1 Natural extremes

1.1 Akrology

1.1.1 Extremes

The dynamic processes operating around us are often treated as transients that are not important when compared with the fixed states they precede. However, an ever-increasing knowledge base has illuminated this view of the operating physics and confirmed that extreme regimes can be accessed for engineering materials and structures. Matter is ever-changing, its form developing in a series of nested processes which complete on the timescales on which mechanisms operate; processes that occur on ever smaller timescales as length scales decrease. This book is concerned with the response that occurs when loads exceed the elastic limit. This affects behaviour in the regime beyond yield which encompasses a range of amplitudes and responses. However, it concerns condensed materials and loading, eventually taking them to a state where they bond in a different manner such that strength is not defined; this limit represents the highest amplitude of loading considered here. Nonetheless the driving forces are vast and awe-inspiring, while the different rates of change observed in operating processes are on scales that span many orders of magnitude. The following pages will highlight prime examples from the physical world and then provide a set of tools that classify mechanisms in order to analyse significant effects of these processes on the materials involved. The wide range of observations and applications create simple but powerful principles that are outlined in what follows.

Materials are central to the technologies required for future needs. Such platforms will place increasing demands on component performance in a range of extremes: stress, strain, temperature, pressure, chemical reactivity, photon or radiation flux, and electric or magnetic fields. For example, future vehicles will demand lighter-weight parts with increased strength and damage tolerance and next-generation fission reactors will require materials capable of withstanding higher temperatures and radiation fluxes. To counter security threats, defence agencies must protect their populations against terrorist attack and design critical facilities and buildings against atmospheric extremes. Finally, exploitation of new deep sea or space environments requires technologies capable of withstanding the range of operational conditions found in these hostile locations. The range of conditions under this umbrella spans high-energy fluxes, severe states and intense electromagnetic loading, but in what follows thermomechanical extremes on condensed matter will be considered. To advance in all of these areas requires a greater understanding of new behaviours and an ability to model the controlling mechanisms.

There is benefit in investing significant effort to map out these nested chronologies, as advances in understanding of materials and processes reveal that dangers and rewards come from embracing new modes of thinking. A key requirement is to consider timescales and length scales that operate outside the regimes in which intuition can operate; regimes in which glass stops an incoming projectile when a metal plate will not, even though the former exists as a pile of dust after the event whilst the latter retains much of its original form. It is the aim of this book to present a simple guide to key methodologies used to define incoming impulses and to track the material response to the extreme loading transmitted. The intention is to build an understanding that may be applied to new, more extreme regimes of loading and response based upon experience gained in the ambient environment.

1.1.2 Extreme material physics

The condensed phase (for most materials) defines a pressure and temperature range of interest which may be approximately fixed at less than 1 TPa and less than 10 000 K respectively. Pressure has one of the largest ranges of all physical parameters in the universe (pressure in a neutron star is *c*. 10^{33} Pa), so that most of the materials in the universe exist under conditions that are very different from the ambient state on the surface of the Earth. Compression induces changes in bonding properties at the atomic scale, synthesising new compounds and causing otherwise inert atoms or molecules to combine. Integrated thermal and mechanical loading creates new structures within matter. These compressions (reducing interatomic spacings by up to a factor of two and increasing densities by over an order of magnitude) result in changes in the electronic structure that begin to shift notions of chemical interaction and atomic bonding. For example, electrons surrounding nuclei or ions become delocalised, changing insulators into metals, and eventually adopting new, correlated electronic states. Instantaneous application of an impulse provides a pump to drive the deformation of materials, and varying its amplitude and duration allows a window into the operative mechanisms that lead to plasticity and damage evolution within them. Under dynamic loading these extreme conditions may be exploited to explore the balance between mechanical ($P\Delta V$) and thermal ($T\Delta S$) energies by examining how this dichotomy governs physical and chemical phenomena in the condensed state. Additionally, shortened loading periods provide a filter to select governing mechanisms according to operating kinetics. The system may then attain a final metastable state that lies beyond equilibrium thermodynamic constraints.

