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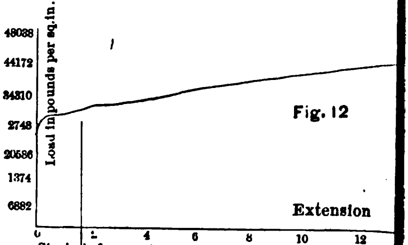


Fig. 12

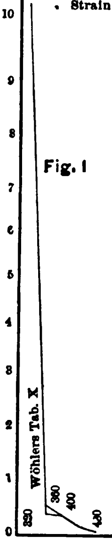


Fig. 1

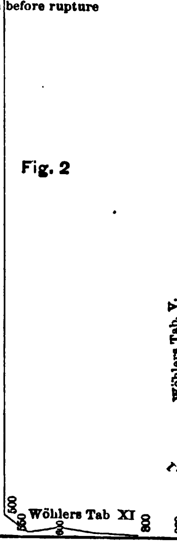


Fig. 2

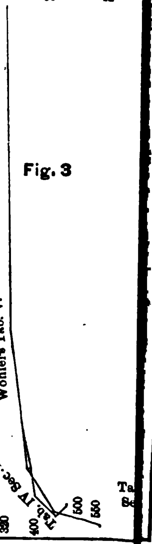


Fig. 3

THE

FATIGUE OF METALS

UNDER

REPEATED STRAINS.

With various Tables of Results of Experiments.

FROM THE GERMAN OF

Prof. LUDWIG SPANGENBURG,

WITH A PREFACE BY

S. H. SHREVE, A. M.

NEW YORK:
D. VAN NOSTRAND, PUBLISHER,
23 MURRAY AND 27 WARREN STREET.
1876.

PREFACE.

"The Fatigue of Metals" is the name which has been given to the effect produced by oft-repeated impacts or strains.

Spangenberg's experiments, an account of which, translated for VAN NOSTRAND'S MAGAZINE, is given in the following treatise, were, as will be seen, in continuation of Woehler's. The results of these very important experiments have been before the profession for some years, but, strange to say, seem to have attracted no attention; and tests of iron and steel still go on for the purpose of determining their elasticity, their elongation under strain, their ultimate strength and other qualities, while Wohler and Spangenberg's experiments show that it is very doubtful that these bear any proportion to the durability of the metals.

These experiments prove that there is a limit of strain within which iron is practically indestructible, and that that limit is but little over

30,000 lbs. per square inch for the best iron. If, as in some of the braces of the Warren truss, and other forms, there is both tension and compression at different times, the limit is the sum of the two strains. They further show the dangerous character of truss work when there is ambiguity of strains. It is to be hoped that the translation of Spangenberg's book will excite sufficient interest to lead to a continuation of these experiments in this country.

S. H. SHREVE.

NEW YORK, *May*, 1876.

THE

FATIGUE OF METALS.

IN vols. X., XIII., XVI. and XX. of the *Zeitschrift f. Bauwesen* are published the experiments of A. Wöhler upon the strength of iron and steel, with a description of the apparatus used, a statement of his views of the laws, and a mathematical comparison of the different kinds of resistance. Wöhler, induced by the novelty of the results obtained, requested the Industrial Bureau to authorize the repetition of his experiments. At the suggestion of Prof. Reuleaux, the writer was intrusted with the investigation.

We quote the laws deduced by Wöhler, and give a brief account of his processes. He says :

"Rupture of material may be caused

by repeated vibrations, none of which attain the absolute breaking limit."

"The differences of the limiting strains are sufficient for the rupture of the material."

Assuming the lower limit of tension at zero, it follows from this law that the number of repeated strains necessary for rupture is inversely proportional to the greatest tension borne by the fibres which are subject to greatest strain.

Wöhler's apparatus was of four kinds:

(1) For rupture by repeated load.

(2) For repeated bending in one direction of prismatic rods.

(3) For experiments on loaded rods under constant bending strain.

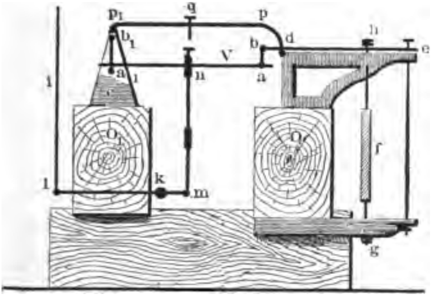
(4) For torsion by repeated load (strain).

The power was transmitted by a shaft to (1), (2) and (4) by means of an eccentric; to (3) by a drum on a steel shaft having ends with conical bores, into which the piece subjected to torsion was fastened with an apparatus of screws.

Apparatus (2) is shown in the diagram (Fig. 1).

The rod to be tested rests upon the supports *a* and *a*, which are connected with the link pieces *a b* and $a_1\ b_1$; the latter turning at b_1 in the cast iron block *c*; the first being attached to the short arm of the lever *b e*. The spring dynanometer *f*, which can be stretched within certain limits by screws at *g* and *h*, prevents the long arm from ris-

FIG. 1.



$^1/_{36}$ n. s.

ing when the short is loaded. The strain is applied by means of the eccentric-rod *i*. This is connected with the lever *l m*, whose fulcrum is at *k* ; so that when the rod rises the end *m* descends, and transmits a bending strain through *m n* to the rod V, then to *b* and b_1. Six of these machines are set upon the beds O and O ; so as to be operated by the same rod *i*. If each of the six test rods is to be subjected to maximum strain, the dynanometer *f* operates as follows :

Let S'=the required maximum tension per square unit.
b=the width of the test-rod.
h=the depth of the test-rod.
$a\,a_1=l$.
P=the required strain at the middle ; then we have

$$P=\frac{4}{6}S\frac{b\,h^2}{l}$$

This force is borne equally at a and a_1, so that $\frac{P}{2}$ at b acts downward, and is balanced by the tension S of the dynanometer and the excess of weight of the rod *de*. If H is the weight of the lever reduced to the point *h*, then $\frac{bd}{dh}=\frac{1}{n}$

$$\text{And } S=\frac{P}{2n}-H.$$

As long as the strain *k* on *mn* is less than P, the point *a* must be regarded as fixed, and the rod V bends ; but when *k* is greater than P, the point *b* yields, and while the rod is under bending strain there is a rotation of V about a_1, which is shown at the end of the lever *e*.

The rod *mn* has at the top a stirrup through which passes the rod to be tested ; and at the lower end is a slot in which is fixed a pin attached to the lever *lm*, so that when the rod *i* rises a downward pull is caused ; but when it descends the rod is set free and is restored by its own elasticity to its first position. In the middle of the rod *mn* is a screw with a nut to adjust the length, so that only for a moment before the point *n* reaches its lowest position, does the point *a* descend. The tension is therefore maintained for a very short time.

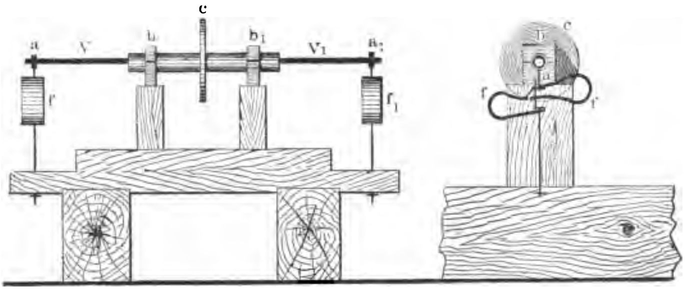
If the tension is to be restored, not to zero, but to some minimum value, the screw *q* is set down so as to keep the rod bent the required amount.

In a similar way the limiting strains in apparatus (1) and (4) are determined, while in (3) the constant deflection of the rod is produced by a spring dynanometer *f* (Fig. 2).

In torsion each fibre, except those lying in the neutral plane, was subjected first to compression, then to tension.

Wöhler, after testing a metal to the limits of elasticity and rupture in the ordinary way, had rods made of the same metal, and subjected the first test-rod of each set to a tension nearly equal to the absolute rupturing strain. Each successive rod of the same set of experiments was subjected to a diminished strain. It appeared that the num-

Fig. 2.



$^1/_{36}$ n. s.

ber of strains required for rupture increased much more rapidly than the strains diminished.

Diminish the intensity of the strains until the number is reached which a member of any structure, subjected to repeated stresses, may bear before becoming crippled, and introduce a safety factor $\frac{1}{n}$ (which Wöhler makes $\frac{1}{2}$) and we have the value of the permissible strain. The *practical* proof strain is thus directly determined.

