Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 4 (1969)

Artikel: Variations in the mechanical properties of structural steels

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DOI: https://doi.org/10.5169/seals-5935

IV

Variations in the Mechanical Properties of Structural Steels

La dispersion des caractéristiques mécaniques des aciers de construction

Die Streuungen der mechanischen Eigenschaften von Baustählen

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1.0 INTRODUCTION

This report is limited to a discussion of some of the factors which influence the strength of structural steel members and in particular deals with the variations in the mechanical properties of steels and their effect on strength and safety.

1.1 Characteristic Strength As discussed by Rowe(1), semi-probabilistic methods are currently being introduced into British and European structural design recommendations which will require the designer to use 'characteristic values' for strengths and loads. The characteristic strength is defined as a load bearing capacity which will be exceeded by a prescribed percentage (taken as 95% in this report) of a population of similar elements or structures. With these methods, it is not necessary to know the exact distribution functions of these main variables, but the problem of assessing realistic characteristic values for different materials still remains. Where data are available, characteristic values can be calculated by suitable methods of statistical analysis, but the results may be misleading unless the origin of the data and the method of sampling are known.

For structural members which do not collapse as a result of buckling or instability, the yield strength of the steel is the predominant source of variability in the strength of the member. The variations in yield strength result from differences in chemical composition and strain/temperature history during rolling and subsequent handling. The reasons for the variability in the yield strength of steel plate and reinforcing bars have been discussed by Leclerc(2) and in general it can be concluded that the distribution function for the yield strength depends on:-

- (i) the grade of steel produced, the type of product rolled and its approximate chemical composition
- (ii) the thickness of the finished material
- (iii) the characteristics of the steel mill (e.g. rolling sequence, temperature, etc.)

From the results given in Section 2.0 it can be concluded that changes in any of the above conditions result in systematic variations in yield strength and give rise to different distribution functions. If the above conditions are constant, the yield strength can then be considered to be a random variable, the variability being due to the combined effects of a considerable number of small random variations.

However, the statistical distribution of a series of tensile test results may differ from the distribution of the true average yield strength of the material they are intended to represent, because of systematic deviations of the recorded yield strength due to tests at high and differing strain rates(3), and because of the positions from which the test specimens have been cut.

2.0 VARIATIONS IN YIELD STRENGTH OF STRUCTURAL STEELS

The variability of several grades of structural steel has been investigated by the statistical analysis of results of tests obtained from different sources for the purpose of assessing characteristic strengths and in an attempt to compare the relative safety of structures constructed from different materials. In all cases (except Section 2.6) the data refer to tests on steel as rolled prior to any rejection of material of less than specified quality and not as delivered to the customer.

2.1 Mild Steel Plates to British Standard 15:1961* These data have been obtained from about 4000 tests relating to steel ordered by British Rail between 1961 and 1966, and can be considered to be a series of random samples selected from the five mills which supplied the steel. The test results below the guaranteed minimum yield strength originate from material subject to retest, but it is probable that some low values may have been omitted from the sample. This would have the effect of decreasing the observed variance. Some statistics are given in Figure 1 and from these results and further statistical analysis it can be shown that:

(i) there are significant differences in the mean and variance of the measured yield strength of steel supplied by different mills (compare mill 'V' and mill 'X')

(ii) these differences exist for all thickness ranges

(iii) the degree of control shown by mill 'V' is such that (a) changes in the target minimum yield strength for different thicknesses of plate is accurately reflected by the mean strength, (b) there is no significant difference between the variances for different thicknesses, and (c) the characteristic strength (based on a 95% probability of being exceeded, and an assumed normal distribution) is in all cases only a little above the guaranteed minimum value

(iv) there is a significant decrease in mean strength with increase in plate thickness

(v) for mill 'W', the characteristic strength is about 1 tonf/in^2 (15.5 N/mm^2) above the minimum yield strength for all thickness ranges (except one), and because of the consistently small variance, steel from this mill can be shown to give structures with the smallest probability of collapse

* These British Standard Specifications were in force at the time of production, but have now been superseded by B.S 4360:1968.

