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The Basis for Reliability-Based Mechanical Properties of Structural Aluminium Alloys

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Featured Application: By providing relevant statistical data of structural aluminium's main mechanical properties, the conducted analysis represents an essential step for the implementation of the correct probabilistic approach in Eurocode 9.

Abstract: Adequate knowledge of mechanical properties and their statistical description is the basis for performing reliable verification of design methods and design of structures in general. The probabilistic design approach implemented in Eurocodes requires statistical data on all variables used in the design procedure. Although aluminium was introduced in structural Eurocodes more than four decades ago (ENV), the statistical database of mechanical properties is still inadequate. To provide a reliable statistical background, data collection was performed concerning aluminium products mainly found in the European market, within the last 20 years regarding certificates from the aluminium industry and 30 years regarding data from the research community. The collected data include aluminium alloy series 1xxx, 5xxx, 6xxx, and 7xxx, mainly extruded, and relevant mechanical properties such as 0.2% proof strength, ultimate strength, Young's modulus, and Poisson's ratio. They were fit to distributions, and relevant fractiles were determined, along with an analysis of nominal to characteristic and design value ratios. Variation of ratios obtained shows that that the majority of nominal values are economical and reliable. However, certain adjustments to nominal values are required to achieve a uniform reliability level in terms of the choice of alloy and temper.

Keywords: reliability; Eurocode 9; statistical parameters; basic variables; mechanical properties; material partial factor

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1. Introduction

The first edition of the recommendations for the design of aluminium structures was published in 1978 by the ECCS committee T2 which was chaired by F. M. Mazzolani [1]. Up until the publication of the final version of Eurocode 9 in 2007 [2], substantial work has been conducted by the Technical committee CEN-TC 250/SC9, and the limitations imposed by the absence of standards and regulations for the design of aluminium structures have finally been successfully surpassed. The revision of the structural Eurocodes is now in the final phase, and soon the second generation of Eurocodes will be published, along with a revised and upgraded version of EN 1999, again by CEN-TC 250/SC9, chaired by F. M. Mazzolani. Nevertheless, a formal link between Eurocode 9 and Eurocode 0 regarding the achieved level of reliability, in terms of probabilistic analysis of design rules given in Eurocode 9 (partial factors on the resistance side), is still missing. This is additionally stressed by the requirements of EN 1998 [3] and especially with the upcoming upgraded version of EN 1998, regarding minimum and maximum mechanical properties and planned plastic mechanisms. To bridge this gap, the TC 250 SC10 ad-hoc group on reliability is working actively on the 'Technical report for the reliability background of Eurocodes', and all TC 250 SCs are supposed to support this activity with appropriate data.

It is a well-known fact that various factors influence the reliability level of structures designed according to (Euro)codes. In a limit-state equation, the action side variables are generally dominant, but resistance side variables are also important and should not be ignored. Generally, from the resistance side, mechanical properties are variables with the highest weights and should be the first aspect to consider. Additionally, by separating the model uncertainty in structural resistance and the uncertainty in material properties, a more straightforward approach to determining the partial factor with uniform reliability can be achieved. Namely, model uncertainty in structural resistance, especially regarding stability issues, includes multiple influential variables being researched [4], and the separation of the material variability as a variable can provide an easier and superior calibration process. In the current Eurocodes (as in previous national standards) for metals, the guaranteed (minimum) mechanical values according to relevant product standards are used as characteristic values. Although from the aspect of a semi-probabilistic approach guaranteed values are not characteristic values, they are the most reliable substitute as it is proven that the material fulfils the guaranteed (minimum) values. This approach can be regarded as non-economic, given that nominal values are much closer to design values than characteristic values.

Even though aluminium is a homogenous material, the type of treatment (temper) and the content of alloying elements affect the uniformity of mechanical properties [5]. To properly quantify the extent of variability of mechanical properties, its influence on the material level itself has to be considered using uniaxial tensile test results, excluding possible variability introduced by the testing method [6,7]. So far, limited research has been conducted regarding the variability of mechanical properties of aluminium, in contrast to structural steel [8] with which aluminium is often compared. Several authors from the Royal Institute of Technology in Stockholm as part of wider research programmes [9–13] conducted a number of tensile tests to determine the mechanical properties of aluminium. However, the purpose of those tests was to obtain mechanical properties for the development of the numerical model, with not enough results to statistically characterise the mechanical properties of aluminium alloys. Ferenc [14] investigated the variability of mechanical properties (ultimate strength, 0.2% proof strength, and modulus of elasticity) using a series of tensile tests performed on aluminium bars made from EN AW-6060 and EN AW-5754 alloys. The author stated that the coefficient of variation for both ultimate strength and 0.2% proof strength was less than 1%, concluding that aluminium has a much lower scatter of mechanical properties than steel. Ferenc [14] also hypothesised that the stochastic variance of mechanical properties of aluminium alloys is so small that there is negligible effect on coefficient γ_M = 1.1 given in Eurocode 9 [15]. Dokšanović, Džeba, and Markulak [5] explored the variability of mechanical properties of aluminium alloys with emphasis on 0.2% proof strength and ultimate tensile strength. The authors collected results from published literature and expanded them with experimental work. In total, 404 tensile test results for both welded and unwelded samples were obtained and processed. Distributions were fitted to mechanical properties of aluminium, and characteristic values were determined. Based on nominal to characteristic value ratios, it was concluded that nominal values of mechanical properties of aluminium can be unsafe or have a margin of safety in excess. Accordingly, the authors proposed new nominal values. Aakash et al. [16] presented a series of stress–strain curves obtained for aluminium alloy 6061-T651. Coupons were taken from nine lots of several aluminium producers and tested under six different temperatures. A total of 100 uniaxial tensile tests were performed as well as 54 plane strain tensile tests. Dokšanović et al. [17] analysed 36 stress–strain curves from alloys 6082-T6 and 6060-T66 and compared their suitability with eight constitutive laws.

Although the mentioned authors investigated the variability of the main mechanical properties of aluminium alloys, their databases were insufficient for global conclusions. Another important issue related to the variability of mechanical properties is the market area, i.e., the regional context of alloy use. Based on the proximity of production, regional areas are supplied by different producers, which due to numerous variables may produce products in conformity with related specifications but with greater or lower variability. This is due to differences in minimum values of strength for the same alloy and temper [5]. Consequently, as a first step for the development of probabilistic design procedures for the reliable design of aluminium structures, quantification of the variability of a large quantity of data of relevant mechanical properties of aluminium must be conducted. With this goal in mind, 12,524 material test certificates and tensile test results of various aluminium construction products that can be found on the European market were collected. At this stage of the research, only 0.2% proof strength, ultimate tensile strength, Young's modulus, and Poisson's ratio were analysed since they are the four main properties for the design of aluminium structures. Furthermore, the safety levels of the current nominal (guaranteed) values were evaluated.

To provide the required input data for the calibration of resistance factors and other reliability studies, this paper presents the statistical characterisation of the variability and distribution functions of the main random parameters affecting the strength of aluminium structures. The purpose of this paper is to statistically evaluate the variability of mechanical properties in a European context considering test results from a large and robust databank. An additional goal is to provide a reliability analysis basis for further research and considerations of current reliability levels in the valid normative documents, considering that calibration exercises for target probability are mostly derived directly from specific failure modes [5], contrary to the design methodology given in EN 1990 [18].