If the fundamental mechanisms can be understood, exciting opportunities to use such extreme thermomechanical conditions to design and manufacture new classes of materials will open up. Such advances may allow limits such as the theoretical strength (the stress needed to shear atomic planes of an ideal crystal across one another) to be attained. In this manner materials may be designed for application and clearly the key property of interest is the strength of a material statically and during flow. Empirical discovery techniques can achieve incremental advances. Steel-making, for example, dates back over 30 centuries, but the strengths of most present-day commercial alloys are less than a factor of two higher than the steel used in swords during the medieval era. The strengths of commercially available steels are of the order of 1 to 5% of the ideal strength limit and this is typical for currently available bulk materials. This is principally linked to the misconception that the properties of materials can be derived on the basis of atomic structure alone, whilst in reality most engineering properties are dominated by defects within the microstructure. Thus a shift in perception and boundary conditions is necessary to bridge the gap between materials today and the theoretically achievable and this requires critical questions to be answered. What are the most important length scales and defect distributions that control deformation and fracture? What are the ultimate strength and temperature performance limits for structural materials and what is their development after yield? Finally, can dynamic processes be harnessed to capture and maintain theoretical limits for some operating period if not permanently?

Materials found across natural environments experience mechanical extremes of pressure, temperature and strain rate or survive electromagnetic loads of great violence. Reaching an understanding of such states and the response of materials subject to them is key in fully describing operating deformation mechanisms. With the knowledge gained it would be possible to contemplate designing not only structures to operate within such environments, but also to adopt strategies to engineer materials with optimised properties to survive there, should physically based models become available. These extreme material states may exist in nature in inaccessible repositories such as at high temperature and pressure at the centre of planets. Alternatively, they may represent the results of one of the two principal dynamic inputs that may reach these states in short times. These two driving stimuli come from forces generated during explosion or impact, and whilst both of these may occur as a result of some natural process, they may also be harnessed to engineer particular effects such as welding or cutting in a controlled manner.

The mechanical response of objects under load is taught to scientists from an early age through Newton's laws. These, in their simplest form, treat a body as a finite mass concentrated at the object's centre and, with the application of conservation of mass, momentum and energy, Newtonian mechanics describes the macroscopic world. A simple illustration of the utility of this treatment is that of the impact of spheres in the once-popular executive toy, the Newton's cradle. Here, equal masses, suspended from a common stationary framework, are allowed to sequentially impact one upon the other (Figure 1.1). When the first impacts a second, momentum is transferred to it and, if it is free, it may travel onward at the same velocity as the impactor. If there are several balls of equal mass, then the force is transferred through the stack to accelerate the last in the sequence to a velocity consistent with its need to match the same momentum to the first. This is a simple and effective illustration of the common experience of impacting bodies, understood using the assumption that the mass acts from a point at the centre of the body.

To move out of the time and length scales that human perception can respond to, requires description of the processes by which momentum is imparted from one sphere to the next. The deceleration of one ball on a face of a central sphere must transmit out a wave front. The contact point is decelerated whilst the first planes of atoms in the

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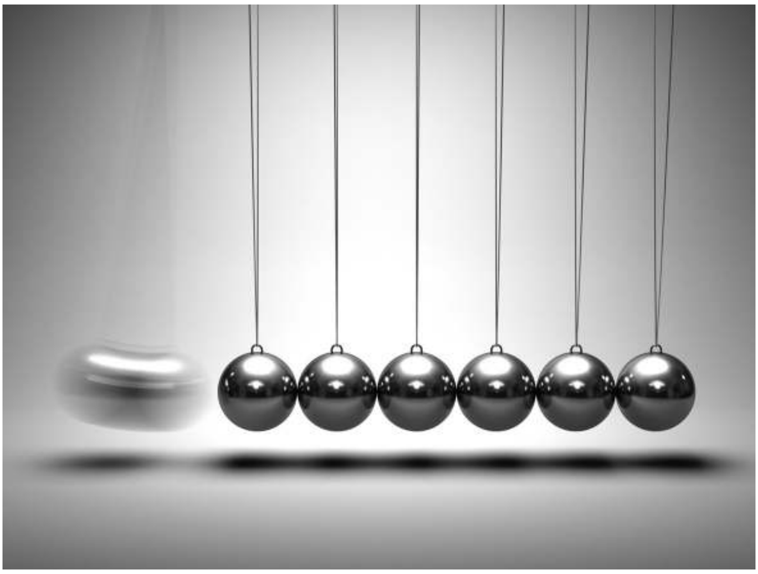