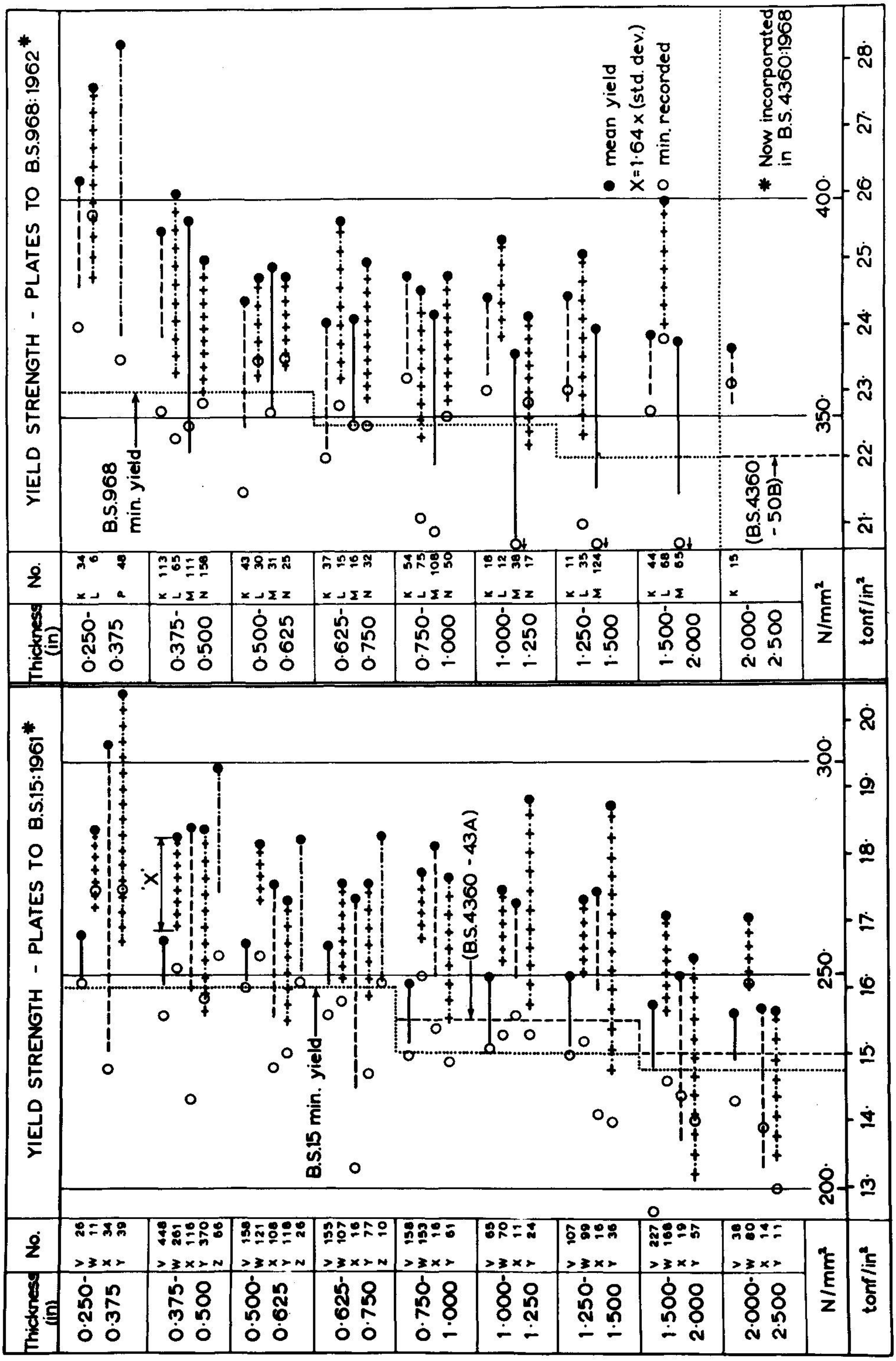
YIELD STRENGTH - PLATES TO B.S.15:1961*
YIELD STRENGTH - PLATES TO B.S.968:1962*
Thickness (in)
No.
N/mm²
tonf/in²
B.S.15 min. yield
(B.S.4360 - 43A)
'X'
B.S.968 min. yield
(B.S.4360 - 50B)
mean yield
X=1·64 x (std. dev.)
min. recorded
* Now incorporated in B.S.4360:1968

FIGURE 1

2.2 High-Yield Steel Plates to British Standard 968:1962 The data have been supplied by the British Heavy Steel Association but unlike the B.S.15 steel relate to consecutive casts produced by each of the four mills over a short period of time and include all results. Summary statistics are given in Figure 1 and show that:

(i) as with mild steel plate, the variance is consistently lower for steel from certain mills than from others and this trend occurs for all thickness ranges

(ii) the 'characteristic' strength as defined above for steel from mill 'M' would be below the specified minimum value for all thickness ranges

As these samples relate to a relatively short period of time it is not possible to show whether the above trends are long term, but the fact that the same trends are shown by plates of all thicknesses, giving ten independent sets of samples, increases the confidence that can be placed in these results.