Wöhler found that a rod of Krupp's cast steel, under a maximum tension of 300 Ctr.* per square inch (German), was broken in apparatus (3) after 45,000,000 revolutions. If this metal were used in an axle which had to make 30,000 rotations per day, or 9,000,000 per year; then for five years' duration (with coefficient $\frac{1}{2}$), the permissible working strain would be 150 Ctr. per square inch.

---

* A Centner is about 110.2 lbs. Eng. The German square inch is equal to 1.0603 Eng. square inches.

Another experiment showed that a rod of Phœnix iron after a maximum strain of 160 Ctr. per square inch after 132,250,000 revolutions was still in working condition. Wohler concludes that the working strength of iron suffering alternate compression and tension is 80 Ctr. per square inch, for a structure intended to be permanent.

Numerous experiments establish Wohler's second deduction that :

Differences of strains at the extremes of vibration are a sufficient cause of rupture of continuity ; and the absolute magnitude of extreme strain is effective only in this respect,—that as the strain increases the differences which are sufficient to cause rupture become less.

The experiments show that vibrations may take place between the following limits with equal security against rupture by tearing or crushing.

$$\text{Iron}\left\{\begin{array}{l}\text{bet.} +160 \text{ Ctr. and} - 160 \text{ Ctr.}\\ \text{bet.} +300 \text{ Ctr. and} - 0 \text{ Ctr.}\\ \text{bet.} +440 \text{ Ctr. and} + 240 \text{ Ctr.}\end{array}\right\}$$

Strain per square inch.

Axle Steel Cast.	bet. + 280 Ctr. and — 280 Ctr.
	bet. + 480 Ctr. and 0 Ctr.
	bet. + 800 Ctr. and + 350 Ctr.

Strain per square inch.

Spring Steel not hardened.	bet. + 500 Ctr. & 0 Ctr.
	bet. + 700 Ctr. & + 250 Ctr.
	bet. + 800 Ctr. & + 400 Ctr.
	bet. + 900 Ctr. & + 600 Ctr.

Strain per square inch.

And for shearing resistance :

Axle Steel Cast.	bet. + 220 Ctr. & – 220 Ctr.
	bet. + 380 Ctr. & 0 Ctr.

Shearing stress per square inch.

Pieces which are subjected to alternate pull and thrust, as piston rods, &c., must be about 9 to 5 stronger than those bearing but one kind of stress.

In the *Zeitchr. f. Bauw.* for 1870, p. 87, Wohler says :

"The results of the experiments give the following permissible working strains for permanent structures :—(*a*) For forge iron strained in both directions 80 Ctr. per square inch ; in one direction, 180 Ctr. per square inch, of which

150 Ctr. at the most may be due to the variable load.

"If the constant strain is less than 30 Ctr., the permissible working strain is diminished.

"(*b*) For cast steel not hardened, strained in both directions, 120 Ctr. per square inch; strained in one direction, greatest total strain 330 Ctr. per square inch, of which 220 Ctr. at most may be due to the variable stress. (The figures apply only to dressed rods.)"

Having given an account of the nature and results of Wohler's experiments and of his conclusions, we now pass to our own experiments.

Tables I. and IV. contain the results of our experiments on round and square iron from the firm of Ravené & Sons, of Westphalia. Table IV. shows a fair agreement with Wohler's Table V.; but the tests stop at 360 Ctr., because in Wohler's experiments strains of 320 and 300 Ctr. did not break rods of Phœnix iron.

The appearances of the rupture surfaces of iron led us to conjecture that the molecular structure was affected by repeated strains. Desiring to make comparison in this respect with a more homogeneous metal, we subjected to tests Firth & Sons' Sheffield steel. The results are given in Tables II. and V., and are compared with Wohler's Tables XI., VII. a and VII. b.

In November, 1872, we tested the Phosphorbronze of Künzel from Hoper's Works at Iserlohn. At the same time tests were made of common bronze from the Neptune Continental Works. The results are given in Tables III., VI. and IX.

In 1873, we received 52 cast steel bars from Krupp, cut by him from a locomotive axle; the results of experiments on these are given in Tables II. and VIII.

Few experiments could be made with Machine IV., because but one bar could be tested at one time. But the results are worth recording (Table IX.), because they indicate a valuable property of phosphorbronze.

The diagrams annexed correspond to the tables. With regard to his Table I., Wohler says:—"The number of rotations before rupture increases inversely as the strain. The irregularities, which must be attributed to the want of homogeneity of material, are so great that no certain law can be derived from this set. The deviation is greatest at 220 Ctr. Ignoring this case, it appears that the number of rotations increase more rapidly in geometric progression than do the loads in arithmetical. With the greatest strain the number of rotations doubled for a difference in load of 24 Ctr.; and it doubled with the lowest strain for a difference of 10 Ctr."

To make this clear, Fig. 6 is drawn, in which the strains are laid off as abscissae, and the number of rotations before rupture as ordinates. This may be easily represented as a curve by leaving out the uncertain point u (220), and connecting the extremity of the ordinate of 240 with that of 200. It is not necessary to regard the point u as taken too high ; for although u_1 would be too low, still we should have a curve agreeing with Fig. 10. Finally, u may be regarded as a reversion-point, the curve having a form agreeing with that shown in Fig. 11. Which of these three hypotheses is most probable can be only determined by at least three complete sets of experiments with the same material ; Wohler having made but one set, except in particular cases of great doubt. As we shall often refer to these curves, we only remark here that the most interesting of the tables are illustrated in Figs. 1 to 9 on the diagram sheet.

Table II. contains Wohler's results showing the inequalities of Firth & Sons' tool steel ; which is a matter of surprise when it is known that the sections of rupture were homogeneous in appearance. We attribute the fact to the presence of a large percentage of carbon; the steel being intended for tools, not for axles. For this reason we have not subjected it to continued torsion.

A decided difference in hardness appeared in rods 3 and 4; so that the remainder were heated dull-red, and were cooled slowly under warm ashes, so that the hardness was made more uniform without affecting the strength.

Tables III. and IV. show that Kunzel's phosphorbronze has much more strength than common bronze and brass. Wrought, *i. e.* cold-beaten phosphorbronze does not seem to have much greater strength than that which is cast. Wrought phosphorbronze shows a very rough, irregular fracture, while the cast breaks with a surface like that of cast-steel, indicating homogeneity of material. In this respect, common bronze and brass more resemble iron. Brass is hardly on equal terms with phosphorbronze in respect to absolute strength; there is a closer equality in respect to bending. With axial strain,

A. Repeated Stretching. I. to III —Table I.

	1872–4. Westphalia Iron.		Wohler's Tab. X. Phœnix Iron.	
No.	Maximum Strain per square inch Ctr.*	No. of rotations before rupture.	Maximum Strain per square inch Ctr.	No. of rotations before rupture.
1	480	4700	480	800
2	440	83199	440	106910
3	440	33230	—	—
4	400	136700	400	340853
5	400	159639	—	—
6	360	180800	360	409481
7	360	596089	360	480852
8	360	433572	—	—
9	320	280121	320	10141645
10	320	566344	—	—

* The Centner (Ctr.)=110.2 lbs. English. | 9 and 10 showed welding joints.

TABLE II. STEEL.

	1872-4. Firth & Sons' Steel.		Krupp's Axle Steel.		Wohler's Table XI. Krupp's Axle Steel.	
No.	Max. Str. per sq. in. Ctr.	No. of tensions before rupture.	Max. tens. per sq. in. Ctr.	No. of tensions before rupture.	Max. Str. per sq. in. Ctr.	No. of tensions before rupture.
					800	18741
			640	81400	700	46286
1	600	83319	—	—	600	170000
2	550	168396	—	—	550	123770
3	500	133910	500	429000	500	473766
4	500	185680	—	—	—	—
5	500	360235	—	—	—	—
6	500	186005	—	—	—	—
7	490	103540	—	—	—	—
8	490	Sound after 12,$_2$ Mil.	—	—	—	—
9	480	229230	—	—	480	Sound after 13,$_6$ Mil.
10	480	692543	—	—	460	Sound after 12,$_2$ Mil.
11	460	Sound after 12,$_2$ Mil.	—	—	—	—

1 and 2 and 5–11 were heated a little and cooled very slowly; 3 and 4 were as they came from the rolling mill.

