^{-2} (77 MPa) for wrought iron structures. Some of these factors are very conservative.

Because of such uncertainties, large-scale static and dynamic tests of model parts of structures were undertaken to aid design, principally in the field of railway engineering [21]. The notion of exactly simulating service loads on structures (or even specimens) of course has persisted to this day under the term 'spectrum loading'.

None of these measures employed strain as a design criterion. The accurate measurement of strain on more reasonably sized specimens has occurred fairly late in materials testing. By 1860, for example, Kirkaldy was only able to state that total elongation in typical tensile tests was uniform in the plastic region (that is, until necking occurred) but the measuring technique was too insensitive for a determination of modulus. However, the passage of some 20 years saw the invention of the mirror extensometer by