2.3 Universal Sections to B.S.15:1961 and B.S.968:1962 The source and method of sampling were the same as for high yield steel plates, and results with the same code letter refer to the same steel producing divisions of the British Steel Corporation (see Figure 2). Except for high yield sections with webs thicker than 1", the calculated characteristic strengths are in all cases greater than the specified minimum strengths. Comparison with Figure 1 shows that there is a much greater change in mean strength with thickness for sections than for plates and this is a direct result of the different rolling sequences required for the two products.

The statistics in Figure 2 relate to the yield strength of specimens cut from the webs of rolled sections, but as the overall strength of the section is more dependent on the mean yield strength of the flanges, the relationship between the mean web and flange strengths of different sections has been investigated. Figure 3 has been compiled from the results of commercial tests on about 200 separate sections, the specimens being cut from $\frac{1}{4}$ points in the webs and flanges. The results are classified according to the ratio of web/flange thickness, t/T.

The mean ratios of flange/web yield strength σ_{yf}/σ_{yw} increase with increasing t/T, but in addition σ_{yf}/σ_{yw} tends to unity as σ_{yw} decreases to the minimum allowable yield strength. Analysis of variance shows that this increase in σ_{yf}/σ_{yw} with decreasing σ_{yw} is statistically significant for both mild and high yield steel. At high values of σ_{yw}, σ_{yf}/σ_{yw} is significantly lower for some mills than

Mean Ratios of Flange/Web Yield Strength - B.S.15 Sections							
	Web Yield Strength - tonf/in^2						
t/T	15.25-16.25	17.25-18.25	18.25-19.25	19.25-20.25	20.25-21.25	21.25-22.25	22.25-23.25
0.55-0.60	-	1.05	0.93	0.91	0.89	0.87	0.87
0.60-0.65	0.99	1.00	0.97	0.93	0.92	0.90	0.87
0.65-0.70	-	-	-	-	0.93	0.91	0.90
0.70-0.75	-	-	1.01	0.93	0.98	0.96	0.93