Table III. Bronze and Brass

a. Phosphorbronze (unworked).			*b.* Phosphorbronze (wrought).		
No.	Maxi. Strain per square in. Ctr.	No. of rotations before rupture.	No.	Max. Strain per square in. Ctr.	No. of rotations before rupture.
1	250	147850	—	—	—
2	200	408350	1	200	53900
—	—	—	—	—	—
3	150	2731161	2	150	Sound after 2,6 Mil.
4	125	1548920	3	125	1621300
5	125	2340000			

No. 3 was very hard.

c. Common Bronze.			*d.* Brass.		
	—	—	—	—	—
1	200	0	—	—	—
2	200	4200	1	200	0
3	150	6300	2	150	0
4	100	5447600		100	53000
No. 1 broke by shortening of tension rod before 200 Ctr.			1 and 2 broke before 200 and 150 Ctr.		

B. REPEATED BENDING IN ONE DIRECTION. TABLE IV. TO VI.

TABLE IV.

	Westphalia Iron.		Wohler's Table VI. Homogen. Iron.		Wohler's Tab. V. Phœnix Iron.	
No.	Max. Str. per sq. in. Ctr.	No. of bendings before rupture.	Max. Str. per sq. in. Ctr.	No. of bendings before rupture.	Max. Str. per sq. in. Ctr.	No of bendings before rupture.
	—	—	550	169750	—	—
	—	—	500	420000	—	—
1	475	612065	—	—	$^{800}/_{400}$	475500
2	450	457229	450	481975	$^{700}/_{300}$	1234600
3	425	799543				
4	400	1493511	400	1320000	400	Sound after 34500000
5	360	3587509	360	4035400		
			320	Sound after 3420000		
			300	Sound after 48200000		

common bronze and brass broke at 200 and 150 Ctr. maximum fibre tension when the tension rod was shortened; but under transverse load with equal maximum tension, they bore millions of stresses. It is obvious that it is not safe to infer that the behavior of a metal will be the same under different kinds of strain. Hence, we cannot agree with Wohler that it is sufficient to make experiments in one kind and deduce results for others.

Table IX. confirms our opinion. Comparison of Tables III. with I. and II. shows that phosphorbronze under 250 Ctr. does not bear as many extensions as Phœnix or Westphalia iron under 400 Ctr. and steel under 600 Ctr. Comparing Table VI. with Tables IV. and V., we observe that phosphorbronze at 200 Ctr. tension does not bear as many bending strains as Westphalia, Phœnix or Homog. Iron at 400 and steel at 500 Ctr. The torsion tables show that phosphorbronze has a greater resistance to

TABLE V. STEEL.

1872–4. Firth & Sons' Steel.			1873–4. Krupp's Axle Steel.			Wohler's Table VII. *b*. Bochumer Verein Axle Steel		Wohler's Table VII. *a*. Krupp's Axle Steel.	
No.	Maximum Strain per square in. Ctr.	No. of bendings before rupture.	No.	Maximum Strain per square in Ctr.	No. of bendings before rupture.	Maximum Strain per square in. Ctr.	No. of bendings before rupture.	Maximum Strain per square in. Ctr.	No of bendings before rupture.
								700	104300
						—	—	600	317275
1	575	281856	1	575	443800	—	—	—	—
2	550	266556	2	550	423400	550	1762300	550	612500
	—	—	3	525	513000	525	1031200	—	—
	—	—	—	—		520	1477400	—	—
3	500	1479908	4	500	1177400	500	5234200	500	729400
	—	—	—	—		500	Sou'd after 40,$_6$ Mil.	500	1499600
4	475	578323	5	475	1185100	—	—	—	—
5	450	5640596	6	450	Sou'd after 1,$_7$ Mil.	—	—	450	Sou'd after 43 Mil.
6	450	Sou'd after 13,$_7$ Mil.		—		—	—	—	—
			7	425	Sou'd after 1,$_7$ Mil.	—	—	—	—

1 5 incl. were heated a little, and cooled very slowly. 5 broke accidentally.

TABLE VI. BRONZE AND BRASS.

Phosphorbronze.			Common Bronze.			Brass.		
No	Max. St. per sq. inch. Ctr.	No. of bendings before rupture.	No.	Max. St. per sq. inch. Ctr.	No. of bendings before rupture.	No.	Max. St. per sq. inch. Ctr.	No. of bendings before rupture.
1	200	862980	1	200	102650	1	200	253100
2	180	8151811	2	180	151310	2	180	1934400
3	150	5075160	3	150	837760	3	150	Sound after $5,_6$ Mil
4	120	Sound after 10 Mil.	4	120	Sound after $10,_4$ Mil.	—	—	—

torsion than Krupp's cast-steel of 1862 and Westphalia iron. This result was so surprising that we interrupted Test 3 in order to substitute the new rod of Test 4. Still we were in doubt, and therefore substituted test No. 5. Both confirmed the previous results. Should further experiments give like results, then phosphorbronze, which is little affected by the action of sea water, ought to be employed in the axles of propeller screws.

The profiles of Fig. 5, correspond to Table VI. That of common bronze appears most regular, showing the material to be of good quality. According to Dr. Künzel (Polyt. Centralblatt, Jan. 1874,) when a phosphorbronze axle is heated to a low red heat a very soft alloy of tin and lead is melted out, leaving the axle hard and spongy. Perhaps in this phenomenon is to be found an explanation of the peculiar behavior of the metal in respect to torsion.

Table IV. (divisions 1 and 2) is represented in Fig. 3. Both polygons agree fairly, leaving out of notice rod 1, whose deflection number is obviously too large.

Fig. 4 corresponds to the first three divisions of Table V. The profile of division 1, is very similar to Wohler's Table VII., to which we shall recur. Firth's steel seems to have a resistance of about 20 Ctr. less per square inch than the older cast steel of Krupp.

Table VII. is represented in Fig. 6 While the first two profiles indicate greater uniformity and strength of homogeneous iron than of Phœnix iron, we found that for spindle iron it was hardly possible to work out a profile including the points from u_1 to u_{16}. We went through with 3 sets of tests between 280 and 340 Ctr., and through 2 sets with strains less than 280, taking differences of 20 Ctr. We hoped to obtain a polygon agreeing with Fig. 10, by taking the arithmetical mean of 3 corresponding rotation numbers; but were disappointed. The great difference in the

C. Continued Loads. Tab. VII. and VIII.

Table VII. Iron.

No.	1872–3. English Spindle Iron.		Wohler's Table I. Phœnix Iron.		Wohler's Table II. Homogen. Iron.	
	Max. Str. per sq. in. Ctr.	No. of rotations before rupture.	Max. Str. per sq. in. Ctr.	No. of rotations before rupture.	Max. Str. per sq. in. Ctr.	No. of rotations before rupture.
	—	—	—	—	380	31586
1	340	r_1 204200	—	—	340	94311
2	340	r_2 204400	—	—	—	—
3	340	r_3 147800	—	—	—	—
	348)		—			
4	320	402900	320	56430	—	—
5	320	911100	—	—	—	—
6	320	503500	—	—	—	—
7	300	384800	300	99000	300	161262

8	300	1035300	—	—	—	—
9	300	1064700	—	—	—	—
10	280	979100	280	183145	280	464786
11	280	1337700	—	—	—	—
12	280	1066000	—	—	—	—
13	260	1142600	260	479490	260	636500
14	260	595910	—	—	—	—
15	240	Sound after 6,$_1$ Mil.	—	—	—	—
16	240	3823200	240	909810	240	3930150
			220	3632588		
17	200	Sound after 8,$_8$ Mil.	200	4917992	—	—
18	200	Sound after 4 Mil.	—	—	—	—
			180	19186791		
			160	Sound after 132 Mil.		

positions of the points corresponding to the same strain, is due not only to the want of homogeneity in the iron but also to errors in determining the number of rotations, caused by defects in machinery. After these were cured the following tests were made and accurately registered : viz. the last 2.7 millions of 16, 17, 18 and the last 2.3 millions of No. 16. We now give attention to the several points u which give a profile probably correct.

The points u and u_2 fairly agree ; but rod No. 3, under 340 Ctr. strain could not be counted, because of an accident that increased the strain by 8 Ctr. In Wohler's Table I. u_5 and u_7 may be rejected, the first as too high, the second, as too low. Whether u_{13} or u_{14} is the more correct could not be determined by two experiments, but we have set u_{13} nearer u_{10} and u_{12}. Hence the profile in Fig 6.

In considering the possible errors, if the lowest points only are regarded the profile u_3, u_7, u_{14}, u_{16} results which seems probably correct. But the question must be settled by experiment.

