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Materials Science for Dentistry

Tenth Edition

B. W. Darvell

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Materials Science for Dentistry

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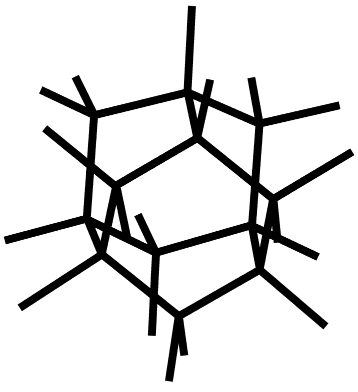
10th edition



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Preface

ἐπεὶ γὰρ τοῦ εἰδέναι χάριν ἡ πραγματεία,
εἰδέναι δὲ οὐ πρότερον οἰόμεθα ἕκαστον πρὶν ἄν λάβωμεν τὸ διὰ τί περι ἕκαστον

"Knowledge is the object of our inquiry,
and men do not think they know a thing till they have grasped the 'why' of it."
Aristotle (c. 350 BCE) *Physics*: Book II Chapter 3

Felix qui potuit rerum cognoscere causas

"Happy is he who gets to know the reasons for things."
Virgil (70-19 BCE) *Georgics ii 490*

As for previous editions, many changes have been made, arising from the notes and feedback gathered in various ways, to correct, revise, augment, extend and clarify wherever possible, as well as arising from my continued study. In adding some 150 pages, involving over 2500 changes or additions, including a new chapter on some further aspects of chemistry, and the beginnings of one on equipment, major new sections have again been included in a number of places, especially on wetting in practice, buckling, fluid mechanics and composite beams, all supported by 370 or so new references and a similar number of new figures. These continuing extensions are still a measure of the explanatory power of materials science in clinical dentistry, for ordinary processes and events, not in high theory or advanced materials, but in cumulative tiny insights into the way things work that tie ideas and phenomena together. However, much of the new material is in areas not covered elsewhere in accessible form and it is hoped that this will prove helpful. Indeed, the diversity of the subject continues to surprise. If I am able to convey any sense of the excitement of discovery, and contribute to another's understanding – and so advance the subject (and thereby patient care) – through this book, I will be happy indeed.

It remains my I hope that I have managed to maintain the right level and tone throughout, allowing an undergraduate access to every issue, whether or not it could be covered in a normal dental course. The availability of the explanations as a resource for use as required is the goal.

As ever, I would be grateful for a note of any errors, infelicities or problems as well as suggestions for new topics or subject matter – the field is by no means exhausted and much remains to be done. In addition, I invite questions and discussion through the online group at http://groups.yahoo.com/group/DentMatSci/. This is a live project that depends on feedback for its effectiveness as a teaching tool, both from the point of view of the teacher and the student. My thanks, again, to those who have helped.

Some 19 years on, I wonder whether those detractors (Preface to the 5th Edition) could sustain their argument? It is my view that the importance of the subject has never been higher, despite curriculum time being very low, and falling.

B.W.D. November 2017

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Preface to the 5th Edition

Much of the success of clinical dentistry depends ultimately on the performance of the materials used. The correct selection and manipulation of those materials will itself rely on an understanding of their structures and properties, but the many types and formulations precludes simple rote learning of data as a means of supporting dentistry. This text provides the basis for study and the development of an understanding which will be of value indefinitely, irrespective of the changes in products that will inevitably occur with time. Even so, this is not a text which can or should stand alone: the subject is closely woven into the whole fabric of dentistry, and must be seen in that light if a full appreciation of its impact is to be gained. It is a key component of effective, practical, clinical dentistry.

This book arises from the undergraduate course in Dental Materials Science delivered at The University of Hong Kong and which has been developed over some 18 years. It has been written to complement existing textbooks dealing with dental materials. It thus avoids manipulation and processing instructions, whether for clinic or laboratory; tabulations of comparative data such as for composition and properties; long lists of product variants and alternatives; and discussion of treatment options and indications. Study of these other textbooks will reveal that the emphasis on manipulation necessarily entails much repetition and overlap of basic ideas, and that the expansion of the scope of the subject in recent years has been dealt with by the study of what may be called 'comparative composition', illustrated by tables of values. The essential unity of the subject is thereby obscured. It is the aim of this text to demonstrate that unity, as well as the general applicability of the fundamental principles by which all materials (not just dental) may be understood. This is done by chapters dealing with specific aspects of structure, behaviour or chemistry. Indeed, some topics are dealt with here for the first time, although they are inarguably within the ambit of the title. Thorough knowledge of a certain amount of basic chemistry and physics is assumed, as is the context of usage, general compositional details and handling or processing instructions for all types of material.

The subject is presented in a largely conceptual fashion. The mathematics present is used either by way of illustration of an approach or unavoidable statement of physical law. It is by being a conceptual approach that the wide range of relevant topics can be treated at the level which answers the question 'why?' in such a way as to maintain flexibility and permit the ideas to be carried forward to new developments for a broad and sound understanding of the field. More immediately, this approach permits the analysis of current problems and the handling of, and constraints on, current materials. What may superficially appear as dogma based on tradition can then be seen as material-dependent, but above all as rational and meaningful. Thus dental materials science can be seen to be in the service of dentistry.

This edition has undergone further thorough revision, with expansion of the discussion of many topics to explore the ramifications of ideas, as well as to improve the clarity of explanations. To this end many figures have been redrawn and many new ones introduced. As before, several suggestions for modifications have been incorporated. Again, some new auxiliary topics have been introduced. All of this remains with emphasis on, and always in the sense of, explaining actual dentistry.

In a sense, this is a work in progress as new topics, previously overlooked, will be developed for inclusion to suit new developments and to fill lacunae. However, and more importantly, development of the presentation of ideas continues in an effort to ease the comprehension and assimilation of ideas. I would be grateful therefore for feedback if passages are found wanting or errors of any kind are detected, even infelicities and gaps. I intend to produce revised editions as necessary.

I am indebted to many people for support and encouragement in producing this, including (in no particular order) Dr. Hugo Ladizesky, Dr. David Watts, Prof. George Nancollas, Prof. Ray Smallman, Dr. Vitus Leung, Prof. Peter Brockhurst and a good number of others. I must also thank Regina Chan for secretarial services, in particular for retyping the equations when the wordprocessor was changed, and my wife, Vivienne, for proofreading this and typing early editions. Nevertheless, any errors remain mine. I also owe a mention to all those who actively disparaged the project over many years claiming that it is irrelevant to dentistry, and to those innumerable publishers who turned it down on the grounds of lack of sales potential or because they "already have one" on their list. It was more of a spur than they would think.

B.W.D. Oct. 1998

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Introduction

It is inevitable in preparing a book such as this that, because of the unusually wide scope of the subject and the interrelationships of the several aspects of any one material (and similar aspects in other classes of material), no one chapter order or sequence of ideas can be entirely logical or without anticipation of themes to be developed subsequently. This should not be taken as an indication of an unwieldy complexity and consequent difficulty of comprehension. Rather, it is a clear indication of the pervasiveness, the universality, of these themes. Time and again, reference will be made to an idea under different headings simply because that idea is a general principle. It will become apparent that there are relatively few major concepts embodied in this text, but that their applications are pretty much limitless.

The corollary to this is of course that it is quite impractical, if not actually impossible, to study each individual material in the context of its application and to analyse separately the contributions and interactions of each of its components. The welter of data would be nothing but indigestible. No student should be obliged to memorize data for its own sake. One implication of this is that pertinent comments are not written out in full at every opportunity. This is not to say that these are not relevant or important: fillers are fillers, with the same general effects, wherever and whenever they appear; surface energy considerations are relevant in almost every chapter, not just chapter 10, as they are in numerous other areas of dentistry which receive no mention here.

The student should aim to identify in any situation the relevant concepts, evaluate whether they are important in the context, and decide what their consequences might be. This procedure is one of analysis and synthesis, and can be recognized as a general approach to any problem. This book provides the wherewithal to do just that in respect of dental materials: a set of fundamental principles which may be viewed as a tool kit for dissecting a system, determining the role of each part, measuring its contribution and its interactions, and then understanding the behaviour of that system – as a whole. This is drawing a very careful distinction between just knowing and understanding[1] – compare Aristotle's remark, quoted in the Preface. Therein lies the key to this subject, as with many others: if its parts are treated independently, without reference to each other or the context, no real progress can be made; viewed in the round, the systems approach, the underlying patterns become much clearer. Basic concepts establish a framework, detail is built on to that.

