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Calibration of predictive formulations and key mechanical properties of reclaimed structural steel

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ABSTRACT

Steel reuse is recently emerging as a necessary alternative not only to demolition and waste disposal, but also to new steel to provide circular and low-carbon stock of structural members for steel constructions.

This work examines the structural behavior of reclaimed steel members with a view to support Eurocode-compliant design for steel reuse. A dataset of 182 members recovered from UK buildings was assembled, including tensile tests, Vickers hardness measurements, Charpy impact tests, and chemical composition analyses. The dataset was sorted by grading schemes consistent with CEN/TS 1090–201 and SCI P427 and included grades from S235 to S460. Correlations between Vickers hardness and both yield and ultimate tensile strength were derived specifically for reclaimed material and compared with existing formulations from literature and current reuse guidelines. The grading outcomes for the various formulations were assessed. The same dataset was then used to calibrate partial safety factors for material strength following the design-assisted-by-testing procedure in EN 1990. For S275 and S355 steel graded under the herein-called "restricted" scheme, the calibrated partial factors for yielding and ultimate strengths are close to the current values adopted for new steel in EN 1993-1-1. The results suggest that reclaimed members which satisfy current grading and testing requirements can be designed with material safety factors comparable to those of new production, while making greater use of non-destructive hardness testing to reduce the need for destructive tests in practice.

1. Introduction

Circularity in the built environment is central to modern European climate initiatives: with a target to eliminate net greenhouse gas emissions completely by 2050, the European Green Deal of 2019 cites one of its key methods as the implementation of circular economy strategies, and one of its target sectors as construction and demolition [1]. Though the structural steel industry is already well-adjusted to recycling processes, with 88% of steel in Europe being recycled at end of life [2], recycling alone is not enough to meet emissions reduction goals.[3] Reuse of intact steel members from dismantled buildings, however, has the potential to reduce emissions further to 16% of those from steel recycled in the energy-efficient electric arc furnace (EAF) [4].

The reuse of structural steel elements recovered from dismantled buildings is not yet a standardized practice and continues to face numerous barriers before it can be widely implemented in the construction industry. Recent studies have identified these barriers and opportunities through different methodological approaches, including stakeholder surveys, case studies and comprehensive literature reviews [2,5–9].

The barriers can be broadly categorized into three domains: (i) supply chain organization, (ii) cost–benefit assessment, and (iii) engineering and technical validation. First, the reuse of steel profiles affects the entire construction ecosystem—designers, producers, fabricators, contractors, and regulatory authorities—whose roles are deeply embedded in the prevailing linear framework of demolition and recycling. In the current system, steel components from demolished structures are melted and reprocessed into new sections. Transitioning to a

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reuse-oriented model requires a fundamental reconfiguration of this supply chain: designers must adopt design-for-deconstruction principles; demolition contractors must disassemble rather than demolish; and new intermediaries or stockists must emerge to purchase, test, and resell reclaimed members.

Additionally, in this redesigned supply chain, costs are redistributed from material production to deconstruction, testing, and storage, thereby shifting the economic balance of the process. However, the overall financial implications remain uncertain, as empirical findings vary according to boundary conditions and assumptions. Dunant et al. [10] reported higher total costs for reuse-based projects, whereas Vares et al. [7] identified potential savings of approximately 5% across the building lifecycle. Berglund-Brown [11] also observed a cost advantage for the U.S. market. A comprehensive international review by Nakajima and Russell [12] emphasized that, in the absence of legislative incentives to create an artificial economic driver, the market for deconstructed materials struggles to achieve economic viability.

A further set of challenges concerns the engineering and certification requirements for reused members, which constitute the central focus of this study. Since July 2014, the CE marking of structural steel has been mandatory within the European Union. This certification ensures that steel profiles comply with all relevant product standards, including geometric tolerances and mechanical properties, thereby guaranteeing their reliability for use in structures designed according to the Eurocodes [13]. For new steel, CE marking is seamlessly integrated into the manufacturing workflow at steel mills. Conversely, when components are sourced from existing buildings, all material and geometric properties required for certification must be verified through testing. At present, standardized procedures for testing and recertification are not uniformly defined across Europe, nor does consistent guidance exist for engineers employing reclaimed members in Eurocode 3–based designs.

This work aims at analyzing an experimental dataset of non-destructive and destructive tests on reclaimed structural steel stock collected from dismantling buildings in UK, with the aim of proposing first design guidelines to correlate non-destructive and destructive tests on reused steel members and calibrate new partial safety factors for reused steel members, according to the procedure proposed in Eurocode 0 “Design assisted by testing” [14].

First, the current guidelines for structural design with reclaimed steel are presented in Section 2. Then in Section 3, the dataset is described and its members are assigned grades based on current guidelines. In Section 4, the data is analyzed in terms of correlation of the results from hardness tests and tensile tests. The correlation is calibrated based on data, then compared with respect to the current formulations available in literature. Grading outcomes for the hardness testing correlations are also evaluated. In Section 5, the analysis is then aimed at calibrating partial safety factors of the material strength for reused steel members, by considering the distribution of material strength values within the available dataset of experiments.

The results are intended to propose first results for structural design of steel reuse, aimed at reducing the need of destructive tests as well as calibrating first design values for reuse to enhance its adoption on a wider scale.

2. Structural guidelines for steel reuse

2.1. General European guidelines

Over the past decade, several collaborative European initiatives funded by the Research Fund for Coal and Steel (RFCS) have addressed the barriers to steel reuse through research, guidelines, and tool development. Some projects have focused on specific aspects of sustainability and circularity. For instance, the Sustainable Building Project in Steel [15], completed in 2013, developed a sustainability assessment toolkit. The Large Valorisation on Sustainability of Steel Structures [16] examined the broader sustainability and environmental performance of steel and composite buildings. The Reuse and Demountability using Steel Structures and the Circular Economy project (REDUCE) [17] funded by the Research Fund for Coal and Steel (RFCS) explored design-for-deconstruction principles applicable to steel and composite structures, while the more recent Delivering Innovative Steel Reuse Project (DISRUPT) produced a practical guide for advancing steel reuse within supply chain and business model frameworks [18].

Two subsequent projects—Provisions for Greater Steel Reuse (PROGRESS) and Accompanying Measure for Dissemination, Valorisation and Collaborative Exploitation of Circularity of Constructional Steel Products (ADVANCE)—adopted a more integrated approach that spans technical, economic, and procedural aspects of steel reuse [19].

The PROGRESS project represented a significant milestone, as it was the first to address the reuse of structural steel and façade components from a full life-cycle perspective. Its Design Guide [20] defined a structured process chain for enabling reuse within building projects, comprising five primary stages:

1. Pre-deconstruction audit and assessment for reuse: collection and verification of design documentation, field investigations, and preliminary testing to assess component quality, demountability, and suitability for future applications.
2. Labelling, batching, and deconstruction: systematic tracking and documentation of components during dismantling.
3. Sampling and testing: execution of geometric surveys and material testing (both non-destructive and destructive) to characterize mechanical properties for distinct batches.
4. Design with reuse: integration of reclaimed components into new structural designs, considering actual material properties, safety, and reliability.
5. Reconditioning for reuse: surface treatment, re-manufacturing, and adaptation of elements for reuse in new contexts.

The guide includes detailed procedures for each step, such as pre-deconstruction audit templates, testing protocols, and recommended safety factors for design. It also discusses economic considerations, life-cycle impact calculations, and design-for-deconstruction approaches supported by multiple case studies. The project scope was limited to single-storey donor buildings constructed after 1970.

Building on these foundations, the ADVANCE project further expanded the methodological framework established in PROGRESS. It extended applicability to multi-storey donor buildings and incorporated digital tools, including a web-based application for performing Life-Cycle Assessment (LCA) calculations, thereby enhancing accessibility and practical implementation of circular construction practices across Europe.

2.2. Engineering-specific guidelines

The overarching challenge facing the structural steel reuse domain is the establishment of a standardized procedure for evaluating existing steel members, such that reclaimed elements can be re-certified in accordance with EN 1090–2 and the relevant product specifications [21]. The objective is to ensure that reused components achieve an equivalent reliability level to newly produced sections when employed within the framework of the reliability-based design code (Eurocode 3) [13].

Recent research by Bartsch et al. [3], Feldmann et al. [4], and Knobloch et al. [22] proposes a detailed reuse process chain that advances beyond the PROGRESS framework and emphasizes several critical engineering considerations. These can be grouped around three guiding enquiries:

- Component inspection and testing: which parameters are essential to characterize, and which test methodologies yield the most accurate measurements?

- Component assessment and classification: how can the obtained data be used to derive design-relevant material properties, and how can components be assigned to established structural steel classes?
- Design integration: what additional measures are necessary to maintain appropriate safety levels when applying Eurocode 3 to structures utilizing reused steel?

Ongoing work across Europe is addressing these questions. Beyond the PROGRESS and ADVANCE projects, which already proposed protocols for testing and assessment, along with preliminary design considerations, a dedicated European technical specification, CEN/TS 1090–201:2024 [23], now provides formal guidance for the testing and evaluation of reclaimed steel in pursuit of CE marking eligibility.

Nevertheless, this technical specification has not yet been uniformly adopted, and several countries have developed national-level guidelines that vary in technical scope and legal authority. Among these, the UK's Steel Construction Institute publication SCI P427 [24] presents a detailed framework, largely derived from the PROGRESS methodology, while the Dutch agreement NTA8713:2023 [25] defines corresponding procedures for the Netherlands. A comprehensive survey of current European guidelines is included in the ADVANCE report “D2.1 - Circular Economy of Steel Based Components” [26].

These documents generally agree that only elements free from fire damage, impact deformation, or significant plastic strain should be considered for reuse. Some guidelines restrict application to post-1970 steel—reflecting the advent of standardized steel grades and modern quality control—whereas others also include earlier material. Testing protocols typically combine non-destructive and destructive techniques, applied to batches of components, with the number and type of tests determined by the degree of prior knowledge available. The resulting data permit classification within established steel grade systems.

On the design side, under Eurocode 3, existing guidelines provide only limited direction. Some recommend modestly increased safety factors—particularly for buckling verifications—but no comprehensive standard yet exists. Consequently, Bartsch et al., Feldmann et al. and Knobloch et al. [3,4,22] advocate for the development of a unified European design standard for reused structural steel, envisioned as a dedicated supplement to Eurocode 3. Work on this standard is ongoing under CEN/TC 250/SC 3, aimed at codifying provisions for safety factors, global and plastic analysis, and detailing considerations such as joints, extensions, modifications, and strengthening strategies.

2.3. *Testing for material properties*

Testing is necessary to determine the material properties of a reclaimed member which can be used by an engineer in the design of a new structure, ensuring safety and reliability, and is addressed in various aforementioned guidelines.

The British guideline for reuse (SCI P427) [24] includes a comprehensive table for properties to be declared for reclaimed steel, shown here as Table 1. Columns labeled “Item”, “Property”, “To be declared”, and “Procedure” are taken directly from the guideline (Table 3.1 in [24]); other columns are added by these authors. The CEN Technical Specification PD CEN/TS 1090–201 also requires items a, b, d, f, and j [23].