Figure 3

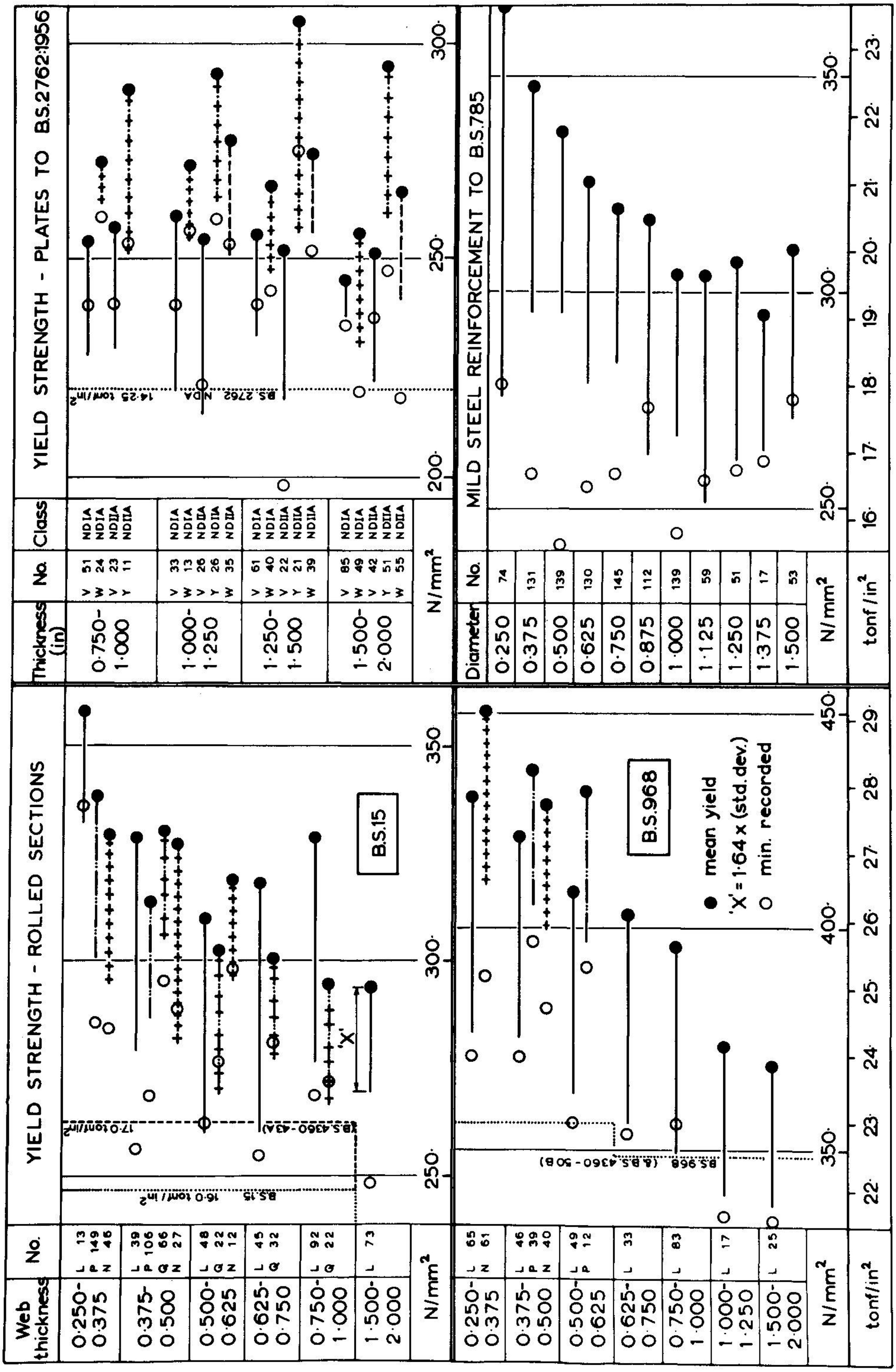
YIELD STRENGTH - ROLLED SECTIONS
YIELD STRENGTH - PLATES TO B.S.2762:1956
MILD STEEL REINFORCEMENT TO B.S.785
B.S.15
B.S.968
mean yield
'X' = 1·64 x (std.dev.)
min. recorded
N/mm²
tonf/in²

FIGURE 2

for others (for all thicknesses), but at low values of σ_{yw} there are no significant differences and $\sigma_{yf}/\sigma_{yw} \doteq 1.0$ for all cases.

From the above, it follows that if any population of web yield strengths is normally distributed, then the distribution of the associated flange yield strengths will be negatively skew.

2.4 Notch Ductile Steel Plates to B.S.2762:1956 Figure 2 gives some statistics for plates having Charpy impact properties of 20 ft lb at 0°C and -15°C (corresponding to Classes NDIA and NDIIA respectively). As with the mild steel plates these data have been supplied by British Rail and results with the same mill code letter refer to the same steel mill.

2.5 Rectangular and Circular Hollow Sections to B.S.4:Pt. 2:1965 These data, comprising some 5300 test results on grade 16 and grade 23 steels, relate to the total production of a single manufacturer for the period 1964-1967 and are summarized in Figure 4.

2.6 Mild Steel Reinforcement to B.S.785 The results in Figure 2 for mild steel reinforcement relate to 1050 bars of different diameters supplied by an unknown number of mills and tested by an independent commercial test-house. Mean and characteristic yield strengths both show a marked decrease with increase in bar diameter, but as these results are based on samples which may originate from populations with different means and different standard deviations, the statistics are less meaningful than for other products studied.

3.0 STATISTICAL ANALYSIS

3.1 Normality The data discussed in Section 3 above have been checked for asymmetry and kurtosis to detect departures from the normal distribution. To eliminate errors due to the increase in mean strength with decrease in material thickness, only samples containing specimens of similar thickness have been selected from each size range for each material.