This procedure, of building a mental model of a system, must be done gradually. Many concepts will be new, and the language used, the terminology, closely defined and specific. Learning the language will give a new view of the world, an alternative (and more explanatory) view of matter.

There are distinct parallels in other areas. It would be odd now, if once having grasped the concept of an atom or a cell, and thus their fundamental role in understanding the whole of chemistry and the organization of life respectively, that a new problem would require a reappraisal of that initially hard-won understanding. These ideas are second-nature, and are used as basic components of more complicated schemes. So it is with the concepts of materials science: rather than 'just' chemistry or physics, rather than 'just' observing behaviour, they are concerned with a composite of all of these, the intersection of all three major fields of Fig. 1.1. Dental materials science adds a further sphere, intersecting the first three, that of the clinical context, although this is more by way of changing the demands put on materials in service than on the underlying science.

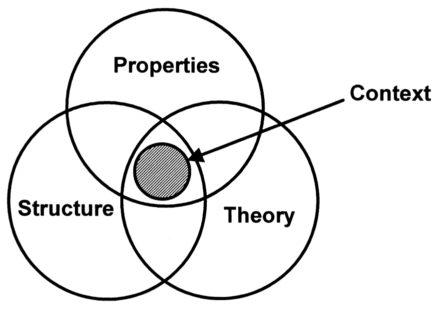

Fig. 1.1 Materials Science requires input from all aspects of a system.

An alternative approach is to consider the organizational hierarchy of matter in general (ignoring the sub-atomic!) (Fig. 1.2). The technology of dentistry deals with creating systems, primarily foreign objects in a biological environment, intended to be functional in some designed sense. Understanding of the system depends on that of the objects, which in turn depends on comprehending the constituent materials,[2] themselves derived from their component substances. This dependency provides one motivation for the organization of this book, and therefore in principle the manner of one's study of dental materials science within dentistry.

It is the existence of the clinical dental context – the motivation for the subject itself – that leads to the increasing use of the term 'biomaterials'. There is frequently confusion over how this term should be interpreted. The original use of the word, and the most intuitive, was as a contraction of 'biological materials', and referring to the materials of living organisms: skin, bone, shell, hair, cartilage and so on.[3] This usage is still to be preferred. Increasingly, however, foreign materials have been introduced into the body, primarily as prostheses (such as in hip replacements), but also surgical and other devices of various kinds (*e.g.* sutures, stents, pacemakers, boneplates and screws) where there is intimate contact with the internal environment, and these have, by association, been labelled biomaterials.[4] However, in dentistry, where contact may range from brief (impressions) through superficial semi-permanent (artificial dentures) to the intimate and invasive (transmucosal implants) *via* enamel-only restorations and pulp-capping, for some time the tendency has been more and more to apply the same term.[5] Where this is meant to leave investments and model materials, for instance, is unclear. Nevertheless, it is the application of the material which controls the properties of interest, whatever the context, whatever the label – the word is not the thing, the map is not the territory.[6]

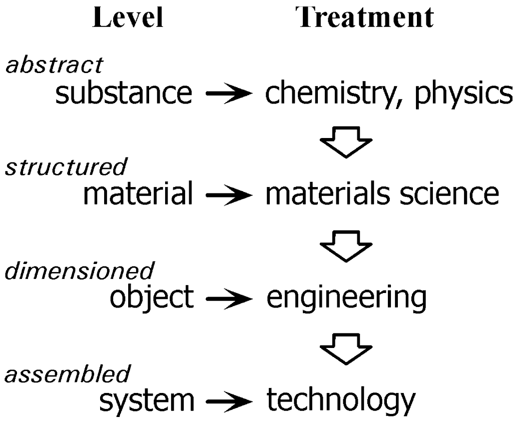

Fig. 1.2 The organizational hierarchy of matter. Understanding at one level depends on the level below in organizational complexity. Topics in the dental context form a subset at each level. Dentists are engineers using technologies.

With but a little thought the properties of a material which would be satisfactory to do a specific job can be identified. It is quite another matter to say what the ideal properties are, and one which reveals a major thread running through all aspects of real materials: compromise. The sad fact is that ideality simultaneously in several respects can never be approached because of the trade-off between one factor and another. The desired goals are on the two faces of the same coin; there is always a price to pay, and that price can be determined, in context, by reference to the ideas of this book.

There is yet another aspect of the subject which will be understood with advantage: "dental materials" includes all oral tissues. The tooth is part of the system which must be studied, as are the gingivae and other structures. They are certainly the contexts of many materials, but the interactions must be sought. Such an appreciation will be implicit in what follows.

If there is a message in this for the undergraduate it is probably that materials science is not so much an array of facts to be learned for their own sake, but more an attitude of mind. Necessarily the vocabulary and syntax of its language will need to be learned. But, as in any language, when these are mastered the number of sentences that can be constructed is unlimited. Some confidence can be taken from the thought that the ideas in this book are universal and enduring, unlike the commercial products themselves – or even the material itself – and the treatments. They are as valid now as they will be on the day you retire from practice.

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[5] Burdairon, G. Abrégé de Biomateriaux Dentaires. Masson, Paris, 1981.

[6] Korzybski A. Science and Sanity. p. 58 [5th ed. 1973; CD-ROM edition 1996] http://esgs.free.fr/uk/art/sands.htm

How To Use This Book

This book functions in several ways. Firstly, it is a reflection of the huge scope of materials in dentistry today, and thus the challenge to the dentist of tomorrow, no less than to those already in practice. There can be no reduction in this challenge as time goes on, rather will it increase, even if some materials fade away. In that light, this book is a toolkit of ideas that can be applied both in principle and in fact to any conceivable product in the future. This may seem like a grandiose claim, but if the identification of the fundamentals has been successful it must be true. That is the nature of materials science. Specific new polymers or composite combinations will almost certainly appear that have not been anticipated, but this should not matter. This is not meant to be an encyclopaedic treatise, but a foundation text that nevertheless serves that long-term purpose. It should permit answers to many questions not specifically addressed here to be worked out. Indeed, the focus on principles is for that very reason. It should be clear that whilst much work in a dental practice may be routine, it is the ability to recognize and deal with the non-routine events or conditions that is the mark of the professional. One must be prepared to think, but first observe.

Secondly, it provides material for an undergraduate-level course in the subject (although now the text has grown well beyond the needs of or timetable space for such a course). The level has, however, been chosen appropriately, and has been shown to be well within such a student's ability, and the 'reading age' set accordingly. That is not to say that an intellectual effort is not required – some topics are indeed challenging, but every effort has been made to explain rather than just declare: declaration is not teaching. Broadly speaking, though, more advanced ideas appear towards the ends of chapters and in the later chapters. Even so, everywhere the target in mind in writing has been the explanation in chemical and physical terms of the choices of material and procedure that are in use in everyday, clinical dentistry in a manner that empowers the student (and thus the practising dentist) to be in charge and control of what is done, rather than blindly following instructions with no capacity to recognize what is happening and intervene, adjust, or make independent, rational, scientific decisions, or indeed explain and justify treatment. This will be required more and more in respect of health insurance claims. In addition, in an increasingly litigious and regulated world, where accountability is paramount, a professional is no longer protected by a qualification and afforded unquestioning trust. As a professional, one may be called upon to defend a decision where something has gone wrong. It would seem essential that an appropriate knowledge and demonstrable understanding of the materials be part of the duty of care.[1] I have argued elsewhere that the ultimate competency in dentistry is this:

> *To be able to defend competently in a court of law the selection, manner of use, and all aspects of the handling of products, instruments and devices used in the course of treatment and related processes as they affect patients, ancillary staff and others.*

Thirdly, this is a source book, a reference for pursuing, as a first step, the ideas and equations needed for laboratory work, whether as part of undergraduate curriculum practical classes or further study, whether for a Master's degree or doctorate, or just research in general. At the undergraduate level, and in the vast majority of cases, it is not necessary to learn the equations or their derivation deliberately and explicitly. The practising dentist does not need them. It is therefore not appropriate that they be examinable as such (just as detailed compositions and property values are pointless). Nevertheless, it is important that the essence of these equations is understood: what variables are involved (*e.g.* stress, time), and in what sense (such as proportionally, inversely). The simpler equations, for example for Young's modulus, viscosity or surface tension, will in any case be absorbed almost automatically. The algebraic manipulations have deliberately been kept simple, but even if one's mathematical abilities are not up to reading and following these step by step, the text is intended to provide a parallel description of the process. Likewise, many diagrams are included to illustrate behaviour, structure and so on. These, too, should not be memorized. Rather, the nature of the trend or pattern of behaviour in broad terms should be identified. If the controlling factors are understood, the goal will have been achieved.

