ADDRESS

ON THE APPLICATION OF

THE SCIENCE OF MECHANICS

TO

ENGINEERING PRACTICE.

BY

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"The Application of the Science of Mechanics to Engineering Practice."

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By ARCHIBALD BARR, D.Sc., M. Inst. C.E.,

Regius Professor of Civil Engineering and Mechanics in the University of Glasgow.

OUR President and Council have done me the honour of asking me to address you this evening upon a subject the importance of which can hardly, I think, be overestimated—"the application of the science of mechanics to engineering practice."

Even in their narrowest interpretation, these words suggest a topic wide enough in scope to satisfy the taste of the most discursive of lecturers—a topic which represents the major portion of a two or three years' course of lectures upon engineering science, and which could only be treated in outline in a volume or two on applied mechanics. The comprehensiveness of my subject—which makes any detailed treatment of it impossible, in the time at our disposal this evening—might in itself form a good excuse for dealing only with one or two questions of a very general character, and for making no attempt to discuss such detailed examples of the application of dynamical science to engineering practice as find their proper place in the special treatise or in the class-room demonstration. But I am further advised that, while I may take the title prescribed as indicating in a general way the kind of subjects to bring under your consideration, it is not intended that I should confine myself to any restricted interpretation of the words of the title.

I gather that it is the Council's intention that the Students should be addressed from time to time by Members of the Institution on various matters connected with the scientific basis of their professional work, and it has fallen to me to deliver the first lecture of the series.

There are already published in the Proceedings of the Institution two lectures to which I shall have occasion to refer in what follows, but which may at present be mentioned as dealing with subjects very closely connected with that of our present study—I mean the first and second "James Forrest" lectures. In the first, Sir William Anderson dealt with "The Interdependence of Abstract Science and Engineering,"[1] and in the second, Dr. Hopkinson treated of "The Relation of Mathematics to Engineering."[2] The year that has just closed will long be remembered with sorrow and regret by all connected with this Institution as that in which these two great leaders, eminent both in engineering science and in scientific engineering practice, have been lost to the profession in bodily presence, but the results of their labours will remain as cherished parts of that inheritance of example and of precept which forms the patrimony of our profession. This is not the occasion on which to attempt to estimate their services, nor would it become me to presume to adequately discharge such a task. I would also mention Dr. Kennedy's "James Forrest" lecture on "Physical Experiment in Relation to Engineering"[3] as closely connected with our present subject.

I commend these lectures for your most careful and detailed study. They come from leaders in the profession whose words have all the weight due to distinguished careers and intimate knowledge. If, by referring you to these addresses, I induce any of you who have not already done so, to give them your careful and prolonged study, I shall do a much greater service than I can hope to accomplish by anything I can myself offer for your consideration. No Student of the Institution can read these addresses without gaining at once a sense of the dignity and the responsibilities of his profession, and an incentive to equip himself, by every means within his reach, for the great possibilities that lie before him.

My presence here this evening has no doubt some connection with the examination scheme recently instituted by the Council, or at least with the creed and policy of which that scheme is the outcome. I do not think that it will be considered necessary in these days to discuss the wisdom of the new policy of the Institution, and I daresay that in any case objectors to the scheme—a few of whom no doubt exist within and without the Institution—

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[1] Minutes of Proceedings Inst. C.E., vol. cxiv. p. 255.

[2] *Ibid*, vol. cxviii. p. 331.

[3] *Ibid*, vol. cxxvi. p. 314.

would hardly be disposed to account as of much weight any views or argument that might be advanced by one whose special business it is to offer to students the kind of training that the Institution demands. Justification of the Council's action, if it is required in verbal form, must come, as it has in the Presidential addresses of Sir John Wolfe Barry and our present President, from leaders in engineering practice. For the rest the scheme must await the arbitrament of results.

Had the examination system now instituted by the Council—and accepted with such very general approval—been proposed eight or ten years ago it would no doubt have met with strenuous opposition. A hard fight has been fought in this country over the scientific training of engineers. The action of the Institution, coming as it does with all the weight of authority from the recognized headquarters staff of the profession, sets the question at rest, in one of its aspects at least. But let me here say that much confusion has been introduced into the discussion by those who have opposed the view that scientific knowledge is necessary or even valuable to the engineer, by the continual reiteration of the view that it was a question as *between* scientific and practical training. I had thought that this absurd view of the matter had finally been banished from the minds of objectors to scientific training, but it has again cropped up, in the old form, in a criticism of the Council's scheme. A writer in one of the engineering papers informs us that "at the present moment the profession is divided into two camps—the one believers in theory, the other in practice." One of these camps has no doubt had its occupants, but they seem of late to have been greatly reduced in numbers—I have never known anyone who claimed to belong to the other, and one has only heard of its existence from a few occupants of the camp which relegates to itself the exclusive right to the claim of practical knowledge. It has always seemed strange to me that anyone should specially pride himself in being a practical man, when he means thereby—on some strange and inexplicable principle of exclusion—a man who cares nothing for those natural truths which underlie his practice and form the connections between it and other branches of the constructive arts. The great majority of the leaders and followers of the profession—including those who at present control the destinies of this Institution—are left severely out of the classification referred to.

