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Report on the suitability of materials and components to be used in a new design situation

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Executive summary

This deliverable aims to summarize the phenomena influencing reusability of structural steel and steel-based components in order to establish a scientific basis for development of verification and approval procedures. Reusing steel components in a new construction or in the same, but in different design situation compared with the initial one has to face the challenge of identification and evaluation of the effects of different deterioration processes such as ageing and weathering, time-variant loadings, and maintenance and repair interventions, among others, all of them inducing uncertainty in characterization of material and geometrical properties and definition of physical models. First, material properties (based on Task 2.3) and acceptability criteria (in terms of geometrical imperfections, based on Task 2.4) have to be defined to enable or limit the potential reuse of these components. Secondly, definition and classification of reusing situations will be proposed, with associated acceptability criteria for the steel products.

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Notation

The notation follows that of the Eurocodes and relevant European Standards, where possible.

Lower cases

f_u	Tensile strength
f_y	Yield strength

Upper cases

D	Damage level
E	Young's modulus
H_v	Vickers hardness
N_f	Fatigue life
R_{eH}	Yield strength from testing or relevant product standard
R_m	Ultimate strength from testing or relevant product standard
T	Time

Greek letters and symbols

Δe	Decrease in elongation as a result of strain ageing
ΔU	Increase in tensile strength as a result of strain ageing
ΔY	Increase in yield strength as a result of strain ageing
ε	Strain
ε_f	Elongation at failure
ε_n	Local elongation
ε_u	Uniform elongation
γ_{M0}	Partial factor for resistance of cross-sections
γ_{M1}	Partial factor for resistance of members to instability
γ_{M2}	Partial factor for resistance of cross-sections in tension to fracture
σ	Stress

Abbreviations

ASTM	American Society for Testing and Materials
CC	Consequence Class
CEN	European Committee for Standardisation
CHS	Circular Hollow Sections
CPR	Construction Products Regulation

DP	Dual Phase
DoP	Declaration of Performance
DT	Destructive Testing/Test
DWP	Design Working Period
EN	European Norm
ETA	European Technical Assessment
EXC	Execution class
HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue
LYP	Low Yield Point
LSDM	Limit State Design Method
MW	Mineral wool
NA	National Annex(es)
NAD	National Application Document
NDT	Non-Destructive Testing/Test
ODS	Ozone Depleting Substances
PC	Production Category
PF	Phenolic Foam
PIR	Polyisocyanurate
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinylchloride coating
PVDF	Polyvinylidene fluoride paint coating
RHS	Rectangular Hollow Sections
SA	Special Assessment
SC	Service Category
SLS	Serviceability Limit State(s)
ULCF	Ultra-Low Cycle Fatigue
ULS	Ultimate Limit State(s)
Axes	
x	Longitudinal axis along the member
y	Major axis (parallel to flanges)
z	Minor axis (parallel to web)

1. Introduction

1.1 General

This report is deliverable D2.2 of the *PROGRESS* project. It covers the work carried out under Tasks 2.3 and 2.4, and will serve as a basis to produce an affordable specification/protocol for testing reclaimed structural steel that can be accepted by the authorities and therefore solve the current liability problem, which has been identified as a key question to be answered if reclaimed steel is to be incorporated into current and future projects. Ultimately, the designers have to trust that they will work with undamaged, clean and certified reclaimed steel sections for (re)use in new buildings.

The general reuse framework developed by Durmisevic [1] was adapted and extended in the scope of *PROGRESS* to show different material flows and distribution chains, see deliverable D1.2 [2] and Figure 1. This basic classification of the salvaged components and structures is in line with the terminology from EN 1090-2:2018 [3]: (i) the components are produced from the constituent products, and (ii) then assembled into a structure. Reuse can be considered at all structural levels, i.e. (i) constituent product, e.g. individual members, (ii) structural component, e.g. sandwich panel, or a truss system, and (iii) whole structure or part of it, e.g. single bay of a multi-span building.

The objective of the current work is to establish a basis for design recommendations concerning the various adaptation/modification options to implement the reclaimed building components either in-situ or in a new building design. Acceptability criteria in terms of geometry, member condition and material properties are defined to enable or limit the potential reuse of these components.

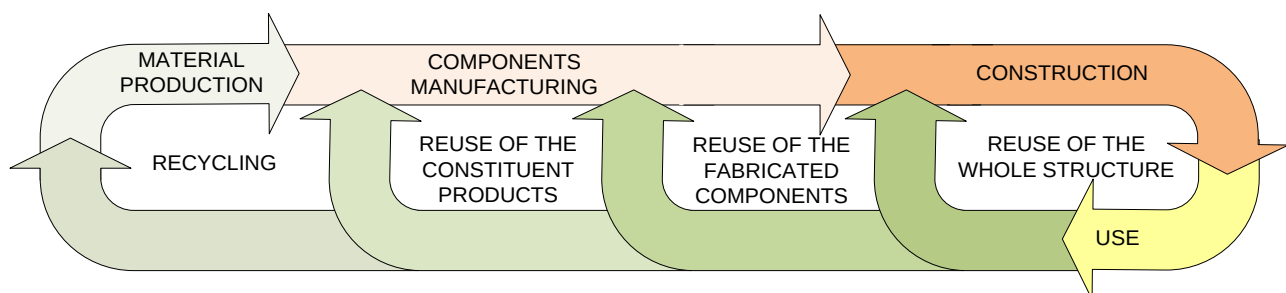


Figure 1. General description of material flows

1.2 Scope of reuse of structural steel

Using reclaimed structural steel on a project is an effective strategy to reduce the environmental impact of a building by eliminating the energy required to recycle scrapped steel into new structural sections. This practice cannot be generalised to all structural steel though, as not all components can be effectively reused.

PROGRESS focuses on single-storey buildings, and within this project, the reuse scenarios can be broadly divided into three categories: (i) entire primary structure, (ii) components (elements of the primary structure), and (iii) individual members, and may involve or not relocation. The scope of physical reuse of structural steel, in all scenarios, is limited to, see also Section 2:

- Damage-free building structures, i.e. structural members that have not been subjected to extreme-event limit states, e.g. large-scale earthquake, fire, or to fatigue etc.,
- Members to be reused shall not have areas of accelerated localised corrosion or show evidence of localised section loss,
- All members to be reused should come from a building structure (never from bridge structures, in order to preclude fatigue loading history) constructed after 1970, which is about the time when the Limit State design philosophy became common practice in Europe,
- All salvaged members considered as constituent products are continuously rolled. Welded and built-up members are not included in the scope of reuse as constituent products,
- For members to be reused, they must be recovered in as much of its original intact length as possible for design freedom (design with reclaimed steel may require some modification to the overall design to make best use of available materials).

Functional reusability requirements are set out in Sections 4 to 8. The two other key areas that support the decision-making process for reuse of structural steel are (i) economic value for reuse, and (ii) environmental advantage, and are not covered in this report.

1.3 Identified challenges

Reuse of structural steel offers great potential for reducing the environmental impact of the steel construction industry by reducing the significant CO₂ emissions and energy demands associated with steel production and/or recycling. Single-storey buildings are particularly attractive for reclaiming and reusing structural steel because these structures (i) typically lack fire proofing, (ii) use dry and lean construction systems that facilitate the deconstruction system, and (iii) are low occupancy structures. Before these benefits can be fully realised, there are significant challenges that need to be addressed, particularly concerning adequacy and reliability assessment of the reclaimed steel, that ultimately ensure that:

- The reclaimed material satisfies the performance requirements, which are essential for the mechanical, physical, dimensional, and/or other relevant properties of steel materials to ensure their adequacy to be used in structural design to EN 1993-1-1 [4],
- The salvaged material meets the quality requirements from nominal specifications to ensure their reliability to be used in the structural design to EN 1993-1-1 [4].

The assessment of the steel structure condition by using different testing techniques is thus crucial. The potential techniques are identified in the next section.

1.4 History of steel in products and design standards and codes

The knowledge of structural steel history is important if reuse of components is to be adopted. During the 1970s, essentially our starting point for potential steel reuse within the scope of this report, European countries issued detailed descriptions of material, e.g. chemical composition, physical and mechanical characteristics, to ensure the supplies met certain quality country-specific standards, as can be seen in Figure 2. During the first decade of the 21st century, incompatible standards and certification were recognised as barriers for the European Union economy, and therefore the need for harmonisation emerged.