Fourthly, it is intended to demonstrate that instructions for use or clinical procedures are (or, at the very least, should be) justifiable, founded in reason, and logically traceable. Nothing should be taken on faith – including what is in this book![2] Be prepared to challenge dogmatic teaching or unsubstantiated claims. There must exist an explanation for every decision, every observation, every effect. Even so, in some cases, our understanding is incomplete (abrasion springs to mind), but the principle still stands. Therefore, identifying the path of the explanation, the chain of reasoning, should give confidence that dentistry has emerged from the mire of mediaeval magic, from the mystical arts of mere technical craftsmen, from the not-to-be questioned received wisdom of dogmatic practitioners, and from the era of the data handbook that lists simply what is rather than why. In that sense, nothing in this book is here just because it is interesting: it all has a purpose, a place in that chain intended to illuminate one idea or another. Thus, commonplace examples – or other non-dental topics – may be mentioned in order to underline the reality and broad applicability of the ideas, and to provide an image that may be better grasped by being familiar. Because, in places, the path is long, the student may not be able to see the ultimate goal or the part being played by a given idea. A little patience is required for things to fall into place – not everything can be said at once. Then again, the experience, background and knowledge of students do vary. It has been necessary in places to overlap what may have been taught prior to entry into university in order better to ensure that the path is complete for everyone (little has been assumed in this regard). In that case, the material will serve for revision. There are also many paths, which touch and cross each other in an elaborate network, so that cross-references are included liberally to assist in recognizing when other ideas are relevant, and as a guide to revision, if required.

This book does not deal with the operative techniques, instructions for use, laboratory procedures, or other matters of a direct treatment kind. These issues are dealt with in many other texts, and cross-reference should be made to those for the clinical background, handling instructions and so on. In addition, no attempt is made to deal with product comparisons or selection for purpose, but instead offers the means to support such judgements. It is emphasized that dental materials science is a foundation on which clinical dentistry totally and inescapably relies, whether or not it is recognized or acknowledged, and the implications and value of its contribution can only be found in the proper context. Study of dental materials science in isolation is not a meaningful proposition because clinical decisions should be in terms of and based on what it teaches. This may be understood better by reference to Fig. 1.3. The factors include not just the properties of the material but also the manner and conditions of use. These are seen to be acting on or through some kind of process, which then has an identifiable outcome. But the crucial point is then how this affects dentistry: what is the clinical implication of that outcome? How is treatment constrained? What limitations to performance in actual service might there be? Again, the ultimate purpose is patient well-being, and the present aim is to enable, facilitate and enhance just that.

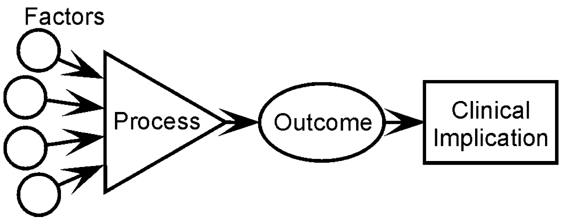

Fig. 1.3 Materials Science requires input from all aspects of a system, but end-point comprehension is the goal.

As indicated above, this is not an encyclopaedia. There is no attempt to cover all the many varieties of monomer, adhesives, and filler, for example. Such catalogues are available elsewhere (*e.g.* [3]) There are no tables of products, their recipes, and their property values – ephemera are pointless. Examples are used to illustrate principles, with such alternatives as are necessary to make a specific point, but always in a manner that may be applied elsewhere, including for products and systems yet to be invented. Even so, a deliberate attempt has been made to extend coverage into many areas not commonly dealt with (if ever), despite their evident importance. This is both a spur to thinking, and a resource for the curious, but all have emerged from questions put to me by students[1] or through observation of what dentistry uses or does (sometimes unwittingly). In that sense, the 'contained' undergraduate course needs to be created selectively by the teacher, omitting those many topics of lesser immediate need, according to the (ever diminishing) curriculum time available, yet allowing deeper discussion when the need arises.

So, to study. The terminology is of evident importance: knowing what the words mean and the context of their use allows comprehension of what is said, and the means of communication for reports and examinations (see the companion "Glossary"[4]). Much of this can be achieved by simply reading the appropriate portion of text once through, as for example in preparation for a lecture. At this stage one should not worry whether the chain of reasoning has been understood or a mechanism is clear – it is unimportant. What is more important is establishing a framework, a skeleton to be fleshed out in due course. If a lecture then follows, it will be far easier to understand. The relevant text can then be read through again, but now more carefully, this time identifying passages which cause some difficulty, but not dwelling unduly on them. There are many approaches to understanding concepts, and it may be that after reading other material, whether in other chapters of this book or in other dental materials texts, the ideas will be clearer. Still, if not, do not waste time struggling – ask for

1 *sensu lato*: undergraduates, post-graduates, teachers, and others trying to understand.

help. In any case, if there is any doubt about the relevance or comprehension of a cross-reference, follow it up until a secure foundation is found. Then retrace your steps. Reinforcement will give you confidence. It is worth bearing in mind that total comprehension is not required to make coherent sense of system – missing pieces can be filled in later if there is a sufficient framework, indeed, it becomes easier as you proceed, just like a jigsaw puzzle (Fig. 1.4).

Fig. 1.4 The full picture can be built slowly – it does not have to be complete for the essence to be grasped.

Try also to develop mental models, images in your mind of what is going on. Do not let the ideas remain just words on the page. Much of what is of interest here is dynamic: active processes of flow, diffusion, reaction and deformation. Ultimately, what is being described is observable behaviour, the macroscopic dependent on the microscopic. Verbal memory is not comprehension; it is not a viable route to understanding, as indicated in the Introduction.

It will also be of value in consolidating the ideas, and in integrating them with clinical teaching, to begin to think about what is being done in the laboratory and on the clinic in terms of this subject. Try to relate your observations to the theory, and to answer clinical questions in these terms. This will give practice in using the tool kit, practice in thinking, and confidence in the meaning and utility of the subject.

Overall, a systematic, steady, integrated approach to study will yield a comprehension of the basis of much of modern dentistry in a manner that will become a second-nature, background, almost invisible part of your dentistry. It will be an investment for a long career, no matter what changes occur in the products and techniques.

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[4] https://www.academia.edu/1120368/Glossary_of_Terms_for_Dental_Materials_Science_12th_ed

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Conventions

To facilitate the linking of ideas, copious cross-references are included in the text. Within a Chapter, the necessary section is indicated by the section mark thus: §4; if the section is in a different Chapter, the Chapter number is prefixed: 12§5. Figures, tables and equations are referred to the section always by the decimal form: equation 5.2 means equation 2 of §5, Fig. 3.12 means Fig. 12 in section 3, whether the reference is in the same section or not, but within the same Chapter. A figure, table or equation in a different Chapter is indicated by a prefixed Chapter number and section mark, thus: equation 1§2.3, Fig. 4§5.6. Ordinarily, it should not be necessary to cross-refer to these other locations to follow the sense of the text. The cross-references are to simplify the process, avoiding the index, when an idea is to be checked back. In many cases the cross-references indicate parallels in other systems that underline the general applicability of ideas.

References to selected primary and secondary sources in the literature are indicated by a superscript bracketed number, *e.g.*[1]. These references are listed at the end of each Chapter. Footnotes are indicated by a plain superscript number, *e.g.*2

SI units are used throughout except for a number of specialized uses where conversion of practice has yet to occur. These non-SI units are retained only for comparability with our sources.

A Note on References

In assembling a text of this sort, especially in view of the strongly multidisciplinary nature of the subject, a great many sources and influences will have been involved and their contribution to the narrative both diverse and intertwined, sometimes unconsciously. I acknowledge my indebtedness to all that have taught me, one way or another. Accordingly, many of the references given are of a general nature that may be relevant in a number of places in a chapter; I have given that reference on first use. In addition, many sources might now seem rather old. This only emphasises that the fundamental principles on which dental materials science is founded are universal and enduring, and well-established. On the other hand, no attempt is made either to be comprehensive or to track the latest information on all topics; this cannot be a key to the whole literature, which would be an impossible goal. Instead, in selected instances, some general reading or authority is cited to support the story being developed and to acknowledge sources. (I trust that there are no glaring oversights, but I apologize in advance for any that may be present. I should be obliged for advice of such omissions for correction in the next edition.) Even so, for material that is less commonly addressed, there are more given. For more advanced study, one's reading is researched in the usual way: cited instances of the references given may be a good start. However, I hope that I may be able to guide that study from firm foundations.