The aim of the Council in the new movement has, I need hardly say, from the first been perfectly clearly defined. That object is and has been to secure that those who enter the membership of the Institution in the ordinary and normal course, shall be those who have a sufficient belief in the dignity and responsibility of the profession to qualify themselves for a recognized place in its ranks by acquiring, on the one hand, a knowledge of those fundamental principles which must, in the very nature of things, underlie all successful practice, and who, on the other hand, have gained such experience of the details of some particular branch of actual engineering work as will entitle them, in a greater or less degree, to be considered experts in its practice. The present examinations have to do with the former qualification alone. I would express the hope that the Council will not attempt to measure the latter—the practical training—by any examination standard.

Incidentally I may refer to the fact, as very directly bearing upon the arguments I wish to bring before you, that a further confusion has been introduced into the question of the training of engineers by the use of the somewhat ambiguous expression "technical education." It is, I believe, an acknowledged principle in logic that our ideas are never clearly formed unless we have appropriate words in which to clothe them, and for that reason it would be well either to give up the use of the abused word "technical" in regard to education and training, or else to define more precisely what we mean by it. The word "technical" would appear to have as its root meaning, "pertaining to any art"—that is to say, pertaining in a special and exclusive sense to some particular branch of productive work. I take it that, properly speaking, the term should not be applied to any general laws or principles as such, but only to the modes of operation adopted by man in the practice of an art. In this sense the term "technology" is opposed to the term "philosophy," which latter refers to reasoning regarding the essential nature of things. Natural philosophy is that comprehensive science which deals with the laws of nature, and includes dynamics, physics, chemistry, and other branches of our reasoned knowledge of natural laws and phenomena. "Natural philosophy," then, has to do with the unchanging laws of nature, "technology" with the practice—it may be the mutable and temporary practice—of the arts of production. If this be the proper use of the terms, then the study of the essential principles of mathematics, dynamics, physics, chemistry and other branches of pure science, and the application of these to general questions of construction, should not be included under the term "technical education"; and much confusion would be avoided if we used the word "scientific" in place of the word "technical" in regard to training in these branches of knowledge. My purpose in attempting to make this distinction somewhat clearer than it appears to be in the minds of some who use such terms is not merely to explain the origin of much of the confusion to which I have referred—I have a more important object in view. I wish to bring before you as clearly as I can the distinctions between the two classes of knowledge which should form the mental equipment of the engineer.

Something of value regarding the technology of engineering may, I believe, be learned by engineering students in the class-room or from the special manual, more especially, perhaps, of the technology of branches of the profession which lie beyond their own experience and practice. The more one can learn of arts allied to his own the better, and the more likely is he to perceive the directions in which he may make advances in his special department. To that end attendance at the meetings of this and similar institutions, and the study of their proceedings, is of the greatest value, especially to the younger members of the profession. But undoubtedly it is, and I believe it always will be, by actual experience of practical work that the engineer will gain the most valuable portion of his *technical* knowledge.

Many engineering students are only too apt to look to being equipped with a conglomeration of practical "tips" as the outcome of their college course or private study; and a somewhat analogous feeling is manifested in the desire expressed by some of those who have discussed the Council's examination scheme that the questions set should be of what is called a directly practical kind. The duty that has been laid upon me by the Council is to endeavour to show, in regard to one branch of science, that a knowledge of fundamental principles can be of value to the engineer in the practice of his profession—a knowledge, that is, of principles and results of science which are independent of the changing conditions of engineering practice.

And, in the first place, I would urge upon the student to banish, once and for all, from his mind the fatal idea that every phenomenon and every principle presented for his study should have an immediate practical application, or even obvious practicability. If his studies be only general enough, and fundamental enough, and if the principles be grasped in their essences, applications will come in ways he cannot possibly foresee.

The stoic philosopher had a just conception of the end and aim of education when he observed that "the sheep are not to produce the grass which they have eaten, but wool and milk." May we not pursue the simile one step further and note that it is only the lamb or the calf that should seek to be fed upon such milk as it may be one of her functions in after life to produce.

Acting upon the principle indicated, and considering that I have to do with organic beings of some maturity, I do not propose this evening to supply much fluid nourishment in the shape of rules or formulas which you can to-morrow apply in the office or the workshop. I trust to your powers of digestion and assimilation to enable some of you to extract a little nourishment from the raw and possibly green material I put before you, and to produce from it, in other and more directly applicable forms, any nutriment it may contain, or, if the nutritive value be small, at least to find in it some tonic properties.

I notice that someone has been writing to the engineering papers, taking exception to a question set at a recent Institution examination regarding the communication of vibrations to a weight suspended from a spiral spring. I am not surprised that objections should be raised to that question. The connections between subjects very different in their natures, from the practical point of view, can be apparent only to one who has at least some sound knowledge of principles more or less fundamental, and every one has not such knowledge.

