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STATISTICAL RESEARCH OF STEEL GRADES: DX51D, DX52D AND DX53D

BADANIA STATYSTYCZNE GATUNKÓW STALI: DX51D, DX52D I DX53D

A b s t r a c t

This article presents the results of the statistical research of the mechanical properties of sheets of Polish grades DX51D, DX52D and DX53D, made of low carbon steel for cold forming, continuously hot-dip coated. DX-type sheets, in particular DX51D, produced according to standard EN 10346 [4], can be used, inter alia, to produce corrugated metal sheets and sandwich panels. Standard EN 10346 [4] does not give at all, or gives in the form of very wide intervals, strength parameters for sheets of DX type. Characteristic and design values of yield strength and tensile strength have been presented in the article. Also, the values of partial factors for DX-type steel have been analyzed.

Keywords: *DX51D*, *DX52D*, *DX53D*, *steel sheets*, *statistical research*

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań statystycznych cech wytrzymałościowych dla krajowych blach gatunku DX51D, DX52D i DX53D ze stali niskowęglowych do obróbki plastycznej na zimno powlekanych ogniowo w sposób ciągły. Blachy typu DX wg normy EN 10346 [4], w szczególności DX51D, mogą być stosowane m.in do produkcji blach trapezowych i płyt warstwowych. Norma EN 10346 [4] nie podaje wcale lub podaje w postaci bardzo szerokich przedziałów parametry wytrzymałościowe blach typu DX. W pracy wyznaczono wartości charakterystyczne i obliczeniowe dla granicy plastyczności i wytrzymałości na rozciąganie oraz przeanalizowano wartości częściowych współczynników bezpieczeństwa dla blach typu DX.

Słowa kluczowe: *DX51D*, *DX52D*, *DX53D*, *blachy stalowe*, *badania statystyczne*

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1. Introduction

According to standard EN 10346 [4], contemporary corrugated sheets [8] and external layers of sandwich panels [9] are mainly made of thin sheets of the following steel grades – S220GD, S250GD, S280GD, S320GD, S350GD (continuously hot-dip coated strips and sheets of structural steel) or DX51D (continuously hot-dip coated strips and sheets of low carbon steel for cold forming).

The strength parameters for the national continuously hot-dip coated strips and sheets of structural steel manufactured according to [4] have been verified on the basis of a large statistical test in [5]. For DX-type steel, the standard EN 10346 [4] only specifies intervals of its mechanical properties or does not provide the information at all. While comparing the tables contained in standards EN 10346 [4] and EN 1993-1-3 [3], it can be noted that the standard for designing steel structures [3] defines the minimum values of the intervals specified in standard [4] (for transverse direction) – c.f. Table 1. The aim of this paper is to determine the characteristics and design values of the strength parameters and partial safety factors for DX-type sheets on the basis of statistical research. The calculations shall be performed for Polish steel products.

Table 1

Mechanical properties of steel grades: DX51D, DX52D and DX53D

	EN 10346 [4]			EN 1993-1-3 [3]	
Steel grade	Yield strength R_e MPa	Tensile strength R_m MPa	Elongation A_{80} % min	f_{yb} MPa	f_u MPa
DX51D	–	270–500	22	140	270
DX52D	140–300	270–420	26		
DX53D	140–260	270–380	30		

According to [3], properties of the base material, in particular, the nominal yield strength f_{yb} and ultimate tensile strength f_u can be adopted either by assuming values $f_y=R_{eh}$ or $R_{p0.2}$ and $f_u=R_m$ direct from product standards, by using the values given in the tables contained in the standard, or by appropriate tests, according to EN 1990 [1]. This work will use the provisions of Appendix D to the standard EN 1990 [1].

Determining the design values of material properties from statistical research may be carried out in one of the following ways:

– by assessing a characteristic value X_k, which is then divided by a partial factor γ_m and multiplied by an explicit conversion factor η_d (method *a*),
– by direct determination of the design value X_d, implicitly or explicitly accounting for the conversion of results and the total reliability required (method *b*).