Only the first two divisions of Table VIII. are represented in Fig. 7; the third showing too great differences, and the fourth not agreeing with the foregoing.

Both profiles are similar, except that the one corresponding to Krupp's new steel is much higher than that of the old, showing an improvement in the manufacture.

In No. 6 appears a more careful diagram of the experiments of Table VII., made with the hope of being able to deduce the equations of the curves. This has not yet been accomplished.

The experiments of Wohler were for the most part with the Phœnix axle iron and with tool steel and cast-spring steel. His tests of rails by torsion (having a special object in view) are not important because they are not subjected to that kind of strain.

TABLE VIII. STEEL

	1873–4. Krupp's Axle Steel.		Wohler's Table III Krupp's Axle Steel.		Wohler's Tab. III. Bochumer Verein Axle Steel. 1863.		Wohler's Tab. III. Borsig Axle Steel 1863.	
No.	Maximum Strain per square in. Ctr.	No. of rotations before rupture.	Maximum Strain per square in. Ctr.	No. of rotations before rupture.	Maximum Strain per square in. Ctr.	No. of rotations before rupture.	Maximum Strain per square in. Ctr.	No. of rotations before rupture.
	—	—	420	55100	—	—	—	—
1	400	367400	—	—	—	—	—	—
2	380	428250	—	—	—	—	380	157700
3	360	925800	360	127775	360	127775	360	239875
4	340	Sou'd after 4 $_9$ Mil.	340	797525	340	342850	340	553850
5	320	Sou'd after 4,$_8$ Mil.	320	642675	320	627000	320	1373225
—	—	—	320	1665580	320	20467780		
—	—	—	320	3114160	—	—		
6	300	Sou'd after 5 Mil.	300	4163375	300	2845250	300	1025625
			300	45050640		Sou'd after 57 Mil.		
					280	3558700		

In our attempt to collect the results of experiments, we received valuable information from a paper by Launhardt (Zeits, des Arch.-und Ing.-Ver. Zu Hannover 1873, Heft. II.). He gives the name of working resistance to that (greatest) amount of strain which is not sufficient to break the material after an indefinite number of applications; and of original resistance (ursprungsfestigkeit) to the amount when the material is allowed to return to a strainless condition, instead of to some minimum strain. He regards the working resistance (a) as a function of the breaking resistance (b), the original resistance (u), or of the ratio

$$\frac{\text{S min.}}{\text{S max.}} = \frac{\text{Its own weight}}{\text{total load}}$$

and employs the formula

$$a = u\left(1 + \frac{b-u}{u} \cdot \frac{\text{S min.}}{\text{S max.}}\right)$$

With reference to Wohler's results for cast steel

$$a = 500\left(1 + \frac{6}{5}\,\frac{\text{S min.}}{\text{S max.}}\right) \text{ Ctr. per sq. in}$$

And for wrought iron

$$a=300\left(1+\frac{5}{6}\cdot\frac{\text{S min.}}{\text{S max.}}\right)$$

These formulas are of some practical value ; but they would be more trustworthy if they had been derived by direct experiments on material for bridges.

Wohler's experiments have required a period of 12 years ; and a time equally long would be necessary to obtain a complete set of parallel tests for bridge material, unless the curve equation for some material recognized as good could be obtained. It would then be necessary to try a few tests only of high strains upon any other metal in order to determine with respect to quality, homogeneity and resistance. For example ; assuming Fig 6 as such a "normal curve" the figure shows that the second polygon (Hom. iron) corresponds to a stronger material than does the first, since the latter at 240 Ctr. strain shows just as many rotations as the former at 210 Ctr. And it may be conjectured that the working resistance of homogeneous iron is at least 190 Ctr., while that of Phœnix iron is 160 Ctr. If this is clear on a diagram to a very small scale, it would be more certain if the normal curve were known.

Of course the number of rotations u, diminish when the strains increase and conversely. Hence we may assume $u=f\left(\frac{1}{S}\right)$. Substituting in the formula

$$y=A+Bx+Cx^2+Dx^3+\&c.$$

u for y and $\frac{1}{S}$ for x.

we have

$$u=A+\frac{B}{S}+\frac{C}{S^2}+\frac{D}{S^3}+\ \&c.$$

If we close this series say at the 4th term, the co-efficients A, B, C, D can be determined by 4 experiments. If more experiments, say 8, 12 or 16, were made, then they would be determined with greater accuracy by the method of Least Squares; remembering that if S is infinite

D. EXPERIMENTS WITH RODS BENT IN TWO DIRECTIONS.

TABLE IX.

Material.	No.	Maximum Strain per square inch. Ctr.	No. of rotations before rupture.
Westphalia Iron of 1872–4	1	240	431306
Firth & Sons' Cast Steel	2	240	Crippled after 6497800
Hammered Phosphorbronze	3	240—320	Crippled after 14916800
" "	4	300—360	4032680
" "	5	360	Sound after 1301600
Wohler's Table XIII.			
Krupp's 1862 Cast Steel		260 240	1007550 859700

Remarks.—No. 3 had borne under a strain of 240 Ctr.	7743000
Again under a strain of 300 Ctr.	3993800
Again under a strain of 320 Ctr.	3180000
	14916800

And dynanometer allowed no higher strain.

No. 4 had a smaller diameter than No. 3, and had borne

Under 300 Ctr. strain	1000000
Under 320 Ctr. strain	1200000
Under 340 Ctr. strain	8000000
Under 360 Ctr. strain	1032680
	4032680

Before rupture.

$u = 0$ and, therefore, $A = 0$. As the experiments show that u increases either in simple or quadratic ratio if S diminishes arithmetically, at least 3 terms must be taken, so that we have

$$u = \frac{B}{S} + \frac{C}{S^2} + \frac{D}{S^3}$$

If Newton's or Lagrange's formula of interpolation is used, it is better to make $y = \frac{1}{u}$ and $x = S$, giving the equation $A S^3 + b S^2 + C S = \frac{1}{u}$; because the successive values of S can be taken with equal differences, so as to simplify the calculation. Whether the series so found is sufficiently convergent to determine the coefficients B, C, D from a few experiments so as to give trustworthy values for u, cannot be determined *a priori;* for the coefficients of safety must be first fixed by a great number of experiments.

Wohler's tables require a careful revision. First with regard to division No. 1, viz.:

$$\text{For iron}\left\{\begin{array}{llll} \text{bet. } +160 & \text{and} & -160 & \text{Ctr.} \\ \text{bet. } +300 & \text{and} & 0 & \text{Ctr.} \\ \text{bet. } +400 & \text{and} & +240 & \text{Ctr.} \end{array}\right\}$$

Tension per square inch.

Both limits, + 160 and — 160, agree with Wohler's Table I. for continuous torsion and Phœnix iron; the corresponding rotation-number 132¼ million is regarded as "unlimited duration." If, according to Wohler (Zeits. f. Bauw., 1858, p. 446), the maximum duration of an axle corresponds to a run of 200,000 miles, and the circumference of the wheel makes 2,400 revolutions per mile, then 480 million revolutions are sufficient to wear out the axle. Now, it is not certain that rod No. 9 of Wohler's Table I., after 132 millions, would stand 348 millions more; but it is probable; because for equi-different strains the number of rotations increases in a ratio higher than the duplicate, and the number of rod No. 8 is 19 millions. For axle torsion, these limits hold; but not for axle compression and tension, as in the case of piston-rods ; for according to Wohler's Table X. a rod of Phœnix iron was torn apart under a strain of 320 Ctr. after 10,100,000 tensions, and therefore would not have borne alternate strains of tension and compression to the number of 10 millions. Hence, although in the tables, to ensure two-fold security for wrought iron strained permanently in both directions, the strain 80 Ctr. per square inch is assigned as permissible ; still this can be accepted only for the coefficient 2, which must therefore have another office besides that of compensating for the non-homogeneity of the material. In this regard Launhardt's coefficient $\frac{1}{8}$ seems to be worth testing by further experiments ; especially for iron when greater resistance is called for in one direction than in the other.

The limits 300 and 0 are derived from Wohler's Table V., rod 7, which was sound after 48 million bendings. The jump from 360 with 4 millions to 300 with unlimited number, is somewhat conjectural; and the assumption is made probable only by Fig. 3. The assumption derived from Table X. that for 300 Ctr. strain the duration is "unlimited," because for 320 Ctr. strain rupture occurred after 100 million extensions, is not justified either by the table or Fig. 1; so that Wohler's assumption that the "original resistance," shown in bending, agrees with that shown in extension, requires the confirmation of experiment.