Greek Alphabet

Greek letters are used as symbols quite freely in many materials science contexts, and no less here. This list is given to facilitate reading. Upper case letters identical to the Roman are not used. (` indicates stress)

Α	α	alpha	[`al-fuh]	Ν	ν	nu	[new]
Β	β	beta	[`bee-tuh]	Ξ	ξ	xi	[zy]
Γ	γ	gamma	[`gam-uh]	Ο	ο	omicron	[`o-mick-ron]
Δ	δ	delta	[`dell-tuh]	Π	π	pi	[pie]
Ε	ε, ε	epsilon	[`ep-sill-on]	Ρ	ρ	rho	[row]
Ζ	ζ	zeta	[`zee-tuh]	Σ	σ	sigma	[`sigg-muh]
Η	η	eta	[`ee-tuh]	Τ	τ	tau	[tore]
Θ	θ	theta	[`thee-tuh]	Υ	υ	upsilon	[`up-sill-on]
Ι	ι	iota	[aye-`owe-tuh]	Φ	φ	phi	[fy]
Κ	κ	kappa	[`cap-uh]	Χ	χ	chi	[ky]
Λ	λ	lambda	[`lam-duh]	Ψ	ψ	psi	[sigh]
Μ	μ	mu	[mew]	Ω	ω	omega	[`ohm-egg-uh]

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Chapter 1 Mechanical Testing

One of the central requirements of any product in service is that the mechanical properties are suitable to the task. We may view mechanical testing as an attempt to understand the ***response*** *of a material (deformation, failure) to a* ***challenge*** *experienced in service (loading). A range of relevant mechanical properties are described, introducing the terminology and interrelationships, as well as some of the tests themselves that are used to measure those properties in the laboratory. Much advertising reports the comparative merits of products in terms of these test data, and unless the tests are properly comprehended – and their limitations recognized – sensible buying and application decisions cannot be made in the clinic or dental laboratory.*

The challenges experienced by materials in dentistry extend beyond masticatory forces acting on restorations and prostheses. There are the deliberately applied forces such as in the deflection of a clasp as it moves over the tooth before seating, the seating of a crown, in rubber dam clamps and matrix bands, and in orthodontic appliances. In the laboratory, casting requires the hot metal to be forced into the mould, which must then be removed by mechanical means. In either context, shaping and finishing involves the application of forces through various tools, including the preparation of teeth and models.

The responses of the materials of greatest concern include the ***deformation****, both reversibly and irreversibly, and the outright* ***failure*** *in service or in preparation. Thus, reversible or elastic deformation is important in controlling the shape and continued functioning of a device whilst under load. Equally, whatever deformation occurs here should only be temporary: permanent deformation would ruin dimensionally accurate work. Undesired permanent deformation is a type of failure, but cracking and collapse is plainly not intended in many cases. Yet cutting, shaping and finishing, the debonding of orthodontic brackets and other procedures involve intentional breakage. These too must be understood to be controlled.*

In normal service, except for dropping or traumatic events, loads are not instantaneous, one-off events – they have a duration, and are usually repetitive. This means that the ***time scales*** *of loading and of the response mechanism must be considered, as well as the pattern of loading in the sense of* ***fatigue****.*

The fact that a wide range of types of property are of interest to dentistry means that product selection must be based on a consideration of all of them. The problem is that not all can be optimal in the intended application, and some may be undesirable. The essence of this is that ***compromise*** *is always involved, trading a bad point for a good, or putting up with a less than perfect behaviour in one respect to avoid a disaster in another or to ensure better performance in yet another. This theme recurs in all dental materials contexts.*

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The purpose of mechanical testing in the context of dental materials, as with all materials in any context, is to observe the properties of the materials themselves in an attempt to understand and predict service behaviour and performance. This information is necessary to help to identify suitable materials, compositions and designs.[1] It is also the most direct way in which the success or failure of improvements in composition, fabrication techniques or finishing procedure may be evaluated. The alternative would be to go directly to clinical trials which, apart from being very expensive, time-consuming, and demanding of large numbers of patients (of uncertain return rates for monitoring) in order that statistically-useful data be obtained, would provide the ethical problems of using people in tests of materials and devices which could possibly be to their detriment. Laboratory screening tests used at the stages of development and quality control are thus cheaper, easier, faster and (usually) without ethical problems. The results of such tests are generally the only information on which to base decisions. The comparison of products and procedures, to aid in the choices to be made at the chairside, are also informed by such data in publications in the scientific literature. It is therefore a prerequisite to understanding mechanical properties in general, and the basis of recommendations for clinical products and procedures in particular (making rational choices of materials and techniques), that the tests which are employed to study them, as well as their interpretation and implications, be understood thoroughly.

§1. Initial Ideas

We are all too well aware that things break (Fig. 1.1). Such breakages can be costly, even dangerous to patient or operator, and certainly an inconvenience, at the very least. Evidently, in such examples the forces applied were in excess of the objects' capacity to carry them. What needs to be understood, therefore, is what controls such behaviour: what is meant by strength, what determines it, how we can avoid exceeding it during use. Can we judge what is normal usage, what is abuse? Such damage does not arise spontaneously, but it depends on the forces acting during use. That is, the magnitudes, locations and directions of the loads applied, whether these were as intended by design, or inappropriate by accident or ignorance.

Fig. 1.1 Things break: probes, chisels, scalers, burs, clasps, rubber dam clamps.

There are several types of loading that an object or body may experience in practice: for example, tension, compression and shear (Fig. 1.2). We can therefore envisage that there will similarly be a number of ways or modes of testing which might be used in an attempt to understand the response of bodies to such loads in service. But even if such loading is externally realistic, and thus said to be modelling service conditions, it will be found that the internal conditions may be considerably more complex. All three kinds of loading are typically present in any test, and they vary in intensity from place to place within the test piece. The interpretation of the results of such a test must therefore be done with care.

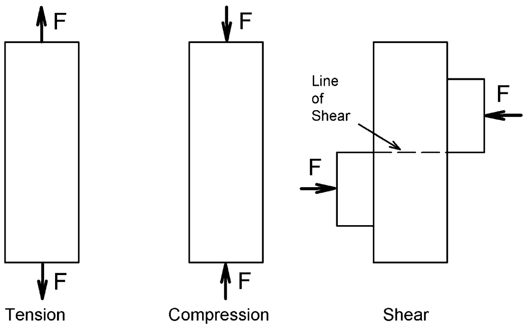

Fig. 1.2 Some of the principal kinds of applied load as might be used in laboratory tests. The applied forces are marked *F*.

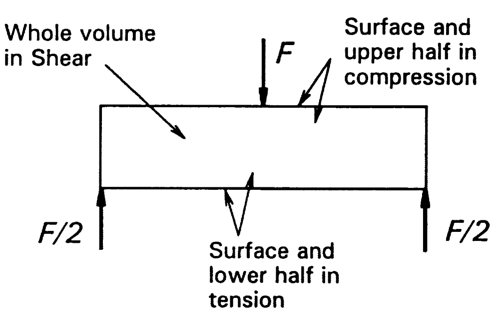

Fig. 1.3 The kinds of load acting in a body in a three-point bend test. The bending resulting from the application of the load makes the upper surface concave and the lower surface convex.

In a three-point bend test, for example (Fig. 1.3), we can identify a region where the principal result of the applied load is compression (extending from about the middle of the thickness of the beam to the concave surface), and a region in tension (similarly extending to the convex surface), but the entire region between the supports is in shear as well. This bend test thus gives us information about the performance of the material under those particular conditions of loading, but it may not say very much about any other circumstances. The deformation behaviour of the test piece certainly reflects contributions from all three aspects of the loading, although failure – meaning plastic deformation or crack initiation leading to collapse – may be attributable to one mode only. In the three-point bend beam case it is likely to be due to the tension on the lower, convex surface.

At the outset, then, we find that a major factor in testing materials is to match the conditions under which they will be put into service. Here, we are concerned about the mode of loading. This of course depends on an analysis being done of the service conditions themselves in order to determine what will occur and what will be relevant. It is this kind of thinking that underlies the selection of materials for particular purposes.

