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Seventh wrangler in the Cambridge mathematical tripos in 1826, Henry Moseley (1801–72) was adept at applying mathematical analysis to a wide variety of problems. Appointed professor of natural and experimental philosophy and astronomy at London's newly established King's College in 1831, he was instrumental in creating the institution's department of engineering and applied science. This 1843 textbook is based on the lectures in statics, dynamics and structures that he gave to students of engineering and architecture. Moseley draws on the latest continental work in mechanics, and the treatment of problems is mathematically sophisticated. Starting with basic statics and dynamics, Moseley covers topics of interest to both civil and military engineers, with sections on the theory of machines and on the stability of walls, arches and other structures. Notably, the American edition of this work was adopted as a textbook by the United States Military Academy at West Point.

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The Mechanical Principles of Engineering and Architecture

Henry Moseley

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THE

MECHANICAL PRINCIPLES

OF

ENGINEERING

AND

ARCHITECTURE.

By the same Author,

ILLUSTRATIONS OF PRACTICAL MECHANICS;

AND

A TREATISE

ON

HYDROSTATICS AND HYDRODYNAMICS.

London:
Printed by A. Spottiswoode,
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THE

MECHANICAL PRINCIPLES

OF

ENGINEERING

AND

ARCHITECTURE.

BY

THE REV. HENRY MOSELEY, M.A. F.R.S.

LATE OF ST. JOHN'S COLLEGE, CAMBRIDGE; PROFESSOR OF NATURAL PHILOSOPHY AND ASTRONOMY IN KING'S COLLEGE, LONDON.

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1843.

PREFACE.

In the following work, I have proposed to myself to apply the principles of mechanics to the discussion of the most important and obvious of those questions which present themselves in the practice of the engineer and the architect; and I have sought to include in that discussion all the circumstances on which the practical solution of such questions may be assumed to depend. It includes the substance of a course of lectures delivered to the students of King's College in the department of engineering and architecture, during the years 1840, 1841, 1842.*

In the first part I have treated of those portions of the science of Statics which have their application in the theory of machines and the theory of construction.

In the second, of the science of Dynamics, and, under this head, particularly of that union of a continued pressure with a continued motion which has received from English writers the various names of

* The first 170 pages of the work were printed for the use of my pupils in the year 1840. Copies of them were about the same time in the possession of several of my friends in the Universities.

" dynamical effect," " efficiency," " work done," " labouring force," "work," &c.; and "moment d'activité," "quantité d'action," "puissance mécanique," "travail," from French writers.

Among the latter this variety of terms has at length given place to the most intelligible and the simplest of them, " travail." The English word " work" is the obvious translation of " travail," and the use of it appears to be recommended by the same considerations. The work of overcoming a pressure of one pound through a space of one foot has in this country been taken as the unit, in terms of which any other amount of work is estimated; and in France the work of overcoming a pressure of one kilogramme through a space of one metre. M. Dupin has proposed the application of the term dyname to this unit.

I have gladly sheltered myself from the charge of having contributed to increase the vocabulary of scientific words by assuming the obvious term " unit of work" to represent concisely and conveniently enough the idea which is attached to it, without translation.

The work of any pressure operating through any space is evidently measured in terms of such units, by multiplying the number of pounds in the pressure by the number of feet in the space, if the direction of the pressure be continually that in which the space is described. If not, it follows, by a simple geometrical deduction, that it is measured by the product of the number of pounds in the pressure, by the number of feet in the projection of the space described*, upon the direction of the pressure ; that is, by the product of the pressure by its virtual velocity. Thus, then, we conclude, at once, by the principle of virtual velocities, that if a machine work under a constant equilibrium of the pressures applied to it, or if it work uniformly, then is the aggregate work of those pressures which tend to accelerate its motion equal to the aggregate work of those which tend to retard it ; and, by the principle of *vis viva*, that if the machine do not work under an equilibrium of the forces impressed upon it, then is the aggregate work of those which tend to accelerate the motion of the machine greater or less than the aggregate work of those which tend to retard its motion by one half the aggregate of the *vires vivæ* acquired or lost by the moving parts of the system, whilst the work is being done upon it. In no respect have the labours of the illustrious president of the Academy of Sciences more contributed to the developement of the theory of machines than in the application which he has so successfully made to it of this principle of *vis viva*.† In the elementary discussion of this principle, which is given by M. Poncelet, in the introduction to his *Mécanique Industrielle*, he has revived the term *vis inertiæ* (*vis*

* If the direction of the pressure remain always parallel to itself, the space described may be any finite space; if it do not, the space is understood to be so small, that the direction of the pressure may be supposed to remain parallel to itself whilst that space is described.