The laws of vibration of a pianoforte wire may seem to some people to have little connection with any questions of practical bridge design, and the conditions which govern the communication of such vibrations from one string to another may not, to some people, have any connection with questions of naval architecture and marine engineering. Nevertheless there are such connections, and these are of a most intimate and practically important kind. To anyone who is not able to see that the study of such principles as those embodied in the question referred to, is of importance in relation to engineering practice, I commend a study of Dr. Hopkinson's lecture.[1]

Now I ask you to note very particularly that our subject is the Application of the Science of Mechanics to Engineering Practice. I might adopt the words of the title as a text in the orthodox pulpit style of the "Old Mother Hubbard" sermon, and expatiate upon their appropriateness individually as well as collectively.

In the first place we may ask ourselves, what is meant by

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[1] Minutes of Proceedings Inst. C.E., vol. cxviii. p. 331.

"Engineering Practice"? The vocation of the engineer is a many-sided one, but all of its sides are not engineering practice. The Civil Engineer—to adopt for the moment the popular distinction between different branches of the profession—has to do with many questions of policy and even of politics. The Mechanical Engineer again may come to devote himself entirely to the commercial management of his business. We are not concerned at present with the question of the bearing of scientific knowledge upon such pursuits. Dr. Hopkinson, in the lecture I have already referred to, advised the engineer, who looks upon his profession as "a mere means of making money," to "manage his board and buy his mathematician."[1] No doubt this is sound advice. Old Sackett, you may remember, works on that principle. "There is no science in him, but he knows the value of science . . . . He don't know a logarithm from a twinge of the lumbago. . . . He is no genius and can't contrive anything, but he keeps a genius and works him hard. . . . . He calls himself the business manager of his concern."[2]

Though the political and financial promotion of great schemes and the business management of companies may naturally fall into the hands of engineers, and may demand extensive engineering knowledge and experience, they do not constitute any part of "engineering practice" properly so-called. Engineering is "the art of directing the great sources of power in nature," and I fancy that Tredgold, when he formulated this, which has come to be the authoritative definition of "the profession of civil engineers," had neither Parliamentary Committees nor pounds, shillings and pence in his mind "as the great sources of power in nature."

I take it, then, that in our title or text, "engineering practice" means the design and execution of works in respect to their structural fitness for the purposes they are required to serve. But again it should be borne in mind that it is the art of "directing" the sources of power that constitutes the profession of the engineer—the mere guiding of them in ready-made channels can hardly be looked upon as "engineering practice." There may be a great deal of engineering in the designing of an automatic bolt-making machine—there is none in the turning out of a thousand bolts by its means. There may be a great deal of engineering in the preparation of a standard design for a railway bridge, but there is none in the copying of that design when it has been

[1] Minutes of Proceedings Inst. C.E., vol. cxviii. p. 346.
[2] Extracts from "Chordal's Letters," p. 183.

schemed out. If you are content to adopt what others have schemed, you may be serving a useful purpose in the world, but your work will be that of a mechanic—not that of an engineer—just as much as if you were making those bolts by the thousand on the automatic machine. In civil engineering, we usually distinguish the engineer from the contractor, but there is often more true engineering, that is, more originality and fertility of resource, on the part of the contractor than on the part of the so-called professional man. The "engineer's" share in the work may have consisted in prescribing that at a certain place and time a structure shall be erected the design of which has been evolved by the application of certain rules which constitute a kind of automatic machine tended by a mechanic who claims the title of civil engineer.

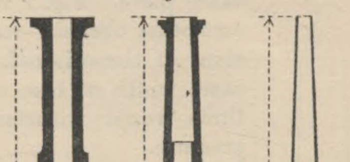
It is original design, then, either in regard to structural features or to modes of execution, that constitutes "engineering practice" properly so called, and to such alone we refer in considering the application of mechanical science. So much, then, for the last words of our text.

Now what do we mean by "the science of mechanics"—I wish we more habitually called it "dynamics"—but, anyway, what do we mean? I have practically answered that question by analogy. We do not mean a "cut and dry" set of rules and formulas, but a reasoned and systematised knowledge of the laws that govern the action of matter under the influence of force. Molesworth's Pocket Book—"the Bible of the engineer," as it has been called—is not a book of dynamical science. It is a book of engineering information if you will—and a most useful one too, to those who know how to use it—but not of science, properly so-called. On the value of a knowledge of the science of mechanics, as distinguished from a set of rules and formulas, I must enlarge later on.

Meantime I shall endeavour to show you, by one or two general illustrations, that a knowledge of something more than customary practice, and the possession of something beyond common sense, are necessary for the engineer, always remembering what we mean, or should mean, by "engineering."