	Austria	Belgium	Finland	France	Germany	Italy	The Netherlands	Norway	Portugal	Romania	Spain	Sweden	UK
EN 10025-2:2004	Product Standards: Equivalent former designations corresponding to EN 10025-2												
	EN 10025:1990 +A1:1993	EN 10025:1990											
	M 3116	NBN A 21-101	SFS 200	NF A 35-501	DIN 17100	UNI 7070	Euronorm 25-72	DIN 17100	NP 1729	STAS 5002-76	UNE 36-080	SS followed by number steel grade	BS 4360
	S235JR	Fe 360 B	AE 235-B	E 24-2	St 37-2	Fe 360 B	Fe 310 0	St 37-2	Fe 360-B	OL37-1/1a/1b	AE 235 B-FU	13 11-00	
	S235JRG1	Fe 360 BFN			USI 37-2	Fe 360 A	Fe 360 A	USI 37-2					
	S235JRG2	Fe 360 BFN	Fe 37 B		RSI 37-2	Fe 360 BFN	Fe 360 BFN	RSI 37-2		OL37-2	AE 235 B-FN	13 12-00	40 B
	S235J0	Fe 360 C	AE 235-C	E 24-3	St 37-3 U	Fe 360 C	Fe 360 BFN	St 37-3 U	Fe 360-C		AE 235 C		40 C
		Si 360 CE					Fe 360 CFN			OL37-3k3kf			
	S235J2G3	Fe 360 D1	Fe 37 D	E24-4	St 37-3 N	Fe 360 D	Fe 360 DFN	St 37-3 N	Fe 360-D	OL37-4kf	AE 235 D		40 D
	S235J2G4	Fe 360 D2											
EN 10025-2:2004	S275JR	Fe 430 B	AE 255-B	E 28-2	St 44-2	Fe 430 B	Fe 430 A	St 44-2	Fe 430-B	OL44-2k	AE 275 B		43 B
	S275J0	Fe 430 C	AE 255-C	E 28-3	St 44-3 U	Fe 430 C	Fe 430 BFN	St 44-3 U	Fe 430-C		AE 275 C		43 C
		Si 430 CE					Fe 430 CFN			OL44-3k3kf			
	S275J2G3	Fe 430 D1	Fe 44 D	E 28-4	St 44-3 N	Fe 430 D	Fe 430 DFN	St 44-3 N	Fe 430-D		AE 275 D		43 D
	S275J2G4	Fe 430 D2								OL44-4kf			
	S355JR	Fe 510 B	AE 355-B	E 36-2		Fe 510 B	Fe 510 BFN		Fe 510-B	OL52-2k	AE 355 B		50 B
	S355J0	Fe 510 C	AE 355-C	E 36-3	St 52-3 U	Fe 510 C	Fe 510 CFN	St 52-3 U	Fe 510-C		AE 355 C		50 C
	S355J2G3	Fe 510 D1	AE 355-D		St 52-3 N	Fe 510 D	Fe 510 DFN	St 52-3 N	Fe 510-D	OL52-3k3kf	AE 355 D		50 D
	S355J2G4	Fe 510 D2											
	S355K2G3	Fe 510 DD1	AE 355-DD	E 36-4			Fe 510 DDFN		Fe 510-DD	OL52-4kf			50 DD
	S355K2G4	Fe 510 DD2											
Codes of Practice for the Design of Steel Structures: Equivalent former designations corresponding to EN 1993													
EN 1993:2005													
	ENV 1993-1-1:1992	ONORM B 4300	Rakennus-määräys-kokoelma B7	Règles CM66	DIN 1880		NEN 6770, part 2 (1997-2012)	NS 3472: 1984	REAE, Decreto n.º 46160	STAS10108/0-78	NBE MV 10X and 11X series (before 1996)	BSK 99 Handbooks SIBK-NX, X = 1, 2, 3, 4, 5	BS 5950 (after 1985) BS 449 (before 1985)
		NBN 212:1970 and NBN E 27-071:1987					NEN 6770, part 1 (1990-1997)	NS 3472: 2001			NBE EA-95 (after 1996)		
							NEN 3851 (1972-1990)						
							N 1055 (1955-1972)						

Figure 2. National product and structural design standards before 2004

The design basis according to limit state principles coincides with the introduction of plastic design of portal frame structures in the early 1970's. At this time, the mild steel used in constructional work has been confirmed for its mechanical properties, compared to early cast iron or wrought iron and even steels used at the beginning of the 20th century, with a larger domain for the resistances that had to be taken into account in the design. In the UK it took 15 years to publish the first version of the steelwork design code BS 5950 [5] in 1985, while the first one is known to be applied in Canada [6] since 1974. In Romania, Limit State Design method for steel design has been introduced in 1978 through the National Standard STAS 101008-0-78 (Design of Structural Steel Members) [110].

The vast data recorded from the uptake of mild steel as a construction material made possible the transition from the permissible/allowable stress design to a superior design method, the Limit State Design Method (LSDM). While the design philosophy using permissible stress can be applied to the resistance of an element subjected to an internal force or a combination of internal forces, the LSDM considers separately the load cases, the material and the element strength. In the LSDM, the probabilistic computation allows consideration of different variations for loads (live load usually varies more than permanent load) and for strengths of different materials through the use of separate safety factors for each load case and for each material type, respectively.

Because the first draft of the British steel design code according to the LSDM was based on the design code of permissible/allowable stress design and calibrated to give the same results, it attracted more criticism that latter forced the studies [9] to obtain a simplified method or to offer a greater economy. The study leads to a calibration of the material safety factor from 1.075 to 1.0.

Simultaneously, the Commission of the European Community decided to act in the field of construction and establish a set of technical rules for the design of construction works. The first set of Eurocodes were available in the 1980s. In the first stage, the individual codes were published as European Pre-standards, with the indicative ENV. After a test period for comments and amendments, these were converted into EN standards.

Generally, the LSDM checks the conformance of the structure to limiting conditions (or limit states) regarding resistance and deformations. The two situations are grouped under the nomenclature of Ultimate Limit State (ULS) and Serviceability Limit State (SLS), respectively [10]. The ULS verifications concern states beyond which the increase of load cannot be sustained, relating to life safety, and therefore the conditions must be fulfilled in a compulsory manner. On the other hand, the SLS verifications relating to the conditions for appearance of non-structural components, a proper equipment functioning or comfort of building occupants, are subjective or particular, and therefore are often not mandatory.

This is the reason why all members/structures to be reused should come from a building structure constructed after 1970, which is about the time when the LSDM philosophy became common practice in Europe and the mild steel used in constructional work has been confirmed for its mechanical properties.

The first European code for the design of steel structures was issued in 1992, as a Pre-standard ENV 1993-1-1:1992 [7], and was developed by the European Committee for Standardisation (CEN). It was intended to serve as a framework for drawing up harmonised prescriptive technical specifications for construction products in the various European countries, in conjunction with a National Application Document (NAD) valid in the country where the building was located. It had, as such, no legal standing of its own until it was officially adopted by the specific country. As time progressed,

this Pre-Standard was converted into a European Norm (EN) and the NADs became National Annexes (NA), and as of 2005~2010 is widely applied in all European countries and have generally replaced National Structural Design Standards.

The designation of steel products in current EN 1993 is in accordance with EN 10025-2:2004 [8]. For a list of corresponding former national designations and the former designations from EN 10025:1990 and EN 10025:1990+A1:1993, which were superseded by the 2004 edition, see Figure 2.

1.5 Terms and definitions

For the purposes of this report, the following terms and definitions apply, with specific reference to single-storey buildings.

Component	Part of a steel structure, which may itself be an assembly of several smaller components
Consequences classes	Classification based on the consequences of failure or malfunction of the structure; different reliability indices are associated with each consequences class
Constituent product	Materials or products used in manufacturing with properties which enter into structural calculations or otherwise relate to the mechanical resistance and stability of works and parts thereof, and/or their fire resistance, including aspects of durability and serviceability
Execution class	Classified set of requirements specified for the execution of the works as a whole, of an individual component or of a detail of a component
Primary structure	The primary steel frame, consisting of columns, rafters and bracing
Secondary structure	The secondary steelwork, consisting of side rails and purlins for the walls and the roof respectively

2. Parameters influencing reuse of structural steel

2.1 General

Reuse of steel components or entire structures can offer greater environmental and economic advantages, when compared to the recycling option. The reclaimed structural steel market is still small, but there is significant scope for growth. In various other situations, repair and rehabilitation of partially damaged steel structures or in-situ reuse are implemented in place of demolishing the structure and constructing a new one. From this point of view, a certain degree of standardisation is necessary.

There are three types of structural deficiencies that need careful consideration when assessing a steel building or structural component [11]: (i) deterioration, (ii) defects, and (iii) damage. Deterioration is the reduction in material property characteristics and/or size due to exposure conditions, e.g. steel corrodes under adverse exposure conditions and this may threaten safety and performance through loss of material or through perforation by pitting. A defect is a reduction in structural capacity due to inadequate design, or variation from the design intent during construction, leading to the visible manifestation of loads exceeding the structural capacity or to failure of elements or systems due to material deficiency and/or material behaviour which was not designed for or accommodated in construction, e.g. excessive deflections. Damage is the result of extraordinary loads which could not reasonably be foreseen or designed for, e.g. seismic loading.

Steel undergoes no major changes in time, except for rust or plastic deformations. Rust problems can be avoided by means of appropriate corrosion protection that usually includes surface preparation and application of paint systems or metallic coatings by means of thermal spray or galvanizing. Plastic deformations from loading cannot always be avoided and may cause partial damage in structural members. For completeness, the age-related phenomena are listed below and commented in various sub-sections.