As seen in Table 1, various destructive and non-destructive testing typologies exist to determine these characteristics. Usually, destructive test methods produce more accurate results, however require that material be extracted from existing members. Recent research studies proposed a new non-destructive test procedure known as Indentation Plastometry, which however is still at its first applications in metallurgical sectors [27].

Guidelines for reuse tend to put forward testing protocols which use a combination of these destructive and non-destructive methods. More destructive methods are specified for situations either where there is greater uncertainty in the material properties (e.g., no prior documentation to guide the investigation) or where there is a higher demand for structural safety (e.g. high consequence classes), or both. The details of the protocols found in various testing regimes will be elaborated on later, see Tables 4 and 5 in the next Section.

Table 1
Material properties required to be declared in a reuse scenario. Columns labeled “Item”, “Property”, “To be declared”, and “Procedure” are originally published in SCI P427 [24].

Item	Property	To be declared	Procedure	Destructive Test	Specification	Non-Destructive Test	Specification
a)	Strength (yield and tensile)	Yes	Determined by destructive and non- destructive tests.	Tensile Test	EN ISO 6892	Hardness	Varies
b)	Elongation	Yes	Determined by destructive tests.	Tensile Test	EN ISO 6892		
c)	Stress reduction of area requirements (STRA)	If required	Generally not required to be declared.	Tensile Test	EN ISO 6892		
d)	Tolerances on dimensions and shape	Yes	Based on dimensional survey.				
e)	Impact strength or toughness	If required	If required, determined by destructive tests. Conservative assumption as the default.	Charpy Impact Test	EN ISO 148		
f)	Heat treatment delivery condition	Yes	Conservative assumption as the default.				
g)	Through thickness requirements (*Z*-quality)	If required	Generally not required to be declared.	Through-thickness Tensile Test	ISO 7778 EN ISO 6892		
h)	Limits on internal discontinuities or cracks in zones to be welded	If required	Generally not required to be declared.				
In addition, if the steel is to be welded, its weldability shall be declared as follows:							
i)	Classification in accordance with the materials grouping system defined in CEN ISO/TR 15608, or	Yes	Not applicable for reclaimed steelwork.				
j)	A maximum limit for the carbon equivalent of the steel, or;		Maximum to be declared from manufacturer's test certificates.				
k)	A declaration of its chemical composition in sufficient detail for its carbon equivalent to be calculated		Determined by non-destructive and destructive tests.	Varies	See CEN/TR 10261 for element-by-element tests	Optical Emission Spectroscopy	ISO 19272

3. Experimental dataset of reclaimed steel members

3.1. Aims

This work interrogates material testing processes in steel reuse via an analysis of test data on 182 individual reclaimed members, obtained from Cleveland Steel and Tubes Limited (hereafter referred to as "Cleveland Steel"). Cleveland Steel is a UK company, part of whose business includes purchasing, testing and stocking reclaimed members for resale. Data was shared for research purposes and are also available in a dedicated data repository.

The data is used here to pursue two potential engineering efficiencies for reused steel: the possibility to use non-destructive testing for material strength to eliminate material waste and labor from destructive tensile testing, and the evaluation of grading schemes and material safety factors for better alignment with Eurocode 3 for steel design.

3.2. Dataset

For this analysis, Cleveland Steel shared test reports for 182 unique reclaimed members. The testing was completed with the original aim of grading steel for reuse. The reports are dated between 2022 and 2025, and per informal Cleveland Steel communication, members are of fairly recent provenance (i.e. assumed post-1970). Further information about the sourcing of steel members or their donor buildings was not provided. A full list of pieces and test data received can be found in [28]. Section types and quantities are summarized in Table 2, as well as their governing standards.

Testing was executed by two companies: Oceaneering (with chemical composition reports by Element Materials Technology), and AMS Ltd Testing, both UKAS-accredited laboratories. Reports include information summarized in Table 3.

This study focuses primarily on strength properties utilizing predominantly the tensile test and hardness test results; Charpy impact data defines subgrade and chemical composition information is used insofar as it indicates compliance with grade parameters.

3.3. Grading test members

3.3.1. Grading methodology

From the protocols put forward by CEN/TS 1090–201 and by SCI P427 summarized in Tables 4 and 5, there are two possibilities for defining the grade of tested reclaimed steel. One approach will be called the "nominal" grading scheme, whereby the test result is compared directly against the minimum specified upper yield strength ($R_{eH,min}$) value for that grade in the product standard (typically equal to or less than the nominal value, depending on thickness). The other approach will be called the "restricted" grading scheme, whereby the test result is compared against the minimum values shown in Table 6. These minimum values are the true 5% fractile values based on the normal curve derived from the means and coefficients of variation for each grade given in Table E.1 of Eurocode 3 [13]. The nominal grading scheme is found in CEN/TS 1090–201:2024 Protocols C and D, while the restricted grading scheme is generally found in CEN/TS 1090–201:2024 Protocol B and in SCI P427 [24].

Table 2
Summary of structural shapes included in Cleveland Steel test data.

Section Type	Quantity	Standard for Shape	Standard for Execution
HEA	1	EN 10365	EN 10025
HEB	1	EN 10365	EN 10025
UB	102	EN 10365	EN 10025
EC	64	EN 10365	EN 10025
PFC	3	EN 10365	EN 10025
RSA	2	EN 10056	EN 10025
SHS	8	EN 10210 (hot-rolled) EN 10219 (cold-rolled)	EN 10210 (hot-rolled) EN 10219 (cold-rolled)
Unknown	1	–	–

Within the scope of the present work, Cleveland Steel test data were sorted based on the nominal and restricted grading schemes. Chapter 4 will reference these results as it concerns the grading outcomes from hardness correlations. Chapter 5 will use the results to evaluate the relative reliability in adopting either of these schemes.

The grade determination of each member entails not just sorting by the yield and ultimate tensile strength parameters, but also defining the subgrade (toughness) based on the Charpy impact test and confirming that the piece then meets other parameters like ductility and weldability required for that grade. The process is represented by the flowchart in Fig. 1.

This workflow was implemented to automatically grade steel in the complete Cleveland Steel dataset and perform checks on elongation parameters and chemical composition.

First, a parameter table was created to synthesize limits from several tables found in standards. For hot-rolled open sections, mechanical properties are found in Tables 6 and 8 of EN 10025–2:2019, and chemical composition in Tables 3 and 5 of EN 10025–2:2019, with additional limits in Table 1 of EN 10020:2000. For hollow sections, which are conservatively assumed cold-rolled as per guidelines, mechanical properties are found in Table A.3 of EN 10219–1:2006, and chemical composition in Tables A.1 and A.2 of EN 10219–1:2006, with additional limits in Table 1 of EN 10020:2000.

Organized by grade, subgrade, and material thickness, the parameter table includes minimum and maximum strength values, elongation requirements and chemical composition limits associated with each group. The workflow selects the highest possible grade based on strength parameters, the subgrade based on Charpy impact data, and then checks elongation and chemical composition for compliance. The workflow was set up for both the "nominal" and "restricted" grading schemes.

3.3.2. Grading of test data

Following the workflow described in Section 3.3.1 and Fig. 1, Table 7 shows the frequency with which members fall into each grade and subgrade, while Fig. 2 represents the total number of members for each grade and subgrade.

Grading by both the nominal and restricted grading schemes results in two members that did not pass elongation checks. Chemical composition reporting was inconsistent across the various specimens, therefore compliance results are not reported here. For the purpose of the evaluations pertaining to strength results, in the following chapters all 182 members are still considered.

4. Correlation studies between hardness and tensile tests data for steel reuse

4.1. Aims

In re-certifying reclaimed steel, testing material strength for assignment of a grade is imperative. Destructive tensile testing per EN ISO 6892 [29] is currently the most widely-accepted, reliable way to test material strength as detailed in reuse guidelines. Hardness testing, which is non-destructive and can often be done in situ, is seen as a supplement to tensile testing when dealing with large batches of members, but does not fully replace it.

Both the CEN/TS 1090–201 guideline [23] and the British SCI P427 [24] currently require 100% non-destructive (hardness) testing of every member of a group in order to establish that the group can, in fact, be considered together. Test "groups" are comprised of members having the same section size, from the same donor building, and which served the same structural purpose in that donor building (SCI P427 additionally requires that they have the same exact detailing).

Then, the number of destructive (tensile) tests required to actually determine the strength properties for that group varies. For CEN/TS

Table 3
Summary of test types included in Cleveland Steel test data.

Information / Evaluation Type	Test Standard	Quantity of Members	Result Type	Notes
Section Size		181		
Tensile Testing	BS EN ISO 6892-1	182	Yield or 0.2% Proof Stress, Maximum Stress, % Elongation	Some tests include Reduction of Area
Charpy Impact Testing	BS EN ISO 148-1:2016	175	Toughness	
Vickers Hardness Testing	BS EN ISO 6507-1:2018	60	Vickers Hardness	
Chemical Composition	Varies	175	% by mass of various elements; Carbon Equivalent Value	Oceaneering typically includes: C, Si, Mn, P, S, Cr, Ni, Cu, Mo, V, Nb, Ti, and calculation of Carbon Equivalent Value AMS typically includes: C, Si, Mn, P, S, Cr, Ni, Cu, Mo, V, sometimes N, and always calculation of Carbon Equivalent Value

Table 4
Protocols for strength determination found in CEN/TS 1090–201:2024.

Criteria	# Non-Destructive Tests	# Destructive Tests (min.)	Type of Evaluation	Selection of Destructive Test Pieces	Strength Determination / Grading Protocol
Protocol A: Post-1970 with Original Documentation	0%	0	Values from original inspection documents	N/A	Grading from original inspection documents
Protocol B: Post-1970 with Known Provenance*	100%	1	Non-statistical	Member with lowest hardness test result	Compare to minimum values in Table 8 OR determine characteristic values of yield and ultimate strength using EN 1990:2023 Clause D.7
Protocol C: Pre-1970 with Known Provenance	100%	3	Statistical	Member with lowest hardness test result, member with highest hardness test result, AND at least one additional randomly selected member	Determine characteristic values of yield and ultimate strength using EN 1990:2023 Clause D.7 for direct use OR compare determined characteristic value directly to nominal values of yield and ultimate strength in the product standard.
Protocol D: Other (Unknown Provenance)	100%	100%	Non-statistical	Every member	The measured yield and tensile strengths can be declared as characteristic values, OR compare measured values directly to nominal values of yield and ultimate strength in the product standard.

[*] "The provenance should be considered as known when at least the geographic location, building year and former function of the components are known" [21].

Table 5
Protocols for strength determination found in SCI P427 [24].

Criteria	# Non-Destructive Tests	# Destructive Tests (min.)	Type of Evaluation	Selection of Destructive Test Pieces	Strength Determination / Grading Protocol
Consequence Class 1*	100%	1	Non-statistical	Random	Compare to minimum values in Table 8.
Consequence Class 2	100%	1	Non-statistical	Random	Compare to minimum values in Table 8.
Consequence Class 3 or unreliable knowledge of provenance	100%	3	Statistical	Random	Determine a characteristic value from the data via statistical methods, then compare to minimum values in Table 8.

*See EN 1990:2023 Table 4.1

1090–201, the amount of destructive testing is dependent on the amount of prior information known about the donor material. For SCI P427, it is based on the consequence class of the recipient structure.