The formulas specified in the design standard PN-EN 1990 [1] are based on the assumption that all random variables have normal or log-normal distributions and there is no prior information about their mean values. The estimation of the design values can be performed either when there is no prior information about the dispersion measurement of the random variable in the form of a coefficient of variation v_x, or when there is full information about a coefficient of variation.

In the case of method *a, the* design value of a property *X* can be calculated from the formula:

– for the normal distrubution

$$X_d = \eta_d \frac{X_k}{\gamma_m} = \frac{\eta_d}{\gamma_m} m_x (1 - k_n v_x) \tag{1}$$

$$v_x = s_x / m_x \tag{2}$$

$$m_x = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{3}$$

$$s_x^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - m_x)^2 \tag{4}$$

– for the log-normal distribution

$$X_d = \frac{\eta_d}{\gamma_m} \exp(m_y - k_n s_y) \tag{5}$$

$$m_y = \frac{1}{n} \sum_{i=1}^{n} \ln(x_i) \tag{6}$$

$$s_y = \sqrt{\ln(V_x^2 + 1)} = v_x \quad \text{– if } v_s \text{ is known from prior knowledge} \tag{7}$$

$$s_y = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\ln x_i - m_y)^2} \quad \text{– if } v_x \text{ is unknown from prior knowledge} \tag{8}$$

where:

η_d – design value of the conversion coefficient,
γ_m – partial safety factor associated with the uncertainty of material properties,
n – number of test results,
x_i – value of a single result,
k_n – value of statistics, depending on the number of test results according to Table 2.

In the case of method *b,* the design value of *X* is determined from the following formulas:

– for normal distribution

$$X_d = \eta_d m_x (1 - k_{d,n} v_x) \tag{9}$$

– for log-normal distribution

$$X_d = \eta_d \exp(m_p - k_{d,n} s_y) \tag{10}$$

where:

$k_{d,n}$ – value of statistics according to Table 3.

If the value of the coefficient of variation $v_x \leq 0.1$ (as is usually the case for the strength properties of steel products), the difference between the results of the statistical analysis for normal and log-normal distribution is practically insignificant. While analyzing the values of statistics in each row of Tables 2 and 3, it can be observed that for large sample sizes, the values of statistics tend asymptotically to the same value, irrespective of whether the coefficient of variation is known or estimated from the test.

Table 2

Values of statistics k_n for the 5% characteristic value

n	1	2	3	4	5	6	7	8	9	10	∞
v_x (known)	2.31	2.01	1.89	1.83	1.80	1.77	1.74	1.72	1.68	1.67	1.64
v_x (unknown)	–	–	3.37	2.63	2.33	2.18	2.00	1.92	1.76	1.73	1.64

Table 3

Values of statistics $k_{d,n}$ for the design value

n	1	2	3	4	5	6	7	8	9	10	∞
v_x (known)	4.36	3.77	3.56	3.44	3.37	3.33	3.27	3.23	3.16	3.13	3.04
v_x (unknown)	–	–	–	11.40	7.85	6.36	5.07	4.51	3.64	3.44	3.04

2. Statistical research

In order to determine the mechanical parameters of the DX-type sheets manufactured according to standard EN 10346 [4], the data on the mechanical properties of metal sheets from the years 2005–2010, provided by the Quality Control Department of Arcelor Mittal, have been used by the author. The presented statistical test includes properties of the sheets with a nominal thickness of 0,45–2,00 mm. The results of statistical research for the different grades of steel have been presented in Table 4. The number of the data set for each property was 63292.

Particularly interesting, from a practical point of view, are the results for the DX51D steel grade, which is used in the manufacturing of corrugated sheets, external layers of sandwich panels and cold formed sections. Sheets made of grade DX52 are intended primarily for drawing and DX53D for deep drawing. A large number of the results since 2007 are due to the introduction of the electronic archiving system by the company. The results of earlier years were obtained from the archives stored in the paper version. A small number of the results for the DX52 and DX53 steel grades are caused by a relatively small production volume compared to the DX51D steel.