Figure 1.1 Newton's cradle illustrates the effects of waves propagating in a system where all the collisions are elastic. Higher stress impacts can deform materials and produce counter-intuitive physics at the shock front. Source: image copyright shutterstock.com/FreshPaint.

target start to accelerate. Since the two are touching they must travel at the same speed and a wave front travels forward into the target and back into the projectile, accelerating the one and decelerating the other. When the returning wave reflects at the free rear surface it releases stresses in the impactor to zero and accelerates the material ahead of the returning front to the initial impact speed whilst stopping the material behind. Momentum is conserved and Newton mechanics correctly describes the response: forces may act from the centre of mass of the moving objects in the time frame of the office in which the toy sits.

This process has a short high-pressure (or more correctly, high-stress) phase, and after some time, equilibration (a key concept of this book) has occurred; this governs the processes of inelastic flow and chemical reaction described in what follows. The impact state exists until the stress has been relieved within the spheres and the appropriate masses accelerated to their steady speed. In the case of elastic waves the approximate time to reach equilibration, t_{equil}, is given by

$$t_{\mathrm{equil}} = \frac{2d}{c_{\mathrm{L}}}, \tag{1.1}$$

where d is the diameter of the sphere and c_{L} is the wave speed in the metal. Whether the mass is in equilibrium or not depends upon the moment at which an observer chooses to sample the state of the system. If the waves have not released the stresses the state is still equilibrating; if they have, it is in equilibrium and Newtonian mechanics applies. Rheology defines a dimensionless parameter, the Deborah number, to represent the state of fluidity of a material and this is used in glaciology to describe how morphology develops over time – 'the mountains flow before the lord' as the prophet Deborah foretold in the Old Testament (Judges 5:5). Whereas the Deborah number is qualitative, another criterion is defined here to include the impulse properties and kinetics of the operating equilibration or localisation mechanisms. In this picture, all processes are regarded as dynamic and, moving into Norse mythology, the Freya number, F, is defined to reflect dynamic transformation and liberation of energy within materials under load since 'it is Freya who makes fire with steel and flintstone' (Schön, 2004).

The Freya number determines the totality of the deformation mechanism and flags the achievement of a stress-equilibrated state. It is defined to represent the extent to which a mechanism is driven to completion by a stress or temperature excursion during the time for which the impulse is active in the following manner:

$$F = \frac{t_{\text{relax}}}{t_{\text{obsvn}}}, \tag{1.2}$$

where t_{relax} refers to the characteristic relaxation time for the step in the rate-limiting process and t_{obsvn} is the length of the observation period on the system. If there is time for compression and release to decelerate the incident sphere and accelerate the impacted one, then stress equilibration has occurred. If this is the case F will be small and the state will be defined. Conversely, if one observes whilst the waves are travelling then F will be large and the state observed will be transient and contain some material in the initial state of the material at the start of the process. Thus F is a means to define thresholds for the equilibration of states in dynamic processes and will be used through the book to define the observed response. From the office frame the stress-state equilibration within the impacting sphere takes a few microseconds whilst the seated executive has seconds to observe the impact. In this case F is very small so that the details of the process can be neglected in describing the cradle. If the same sphere were fired at a police officer in a protective vest the failure time of the ceramic insert would be of the same order as the slowing of the bullet on impact – in this case F must be greater than 1 if the officer is to survive.