2. Scope of Analysis

2.1. Aluminium Alloys for Structural Applications

Aluminium as a material is characterised by a large number of different alloys, which can be both heat-treated (HT) and non-heat-treated (NHT). Many of those alloys are used in civil engineering practice for various applications [19–21]. Load-bearing and secondary aluminium elements can be made from 3xxx, 5xxx, 6xxx, and 7xxx alloy series, alloyed primarily with manganese (Mn), magnesium (Mg), magnesium and silicon (MgSi), and zinc (Zn), respectively. Many of the relevant aluminium properties, such as strength, ductility, corrosion resistance, and weldability, are strongly influenced by chemical composition. Additionally, treatments (tempers) of aluminium alloys greatly affect the properties of aluminium products as well [22]. Most commonly, wrought aluminium alloys are used. Cast aluminium products must be in accordance with EN 586 [23] but are rarely used as they contain a higher percentage of alloying elements and are more prone to manufacturing defects [24]. European standards for aluminium products divide wrought aluminium products into following groups: sheet (SH), strip (ST), plate (PL), extruded tube (ET), extruded profile (EP), extruded rod/bar (ER/B), drawn tube (DT), and forgings (FO). All aluminium products which are to be used in Europe must be in accordance with EN 485 [25] for plates, sheets, and strips or with EN 755 [26] for extruded rods, bars, tubes, and profiles. Wrought aluminium alloys for structural applications according to EN 1999-1-1 are shown in Table 1.

Table 1. Wrought aluminium alloys to be used in structural applications according to EN 1999-1-1 [15].

Aluminium Alloys	Common Tempers	Structural Use in Europe
EN AW-3004		NC
EN AW-3005		NC
EN AW-3103		NC
EN AW-5005/5005A		NC
EN AW-5049		NC
EN AW-5052		NC
EN AW-5083	O/H111, H24, H36, H116/H321	C
EN AW-5383	H12 | H22/H34	C
EN AW-5454		C
EN AW-5754	O/H111, H12 | H22/H34	C
EN AW-6060	T6	C
EN AW-6061	T6	C
EN AW-6063	T6, T66	C
EN AW-6005A	T6	C
EN AW-6082	T6, T4	C
EN AW-6106	T6	C
EN AW-7020		NC
EN AW-8011A		NC

Key: NC—not common, C—common.

2.2. Important Mechanical Properties

Minimum (guaranteed) values of relevant mechanical properties of aluminium at room temperatures for all types of alloys and tempers are specified in EN 755-2 [27] for extruded rods, bars, tubes, and profiles and in EN 485-2 [28] for sheets, strips, and plates. Various mechanical properties such as 0.2% proof strength, ultimate tensile strength, elongation at failure, and hardness are prescribed for all types of alloys, tempers, and ranges of thickness. Values related to the reduction of mechanical properties in the heat affected zone (HAZ) for MIG and TIG welding methods are given in EN 1999-1-1 [15], related to nominal values via a reduction factor. Even though a unified designation system should ensure that prescribed values of mechanical properties are the same for all the alloys in the norms worldwide, certain differences between countries are possible [5].

The main mechanical property for the reliability assessment of aluminium structures is the 0.2% proof strength as it is required for all the design calculations of cross-sectional and member resistances. Ultimate tensile strength is required for the verification of connections or tension failure of the net cross-section. Young's modulus is important in stability verification and the serviceability design of members. Poisson's ratio is needed for the calculation of shear modulus used in lateral-torsional buckling stability verification and various other torsional failure modes. In accordance, the first stage of the research focuses on the statistical analysis of these four mechanical properties of aluminium. Other mechanical properties such as elongation after fracture were not considered in this study. Additionally, properties regarding HAZ were not considered as these need to be analysed after the establishment of a base for non-HAZ values is completed, along with the many parameters regarding welding that are often not reported but are highly influential in terms of mechanical properties.

2.3. Description of Database

To quantify the variability of the mechanical properties of aluminium, a large number of uniaxial tensile test data was obtained from various, mostly European, aluminium producers, as detailed in Figure 1. In total, 12524 material test certificates and tensile test results, which included 14 different alloys and 17 different tempers, were gathered and analysed to quantify the variability of aluminium 0.2% proof strength (f_0), ultimate tensile strength (f_u), Young's modulus (E), and Poisson's ration (υ). Only non-welded aluminium samples were considered.

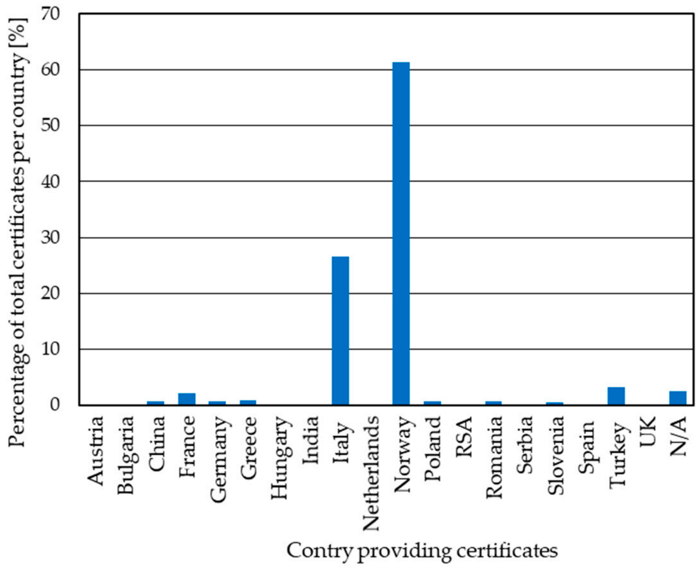

Figure 1. Distribution of obtained material test certificates (tensile test results) by country.

In Figure 1, it can be seen that material test certificates were obtained from a large number of aluminium producers located in 19 different countries. Note that RSA stands for the Republic of South Africa, while test results obtained from various laboratories [5,9–13,29] were labelled as N/A since the country of origin of the producer could not be determined. Most of the material test certificates originated from Norwegian and Italian producers, 61.4% and 26.6%, respectively. Figure 2 represents the distribution of obtained material test certificates without Norwegian and Italian producers. It is visible that producers from other countries amounted to less than 1% of the total number of material test certificates, except for Turkish and French aluminium producers with 3.2% and 2.0% of the total number of material test certificates, respectively. The total number of certificates obtained from laboratory research amounts to 2.5%.

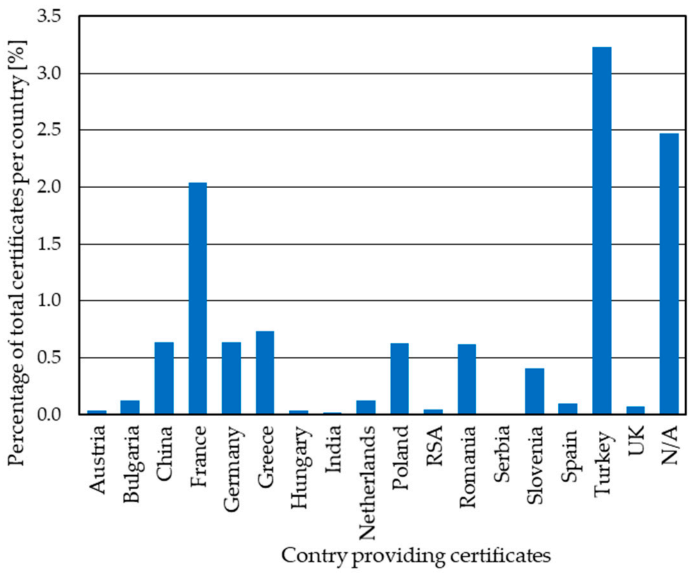

Figure 2. Distribution of obtained material test certificates (tensile test results) by country excluding Norway and Italy.

The distribution of certificates by alloys and tempers is also not uniform, as seen in Figure 3. The highest number of material test certificates is related to three specific alloys: EN AW-6063 (48.6%), EN AW-6082 (24.8%), and EN AW-6060 (16.9%), as can be seen in

Figure 4. Most of the material test certificates are related to heat-treated and artificially aged aluminium tempers (T6 and T66), as shown in Figure 5. Furthermore, only 6% of test results are related to rolled products (sheets, strips, and plates), while 94% are related to extruded products (profiles, tubes, rods, and bars).