I shall begin with one of the simplest questions in mechanics—that of the stability of a rigid body. Let us consider the case of a person who has been engaged all his life in the erection of chimneys of, say, about 25 feet in height. He will have had great experience. Will that experience alone be a good guide to him if he is called upon to erect a chimney of 100 feet in height? I have shown in *Fig. 1* the sections of three chimneys of, say, 25 feet, 100 feet, and 400 feet respectively. I think it will be clear that such limited experience as we have supposed would probably lead the 25-foot-chimney-specialist to very erroneous ideas as regards the thickness of wall required for a 100-foot structure. Again, if he were called upon to design a chimney of 400 feet in height, would he be likely to propose such a section as that shown in the third figure? Yet these are reasonable and practical designs for the respective heights. The third shows the actual proportions of the chimney at St. Rollox, Glasgow, which is 435 feet in height.[1] Here I have supposed the case of a man having no knowledge of mechanics being called upon to design a structure of the kind in which he is a specialist, but of dimensions outside the range of his experience.

Fig. 1.



Now no step could take the man less out of the lines of his experience, I should fancy, than one in respect to dimensions only. You will readily see that some calculations will be necessary in order to pass from one of these cases to another. Nor would the specialist's experience combined with "common sense" constitute a sufficient equipment. Sir Benjamin Baker, in his most admirable presidential address,[2] well remarked that "it avails" the engineer "little in many things to rely solely upon what is popularly known as 'plain common sense' based upon his own general experience."

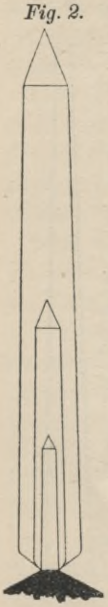
Common sense would hardly, I think, lead one to put confidence in the stability of Cleopatra's Needle as it originally stood on the Thames Embankment; still there is little doubt that it might have remained permanently erect without the support of the castings within which its base is now enclosed. (I do not criti-

[1] For the dimensions of this chimney see Rankine's "Applied Mechanics," Appendix.

[2] Minutes of Proceedings Inst. C.E., vol. cxxiii. p. 29.

cise the wisdom of the authorities in making assurance doubly sure, nor even of humouring the public by giving the obelisk an unnecessary appearance of stability, if that was their object.) Still less do I think that either common sense or the general experience of an engineer would cause him to conclude that an obelisk of half the dimensions and again another of double the dimensions of Cleopatra's Needle—but similar to it in all other respects—would require the same width of base as the obelisk has (or had) to secure like stability against wind-pressure. The most elementary mechanics is, however, sufficient to show that this is the case if no crushing of the material of the obelisk or of its support takes place. *Fig. 2* represents Cleopatra's Needle and two other obelisks—one double and one half the dimensions of the original. All three are shown with the same width of base and, on the assumption made, all three would withstand the same severity of wind pressure.

Fig. 2.



Now let us consider another simple problem. We will take the case of a water-tank supported on a column. *Fig. 3* shows one of usual dimensions and proportions. Suppose it were required to build one of double the dimensions in every respect—except that considerations of strength of structure are to be attended to. Consider merely the weight of the structure and the water it carries. We find at once that to double all the dimensions of the column will not do, since by doubling every size of the tank we increase the weight eightfold, while doubling all the dimensions of the column would only increase the area of section fourfold. The stress per square inch would, therefore, be twice as great as before. We must, then, increase the thickness of the column more than in proportion to the other dimensions—nearly fourfold instead of twofold in fact when we consider the strength necessary to bear the weight only. This is illustrated by *Fig. 4*, which is the larger structure drawn to half the scale on which the original tank is shown in *Fig. 3*.

Now note that increase of dimensions in the case of chimneys made much less than proportional thickness sufficient to give like stability, but in this second case a much greater than proportional thickness is necessary for strength to bear the load.

As a third case, suppose that we consider the same pair of water-tanks, and find what proportions of column that would give suitable strength to resist breaking across by wind-pressure acting on the tanks. We shall find that the thickness of the column need only be increased in proportion to the other dimensions, so that a change of the scale written on the drawing would be enough in that case.

These illustrations show at once that the eye of the draughtsman would be an exceedingly bad guide. If, then, even in these simplified cases experience is not enough, will it suffice in the case of a structure which depends for its permanence upon a combination of stability and strength, and that has to carry its own weight, and some useful load, and to bear wind-pressure as well? I think it clearly will not. Neither common sense, nor

Fig. 3.

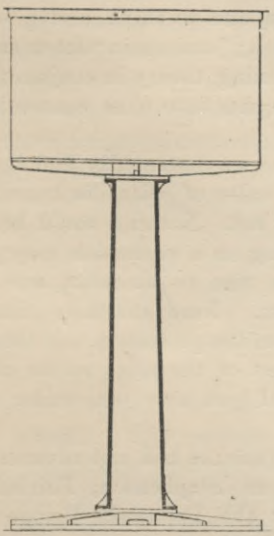
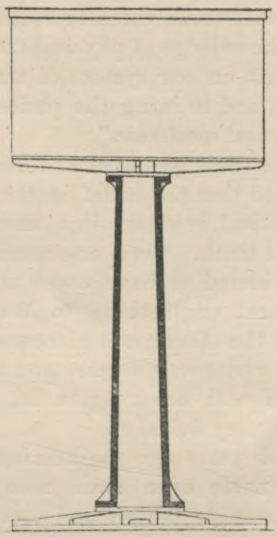


Fig. 4.



past experience, nor any combination of these, unaided by the application of dynamical principles, will enable the engineer to make an important departure in design or construction, nor will it be sufficient to enable him to take any considerable step in regard to magnitude alone even in the most favourable case, that of the kind of structure in respect to which his experience has been gained.