While batching members for selective destructive testing reduces effort as compared to tensile testing every piece, it may not be realistic in a reclaimed steel marketplace where individual pieces are bought and sold. Moving entirely to hardness testing for grading purposes would eliminate this burden and streamline the reuse process further: hardness testing can usually be done in situ, it preserves the usable length of the member, and it does not require laboratory equipment, decreasing costs [30].

The aim of this chapter is to correlate hardness with strength from the Cleveland Steel test data to demonstrate this relationship specifically among reclaimed members and evaluate grading outcomes.

4.2. Data summary

In the Cleveland Steel test data, 60 specimens underwent Vickers Hardness testing per ISO 6507-1:2018 [31]. In Vickers testing, a diamond pyramid with a square base and 136° included angle is pressed into the surface under a defined load. A load of 10 kgf is commonly assumed (denoted as "HV10"), but other loads may also be specified. The length of the diagonals of indentation is measured under a microscope.

In the Cleveland Steel test reports, three hardness measurements were taken on each member under 10 kgf load, then averaged. For the purpose of this data analysis, 58 specimens were used whose average HV10 values range from 131 to 187. There were two outlier specimens with averages of 251 and 276 (pieces #178 and #104, respectively)

Table 6

Cutoff values for grading by the restricted grading scheme.

Steel grade	Yield Strength (MPa) Minimum	Yield Strength (MPa) Mean	Ultimate Strength (MPa) Minimum	Ultimate Strength (MPa) Mean	f_u/f_y mean	Standard
S235	267	293	397	432	1.47	EN 10025–2; EN 10219–1
S275	313	343	452	492	1.43	EN 10025–2; EN 10219–1
S355	391	426	505	540	1.26	EN 10025–2; EN 10219–1
S460	490	529	560	595	1.12	EN 10025–3/4; EN 10219–1

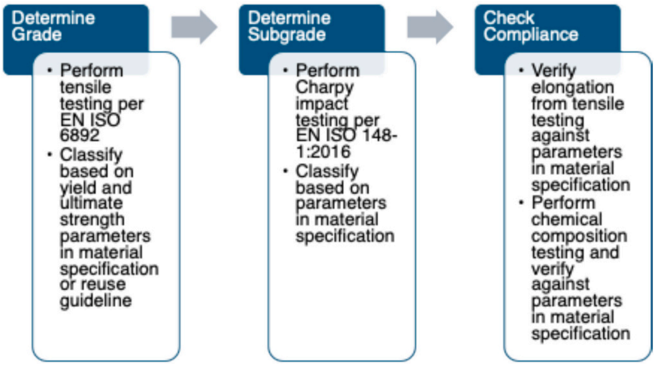

Fig. 1. Steel grading workflow.

which were omitted from the following analyses so as not to skew data.

4.3. Calibration of the analytical formulation

Fig. 3 plots the correlation of yield strength vs hardness of all relevant data (58 specimens). The regression analysis of hardness versus yield strength then results in the following equation:

$$f_y = 2.0793 \cdot H_V + 50.106; \quad R^2 = 0.4297 \tag{1}$$

However, when this group is split between tensile test results that showed yielding behavior (17 specimens, Fig. 4) and those for which 0.2% proof strength was calculated (41 specimens, Fig. 5), the former shows better correlation (higher R^2):

$$f_{y_{yield}} = 2.9421 \cdot H_V - 80.653; \quad R^2 = 0.6360 \tag{2}$$

$$f_{y_{0.2}} = 1.7791 \cdot H_V + 95.147; \quad R^2 = 0.3641 \tag{3}$$

The correlation of hardness to ultimate strength is shown in Fig. 6, resulting in a regression formulation as follows:

$$f_u = 1.9238 \cdot H_V + 202.11; \quad R^2 = 0.5585 \tag{4}$$

In order to maintain consistent data sets, correlations were also developed for hardness to ultimate tensile strength specifically for the same pieces that fell into the yield and 0.2% proof strength categories in Eqs. (2) and (3). The regression formulations remain very similar to Eq. (4):

$$f_{u_{yield}} = 1.9397 \cdot H_V + 205.706; \quad R^2 = 0.5995 \tag{5}$$

$$f_{u_{0.2}} = 1.9304 \cdot H_V + 198.477; \quad R^2 = 0.5583 \tag{6}$$

4.4. Comparison with current formulations from literature

4.4.1. Formulations in literature

The development of correlation equations for Vickers Hardness (H_V) to yield and tensile strength follows two paths. The first, developed by Tabor [32] and then by Cahoon et al. [33], uses a direct proportionality between H_V and strength, multiplied by a constant that varies by the strain hardening coefficient n, where $n = m - 2$, and m is the Meyer's hardness coefficient. The equations for yield strength and ultimate tensile strength given by Cahoon are as follows, with units of kg/mm^2:

$$f_y = \frac{H_V}{3} \cdot (0.1)^{m-2} \tag{7}$$

$$f_u = \frac{H_V}{3} \cdot [1 - (m-2)] \cdot \left[\frac{12.5(m-2)}{1-(m-2)}\right]^{m-2} \tag{8}$$

The challenge of this series of equations is that the Meyer's hardness coefficient must be determined via a separate indentation test. For the graphs presented in Figs. 7 and 8, the Meyer's hardness coefficient is estimated at 2.1 [34]. This value is assumed to be valid on average for

Table 7

Cleveland Steel test data grading results.

Grade	Subgrade	Nominal Grading: Open Section (EN 10025)	Nominal Grading: Hollow Section (EN 10219)	Nominal Grading: Total	Restricted Grading: Open Section (EN 10025)	Restricted Grading: Hollow Section (EN 10219)	Restricted Grading: Total
S235	JR				4	1	5
	J0				11		11
	J2						
	Unknown						
S275	JR	5		5	4		4
	J0	32	1	33	58		58
	J2	2		2	4		4
	Unknown				7		7
S355	JR	4		4	1		1
	J0	113	4	117	79	5	84
	J2						
	K2	7	1	8	5	1	6
	Unknown	7		7	1		1
S460	JR						
	J0	4	1*	5*			
	J2						
	K2		1*	1*		1*	1*
	Unknown						

[*] S460 is not present in the EN 10219–1 Annex A standard for hollow sections made of non-alloy steel. Hollow sections categorized into S460 for this dataset meet strength thresholds per EN 10025. This was done in order to avoid high values skewing statistical data in Section 5, as that section does not consider section types separately.

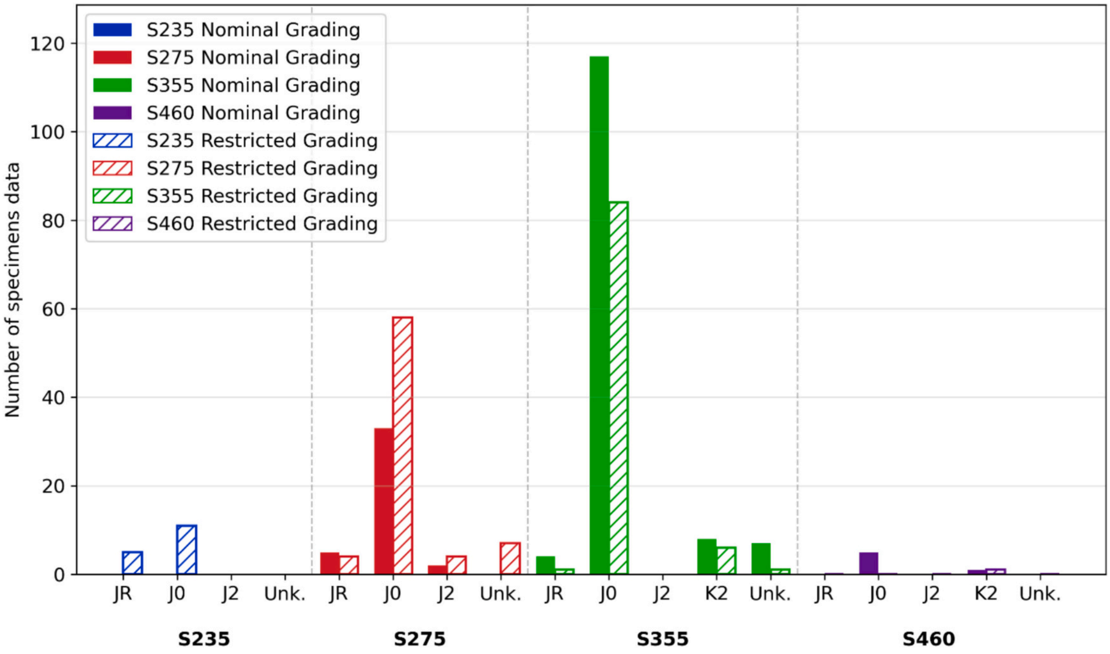

Fig. 2. Cleveland Steel data grading results.

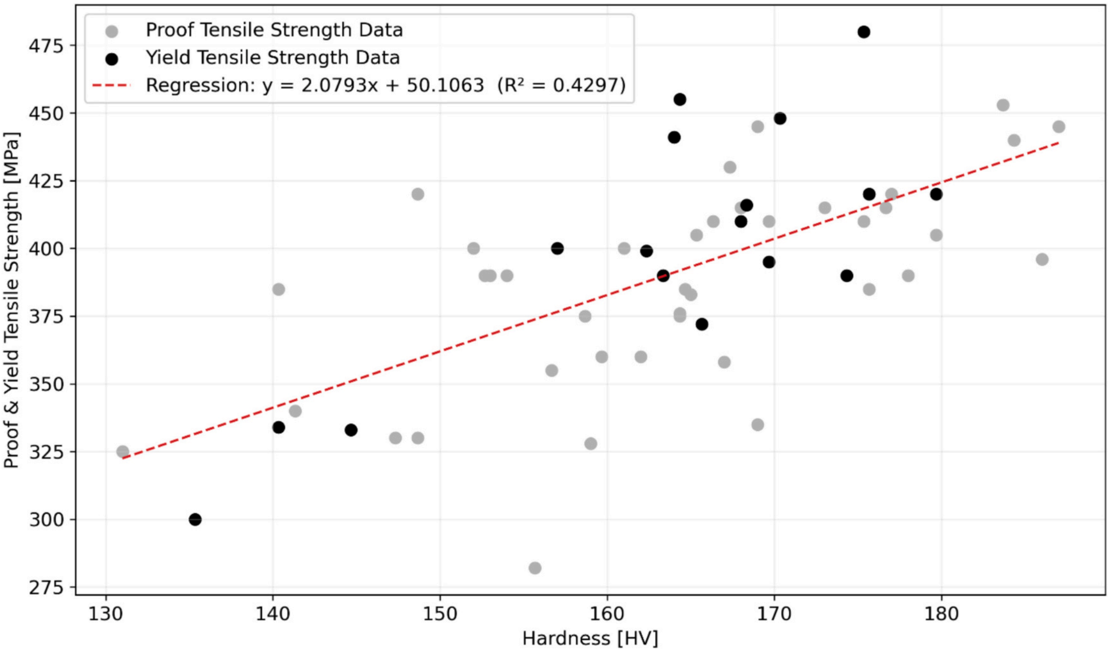

Fig. 3. Yield or 0.2% proof strength vs hardness (all relevant data).

regular carbon steels, for which the strain hardening coefficient could be taken between 0.05 and 0.2 [35,36].