The third pair, + 440 and + 240, agree with Wohler's Table X. Rod 8 was in working order after 4 million extensions, while rod 7 under $\frac{400}{200}$ strains bore only 2,400,000 extensions. It seems unsafe to draw conclusions from these results without further tests.

The 2d division gives results which are more certain, viz.:

$$\text{Axle steel}\left\{\begin{array}{l}\text{bet.} + 280 \text{ and } - 280 \text{ Ctr.}\\ \text{bet.} + 480 \text{ and } \quad 0 \text{ Ctr.}\\ \text{bet.} + 800 \text{ and } + 350 \text{ Ctr.}\end{array}\right\}$$

Strain per square inch.

The limits $\frac{+280}{-280}$ are more exact, because for $\frac{+300}{-300}$ the numbers of rotations rose to 45 millions. Less reliable is $\frac{480}{0}$ and $\frac{800}{350}$ from Wohler's Table XII., since by $13,_6$ millions, with respect to 12 millions, an "indefinite duration" was indicated.

The 3d division is:

For unhardened spring cast steel.	between 500 and 0 Ctr. between 700 and 250 Ctr. between 800 and 400 Ctr. between 900 and 600 Ctr.

Strain per square inch.

Here there is no doubt, since the 4 experiments were made with the same metal, and the bending numbers varied between $44,_6$ and $33,_6$ millions, which may be regarded as "unlimited duration," in view of the uniformity of the metal and the number of tests. The same may be said of the part respecting torsion.

The experiments with spring steel may be regarded as conclusive; and there remained for us only to repeat the tests on axle steel, and on metals for railway bridges and permanent way.

[The writer here regrets that his experiments are incomplete, refers to facts that caused an interruption of his tests, and expresses the hope that he will be able at some time to take them up again.]

We will now consider our subject in a more scientific and less practical point of view; with regard to the aspect and condition of the surfaces of rupture of the metals broken during our tests.

In most cases one or more spots of fine grain were observed upon the surface, showing the places where rupture first occurred. The broken surfaces of iron and steel were often marked by a dark spot; in other cases there was a smooth, fine grained spot, and in steel and bronze this was the centre of a set of radiating lines. This formed an elliptical surface, which, in Firth steel, had an oil-like smoothness and a lustre under oblique light; while the rest of the surface was rough. In Krupp's steel the elliptical surface is dull and close grained, the rest being crystalline and bright. The ellipse of phosphorbronze is yellower, and the remainder is dark brown in color.

Fracture generally began on the tension side near a corner; but sometimes near the middle.

The fracture of iron extended only to the neutral axis, so that the compression-side had to be sawed apart. Above the neutral plane, on each vertical section, appeared a shell-like depression. From the fact that the compression-side bore the strain for a longer time than the tension-side, we infer that the absolute strength of wrought iron is less than its resilient resistance; contrary to the statements in most of the books. It does not occur to the writers that it is possible that, under repeated bending towards one side, the resilience of the compression side as well as its tenacity may gradually increase. The rupture of steel takes place through the entire section, apparently by tension, while the neutral plane is generally higher. This is due to the brittleness of the metal. But sometimes there appears on the upper edge a plane inclined 45° to the other rupture planes, which obviously has been caused by compression. A similar result appears in the axle steel, tested by falling weights; the section being perpendicular to the convex side, and forking at three-fourths the height, so that the piece forced out is in the shape of an equilateral triangle.

Phosphorbronze resembles steel in fracture; common bronze is like iron.

In the case of two steel rods under torsion, the rupture plane was divided into two entirely different parts by a chord perpendicular to the radius drawn to that point of fracture which was the centre of radiation. This is always on the tension-side in bent rods, so that it may be inferred that the rupture of heavy (massive), and are so small in comparison with the corporeal atoms, and with the ethereal interspaces, that their form need not be regarded. The action between them is repulsive.

II. Among atoms the following forces operate:

(1.) *Universal gravitation; i. e.* the intensity of attraction between two corporeal atoms varies as the product of their masses directly, and inversely as the square of their distance from each other; and is independent of their material constitution.

(2.) *Physical attraction.* By this is meant that force by virtue of which the same pair of corporeal atoms attract each other with a force varying directly as the product of their masses, and which diminishes very rapidly as the atoms are separated.

(3.) *Chemical attraction,* or affinity, by virtue of which two heterogeneous corporeal atoms attract each other.

(4.) *Ethereal forces.* Between ether

atoms repulsion takes place; but between ether atoms and corporeal atoms there is attraction, varying directly as the product of the masses, and in a rapidly diminishing ratio of the distances.

III. Because of repulsion the weightless atoms of ether expand throughout space, penetrating all bodies, but concentrate more or less about corporeal atoms because of their attraction. Assuming that the distance between corporeal atoms is very great compared with their magnitude; and that the intensity of attraction between corporeal and ethereal atoms is very great compared with the repulsion between ether atoms; and that the number of ether atoms in a given volume is indefinitely greater than the number of corporeal: it is obvious that the ether will be disposed atmospherically about the corporeal atoms, and that each atmosphere will be of definite form and limit, so that a large part of the space between two corporeal atoms will be utterly void. It would also follow that the density of the ethereal envelop would decrease outward from the atom. Such an atom with its envelop is called a *Dynamid.*

IV. A molecule is a balanced group of two or more dissimilar corporeal atoms having a common ether envelop. As two distinct atoms can form a molecule A, so two like or unlike molecules may unite to form a compound molecule B.

V. Redtenbacher conjectures that the radial oscillations of ether atoms, which cause expansion of the envelop and increase of repulsion are connected with the phenomena of heat, while their continuous rotatory motion corresponds to the electric current.

The proposition of III, regarding the void spaces between atoms, we cannot reconcile with the hypothesis that ether fills entire space. We rather adopt Cauchy's view; that the intervening space is entirely filled with ether. This, Redtenbacher thinks, is the case only with solid substances, in which the corporeal atoms attract the ether atoms but feebly.

We shall now attempt to establish our hypothesis heretofore stated, by the application of these principles, and by the results of our experiments.

It is known that most, if not all, of the important technic metals show a tendency to crystallize when cooled from a melted to a solid condition (especially if the cooling be rapid). The atoms group about axes of symmetry, if unhindered. That is, a crystalline joint is formed. For example, if melted metal is poured into a cylindric vessel, made of a material which is a good conductor of heat, so that the metal near the outside cools rapidly, while that within remains fluid; then if the interior molten portion is drawn off at the bottom, it is found that the metallic shell left behind shows crystalline forms upon its surface. This tendency to crystallize extends throughout the entire mass when it is cooled.

This may be regarded as the first normal condition,* in which there is equilibrium between the attractive forces of the several groups of atoms, and the repulsive forces in the ether envelopes.

If the body has the temperature of the surrounding air, the radial ether vibrations of both are of equal intensity, and the velocities are equal. Every change of temperature, therefore, causes a destruction of the internal equilibrium, and a consequent wave-motion of the groups, causing decomposition into atoms or molecules, with a consequent change of volume, which, if maintained, corresponds to a new normal state. If besides temperature, mechanical forces are acting, such as compression or tension, the wave-motions or disturbances of the groups are either suppressed or hindered; hence the new normal state depends upon the qualitative or quantitative operation of the external forces.

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* Two molecules may be so situated that their molecular forces are in equilibrium. Such a condition, due to internal forces only, is called a *normal state*.

Cast iron, bronze and brass, are generally in the first normal state when taken from the foundry, but not so wrought iron and steel. The latter metals run through a series of normal states under the hammer and roller before they are ready for use.

Experience shows that in the case of iron, which contains only a small per centage of coal, hammering and rolling while hot, when the atoms are in oscillation and the groups are for the most part decomposed, causes a distribution which produces a fibrous grain. This may be explained as follows: The motion of the ether is diminished, or turned in other directions by the hammer or the roller, so that groupings of atoms take place; these groups are brought nearer each other by the working of the metal, until the ether envelopes by virtue of their force of repulsion prevent a further approach of the groups. Suppose the direction of the pressure of two rollers to be vertical, then the vertical dimensions are diminished and the horizontal increased, so that the atom-groups of some of the vertical series are displaced, and push the groups of other series in such directions that no external forces oppose them; and as a consequence new series are formed, so that, for example, groups which were at the corners of cubes assume a pyramidal form.