† See Poncelet, *Mécanique Industrielle*, troisième partie.

inertiæ, *vis insita*, Newton), and, associating with it the definitive idea of a force of resistance opposed to the acceleration or the retardation of a body's motion, he has shown (Arts. 66. and 122.) the work expended in overcoming this resistance through any space to be measured by one half the *vis viva* accumulated through the space; so that throwing into the consideration of the forces under which a machine works, the *vires inertiæ* of its moving elements, and observing that one half of their aggregate *vis viva* is equal to the aggregate work of their *vires inertiæ*, it follows, by the principle of virtual velocities, that the difference between the aggregate work of those forces impressed upon a machine, which tend to accelerate its motion, and the aggregate work of those which tend to retard the motion, is equal to the aggregate work of the *vires inertiæ* of the moving parts of the machine: under which form the principle of *vis viva* resolves itself into the principle of virtual velocities. So many difficulties, however, oppose themselves to the introduction of the term *vis inertiæ*, associated with the definitive idea of an opposing force, into the discussion of questions of mechanics, and especially of practical and elementary mechanics, that it has appeared to the author of this work desirable to avoid it. It is with this view, that in the following work a new interpretation is given to that function of the velocity of a moving body which is known as its *vis viva;* one half that function being interpreted to represent the number of units of work *accumulated* in the body so long as its motion is continued, and which number of units of work it is capable of reproducing upon any resistance which may be opposed to its motion, and bring it to rest. A very simple investigation (Art. 66.) establishes the truth of this interpretation, and gives to the principle of *vis viva* the following new and more simple enunciation:—"The difference between the aggregate work done upon the machine, during any time, by those forces which tend to accelerate the motion, and the aggregate work, during the same time, of those which tend to retard the motion, is equal to the aggregate number of units of work accumulated in the moving parts of the machine during that time if the former aggregate exceed the latter, and lost from them during that time if the former aggregate fall short of the latter." Thus, then, if the aggregate work of the forces which tend to accelerate the motion of a machine exceeds that of the forces which tend to retard it, then is the surplus work (that done upon the driving points, above that expended upon the prejudicial resistances and upon the working points) continually accumulated in the moving elements of the machine, and their motion is thereby continually accelerated. And if the former aggregate be less than the latter, then is the deficiency supplied from the work already accumulated in the moving elements, so that their motion is in this case continually retarded.

The moving power divides itself whilst it operates in a machine, first, into that which overcomes the prejudicial resistances of the machine, or those which are opposed by friction and other causes, uselessly absorbing the work in its transmission. Secondly, into that which accelerates the motion of the various moving parts of the machine, and which accumulates in them so long as the work done by the moving power upon it exceeds that expended upon the various resistances opposed to the motion of the machine. Thirdly, into that which overcomes the useful resistances, or those which are opposed to the motion of the machine at the working point, or points, by the useful work which is done by it.

Between these three elements there obtains in every machine a mathematical relation, which I have called its MODULUS. The general form of this modulus I have discussed in a memoir on the "Theory of Machines" published in the *Philosophical Transactions* for the year 1841. The determination of the particular moduli of those elements of machinery which are most commonly in use is the subject of the third part of the following work. From a combination of the moduli of any such elements there results at once the modulus of the machine compounded of them.

When a machine has acquired a state of uniform motion work ceases to accumulate in its moving elements, and its modulus assumes the form of a direct relation between the work done by the motive power upon its driving point and that yielded at its working points. I have determined by a general method* the modulus in this case, from that statical relation between the driving and working pressures upon the machine which obtains in the state bordering

* Art. 152. See *Phil. Trans.*, 1841, p. 290.

upon its motion, and which may be deduced from the known conditions of equilibrium and the established laws of friction. In making this deduction I have, in every case, availed myself of the following principle, first published in my paper on the theory of the arch read before the Cambridge Philosophical Society in Dec. 1833, and printed in their *Transactions* of the following year:—"In the state bordering upon motion of one body upon the surface of another, the resultant pressure upon their common surface of contact is inclined to the normal, at an angle whose tangent is equal to the coefficient of friction."

This angle I have called the limiting angle of resistance. Its values calculated, in respect to a great variety of surfaces of contact, are given in a table at the conclusion of the second part, from the admirable experiments of M. Morin *, into the mechanical details of which precautions have been introduced hitherto unknown to experiments of this class, and which have given to our knowledge of the laws of friction a precision and a certainty hitherto unhoped for.

Of the various elements of machinery those which rotate about cylindrical axes are of the most frequent occurrence and the most useful application; I have, therefore, in the first place sought to establish the general relation of the state bordering upon motion between the driving and the working pressures upon such a machine, reference being had to the weight of

* *Nouvelles Expériences sur le Frottement,* Paris, 1833.

the machine.* This relation points out the existence of a particular direction in which the driving pressure should be applied to any such machine, that the amount of work expended upon the friction of the axis may be the least possible. This direction of the driving pressure always presents itself on the same side of the axis with that of the working pressure, and when the latter is vertical it becomes parallel to it; a principle of the economy of power in machinery which has received its application in the parallel motion of the marine engines known as the Gorgon Engines.