The second path derives correlations via linear regression. One set of proposed equations was published by Fujita and Kuki [37]:

$$f_y = 2.736 \cdot H_v - 70.5 \tag{9}$$

$$f_u = 2.5 \cdot H_V + 100 \tag{10}$$

A separate study conducted at the Colorado School of Mines by Pavlina and Tyne used over 150 test results with a wide range of strengths due to varying compositions and microstructures (though all nonaustenitic hypoeutectoid steels) to derive its own equations, as follows [38]:

$$f_y = 2.876 \cdot H_V - 90.7; \quad R^2 = 0.9212 \tag{11}$$

$$f_u = 3.734 \cdot H_V - 99.8; \quad R^2 = 0.9347 \tag{12}$$

The study then found several additional regression lines for subsets of the data based on microstructure (martensitic, non-martensitic, and complex phases), on strain-hardening potential (the ratio of tensile to yield strength) and on average strength. The regression lines for non-martensitic steel (relevant to the test data here analyzed) are as follows:

$$f_y = 2.646 \cdot H_V - 84.8; \quad R^2 = 0.8414 \tag{13}$$

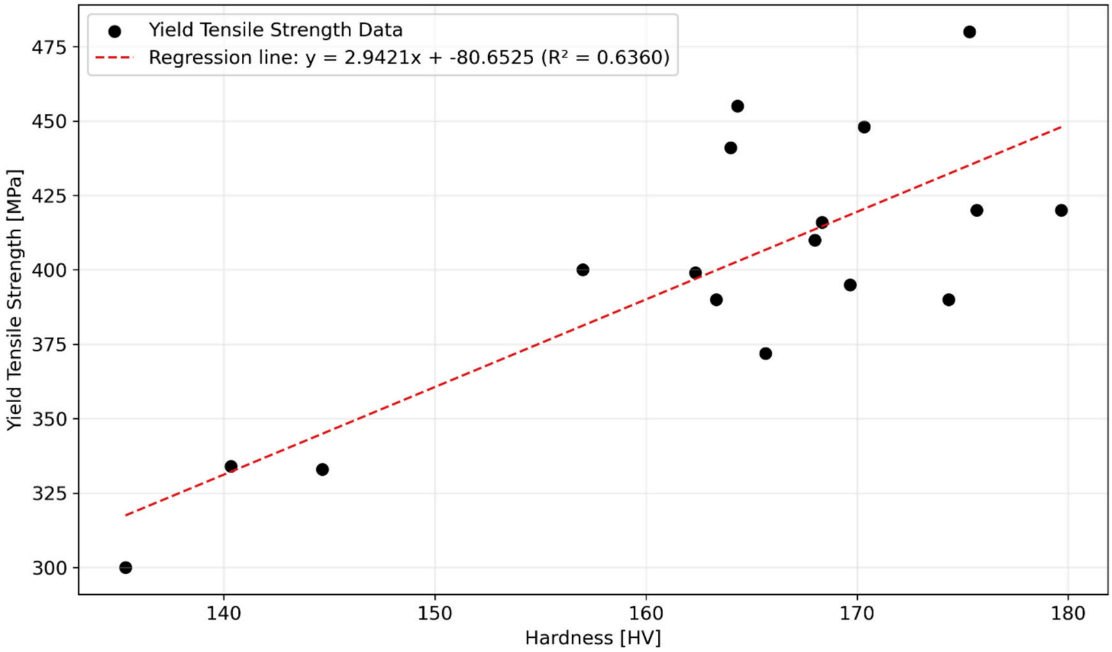

Fig. 4. Yield strength vs hardness (average prediction band width of ±63.3 MPa, with an average confidence band width of ±15.2 MPa).

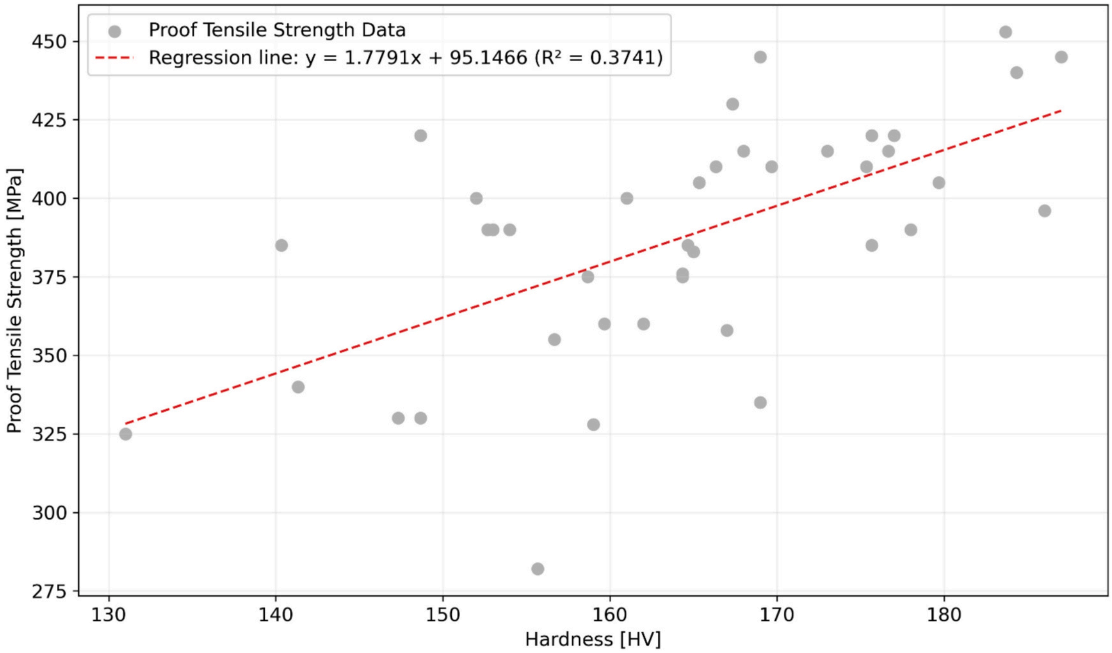

Fig. 5. 0.2% proof strength vs hardness (average prediction band width of ± 65.7 MPa, with an average confidence band width of ± 22.0 MPa).

$$f_u = 3.339 \cdot H_V + 2.5; \quad R^2 = 0.8910 \tag{14}$$

The regression lines for "medium" tensile to yield strength ratio ($1.23 < TS/YS < 1.56$) are as follows:

$$f_y = 2.736 \cdot H_V - 70.5; \quad R^2 = 0.9719 \tag{15}$$

$$f_u = 3.800 \cdot H_V - 99.8; \quad R^2 = 0.9620 \tag{16}$$

4.4.2. Formulations in reuse guidelines

CEN/TS 1090–201 does not put forth a specific correlation equation for hardness to strength, but rather references the conversion tables in Annex A of EN ISO 18265:2013. The conversion tables provide HV10 to ultimate tensile strength (not to yield strength), and include a caveat that this relationship is approximate and cannot take the place of tensile testing. The regression that can be derived from the points given in the tables is approximately:

$$f_u = 3.22 \cdot H_V - 2.86 \tag{17}$$

The PROGRESS Report D2.3 [20] includes a deeper exploration of hardness testing, looking at several correlations from literature and codes. The report ultimately recommends to adopt the following set of equations:

$$f_y = 2.70 \cdot H_V - 71 \tag{18}$$

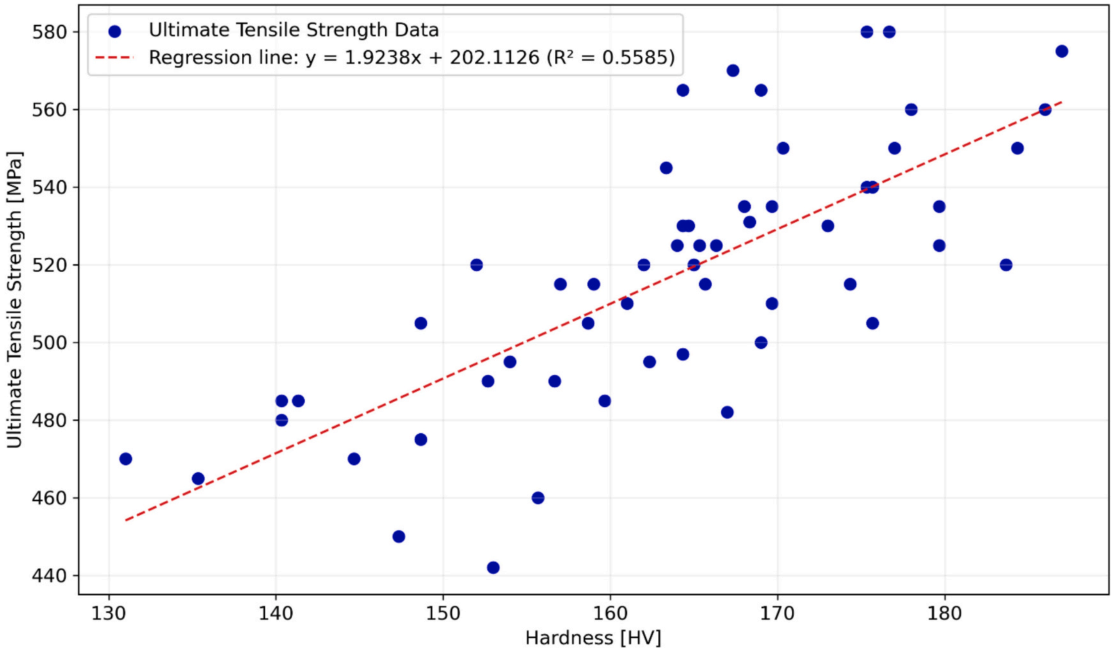

Fig. 6. Ultimate tensile strength vs hardness (average prediction band width of ±45.3 MPa, with an average confidence band width of ±9.3 MPa).

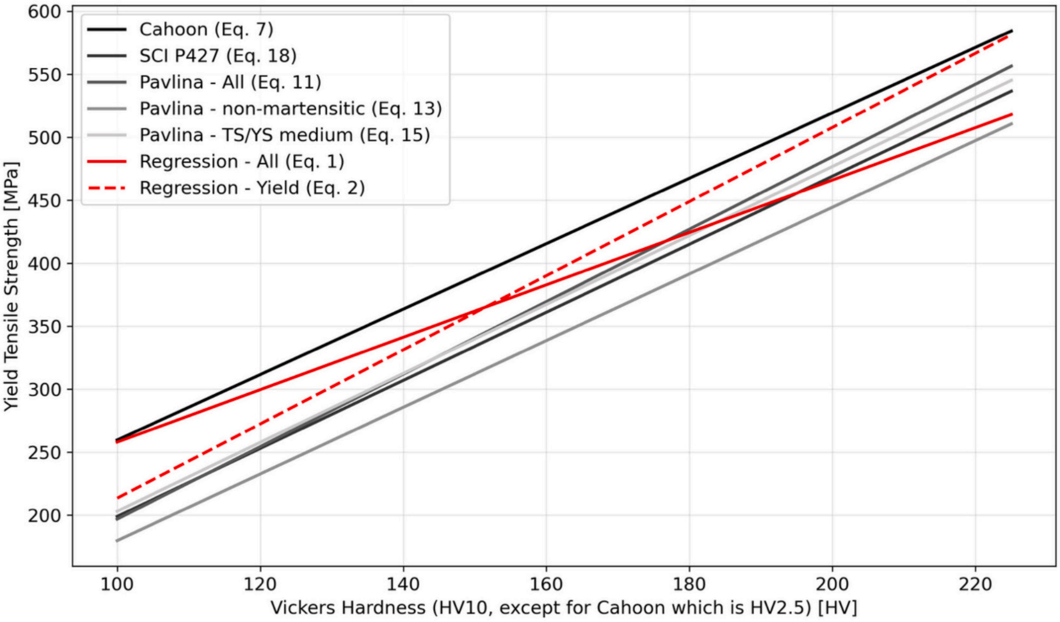

Fig. 7. Correlation formulations of yield strength vs hardness experimental data.

$$f_u = 2.50 \cdot H_V + 100 \tag{19}$$

SCI P427 includes the same formulas as Eqs. 18 and 19, which are more conservatively-rounded versions of the formulas presented by Fujita (Eqs. 7 and 8). It should be noted that in both the PROGRESS and SCI P427 recommendations, the H_V to be used in the above formulas should be the statistically-determined characteristic value derived from tests on three or more members.