The square form of a perpendicular section is changed to a lozenge, then to a rectangle. Now, if a body of the last form is broken by slow bending, the horizontal laminæ separate from one another, because the ether in the vertical series is compressed, and the upper horizontal series are stretched. As this extension is not uniform the rupture section has a fibrous grain. Perhaps, large crystals have been resolved into smaller, and these, working in between the larger, give a fibrous look. But if the rod is broken by a sudden blow, the rupture has a crystalline aspect, because the rupture is due to shearing, and the longitudinal fibres have not had time to become extended.

So it is with steel; with the qualification that the form of the molecules and the distribution of groups is different.

It is not possible that working and rolling can force the atoms or molecules of a crystalline group into actual contact; since, in that case the repulsive force of the ether must be done away with, and the attraction of the atoms would become infinite, so that the decomposition of a crystal would be impossible. Hence, we may assume that in every group in the condition under consideration, there is a very dense ether atmosphere, which, when aided by external forces, causes a subdivision into smaller crystals, and then a reduction of these into atoms or molecules brought into close contact, so as to produce an amorphous condition. This decomposition is helped along by the mutual attractions of the exterior atoms of two adjacent crystals, and hindered by the intervening ether. Suppose two opposed bands of external parallel forces uniformly distributed through a very thin plane section, whose resultants are P and P_1, then the external forces will draw away the crystals a, a_1, a_2, and c, c_1, c_2,* from the middle set b, b_1, b_2, because the repulsive forces of the ether envelopes is aided by the external forces. The squares change into rectangles, and a motion of the easily disturbed ether is

$$\begin{array}{ccc} \multicolumn{3}{c}{\overbrace{a \qquad\qquad a_1 \qquad\qquad a_2}^{P}} \\ \\ b & \qquad b_1 \qquad & b_2 \\ \\ \multicolumn{3}{c}{\underbrace{c \qquad\qquad c_1 \qquad\qquad c_2}_{P_1}} \end{array}$$

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* For the easier comprehension of this, let a, b, c, etc., represent cubic crystals, each separable into 8 equal cubes.

induced. It becomes denser in the horizontal intervals $a a_1$, $b b_1$, &c., than in the vertical, $a b$, $b c$, &c., so that there is a flow from the latter to the former. But at the same time a radial motion of the ether takes place from a to b and back again; hence the heat phenomena observed by Wohler in cases of great strain. Electric and magnetic phenomena may also occur, since there must be rotatory motion of the ether on account of the greater density about the horizontal diameter of the crystal. In the first stage the equilibrium of the ether external to the crystal takes place, diminishing density in a horizontal direction so that the attraction of the crystal is less hindered, and the vertical elements a b c, a_1 b_1 c_1, etc., approach one another, diminishing the transverse dimensions in the second stage.

The envelops within the crystal are induced by their repulsive force to take part in the equilibrating movement of the external ether; but are hindered by the attractions of the crystal molecules or atoms, and can therefore express their force only by operating upon the atoms or molecules of the crystal, thereby setting in motion those parts which are applied to adjacent crystals, since these suffer a less pressure on the opposite side. In this way a disintegration is effected of crystals of the first into the second, third, etc. order so that in the third stage the material is uniformly distributed. These three stages are included in the short interval of time of a single stress within the limits of elasticity. If the forces P and P_1 cease to act, then the original condition recurs : but in our experiments the strains occur in rapid succession, and, only those displaced atoms or molecules which are in close proximity can reunite into crystals of the second or third order. Here we discover the reason that not only the number but the time of duration of stresses has an influence upon rupture.

Perhaps it is not certain that crystalline structure changes to amorphous with every stress, especially with the first; for rods broken after a few strains show a crystalline rupture. But that regular forms become smaller and that the amorphous condition increases, is shown by the smooth mirror-like elliptical spots on the broken surfaces of different kinds of steel. The molten-like spots in iron are to the same effect.

A new normal state occurs at each diminution of crystals, corresponding to a new kind of elasticity; so that instead of a single limit there is a series. But with each change of limit the strength of resistance increases; and the raising of the limit by working and loading is proven by many experiments.

Moll says: "The more crystalline the structure of a body, the less its resistance. The rupture of such bodies is due to the separation of the small crystal groups, not to the breaking up of single crystals. . The cohesion of the molecules that form a crystal is greater than that of crystals with one another. The strength of a body increases as its structure approaches the amorphous state when its atoms have a homogeneous distribution."

Though the truth of this statement has been shown by experiment, it will be instructive to investigate the causes. Consider a vertical column of crystals *a*, *b*, *c*, etc, each of mass *m;* which may be regarded as concentrated at its centre of gravity. Let *e*, be the common distance between the centers of gravity ; and K an unknown co-efficient, then the attraction of *b* by *a*, is

$$A_1 = K \frac{m^2}{e^2}$$

Suppose each crystal divided into two equal crystals, *e.g.*, *a* into *a′* and *a″*, *b* into *b′* and *b″*, &c., and suppose *a′* remains in the place of *a* ; that *a″* is displaced through one-half of the space *a b*, so as to be distant ½ *e* from *a″*; then *a″* is attracted by *a′* with the force

$$A_{\frac{1}{4}}=K\,\frac{m^2}{4}\div\frac{e^2}{4}\,;$$

obtained by putting $\frac{1}{2}m$ for m and $\frac{1}{2}e$ for e in the above equation. Of course $A_{\frac{1}{4}}=A_1$; hence the attraction of two adjacent groups has not increased according to the law of gravitation. Taking four groups, a, b, c, d, we have the following results:

b by a, attractive force, $K\frac{m^2}{e^2}$

c by a, attractive force, $K\frac{m^2}{4e^2}$,

d by a, attractive force, $K\frac{m^2}{9\,e^2}$,

$$\text{Total, } S_1=K\frac{m^2}{e^2}\left(1+\frac{1}{4}+\frac{1}{9}\right)$$

Suppose these groups broken up into crystals of half the size a', a''; $b'\,b''$, we then have:

a'' by a', attr'tive force, $K\frac{1/4\,m^2}{1/4\,e^2}=K\frac{m^2}{e^2}$

b' by a', attr'tive force, $K\frac{1/4\,m^2}{e^2}=K\frac{m^2}{4\,e^2}$

b'' by a', attr'tive force, $K\frac{1/4\, m^2}{9/4\, e^2} = K\frac{m^2}{9\, e^2}$

c' by a', attr'tive force, $K\frac{1/4\, m^2}{16/4\, e^2} = K\frac{m^2}{16\, e^2}$

c'' by a', attr'tive force, $K\frac{1/4\, m^2}{25/4\, e^2} = K\frac{m^2}{25\, e^2}$

d' by a'. attr'tive force, $K\frac{1/4\, m^2}{36/4\, e^2} = K\frac{m^2}{36\, e^2}$

d'' by a', attr'tive force, $K\frac{1/4\, m^2}{49/4\, e^2} = K\frac{m^2}{49\, e^2}$

hence $S_2 = K\frac{m^2}{e^2}\,[1 + 1/4 + 1/9 + 1/16 + 1/25 + 1/36 + 1/49]$

We find $S_2 > S_1$; and as *a*, *b*, *c*, *d* are subjected to the same attractive force S_1, while a' is attracted by a'', b' by b'', &c., with the force S_2, it follows that the cohesion of a' with the vertical fibre is greater than that of *a*. But whatever holds true of one fibre, holds for the sum of all the vertical fibres of a rod; and we may infer that the tensile resistance of a rod increases along with the disintegration of the primitive crystals up to the amorphous condition. This increased resistance might be weakened again if the repulsive force of the ether increased in the same ratio. But the ether envelops of the new crystals become less dense because of the diminished mass of the latter; and the ether in the body is spread throughout a larger space, since the specific gravity of a body diminishes as the volume is increased.

The disintegration of crystals of the first order may also be due to continuous load, when sufficiently small increments of load are added at regular intervals. As soon as resolution of crystals of the first order into the second is effected, permanent extension results; that is, the first limit of elasticity is reached. But as long as only a few crystals have parted from the mother-crystal and are lying in close proximity, it is possible that these may be restored with the removal of the strain, or when it has been reduced to a very small amount. If the crystals of the second order have been changed to the third the second elastic limit is reached, and between this and the first limit the metal is as elastic as before. This explains the raising of the elastic limit under increasing tension.