Ageing of material is gradual (due to time or use) deterioration of mostly mechanical and physical properties. There are two basic types of ageing: (i) thermal ageing embrittlement, and (ii) strain ageing. Thermal ageing embrittlement represents a process of change of material properties due to the disintegration of oversaturated solid ferrite solution over a long period of time without any external mechanical load. It manifests especially in low carbon steel, namely up to 0.2% Carbon, and gradually leads to (i) decreased ductility, notch toughness and fracture toughness of the material, (ii) increased transition temperature, and (iii) increased lower and upper limit of notch toughness. Strain ageing refers to a process consisting of material property changes after and/or during plastic deformation. There are two types of strain ageing: (i) static strain ageing, e.g. foundation settlement, where material properties change after plastic deformation, and (ii) dynamic strain ageing, e.g. large-scale earthquakes), where material properties change during deformation. Strain ageing mainly affects the mechanical characteristics as follows: (i) the yield strength measured after ageing is higher, (ii) the ultimate strength can also increase, and (iii) ductility and percentage reduction of area after fracture decrease. The two phenomena are frequently considered in combination and so the term ageing is used below interchangeably.

Fatigue is defined as a process of cycle-by-cycle accumulation of damage in a material undergoing fluctuating stresses and strains. A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after a certain number of load fluctuations have been

experienced, i.e. after the accumulated damage has reached a critical level. For example, crane runaway girders are fatigue-prone structures.

Steel may creep, i.e. may experience slow plastic deformations, at high (constant) temperature, under time-dependent constant external stress. The creep strength in the range of temperatures where creep applies is always lower than the material yield strength.

2.2 Age-related phenomena

Ageing is known to cause an increase in yield strength and ultimate tensile strength, while tensile elongation capacity will be less in aged steel. The phenomenon was first observed during the 19th century when the maximum load carrying capacity of a test piece was increased after it had been retested, following a previous series of testing in the plastic range. Over the last 50 years, a vast range of research has shown that all structural steels are potentially susceptible to ageing. Naturally, this behaviour is also significantly affected by the steel chemical composition and the method of production.

When steel is strained (deformed plastically) and then allowed to age, it is subjected to what is known as strain ageing. Figure 3 shows the typical stress-strain curve for mild steel (low-carbon steel) compared with that for the same steel pre-strained up to point B and then subjected to ageing. As a result of the strain ageing, the yield strength and the tensile strength were increased by ΔY and ΔU respectively, and the elongation was decreased by Δe . In general, ageing increases strength to some extent but results in a loss of ductility [12]. The increase of yield stress and the decrease of uniform elongation are smaller for steels with greater yield stress [13]. However, if the sample is allowed to rest before retesting, the yield point will return [14].

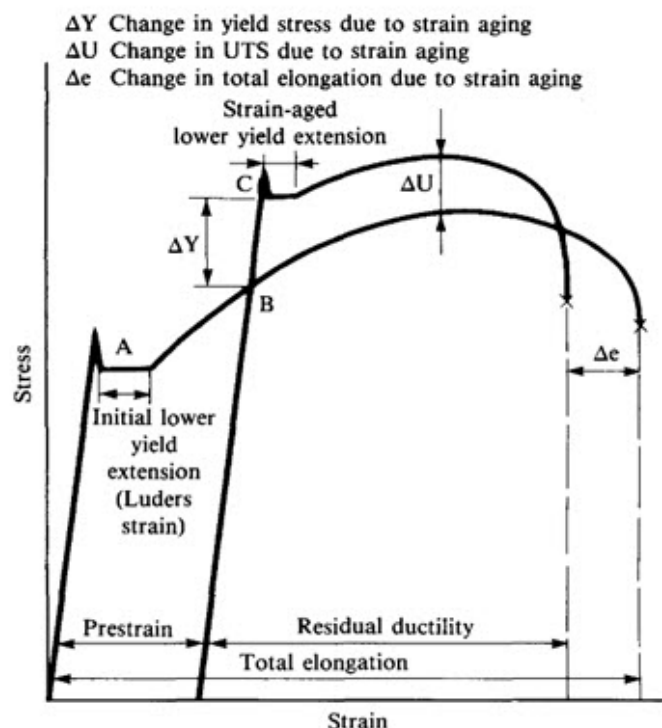


Figure 3. The influence of strain ageing on the stress-strain curve for mild steel [12]

Unknown until the first quarter of the XXth century, another important side effect of cold strain is the loss of toughness that results in brittle fractures. While it was understood that brittle fractures were associated with low toughness in steels, the causes and mitigation of these fractures was not very well understood until ground-breaking research on ship hull fractures, undertaken during World War II. From these studies came an understanding that steels underwent a transition in toughness with temperature and that this transition could be measured by the Charpy impact test, see Figure 4 and Refs.[15] and [16].

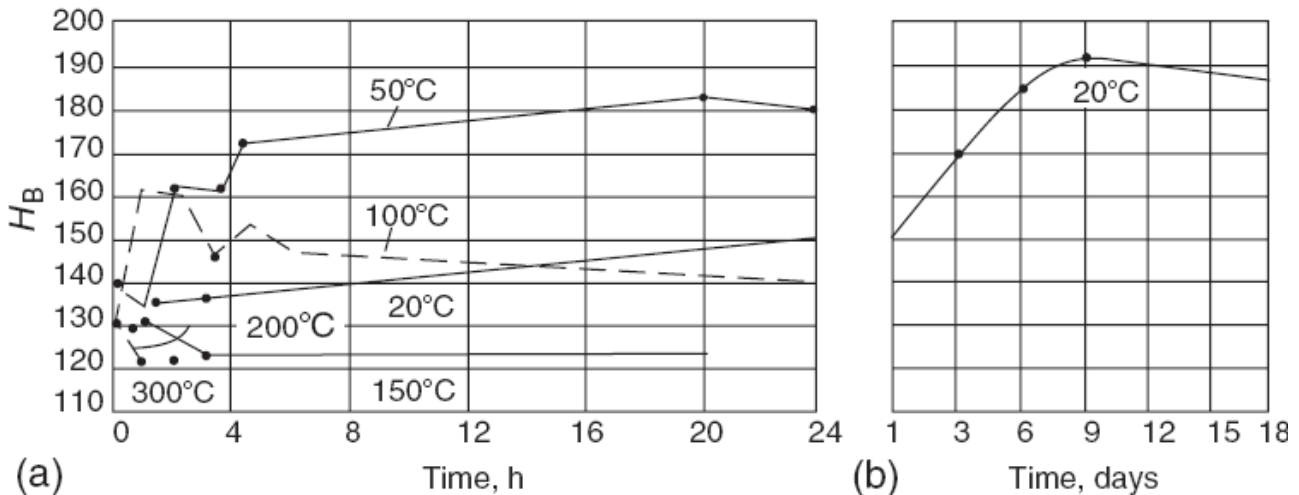


Figure 4. The ageing temperature dependence of hardness of carbon steel [15]

Zamani et al. [17] studied the natural ageing behaviour of a low carbon Dual Phase (DP) steel and the effect of martensite content was taken into account. The enhancement of strength and hardness by ageing at room temperature was related to quench ageing via the formation of fine precipitations in the ferrite grains. It was revealed that increasing the inter-critical annealing temperature diminishes this precipitation hardening effect. The maximum quench ageing effect was observed by annealing the ferritic-pearlitic steel at a subcritical temperature close to the eutectoid temperature, where the solute carbon content of ferrite reaches the maximum value. However, in contrast to aged DP steels, the tensile stress-strain curves showed yield-point phenomenon. The ageing effect was rationalised by the Ashby-Orowan relationship and the effect of the silicon in the chemical composition of the studied steel was discussed.

The whole effect of ageing on the strength properties of alloys is determined by (i) the strength of the precipitates that form, (ii) the volume fraction of precipitates, (iii) the degree of precipitate dispersion, (iv) morphology, structure, and type of binding with the matrix, and (v) test temperature [15].

Cold plastic deformation greatly accelerates precipitation of a supersaturated solid solution. This is due both to an increase in the density of dislocations, which are preferable sites of heterogeneous nucleation of precipitates, and to an increase in the concentration of vacancies, which facilitates the diffusion of carbon to clusters. The phenomenon has also been observed in other ageing alloys. Mechanical properties change during ageing after cold deformation in the same way as after quenching, see Figure 5. That is, the yield stress, the fracture stress, and hardness are modified. With an increase in ageing time, specific elongation and reduction of area decrease and the tendency to brittle fracture is enhanced.

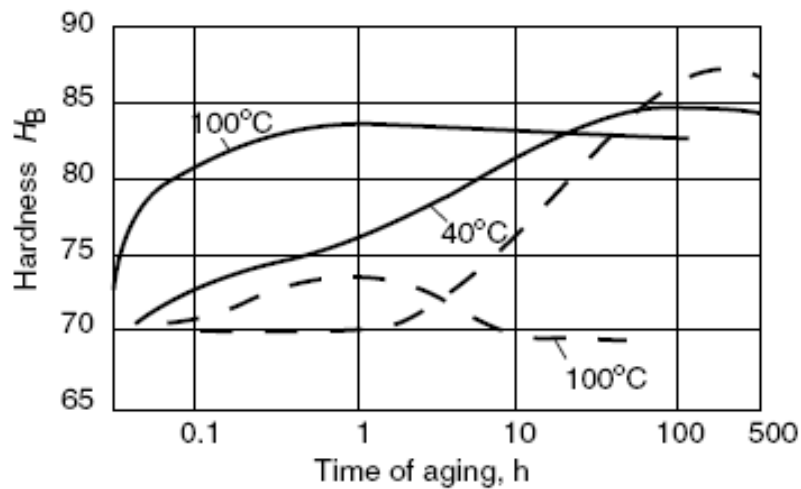


Figure 5. Ageing after quenching (dashed lines) and after 10% cold deformation (continuous lines) [15]

Another effect of ageing may be considered for painted galvanised steel. The effects of thermo-mechanical degradation on the protective properties of coil coated samples are analysed in [18]. The ageing procedure and the electrochemical measurements were useful to evaluate the barrier and adhesion properties for the various coating formulations and to define the influence of the different strain levels.