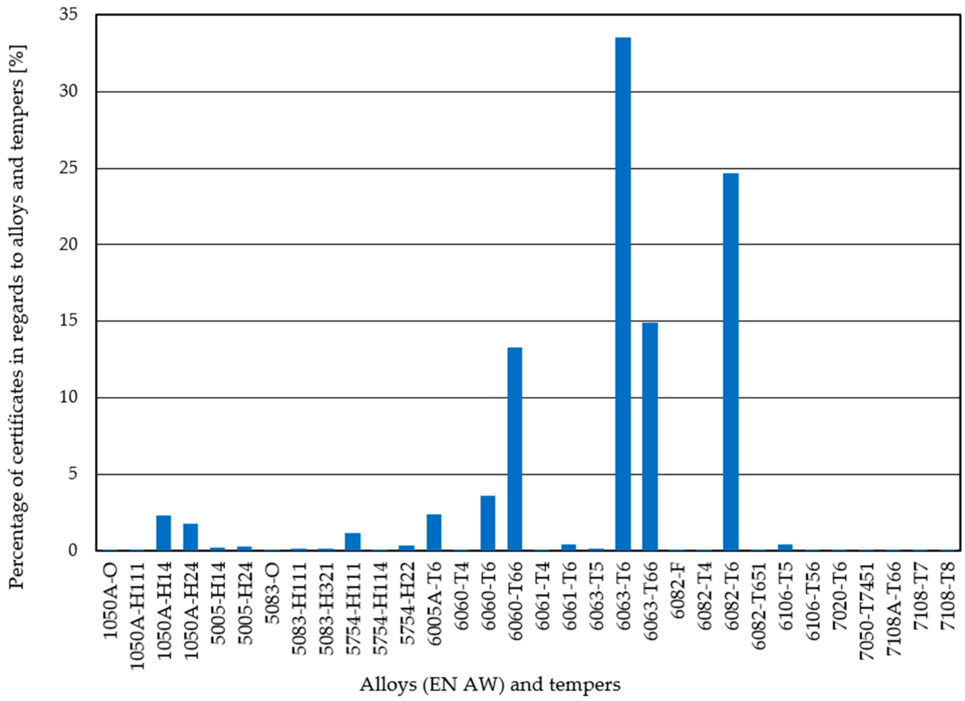

Figure 3. Distribution of obtained material test certificates (tensile test results) by alloys and tempers.

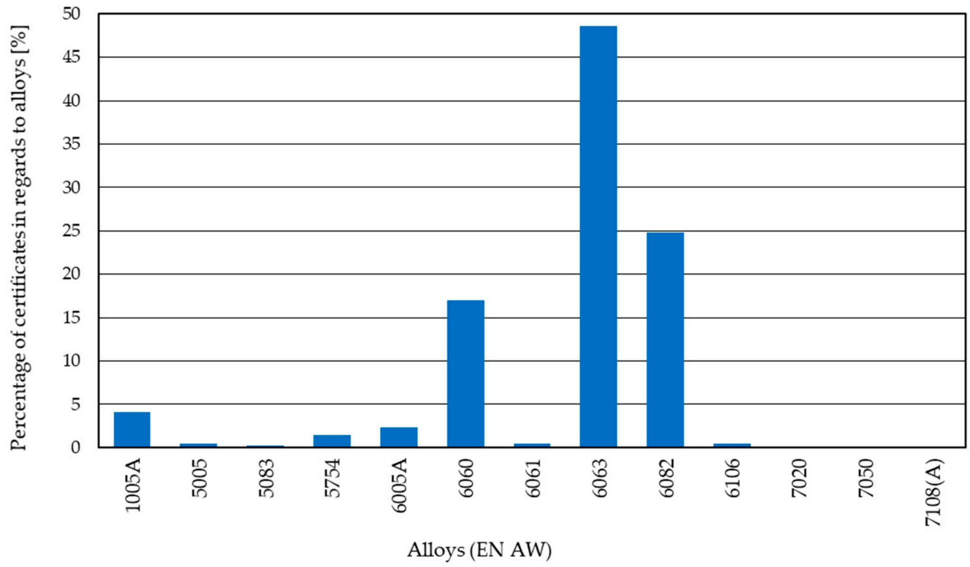

Figure 4. Distribution of obtained material test certificates (tensile test results) by alloys.

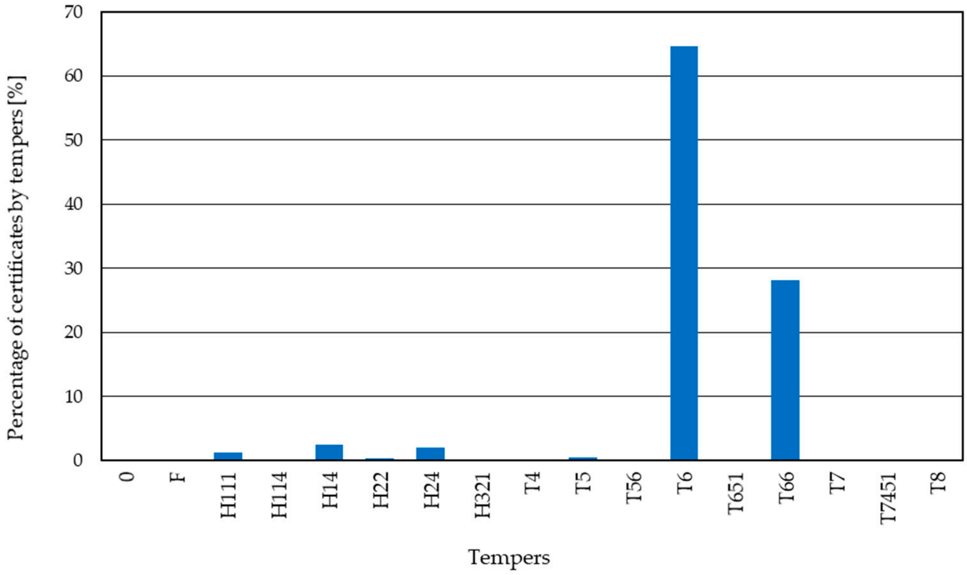

Figure 5. Distribution of obtained material test certificates (tensile test results) by tempers.

3. Methodology for Data Analysis

3.1. Uncertainties of Mechanical Properties

Mechanical properties of any material are not constant but vary randomly in space. A particular mechanical property will vary from one structure to another (global variations) or from one member to another (meso variations). Spatial variation can be observed within the same element as well (local variations) [30]. In addition to spatial variation, uncertainties in the material modelling are caused by the deviation between the measured properties and the properties of a real member or a structure.

Even though aluminium is a homogeneous material, and the production of all structural aluminium members must meet the defined requirements in relevant specifications, various factors can affect the uniformity of mechanical properties. Variability of mechanical properties of aluminium alloys is induced by the deviations in chemical composition, welding procedure, and heat treatment parameters [5]. It is expected that mechanical properties of aluminium alloys, similar to structural stainless steel, will introduce a higher level of uncertainty in structural reliability analysis compared to structural steel due to a large number of different alloys and tempers available on the market and pronounced nonlinearity of the stress–strain curve [31].

3.2. Criteria for the Validation of Appropriate Statistical Distribution

Prior to conducting a statistical analysis of the mechanical properties of aluminium, material test data were divided into groups regarding relevant properties given in [15]: alloy, temper, product form, and thickness. After the data were divided, a manageable form of quantitative descriptions was established, and the susceptible outliners were discharged.

Using Vose ModelRisk 6 [32], the results were processed and fitted to continuous distributions. To estimate distribution parameters, maximum likelihood estimation (MLE) was used as this method provides a consistent approach to parameter estimation problems, i.e., it can be developed for a large variety of estimation situations, including missing or censored data. In addition, MLE methods have desirable mathematical and optimality properties as they become minimum variance unbiased estimators as the sample size increases. The ranking of fit for distributions was performed using the Schwarz information criterion (SIC), Akaike information criterion (AIC) and Hannan–Quinn information criterion (HQIC), and the model fit with the lowest value of deviance according to all three criteria was selected. Information criteria were used for goodness of fit as they penalise overfitting and consider the number of estimated parameters, unlike other ranking criteria.