•1.1 Need to define properties

Now while we are perfectly capable (at least in principle) of determining the load that would cause a certain amount of deformation or even the collapse or failure in any sense of almost any given object, this in general is not a useful approach. There are an infinite number of possible shapes and sizes of object that might be put to some practical use, to say nothing of the variety of materials from which they could be made. The tabulation of such results would be impossibly cumbersome for even a small proportion of cases. Accordingly, a primary goal of materials science is to understand material behaviours in an abstract sense, that is, independent of shape and size. Thus, the underlying **postulate of consistency**[1] is that

a given material under chosen conditions will always behave in the same way, if subject to the same challenges

no matter what shape or size the object in which it is found. Notice that this is treating a material as having extent, as being a continuous but generalized 'body'. This is to distinguish **material properties** from the even more abstract sense in which the chemical and physical properties of substances are understood – the behaviour of matter itself – without any sense that we need be handling objects.

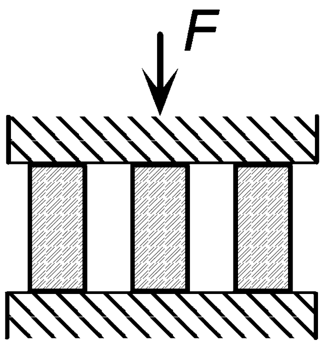

Fig. 1.4 A bearing capacity test on three identical objects simultaneously.

Consider an object that has an increasing compression load applied to it (as in Fig. 1.1, centre) until it collapses. We might term the ability of that object to carry a load without collapse the **bearing capacity**. Intuitively, this is what we need to know about any object that is meant to be load-bearing in any sense if we are to avoid overloading it. In other words, to determine if it is fit for duty under the conditions to which it will be exposed. Then, apply the same manner of loading to two, then three identical objects simultaneously (Fig. 1.3). Our elementary expectation is that the bearing capacity of the assemblage of objects will increase in a strictly linear fashion (Fig. 1.4). We naturally assume that each object carries its share of the load. We would therefore deduce that it is strictly unnecessary to test more than one such object at a time – there is no more *information* to be had in the multiple object test. Now, a little thought might suggest that perhaps in some sense it was the cross-sectional area of the set of objects being tested that was the underlying controlling variable. We should, for example, expect the same results whether we tested cylinders or rectangular objects – just so long as the cross-sections were the same.

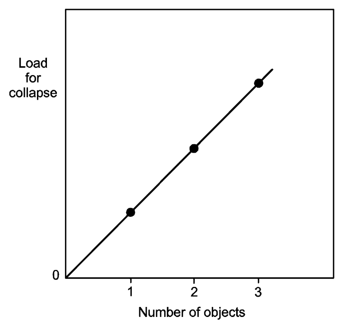

Fig. 1.5 The results of bearing capacity tests are expected to be strictly linear in the number of objects tested simultaneously.

Accordingly, our first efforts are directed to defining the **mechanical properties** of materials in just this size- and shape-free, abstract sense. We may therefore be in a better position to tabulate data in reference collections, having made the problem tractable. The intention is then that using such data we may calculate the expected behaviour of any

[1] This, indeed, is a version of the underlying fundamental belief system on which the whole of science and 'scientific method' is founded.

arbitrary but real object, taking into account its shape and size, in order to determine its suitability or otherwise in a given application or circumstances. At the risk of being overly simplistic, **materials science** is about understanding such abstract properties as they affect the behaviour of objects, **engineering** is the design of real objects using that information. We shall return to consider the effects of shape in Chapter 23, indicating briefly how this is done.

Before proceeding, a distinction can be made with value. A mechanical property is limited to expressing the response of a material to externally applied forces in a scale-independent (that is, **intensive**) manner. In contrast, a **physical property** of a substance, compound or material, is an intensive character dependent on the spatial disposition of its matter (*e.g.* density), its response to a change in energy (*e.g.* thermal expansion coefficient), its effect on radiation (*e.g.* refractive index), or its effect on or response to fields (*e.g.* dielectric constant). This separation permits a clearer sense of the interactions occurring when we use or test materials.

§2. The Equations of Deformation

Perhaps the first inquiry to be made about the response of bodies to applied loads is the resulting deformation, the change in shape. In a great many aspects of dentistry it is the resistance to deformation – or the lack of it – that controls the suitability of a material for the application. Thus, the success of a partial or a full denture depends in part on its rigidity, but orthodontic devices must have readily-flexible components to do their intended job.

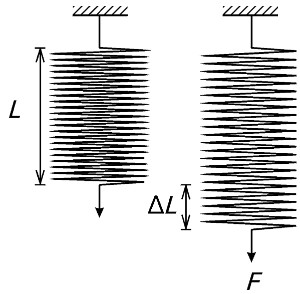

Fig. 2.1 Hooke's Law: the extension under load of a spiral spring. Note the conventional representation of a fixed anchorage at the top.

If a deformation is small enough then **Hooke's Law**[2] applies. This relates a deformation, for example the change in length of an object, L, to the force applied, F, through a **spring constant**, *k* (Fig. 2.1):

$$F = k \cdot \Delta L \tag{2.1}$$

This force, for the moment, will be taken as acting in one axis only, *i.e.* the force is **uniaxial**. The spring constant here is relevant only to that particular test piece, and to no other, because it 'hides' the information about the material, length and cross-sectional area, even the shape, of the particular specimen.

•2.1 Stress and strain

To make things simple to start with, we first restrict the discussion to an object that is of uniform cross-section, that is, every section through the object perpendicular to the axis in which the load is applied is constant in both shape and area. We then imagine that the applied force is distributed uniformly over the entire cross-section at the end of the piece. We may now *define* **stress**, σ, as being force per unit area, A:

$$\sigma = F/A \tag{2.2}$$

However, if the material from which the body is made is **homogeneous**, that is, uniform in composition and structure throughout, we have a reasonable expectation that the response of every part to the forces acting will be similar. Thus, the stress acting on each layer of the piece is expected to be identical, transmitted from layer to layer unchanged and uniform (Fig. 2.2). This may be called the **principle of uniformity**, and is a version of the postulate of consistency.

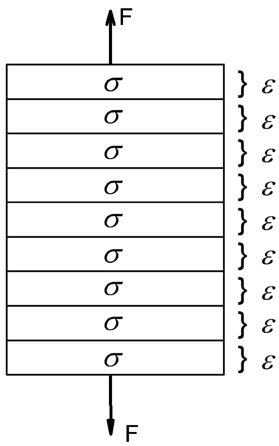

Fig. 2.2 The principle of uniformity – for all layers of a body.

To define the response of a unit portion of the body to the applied stress, we define **strain**, ε, as the change in length per unit original length, L_o:

$$\varepsilon = \Delta L/L_o \tag{2.3}$$

[2] First enunciated in 1678 by Robert Hooke (1635 - 1703).

This is on the basis of the principle of uniformity again: each layer is expected to respond to the applied stress in identical fashion. Similarly, this principle may be applied to the body divided into separate columns (parallel to the load axis). Not only do we anticipate that every unit area column within the body will behave identically, we have no reason to expect that any portion of such a column will behave any differently from any other portion (Fig. 2.3). To see this, consider their behaviour if the columns were not joined to each other: there can be no change. This is because the situation is then as depicted by Fig. 1.3.

The classification of the loading on a body includes the number of axes in which the forces are effectively acting. Along one axis only is **uniaxial**, along two mutually perpendicular axes is **biaxial**, while along all three Cartesian axes is called **triaxial**. The loads do not have to be equal, or even in the same sense. Thus, in the biaxial case, we may have tension in one axis and compression applied in the other. Similarly for triaxial loading we may have any combination. The special case here of all three stresses being equal is called **hydrostatic** loading.

These two views (Figs 2.2, 2.3) can be combined to show that all regions of a body subject to uniform loading, must behave in identical fashion (Fig. 2.4). Therefore, identical stresses and identical strains occur at every point.

It can now be seen that in defining stress and strain both the applied load and the resulting deformation have been scaled by the dimensions of the object, to make its actual shape and size irrelevant. Hooke's equation can therefore be reduced to a form which is, in principle, applicable to a test piece of any size and shape (but considering only regions of constant cross-sectional area and shape along the load axis). This version of Hooke's Law says that the stress (substituted for force) is proportional to the strain (instead of change of length overall), with E as the new constant of proportionality:

$$\sigma = E.\varepsilon \qquad (2.4\ a)$$

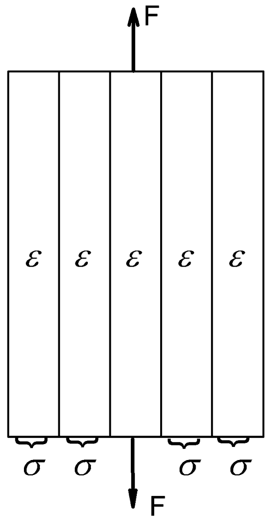

Fig. 2.3 The principle of uniformity – for all columns of a body.