Figs. 7 and 8 graphically report the correlation formulations between yield strength vs hardness test data and ultimate strength vs hardness test data, respectively. In these figures, also the correlation formulations extracted from linear regression of the Cleveland Steel data (as presented in Eqs. 1 and 4 of Section 4.3) are reported in red.

4.5. *Evaluation of grading outcomes for hardness formulations*

4.5.1. *Discussion of the results*

Table 8 reports the significant results of the strength and grading results. The number of specimens for which residuals are above or below the regression line indicates whether the formulation tends to under- or over-estimate the actual strength. The paired *t*-test *p*-values indicate whether the data set exhibits significant bias away from the linear regression used.

The same grading procedure explained in Section 3.3.1 was then implemented to assign predicted grades to the members within the hardness testing data set based on the yield and tensile strength values predicted by each formulation. The final six columns in Table 8

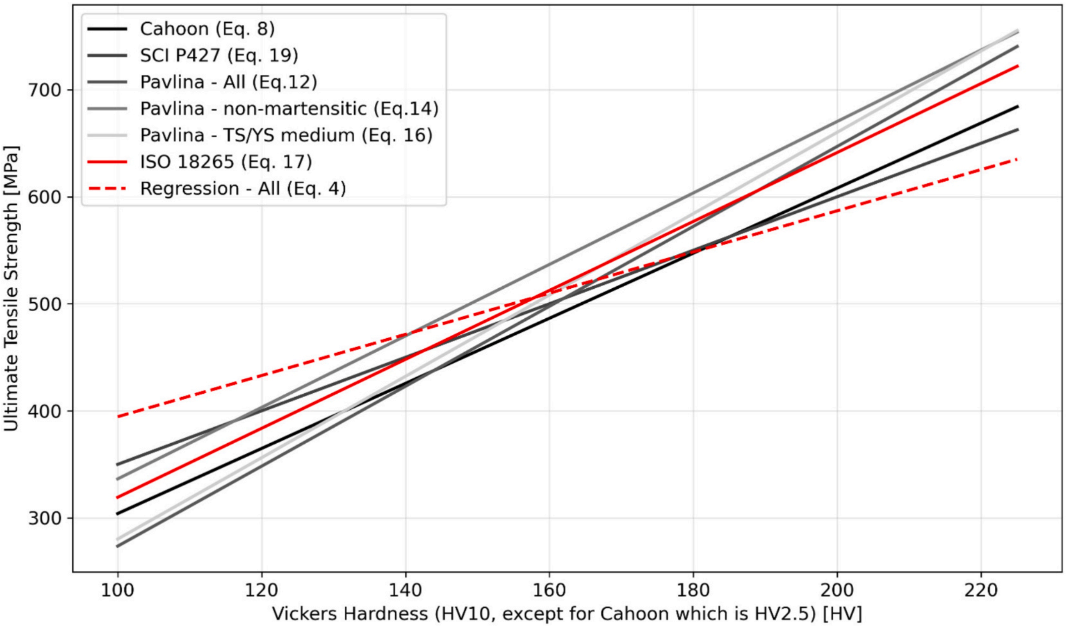

Fig. 8. Correlation formulations of ultimate strength vs hardness experimental data.

enumerate the results qualitatively in terms of over- and under-grading and correct matches, using both the nominal and restricted grading schemes.

Following the nominal grading scheme, the three pairs of experimental regressions derived from this dataset for all data, yielding behavior and nonlinear behavior (when 0.2% proof strength is reported) show similar or improved accuracy with respect to the others from guidelines and literature. The use of the regression based on pieces with yielding behavior shows comparable conservativeness.

When following the restricted grading scheme, the three pairs of regressions from the data again show improved accuracy compared to those from literature, but have less conservative outcomes.

5. Calibration of partial safety factors for steel reuse

5.1. Statistical distributions

With the aim of evaluating the alignment of each grading scheme with Eurocode probabilistic models, specimens were grouped by grade and nominal thickness. It should be noted that $R_{eH,min}$ as well as elongation and chemical composition requirements reported in material standards EN 10025–2 and EN 10219–1 depend on thickness. Experimental statistical parameters were found for each group and compared to those for each grade in EN 1993-1-1:2022 Table E.1. Statistical data for yield and ultimate tensile strength can be found in Annex A.

For both yield and ultimate tensile strength, the nominal grading scheme usually leads to lower experimental mean ($X_{fy,exp,m}$ and $X_{fu,exp,m}$), 5% fractile or “characteristic” ($X_{fy,\exp,k}$ and $X_{fu,\exp,k}$) and 0.12% fractile or “design” ($X_{fy,\exp,d}$ and $X_{fu,exp,d}$) values among each group, while the restricted grading scheme usually leads to higher experimental mean, characteristic and design values among each group.

Only in the case of design values for yield strength ($X_{fy,exp,d}$) do both schemes lead to lower values than in standards. This is because the yield strength tends to show higher standard deviations than ultimate strength, which, when multiplied by the higher k_n values for design strength, more significantly reduce the design value as compared to the mean.

It should be noted that in all cases the coefficient k_n was chosen for unknown coefficient of variation, because the calculation is using the experimental coefficient of variation rather than the prior coefficient of variation from the standard.

The restricted grading scheme typically results in an experimental normal curve that more closely matches that expected of new steel of the same grade per Eurocode, with the exception of the yield strength values for S275. Figs. 9–16 show the statistical distributions and referenced normal curves for S275 (Figs. 9–10 for yield strength, Figs. 11–12 for ultimate strength) and S355 gradings (Figs. 13–14 for yield strength, Figs. 15–16 for ultimate strength), differentiating between nominal and restrictive grading schemes, respectively.

The results reported numerically in Annex A should not be treated as actual characteristic or design values for use in design. Instead, these results and their graphical interpretation indicate that using the restricted grading scheme for individual members should lead, overall, to more reliable outcomes when designing within the assumptions of Eurocode since the distribution of values within a grade match more closely the data of EN 1993-1-1:2022. This is validated quantitatively by the evaluation of partial safety factors in Section 5.2.

5.2. Partial safety factors

5.2.1. Conceptual framework

Calibrating partial safety factors specifically for reclaimed steel is a critical component to safely designing structures using reclaimed members. Currently, the only additional material safety factor recommended by steel reuse guidelines [20,24] is for buckling analysis (i.e. $\gamma_{M1,mod} = 1.15{\cdot}\gamma_{M1}$). Guidelines at present do not suggest a change to safety factor γ_{M0}, which applies to the tensile strength of steel. This is investigated in what follows.

The calculation of safety factors has its basis in the probabilistic distribution of strengths within a given grade. EN 1993-1-1:2022 Table E.1 identifies two key values for each grade: $X_{5\%}$, or the 5% fractile of strength, typically called the “characteristic” value or X_k, and $X_{0.12\%}$, or the 0.12% fractile of strength, called the “design” value or X_d.

Mathematically, a material safety factor γ_M is a divisor by which X_k is reduced to reach X_d:

$$X_d = \frac{X_k}{\gamma_M} \tag{20}$$

The values in Eurocodes have been calibrated on large quantities of data for newly produced steel; the same must be done for reclaimed

Table 8
Strength and grading results applying linear correlations to Cleveland Steel test data.

				Analysis of Residuals			Analysis of Grade Assignment: Nominal Method					Analysis of Grade Assignment: Restricted Method				
Source	Equation	Equation #	# Data	Regression Over-Estimates	Regression Under-Estimates	Paired T-Test P-Value	Over-Grades	Matches Grade	Under-Grades	% Match	% Match or Under-Grade	Over-Grades	Matches Grade	Under-Grades	% Match	% Match or Under-Grade
Guidelines	$f_y = 2.70H_V - 71$	18	58	13	45	2.08E-5	3	48	7	83%	95%	6	32	20	55%	90%
	$f_u = 2.5H_V + 100$	19		18	40	1.49E-2										
Pavlina - All Data	$f_y = 2.876H_V - 90.7$	11	58*	23	35	2.02E-2	3	48	7	83%	95%	6	38	13	67%	89%
	$f_u = 3.734H_V - 99.8$	12		24	34	2.33E-1										
Pavlina - Non-Martensitic	$f_y = 2.646H_V - 84.8$	13	58*	4	54	2.24E-14	1	36	21	62%	98%	2	25	30	44%	96%
	$f_u = 3.339H_V + 2.5$	14		49	9	4.74E-12										
Pavlina - Medium TS/YS	$f_y = 2.736H_V - 70.5$	15	50	16	34	6.98E-3	1	45	4	90%	98%	5	30	15	60%	90%
	$f_u = 3.8H_V - 99.8$	16		30	20	2.68E-1										
Data - All	$f_y = 2.0793H_V + 50.106$	1	58	28	30	9.98E-1	7	49	2	84%	88%	14	40	4	69%	76%
	$f_u = 1.9238H_V + 202.11$	4		26	32	9.98E-1										
Data – Yielding Behavior	$f_y = 2.9421H_V - 80.653$	2	17	9	8	1.0E+0	1	15	1	88%	94%	5	11	1	65%	71%
	$f_u = 1.9397\,HV + 205.706$	5		8	9	1.0E+0										
Data – 0.2% Proof Strength Reported	$f_y = 1.7781\,HV + 95.147$	3	41	20	21	1.0E+0	6	34	1	83%	85%	7	29	5	71%	83%
	$f_u = 1.9304\,HV + 198.477$	6		17	24	1.0E+0										

[*] The starred equation pairs returned only 57 gradeable results by the restricted grading scheme due to one piece being below the S235 threshold.