Preference was given to lognormal and Weibull distributions as they are recommended for resistance variables in EN 1990 [18] and ISO 2394 [33].

Cumulative function fractiles relevant for the design purposes (0.1% and 5%) were determined based on fitted distributions. It should be noted that 0.1% and 5% fractiles represent design and characteristic values, respectively. Furthermore, as an additional check, 0.1% and 5% cumulative function fractiles were determined based on distribution type and equations presented in EN 1990 [18], with necessary derivations for certain distributions.

3.3. Material Partial Factor Determination

The structural design principle adopted in the Eurocodes applies the partial factor format in combination with the concept of limit states [18]. The partial factors, γ_{Mi}, ensure that in all the relevant design situations no relevant limit state is exceeded and are calibrated to achieve the desired level of the reliability of a structure. Design values take different uncertainties into account applying partial factors, characteristic values, and other measures of reliability [5]. The design value R_{d} can be defined using the following simplified expression [18]:

$$R_d = \frac{R_k}{\gamma_M} \tag{1}$$

In Equation (1), R_k is the characteristic value, and γ_M is the partial factor that includes uncertainties in the mechanical properties (γ_M) as well as model uncertainties in the structural resistance (γ_{Rd}) [18]:

$$\gamma_M = \gamma_{Rd} \cdot \gamma_m \tag{2}$$

Such a format of partial factor γ_M defines uncertainties of the structural resistance and uncertainties of mechanical properties as independent variables, thus allowing for a separate calculation of the material variability. Accordingly, the design value of a mechanical property can be defined with the following expression:

$$X_d = \frac{X_k}{\gamma_m} \tag{3}$$

Unless stated otherwise in EN 1991 to EN 1999, the characteristic value of a mechanical property X_k should be defined as a 5% fractile value where a low value of a mechanical property is unfavourable, or as the 95% fractile value where a high value of a mechanical property is unfavourable. The design value of a mechanical property is defined in EN 1990 [18] and ISO 2394 [33] as a 0.1% fractile value in order to reach a target reliability level. Therefore, the partial factor for mechanical properties can be directly calculated:

$$\gamma_m = \frac{X_k}{X_d} \tag{4}$$

Nominal values of material properties X_{tk} can be taken as the characteristic values when there are insufficient statistical data available to establish the characteristic values [18]. Such an approach is adopted in the current version of Eurocode 9 [15] regarding mechanical properties of aluminium. Consequently, the partial factor for mechanical properties related to the nominal values γ_{mk} takes the following form:

$$\gamma_{mk} = \frac{X_{tk}}{X_d} = \gamma_m \cdot \Delta_k = \gamma_m \cdot \frac{X_{tk}}{X_k} \tag{5}$$

Note that the factor Δ_k indicates if the nominal value is safe compared to the characteristic value (less than 1 is safe).

4. Data Analysis and Discussion

4.1. 0.2% Proof Strength

Statistical analysis of 0.2% proof strength (f_o) was based on 12453 material test results covering 11 different alloys with different tempers and thicknesses. As can be seen in Table 2, the obtained data were divided into groups depending on aluminium alloy, temper, product type, and thickness ranges taken from EN 755-2 [27] and EN 485-2 [28]. For some of the data groups (shaded grey), an insufficient number of test data (<100, bolded) was collected for robust results in terms of reliability. Those results are omitted from further discussion.

Table 2. Statistical analysis of 0.2% proof strength.

<table>
<tr><th>Alloy</th><th>Temper</th><th>Product Form</th><th>Thickness t (mm)</th><th>Nominal Value [1] f_o (MPa)</th><th colspan="2">Number of Samples n</th><th colspan="2">Mean (MPa)</th><th colspan="2">Minimum (MPa)</th><th colspan="2">CofV (−)</th><th colspan="2">Distribution [2]</th></tr>
<tr><td rowspan="2">AW-1050A</td><td>H14</td><td>SH, PL, ST</td><td>≤25</td><td>85</td><td colspan="2">287</td><td colspan="2">123</td><td colspan="2">99</td><td colspan="2">0.05</td><td colspan="2">Norm.</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>75</td><td colspan="2">220</td><td colspan="2">118</td><td colspan="2">86</td><td colspan="2">0.07</td><td colspan="2">Weib.</td></tr>
<tr><td rowspan="2">AW-5005, AW-5005A</td><td>H14</td><td>SH, PL, ST</td><td>≤12.5</td><td>120</td><td colspan="2">23</td><td colspan="2">154</td><td colspan="2">139</td><td colspan="2">0.06</td><td colspan="2">Weib.</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>110</td><td colspan="2">33</td><td colspan="2">149</td><td colspan="2">133</td><td colspan="2">0.07</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="2">AW-5083</td><td>0, H111</td><td>SH, PL, ST</td><td>≤50</td><td>125</td><td colspan="2">21</td><td colspan="2">164</td><td colspan="2">142</td><td colspan="2">0.09</td><td colspan="2">LogN.</td></tr>
<tr><td>H321</td><td>SH, PL, ST</td><td>≤40</td><td>215</td><td colspan="2">15</td><td colspan="2">235</td><td colspan="2">215</td><td colspan="2">0.05</td><td colspan="2">Weib.</td></tr>
<tr><td rowspan="2">AW-5754</td><td>H111</td><td>SH, PL, ST</td><td>≤100</td><td>80</td><td colspan="2">143</td><td colspan="2">125</td><td colspan="2">85</td><td colspan="2">0.11</td><td colspan="2">LogN.</td></tr>
<tr><td>H22</td><td>SH, PL, ST</td><td>≤40</td><td>130</td><td colspan="2">45</td><td colspan="2">175</td><td colspan="2">132</td><td colspan="2">0.14</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="3">AW-6005A</td><td rowspan="3">T6</td><td>EP/O, ER/B</td><td>≤5</td><td>225</td><td>197</td><td rowspan="3">288</td><td>254</td><td rowspan="3">258</td><td>225</td><td rowspan="3">206</td><td>0.04</td><td rowspan="3">0.05</td><td>Norm.</td><td rowspan="3">Norm.</td></tr>
<tr><td>EP/H, ET</td><td>≤5</td><td>215</td><td>17</td><td>279</td><td>248</td><td>0.04</td><td>Weib.</td></tr>
<tr><td>EP/H, ET</td><td>>5, ≤10</td><td>200</td><td>74</td><td>263</td><td>206</td><td>0.03</td><td>Weib.</td></tr>
<tr><td rowspan="3">AW-6060</td><td>T4</td><td>EP/H</td><td>≤25</td><td>60</td><td colspan="2">6</td><td colspan="2">76</td><td colspan="2">64</td><td colspan="2">0.10</td><td colspan="2">Weib.</td></tr>
<tr><td>T6</td><td>EP/H</td><td>≤5</td><td>150</td><td colspan="2">454</td><td colspan="2">187</td><td colspan="2">152</td><td colspan="2">0.07</td><td colspan="2">LogN.</td></tr>
<tr><td>T66</td><td>EP, EP/H, ER/B</td><td>≤5</td><td>160</td><td colspan="2">1658</td><td colspan="2">205</td><td colspan="2">160</td><td colspan="2">0.09</td><td colspan="2">LogN.</td></tr>
<tr><td>AW-6061</td><td>T6</td><td>EP, EP/H, ET</td><td>≤25</td><td>240</td><td colspan="2">27</td><td colspan="2">263</td><td colspan="2">241</td><td colspan="2">0.07</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="3">AW-6063</td><td>T5</td><td>EP, EP/H, ET</td><td>≤10</td><td>130</td><td colspan="2">16</td><td colspan="2">166</td><td colspan="2">134</td><td colspan="2">0.12</td><td colspan="2">LogN.</td></tr>
<tr><td>T6</td><td>EP, EP/H</td><td>≤10</td><td>170</td><td colspan="2">4199</td><td colspan="2">214</td><td colspan="2">164</td><td colspan="2">0.04</td><td colspan="2">Norm.</td></tr>
<tr><td>T66</td><td>EP, ET, ER/B</td><td>≤10</td><td>200</td><td colspan="2">1858</td><td colspan="2">238</td><td colspan="2">200</td><td colspan="2">0.04</td><td colspan="2">Norm.</td></tr>
<tr><td rowspan="4">AW-6082</td><td>T4</td><td>EP/H</td><td>≤25</td><td>110</td><td colspan="2">6</td><td colspan="2">145</td><td colspan="2">111</td><td colspan="2">0.17</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="2">T6</td><td>EP/H</td><td>≤5</td><td>250</td><td>2154</td><td rowspan="2">3093</td><td>303</td><td rowspan="2">305</td><td>250</td><td rowspan="2">250</td><td>0.07</td><td rowspan="2">0.06</td><td>Norm.</td><td rowspan="2">Norm.</td></tr>
<tr><td>EP/H, EP/O</td><td>>5, ≤15</td><td>260</td><td>939</td><td>309</td><td>263</td><td>0.05</td><td>Norm.</td></tr>
<tr><td>T651</td><td>SH, PL, ST</td><td>>6, ≤12.5</td><td>255</td><td colspan="2">4</td><td colspan="2">288</td><td colspan="2">281</td><td colspan="2">0.02</td><td colspan="2">Norm.</td></tr>
<tr><td>AW-6106</td><td>T6</td><td>EP</td><td>≤10</td><td>200</td><td colspan="2">57</td><td colspan="2">245</td><td colspan="2">227</td><td colspan="2">0.04</td><td colspan="2">LogN.</td></tr>
</table>