Verification of a type of probability distribution for random yield strength $\underline{R}_e$ and random ultimate tensile strength $\underline{R}_m$, was performed with a graphical method using probabilistic grids where the statistical results have been applied. Figure 1a presents a verification of the probability distribution of yield strength of the DX51D grade steel sheets on the grid of normal distribution. Linear approximation of empirical data seems reasonable. Similar results were also obtained for the other two analyzed grades of steel.

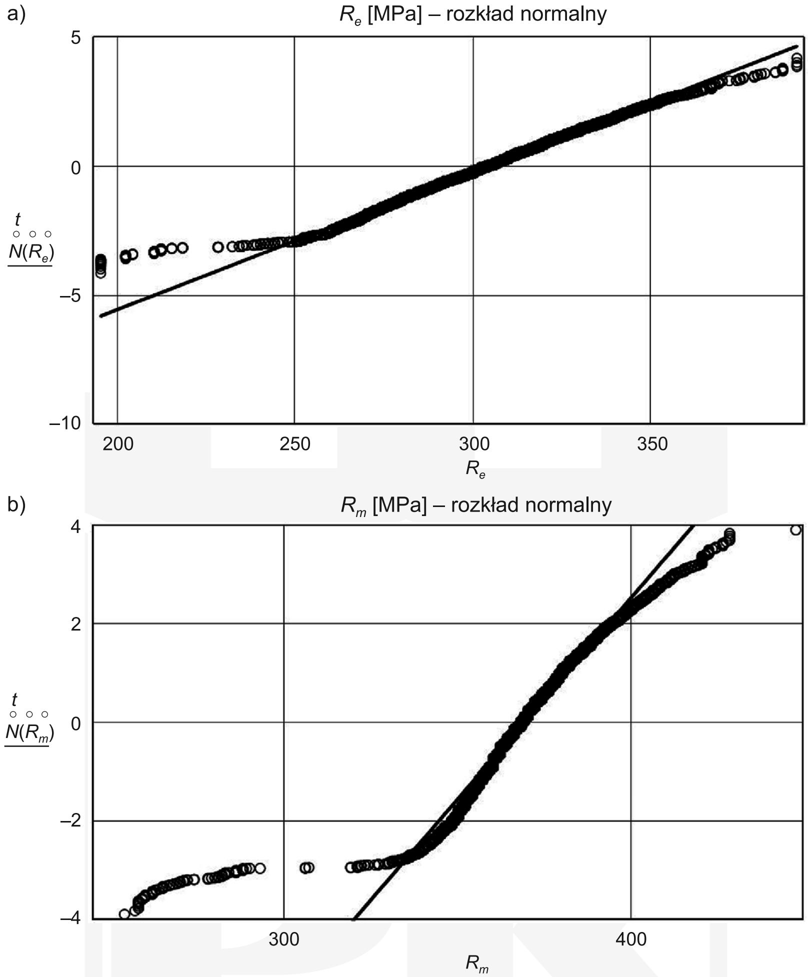

Fig. 1. Statistical test for the DX51D steel (years 2005–2010) on the normal probability grid for: a) yield strength R_e, b) ultimate tensile strength R_m

The results obtained for the ultimate tensile strength R_m (c.f. Fig. 1b) imply a possibility of using linear approximation only for results concentrated around the central values. The assumption of normality of distribution of ultimate tensile strength R_m is therefore satisfied in approximation. Figure 2 depicts sets of implementation on the plane R_e – R_m, and linear regression lines for the DX51D grade steel. The values of the correlation coefficients have been included in table 4, column (9). In the case of the DX51D steel of the largest number of data, for the joint test of years 2005 to 2010, a moderate [7] dependence of the correlation $\rho = 0{,}498 \in \langle 0{,}4;0{,}6)$ was obtained.