When a great bridge over the Menai Straits was required half a century ago, was all the experience that engineers had previously acquired in bridge-building sufficient? We need not for present purposes enter into the old controversy regarding the relative shares of Robert Stephenson and Sir Wm. Fairbairn in the conception and execution of that epoch-marking work. Both men were eminently qualified to act the part of pathbreakers. What does Robert Stephenson say? "It is to Mr. Bruce's tuition and methods of modelling the mind that I attribute much of my success as an engineer; it was from him that I derived my taste for mathematical pursuits and the facility I possess of applying this kind of knowledge to practical purposes and modifying it according to circumstances." Fairbairn had fewer opportunities than Stephenson who studied science in Edinburgh University, and he felt the difficulty under which he laboured. He says: "I trust the time is not far distant when we shall witness establishments suitable for their (engineers') education;" "an education which above all others will teach them to reason, and to think, and give a more correct knowledge of physical truth;" and again "let us endeavour to engraft on our system of training theory in conjunction with practice, and to bring the philosopher into close connection with the practical mechanic."

I make these quotations because we continually find it assumed and stated that the belief in the value of scientific knowledge to the practical engineer is a new fad. Nothing could be further from the truth. Civil engineering as a profession may properly be considered to have owed its rise to Smeaton, and modern mechanical engineering to Watt. Read carefully their lives, those of the other great pioneers of the profession, and those of the men to whom we owe the greatest of the more recent advances, and you will never again be, if you now are, under such an extraordinary delusion.

But 50 years ago engineering science had not advanced so far as to enable even such men as Stephenson, Fairbairn, and Hodgkinson to design and erect the Britannia Bridge without much special experimental investigation.

The Boyne Viaduct at Drogheda may be looked upon as marking the next conspicuous step in iron-bridge design. Sir William Anderson, in the lecture I referred to,[1] speaks of this work as "a signal illustration of the successful application of abstract principles to a great work by men who were capable not only of appreciating them, but of following their guidance in a practical manner." Only minor experiments on structural parts were required in that case.

Then we come to the greatest work of the class that has yet

[1] Minutes of Proceedings Inst. C.E., vol. cxiv. p. 266.

resulted from the labours of engineers—the Forth Bridge. In its design and realization practical skill, gained necessarily in the execution of works of a very different order, was linked with the most advanced scientific knowledge. Fairbairn looked forward to "a coming age" "when the exact rules of physical truth will be brought to bear upon the constructive and useful arts with the same certainty and effect in the practical operation of the artificer and the mechanic as they now do in the laboratory of the chemist or the observatory of the astronomer."[1] Had he lived to see that work of conspicuous novelty and gigantic proportions carried out without the aid of tentative experiments he would have realized that his "coming age," which no doubt seemed to him to be a great way off, had nearly, if not quite, arrived for some engineers, and that within the short space of 40 years from the day on which he spoke these words—a shorter time than our politicians have required, since the question was first pressed upon their attention, to avail themselves of the facilities engineering has afforded them for the introduction of an ocean penny post.

We pass next from questions of statics of structures to some involving kinetic considerations. We could hardly expect such questions to have more obvious solutions than statical ones.

I have been quoting the opinions of great engineers on the value of scientific knowledge, and remarking on the insufficiency of common sense. I am reminded of a passage I read some years ago from the pen of one of those who made it his business to denounce, in high places, what he seemed to consider the new error of placing confidence in the methods and results of physical science. The passage will, I think, bear quoting, as being more eloquent than any direct arguments that one could bring before you on the subject we are considering this evening. "That much-despised faculty common sense," says this writer, "has always told engineers that when a given volume of air is passed through a channel or trunk its pressure will fall as the trunk augments in dimensions." Now this statement as a whole may be true—common sense may have produced such a delusion; but if so, it is surely high time that common sense should be despised, in regard to such matters, when the science of mechanics is available as an alternative. Venturi, at the end of last century —to name no earlier authorities—knew that the reverse of the supposed phenomenon referred to by the writer was the case in regard to the flow of water at least, and it seems strange that at

[1] "Useful Information for Engineers," by William Fairbairn, p. 100.

the end of the nineteenth century one should place so much confidence in a faculty—if we are to credit the writer with its possession—that leads to the denial of a principle so extensively made use of in practical engineering in such familiar appliances as the jet pump and the injector, not to speak of the denial involved of the principle of the conservation of energy.