Hosseini et al. [19] investigated the changes in mechanical properties of partially damaged steel material due to strain ageing, on coupon specimens of Grade 350 mild steel plates. The effect of strain ageing on the ultimate strength, f_u , uniform strain, ϵ_u , and fracture strain, ϵ_f , was also investigated. Two-stage loading case was applied. During stage I, the specimen was subjected to uniaxial tensile loading until partial damage occurred in the specimen. Since the damage level may affect the mechanical properties of the material, three different damage levels D of 1.5%, 13% and 19% strain were considered. $D = 1.5\%$ represented the strain close to the onset of strain-hardening whilst $D = 19\%$ represented the uniform strain. As soon as the magnitude of the strain reached the pre-defined damage level the test was terminated. After a lapsed time T , the specimen then underwent stage II testing in which uniaxial tensile loading was applied to the specimen to failure. Three levels of lapsed time including $T = 0$ (no-age), $T = 2$ days and $T = 7$ days, were examined so that the effect of the strain ageing on the partially damaged materials was studied.

Figure 6 illustrates the influence of ageing on the material behaviour depending on the damage level, see, as an example, the cases of samples damaged to 13% (Figure 6b) and 19% (Figure 6c). For higher damage levels, the effect of strain ageing is greater. The ultimate stress may increase up to 40% whilst the reduction in ultimate strain might be up to 80%.

Settlements of the supports represent a common case of ageing process that cause plastic deformations in steel structures. It is known that during the lifetime of a structure, especially in areas with softer soils, there may be relative displacements between points less than 5 m apart. These actions have different duration in time, either years or several minutes. The settlements of the supports induce high internal forces in the structure, which represent the first stage of an ageing process. If the structure is not subjected to other loads, e.g. snow, wind or temperature, the structure is considered to be at rest and the material of the structure is able to age. If the loading actions presented

before will not act in the same time with the settlement of the supports, the resistance of the base material for the structure will be increased but the ultimate elongation will be decreased. Function of the plastic deformation of the material caused during the settlements of the support, the structure will be able to withstand a higher load but the deformation criteria for plastic analysis that are requested for seismic design, should be assessed as well as the bearing ratio between structural elements. Since in seismic design a minimum ultimate elongation limit must be satisfied, the effect of ageing should be assessed.

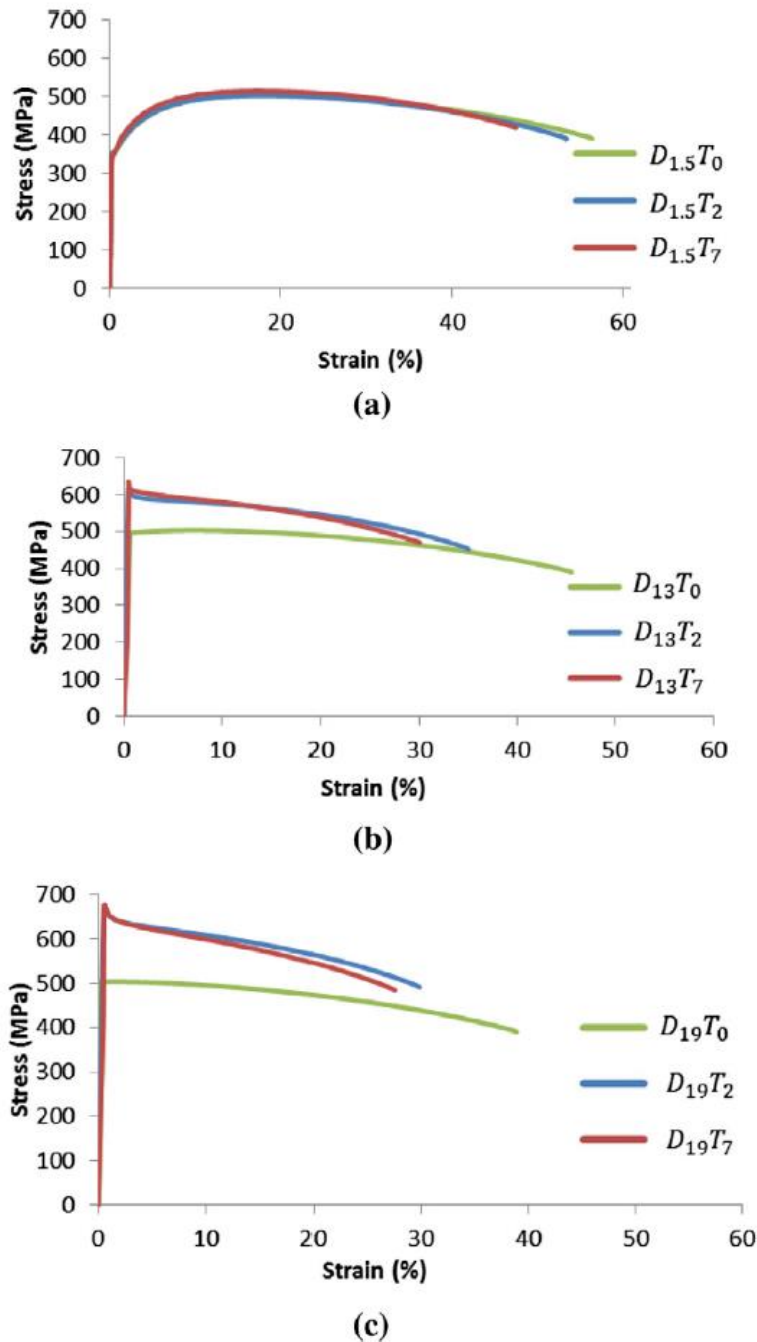


Figure 6. Stress–strain curves at (a) 1.5% damage level (b) 13% damage level (c) 19% damage level [19]

For industrial buildings with transport machinery, accidental crushes are encountered. The accidental load may affect the structure locally, on individual elements or, due to redundancy of the structure, it may affect parts of the structure. Function of the crush intensity, the plastic deformation required for the first stage of ageing process, may be attained. If the situation is not assessed / repaired in following period, the affected material continues to age.

Also, the seismic action itself affects the structures and since most of the economical designs are performed with a behaviour factor “ q ” greater than 2, meaning that plastic hinges are allowed to develop in order to dissipate the energy, the areas of the plastic hinge may also be affected by ageing. Most of the interventions after a major earthquake are not performed immediately so the strain ageing is initiated.

2.3 Fatigue

Fatigue is a progressive, localised, and permanent structural change that occurs in a material when subjected to repeated or fluctuating strains at nominal stresses that have maximum values less than (and often much less than) the tensile strength of the material. Fatigue may lead to cracks and cause fracture after a sufficient number of fluctuations [20].

Originally, fatigue was considered to be a fracture phenomenon occurring after a large number of load cycles where a single load of the same magnitude would not do any damage. In the XIXth century, it was considered to be mysterious that a fatigue fracture did not show visible plastic deformation. It was recognized that small radii in the geometry of the structure should be avoided. In 1903 Ewing and Humfrey [21] performed a microscopic investigation which showed that fatigue crack nuclei start as microcracks in slip bands. In his review, Timoshenko [22] discussed the significance of stress distributions and emphasized stress concentrations around notches. However, some basic concepts remained, such as that fatigue in metallic materials is due to cyclic slip, and stress concentrations contribute to a reduced fatigue endurance. The three aspects presented previously, large number of loading cycles, stress concentration and crack initiation, are encountered for the steel structures affected by fatigue.

The American Society for Testing and Materials (ASTM) defines fatigue life, N_f , as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs [23]. As a function of the number of cycles to failure, fatigue was divided in two categories [24]: High Cycle Fatigue (HCF) and Low Cycle Fatigue (LCF) if the failure occurs after 10^4 cycles or before, respectively. In recent studies, if the number of cycles to failure is less than 20 cycles, the term extremely low cycle fatigue is used [25]. Usually, HCL refers to cases where the stresses are within the limit of elastic range, and the materials performance is commonly characterised by an $S-N$ curve, also known as a Wöhler curve [26].

For design purposes, the fatigue is assessed using EN 1993-1-9:2005 [27], by means of (i) the damage tolerant method, or (ii) the safe life method. The damage tolerant method should give an acceptable reliability that a structure will perform satisfactorily for its design life, provided that a prescribed inspection and maintenance regime for detecting and correcting fatigue damage is implemented throughout the design life of the structure. The safe life method should provide an acceptable level of reliability that a structure will perform satisfactorily for its design life without the need for regular in-service inspection for fatigue damage. The safe life method should be applied in cases where local formation of cracks in one component could rapidly lead to failure of the structural element or structure.