Note: [1]. Nominal values of 0.2% proof strengths, f_o, are taken from relevant product standard EN 755-2 [27] or EN 485-2 [28]; [2]. SH—sheet, PL—plate, ST—strip, EP—extruded profiles, EP/O—extruded open profiles, EP/H—extruded hollow profiles, ER/B—extruded rod and bar, ET—extruded tube; 3. Distributions: Norm.—normal, LogN.—lognormal, Weib.—Weibull.

Results show that the mean values of f_o are significantly higher than the nominal values prescribed in EN 755-2 [27] and EN 485-2 [28]. Furthermore, reported minimum values are higher or equal to nominal values for all the data groups except for EN AW-6063-T6. The highest scatter of the results was obtained for EN AW-5754-H111 alloy with a coefficient of variation (CofV) equal to 0.11. The lowest scatter of the results was obtained for EN AW-6063-T6 and -T66 alloys with CofV equal to 0.04. For most of the data groups, lognormal and normal distribution showed to be the best fit, with only EN AW-1005A-H24 being best suited for Weibull distribution.

Partial factors for f_o with associated 0.1% and 5% fractile values are presented in Table 3. Data groups with an insufficient number of test data (<100) are marked per Table 2 and are omitted from further discussion.

Table 3. Material partial factor determination for 0.2% proof strength.

<table>
<tr><th>Alloy</th><th>Temper</th><th>Product Form</th><th>Thickness t (mm)</th><th>Nominal Value f_o (MPa)</th><th colspan="2">0.1% Fractile Value(MPa)</th><th colspan="2">5% Fractile Value (MPa)</th><th>Model Risk Δ_k</th><th>Material Partial Factor γ_m</th><th>Material Partial Factor Considering the Nominal Value γ_{mk}</th></tr>
<tr><td rowspan="2">AW-1050A</td><td>H14</td><td>SH, PL, ST</td><td>≤25</td><td>85</td><td colspan="2">103</td><td colspan="2">112</td><td>0.76</td><td>1.09</td><td>0.83</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>75</td><td colspan="2">81</td><td colspan="2">101</td><td>0.74</td><td>1.25</td><td>0.93</td></tr>
<tr><td rowspan="2">AW-5005, AW-5005A</td><td>H14</td><td>SH, PL, ST</td><td>≤12.5</td><td>120</td><td colspan="2">113</td><td colspan="2">136</td><td>0.88</td><td>1.20</td><td>1.06</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>110</td><td colspan="2">122</td><td colspan="2">134</td><td>0.82</td><td>1.10</td><td>0.90</td></tr>
<tr><td rowspan="2">AW-5083</td><td>0, H111</td><td>SH, PL, ST</td><td>≤50</td><td>125</td><td colspan="2">124</td><td colspan="2">141</td><td>0.89</td><td>1.14</td><td>1.01</td></tr>
<tr><td>H321</td><td>SH, PL, ST</td><td>≤40</td><td>215</td><td colspan="2">185</td><td colspan="2">214</td><td>1.00</td><td>1.16</td><td>1.16</td></tr>
<tr><td rowspan="2">AW-5754</td><td>H111</td><td>SH, PL, ST</td><td>≤100</td><td>80</td><td colspan="2">89</td><td colspan="2">104</td><td>0.77</td><td>1.17</td><td>0.90</td></tr>
<tr><td>H22</td><td>SH, PL, ST</td><td>≤40</td><td>130</td><td colspan="2">115</td><td colspan="2">139</td><td>0.94</td><td>1.21</td><td>1.14</td></tr>
<tr><td rowspan="3">AW-6005A</td><td rowspan="3">T6</td><td>EP/O, ER/B</td><td>≤5</td><td>225</td><td>222</td><td rowspan="3">221</td><td>237</td><td rowspan="3">238</td><td>0.95</td><td>1.07</td><td>1.02</td></tr>
<tr><td>EP/H, ET</td><td>≤5</td><td>215</td><td>228</td><td>258</td><td>0.83</td><td>1.13</td><td>0.94</td></tr>
<tr><td>EP/H, ET</td><td>>5, ≤10</td><td>200</td><td>247</td><td>257</td><td>0.78</td><td>1.04</td><td>0.81</td></tr>
<tr><td rowspan="3">AW-6060</td><td>T4</td><td>EP/H</td><td>≤25</td><td>60</td><td colspan="2">47</td><td colspan="2">62</td><td>0.96</td><td>1.34</td><td>1.29</td></tr>
<tr><td>T6</td><td>EP/H</td><td>≤5</td><td>150</td><td colspan="2">151</td><td colspan="2">167</td><td>0.90</td><td>1.10</td><td>0.99</td></tr>
<tr><td>T66</td><td>EP, EP/H, ER/B</td><td>≤5</td><td>160</td><td colspan="2">157</td><td colspan="2">177</td><td>0.90</td><td>1.13</td><td>1.02</td></tr>
<tr><td>AW-6061</td><td>T6</td><td>EP, EP/H, ET</td><td>≤25</td><td>240</td><td colspan="2">216</td><td colspan="2">236</td><td>1.02</td><td>1.10</td><td>1.11</td></tr>
<tr><td rowspan="3">AW-6063</td><td>T5</td><td>EP, EP/H, ET</td><td>≤10</td><td>130</td><td colspan="2">116</td><td colspan="2">137</td><td>0.95</td><td>1.18</td><td>1.12</td></tr>
<tr><td>T6</td><td>EP, EP/H</td><td>≤10</td><td>170</td><td colspan="2">185</td><td colspan="2">199</td><td>0.86</td><td>1.07</td><td>0.92</td></tr>
<tr><td>T66</td><td>EP, ET, ER/B</td><td>≤10</td><td>200</td><td colspan="2">208</td><td colspan="2">221</td><td>0.90</td><td>1.07</td><td>0.96</td></tr>
<tr><td rowspan="4">AW-6082</td><td>T4</td><td>EP/H</td><td>≤25</td><td>110</td><td colspan="2">87</td><td colspan="2">110</td><td>1.00</td><td>1.26</td><td>1.26</td></tr>
<tr><td rowspan="2">T6</td><td>EP/H</td><td>≤5</td><td>250</td><td>241</td><td rowspan="2">247</td><td>269</td><td rowspan="2">273</td><td>0.93</td><td>1.12</td><td>1.04</td></tr>
<tr><td>EP/H, EP/O</td><td>>5, ≤15</td><td>260</td><td>265</td><td>285</td><td>0.91</td><td>1.08</td><td>0.98</td></tr>
<tr><td>T651</td><td>SH, PL, ST</td><td>>6, ≤12.5</td><td>255</td><td colspan="2">271</td><td colspan="2">279</td><td>0.92</td><td>1.03</td><td>0.94</td></tr>
<tr><td>AW-6106</td><td>T6</td><td>EP</td><td>≤10</td><td>200</td><td colspan="2">218</td><td colspan="2">230</td><td>0.87</td><td>1.06</td><td>0.92</td></tr>
</table>