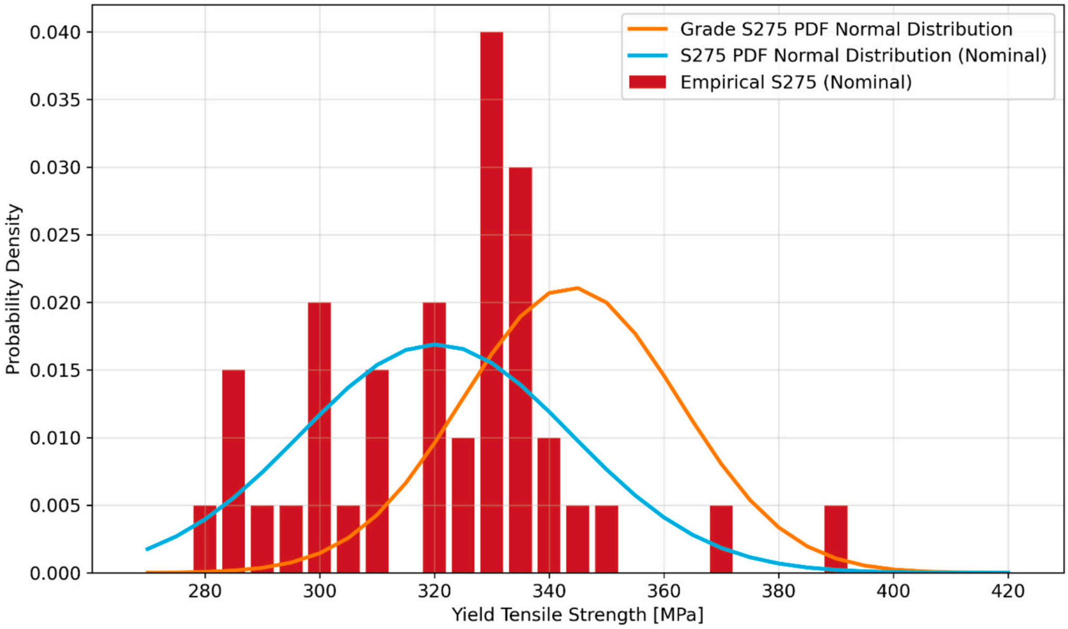

Fig. 9. Experimental and EC3 statistical distributions of yield strength for S275 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by nominal grading scheme.

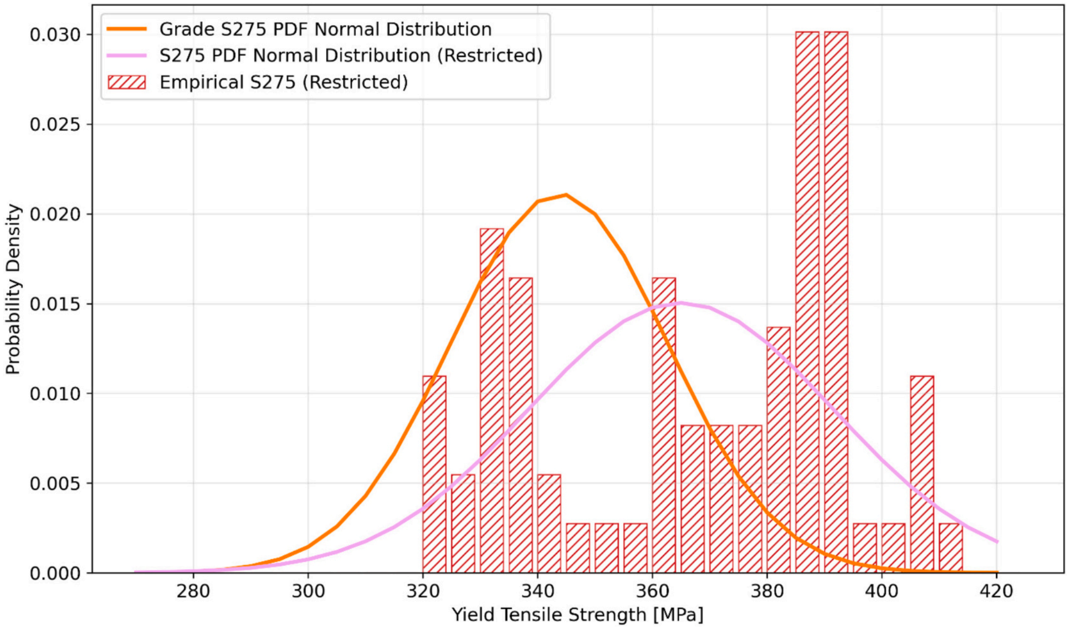

Fig. 10. Experimental and EC3 statistical distributions of yield strength for S275 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by restricted grading scheme.

steel.

For this study, the Cleveland Steel test data was grouped by grade as per Section 3.3.2, then statistical parameters and fractile values were calculated, and safety factors were determined.

5.2.2. Partial safety factors by grade

While the evaluation of grading schemes in Section 5.1 serves as a general check for the alignment of each scheme with Eurocodes, a more useful quantitative result for structural design of steel reuse concerns safety factors. Table 9 collects the results in terms of material safety factor, as determined by the formulation provided in Eq. 20.

The table reports both the "true" safety factor, hence based on statistics, and the "nominal" safety factor, based on the nominal value of the associated grade. This is key for engineers designing with Eurocode 3, as the code currently defines safety factors with respect to nominal values. It should be noted that for ultimate strength values, the lowest value from the range given in EN 10025–2:2019 Table 6 by grade for thicknesses 3 mm to 100 mm (inclusive) is used as the nominal value.

For new steel, following the protocol in Eurocode 3 (EN 1993-1-1:2022), the nominal value for a structural steel grade can be declared as the characteristic value. The partial safety factor for the section properties of structural steel is given as γ_{M0}=1.00 (unless specified otherwise in a National Annex), therefore the nominal value is used as the design value. This achieves sufficient structural safety as the nominal

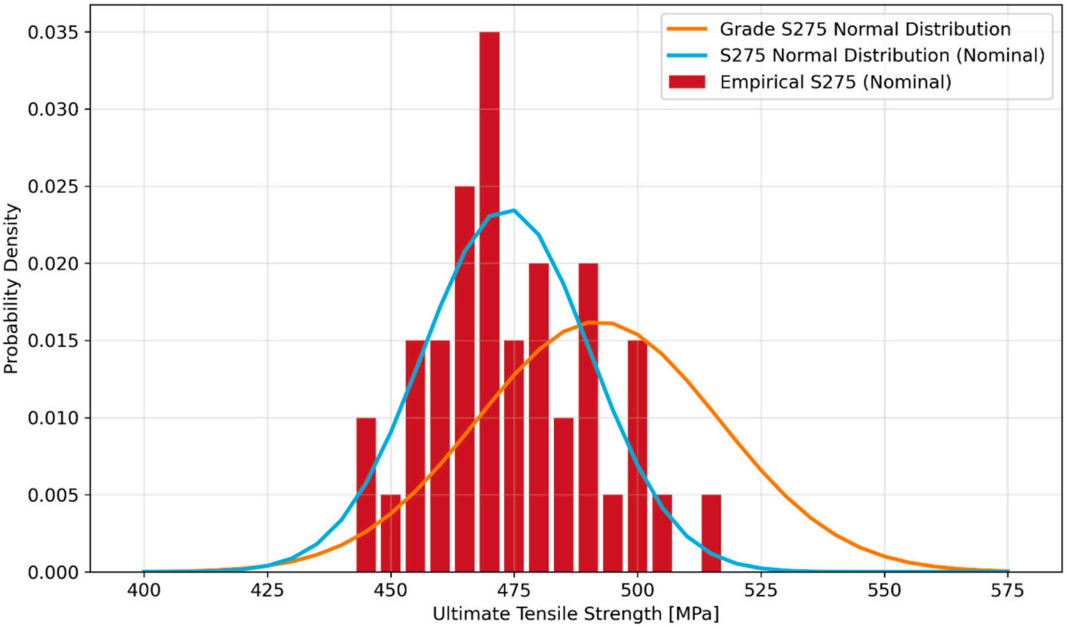

Fig. 11. Experimental and EC3 statistical distributions of ultimate strength for S275 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by nominal grading scheme.

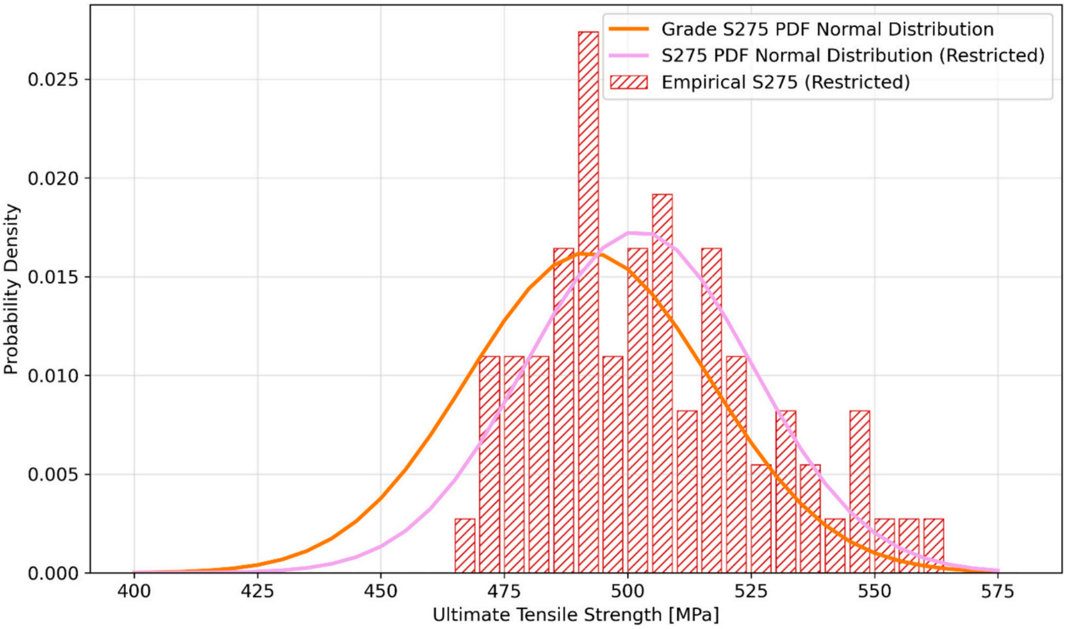

Fig. 12. Experimental and EC3 statistical distributions of ultimate strength for S275 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by restricted grading scheme.

values adopted in calibrating this factor are actually lower than the 0.12% fractiles associated with their grades.

Thus, comparing the 0.12% fractile value of the empirical distribution for the reclaimed steel data with the nominal value of the grade determines whether the current code-determined material safety factor of γ_{M0}=1.00 remains applicable to reclaimed steel.

As the last column of Table 9 shows, when the restricted grading scheme is used, the 0.12% fractile yield strength of the reclaimed steel remains approximately equal to or less than the nominal value of the grade, indicated by $\gamma_{M,N}$ values around or even slightly below 1.00. By this metric, the restricted grading scheme is the option that allows for consistent use of Eurocode design rules for partial safety factors.