During cyclic loading, the stress-strain relationship can usually be described by a loop, such as that shown in Figure 7. For purely elastic loading, the loop becomes a straight line with a slope equal to the Young's modulus E of the material. The occurrence of a hysteresis loop is the most common case. A series of fatigue tests, each having a different total strain range, will generate a series of hysteresis loops. For each set of conditions, a characteristic number of strain reversals is necessary to cause failure [20].

The application of fatigue data in engineering design is not straightforward given (i) the inherent scatter of fatigue data, (ii) the variations in surface conditions of actual parts, (iii) the variations in manufacturing processes such as bending, forming, and welding, and (iv) the uncertainty of environmental and loading conditions in service. Despite the scatter of fatigue data, it is possible to estimate service life under cyclic loading. It is essential to view such estimates for what they are, that is, estimates of the mean or average performance, and to recognise that there may be large discrepancies between the estimated and actual service lives [20]. The model that is mainly used to obtain a nonlinear relation for the material behaviour function of the cyclic tests is presented in [28]. The Ramberg-Osgood equation was derived to describe the nonlinear relationship between stress and strain, i.e. the stress-strain curve, in materials near their yield points. It is especially useful for metals that harden with plastic deformation. Prediction models for the cyclic life of materials are thus often based on the alternating plastic strain amplitude. In this regard, the most commonly used relationship between the alternating plastic strain and the life cycles is the so-called Manson-Coffin law [29].

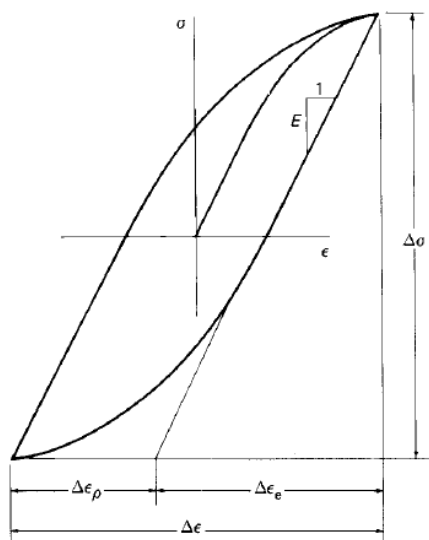


Figure 7. Stress-strain hysteresis loop [20]

LCF tests were performed using non-European steel grades for either carbon steel e.g. GR345 ($f_y = 345$ MPa), HPS485 ($f_y = 485$ MPa) and HT440 ($f_y = 440$ MPa) or Low Yield Point (LYP) steels, showing similar LCF life [30]. In [31], axial and bending tests showed similar strain-life relationships for (i) carbon steels S235JRH ($f_y = 235$ MPa), S355J2H ($f_y = 355$ MPa), and (ii) cold-formed stainless steel EN 1.4301 ($f_y = 210$ MPa) and 1.4307 ($f_y = 205$ MPa), despite of their elongations at fracture in monotonic tensile tests. A comparison between two structural steels S960QL ($f_y = 960$ MPa) and S355J2 ($f_y = 355$ MPa) subjected to loadings in the domain on LCF showed similar fatigue life under higher values of total strains amplitude, but the fatigue life under strains amplitude lower than 0.5%, is greater for S960QL steel [32]. S185 steel ($f_y = 300$ MPa) was investigated for the Ultra-Low Cycle Fatigue (ULCF) behaviour on notched specimens [33]. Starting from LCF parameter assessment

and modification of existing models, satisfactory predicted results were obtained in the domain of ULCF. Steel grades X52 ($f_y = 360$ MPa), X60 ($f_y = 415$ MPa) and X65 ($f_y = 450$ MPa) used for seamless pipes were studied for their response to monotonic, LCF and ULCF behaviour, resulting in the need for multiaxial stress/strain parameters [34].

In case of particular structures subjected to high alternating stresses and with a less problematic stability, e.g. cranes, the use of high strength steel is preferred. The means of connection between elements made from these steels is of concern, and therefore studies have been conducted on the response of welds to LCF showing a good performance with respect to the provisions of the welding standards [35].

Simple steel frame damage predictions under alternating loads, which correlates well with the observed behaviour in existing structures, may be found in the literature [36]. However, without the information related to the cyclic response of steel, the method is not a replacement for traditional engineering damage measures. It merely gives the engineer an additional tool that can be used to better understand the performance of their design under seismic loads [36].

Predicting the fatigue life of a metal part is complicated because materials are sensitive to small changes in loading conditions and stress concentrations and to other factors. The resistance of a metal structural member to fatigue is also affected by manufacturing procedures such as cold forming, welding, brazing, and plating, and by surface conditions, such as surface roughness and residual stresses. Fatigue tests performed on small specimens are not sufficient for an accurate evaluation of the fatigue life of a structural part. These tests are useful for rating the relative resistance of a material and the baseline properties of the material to cyclic stressing. The baseline properties must be combined with the load history of the part in a design analysis before a component life prediction can be made [20].

The large number of loads are considered for the structures with overhead cranes. Although their fatigue life is implicitly considered from the maximum load the overhead cranes become a source of an increased fatigue in case of malfunction. As in the previous case of material ageing, the settlement of the supports may induce misalignments of the crane railway. Excessive loads are then induced in the structure of the building. Therefore, a rigorous inspection of the overhead cranes and their rolling device must be performed and the effects to be assessed [37].

Another situation encountered for the buildings with overhead cranes are the local action of the crane. This situation is described by the buildings where a part of the area served by the overhead crane is used as storage and seldom used by the crane. For the area where the overhead crane is in action for longer periods, a more obvious wear of the railway is observed. Beside the higher damage risk of the runway beam of the overhead crane, such situations imply a higher concentration of loads in this area and a smaller fatigue endurance of the structural elements supporting the crane.

The second aspect regarding stress concentration must be assessed by the technological process of manufacturing the structural elements and their components. Due to the fast operation and high efficiency for the steel cutting, the plasma-based machines are used. Depending of the technique, notches may be observed along the processed side of an element. Lately, the holes for bolting are easily performed using the same technological process. Unfortunately, the holes are not perfectly circular and notches as well as a knob appear at each hole, increasing the probability of stress concentrations. Though components of connections subjected to bending (e.g. endplates), are not sensitive to these defects, if shear forces are large the fatigue life of the connection due to concentration of stresses may be limited. A more dramatic case appears for the splices, the plates being

subjected mostly to tension, the defects accumulating higher stresses. The crack initiation represents the usual cause of failures caused by fatigue. If the brackets supporting the overhead crane railway are connected to the main columns by bolts, a special attention must be paid to the fatigue of bolts. The assessment of the reliability of an existing structure aims at producing the evidence that it will function safely over a specified residual service life.

Concerning second-hand cranes, when the intention is to be reused, general guidelines are available. In case of a second-hand crane, it is essential to specify the remaining lifetime. Before the remaining life can be specified, all documentation of the crane has to be collected and analysed. Documentation of the crane normally contains inspection, maintenance, design calculations, anomaly reports, duty records, drawings, photos, interviews, material specifications, etc. The completeness of the documentation affects the reusability of the crane and how the evaluation of the remaining life is approached.

Based on the information of documentation, the remaining life of the crane can be evaluated as specified in [37]. The so-called design working period (DWP) has to be assessed, with the purpose of estimating the accumulated duty of the crane and assess its remaining life. The applied DWP calculation method should follow the original design standard as closely as possible. If the design of the crane is based on older standards, not in line with the current standards, re-calculation can be conducted in accordance with the applicable crane standards.

In cases when a second-hand crane is taken into operation and there is no information on earlier operation, the special assessment (SA) in accordance with [37] must be performed prior to taking the crane into use. The SA is a comprehensive examination and evaluation of the crane.

The reusability assessment of the crane can be completed by comparing the remaining life, determined based on the DWP procedure added by SA procedure if needed, with the thresholds expected in the new use scenario. Procedures for the dismantling, packaging, handling, transport and storage of cranes and crane components are described in section 6.2 of [37].

2.4 High temperatures

Behaviour of steel structures at high temperatures is greatly influenced by the level of creep strains that occur after reaching the temperature above one third of the melting point of steel. For structural carbon steel, this occurs after reaching the steel temperature of approximately 400°C. Generally, for simply supported steel elements with no axial restraints, the creep strain affects the vertical deflections, while in the elements which are axially restrained, the creep strain induces development of additional forces in the structure [38].

Creep is defined as time-dependent plastic deformation (elongation) of the metal at a constant tensile load. It is also defined as high temperature progressive deformation at constant stress. "*High temperature*" is a relative term dependent upon the materials involved. Creep rates are commonly used in evaluating materials for boilers, gas turbines, jet engines, ovens, or any application that involves high temperatures under load. Understanding high temperature behaviour of metals is useful in designing failure resistant systems. A creep test can be studied by measuring the permanent extension, after various time intervals, of test pieces maintained at a constant temperature. Measurements of strain are then recorded over a period of time, as can be seen in Figure 8. After an initial instantaneous extension, it shows that creep occurs in three stages:

- Stage 1 (Primary creep): this stage occurs at the beginning of the tests, and creep is mostly transiently, not at a steady rate. Resistance to creep increases until stage 2 is reached.
- Stage 2 (Secondary creep): this stage is often referred to steady state creep.
- Stage 3 (Tertiary creep): the creep rate begins to accelerate as the cross-sectional area of the specimen decreases due to necking, or if internal voiding decreases the effective area of the specimen. If stage 3 is allowed to proceed, fracture will occur.