Of course the impulses considered in Newton's cradle only induce elastic responses. Our interest is in inelastic behaviour where the amplitude of the stress will overcome the strength of the material and deform it irreversibly. As a result the processes will not be periodic like the cradle but rather unique, increasing the entropy of the systems on which they act. It is important to consider the effects of densification on the metals' microstructure and thus the rise of the pulse, and the time and length scale over which the rising pressure will act, will have an important effect. Further, the period for which the loading is maintained will determine whether mechanisms can act to equalise these compressed states over the body. Finally, the induced states will not only be those of high pressure and velocity within the material (which increase strain and change its volume) but also high induced temperatures since shock waves may be applied for a time so brief that there is insufficient time for heat to conduct away.

The characterisation of condensed matter under extremes of loading is best bounded within a region of common physics described not by the pressure applied but by the

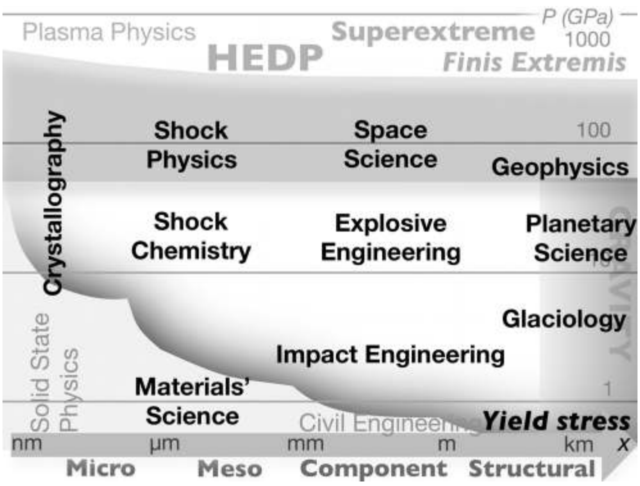

Figure 1.2 The range of disciplines accessed across a notional *P*–*x* space. At the smallest length scales atomic physics dominates, with the emphasis on energy levels and structure, at the largest planetary science describes the development of structures in solar systems. The world of engineering occupies the continuum scale. These disciplines span matter across its extreme states and define akrology, the science of extremes. The details and terms used in the diagram will return through the text and be explained as they arise.

strength of the microstructure it adopts. This region spans the elastic limit at the lower boundary and at the upper boundary the electronic states correlate so that valence electrons no longer determine bonding and delocalisation occurs. Beyond this point the strength of the compressed solid has a different nature to that in the regimes considered in this book and in what follows this is called the super-extreme state. As pressure increases at all scales, the response homogenises. At a particular pressure a threshold called the *finis extremis* is reached, which represents the upper limit for valence electrons bonding. Above this limit, high-energy-density physics (HEDP) describes the homogeneous state that exists. Within the bounds between this threshold and the yield stress of condensed matter, the range of subject interests extends from atomic physics excited by laser impulses, to integrated systems of behaviour found in planetary science. The variety of subjects amassed across this slice of pressure–volume space is illustrated in the cartoon of Figure 1.2.

Between the yield surface and the *finis extremis*, observed behaviour is defined by the pressure applied and the strength observed. The former is a thermodynamic variable, defined at scales beyond the unit cell and the latter is a function of the volume element sampled by the experiment or phenomenon of interest. The interpretation of measurement in the laboratory thus depends on this sampled volume (a function of the defect population contained with the material under load), the length of the impulse applied and the resolution limit of the detector. Thus the impulse defines the state observed at the length scale of interest and the physics that results is contained within a region where a common terminology and common physics defines a common space which may be described by the developed methodologies of solid mechanics.

Akrology: The science of the mechanisms operating and the responses resulting in condensed matter loaded to an extreme, mechanical state. (Origin: Greek, *akros*, 'extreme, highest, topmost'.)

This book will explain the principal mechanisms that reorder a material's structure and change the mechanical and physical properties it exhibits. Of course there are many extremes and loading by intense radiation pulses for instance will not be considered here. Such materials may be metallic, polymeric, brittle or even reactive. Connecting understanding of the mechanisms operating with mathematical description of the behaviours observed permits the principles of material response to be classified to allow the engineer to design structures.

