Photo-Elasticity

LONG ago it was remarked by Brewster that a transparent elastic solid such as glass ceases to be optically isotropic when it is bent or otherwise strained by external forces. It then shows chromatic effects in the polariscope, which vanish if the state of strain be relieved. That was the beginning of photo elasticity, a science which, many years later, has become developed into a powerful means of investigating complex conditions of stress for the information of the engineer. It can readily be applied in cases which are too complicated for mathematical analysis; and even in less complex conditions photo-elastic experiments are often highly useful, providing short-cuts to the required results, or confirming the analysis of the mathematician. Whether the distribution of stress is simple or otherwise, the photo-elastic method makes the mode of distribution strikingly apparent. The polariscope is an incomparable showman, as entertaining as it is instructive. It appeals alike to the mathematical and the non-mathematical mind. The distribution of stress exhibited by the transparent solid applies to an engineering material such as steel, provided the elastic limit is not passed.

Lately, I saw in Prof. Coker's laboratory a transparent model of a locomotive driving-wheel revolving in contact with a loaded roller which pressed on the rim as the rail presses on the real wheel, the whole working in circularly polarised light and throwing its image on a screen. The chromatic effects, as each part of the rim and each spoke in turn took up its duty and then passed it on, made a brilliant spectacle—as fascinating a ' movie ' as any engineer could wish to see, all the more as the spectator could control the speed or introduce a pause at any stage.

In modern developments of the subject the favourite medium for the study of stress is not glass but some form of celluloid. Xylonite, which engineers know as a material of which set-squares are often made, answers well. It is inexpensive, and is easily procured in transparent plates which are sufficiently uniform in thickness and quality, are free from internal stress, and come near enough to the ideal of perfect elasticity. It is not brittle, and is easily cut into strips or rings or flat pieces of any form, so that it may serve as a replica in miniature of the engineering article the behaviour of which under stress is to be studied—such, for example, as a plate weakened by rivet-holes. Readers of NATURE who are unacquainted with the subject may like to be told briefly what is the process by which the polariscope is made to reveal the condition of stress in such a specimen.

Imagine, then, an optical bench with a source of light such as a pointolite lamp at one end and a projection screen at the other. The bench carries a pair of crossed Nicol prisms, between which the specimen is placed—a flat strip or plate of xylonite a quarter of an inch thick, or less, with its plane at right angles to the rays—so that light polarised by the first nicol passes through the specimen in the direction of the thickness. The piece is held in what is virtually a small testing-machine, in order that measured loads—pulls or pushes or both—may be readily applied in its own plane. Each of the nicols is furnished with a removable quarter-wave plate of mica, allowing either circularly polarised or plane polarised light to be used at pleasure, and the nicols may be rotated together in order that their crossed axes may be set at any angle to fixed axes in the specimen. The specimen is cut from a uniformly thick plate, so that the polarised light traverses the same thickness at all points of the material under examination.

So long as no load is applied, the material is isotropic, and has consequently no action on the polarised light. In that condition no light passes through, for the second nicol stops what has come through the first. But let stress be applied; the xylonite then develops a birefringent quality, causing a relative retardation of part of the polarised ray, with the result that colour effects appear on the screen. To take the simplest case, let the piece be a strip under uniform tensile stress in the direction of its length, then the image will have a definite uniform colour depending on the amount of that stress, and as the stress is increased the colour will change through a sequence of tints that correspond to Newton's colour scale for thin plates. Let uniform push be applied instead of pull, and gradually increased; the same sequence of colours is again seen, the colour for push being the same as for an equal intensity of pull. Or, to take another example, let the piece be stressed as a beam under uniform bending moment in its own plane; the image will then show a set of longitudinal colour bands. The neutral axis will appear as a black central band, since there is no stress there, and on either side of it—above and below—there will be a series of parallel colour bands grading into one another, which show how the intensity of longitudinal push or pull increases with the distance from the neutral axis towards one or the other edge.

In each of these examples there is only one principal stress P at any point, and the colour there directly exhibits the value of P. But in general, for less simple states of elastic strain in a loaded plate, there will be two principal stresses P and Q, at right angles to each other, and it is easy to show that what the colour really tells is the difference $P-Q$. At any point where Q happens to be equal to P no light gets through the polariscope. There the image has a dark spot: at all other places there is colour. As the magnitude of $P-Q$ increases from point to point of the plate the tint changes, following the Newton colour sequence, and the image on the screen accordingly exhibits strong colouring in the form of isochromatic curves, each such curve being a locus of points at which the value of $P-Q$ is constant. Incidentally, therefore, these isochromatic curves exhibit directly the amount of shearing stress at each point, for the shearing stress is everywhere proportional to $P-Q$.