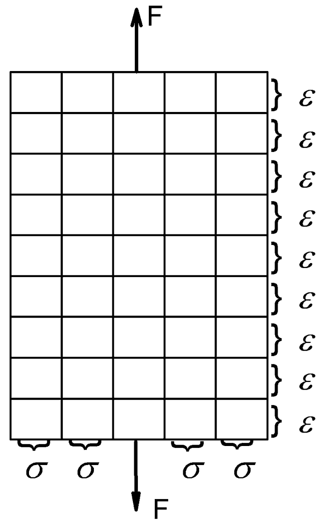

Fig. 2.4 The principle of uniformity – for all infinitesimal regions.

Instead, therefore, of having to consider the behaviour of all kinds of shapes and sizes of bodies, we are now able to consider the behaviour of the material from which they are made, independently of size and shape. But, of course, from such data we can now *calculate* the response, if we so choose, for any other size and shape, not just that which was tested to get the data in the first place.

Care has to be taken to ensure that these defined terms are not confused as they are in ordinary, non-technical usage. The language of materials science, as in science in general, depends on the agreed definitions of such terms for effective communication.[3] The units of stress are N/m^2, or Pa, whereas strain is a dimensionless quantity, being the ratio of two lengths (in this example; there are also areal, volumetric and shear strains which could just as easily be considered in precisely the same manner).

The graphical expression of Hooke's Law is that the plot of stress against strain is a straight line (Fig. 2.5), the slope of which is the constant of proportionality between the two variables. The experimentally determined value of the slope of this line, E, is known as **Young's modulus** or the **modulus of elasticity**, which from equation 2.4 a is therefore defined by the ratio of stress to strain:

$$E = \sigma/\varepsilon \qquad (2.4\ b)$$

[3] There are, unfortunately, many instances in dentistry where terms are used loosely or incorrectly, without regard to their meaning outside the field. Sloppy terminology is unhelpful. Great care is suggested in reading some of the dental literature to ensure that usage is proper, dimensions match, and so on.

This quantity is therefore a measure of **stiffness** or resistance to deformation of the material.

Sometimes it is more convenient to think in terms of the reciprocal property, the **flexibility** of the material (sometimes called "springiness"), in other words the deformation obtained for unit applied stress. The term **compliance**, symbol J, is commonly used for this:

$$J = 1/E = \varepsilon/\sigma \qquad (2.4\ c)$$

If the stress were to be increased still further, we might be able to see the plot deviate appreciably from a straight line. We may then define another quantity from a stress-strain plot: the maximum stress which may be applied and still have the proportionality hold is known as the **proportional limit**. It is implied that the behaviour is **elastic** of course, that is, the piece will return to its original dimensions (zero strain) when the stress is reduced to zero. However, elastic deformation may continue beyond the proportional limit, it is simply not a continuation of the straight line plot. But, at some point, if the piece has not broken already, we will reach a stress at which some permanent deformation occurs, deformation which is not recovered on unloading. This stress is called the **elastic limit.**

We have now to emphasise the very important distinction between the elastic and proportional limits. The proportional limit only refers to the applicability of Hooke's Law: *strict* proportionality between stress and strain. If it is identifiable at all, and for some stiff brittle materials it might not be, it is necessarily always less than the elastic limit.

This essential *condition* – zero strain at zero stress after the temporary application of a stress – is a sufficient definition of **elasticity**. However, it says nothing about the kind of *deformation behaviour* shown by the piece under stress. There is no fundamental obligation for strict proportionality between stress and strain in any system. In fact, in some classes of material (**elastomers**, for example, Chap. 7) even a working approach to proportionality cannot be observed (see also §13). Even so, many other materials, such as metals and ceramics, show a substantially linear region in a plot of stress against strain and therefore may be considered to approach ideal Hookean behaviour sufficiently well. But some metals, for example, show a more obvious deviation from ideality: a region of proportional deformation is followed by a small, **non-Hookean** but still *elastic* deformation. We must therefore state that although under many circumstances the elastic limit is indistinguishable from the proportional limit, the elastic limit is always the higher of the two if there is a difference. Equally, the proportional limit may be zero, *i.e.* non-existent (which means not detectable), for some classes of material. The important point is the distinction between the definitions.

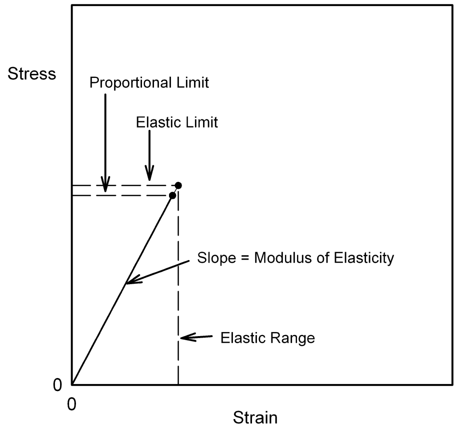

Fig. 2.5 A stress-strain diagram.

Modulus: In physics and mechanics, this term refers to a constant indicating the relation between the amount of a physical effect and that of the force producing it. In this kind of sense it was originally applied by T. Young (1807) to the quantity by means of which the amount of longitudinal extension or contraction of a bar of a given material, and the amount of the tension or pressure causing it, may be stated in terms of each other, *i.e.* the modulus of elasticity. On its own the word modulus does not convey any information, it must be qualified to indicate what it is a modulus *of*.

Proportional Limit: While it is very commonly mentioned in accounts of mechanical behaviour, as here, in practical terms it means very little. Essentially, its existence as a concept is merely a recognition and reminder that ideality is not to be found: reality is messier and less convenient. All it can indicate is when the value of E – the slope of the line – becomes *noticeably* different. It accounts for the comment for the applicability of Hooke's Law: "if the deformation is small enough". But, obviously it depends on the sensitivity of the detection: how far can the deviation be for it to count? Determination of a value is therefore not a precise matter, and there is no underlying physical event or condition change to mark it. Thus, it is not even a material property in any fundamental sense. This will become clearer in 10§3.6.

In the field of orthodontics it is common to characterize wires in terms of the strain ε_{max} observed at the elastic limit, σ_e, sometimes confusingly called the **maximum flexibility** or **springback**, and explicitly defined by:

$$\varepsilon_{max} = \sigma_e/E \tag{2.4d}$$

A clearer term for this is **elastic range**. Thus, the strain at the elastic limit indicates how much deformation may be tolerated before the test piece will not return to zero strain when released. This needs to be known to avoid overloading a spring, for example. This quantity may also be found to be called the "range" (without further qualification). It can be seen that this assumes that the proportional limit and the elastic limit are the same, although for many metals the difference is not very great. These kinds of usage re-emphasize the need for very great care in reading and interpreting the dental literature, where technical definitions are often weak and terminology confused. This is not to say that the ideas themselves are not useful in certain contexts, but that the terms and their exact meanings may not be immediately obvious.

•2.2 Poisson Ratio

Experimentally it is commonly found that if a test piece is loaded in tension or compression, then, in directions perpendicular to the load axis, corresponding **lateral strains** will appear: a contraction if the load is tensile, an expansion if it is compressive (Fig. 2.6). This is known as **Poisson strain**. The behaviour under tension and compression is quite symmetrical, always so long as the deformations are small. The co-variation of lateral and axial dimensions is expressed through the **Poisson ratio**, ν. This material constant, also known as a modulus, is the ratio of the lateral strain to the axial strain, but given a negative sign because the strains themselves have opposite signs:

$$\nu = -\varepsilon_y/\varepsilon_x \tag{2.5}$$

This is adopting the convention that the *x*-direction is the load axis, and the *y*-direction is perpendicular to that. Values of ν for typical metals and ceramics lie in the range 0.2 ~ 0.4. On grounds of uniformity, as above, we expect the response will be similar in all directions perpendicular to the load axis, and in particular that:

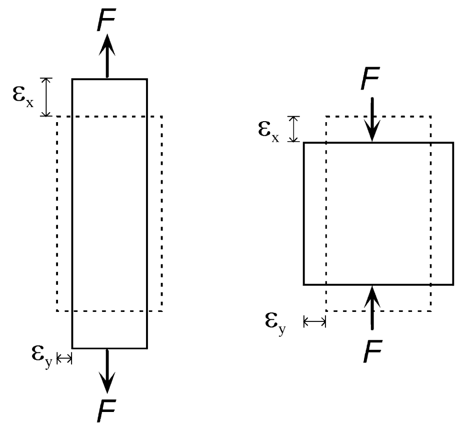

Fig. 2.6 Poisson strain is perpendicular to the load axis and (in most ordinary materials) of opposite sign to that of the axial strain.

$$\varepsilon_y = \varepsilon_z \tag{2.6}$$

where the *z*-direction is, as usual, mutually perpendicular to the other two.