Knutt Styffe, Director of the Institute of Technology at Stockholm, defines the limit of elasticity as follows: "If a rod of steel or iron is stretched by continual increase of load, at first so small as to cause no sensible permanent extension, then gradually increased, and allowed to act for a number of minutes depending on the ratio of the increase of weight to that of the whole rod: then the elastic limit is the weight which produces a permanent extension amounting to about the ratio of the increase of weight to the entire load. Let P represent the total load; dP the constant increment of load; L the length of the rod; dL the increase of permanent extension due to $P + dP$, if this acts for $100 \frac{dP}{P}$ minutes: then the elastic limit corresponds to the weight for which $\frac{d\,L}{L}$ is approximately equal to 0,01 $\frac{d\,P}{P}$. That is, 100 $\frac{d\,L}{L}\,\frac{P}{d\,P}$ $=1$ or nearly 1."

With this definition as datum, Styffe determines in an arbitrary way one of the many elastic limits which lie between the first normal and the final amorphous state.

Styffe gives several curves as examples in which the applied weights are laid off as ordinates, and the per cents. of extension, as abscissæ. One of these curves is represented in Fig. 12. Observe the several elevations of the curve (in which there is an appearance of periodicity) which may correspond to what we have called the several normal conditions. Fig. 13 is the beginning of Fig. 12 to a larger scale: the elastic limit lies near the point where the curve has the smallest radius of curvature. These curves have some similarity to the curves

3, 5 and 6; and possibly some relations, not yet made obvious.

Moll & Reuleaux maintain that the elastic limit may be changed by a change in the normal states; but that in the case of some metals, as wrought-iron for example, its magnitude is slightly affected.

Wohler also found in experiments in bending that the elastic deflection depends not upon the increase of the total deflection, but upon the total load alone. He concludes that permanent and elastic change of form cannot depend upon the same physical property. This opinion we share with him, for this and other reasons. According to our hypothesis permanent extension is associated with disintegration of mother-crystals caused by the ether-repulsion. The diminution of transverse dimensions, when a rod is lengthened, is proportionally smaller than the elongation, since under extension the specific gravity diminishes.

Elastic extension is due to the fact that the equilibrium between the attractive forces of the nuclei and the repulsive forces in the envelops is disturbed by the external attractive forces with loss to the former ; the disturbance disappearing at the same time with the cessation of the action of external force. Perhaps we may say that the elastic extension depends upon the momentary suppression of the general attraction of the masses (excluding physical and chemical forces); and that it remains constant with equal increments of the strain, because the mass of the rod remains constant.

Fig. 14, shows that the limitation of elastic phenomena to certain metals is a necessary conclusion. The ordinates of the full curve show the total extension in English inches of a bar of phosphor-bronze ; the abscissæ correspond to the loads in English pounds ; the ordinates of the broken curve represent the permanent extensions. The differences of the ordinates correspond to the elastic extensions which increase from 0, to 22000 lbs., then decrease to 33916 lbs, when rupture took place. Perhaps it happened that after the breaking up of the compound molecules, groups of copper, tin or phosphorus formed, and the groups of the last-named flowed among the other groups so as to prevent the approach of the first two kinds.

The above explanations seem to contradict the well-known phenomenon that extensions generally increase more rapidly as the load approaches the breaking weight. We think that this is true only up to the beginning of the amorphous condition due to repeated or increased load. A body is then perfectly elastic, only so far as this term applies to bodies not absolutely homogeneous. While each increase of load induces a separation of the crystals such that the sectional area does not diminish just as the length increases, no increase of volume can be caused by increase of external forces after the uniform juxtaposition of the atoms. The next addition of tension, if not too great, may cause only a lengthening parallel to its own direction and a contraction of cross-dimensions. But the molecules of the cross-section are brought together as closely as if pressures from without were acting. Hence molecules may be forced out of the cross-rows to form new rows; or new groups are formed, so that the section is permanently diminished: for if tension breaks up groups then pressure must tend to construct them.

Together with the permanent diminution of the section there occurs a permanent increase of length and *vice versa*. Hence results formation and dissolution of groups, with a rapidity proportional to the increase of the force of tension. Finally there comes a load so effective that the groups have not time to break up, and rupture takes place by means of shearing.

Indicate the breaking load per square

unit of original section by P_b; this strain, in case of repeated tensions, does not correspond to unlimited duration; but possibly to the smaller value P_a, which is in equilibrium with the amorphous condition. But this can hardly be granted, since P_a as soon as brought into action would cause sudden and various changes of crystals, so as to cause an amorphous condition in some fibres, not in others; so that shearing would be induced and rupture would follow. This view is supported by the fact that iron rods which had borne repeated tensions, when broken by pull were found to be bent, though before rupture they were quite straight. This could not be charged to the excentric application and working of the tension, since in most cases the curvature was opposite in direction to that which might be due to transverse operation of the machine.

It may be shown that the strain corresponding to an unlimited number of tensile strains is $u = \frac{1}{n} P_a$. Since the time of change to the amorphous condition (and therefore n) cannot be determined in the ordinary experiments, it is best to determine u, or the working resistance a by Wohler's method. Wohler's question : "Is there any limit of tension which is perfectly safe?" cannot be answered in the affirmative, since that strain must be sufficient to produce the amorphic condition directly and must not be great enough to form crystals in the cross-section by pressure. The use of iron for girders in buildings need not be rejected ; yet it is worth while to consider what may be the effect of the vibrations produced by the continual passing of vehicles.

It hardly needs mention, in order to reconcile an apparent discrepancy in the experiments of Styffe and Sandberg, that if the strain P_b is applied, rupture must take place by sudden shearing, because the groups have not time to break up and pass over to the elastic limits of new normal states.

The results of the experiments of the former on extensions between — 37.7° and 200° C, were: (1.) The absolute strength of steel and iron is not diminished by cold; being at least as great at the lowest temperature in Sweden as at the ordinary. (2.) The extensibility of steel and iron is not less at very low temperatures than at ordinary. The fact that car rails and axles break more readily in cold weather, Styffe attributes to the circumstance that the road-bed is less elastic, so that shocks are more intense.

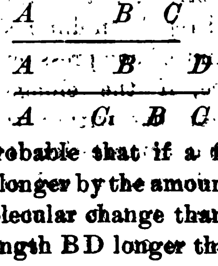
In order to test this explanation, Sandberg, who translated Styffe's work into English, made experiments on steel, the results of which he published in the appendix to his translation. He assumed that the elasticity of granite does not vary between the limits of a hot summer and a cold winter day. He had a granite rock smoothed and leveled and placed upon it two cubical blocks of granite to serve as supports for the rails to be tested. Each rail was divided into two halves; one of which was tested in summer at + 29° C.; the other, in winter, at −12° C., by dropping upon them a sphere weighing nearly nine centners. The sections of ten bars showed that at the lower temperature iron had but one-third or one-fourth of the resistance which it had at the higher; also that the tenacity and resistance to bending were notably affected by cold.

Regarding these results as trustworthy, we explain them as follows: The radial motion of ether which appears in the form of heat, after some time causes the same disintegration of crystals as repeated or increased strains. But cold, like compression, which is attended with less vibration, promotes the formation of groups; these diminish tensile resistance, and make the material brittle on account of its crystalline structure. Sandberg subjected the rails, which had become crystalline under the influence of cold, to a sudden blow; of course they broke more readily in winter than in the summer. On the other hand, Styffe broke his rods with a hydraulic machine ; increasing the strain gradually, so that he gradually broke up the connection of the crystals, thus substituting mechanical work for ethereal vibrations.

As fibers are not homogeneous in their structure, they must contain a varying number of crystals. Those fibers in which the crystals are not so dense, are more strained by tension so that the groups are quickly broken up. Forced by the ether they leave the molecular groups of fuller fibers and seek the fiber most strained in order to restore equilibrium. Hence the ray-like appearance of the fracture-surfaces of steel and phosphor bronze. The fibers nearest the weakest fiber are more extended, and are successively brought beyond the amorphous condition so as to have less tenacity. The effective section of resistance becomes gradually smaller; and at last the dynanometer breaks the remaining crystalline section, which therefore has an appearance as if sawed or broken with the hammer.

That bars of square section break at the corners is explained by supposing that the flow of molecules to those parts is less free than to others. In the broken steel rods there appeared on the upper edge a small plane (wedge) inclined 45°, having the appearance of being pushed out. This is the angle of maximum shearing effect.