Table 4 summarizes the detailed statistical research results both for the annual tests, and for the joint tests of years 2005–2010. Columns (3), (6) and (10) of the table include:

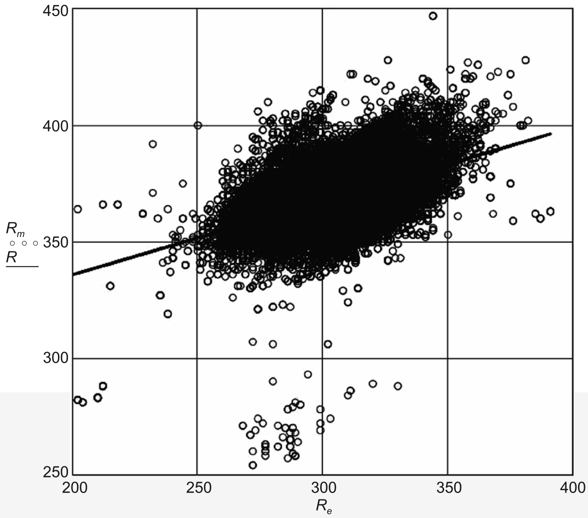

Fig. 2. Linear regression between yield strength R_e and ultimate tensile strength R_m for the DX51D grade steel

Table 4

The results of statistical research of mechanical properties of the following steel grades: DX51D, DX52D and DX53D

Year	Number of results n	$\bar{R}_e$ MPa	μ_{Re} MPa	v_{Re}	$\bar{R}_m$ MPa	μ_{Rm} MPa	v_{Rm}	ρ	$\bar{A}$ %	v_A
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
2005	75	315.92	18.07	0.057	372.27	13.82	0.037	0.783	32.04	0.053
2006	35	307.11	11.91	0.039	368.43	10.71	0.029	0.744	32.17	0.063
2007	6534	314.41	15.25	0.048	368.44	11.12	0.030	0.516	31.33	0.068
2008	12127	316.22	16.62	0.053	367.97	11.12	0.030	0.595	31.98	0.069
2009	27326	299.19	18.28	0.061	367.44	12.07	0.033	0.499	31.02	0.100
2010	18100	300.02	16.56	0.055	371.66	11.89	0.032	0.657	31.39	0.102
DX51D –2005–10										
2005–10	64197	304.21	18.69	0.061	368.84	11.89	0.032	0.498	31.34	0.093
DX52D										
2007–10	156	299.23	13.97	0.047	366.10	9.93	0.027	0.254	31.97	0.087
DX53D										
2007–9	39	248.97	21.62	0.087	336.44	25.49	0.076	0.958	33.64	0.151

mean values $\bar{R}_e$, $\bar{R}_m$ and $\bar{A}$ – respectively for random yield strength $\underline{R}_e$, random ultimate tensile strength $\underline{R}_m$ and random elongation of the tested sample $\underline{A}$ – calculated according to the formula (3). Columns (5), (8) and (11) represent the values of the coefficient of variation determined according to formula (2). Columns (4) and (7) contain the values of standard deviation obtained from formula (4) ($\mu = s$).

3. Characteristic and design values

The next stage of the analysis was to determine the characteristic and design values of the strength properties of the analysed grades of steel. The columns (5) and (10) of Table 5 compare the characteristic values calculated according to formula (1), as the lower 5% quantiles of the normal distribution (assuming the conversion coefficient η_d = 1,0, as in the work in [6]). On the other hand, the columns (6) and (11) contain design values of yield strength R_e and ultimate tensile strength R_m, calculated as 0.1% lower quantiles of a normal distribution.

Table 5

Characteristic and design values of R_e and R_m

No. Year	Number of results n	R_e MPa	v_{Re}	$R_{e,k}$ MPa	$R_{e,d}$ MPa	γ_{m0}	R_m MPa	v_{Rm}	$R_{m,k}$ MPa	$R_{m,d}$ MPa	γ_{m2}
(1)	(2)	(3)	(4)	(6)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
DX51											
2005–10	64197	304.21	0.061	**273.78**	**247.80**	**1.10**	368.84	0.032	**349.48**	**332.96**	**1.05**
DX52											
2007–10	156	299.23	0.047	**276.16**	**256.48**	**1.08**	366.10	0.027	**349.90**	**336.05**	**1.04**
DX53											
2007–9	39	248.97	0.087	**213.45**	**183.12**	**1.16**	336.44	0.076	**294.51**	**258.71**	**1.13**

