XVIII. *Experiments on the elasticity and strength of hard and soft steel. In a Letter to* THOMAS YOUNG, *M. D. For. Sec. R. S. By Mr.* THOMAS TREDGOLD, *Civil Engineer.*

Read March 25, 1824.

SIR, *London, Dec. 16, 1823*

IF a piece of very hard steel be softened, it is natural to suppose that the operation will produce a corresponding change in the elastic power, and that the same load would produce a greater flexure in the soft state than in the hard one, when all other circumstances were the same. Mr. COULOMB inferred from some comparative experiments on small specimens, that the state of temper does not alter the elastic force of steel; and your Experiments on Vibration led to the same conclusion (Nat. Philos. II. 403). But the subject appeared to require further investigation, and particularly because it afforded an opportunity of ascertaining some other facts respecting steel, which had not been before examined.

In making the experiments which I am about to describe, each bar was supported at its ends by two blocks of cast iron. These blocks rested upon a strong wooden frame. The scale to contain the weights was suspended from the middle of the length of the bar, by a cylindrical steel pin of about $\frac{3}{8}$ths of an inch in diameter. And as in experiments of this kind it is desirable to have the means of raising the weight from the bar, without altering its position, in order to know when the load is sufficient to produce a permanent change of structure, I have a powerful screw with a fine thread fixed over the center of the apparatus, by which the scale can be raised or lowered, when the cords on which the screw acts are looped on to the cross pin by which the scale is suspended.

To measure the flexure, a quadrantal piece of mahogany is fixed to the wooden frame; two guides are fixed on one edge of the mahogany, in which a vertical bar slides, and gives motion to an index. The bar and index are so balanced, that one end of the bar bears with a constant pressure on the specimen, and the graduated arc over which the index moves is divided into inches, tenths, and hundredths; and thousands are measured by a vernier scale on the end of the index. There is a screw at the lower end of the vertical bar, by which the index is set to zero, when necessary. Plate XX.

The first trials were made with a bar of blistered steel of a very good quality. It was drawn out by the hammer to the width and thickness I had fixed upon, and then filed true and regular. It was then hardened, and tempered to the same degree of hardness as common files.

The total length of the bar was 14 inches; the distance between the supports 13 inches; the breadth of the bar 0.95 inches, and the depth 0.375 inches; the thermometer varied from 55° to 57° at the times of trial.

	lbs.		inches.
With a load of	54	the depression in the middle was	0.02
	82	- - - - -	0.03
	110	- - - - -	0.04

The last load remained on the bar some hours, but produced no permanent alteration of form.

The temper of the bar was then lowered to a rather deep straw yellow, and it was tried again; when the same loads produced exactly the same flexures as before.

The temper was then lowered till the colour was an uniform blue, or spring temper; and the trials were repeated with the same loads; but the flexures were still the same.

It was now heated to redness and very slowly cooled. In this state the same loads still produced the same flexures; and the load of 110 lbs. caused no permanent change of form.

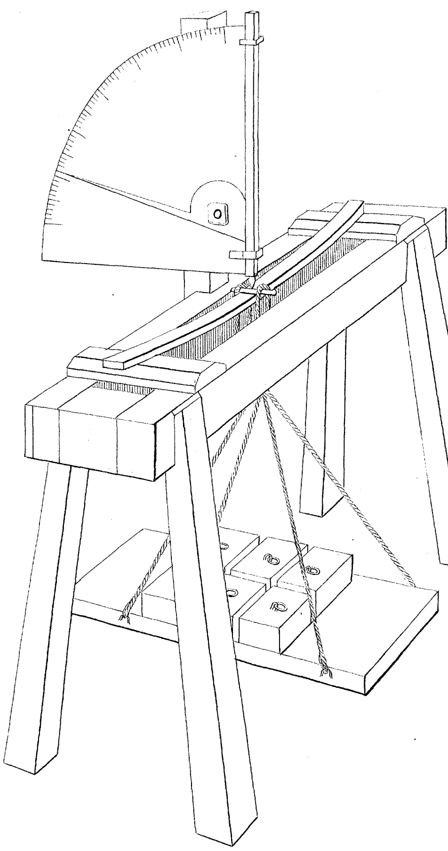
The bar was hardened again, and made very hard; in this state the same loads produced the same flexures; and

	lbs.		inches.
with a load of	300	the depression in the middle was	0.115
	350	- - -	0.130
	580	- - -	broke.