For all alloys, the 5% fractile (characteristic) value was higher compared to the nominal value. Alloys EN AW-6005A-T6 (EP/O, ER/B with thicknesses $\leq$ 5 mm), EN AW-6060-T66, and EN AW-6082-T6 (EP/H with thicknesses $\leq$ 5 mm) had a lower 0.1% fractile (design) value compared to the nominal value. The model risk factor, Δ_k, is obtained as the ratio of the nominal value from EN 1999-1-1 [15], i.e., from the relevant product standard (EN 755-2 [27] or EN 485-2 [28]), and the characteristic value determined as a 5% fractile value; see Equation (5). Accordingly, the model risk factor, Δ_k, indicates if the nominal value is safe compared to the characteristic value (less than 1 is safe). For all the data groups $\Delta_k < 1.0$, confirming that the nominal values f_{o} are generally safe. The lowest values of Δ_{k} were obtained for AW-1050A alloys. The material partial factor, γ_m is calculated as the ratio of the characteristic (5% fractile) and the design (0.1% fractile) value; see Equation (4). The material partial factor considering nominal value, γ_{mk}, is obtained as a product of γ_m and Δ_k; see Equation (5). The analysis of this factor reveals whether the nominal value is safe in relation to the design (0.1% fractile) value.

4.2. Ultimate Tensile Strength

Statistical analysis of the ultimate strength (f_{u}) is analogous to the analysis of the 0.2 proof strength, and it is based on 12426 material test results. Accordingly, data were divided into groups depending on aluminium alloy, temper, product type, and thickness ranges taken from EN 755-2 [27] and EN 485-2 [28], as shown in Table 4. Note that grey shaded data groups with an insufficient number of test data (< 100, bolded) are omitted from the further discussion.

Mean values of f_{u} are significantly higher than nominal values taken from EN 755-2 [27] and EN 485-2 [28]. Minimum values are equal to or slightly higher than nominal values except for alloys EN AW-6060-T6, EN AW-6063-T6, EN AW-6063-T66, and EN AW-6082-T6 (EP/H with thicknesses $\leq$ 5 mm), where minimum values are negligibly lower compared to nominal values.

The highest scatter of results for f_{u} was obtained for EN AW-6060-T66 alloy with CofV equal to 0.06. The lowest scatter of results for f_{u} was obtained for EN AW-6005A-T6 (EP/O, ER/B with thicknesses $\leq$ 5 mm) alloy with CofV equal to 0.02. Lognormal distribution showed to be the best fit for most of the data groups. However, some groups showed better correspondence with normal and Weibull distribution.

Partial factors for f_{u} with associated 0.1% and 5% fractile values are presented in Table 5. Data groups with an insufficient number of test data (<100) are marked per Table 4 and are omitted from further discussion. All the alloys had a higher 5% fractile (characteristic) value compared to nominal value except for alloy EN AW-6060-T66 which had slightly lower. However, except for EN AW-5754-H111 and EN AW-6063-T6, all the alloys had a lower value of 0.1% fractile (design) value compared to the nominal value. Factors Δ_k, γ_m, γ_{mk} were obtained in an analogue way as for 0.2% proof strength (see Section 4.1). Except for EN AW-6060-T66, all the alloys have $\Delta_k < 1.0$, confirming that the nominal values of f_{u} are generally safe. The lowest values of Δ_k were obtained for AW-1050A alloys.

Table 4. Statistical analysis of ultimate tensile strength.

<table>
<tr><th>Alloy</th><th>Temper</th><th>Product form</th><th>Thickness t (mm)</th><th>Nominal Value [1] f_u (MPa)</th><th colspan="2">Number of Samples n</th><th colspan="2">Mean (MPa)</th><th colspan="2">Minimum (MPa)</th><th colspan="2">CofV (-)</th><th colspan="2">Distribution [2]</th></tr>
<tr><td rowspan="2">AW-1050A</td><td>H14</td><td>SH, PL, ST</td><td>≤25</td><td>105</td><td colspan="2">287</td><td colspan="2">129</td><td colspan="2">105</td><td colspan="2">0.06</td><td colspan="2">Weib.</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>105</td><td colspan="2">220</td><td colspan="2">125</td><td colspan="2">105</td><td colspan="2">0.06</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="2">AW-5005, AW-5005A</td><td>H14</td><td>SH, PL, ST</td><td>≤12.5</td><td>145</td><td colspan="2">23</td><td colspan="2">164</td><td colspan="2">156</td><td colspan="2">0.04</td><td colspan="2">LogN.</td></tr>
<tr><td>H24</td><td>SH, PL, ST</td><td>≤12.5</td><td>145</td><td colspan="2">33</td><td colspan="2">164</td><td colspan="2">145</td><td colspan="2">0.06</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="2">AW-5083</td><td>0, H111</td><td>SH, PL, ST</td><td>≤50</td><td>270</td><td colspan="2">31</td><td colspan="2">306</td><td colspan="2">276</td><td colspan="2">0.04</td><td colspan="2">Norm.</td></tr>
<tr><td>H321</td><td>SH, PL, ST</td><td>≤40</td><td>305</td><td colspan="2">15</td><td colspan="2">332</td><td colspan="2">314</td><td colspan="2">0.04</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="2">AW-5754</td><td>H111</td><td>SH, PL, ST</td><td>≤100</td><td>190</td><td colspan="2">143</td><td colspan="2">217</td><td colspan="2">198</td><td colspan="2">0.03</td><td colspan="2">LogN.</td></tr>
<tr><td>H22</td><td>SH, PL, ST</td><td>≤40</td><td>220</td><td colspan="2">45</td><td colspan="2">236</td><td colspan="2">223</td><td colspan="2">0.04</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="3">AW-6005A</td><td rowspan="3">T6</td><td>EP/O, ER/B</td><td>≤5</td><td>270</td><td>171</td><td rowspan="3">286</td><td>284</td><td rowspan="3">283</td><td>270</td><td rowspan="3">262</td><td>0.02</td><td rowspan="3">0.03</td><td>LogN.</td><td rowspan="3">LogN.</td></tr>
<tr><td>EP/H, ET</td><td>≤5</td><td>260</td><td>43</td><td>284</td><td>262</td><td>0.05</td><td>LogN.</td></tr>
<tr><td>EP/H, ET</td><td>>5, ≤10</td><td>250</td><td>72</td><td>281</td><td>263</td><td>0.02</td><td>Weib.</td></tr>
<tr><td rowspan="3">AW-6060</td><td>T4</td><td>EP/H</td><td>≤25</td><td>120</td><td colspan="2">6</td><td colspan="2">165</td><td colspan="2">145</td><td colspan="2">0.07</td><td colspan="2">Weib.</td></tr>
<tr><td>T6</td><td>EP/H</td><td>≤5</td><td>190</td><td colspan="2">449</td><td colspan="2">219</td><td colspan="2">187</td><td colspan="2">0.05</td><td colspan="2">LogN.</td></tr>
<tr><td>T66</td><td>EP, EP/H, ER/B</td><td>≤5</td><td>215</td><td colspan="2">1656</td><td colspan="2">231</td><td colspan="2">215</td><td colspan="2">0.06</td><td colspan="2">LogN.</td></tr>
<tr><td>AW-6061</td><td>T6</td><td>EP, EP/H, ET</td><td>≤25</td><td>260</td><td colspan="2">31</td><td colspan="2">279</td><td colspan="2">259</td><td colspan="2">0.06</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="3">AW-6063</td><td>T5</td><td>EP, EP/H, ET</td><td>≤10</td><td>175</td><td colspan="2">15</td><td colspan="2">195</td><td colspan="2">176</td><td colspan="2">0.08</td><td colspan="2">LogN.</td></tr>
<tr><td>T6</td><td>EP, EP/H</td><td>≤10</td><td>215</td><td colspan="2">4164</td><td colspan="2">235</td><td colspan="2">203</td><td colspan="2">0.03</td><td colspan="2">LogN.</td></tr>
<tr><td>T66</td><td>EP, ET, ER/B</td><td>≤10</td><td>245</td><td colspan="2">1853</td><td colspan="2">262</td><td colspan="2">244</td><td colspan="2">0.03</td><td colspan="2">LogN.</td></tr>
<tr><td rowspan="5">AW-6082</td><td>T4</td><td>EP/H</td><td>≤25</td><td>205</td><td colspan="2">6</td><td colspan="2">261</td><td colspan="2">226</td><td colspan="2">0.09</td><td colspan="2">Norm.</td></tr>
<tr><td rowspan="3">T6</td><td>EP/H</td><td>≤5</td><td>290</td><td>2133</td><td rowspan="3">3078</td><td>330</td><td rowspan="3">331</td><td>288</td><td rowspan="3">288</td><td>0.05</td><td rowspan="3">0.05</td><td>Norm.</td><td rowspan="3">Norm.</td></tr>
<tr><td>ER/B</td><td>≤20</td><td>295</td><td>51</td><td>327</td><td>303</td><td>0.04</td><td>LogN.</td></tr>
<tr><td>EP/H, EP/O</td><td>>5, ≤15</td><td>310</td><td>894</td><td>335</td><td>310</td><td>0.04</td><td>LogN.</td></tr>
<tr><td>T651</td><td>SH, PL, ST</td><td>>6, ≤12.5</td><td>290</td><td colspan="2">4</td><td colspan="2">317</td><td colspan="2">309</td><td colspan="2">0.03</td><td colspan="2">LogN.</td></tr>
<tr><td>AW-6106</td><td>T6</td><td>EP</td><td>≤10</td><td>250</td><td colspan="2">57</td><td colspan="2">273</td><td colspan="2">261</td><td colspan="2">0.03</td><td colspan="2">LogN.</td></tr>
<tr><td>AW-7020</td><td>T6</td><td>EP</td><td>≤12.5</td><td>350</td><td colspan="2">24</td><td colspan="2">401</td><td colspan="2">367</td><td colspan="2">0.05</td><td colspan="2">LogN.</td></tr>
</table>