When looking at ultimate tensile strength, both grading schemes give similar results hovering around $\gamma_{M,N}$=1.00. This result is consistent with the fact that the ultimate tensile strength distributions tend to have lower standards of deviation than yield strength as noted in Section 5.1. This phenomenon is likely related to intrinsic mechanical properties of the material: yield strength is a mechanical property that is highly sensitive to the local thermomechanical condition of the specimen, residual stresses, and small microstructural variations arising from manufacturing processes, which results in high intrinsic variability and fragmented or multimodal histograms. In contrast, ultimate tensile strength is measured at the final stage of the test, after the material has undergone extensive plastic deformation. This significant strain-

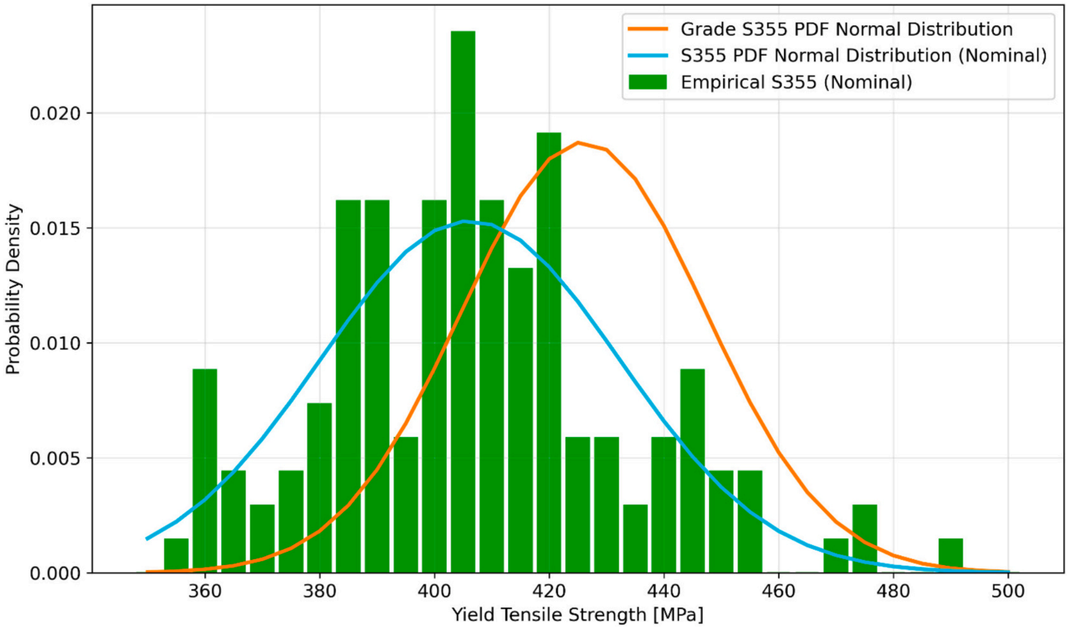

Fig. 13. Experimental and EC3 statistical distributions of yield strength for S355 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by nominal grading scheme.

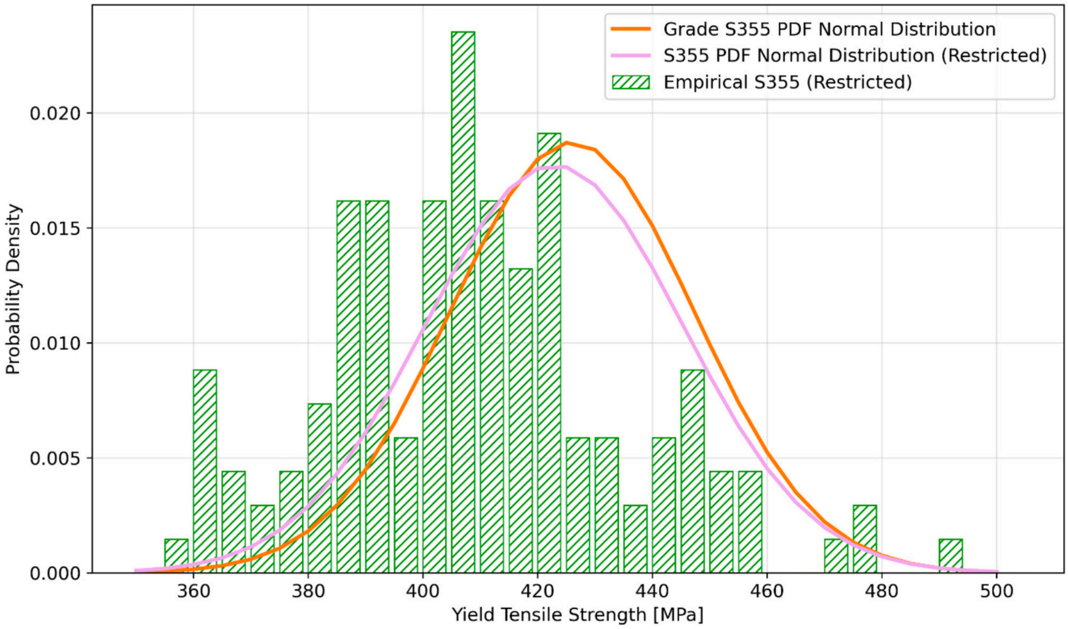

Fig. 14. Experimental and EC3 statistical distributions of yield strength for S355 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by restricted grading scheme.

hardening phase acts as a homogenization process that eliminates or redistributes residual stresses and minor initial inhomogeneities. Consequently, the fracture behavior of the material becomes predominantly dependent on its overall chemical composition, producing measurements that cluster symmetrically around the mean value and naturally assume the bell-shaped form typical of a normal distribution, as can be clearly observed in the graphs.

It should be noted that the calculated partial safety factors are calibrated on a large but confined dataset of experimental results. Therefore, validation through calibration with a larger dataset is advised. Nonetheless, this study suggests that the nominal strength of reclaimed steel could be treated with the same material strength reduction factor as new steel per Eurocode 3 as long as it has been graded per the restricted grading scheme.

With a larger data set, it would be possible to create a new grading scheme specifically tailored to reclaimed steel. This would define minimum cutoff values for each grade which result in strength distributions that may even more closely match those of new steel, or which can be

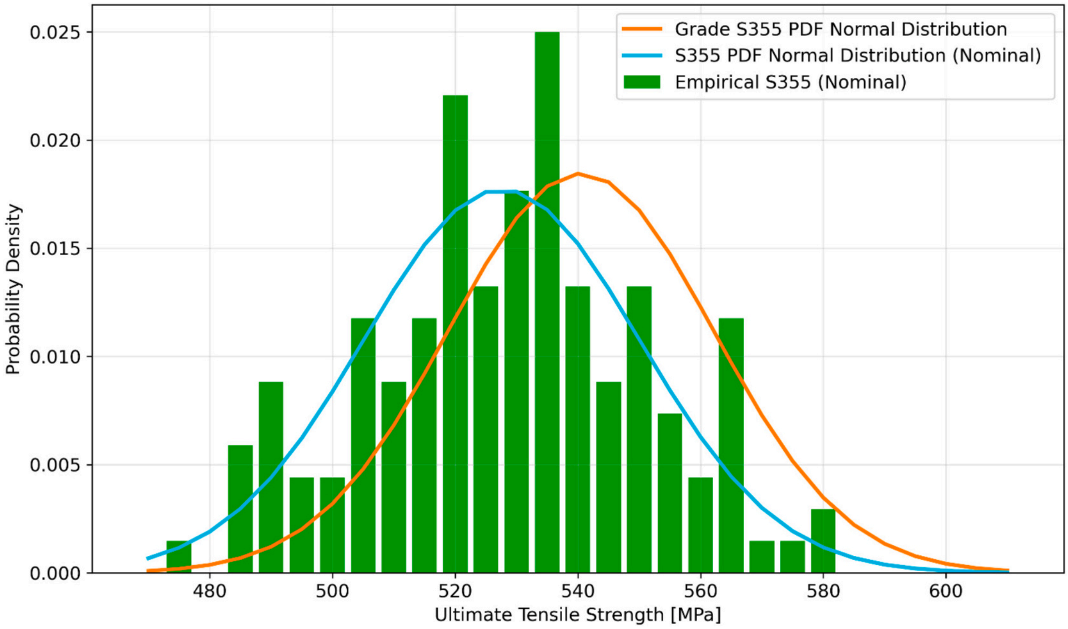

Fig. 15. Experimental and EC3 statistical distributions of ultimate strength for S355 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by nominal grading scheme.

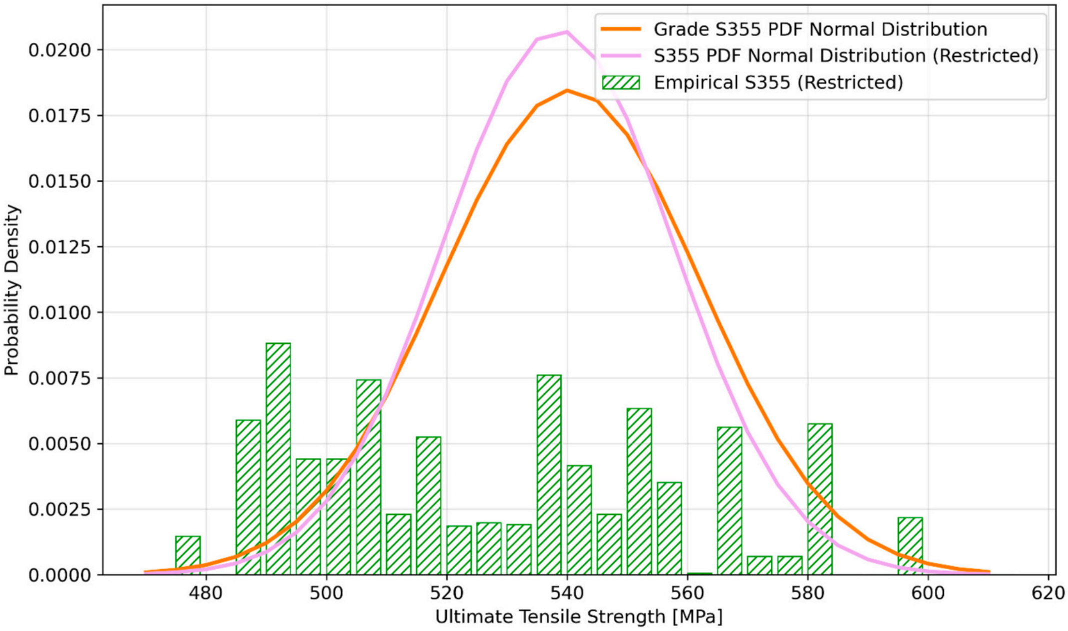

Fig. 16. Experimental and EC3 statistical distributions of ultimate strength for S355 of thickness greater than or equal to 3 mm and less than or equal to 16 mm. Experimental data categorized by restricted grading scheme.

catered to prioritize matching certain statistics like 0.12% fractile values.

6. Conclusions and future outlook

This study used a comprehensive experimental dataset from reclaimed structural steel members to assess two key aspects of design for steel reuse: the suitability of hardness testing as a basis for strength estimation, and the calibration of partial safety factors for material strength under Eurocode-consistent grading schemes.

The following conclusions may be drawn:

- Reclaimed members drawn from post-1970 building stock exhibited strength and ductility levels that are broadly comparable with the nominal properties of corresponding standardized grades. The observed scatter in yield and ultimate strengths is within the range

Table 9
Determination of partial safety factors from statistical data.