So far I have endeavoured to show that at least the *results* arrived at by scientific investigators are necessary for the engineer who would discharge his true function—that of going beyond his actual experience of work hitherto accomplished. But there are some who hold that a knowledge of the methods and abstract principles of science are unnecessary when one has access to pocket-books of formulas and tables; and, indeed, I fear that even engineering students are to be met with now and then who consider that the acquisition of ready-made formulas is of more value to them than the systematic study of general principles. It is not surprising that such should look upon the whole matter as one of "cram," and feel some dismay in the contemplation of the vast array of results to be got up. It must indeed be a truly appalling task to learn the written language of China if one is to become familiar with the significance of some 50,000 more or less arbitrary symbols. Science, however, is not built up in that way, nor is the acquisition of isolated facts education. Now and then a student is met with who seems anxious to place himself more or less in the position of Russell Lowell's "Heavy Reviewer."

> "'Twould be endless to tell you the things that he knew,
> All separate facts, undeniably true,
> But with him or each other they'd nothing to do;
> No power of combining, arranging, discerning,
> Digested the masses he learned into learning."

It is no cause for wonder that

> "His blunders aspired to the rank of an art,
> For his lore was engraft, something foreign that grew in him,
> Exhausting the sap of the nature and true in him."

And so it will be, and is, with the engineer who follows a similar course, but in his case the blunders are put down to the discredit of science. He is called a "theorist," whereas his defect is that he knows no theory.

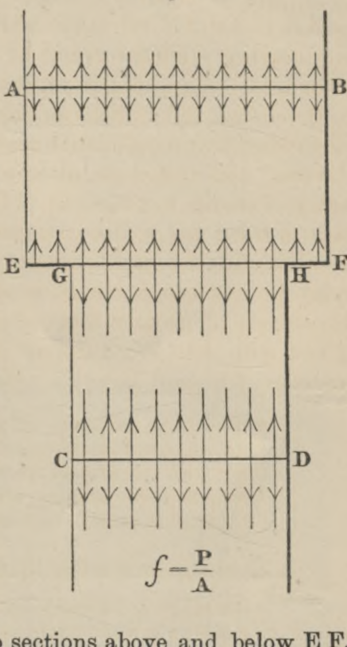
There is nothing I desire so much to impress upon you as the wisdom of having a profound distrust of formulas. You cannot safely use a single formula in Molesworth that has to do with a question of mechanical science unless you know what is behind the symbols. Every formula must be based on a host of assumptions, and it is only one who knows how a particular formula is derived that can be trusted to apply it.

Let me take an illustration or two. I suppose that the formula

$$f = \frac{P}{A}$$

expressing the stress per unit area in a bar subjected to tension, is about as simple a one as could be chosen. I do not know any case in which that formula is strictly true for a member of a structure as a whole, but I do know many cases in which it is not even approximately true.

Fig. 5.



Take, for example, a rod in which there is an abrupt change of sectional area, and subject it to a pull as shown in *Fig. 5.* Suppose the area of the section at A B to be double that of the section at C D. Then, by the formula, the unital stress (stress per square inch, say) will be double as great at C D as it is at A B. If these sections are at some considerable distance from the shoulder E F, and also from the ends of the bar at which the pulling forces are applied, it may be assumed that the stress will be uniformly distributed over these sections—or at least very approximately so. The magnitudes of the stresses will then be as indicated in the figure. Now apply the formula to sections above and below E F, but very close to it, and we get there also the sets of forces shown in the figure. But it is evident that a thin transverse plate in the plane E F cannot be subject to small forces on its upper face and great ones on its lower face. The forces which act on the two faces must be very approximately equal, and the thinner the plate the closer will be the approximation to equality; that is, there can be no abrupt change at the section E F from the smaller forces to the larger ones. It will be seen, further, that near the axis of the bar the forces must have a value between the two

Fig. 6.

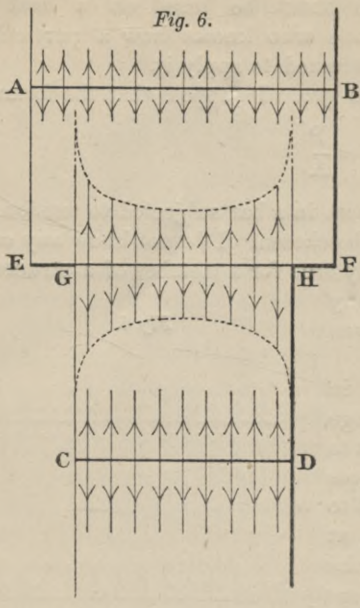
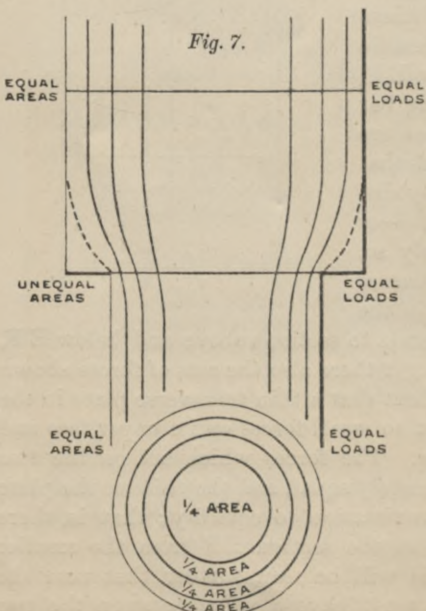