The application of such principles additionally provides understanding of observed events on Earth and in the cosmos. These extreme events may be subdivided into those found in nature and those man-made. There are miscellanies of man-made dynamic events of note, in both the civil and defence fields, including terrorist devices that provide a pressure pulse by explosion or cutting devices that use metal jets. Even transportation exceeds the sound speed of the air surrounding us, requiring knowledge of supersonic flows (although the fluid mechanics of shock waves in gases will not be considered in this book). The result of the detonation of a reactive material or the acceleration of a metal jet requires the generation and propagation of a shock wave and it is the shock, a pressure impulse of rapid rise travelling through matter, that represents the limit in rate for dynamic loading.

1.2 Natural extremes

In the natural world the forces of nature frequently reach extreme states and, as the globe warms and kinetic energy within the atmosphere increases, provide increasing dynamic loading upon structures or even populations. The scale of planets and stars, and the laws of gravitational attraction, inevitably mean that at their centre, pressures and temperatures are extremely high. At the centre of the Earth, for example, the pressure is believed to be of the order of 360 GPa and the temperature of the order of 7000 °C. Furthermore, these static extremes mean that the core is primarily iron and behaves as if a single crystal in the anisotropic hexagonal close-packed (HCP) phase. In the centre of stars the mechanical states quickly exceed these and elements exist here as condensed plasmas. In these regimes the electronic states have homogenised; indeed the centre of the Earth is in this state and analogies with single crystals under ambient states may not be useful. This book will consider states of matter in which concepts of strength are extended to the point at which the energy density in the impulse exceeds the bond energy of the material (which is *c*. 300 GPa for an element like tungsten). Beyond this point the term strength as it is understood from solid mechanics has a different meaning.

On planets, impact has shaped their topography, and indeed one theory has our Moon as part of a Mars-sized object *Theia* (around 10% of the Earth's mass) that impacted the young Earth around 4.5 billion years ago (4.5 Ga). Smaller impactors have continued to pepper the Earth's surface as the solar system cleared rocky bodies such as asteroids into stable orbits and, at much higher impact speeds, so have comets from outside the solar system. Today there are over 175 confirmed impact structures on Earth and the number is growing as surface topography is better resolved. One in particular has caught public imagination since there is now general agreement that 65 million years ago (65 Ma) a bolide impacted the Earth and caused sufficient disruption to the ecology that all non-avian dinosaurs became extinct (this will be considered further in the last chapter). But such impacts are thankfully not common. More often found are the smaller-scale dynamic effects that result, for example, from mass movement of snow in avalanches, soil in landslides or water in tsunamis. When a process leads to explosion, wave propagation, with travelling mass and elevated pressure, is the necessary progenitor for shock wave formation. Such waves may also result from a series of natural phenomena such as earthquake, or volcanic eruptions.

To belittle such phenomena as small scale belies the devastating effect these natural processes can have on populations. Of the top ten deadliest natural disasters, half can be attributed to earthquake and tsunami, whilst of the remainder, the Baqiao Dam disaster (1975) occurred by catastrophic material failure under extreme loading under torrential rainfall from the super typhoon Nina. Earthquake, tsunami, volcanic eruption or impact provide an input stimulus which defines the initial state and the development of conditions that a material or structure must withstand. To acquire insight into how matter itself responds requires the deformation to be tracked for the time over which the pulse develops. In the text below these methodologies will be followed to show common links in the operating phenomena that underpin extreme loading events.

1.2.1 Volcanoes

Many Europeans encounter active volcanoes in Italy at either Etna on Sicily or Vesuvius on the bay of Naples; the latter is famed for the devastation and destruction of two Roman cities (Pompeii and Herculaneum) and was documented by the historian Pliny. The macabre secrets of those events are still emerging as more archaeological evidence is uncovered, but the key features of the event are written in the deposits around the volcano. The eruption occurred in two phases in the late summer of 79 AD. Small earthquakes started taking place, building in intensity over four days to failure of the dome that left a vertical plume of ash hovering in the sky above the volcano, which then collapsed down the mountain's west side in a torrential, pyroclastic flow that buried all in its path. This black cloud descended the slopes of Mount Vesuvius and flowed down to the Roman resort of Herculaneum. The first Plinian eruption vented the upper magma chambers and launched a column of ash and pumice 30 km into the sky. It has been estimated that the mountain was pumping out mass at a rate of 150 000 tons per second and that, in all, 2.6 km^3 of rock were exhausted out of the mountain. The first effects on Pompeii consisted of a rain of ash and pumice onto the roofs of the city until, bowed by the ever-increasing load, many collapsed under the weight, killing inhabitants sheltering in misperceived safety (Figure 1.3).