Note: [1]. Nominal values of ultimate tensile strengths, f_u, are taken from relevant product standard EN 755-2 [27] or EN 485-2 [28]; [2]. SH—sheet, PL—plate, ST—strip, EP—extruded profiles, EP/O—extruded open profiles, EP/H—extruded hollow profiles, ER/B—extruded rod and bar, ET—extruded tube; 3. Distributions: Norm.—normal, LogN.—lognormal, Weib.—Weibull.

Table 5. Material partial factor determination for ultimate tensile strength.

Alloy	Temper	Product Form	Thickness t (mm)	Nominal Value f_u (MPa)	0.1% Fractile Value (MPa)		5% Fractile Value (MPa)		Model Risk Δ_k	Material Partial Factor γ_m	Material Partial Factor Considering the Nominal Value γ_{mk}
AW-1050A	H14	SH, PL, ST	≤25	105	93		114		0.92	1.22	1.12
	H24	SH, PL, ST	≤12.5	105	104		113		0.93	1.09	1.01
AW-5005, AW-5005A	H14	SH, PL, ST	≤12.5	145	147		155		0.94	1.05	0.99
	H24	SH, PL, ST	≤12.5	145	135		147		0.99	1.09	1.08
AW-5083	0, H111	SH, PL, ST	≤50	270	269		286		0.94	1.06	1.00
	H321	SH, PL, ST	≤40	305	296		312		0.98	1.05	1.03
AW-5754	H111	SH, PL, ST	≤100	190	196		205		0.93	1.05	0.97
	H22	SH, PL, ST	≤40	220	210		221		0.99	1.06	1.05
AW-6005A	T6	EP/O, ER/B	≤5	270	263	260	272	270	0.99	1.03	1.02
		EP/H, ET	≤5	260	245		262		0.99	1.07	1.06
		EP/H, ET	>5, ≤10	250	264		275		0.91	1.04	0.95
AW-6060	T4	EP/H	≤25	120	123		147		0.82	1.20	0.98
	T6	EP/H	≤5	190	186		201		0.95	1.08	1.02
	T66	EP, EP/H, ER/B	≤5	215	190		207		1.04	1.09	1.13
AW-6061	T6	EP, EP/H, ET	≤25	260	233		253		1.03	1.09	1.12
AW-6063	T5	EP, EP/H, ET	≤10	175	151		170		1.03	1.12	1.16
	T6	EP, EP/H	≤10	215	215		224		0.96	1.04	1.00
	T66	EP, ET, ER/B	≤10	245	237		248		0.99	1.05	1.03
AW-6082	T4	EP/H	≤25	205	186		221		0.93	1.18	1.10
	T6	EP/H	≤5	290	276	281	300	304	0.97	1.09	1.05
		ER/B	≤20	295	288		305		0.97	1.06	1.03
		EP/H, EP/O	>5, ≤15	310	299		315		0.98	1.05	1.04
	T651	SH, PL, ST	>6, ≤12.5	290	287		300		0.97	1.05	1.01
AW-6106	T6	EP	≤10	250	251		260		0.96	1.04	1.00
AW-7020	T6	EP	≤12.5	350	341		367		0.95	1.08	1.03

4.3. Young's Modulus

Material test certificates obtained by the aluminium industry rarely included data on the value of Young's modulus. Therefore, statistical analysis of Young's modulus was based on a notably smaller number of material test results compared to f_o and f_u. However, 2948 test results were obtained covering seven different alloys with different tempers, as detailed in Table 6, which is a robust base concerning Young's modulus. Although the collected data contain subgroups of fewer than 100 samples, they were all collected into a single dataset, as unlike for proof 0.2% and tensile strength, alloy and temper do not significantly influence the value of Young's modulus. This is in line with EN 1999-1-1 [15] and AA ADM [34], in which a single value of Young's modulus is valid for all alloys and tempers.

Table 6. Statistical analysis of Young's modulus.

Alloy	Number of Samples n	Mean (MPa)	Median (MPa)	St. dev. (MPa)	CofV (-)
AW-5083-H111	**4**	71,494	71,488	187.5	0.003
AW-6060-T4	**3**	65,929	66,820	2824.5	0.043
AW-6060-T6	444	69,012	69,146	1227.6	0.018
AW-6060-T66	**43**	66,079	65,924	1117.6	0.017
AW-6061-T6	**56**	67,682	67,855	1873.2	0.028
AW-6063-T4	**8**	69,375	69,124	4160.6	0.060
AW-6063-T5	**17**	68,176	67,500	2405.8	0.035
AW-6063-T6	1082	71,985	72,235	4246.2	0.059
AW-6063-T66	843	67,050	67,239	2316.8	0.035
AW-6082-T4	**6**	71,868	71,904	1978.3	0.028
AW-6082-T6	430	72,206	72,820	2844.7	0.039
AW-7050-T7451	**10**	69,295	69,289	210.0	0.000
AW-7108-T7	**1**	68,155	-	-	-
AW-7108-T8	**1**	70,534	-	-	-
All	**2948**	**69,943**	**69,135**	**3858.0**	**0.055**

Lognormal distribution showed to be the best fit. Alloy EN AW-6063-T66 had the lowest mean value of Young's modulus, while alloy EN AW-6082-T6 had the highest (67,050 MPa and 72,206 MPa, respectively). The total mean value of Young's modulus (69,943 MPa) deviates only slightly from the prescribed value (70,000 MPa) given in [15] and [34]. The highest scatter of the results was obtained for EN AW-6063-T6 alloy with CofV equal to 0.059. The lowest scatter of the results was obtained for EN AW-6060-T6 alloy with CofV equal to 0.018, while the entire dataset CofV value is equal to 0.055, which indicates a low dispersion of results.