In many cases, the three parts of the curve are not clearly distinguishable. To obtain a complete picture of the creep properties of a material, it is necessary to make creep curves for a range of stresses over a range of temperature. Such curves usually show that as the applied stress decreased the primary creep is also decreased, secondary creep is prolonged, and the possible extension during tertiary creep tends to increase, as shown in Figure 9. Very low applied stress may indicate that tertiary creep does not occur even after lengthy service life.

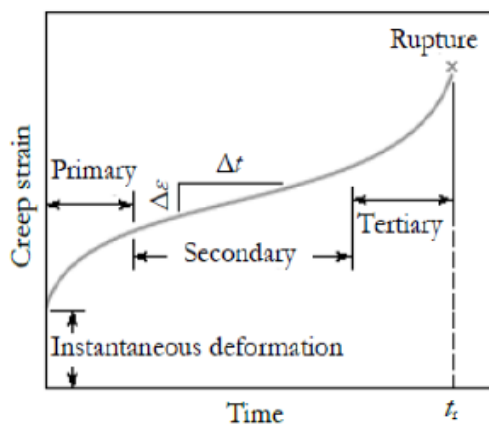


Figure 8. Creep strain vs. time [38]

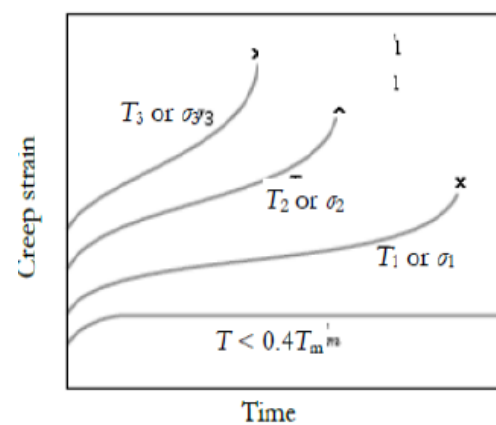


Figure 9. Creep curves for a range of stresses over a range of temperature [38]

Recent studies show that explicit consideration of creep is more appropriate and result in more accurate representation of the real case, see References [39] and [40]. Kodur et al. [41] made a comparison between different models available in literature including EN 1993-1-2:2005 [42] temperature-stress-strain relationships. The results show that when effect of creep is explicitly considered, the predicted deflections compare well with the experimental results. Also, when using the Eurocode temperature-stress-strain relationships, which consider the effect of creep implicitly, the analyses show a conservative prediction of beam deflections when compared with the experimental results.

As indicated in previous studies, implementing creep material models in computational tools allows the explicit evaluation of the time- and temperature-dependent response of steel members and assemblies at elevated temperatures. This quantification of structural behaviour in terms of both temperature and time is of utmost importance in developing performance-based design frameworks for the fire safety of steel structures. However, since the time-dependent behaviour of steel is obtained under constant temperature in a creep test, there are arguments against the applicability of creep test results for structural fire applications where temperatures are changing throughout the course of a building fire [43].

Morovat [44] shows that the analytical and computational results clearly indicate that accurate knowledge of material creep is essential in studying creep buckling phenomenon at elevated temperatures, and that neglecting creep effects can lead to potentially unsafe predictions of the strength of steel columns subjected to fire.

The creep tests performed reported in [45] on ferritic steel in its original state exhibit lower values for the creep coefficient of stress and activation energy when compared with those obtained on steel with a higher content of chromium. This explains its lower mechanical strength. The heat-treated steel improves its service conditions, especially its creep resistance.

Implementation of creep strains into the calculation of the structural response is made by means of explicit or implicit creep models. Explicit creep models include creep strains directly into the strain profile of the cross-section, where the calculation procedure involves finding the strain profile for which the internal forces are in equilibrium with the applied load forces at one cross-section. Afterwards, the moment-curvature relationship for every cross-section is calculated, and in dependence on the equilibrated strain profile (curvature), the bending stiffness of the structure member is calculated. Implicit creep models include creep strains directly into the stress-strain curves of the material, thus creating effective relationships in which stress-strain curves are highly nonlinear. However, implicit creep models only take into account high temperature creep strain at elevated temperatures, since no calculation of creep strain exists in implicit creep models [41].

As the steel grades used in structural engineering have higher performances, recent studies focus on the creep of high strength steels response. The analysis started with tests performed at room temperature, see [46], showing that: (i) the primary creep in all three alloys agrees well with the logarithmic creep law and the creep mechanism has been identified as pure dislocation creep, (ii) higher stresses and high loading rates lead to increased creep strains and strain rates, (iii) reloading after a period of creep results in significantly decreased creep strains and no recovery of the time dependent deformation can be detected. Low-temperature creep has generally been investigated because of two reasons: (i) materials may undergo plasticity that affects its intended performance. This category includes structural alloys, and creep of copper at cryogenic temperatures, and (ii) there has been theoretical curiosity regarding low temperature deformation and the mechanism of plasticity, particularly at cryogenic temperatures [47].

The tests at elevated temperatures performed by Brnic et al. [48] showed that high strength steel may be used in conditions limited by a certain level of temperature and utilisation factor.

The effect of creep on steel structures is exhibited during a fire event, when the elevated temperatures are affecting the building and the structure is loaded or the element subjected to fire is restrained. Since a fire may relate to a various number of heat release rate in time, an additional force is induced due to creep especially for long fires. If the fire load can be estimated and also the exposure to elevated temperature was assessed, the creep models may lead to an estimation of the increased load but also to the elongation during the fire. If the deformed shape is accurately determined the evaluation of the structural resistance has a higher certainty. Since creep is thermally activated one problematic case involves the connections. If the increase of the temperature in a connection allows the bolts material to creep, the connection behaviour changes from rigid to semi-rigid or even become a hinge. Instead of a redundant structure, the loss of rigidity leads to a mechanism structure with high probability of failure. Although if failure does not occur, the creep allows large displacements to be produced. In the eventual case of cooling the structure will keep residual displacements as well as residual stresses which are difficult to be estimated.

2.5 Overview

The important aspect in selecting the structure/member for reuse is that they should originate from damage-free building structures, i.e. structural members that have not been subjected to extreme-events. The main types of extreme events that can appear in the life of single-storey steel buildings are (a) plastic deformations, (b) fatigue, and (c) fire.

(a) In the case of single storey steel structures, steel undergoes no major changes due to ageing, except for rust and plastic deformations. Rust problems can be avoided by means of appropriate corrosion protection that usually includes surface preparation and application of paint systems or metallic coatings. Plastic deformations from loading cannot always be avoided and may cause partial damage in structural members. There are two types of strain ageing: (i) static strain ageing, e.g. due to foundation settlement, where material properties change after plastic deformation, and (ii) dynamic strain ageing, e.g. large-scale earthquakes), where material properties change during deformation. Strain ageing mainly affects the mechanical characteristics as follows: (i) the yield strength measured after ageing is higher, (ii) the ultimate strength can also increase, and (iii) ductility and percentage reduction of area after fracture decrease. In these conditions, the structure will be able to withstand a higher load but, the deformation criteria for elastic/plastic analysis should be assessed as well as the bearing ratio between structural elements. The seismic action itself affects the structures and since many of the economical designs are performed considering that plastic hinges are allowed to develop in order to dissipate the energy, the areas of the plastic hinge may also be affected by ageing. Most of the interventions after a major earthquake are not performed immediately so the strain ageing is initiated. Since in seismic design a minimum ultimate elongation limit must be satisfied, the effect of ageing should be evaluated. Moreover, EN 1993-1-1:2005 [4] imposes a minimum yield ratio f_u/f_y , and a minimum elongation at failure, for plastic and elastic global analysis.

(b) Fatigue is defined as a process of cycle-by-cycle accumulation of damage in a material undergoing fluctuating stresses and strains. A significant feature of fatigue is that the load is not large enough to cause immediate failure. Instead, failure occurs after a certain number of load fluctuations have been experienced, i.e. after the accumulated damage has reached a critical level. For example, crane runway girders are fatigue-prone structures, implying a higher concentration of loads and a smaller fatigue endurance of the structural elements supporting the crane. The technological process of manufacturing the structural elements and their components may lead to stress concentrations decreasing the fatigue life and should be carefully assessed. Some cutting processes (e.g. plasma cutting) may produce notches along the edges, affecting the fatigue life of the elements. Also, due to the technological process, the holes are not perfectly circular and notches as well as a knob appear at each hole, increasing stress concentrations. Though components of connections subjected to bending (e.g. endplate) are not sensitive to these defects, stress concentrations may drastically reduce the fatigue life of the connection if shear forces are large. A more dramatic case appears for splices, the plates being subjected mostly to tension, the defects accumulating higher stresses. The crack initiation represents the usual cause of failures caused by fatigue. If the brackets of the overhead crane railway are connected to the main columns by bolts a special attention must be paid to the fatigue of bolts. The assessment of the reliability of an existing structure aims at producing the evidence that it will function safely over a specified residual service life.