Grade	Strength Category	Grading Scheme	Quantity	Nominal Value (MPa)	Mean Value (MPa)	Standard Deviation (MPa)	Kn,k for Vx Unknown	Characteristic Value (5% Fractile) (MPa)	Kn,d for Vx Unknown	Design Value (0.12% Fractile) (MPa)	Safety Factor from Statistical Values	Safety Factor from Nominal Value
				X_N	X_{mean}	σ	$K_{n,k}$	$X_k = X_{mean} - K_{n,k} \cdot \sigma$	$K_{n,d}$	$X_d = X_{mean} - K_{n,d} \cdot \sigma$	$\gamma_M = X_K/X_d$	$\gamma_{M,N} = X_N/X_d$
S355	Yield	Nominal	136	355	406.19	26.06	1.64	363.45	3.04	326.97	1.11	1.09
		Restricted	92	355	422.85	22.50	1.64	385.96	3.04	354.46	1.09	1.00
	Ultimate	Nominal	136	470	527.57	22.52	1.64	490.64	3.04	459.12	1.07	1.02
		Restricted	92	470	538.52	19.24	1.64	506.97	3.04	480.03	1.06	0.98
S275	Yield	Nominal	40	275	320.25	23.62	1.64	281.51	3.04	248.44	1.13	1.11
		Restricted	73	275	364.97	26.53	1.64	321.47	3.04	284.34	1.13	0.97
	Ultimate	Nominal	40	410	473.45	16.96	1.64	445.64	3.04	421.90	1.06	0.97
		Restricted	73	410	502.23	23.08	1.64	464.39	3.04	432.08	1.07	0.95

assumed in Eurocode 3 provisions for new steel, provided that members comply with basic eligibility criteria (e.g. absence of visible damage, acceptable toughness and chemical composition).

- The analysis of Vickers hardness and tensile test results confirms an approximately linear relationship between hardness and both yield and ultimate tensile strength for the reclaimed members considered. Separate regression models for specimens with distinct yielding behavior improve predictive performance. Selecting a correlation equation that results in conservative grading outcomes may support the use of hardness testing as a non-destructive indicator of strength in grading workflows of steel reuse for preliminary design purposes, potentially reducing the number of required destructive tests, particularly in stockist-based reuse where members are traded individually rather than in large batches.
- Application of both nominal and restricted grading schemes shows that the choice of scheme has a significant influence on the resulting strength distributions within each grade. The restricted grading scheme, based on 5% fractile cut-off values derived from the probabilistic models in Eurocode 3 provisions, leads to experimental design values that are closely aligned with those assumed for new steel. In contrast, nominal grading scheme tends to produce lower experimental characteristic and design values within each grade.
- Partial safety factors for material strength were calibrated by comparing experimentally-derived characteristic and design values with the nominal strengths for each grade under both grading schemes. For S275 and S355 steels graded under the restricted scheme, the calibrated factors for yield and ultimate strength are close to the values currently adopted for new steel in Eurocode 3, and do not indicate a need for systematically higher material factors for reclaimed members that have been tested and graded according to existing guidance. Under the nominal scheme, calibrated factors tend to be slightly more conservative, reflecting the lower design strengths obtained.

Overall, these results suggest that reclaimed steel members that meet current eligibility, testing and grading requirements could be used in Eurocode-based design with material safety factors comparable to those applied to new steel, at least for the grades and thickness ranges represented in the present dataset. In addition, the proposed hardness–strength correlations provide a first practical route to increasing the role of non-destructive testing in reuse workflows, thereby reducing testing effort, material waste and costs.

Future work should extend the database to other grades, section types and provenance conditions, and investigate the implications of these findings at system level, including stability checks and connection design, to further support the development of dedicated codified provisions for steel reuse.

CRediT authorship contribution statement

Elizabeth Berenice Kingsley: Writing – original draft, Investigation, Formal analysis, Data curation. **Elisabetta Savino:** Visualization, Investigation. **Roy Fishwick:** Resources, Investigation. **Giada Gasparini:** Supervision, Funding acquisition. **Vittoria Laghi:** Writing – original draft, Supervision, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Annex A

Table A1
Statistical distribution metrics for yield strengths by grading scheme.

				Yield Strength							
				Mean			Standard Deviation			Coefficient of Variation	
Grading System	Grade	Thickness Group	# Pieces	Prior Mean	Experimental Mean	Experimental Mean *p*-value	Prior Standard Deviation	Experimental Standard Deviation	Experimental Standard Deviation p-value	Prior Coefficient of Variation	Experimental Coefficient of Variation
				$X_{fy,prior,m}$	$X_{fy,exp,m}$		$\sigma_{Xfy,prior}$	$s_{Xfy,\mathrm{exp}}$		$V_{Xfy,prior} = \sigma_{Xfy,prior} / X_{fy,prior,m}$	$V_{Xfy,exp} = s_{Xfy,\mathrm{exp}} / X_{fy,exp,m}$
Nominal	S355	B	101	426.00	407.10	0.00E+00	21.30	25.03	1.41E-02	0.050	0.061
Restricted	S355	B	71	426.00	422.62	1.81E-01	21.30	22.71	4.07E-01	0.050	0.054
Nominal	S355	C	29	414.00	402.55	2.90E-03	20.70	27.85	1.08E-02	0.050	0.069
Restricted	S355	C	18	414.00	421.89	1.06E-01	20.70	20.61	9.30E-01	0.050	0.049
Nominal	S275	B	23	343.75	328.78	1.47E-04	18.91	19.33	8.05E-01	0.055	0.059
Restricted	S275	B	54	343.75	364.83	2.22E-16	18.91	26.97	2.59E-05	0.055	0.074
Nominal	S275	C&D	17	331.25	308.71	3.36E-07	18.22	24.50	4.89E-02	0.055	0.079
Restricted	S275	C	18	331.25	363.50	5.91E-14	18.22	25.34	2.33E-02	0.055	0.070
Restricted	S235	B	5	293.75	321.80	1.04E-04	16.16	40.83	7.83E-05	0.055	0.127
Restricted	S235	C&D	11	281.25	294.09	5.90E-03	15.47	12.58	4.78E-01	0.055	0.043

Thickness A is considered from 0 to 3 mm (exclusive); Thickness B is from 3 to 16 mm (inclusive); Thickness C is from 16 to 30 mm (upper bound inclusive); Thickness D is from 30 to 40 mm (upper bound inclusive); Thickness E is from 40 to 60 mm (upper bound inclusive).

Table A2
Characteristic and design values for yield strength by grading scheme.

				Yield Strength					
				Characteristic Value			Design Value		
Grading System	Grade	Thickness Group	Number of Pieces	Prior Characteristic Yield Strength	[EN1990 Table D.1] Vx Unknown: kn	Experimental Characteristic (Normal, Vx Unknown)	Prior Design Yield Strength	[EN1990 Table D.2] Vx Unknown: kd,n	Experimental Design (Normal, Vx Unknown)
				$X_{fy,prior,k}$	$k_{n,unknown}$	$X_{fy,exp,k}$	$X_{fy,prior,d}$	$k_{d,n,unknown}$	$X_{fy,exp,d}$
Nominal	S355	B	101	394.05	1.64	366.06	365.65	3.04	331.02
Restricted	S355	B	71	394.05	1.64	385.38	365.65	3.04	353.59
Nominal	S355	C	29	382.95	1.73	354.28	355.35	3.46	306.17
Restricted	S355	C	18	382.95	1.79	384.96	355.35	3.81	343.30
Nominal	S275	B	23	313.50	1.75	294.94	291.50	3.58	259.59
Restricted	S275	B	54	313.50	1.64	320.61	291.50	3.04	282.85
Nominal	S275	C&D	17	302.10	1.81	264.42	280.90	3.90	213.14
Restricted	S275	C	18	302.10	1.79	318.09	280.90	3.81	266.86
Restricted	S235	B	5	267.90	2.33	226.68	249.10	7.85	1.32
Restricted	S235	C&D	11	256.50	1.90	270.14	238.50	4.42	238.44

Table A3
Statistical distribution metrics for ultimate strengths by grading scheme.

				Ultimate Tensile Strength							
				Mean			Standard Deviation			Coefficient of Variation	
Grading System	Grade	Thickness Group	# Pieces	Prior Mean Ultimate Strength	Experimental Mean	Experimental Mean p-value	Prior Standard Deviation	Experimental Standard Deviation	Experimental Standard Deviation p-value	Prior Coefficient of Variation	Experimental Coefficient of Variation
				$X_{fu,prior,m}$	$X_{fu,exp,m}$		$\sigma_{Xfu,prior}$	$s_{Xfu,exp}$		$V_{Xfu,prior} = \sigma_{Xfu,prior} \,/\, X_{fu,prior,m}$	$V_{Xfu,exp} = s_{Xfu,\mathrm{exp}} \,/\, X_{fu,exp,m}$
Nominal	S355	B	101	540.50	529.88	7.97E-07	21.62	24.15	9.42E-02	0.040	0.046
Restricted	S355	B	71	540.50	541.56	6.79E-01	21.62	19.72	3.17E-01	0.040	0.036
Nominal	S355	C	29	540.50	521.21	1.54E-06	21.62	15.20	2.35E-02	0.040	0.029
Restricted	S355	C	18	540.50	528.17	1.55E-02	21.62	13.21	1.88E-02	0.040	0.025
Nominal	S275	B	23	492.00	478.52	8.60E-03	24.60	17.86	6.98E-02	0.050	0.037
Restricted	S275	B	54	492.00	502.56	1.62E-03	24.60	23.80	7.85E-01	0.050	0.047
Nominal	S275	C&D	17	492.00	466.59	2.05E-05	24.60	13.24	5.41E-03	0.050	0.028
Restricted	S275	C	18	492.00	501.67	9.55E-02	24.60	22.05	6.18E-01	0.050	0.044
Restricted	S235	B	5	432.00	455.00	1.73E-02	21.60	10.20	1.48E-01	0.050	0.022
Restricted	S235	C&D	11	432.00	460.00	1.71E-05	21.60	7.97	1.40E-03	0.050	0.017

Table A4
Characteristic and design values for ultimate strength by grading scheme.

				Ultimate Tensile Strength					
				Characteristic Value			Design Value		
Grading System	Grade	Thickness Group	# Pieces	Prior Characteristic Ultimate Strength	[EN1990 Table D.1] Vx Unknown: kn	Experimental Characteristic (Normal, Vx Unknown)	Prior Design Ultimate Strength	[EN1990 Table D.2] Vx Unknown: kd,n	Experimental Design (Normal, Vx Unknown)
				$X_{fu,prior,k}$	$k_{n,unknown}$	$X_{fu,exp,k}$	$X_{fu,prior,d}$	$k_{d,n,unknown}$	$X_{fu,exp,d}$
Nominal	S355	B	101	507.60	1.64	490.27	470.00	3.04	456.45
Restricted	S355	B	71	507.60	1.64	509.23	470.00	3.04	481.63
Nominal	S355	C	29	507.60	1.73	494.86	470.00	3.46	468.60
Restricted	S355	C	18	507.60	1.79	504.50	470.00	3.81	477.80
Nominal	S275	B	23	455.10	1.75	447.24	422.30	3.58	414.57
Restricted	S275	B	54	455.10	1.64	463.53	422.30	3.04	430.21
Nominal	S275	C&D	17	455.10	1.81	442.65	422.30	3.90	414.94
Restricted	S275	C	18	455.10	1.79	462.15	422.30	3.81	417.57
Restricted	S235	B	5	399.60	2.33	431.24	370.80	7.85	374.95
Restricted	S235	C&D	11	399.60	1.90	444.82	370.80	4.42	424.73

Data availability

Research Link Provided: https://doi.org/10.5281/zenodo.19000366

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