4.4. Poisson's Ratio

Material test certificates obtained do not report the Poisson's ratio value as its evaluation is based on a test setup usually outside of the scope of the tensile test, requiring transversal deformation monitoring. This property is thus rarely found and out of the 135 collected results; 131 were obtained from tensile tests of extruded products made of alloys EN AW-6060-T66, EN AW-6061-T6, EN AW-6063-T6, and EN AW-6082-T6, conducted by the authors. As with Young's modulus, the data were ultimately evaluated as a single dataset, since there is no reported dependence of Poisson's ratio on alloy or temper, as reported in EN 1999-1-1 [15] and AA ADM [34] with a value of 0.3 and 0.33, respectively. The average value was determined as 0.325 (Table 7), close to the median of 0.328, which is in line with the value in [34]. The entire dataset is best described by a normal distribution.

Table 7. Statistical analysis of Poisson's value.

Alloy	Number of Samples n	Mean -	Median -	St. dev. -	CofV (-)
AW-6060-T66	35	0.331	0.331	0.006	0.018
AW-6061-T6	6	0.323	0.325	0.012	0.037
AW-6063-T6	58	0.328	0.330	0.008	0.024
AW-6082-T6	36	0.312	0.312	0.008	0.025
All	135	0.325	0.328	0.011	0.033

5. Summary of Results

The values of the partial factors for buildings in Eurocode 9 [15] are calibrated considering a reliability index taken equal to 3.8, for a reference period of 50 years for variable actions and mechanical properties and a resistance-side weighting factor of $\alpha_R = 0.8$. The design values of resistance R_d are defined as the ratio between the nominal resistance and the partial factor γ_{Mi} (see Section 3.3). The nominal resistance is evaluated by using nominal values for all basic variables, per Equation (1). Rules for design assisted by testing given in prEN 1990:2020 [35], Annex D, should be applied for the calibration of the partial factors γ_{Mi} for buildings. The scatter bands (mean values, coefficients of variation) for available mechanical properties are given in Table 8. It should be noted that the values in Table 8 represent the materials and products currently available on the European market which satisfy the relevant European product standards.

Table 8. Variability of available mechanical properties.

Property	Alloy EN AW	Temper	Mean Value X_m	CofV	Distribution Type	Upper Reference Value $X_{5\%}$	Lower Reference Value $X_{0.1\%}$
f_o	5754	H111	1.56 $R_{p0.2,min}$	11%	LogN.	1.30 $R_{p0.2,min}$	1.12 $R_{p0.2,min}$
	6005A	T6	1.18 $R_{p0.2,min}$	4.7%	Norm.	1.09 $R_{p0.2,min}$	1.01 $R_{p0.2,min}$
	6060	T6	1.25 $R_{p0.2,min}$	7.0%	LogN.	1.11 $R_{p0.2,min}$	1.01 $R_{p0.2,min}$
	6060	T66	1.28 $R_{p0.2,min}$	8.8%	LogN.	1.11 $R_{p0.2,min}$	0.98 $R_{p0.2,min}$
	6063	T6	1.26 $R_{p0.2,min}$	4.4%	Norm.	1.17 $R_{p0.2,min}$	1.09 $R_{p0.2,min}$
	6063	T66	1.19 $R_{p0.2,min}$	4.1%	Norm.	1.11 $R_{p0.2,min}$	1.04 $R_{p0.2,min}$
	6082	T6	1.20 $R_{p0.2,min}$	6.2%	Norm.	1.08 $R_{p0.2,min}$	0.98 $R_{p0.2,min}$
f_u	5754	H111	1.14 $R_{m,min}$	3.4%	LogN.	1.08 $R_{m,min}$	1.03 $R_{m,min}$
	6005A	T6	1.07 $R_{m,min}$	2.8%	LogN.	1.03 $R_{m,min}$	0.99 $R_{m,min}$
	6060	T6	1.15 $R_{m,min}$	5.3%	LogN.	1.06 $R_{m,min}$	0.98 $R_{m,min}$
	6060	T66	1.07 $R_{m,min}$	6.5%	LogN.	0.96 $R_{m,min}$	0.88 $R_{m,min}$
	6063	T6	1.09 $R_{m,min}$	3.0%	LogN.	1.04 $R_{m,min}$	1.00 $R_{m,min}$
	6063	T66	1.07 $R_{m,min}$	3.3%	LogN.	1.01 $R_{m,min}$	0.97 $R_{m,min}$
	6082	T6	1.12 $R_{m,min}$	5.0%	Norm.	1.03 $R_{m,min}$	0.95 $R_{m,min}$
E	All	All	69,943 MPa	5.5%	LogN.		

f_o—0.2% proof strength, f_u—ultimate tensile strength, E—modulus of elasticity. $R_{p0.2,min}$ and $R_{m,min}$ are the minimum yield strength $R_{p0.2}$ and the lower bound of the ultimate tensile strength R_m, according to the applicable product standard, e.g., of the EN 755 or EN 485 series.

Scatter bands of mechanical parameter values X from production may generally be assumed to be in line with the assumptions made for the calibration of γ_{Mi} values for buildings, if the characteristic value X_k and the design value X_d determined from the production statistics either match or exceed the corresponding reference values $X_{5\%}$ and $X_{0.1\%}$ in Table 8. The mean values of aluminium alloys are, as presumed, considerably higher than their nominal counterparts, and as the variability of individual alloys and their temper properties differ, this is reflected in scatter bands. The multiplier for the nominal values differs as each distribution shape is different, accounting for the fact that each registered alloy has its tolerance in chemical composition amplified by treatments (tempering). This again is reflected in upper and lower reference values as they are connected to the product standard values as well as to the individual CofV. The scatter of multipliers indicates that certain adjustments are needed, i.e., the scatter can be minimised with the tuning of standard values.

6. Conclusions

The statistical evaluation of aluminium alloy mechanical properties was conducted based on data obtained from more than 12,000 material tensile tests (certificates) of unwelded samples. The most important mechanical properties (0.2% proof strength, ultimate tensile strength, Young's modulus, and Poisson's ratio) were analysed in this stage of the research. Based on relevant properties, test data were divided into several groups, and a statistical evaluation was conducted for each one independently. Normal and lognormal distribution proved to be the best fit for almost all data groups. For several data groups, an insufficient number of test data (<100) was collected, and thus those results were omitted from the further statistical analysis and discussion. Although data represent the current state of the European market, the distribution of test data by country of origin and alloy type is highly uneven, pointing to the fact that more test certificates from various sources are favourable. The determined distribution shapes for groups of alloys and tempers are important indicators for the industry and provide confirmation regarding distribution shapes of resistance variables. There are nominal values which point to concern, but most are in line with the design values, meaning that most are safe, but work is needed concerning uniformity of established reliability upon choice of alloy and temper.

Results presented here can serve as a basis for future updates of normative documents for the design of aluminium structures as well as a scientific foundation for analysis regarding the variation of the mechanical properties of aluminium alloys. The collection of data herein is a rare insight into the state of the dispersion of mechanical properties relevant for structural design, beneficial not only for the scientific and technical community but also for the growth potential of aluminium as a reliable and trustworthy material in structural applications. Future directions of the research are to expand the database and connect the partial factors for model uncertainty in structural resistance with established material partial factors.

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