(c) Steel may creep, i.e. may experience slow plastic deformations, at high (constant) temperature, under time-dependent constant external stress. The creep strength in the range of temperatures where creep applies is always lower than the material yield strength. Creep affects steel structures mostly during fire events, when the elevated temperatures are affecting the building and the structure

is loaded or the element subjected to fire is restrained. One problematic case involves the connections. If the increase of the temperature in a connection allows the bolts material to creep, the connection behaviour changes from rigid to semi-rigid or even become a hinge. Instead of a redundant structure, the loss of rigidity leads to a mechanism structure with high probability of failure. Even if failure does not occur, the creep leads to large displacements. In the eventual case of cooling the structure will keep residual displacements as well as residual stresses which are difficult to be estimated.

Table 1 presents the types of loadings that are allowed on single storey steel buildings, as conditions for future reuse.

Table 1. Loadings in case of structures to be considered for reuse

Action	Conditions for future reuse
External actions covered by EN 1991-1-1, EN 1991-1-3, EN 1991-1-4, EN 1991-1-5	YES
Actions leading to plastic deformations of structural components (Extreme actions outside the code limits (large-scale earthquakes, extreme winds, extreme drifted snow etc.))	NO
Fatigue	YES, but with limitations (*)
Structures exposed to fire	NO

(*) The structure/elements can be reused in single storey steel buildings, in structures without cranes. Runway cranes should not be reused.

3. Material properties and condition assessment

3.1 General

Quantification of the material properties and assessment of the condition of the structure, or structural components is essential to evaluate structural reusability. Testing programmes will inevitably include a range of tests, and should be devised with the following factors in mind:

- A balance must be sought between obtaining sufficient information to make a reasonable judgement on risk, and seeking so much information that the examination itself compromises durability by intrusive sampling,
- Tests may be effective in combination, and may be interpreted in combination, e.g. a representative sample of locations revealing a particular characteristic may be examined in greater detail by a variety of more detailed tests,
- Performance evaluation procedures using Non-Destructive Testing (NDT) should prevail, as much as possible,
- In the case of Destructive Testing (DT), drilling or cutting must be carefully located, specified and supervised to avoid potentially serious damage to the structure.

3.2 Inspection techniques

The inspection techniques appropriate to the current project are summarised in *Table 2*.

Table 2. Inspection techniques

Technique	Description	Comments/Value
Visual inspection	Examination for corrosion, cracks, deformities, damage, etc.	Essential. General assessment of the physical condition of the structure. Will not reveal fine or subsurface cracks.
Field survey	Geometrical survey of positions and sizes of members and details.	Essential in absence of drawings, and to (i) check for modifications and repairs, (ii) determine the cross-section dimensions, straightness, verticality, deformation and deflection of members.
Dimensional inspection	Measurements using Vernier callipers, micrometres, three-dimensional laser scanning, ultrasonic measurements, etc.	Essential in absence of original structural drawings. Geometric data collection, size of members.

3.3 Non-destructive testing and measurement methods

NDT is generally carried out by operating equipment close to, against or fixed to the surface of the structure, and has a major advantage that it does not damage the structure, and eliminates the need for time-consuming random sampling, and subsequent laboratory testing. Table 3 sets out some of the techniques.

Table 3. Potential NDT techniques

Technique	Description	Comments/Value
Dye penetrant testing	Dye highlight surface breaking cracks.	Indicates surface cracks in members not otherwise visible to the naked eye.
Hardness testing	Diameter of imprint measured when hardened steel ball is pressed against a smooth surface with known force.	Essential. Provides hardness number, e.g. Vickers hardness, which is a guide to yield and ultimate strength of the material. Not a positive means of identification of steel grade.
Positive metal identification	Uses X-ray Fluorescence and optical emission spectrometry to establish the metallic alloy composition, and grade identification by reading the quantities by percentage of its elements.	Essential for characterisation of weldability of steel structural members, as a function of the carbon equivalent. Provides additional information on the type and associated physical properties of steel and about its alloying materials.
Eddy current welding inspection	Eddy current methods are used for non-destructively locating and characterising discontinuities in magnetic or nonmagnetic electrically conducting materials.	Essential to detect surface and near-surface cracks. Only applicable to simple geometries. Will not detect sub-surface embedded defects. General principles are given in EN ISO 15549:2019 [49] and for welds see EN ISO 17643:2015 [50].
Ultrasonic testing	Transducer converts electrical energy into ultra-high frequency sound waves which are reflected by defects and recorded.	Suitable for detecting embedded planar defects, including cracks, lack of fusion of welds, lamellar tearing, hydrogen cracking. General provisions for this technique can be found in EN ISO 16810:2014 [51]. For welds see EN ISO 17640:2018 [52]

3.4 Destructive testing and measurement methods

DT techniques require retrieving small samples from the existing structure. Recommendations for sampling are given in deliverable D2.3. Potential DT techniques are identified in Table 4. Samples for the testing are extracted by cutting or drilling. It is essential to consider the likely value of the results in relation to possible damage to the structure, e.g. embrittlement following heating when sample is removed by flame cutting, and whether indirect methods might be appropriate. Always desirable, even if it is not always practicable to make sufficient tests to provide adequate data on variability, but a few tests can be useful in giving a broad indication of the quality of materials. Mechanical and metallurgical properties can usually be established from laboratory testing on the same sample. Information about obtaining samples from steel can be found in relevant standards, e.g. for steel see EN 10025 [8].

Table 4. Potential DT techniques

Technique	Description	Comments/Value
Tensile testing	Tensile tests on meaningful samples providing yield and ultimate tensile strength, modulus of elasticity, uniform elongation, and elongation at failure.	Essential in the absence of material certificates, but always desirable. For test details see EN ISO 6892-1:2016 [53].
Small-punch testing	The stress-strain relationship can be also obtained by small-punch test of small sample.	Small punch testing is standardized but the method should be calibrated against the tensile tests of full-size specimen.
Charpy impact test	Brittleness and notch ductility at a range of temperatures determined by measuring the energy required to fracture a standard U- or V-notched sample with a blow from a pendulum.	Desirable. Allows characterisation of the steel sub-grade when material certificates are not available. For test details see EN ISO 148-1:2016 [54]. Impact toughness can be also tested on sub-sized specimen and the results recalculated to match the behaviour of the full-sized tests.

4. Evaluation of reusability: materials

4.1 General

Under the scope of this project, reclaimed structural steel may be allowed in structural design based on EN 1993. For consistency with this code of practice, the material itself needs to comply with specific performance and quality requirements, which are outlined in the current section.

4.2 Proposal for classification of reclaimed steel material for design

Reclaimed steel materials should be classified based on the verification against (i) material performance requirements (adequacy assessment) and (ii) quality assurance requirements (reliability assessment) into the following classes:

- Class A: steel materials that meet performance requirements through essential material testing and with approved quality assurance from original certificates,
- Class B: steel materials that meet all performance requirements through extensive material testing and with approved quality assurance, i.e. certificates of compliancy to the relevant European Product Standards, by re-certification,
- Class C: steel materials classified as the most conservative grade in accordance with structure age and location.

4.2.1 Material performance requirements

The essential material performance requirements for adequacy assessment are (i) mechanical properties, and (ii) chemical composition.

Mechanical properties

As a minimum, the following properties need to be determined [3]:

- Strength, i.e. yield strength, f_y , and the tensile strength, f_u ,
- Ductility, i.e. elongation after fracture, ε_f , that gives information on how much the material deforms,
- Impact toughness.

Strength and strain properties may be available from the original mill certificates. However only tensile coupon testing will inform the designer if there are significant residual strains, e.g. from members overstress, to be considered, see Figure 10. Material testing will also provide information on actual ductility of the reclaimed steel material. EN 1993-1-1:2005 [4] imposes (i) a minimum yield ratio f_u/f_y , and (ii) a minimum elongation at failure, for plastic and elastic global analysis, see Table 5. Note that the values summarised in Table 5 are those included in the revised part 1.1 of EN 1993, expected by 2023. For design purposes, the uniform elongation, at maximum stress, gives more valuable information. It does not account for the deformation after necking. Typical engineering stress-strain curves for mild steels (up to uniform strain) are shown in Figure 11, refer to [55]. For ULS design, a maximum absolute strain of 5% is usually accepted, see also EN 1993-1-5:2006 [56] and working document for future part 1-14 of EN 1993 [56]. Therefore, if the residual strain is larger than 5%, then

the 2nd life design may need to be restricted to an elastic analysis, also complying with the limits set out in Table 5.