When the bar was relieved from the load of 350 lbs. it retained a permanent flexure of 0.005 inches, which increased to 0.01 with the addition of 10 lbs. to the load.

I found that a bar of much greater length might be tempered without difficulty, and therefore had another bar made of the same kind of steel; the length of which being 25 inches, about double the flexure could be given with the same strain upon the material, and therefore any small degree of difference in the elastic force might be more easily detected, for the preceding experiments are sufficient to show that if there be any difference, it must be extremely small.

The breadth of this bar was 0.92 inches; the depth 0.36 inches; and the distance between the supports 24 inches. It was soft, so as to yield easily to the file.



J. Basire sc.

	lbs.		inches.
with a load of	18.6	the depression in the middle was	0.05
	37.0	- - - - - - -	0.10
	47.0	- - - - - - -	0.127

The bar was then hardened, so that a file made no impression on any part of it, and the same loads did not produce flexures that were sensibly different from those in the soft state.

I then lowered the temper till it assumed an uniform straw colour;

	lbs.		inches.
when with a load of	47	the depression in the middle was	0.127
	85	- - - - - - -	0.230
	130	- - - - - - -	0.350
	150	- - - - - - -	0.400

The load of 150lbs. produced a permanent set of 0.012, but 130lbs. produced no sensible effect. The loading was con-

	lbs.		Inches.
tinued, and with	185	the depression in the middle was	0.50
	385	- - - - - - -	1.04

When 385lbs. had been upon the bar about a minute, it emitted a faint creaking sound, and consequently I ceased to add fresh weights; in about fourteen minutes the bar broke, exactly in the middle of the length.

On comparing the fractures of the specimens, there was no apparent difference except in colour. The grain was fine, and equal; the small sparkles of metallic lustre abundant, and equally diffused; but in the harder specimen they had a whiter ground.

From these experiments it appears that the elastic force of steel is sensibly the same in all states of temper.

The height of the modulus of elasticity, calculated by the

formula you have given in your Nat. Phil. (Vol. II. p. 48) is, according to the first experiment, - - 8,827,300 feet.
And according to the second experiment 8,810,000 feet.

Now the height of the modulus, as you had determined it for steel by Experiments on Vibration, is 8,530,000 feet. (Nat. Phil. II. p. 86.) The modulus for cast steel calculated from DULEAU'S experiments (Essai Théorique et Expérimental sur le Fer Forgé, p. 38) is 9,400,000 feet, and for German steel 6,600,000 feet.

The force which produces permanent alteration is to that which causes fracture in hard steel, as 350:580; or as 1:1.66 in the same steel of a straw yellow temper as 150 : 385, or as 1 : 2.56.

When the tension of the superficial particles at the strain which causes permanent alteration, is calculated by the formula given in my Essay on the Strength of Iron, p. 146, 2nd Edition, it is 45,000lbs. upon a square inch in tempered steel; and the absolute cohesion 115,000lbs. Mr. RENNIE found the direct cohesion of blistered steel to be 133,000lbs. (Philosophical Transactions for 1818.)

But in the very hard bar, the strain which produced permanent alteration was 51,000lbs. for a square inch, and the absolute cohesion only 85,000lbs.

From these comparisons I think it will appear, that in the hardening of steel, the particles are put in a state of tension among themselves, which lessens their power to resist extraneous force. The amount of this tension should be equal to the difference between the absolute cohesion in different states. Taking Mr. RENNIE'S experiment as the measure of cohesion in the soft state, it will be 133,000 − 115,000 =

18,000lbs. for the tension with a straw yellow temper; and 133,000 — 85,000 = 48,000lbs. for the tension in hard steel. And if this view of the subject be correct, the phenomena of hardening may be explained in this manner, which nearly agrees with what you have observed in your Lectures I, p. 644: after a piece of steel has been raised to a proper temperature, a cooling fluid is applied capable of abstracting heat more rapidly from the surface than it can be supplied from the internal parts of the steel. Whence the contraction of the superficial parts round the central ones which are expanded by heat; and the contraction of the central parts in cooling, while they are extended into a larger space than they require at a lower temperature, produces that uniform state of tension, which diminishes so much the cohesive force in hard steel. The increase of bulk by hardening agrees with this explanation; and it leads one to expect, that any other metal might be hardened if we could find a means of abstracting heat with greater velocity than its conducting power.

I am, Sir,

Your most obedient Servant,

THOMAS TREDGOLD.

To Dr. Thomas Young,
&c. &c.