The main object of the test, however, is to determine the principal stresses separately, and for that a further experimental analysis is required. We now change from circularly polarised light (which was best for exhibiting the isochromatic curves) to plane polarised light, by removing the quarter-wave plates, and set the crossed nicols at a particular azimuth or direction in the plane of the plate. The image now shows certain dark bands corresponding to places at which the two directions of principal stress are parallel to the axes of the two nicols. A locus of such points is called an isoclinic curve, for at these points the principal stresses have constant inclinations with respect to any arbitrarily chosen co-ordinate axes. Points on the isoclinic are recorded by marking the screen with little parallel crosses, the limbs of which lie in the directions of the principal stresses, these directions being given by the setting of the crossed nicols. Next, the setting is changed by turning the nicols through, say, 15°, and another isoclinic is then observed and is recorded in the same way. Proceeding thus, with progressive turning of the nicols through 15° at a time, we obtain a complete system of isoclinics for the whole plate, from which it is easy, by aid of the marked crosses, to sketch in the double system of lines of principal stress.

These lines give everywhere the directions of P and Q, but the magnitudes of P and Q have still to be determined. The colour bands, as we have seen, depend on $P-Q$, and the value of that quantity may be inferred by matching the colour at any point of the strained specimen with the colour shown by a strip of the same material and thickness strained by a known simple pull. But accurate colour matching is not easy, and a very much better way, due to Coker, is to superpose the auxiliary strained strip so that the polarised light passes in series through it as well as through the main specimen. The auxiliary strip is set so that the direction of pull in it is at right angles to the principal stress P at the place under examination. Then by adjusting the stress P in it until a black spot appears in the image, we know that $P=Q+P'$, and hence P' gives a direct measure of $P-Q$.

To find the value of $P-Q$ is not enough when we want separate values of P and of Q; so, following Mesnager, Coker carries out a supplementary observation. By means of a delicate lateral extensometer, which measures the elastic change of thickness of the plate at any point, he infers $P+Q$ from the observed amount of lateral contraction. Then, combining this information with the results of the optical tests, the whole problem is solved; P and Q are each determined, in magnitude and direction at every point. The process is laborious, but the final results are complete and convincing: in many cases they can be usefully checked by integrating graphically over a section on which the whole stress is known from the conditions of loading. Often the process may be simplified by starting from a free edge, where one of the principal stresses is necessarily zero.

All this, and much more, is fully discussed by Profs. Coker and Filon in their recently issued treatise,* along with an account of how the method has been applied to a host of important practical examples. This fine volume, with its 720 large pages of print, its numerous colour plates, and its many hundreds of admirably drawn illustrations, is a monument not only to the ability and industry of the joint authors, but also to the enterprise and technical skill of the producers, the Cambridge University Press. The typographic form is worthy of the matter, and to say that is high praise. The authors here treat with affectionate completeness a subject they have made peculiarly their own. They have spent many years in perfecting it and demonstrating its uses. Much of their original work has been done in close association. Now they present us with the fruits of a happy collaboration in authorship, where the critical insight of the mathematician and the practical flair of the engineer combine to provide a comprehensive, systematic, and extremely lucid treatise. Readers who know both authors may find material in the book for an interesting guessing game, as to which parts, so to speak, are Sullivan's and which are Gilbert's. But the main point is that the whole is a good blend. The authors make an exceedingly strong team; they pull well together and each supplements the many virtues of the other.

After a short introduction, we have several chapters of general theory. The relevant optics are discussed on the basis of Maxwell's electromagnetic waves, and this is followed by a chapter on the theory of elasticity, before the theory of artificial double refraction is attacked, on which the whole process depends. The first half or so of the work will be of general interest to physicists, apart from the solution of special problems of engineering with which the later sections abound. These comprise many detailed applications of the method, to tension and compression test-pieces and pieces under shear, to beams and bridges, to thick cylinders, to plates with holes and notches and cracks, to eye-bolts and fastenings, to rings, chains, hooks, wheels, to the action of cutting tools, and to other examples too numerous for mention here. Some of them are very recent: they include studies undertaken by Coker for a special committee of the Department of Scientific and Industrial Research, which has not yet reported, in critical examination of certain customary types of test. All of them illustrate the wide sweep of the method, its power to illuminate obscure matters, and its great value as a guide in design. To have produced such a work is a professional service for which engineers—contemporary and future—cannot fail to be deeply grateful.