Results show that for plates, sections and hollow sections the distribution of yield strength tends to be positively skew for mild steel and negatively skew for high yield steel and that these tendencies are more pronounced for thin sections. Other experience has shown positive skewness for high yield steel in certain sections. It follows that characteristic strengths calculated on the assumption that the underlying distribution is normal will tend respectively to underestimate and overestimate the true values for these two types of materials.

In comparison with the above, it has been found that the distribution of ultimate tensile strength for the above samples is more normal than that of the yield strength, and that for all materials the distribution of ductility (as measured by the maximum elongation of tensile specimens) is always negatively skew.

Because of the large differences in the mean and variance of the yield strength of similar products rolled by different mills, data which have been selected at random from different mills to give a single sample will give poor estimates of the distribution of the combined populations from which they have been drawn. For the smaller thicknesses of mild steel plate it can be shown that the variance of the characteristic strength (based on a 95% probability of being exceeded and an assumed normal distribution) for different mills is smaller than the variance of mean strengths. It follows that the distribution of the combined populations for different mills will be positively skew, even if the distributions of the separate populations are statistically normal. This is a direct result of

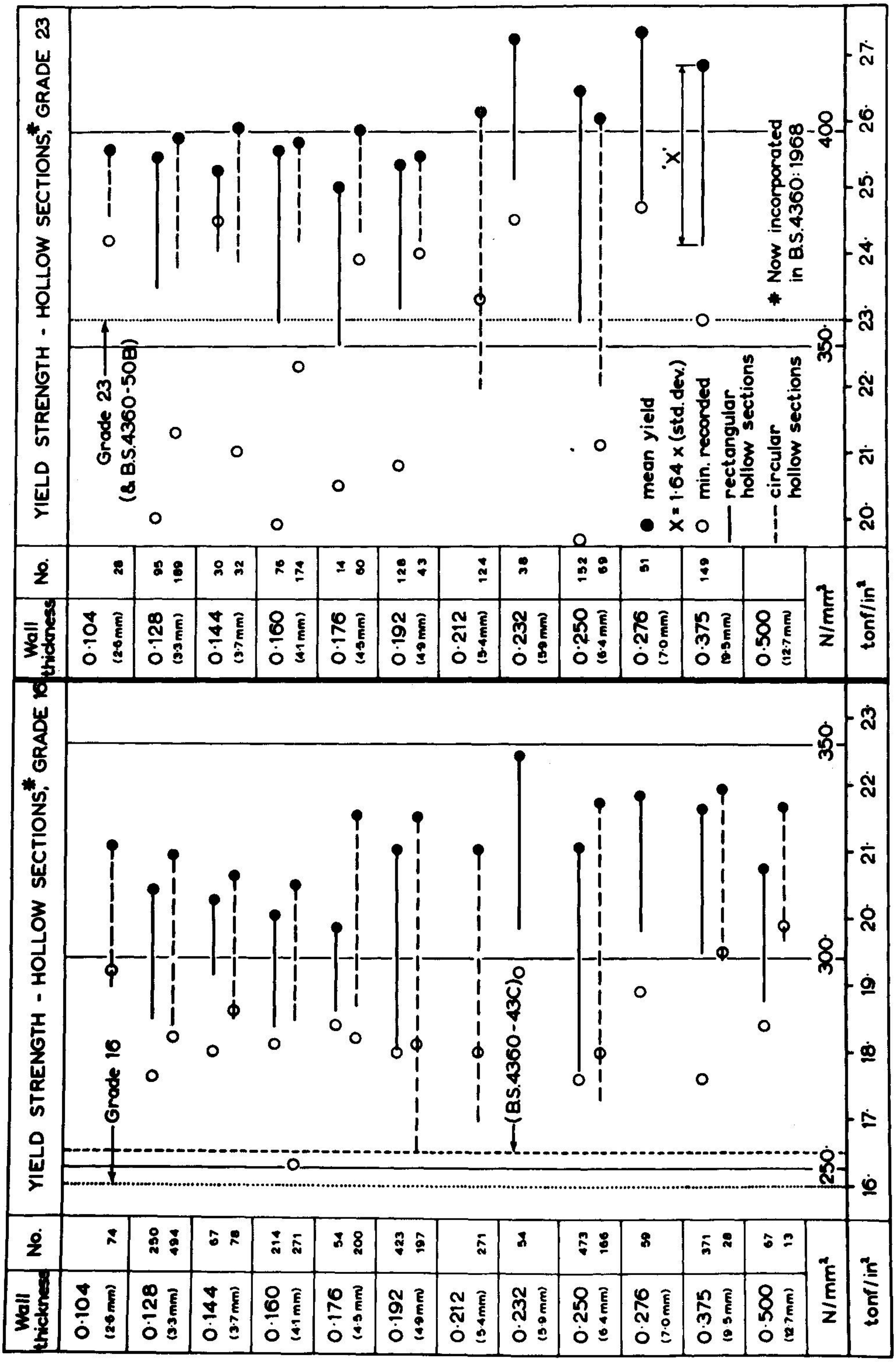
YIELD STRENGTH - HOLLOW SECTIONS,* GRADE 16
YIELD STRENGTH - HOLLOW SECTIONS,* GRADE 23
Wall thickness
No.
0·104 (2·6 mm)
0·128 (3·3 mm)
0·144 (3·7 mm)
0·160 (4·1 mm)
0·176 (4·5 mm)
0·192 (4·9 mm)
0·212 (5·4 mm)
0·232 (5·9 mm)
0·250 (6·4 mm)
0·276 (7·0 mm)
0·375 (9·5 mm)
0·500 (12·7 mm)
N/mm²
tonf/in²
Grade 16
(B.S.4360-43C)
Grade 23
(& B.S.4360-50B)
'X'
mean yield
X = 1·64 x (std. dev.)
min. recorded
rectangular hollow sections
circular hollow sections
* Now incorporated in B.S.4360: 1968