I have devoted a considerable space in this portion of my work to the determination of the modulus of a system of toothed wheels; this determination I have, moreover, extended to bevil wheels, and have included in it, with the influence of the friction of the teeth the wheels, that of their axes and their weights. An approximate form of this modulus applies to any shape of the teeth under which they may be made to work correctly; and when in this approximate form of the modulus the terms which represent the influence of the friction of the axis and the weight of the wheel are neglected, it resolves itself into a well known theorem of M. Poncelet, reproduced by M. Navier and the Rev. Dr. Whewell.† In respect

* In my memoir on the "Theory of Machines" (*Phil. Trans.* 1841), I have extended this relation to the case in which the number of the pressures and their directions are any whatever. The theorem which expresses it is given in the Appendix of this work.

† In the discussion of the friction of the teeth of wheels, the

to wheels having epicycloidal and involute teeth, the modulus assumes a character of mathematical exactitude and precision, and at once establishes the conclusion (so often disputed) that the loss of power is greater before the teeth pass the line of centres than *at corresponding points* afterwards; that the contact should, nevertheless, in all cases take place partly before and partly after the line of centres has been passed. In the case of involute teeth, the proportion in which the arc of contact should thus be divided by the line of centres is determined by a simple formula; as also are the best dimensions of the base of the involute, with a view to the most perfect economy of power in the working of the wheels.

The greater portion of the subjects discussed in the third part of my work I believe to be entirely new to science. In the fourth part I have treated of "the theory of the stability of structures," referring its conditions, so far as they are dependent upon rotation, to the properties of a certain line which may be conceived to traverse every structure, passing through those points in it where its surfaces of contact are intersected by the resultant pressures upon them. To this line, whose properties I first discussed in a memoir upon "the Stability of a System of Bodies in Contact," printed in the sixth volume of the *Camb. Phil. Trans.*, I have given the name of

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direction of the mutual pressures of the teeth is determined by a method first applied by me to that purpose in a popular treatise, entitled *Mechanics applied to the Arts*, published in 1834.

the line of resistance; it differs essentially in its properties from a line referred to by preceding writers under the name of the curve of equilibrium or the line of pressure.

The distance of the line of resistance from the extrados of a structure, at the point where it most nearly approaches it, I have taken as a measure of the stability of a structure, and have called it the modulus of stability*; conceiving this measure of the stability to be of more obvious and easier application than the coefficient of stability used by the French writers.

That structure in respect to every independent element of which, the modulus of stability is the same, is evidently the structure of the greatest stability having a given quantity of material employed in its construction; or of the greatest economy of material having a given stability.

The application of these principles of construction to the theory of piers, walls supported by counterforts and shores, buttresses, walls supporting the thrust of roofs and the weights of the floors of dwellings, and Gothic structures, has suggested to me a class of problems never, I believe, before treated mathematically.

I have applied the well known principle of Coulomb

* This idea was suggested to me by a rule for the stability of revêtement walls attributed to Vauban, to the effect, that the resultant pressure should intersect the base of such a wall at a point whose distance from its extrados is $\frac{4}{9}$ths the distance between the extrados at the base and the vertical through the centre of gravity.

to the determination of the pressure of earth upon revêtement walls, and a modification of that principle, suggested by M. Poncelet, to the determination of the resistance opposed to the overthrow of a wall backed by earth. This determination has an obvious application to the theory of foundations.

In the application of the principle of Coulomb I have availed myself, with great advantage, of the properties of the limiting angle of resistance. All my results have thus received a new and a simplified form.

The theory of the arch I have discussed upon principles first laid down in my memoir on "the Theory of the Stability of a System of Bodies in Contact," before referred to, and subsequently in a memoir printed in the "Treatise on Bridges" by Professor Hosking and Mr. Hann.* They differ essentially from those on which the theory of Coulomb is founded†; when, nevertheless, applied to the case treated by the French mathematicians they lead to identical results. I have inserted at the conclusion of my work the tables of the thrust of circular arches, calculated by M. Garidel from formulæ founded on the theory of Coulomb.

The fifth part of the work treats of the "strength

* I have made extensive use of the memoir above referred to in the following work, by the obliging permission of the publisher, Mr. Weale.

† The theory of Coulomb was unknown to me at the time of the publication of my memoirs printed in the *Camb. Phil. Trans.* For a comparison of the two methods see Mr. Hann's treatise.

of materials," and applies a new method to the determination of the deflexion of a beam under given pressures.