Such a treatise was, in fact, greatly needed. It is a new departure: no book has hitherto been available that covers anything like the same ground. Students of the subject have had to refer to scattered papers or lectures, many of them by Coker and Filon themselves. The book will be welcomed as filling a definite gap in the literature

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* A Treatise on Photo-Elasticity. By Prof. E. G. Coker and Prof. L. N. G. Filon. Pp. xviii+720+14 plates. (Cambridge: At the University Press, 1931.) 50*s*. net.

of scientific engineering. Engineers know that the methods of photo-elasticity—methods of experiment with which they are still for the most part unfamiliar—have already become important auxiliaries in design. Such a treatise will, I believe, be no less attractive to the physicist, to whom it will appeal in the rare moments which find him willing to turn aside from the atom and the photon to revise, and perhaps enlarge, his ideas of what happens to the ‘ classical ’ Maxwellian waves when they traverse solid aggregates. If he discovers how to harmonise the two modes of thought, so much the better.

There is, paradoxically enough, one defect. The book is so big, so full, so thorough, that it must fail of one important purpose: it is not a textbook for the ordinary student of engineering. He needs something much more brief, direct, and simple—something that will show him the optical bench and tell him plainly how to use it. So many elementary accounts have already appeared in lectures and addresses to learned societies that the authors must be tired of that kind of exposition: but it still needs to be embodied in a handbook that will be a really handy book. Such a task is well worth doing. This excellent voluminous treatise will always be there for more advanced study and as an encyclopædia of reference: the small book, which has yet to be written, would introduce readers to it and would spread knowledge, in a way the treatise cannot be expected to do, of a subject which should be taught in every engineering laboratory, and should become, at least in its elements, part of the mental equipment of every educated engineer.

To me the book brings a personal pleasure, for it happens that both Coker and Filon were at one time my pupils. It was in the engineering laboratory at Cambridge, more than thirty years ago, that Filon carried out his earliest photo-elastic research on a loaded beam of glass. For that, however, I can claim no credit, not even the credit of suggestion. His experiments were initiated and pursued in a fine spirit of independence, a virtue only too rare among research students. Nor had I any hand in the subsequent efforts, successful and long sustained, to which this book bears witness. But even so, it gives an old teacher some satisfaction to see original work of high quality proceed from those whose early notions he may have had some small share in shaping, and to sit, as I now do, a learner at their feet. J. A. EWING.

Albertus Magnus

HIS SCIENTIFIC VIEWS

“EVERYTHING there was to be known, he knew.” Thus is the genius of Albert the Great characterised by the Pope in the remarkable Bull “ In Thesauris Sapientiæ ” declaring the blessed Bishop of Regensburg a saint and a doctor of the Church. In this “ Decretal Letter ”, dated Dec. 16, 1931, but published on Jan. 14, 1932, Pope Pius XI. points out that Albert the Great (1206–1280) was not only a lover of God, a pastor of souls, and a master of the sacred sciences, but also a pioneer in secular knowledge. He wrote about astronomy, physics, mechanics, chemistry, mineralogy, anthropology, zoology, botany, architecture, and the applied arts; and the modern edition of his writings makes thirty-eight thick quarto volumes (ed. Jammy O.P. repr. Vivès, Paris, 1890 *sq.*). Indeed, Albert the Great broke the chains that kept natural science in the hands of unbelievers, and vindicated it against the more timid pious persons of his time who were afraid of it for fear of its abuse. For, says the Pope, “ no real theologian is afraid of any damage from the operations of nature or of natural reason rightly investigated, for these very things bear upon them the light of the Creator himself ”.

We do not propose here to give any account of the edifying and active life of St. Albert the Great, or to report on the various causes which led to his canonisation by the Church. Nor do we intend to give an outline of the theological and philosophical views of a master mind who is now honoured as one of the twenty-eight doctors of the Church, together with Gregory, Basil, Ambrose, Augustine, Jerome, Thomas Aquinas, Anselm, Bernard, Beda, Ephraem, John of the Cross, and Bellarmine. We shall endeavour, however, to give a short sketch of the scientific views of Albert the Great, which are of the greatest interest for the history of science, especially as they represent the state of scientific knowledge in the Middle Ages.

Though Albert seems to be less original and forceful as a scientific thinker than his contemporary Roger Bacon, yet he was far more influential on the age in which he lived. The peculiarity of his encyclopædic teaching was that it was based entirely on the writings of Aristotle. This was remarkable because the Aristotelian principles were resisted by the Church at the time; the provincial council at Siena in 1210 going so far as to forbid the use of Aristotle's books on natural philosophy. But though no professor was permitted to lecture on them, and in spite of the fact that in 1215 the “Physics” and the “Metaphysics” were banned by the statutes of the University of Paris, Albert the Great was actively promoting the new philosophy, probably with the connivance of the Church authorities, who allowed a responsible theologian to sift the true from the false the while they acted as the stern guardians of orthodoxy. He soon joined hands with his pupil Thomas Aquinas, who, if he surpassed his master in the theological and philosophical interpretations of the Stagyrite's system, does not, however, compare favourably with Albert in his scientific studies.

The astronomical beliefs of Albert, though partly