When the volcano's upper chambers were exhausted of their stores of gasified lava, a second source, deeper in the mountain was ejected. Changes in the type, temperature

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Figure 1.3 Eruptions at Vesuvius. A reconstruction of the AD 79 event (top: from the Discovery Channel's *Pompeii*, courtesy of Crew Creative Ltd) and as seen by Athanasius Kircher in 1638 (bottom: from *Mundus Subterraneus*, 1664).

and rate of expulsion of this mass led to the collapse of the towering column of pumice above the mountain and the launch of six devastating flows. These blasts are termed pyroclastic surges and flows and they account for the most destructive and lethal aspects of an eruption in a stratovolcano (a volcano built up of alternate layers of lava and ash) such as Vesuvius. In 1902, surges were observed (and photographed) travelling down Mt Pelee on Martinique at speeds of 30 m s^{-1}. The flow engulfed St Pierre and destroyed the city, claiming 26 000 lives. A pyroclastic flow is triggered by an explosion of hot gas, expelled from the volcano as the summit collapses, and is preceded by a surge of a mixture of gases from deep within entraining rocks, and dust. The following incandescent flow is a composite of the volcanic debris and ephemera entrained by the rapidly moving and heated gases. The temperature within it is between 200 and 800 °C, capable of carbonising the timbers of doors in its path and, as observers at Mt St Helens discovered, it can travel at up to 150 m s^{-1}. This lethal wave accounts for around half of volcano fatalities, killing by asphyxiation under the hot ash, burning and boiling under blow-torch temperatures, or impact from the entrained rocks propelled at high velocity in the flow. Six of these waves accounted for Pompeii and Herculaneum and for 20 000 inhabitants in a few hours.

The wave is propelled by the pressures and the blast wave from the rupture of the volcanic summit and driven forward by the potential energy converted by the descent of the entrained mass. In addition, the high gas flow velocities and elevated temperatures can fluidise this moving bed of material to allow high-speed flow. In the case of Vesuvius, the flow terminated as the hot magma intruded into and mixed with sea water, causing vaporisation, explosion and ejection of lapilli, which encased victims in a rock crust tableau that maintained their form long after their bodies decomposed, providing striking evidence of their unfortunate fate. In the case of Mt St Helens (1980), sufficient water was vaporised from Crater Lake to drive a shock front into the upper atmosphere where condensed water droplets formed a cloud layer at the boundary with the troposphere. The largest eruption in recent history occurred at Tambora (Indonesia) in 1815 (the year of Waterloo). The air shock travelled to Sumatra (*c*. 2000 km) and heavy volcanic ash falls were observed a similar distance away. The skies were dark for two days following the eruption and the eventual total death toll was at least 71 000. The year 1816 was the 'year without a summer', with snow in New England in July and August, and crop failure across Europe causing riots and famine. Yet it is still the eruptions that levelled Pompeii and Herculaneum that grasp the imagination since they occurred within a continent with a developing civilisation and have a written account by Pliny. The events of those two days echo down the millenia and tell not only of historic events, but also warn of what might happen today; the next eruption of Vesuvius is overdue with the last major event in 1944. Towns near Naples are rising and falling at a high rate – at one a shift of two metres in three days was measured, showing that, beneath the quiet monster, lava is gathering and stretching the crust above it.

Stratovolcanoes like Vesuvius, Etna or Pelee, placed at convergent plate boundaries, represent a group where viscous magma leads to explosive eruptions. This high-viscosity melt does not allow escape of volcanic gases, which thus build and pressurise the sealed volcano until eventually failure of the cone occurs. Dynamic dome fracture