In the case of a beam loaded uniformly over its whole length, and supported at four different points, I have determined the several pressures upon the points of support by a method applied by M. Navier to a similar determination in respect to a beam loaded at given points.*

In treating of rupture by elongation I have been led to a discussion of the theory of the suspension bridge. This question, so complicated when reference is had to the weight of the roadway and the weights of the suspending rods, and when the suspending chains are assumed to be of uniform thickness, becomes comparatively easy when the section of the chain is assumed so to vary its dimensions as to be every where of the same strength. A suspension bridge thus constructed is obviously that which, being of a given strength, can be constructed with the least quantity of materials; or, which is of the greatest strength having a given quantity of materials used in its construction.†

The theory of rupture by transverse strain has suggested a new class of problems, having reference to the forms of girders having wide flanges connected by

* As in fig. p. 521. of the following work.

† That particular case of this problem, in which the weights of the suspending rods are neglected, has been treated by Mr. Hodgkinson in the fourth vol. of the *Manchester Transactions*, with his usual ability. He has not, however, succeeded in effecting its complete solution.

slender ribs or by open frame work: the consideration of their strongest forms leads to results of practical importance.

In discussing the conditions of the strength of breast-summers, my attention has been directed to the best positions of the columns destined to support them, and to a comparison of the strength of a beam carrying a uniform load and supported freely at its extremities, with that of a beam similarly loaded but having its extremities firmly imbedded in masonry.

In treating of the strength of columns I have gladly replaced the mathematical speculations upon this subject, which are so obviously founded upon false data, by the invaluable experimental results of Mr. E. Hodgkinson, detailed in his well known paper in the *Philosophical Transactions* for 1840.

The sixth and last part of my work treats on "impact;" and the Appendix includes, together with tables of the mechanical properties of the materials of construction, the angles of rupture and the thrusts of arches, and complete elliptic functions, a demonstration of the admirable theorem of M. Poncelet for determining an approximate value of the square root of the sum or difference of two squares.

In respect to the following articles of my work I have to acknowledge my obligations to the work of M. Poncelet, entitled *Mécanique Industrielle*. The mode of demonstration is in some, perhaps, so far varied as that their origin might with difficulty be traced; the principle, however, of each demonstration

—all that constitutes its novelty or its value—belongs to that distinguished author.

30*, 38, 40, 45, 46, 47, 52, 58, 62, 75, 108†, 123, 202, 267‡, 268, 269, 270, 349, 354, 365.§

* The enunciation only of this theorem is given in the *Méc. Ind.*, 2me partie, Art. 38.

† Some important elements of the demonstration of this theorem are taken from the *Méc. Ind.*, Art. 79. 2me partie. The principle of the demonstration is not, however, the same as in that work.

‡ In this and the three following articles I have developed the theory of the fly-wheel, under a different form from that adopted by M. Poncelet (*Méc. Ind.*, Art. 56. 3me partie). The principle of the whole calculation is, however, taken from his work. It probably constitutes one of the most valuable of his contributions to practical science.

§ The idea of determining the work necessary to produce a given deflection of a beam from that expended upon the compression and the elongation of its component fibres was suggested by an observation in the *Méc. Ind.*, Art. 75. 3me partie. An error presents itself in the determination given by M. Poncelet in that article of the linear deflection f of a beam under a given deflecting pressure P. It consists in assuming that the work of the deflecting pressure is represented by Pf, as it would be if, in order to deflect the beam, P must always retain the same value instead of varying directly as the deflection. The true value of the work is $\frac{1}{2}Pf$; the determination of which requires a knowledge of the law of the deflection, which the demonstration does not suppose. It is due to M. Poncelet to state that the *Mécanique Industrielle* was published (uncorrected) without his concurrence or knowledge, in Belgium, from a MS. copy of his lectures lithographed for the use of the workmen at Metz to whom they were addressed.

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ERRATA.

Page 36. line 2. from bottom, *for* $x_1^{\frac{2}{3}}$ *read* $x_1^{\frac{3}{2}}$.
55. line 5. from bottom, *for* ABDC *read* AEFC.
64. line 3. from bottom, *for* Y_2 *read* y_2.
64. line 5. from bottom, *for* Y_{n-0} *read* Y_{n-1}.
122. line 10. from top, *for* half *read* double.
167. line 8. from top, *for* B_1 *read* B.
172. line 3. from top, *for* 114 *read* 119.
173. line 5. from bottom, *for* $\frac{P_2 a_2^2}{a_2^2} V_1^2$ *read* $\frac{P_2 a_2^2}{a_1^2} V_1^2$.
174. line 8. from top, *for* b^2 *read* b_2.
521. line 6. from top, *for* $\frac{1}{2}$ in. square *read* $\frac{3}{16}$ in. by $\frac{7}{16}$ in.

In the table page 152. the words "without unguent" enclosed by a bracket opposite to the words "iron upon oak," belong (with the corresponding numbers) to the following bracket.