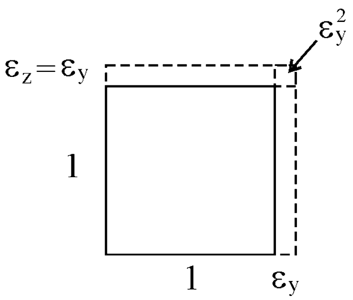

Fig. 2.7 Poisson deformation of the cross-section of an axially-loaded (*i.e.*, in the x-axis) specimen under tension. The squared strain term can be ignored if the strain is small.

The definition of stress (equation 2.2) does not actually specify *when* the area is to be measured. We might assume, for example, that it is the original value, A, just prior to starting the test, that we should take. Yet it is plain from the mere existence of a non-zero Poisson Ratio that under stress the cross-sectional area of the test piece will change during the test, even if it remains within the (apparently) linear elastic range. We may explore the consequence of this changing area. The area A′ after deformation is given by:

$$\begin{aligned} A' &= A + \Delta A \\ &= A(1 + \varepsilon_y)(1 + \varepsilon_z) \\ &= A(1 + \varepsilon_y)^2 \\ &= A(1 + 2\varepsilon_y + \varepsilon_y^2) \end{aligned} \tag{2.7}$$

where ΔA is the change in area. However, $\varepsilon_y = -\nu.\varepsilon_x$ (from equation 2.5) and ε_y^2 may be ignored as it is very small (Fig. 2.7), so that we have:

$$A' = A(1 - 2\nu\varepsilon_x) \tag{2.8}$$

as a good approximation. Therefore, at any point in the test, the actual stress, σ_x^*, is to be calculated from the cross-sectional area A′ at that moment:

$$\sigma_x^* = \frac{F}{A'} = \frac{F}{A(1-2\nu\varepsilon_x)} = \frac{\sigma_x}{(1-2\nu\varepsilon_x)} \tag{2.9}$$

where σ_x is the stress calculated for the original cross-sectional area. Hence, the **true modulus of elasticity**, E_o, is given by:

$$E_o = \frac{\sigma_x}{\varepsilon_x}\cdot\frac{1}{(1-2\nu\varepsilon_x)} \tag{2.10}$$

It can be seen that E_o is very slightly larger than Young's Modulus (E) since this latter is determined experimentally only using a measurement of the original area. The Poisson Ratio is typically about 0.3 for a metal and so is not a negligible parameter if a full description of a material's behaviour is sought. Equation 2.10 also shows that the true stress-strain plot cannot in fact be exactly a straight line because of the extra term in the denominator. Nevertheless, it would in general be somewhat impractical to measure the lateral strain of specimens routinely (elaborate and delicate equipment is necessary), and it is usually sufficiently accurate – certainly easier – to employ the original area and just calculate Young's Modulus, using what is known as the **nominal stress**, *i.e.* from equation 2.2.

The remark "if the deformation is small enough" made for Fig. 2.1 needs a little amplification. In essence, it means that calculations are made on the assumption that the geometry remains unchanged in respect of anything that affects the calculated outcome. Generally, this may be effective as a working approximation, but clearly it has its limitations and these must be recognized – and checked – in all relevant contexts.

•2.3 Volumetric strain

From a knowledge of the magnitudes of the axial and lateral strains we can also calculate a volume strain, ε_v, that is, the relative change in the volume of the test piece. Thus, taking the new volume V′ to be the original volume V plus the change in volume, ΔV, its value can be calculated from the usual expression for the volume of a cuboid in terms of the lengths of its sides. Thus,

$$V' = V + \Delta V = V(1 + \varepsilon_v) \tag{2.11}$$

but

$$1 + \varepsilon_v = (1 + \varepsilon_x)(1 + \varepsilon_y)(1 + \varepsilon_z) \tag{2.12}$$

so that from equation 2.6:

$$V'/V = (1 + \varepsilon_x)(1 + \varepsilon_y)^2$$

$$= 1 + \varepsilon_x + 2\varepsilon_y + \varepsilon_y^2 + 2\varepsilon_x\varepsilon_y + \varepsilon_y^2\varepsilon_x \tag{2.13}$$

Multiplied out, this has given a lengthy cubic expression, but because the strains themselves are typically very small in materials such as metals and ceramics, the quadratic and cubic terms can be considered negligible (see Fig. 2.7); that is, only the first three terms on the right need be considered. The error is only about the order of the square of the lateral strain. Subtracting the value one from each side we then have:

$$\varepsilon_v = \varepsilon_x + 2\varepsilon_y$$

$$= \varepsilon_x(1 + 2\varepsilon_y/\varepsilon_x)$$

$$= \varepsilon_x(1 - 2\nu) \tag{2.14}$$

We thus obtain an expression for the **volume strain** in terms of the axial strain and Poisson Ratio. What this means is that for values of $\nu < 0.5$, which is normally the case, there will be a change in volume of the piece when it is under load.

•2.4 True strain

Even the definition of ε_x itself needs refinement for it to be completely accurate, the point being that each increment of strain should be calculated in terms of the immediately prior value of the length of the specimen. In the limit, this requires the use of some calculus. So, considering the *increment of strain* at any moment, we can write

$$d\varepsilon = \frac{dL}{L} \tag{2.15}$$

which is the limiting version of equation 2.3. When the specimen has been deformed elastically to the new length L, the true total strain ε* is obtained by integration:

$$\varepsilon^* = \int_{L_0}^{L} \frac{dL}{L} = \ln\left(\frac{L}{L_0}\right) \tag{2.16}$$

then, since $L = L_o + \Delta L$,

$$\varepsilon^* = \ln(1 + \varepsilon) \tag{2.17}$$

This means that the true strain is slightly smaller than the **nominal strain** for tension, and slightly more negative for compression, as a few trials with a calculator will easily show. If the deformation is small enough it can be seen that $\varepsilon^* \approx \varepsilon$. In other words the approximation of equation 2.3 may be entirely adequate. However, to indicate that approximations are involved, σ_x and ε_x are sometimes referred to as **engineering stress** and **engineering strain**, to distinguish them from the true values. This also indicates that it is a matter of simple practicality in taking that approach. Most graphs of "stress" *vs.* "strain" are therefore in terms of these **nominal stress** and **nominal strain** values, unless they are explicitly labelled otherwise. We are prepared to compromise with the slightly less accurate values because of the expense and difficulty of obtaining the true values. However, one must not lose sight of the existence of Poisson strain.

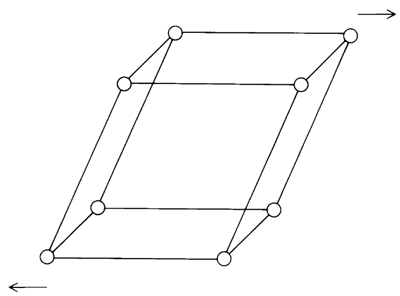

Fig. 2.8 The distortion resulting from the action of shear on a rectangular framework.

•2.5 Shear

After the simple uniaxial tests discussed above, *i.e.* tension and compression, the next most important mode of testing is in **shear** (Fig. 2.8) where the layers of atoms or molecules of the material are envisaged as sliding over one another. The related mode of testing in **torsion** (Fig. 2.9) may be viewed as a particular case of shear. Shear is a common type of stress. For example, it is an aspect of the loading of beams in a three-point bend (Fig. 1.2). It is also relevant to the loading of interfaces such as between a bonded orthodontic bracket and a tooth, where the force is applied in the plane of the layer of cement. Endodontic files are ordinarily loaded in torsion in use, even though there is usually bending as well. There are many other examples.

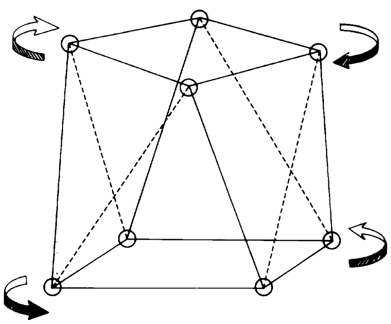

Fig. 2.9 The distortion resulting from the action of torsion on the same rectangular framework.