FIGURE 4

trying to achieve a yield strength in excess of a target minimum value (and corresponds to the zone between the ellipse and the straight line described by Leclerc[3]).

If, for example, two equal samples are selected at random from populations both having characteristic yield strengths of 16.0 tonf/in^2 but means of 17.0 tonf/in^2 and 19.0 tonf/in^2, the calculated characteristic strength of the combined sample will be 15.23 tonf/in^2, 0.77 tonf/in^2 below the true value.

The opposite is true, however, for the distribution of thickness of plates or sections rolled to a given nominal size, where both positive and negative tolerances are allowed. In this case, the combination of results from different sources tends to give a distribution which deviates less from normal than the underlying distributions.

3.2 Truncation There is a tendency for yield strength data based on mill test results to be subject to a certain degree of truncation for values less than the allowable minimum yield strength. With the existing system of batch testing steels (whereby only one test is carried out for every 'x' tons of steel rolled), it is unlikely that the material supplied by the steel mills is subject to the same degree of truncation, and a conservative design assumption is that the distribution of yield strength is not affected by the rejection of the material found to be below the minimum allowable value. However, with good quality control some manufacturers may be able to achieve a 100% cut-off.

Using a method suggested by Hald[(4)], the data discussed in Section 3 have been analysed assuming truncation at the minimum yield strength. For some samples with low characteristic strengths a significant degree of truncation has been detected and it follows that the true characteristic strengths in these cases are lower than the values calculated by simple analysis. This technique can be used only for samples which do not deviate from normal.

3.3 Variations in Mean Strength with Time In addition to random variations, the mean yield strengths of steel produced by a given mill may be found to change systemmatically with time, due to progressive changes in the manufacturing processes. Provided the data can be grouped according to time of manufacture, such changes can be detected by analysis of variance, and a reduction in the overall variance is then justifiable in calculating characteristic strengths.

4.0 THE EFFECTS OF VARIATIONS IN STRENGTH ON SAFETY

Johnson[(5)], Ferry-Borges[(6)] and others have shown how the probability of failure is highly sensitive to the assumed form of the distribution of variables. However, if it is assumed that the type of distribution of the yield strength of a certain grade of steel is the same for all manufacturers, a good estimate of the relative safety of the different products can be obtained by calculating the respective probabilities of failure P_f for a chosen distribution of loading. However, the results are still highly sensitive to errors in the estimated variance of the material properties.

Using the results obtained in Section 2 for different materials, and assuming a normal distribution of variables, the probability of failure of a simple flexural member (laterally restrained) subjected to a load with a coefficient of variation of 0.15 can be shown to vary as follows in Figure 5. For rolled sections, allowance has been made for the difference between web and flange strengths in calculating P_f and the safety factor γ, by using the mean correction factors given in Figures 4 and 5.