According to the interpretation presented in standard EN 1990 [1] and the work in [6], a partial safety factor $\gamma_M=\gamma_m\gamma_R$ is a product of the coefficient γ_m describing the uncertainty in assessing material properties, and the coefficient γ_R describing the uncertainty of the adopted model in structural resistance. Comparing formulas (1) and (9), and assuming k_n and $k_{d,n}$ according to the sample size (c.f. Tables 2 and 3), the value of the coefficient γ_m can be calculated from the formula (11):

$$\gamma_m = \frac{1-1.64v_x}{1-3.04v_x} \quad (11)$$

Values of the coefficient γ_m, for the different grades of steel have been summarized in columns (7) and (12) of Table 5 for yield strength R_e and ultimate tensile strength R_m, respectively. Values of the partial safety factor for the cross-section resistance γ_{M0} have been calculated by multiplying the value of the coefficient γ_{m0} (determined from the tests) by $\gamma_R = 1.0$.

Estimates of the coefficient γ_R value, describing the uncertainty of the model of the cross-section resistance have been obtained making use of the results of similar studies carried out for the thin sheets manufactured according to the standard EN 10346 [4]. For the S280GD and S320GD grades of steel the values of $\gamma_R = \gamma_{M0} / \gamma_{m0} \cong 1.0$ were obtained. Thus, for DX-type sheets, the value of the partial factor is $\gamma_{M0} = 1.0 \cdot \gamma_{m0}$. In the case of partial resistance factor γ_{M2} of the net section at fastener holes, the values of model uncertainty factor in structural resistance are not known to the author. A similar problem is mentioned by the authors of the work in [6].

Starting from the values of the coefficient $\gamma_{M2} = 1.25$ specified in standard EN 1993-1-3 [3], estimation of the model uncertainty in structural resistance coefficient for net sections at fastener holes can be calculated as interval $\gamma_R = 1.25/(1.04 – 1.13) = 1.11 – 1.20$.

4. Conclusions

The statistical data collected by the author allowed for the determination of the characteristic and design values of the strength properties and the values of partial factors for the DX51D, DX52D, DX53D sheets manufactured according to standard EN 10346 [4]. In the case of the Polish steel products, the obtained results allow to adopt for the calculations the significantly higher strength parameters than those specified in the design standard EN 1993-1-3 [3].

References

[1] PN-EN 1990:2004. Eurokod. Podstawy projektowania konstrukcji.

[2] PN-EN 1993-1-1:2005. Eurokod 3. Projektowanie konstrukcji stalowych. Część 1.1: Reguły ogólne i reguły dla budynków.

[3] PN-EN 1993-1-3:2008. Eurokod 3. Projektowanie konstrukcji stalowych. Część 1.3: Regóły ogólne – Reguły uzupełniające dla konstrukcji z kształtowników i blach profilowanych na zimno.

[4] PN-EN 10346:2011. Wyroby płaskie stalowe powlekane ogniowo w sposób ciągły – Warunki techniczne dostawy.

[5] Gwóźdź M., Żwirek P., *Weryfikacja statystyczne współczynników częściowych nośności blach cienkich*, Inżynieria i Budownictwo 9/2011, 492-495.

[6] Mendera Z., Suchodoła M., *Częściowe współczynniki bezpieczeństwa w projektowaniu konstrukcji stalowych według eurokodów*, Inżynieria i Budownictwo 12/2013, 667-671.

[7] Sobczyk M., *Statystyka. Aspekty praktyczne i teoretyczne*, Wydawnictwo UMCS, Lublin 2006.

[8] Technical Approval ITB AT-15-3429/2011, Stalowe blachy profilowane Mauka, Bromo, ACP-, AC-, TR-, V-, TR35, TR40, TS40, TR50, TR60, TR70, TR84, TR94, TR150, TR160, LT40, LT70, EP-, Hacierba-, Haciero-, Frequence-, Floline-, Softline-, Hairbable-, Pampa-, Cofrasol-, PMA-, opracowana dla ArcelorMittal Construction.

[9] Technical Approval ITB AT-15-8519/2010, Ścienne płyty warstwowe PWS-WA Pruszyński z rdzeniem z wełny mineralnej w okładzinach z blachy stalowej pełnej i perforowanej dla firmy Pruszyński Spółka z o.o.