In studying shear we are interested in the relative displacement of one layer sliding with respect to the next (Fig. 2.10). So, in a way analogous to that for direct uniaxial loading, we measure the length (L_o) over which the load is acting and the amount of displacement, Δs, at a given load, measured in the direction of load application. A version of Hooke's Law applies here also, where the shear force is related to the displacement by a shear spring constant, k_s:

$$F_s = k_s \cdot \Delta s \tag{2.18}$$

We can therefore define **shear stress**, τ, as the force per unit original cross-sectional area in the direction of shear:

$$\tau = F_s / A \tag{2.19}$$

and the **shear strain**, γ, as the displacement per unit original length over which the shear stress is applied,

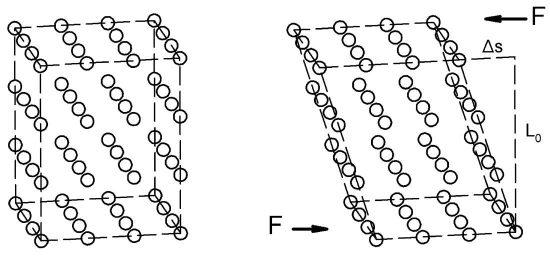

Fig. 2.10 Shear of materials involves the displacement of layers of atoms past each other.

that is, the depth, the distance between the top and bottom layers:

$$\gamma = \Delta s / L_o \tag{2.20}$$

Both of these are entirely analogous to the definitions for uniaxial loading. In particular, it can be seen that the shear stress on each layer is the same, and the relative displacement of each layer with respect to its neighbours must also be the same.

The **shear modulus of elasticity**, G, (sometimes called the **modulus of rigidity**) is then defined simply by:

$$G = \tau/\gamma \tag{2.21}$$

The reciprocal of this is known as the **shear compliance**, which is analogous to 'flexibility' (equation 2.4 c). It can also be shown that this shear modulus is related to Young's Modulus through the Poisson Ratio:

$$G = \frac{E}{2(1 + \nu)} \tag{2.22}$$

It is therefore not necessary to measure both moduli experimentally. To understand shear deformation we can use Young's modulus. Alternatively, it may be difficult to measure Young's modulus, yet the shear modulus might be easy to determine. However, either way it requires a knowledge of the Poisson ratio.

Two other points emerge from this. Firstly, the shear stress is the same on every layer, all the way through the specimen. The force acting over any layer is transmitted undiminished to the layer below. Secondly, also on the principle of uniformity (§2.1), the relative displacement of one layer with respect to the next must be the same for all layers in a homogeneous specimen.

•2.6 Bulk modulus

Using similar reasoning, the behaviour of materials under **hydrostatic loading** can be described with the **bulk modulus**, K [4] (again, it is understood that this is a type of elasticity). Under hydrostatic loading – in which the pressure (*i.e.* stress) on the sample is uniform in all directions – there is no change of shape, only of volume (Fig. 2.11). Again, the bulk modulus is related to the more easily measurable Young's Modulus:

$$K = \frac{\sigma}{(\Delta V/V)} = \frac{E}{3(1 - 2\nu)} \tag{2.23}$$

The reciprocal of this quantity is also known as the **compressibility**, κ, of a material:

$$\kappa = 1/K = \frac{(\Delta V/V)}{\sigma} \tag{2.24}$$

This is the bulk compliance.

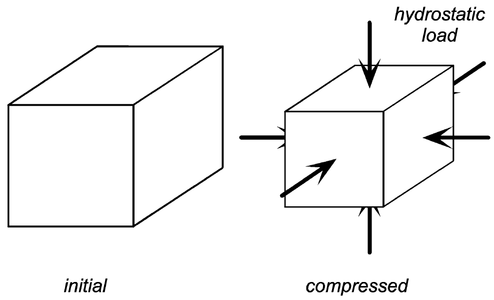

Fig. 2.11 Hydrostatic loading results in a change of volume but not of shape for an isotropic material.

If we combine equations 2.22 and 2.23 we get the following important relationship:

$$\frac{1}{E} = \frac{1}{3G} + \frac{1}{9K} \tag{2.25}$$

which illustrates the interdependence of the three moduli of elasticity.

•2.7 Effect of structure

We have so far assumed that the materials being tested are uniform, homogeneous and **isotropic**. While this may be true enough for an **amorphous** material (such as glass, which shows no long-range order at the molecular level), many materials are crystalline (thus showing long-range order) or heterogeneous. The latter class of materials, known generally as **composite** materials, are dealt with in later chapters as they have their own special characteristics. A crystalline structure necessarily has directionality, there can be no such thing as spherical symmetry in this case and the properties of the material must be **anisotropic**. That is to say, the

[4] The symbol B is also commonly used for bulk modulus.

mechanical properties vary according to the direction chosen for the load axis since the nature (*i.e.* the stiffness and strength) of the atomic or ionic bonds themselves vary with direction. Hydrostatic loading of single crystals will often involve some change of shape, since the three mutually perpendicular strain directions are unlikely to be equivalent if they are chemically or otherwise distinguishable. In fact, some 21 separate independent elastic moduli can be defined to express all of the possible directional variability in properties (for triclinic single crystals – see Table 11§3.1). However, other crystal types have more symmetry and so in practice there are rather fewer independent moduli, that is, the minimum number of moduli which are not algebraically derived from each other – for example, a cubic crystal has just three.

Even so, in dentistry we are very rarely, if ever, concerned with the properties of isolated single crystals. The materials we shall deal with are all **polycrystalline** (Fig. 2.12), such as metals, with usually random orientation of the individual crystals, or **amorphous**, such as glasses, when the local (at the atomic scale) anisotropies cancel out so that the overall effect is of an isotropic material. Because of these effects we can reduce the minimum number of moduli necessary to describe fully the behaviour of the material to just two: Young's Modulus and the Poisson Ratio, because the others can be calculated from these two values (see Table 2.1). (However, it can also be argued that the two fundamental independent moduli are G and B.) However, it must be emphasized that the validity of these properties in describing behaviour depends on the total deformations being small. Extremes lead to departures which require more complicated treatment.

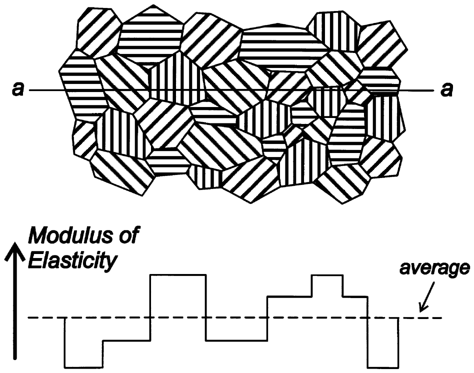

Fig. 2.12 In a polycrystalline material local anisotropies in modulus of elasticity, i.e. at the level of the grain, and therefore both stresses and strains are averaged out, such as is shown for the section *a-a*.

Table 2.1 *Force and deformation moduli. The two most important are marked *.*

Modulus	Symbol	Units	relevant loading	associated with changes in
Elasticity	E_o	Pa	axial	shape + volume
Young's*	E	Pa	axial	shape + volume
Shear	G	Pa	lateral	shape
Bulk	K	Pa	hydrostatic	volume
Poisson*	ν	-	axial	shape + volume

§3. Plastic Deformation

So far we have dealt with the behaviour of materials for small deformations. This was to ensure that the geometry of the system was essentially unchanged, but also to keep the stress lower than the elastic limit. By definition, if a return to zero strain on removing the load is not obtained, there will have been **permanent deformation**, and thus the elastic limit will have been passed.

We may consider as a general example a specimen being tested in tension (Fig. 3.1), as this mode is somewhat easier to understand than compression (a tensile specimen will be assumed unless otherwise specified). The essential features of the test are that the specimen is gripped to apply the load, F, while a representative portion known as the **gauge length**, L (that is, the length of a representative portion before any load is applied), is monitored with some instrument (typically a **strain gauge extensometer**) to determine the change in length, ΔL for the load that is then

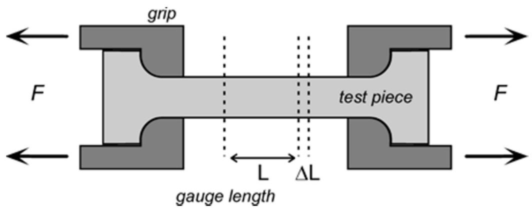

Fig. 3.1 A specimen undergoing a tensile test.