Fig. 7.



values represented in *Fig. 5.* But since the total pull over a section just below E F must be equal to P, and the centre portion does not take its due share of the load, the outer portions will be left to take more than their due share in some such manner as is indicated in *Fig. 6.* There must, therefore, be a concentration of stress near the margin of the neck G H, as shown by the elongation of the barbed lines there. The form of the curve marking the extremities of the force lines will depend upon the properties of the material; but in no case can the stress be uniformly distributed as the formula assumes. The stresses will not be direct-pull stresses, as suggested by the diagram—except just at the axis. The forces shown are only intended to represent the longitudinal components of the actual forces. All we are concerned about at present, however, is that the formula $F = \frac{P}{A}$ is not even approximately true for the section G H of the bar.

This result may be arrived at by a somewhat different mode of reasoning. In *Fig. 7* the same rod is shown with the areas of sections at some distance above and below the shoulder divided into four equal parts. Now consider the portion of the rod which, at any of its transverse sections, bears the central quarter of the total pull. It will have some such outline as that indicated in the *Fig.*, and so also will the portions of the rod which bear each of the other quarters of the load have some such outlines as those indicated. It will be seen that the outermost part has a narrower section in the plane of the shoulder than it has in the region below the shoulder where the stress is uniformly distributed. The outermost quarter of the pull is therefore borne by a smaller area in the region of the shoulder than elsewhere, and, consequently, the outermost element of the section in the plane of the shoulder experiences a greater unital stress than that carried by the material at the section C D, *Fig. 5.* The non-uniformity of distribution may be still more serious when the shoulder constitutes a head which receives or resists the load applied to the bar—as in the case of a bolt.

Fig. 8.

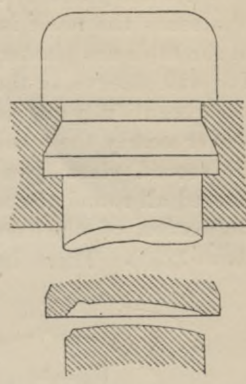
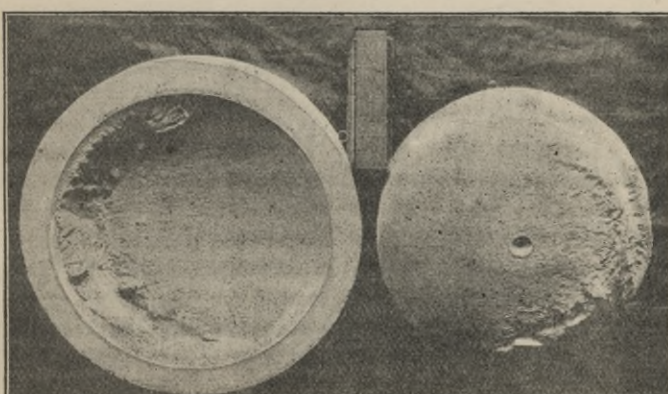
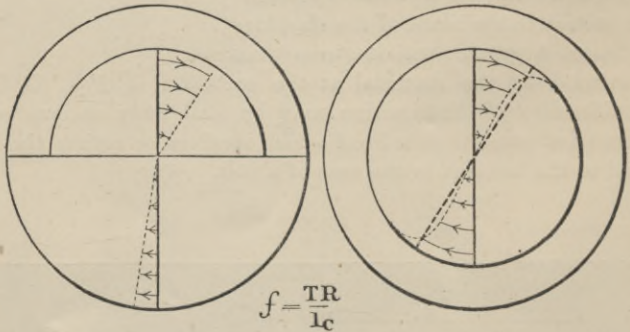


Fig. 9.



The principle above explained is a most important one, and one that is too apt to be neglected. A member of a structure is designed so as to have—by the formula—a stress, say, of 5 tons per square inch, and it is assumed that, as the strength of the steel of which the member is made is, say, 30 tons per square inch, there is a factor of safety of 6. As a matter of fact there may be no margin of safety whatever. The upper diagram in *Fig. 8* represents the head of a hydraulic press tie (or "column," as it is usually called) of 8 inches diameter, and the lower diagram represents the mode in which it actually gave way. The models on the table are plaster casts from the fractured surfaces, *Fig. 9*. You will observe, in the first place, that the surface of the fracture has a beautifully curved form, and is almost as smooth and regular —over nearly the whole area—as if it had been turned. And, in the second place, you will observe that the fracture has commenced all round the margin of the neck at a definite angle (the inclination of the fractured surface to the transverse plane is about $22\frac{1}{2}°$). There has been no capriciousness in this fracture.

Figs. 10.