The comparisons are based on members designed with a safety factor of 1.7

Product	Thickness (in)	Mill	$\bar{\sigma}$	s	P_f	γ
B.S.15 Plates	0.375-0.5	Y	18.38	1.720	2.8×10^{-5}	1.65
	0.375-0.5	W	18.29	0.876	3.2×10^{-8}	1.79
	1.5 -2.0	Y	16.45	2.061	5.6×10^{-4}	1.54
	1.5 -2.0	W	17.08	0.924	3.2×10^{-8}	1.82
B.S.968 Plates	0.375-0.5	M	25.60	2.152	5.2×10^{-5}	1.63
	0.375-0.5	K	25.43	0.966	6.2×10^{-8}	1.77
	1.5 -2.0	M	23.76	1.415	3.4×10^{-6}	1.65
	1.5 -2.0	L	25.89	1.195	6.3×10^{-9}	1.84
B.S.15 Sections	0.375-0.50	Q	19.20	0.991	4.5×10^{-9}	1.93
	0.625-0.75	L	18.98	2.261	1.6×10^{-4}	1.79
B.S.968 Sections	0.25-0.375	N	27.42	1.585	1.5×10^{-9}	1.88
	1.5 - 2.0	L	23.85	1.257	3.4×10^{-6}	1.64
B.S.15 R.H.S.	0.144	-	20.29	1.085	1.3×10^{-10}	1.96
	0.250	-	21.07	1.700	8.0×10^{-8}	1.93
B.S.968 R.H.S.	0.232	-	27.26	1.306	5.4×10^{-9}	1.85
	0.250	-	26.46	2.116	5.4×10^{-6}	1.70

Figure 5

on the specified minimum yield strength of the material and have been selected to show some of the highest and lowest probabilities of failure for each type of steel, for mills with differing quality control. The comparisons do not include the effects of variables other than the basic yield strength of the material and the assumed distribution for loading, and in practice the probabilities will be higher due to other variables.

From the analysis of the variability of plate and rolled section thicknesses, it can be shown that the proportion of variance of the flexural strength of a simple steel member due to variations in cross-sectional dimensions is only about 1/10 of the proportion due to variations in yield strength. For such members, the variation in yield strength is thus the predominant factor governing safety (apart from load effects).

The safety factors γ shown in the last column of Figure 5 relate the load and the calculated values of characteristic strength, and are relative to a value of 1.7 for characteristic strengths equal to the minimum allowable yield strengths specified in existing British Standards. On this basis, the use of steel from different mills and the use of different types of section is equivalent to changing existing load factors of 1.7 to the values shown in the table (i.e. between 1.54 and 1.96).

ACKNOWLEDGEMENTS

This work has been carried out at Imperial College under the direction of Professor A.L.L. Baker and Dr. A.R. Flint and the author is extremely grateful for their advice and encouragement. The author is also grateful for the support of the Construction Industry Research and Information Association in financing this investigation and is indebted to the British Railways Board, the British Steel Corporation Heavy Steel Technical Committee and Stewarts and Lloyds Limited for making data available.

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SUMMARY

Variations in the strength of mild and high yield structural steels have been examined by analysing data from mill and other tests. Comparisons are made between similar steels produced by different mills and between similar steels of different rolled thickness. The results are interpreted in terms of probability of structural failure and recommandations are given for methods of evaluating characteristic strengths.

RESUME

Des variations de la résistance d'aciers de construction, doux et à haute limite élastique, ont été examinées en analysant les données d'essais de réception de laminoirs. Des comparaisons sont faites entre des aciers semblables produits par différents laminoirs et entre des aciers analogues de différentes épaisseurs de laminage. Les résultats sont interprétés en termes de probabilité de défaillance de la construction.

ZUSAMMENFASSUNG

Aufgrund der Auswertung von Walzwerk-Abnahmeversuchen wurden die Festigkeitseigenschaften verschiedener Fluss- sowie Baustähle mit hoher Streckgrenze untersucht. Aus verschiedenen Walzwerken stammende gleichartige Stähle sowie gleichartige Stähle verschiedener Walzstärke wurden jeweils miteinander verglichen. Der Verfasser erörtert die Ergebnisse im Hinblick auf einen etwaigen Bruch von Tragwerken.