Crushing proper cannot be produced by pressure when it causes approach of molecules and formation of crystals. Separation can be caused only by shearing, or by "nicking," or by the increase of sectional area, from the ends toward the middle, causing a deficiency of molecules at the edge. The last may be the reason of the sudden fracture of bars subjected to alternating tension and compression. Wohler says: "Pieces bearing positive and negative strains must be made stronger in the ratio 9 : 5 than those strained only in one direction." The explanation of this is not easy. Launhardt's is not sufficient, for he considers the case in which the limits of elasticity are passed on both sides. Wohler's hypothesis that the difference of strains suffices for rupture, and that in the case of alternating tension and compression this algebraic difference is the sum of the numerical values of the strains, is also insufficient.



It is probable that if a fibre A B is stretched longer by the amount BC, there is less molecular change than if stretched by a length B D longer than B C; but in our opinion it does not follow that B C + B C′ produces the same change as B D, if C C′ = B D. We should rather believe that if the elongation B C were somehow suppressed, the fibre would return to its normal condition, and that the shortening B C′ could not be more injurious than if it occurred in the normal state without previous elongation. The only satisfactory explanation seems to be involved in the theory of Moll and Reuleaux that, for the same normal state, there are two co-existent limits of elasticity, one for tension, the other for compression.

If the elastic limit of tension is raised by repeated strain, *i.e.*, if attraction is increased and repulsion diminished, then the elastic limit of compression is diminished. Hence, if the elongation B C due to tension lies within the elastic limit, the equal compression B C′ causes a permanent shortening, and after some time a rupture. But it is also possible that compression causes a bending toward one side or an elongation of sets of fibers near the periphery, so that a new normal state results in that part, which reduces the section of resistance. The case of a rod under repeated torsion is not relevant to a decision of this question, because each fiber is alternately convex and concave. Other experiments must be made with new machines adapted to changing axial or transversal positive strain into negative. We may then ascertain what is the effect of a greater strain of one kind following a less of the other. We think it will be found that our assumption is not far wrong, that a slight compression following tension is rather advantageous than the contrary.

Wohler's observation that between + 440 and + 240 Ctr., and between + 300 and 0 vibrations may occur with equal safety, requires the confirmation of further experiment.

In consequence of the construction of the machines for bending and pull the dynanometer must first give a strain of 240 Ctr. in the outermost fibres; then the extreme strain of 440 Ctr. is applied; hence a normal state must result different from and higher than that which would follow the tension zero. It may be asked what would be the normal state if the strain 440 were first applied, and then the strain 240. Perhaps the result would be the same as if the force P_b spoken of above should act. The answer may have a practical bearing with reference to bridge building. The weight proper of structure corresponds to the lower limit 240 Ctr., and if the rolling load increases the strain by 200 Ctr. the total permissible strain is reached. Suppose the weight of structure uniformly distributed, then the vertical component is a maximum at the ends and zero in the middle, and the tension members at the abutments are in better condition to bear external forces than those in the middle, on account of the raising of the limit of elasticity. The former may therefore for a total load of 440 Ctr. have "indefinite duration," because they may rise from 240 to 440 Ctr. tension; but not so of the latter, since they pass from 0 to 440 Ctr. strain; 300 being the limit. Assuming

110 Ctr. as the permissible strain, we should have 4-fold security at the abutments, but less than 3-fold in the middle.

We shall now attempt to account for the appearence of the surfaces of fracture of rods broken by repeated torsion. In the case of steel rods the circular section-surface was divided into two unequal segments; one of which, that next the side of initial fracture, and the smaller, was close grained and smooth; the other being coarse-grained and somewhat crystalline in appearance. This seems to contradict the statement above made that rupture takes place only on the tension side and that the adjacent surfaces pass over to the amorphous condition; for each fibre of these rods was pulled during half a rotation and compressed during the other half. The process may be as follows:

If the rupture at *a* is the consequence of tension, the bending of the rod, since the most efficient fibre has ceased to resist, will be greater than if it had turned through an angle α bringing a to a_1 or to a_2 (the neutral section) while an unbroken fibre is brought to the top. In its further progress to a_3 or from a_4 to a_5 the broken fibre induces no greater

bending since the broken parts support each other. Indeed it is possible that the bending is less during the last half rotation than during the first. If before fracture there has been a permanent extension of the fibre a and the adjacent fibres, the rod is permanently bent downward. After a half rotation it would be bent upwards, were it not for the fact that the stress of the dynamometer acts downward. But in no case is the upper fibre so much bent as it would be if the elastic limit of the lower fibres had been passed.

It would now seem to be clear that if the fibre *a* is at the top, the adjacent fibres reach the maximum stress, causing the amorphous condition of the upper segment. Upon the side opposite *a* the crystals are larger than they are near the chord of division, showing a higher state of disintegration.

Appearances similar to those of steel are observed in iron, but they are not so sharply defined.

If the equilibrium of the ether and the consequent amorphizing is in any way hindered, there may be other segments of rupture.

The rupture of iron and steel under torsion shows a smooth surface adjacent to the fracture, while that of bronze is shining, and phosphor-bronze is often dark-brown or blackish on the opposite side. This may be explained by supposing that after the breaking up of crystals into molecules, these partly resolve into atoms, those of tin gathering at one place, those of copper and phosphorus at another.

We must reject the theory that iron is made crystalline by repeated tension, since bending and tension appear, by our experiments, to break up the crystalline structure; while compression promotes it. So the upper parts of rails become crystalline and hard because subjected to compression. Whether irregular shocks promote crystallization remains to be determined by experiment.

The rupture-sections generally show in what way breaking has occurred; whether by repeated strains or by the sudden shock of a great load. This may be of import in discovering the cause of an accident, as, for example, whether it is due to a broken axle or a broken rail.

This might be determined by an examination of the peculiarities of the sections of fracture.

There remains to consider the possible effect of heat in impairing strength by vibration of the molecules. Heat separates the crystals, causing change of position in all directions: and when it is uniformly distributed, if the amorphous state occurs, the strains in cross-section are exactly equal to those in longitudinal, so that there is either diminution of section, or re-grouping only, which is not competent to effect rupture as long as the aggregate state is unchanged.

We have had Krupp's axle steel hardened and then broken; the grain was much closer and smoother than in the same not hardened. But if steel is first heated and then hardened the rupture-surface becomes more like that of the non-hardened, according to the duration of the heating; while the grain of steel heated and not hardened is coarse and globular. So is that of heated iron.

Hence it would seem that red-heat produces no tendency to form groups, while a higher heat, long continued, induces a storm of ether atoms, so that in cooling, they gather in irregular groups; a phenomenon observed in cast metal.

The experiments of Styffe mentioned above, which show that the absolute resistance of steel and iron at high temperatures, up to 200° C., does not diminish, while that of soft iron increases, contradict Muller, in the Zeitschr. des Ost., Ing. u. Arch. ver. (1873) where he says: "When a bridge-member, in the course of twenty-four hours, suffers a lowering of temperature to the amount of 15° C., there is a change of its length amounting to 0,00022. The elastic change of length is the same up to a load of one-third the limit. So a change of temperature has the same effect as a load."

Finally, we refer to the diagrams. In all the polygons there is a point from which the ordinates increase very rapididly. This may be compared with that one in Styffe's curve, Fig. 13, which corresponds to the shortest radius of curvature, in the vicinity of which lies the limit of elasticity. We may conjecture that the abscissa corresponding to this point, *i. e.*, the load, answers to some important condition of the metal, possibly to that in which the irregular crystalline structure becomes more regular. It may be that, up to this point, the number of strains necessary for rupture depends upon the specific nature of the rod, while it afterwards depends upon the general properties of the metal. Hence it may happen that irregularities of the polygons are more frequent before this point is reached. That non-homogeneous metals may be improved by repeated strains is not impossible. Suppose, for example, there is a thin section of slag running across a rod. This may be broken up into several parts by small tensions, which may be disposed by the motion of the ether into a direction parallel to the tension, so that the decomposition of crystals is less hindered. The attraction of homogeneous molecules to both sides of the section may be diminished, but not destroyed; and there may be an equilibrium between the force of attraction and the repulsive force of the ether increased by the action of external forces. A greater external force would break the rod at this section.

The less obvious this point in the polygon the more homogeneous and pure the metal. This appears in Fig. 9. And, from Fig. 7 it may be inferred that Krupp's steel is now much more uniform and stronger than that of 1862.

Time and space forbid further presentation of facts supporting our hypothesis. It is to be hoped that others will pursue the subject further.

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