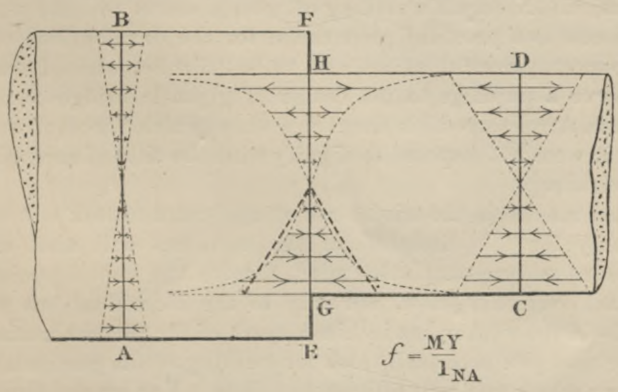
Indeed quite a number of these ties in a set of presses failed in almost exactly the same manner. They were designed so as to be amply safe according to the formula ; the calculated stress was under 5 tons per square inch. Of course it will be said that the corners should not have been so sharp. That is so, rounded corners greatly diminish the concentration of stress at the margin of the neck, but they can only cause the maximum stress to approximate more or less to the conditions of the formula—they cannot make the formula true.

Like reasoning to that given above for tension applies to torsion and to bending in members of discontinuous section, as illustrated in *Figs. 10* and *11*. These figures will need no further description.

The examples given may suffice, by way of illustration, to show the danger of trusting formulas unless the principles and assumptions upon which they are based are fully understood and kept in view.

It may be asked whether such matters as these could not and should not be set down in the books so that the right result could be selected for any case in point. Well, I think the limitations of the applicability of all formulas deduced by mathematical and dynamical reasoning might be, and ought to be, brought much more prominently before the student than they usually are; still, every new case has its own new exceptions to any rules that can be formulated. It is only a thorough understanding of fundamental principles, and of the assumptions involved and required in formulas founded upon them, that can constitute a safe equipment of knowledge in the science of mechanics. No codification

Fig. 11.



of the laws of the land can show an obvious solution of all questions that may arise between man and man, and no dictionary of medicine can ever take the place of the trained practitioner; nor is *Punch's* grand conception of the automatic doctor the model after which any epitome of engineering science can be built—

> "Note the ailment that you've got,
> Cardiac, or else hepatic,
> Put a penny in the slot—
> Lo! the action's automatic."

In any case, though the mechanism might not be beyond the skill of the engineer to produce, rather disastrous effects might result to the man in the street who put his penny in the wrong slot.

Those who have their careers before them should always remember that the practice of to-day may be obsolete to-morrow. Think what changes have come over engineering practice within experience of the present leaders of the profession. If your whole equipment of knowledge is limited to your present needs, and to the conditions of present-day practice, you may find, when the time comes, when you should lead and not follow, that your equipment of knowledge may be of as much value to you as a last year's almanac.

Many engineering pupils and apprentices, again, are too apt to feel that they have not opportunities for gaining experience upon a sufficiently extensive scale. For such I should prescribe, as a tonic, a course of reading of the biographies of the great engineers. Smeaton's and Watt's experience gained in the manufacture of scientific instruments, together with their studies in science, equipped them for the founding of two great branches of our profession. Nasmyth's making of models seems to have sufficed in his case as a practical preparation for the development of one of the most powerful of modern tools. Sir Benjamin Baker did not serve a pupilage to the design of gigantic bridges; and Sir William Arrol served his time in a shop which those of us who knew it were not disposed to dignify with the title of an engineering workshop.

What may seem the trivial round and common task will suffice not only for the discipline of the man, but will also, to the awakened and contemplative mind, furnish the starting-point for new achievements—new, not only to the individual but to the world—if the worker has in him a spark of the pioneer instinct.

Nor need you necessarily look for training in the particular line of work which you will ultimately follow. You cannot foresee in what direction your life-work will lie if you are possessed of the qualities that will lead to high success in your profession. Siemens worked to produce an improved air-engine, and by a natural development was led to the invention of the regenerative steel-melting furnace! There is nothing more characteristic of the history of the arts than the fact that almost every epoch-making departure has been taken by someone whose training lay in an altogether different direction.

What new departures in engineering requirements and practice are before you, I do not consider myself sufficiently invested with the prophet's mantle to presume to indicate; but of this we may be sure, there are as great changes before you as the last half-century has witnessed. Consider then what will be your equipment if, in the course of your professional life, you are brought face to face with new requirements and novel conditions. What will be left to you that is common to the old and the new?

You have it in your power to ensure for yourself at least three possessions which will stand you in good stead. You may carry with you that self-reliance which is the natural result of labour and achievement; you may have developed that faculty, so hard to describe, which is the lasting possession of the man of experience; and lastly, you may retain, in as far as you have acquired it, the knowledge of those principles of science which belong to the nature of things, and are subject to none of the mutations of man's ever-changing needs.

I have endeavoured this evening to say to you, as students of engineering, a few words of hope and of encouragement. Let none deceive you into the belief that you have no concern with the truths of science, or that your calling has no points of contact with that of the investigators who dissect the structure of the physical world. They and we deal with the same materials and the same forces. They teach us how, and of what, the natural universe is built. It is for us, as engineers, to fashion, by the application of the principles they formulate for us, new creations, which shall, so far as they are perfect, take their place side by side with Nature's own handiwork, as being equally with it in conformity with the laws that govern the material world.

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