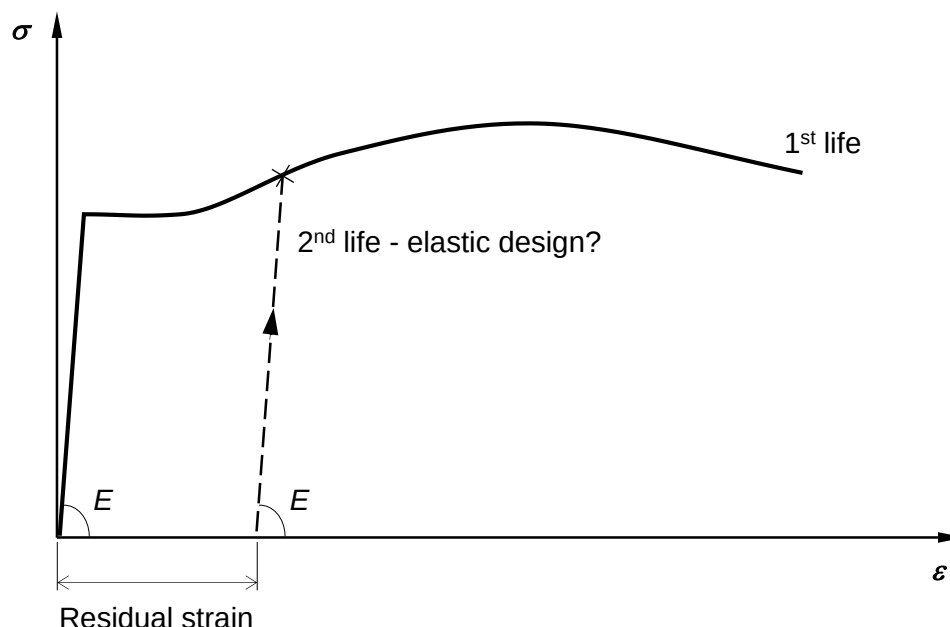


Figure 10. General full stress-strain curve for a mild steel

Table 5. Ductility requirements

Global analysis	Yield ratio f_u/f_y	Elongation after fracture
Elastic	≥ 1.05	$\geq 12\%$
Plastic	≥ 1.10	$\geq 15\%$

For plastic design and for most mild steels, this 5% limitation is quite generous, as can be seen from Figure 11. Therefore, some residual strain should be accepted. Based on the findings from Hosseini et al. [19], and recognising that the 5% limitation is perceived as a very slack rule, the effect of residual strain, i.e. permanent deformation, which can also be caused by strain ageing, is insignificant for levels of 1.5% and below. As can be seen from Figure 11, this value approximately corresponds to the end of the yield plateau. Plastic zones in the material are therefore accepted, provided that the residual strain does not exceed 1.5%. In order to get insight of this permanent deformation, the standard stress-strain curves for mild steels from Figure 11 are suggested as benchmarks. This naturally requires tensile testing of the reclaimed steel material and evaluation of the actual mechanical properties.

For statically loaded structures, the impact toughness of steel mainly depends on (i) the material thickness, and (ii) the service temperature. Therefore, it should not deteriorate for steel that is in use. The characterisation of the material toughness is important to determine the steel sub-grade and specify the type of application for steelwork.

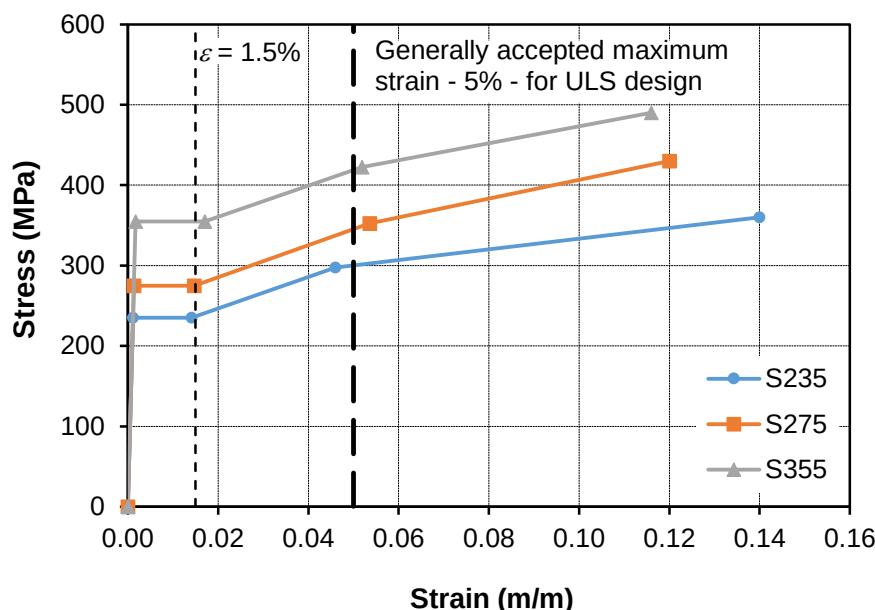


Figure 11. Simplified stress-strain curves for mild steels

Characterisation of mechanical properties by testing

The most accurate method for determining the mechanical properties of reclaimed steel is the tensile testing per EN ISO 6892-1:2016 [53], which is a DT. It involves cutting and testing of steel coupons, i.e. small samples that are removed from the existing structure. It is not always practicable to make sufficient tests to provide adequate data on the variability of strength, but a few tests can be useful in giving a broad indication of the quality of the materials, and results may allow the material to be designed as conforming to a specific product standard, e.g. EN 10025. The number of necessary tests on representative components has to be ultimately decided on a project-specific basis. The minimum number of tests is dictated by available data from (i) the original application, (ii) the type of structural system employed, (iii) the desired accuracy, and (iv) the quality and condition of the reclaimed material.

A good rule of thumb is to take two coupons minimum for each type of steel member in question, as it is not always possible to determine which members are from the same batch from the mill. Coupons shapes and sizes should be in accordance with EN ISO 6892-1:2016 [53]. Rectangular coupons are the most common for analysing open section members. For rolled shapes, the long dimensions of the coupons should be oriented in the direction of rolling. It is preferable to take coupons from the member flanges.

The strength properties will typically vary slightly from sample to sample. The simplest approach is to use the lowest strength values of the tested coupons when estimating the resistance of the member. A more rigorous statistical analysis can be performed to estimate the strength to a specified confidence level, in order to meet the quality assurance requirements, see Section 4.2.2.

As an alternative, or to complement the results from tensile testing, the Vickers hardness measured via NDT with a portable device, which does not require cutting test coupons, can be used to estimate the key mechanical properties of the material. Fujita and Kuki suggest the following relationships [57]:

$$f_y = 2.736H_v - 70.5 \quad (1)$$

$$f_u = 2.5H_v + 100 \quad (2)$$

$$\varepsilon_u = k \left(1 - \frac{f_y}{f_u} \right) \quad \text{and} \quad k \approx 0.6 \quad (3)$$

where H_v is the Vickers hardness,
 ε_u is the uniform elongation.

The elongation after fracture can be calculated as the sum of the uniform elongation and the local elongation, ε_n :

$$\varepsilon_f = \varepsilon_u + \varepsilon_n \quad (4)$$

The local elongation is determined from the plate thickness of the structural member and is proportional to the area reduction after necking of a coupon test. It is not easily determined from NDTs.

Chemical composition

Where welding is anticipated for the structure made from reclaimed steel, the chemical composition has to be determined for use in preparing the welding procedure specification. There are very simple NDTs to determine the steel composition, such as the positive metal identification technique. The full characterisation of the chemical composition is also required should the reclaimed material need to be recertified, due to absence of original certificates.

4.2.2 Quality assurance requirements

Reclaimed steel has to meet certain quality and safety requirements in order to be *re-certified* to ensure their reliability to be used in structural design based on EN 1993. The main question to be answered is “*which specific product standard was the material manufactured to?*”, to check for product conformity, quality and traceability. If the mill certificates are available, then it is possible to trace back the reclaimed steel and check (i) that the steel meets all relevant material specifications, and (ii) if it meets all the reliability requirements.

Material traceability is the ability to trace back the source of a specific steel material to its original identity as delivered from the mill, through proper identification and quality assurance system. For new materials, suppliers and fabricators who intend to reuse structural steel materials have to establish an in-house quality assurance system to ensure the traceability of such materials. Each piece of steel members shall be marked with a unique identification number of which quality control checks are introduced and recorded. Such unique identification will facilitate future reference to the factory production control certificate, manufacturer test certificate, inspection record and/or test report without confusion.

New steel materials intended for repeated use shall be sourced from audited mills with valid factory production control certificate and manufacturer test certificate. Use of the material for the first time shall be governed by the classification framework whereas reuse of the material shall only be permitted upon satisfactory verification against its reusability.

4.3 Implementation of adequacy and quality assessments

All reclaimed steel has to be assessed for adequacy and reliability, which are closely interrelated. All steel has to be certified, i.e. actual material properties have to be evaluated against the material performance requirements. In the absence of such certificates, material testing through appropriate sampling and testing method(s) has to be carried out to demonstrate the adequacy of the material. The reliability assessment is to ensure that the steel materials are manufactured under stringent quality assurance system and that it meets the quality assurance requirements.

Materials can be classified upon completion of these assessments, which are obviously interrelated, according to the system proposed in Section 4.2 and in accordance with the flow chart in Figure 12. The classification is necessary to establish whether the reclaimed steel material should be allowed for structural use to EN 1993 with or without any restriction.

Class A reclaimed steel material can be designed to EN 1993 [4] by (i) reducing the design resistance, e.g. using a slight reduction in yield strength from the product standards, which are assumed to be available, limiting the nominal ultimate strength, and/or possibly increasing the partial factors, or (ii) modifying the required resistance to the relevant load combinations, in accordance with EN 1990 [58]. Both options will be further discussed in D2.3. In this case, there is no need to carry out a separate reliability assessment as the original certificates are assumed to be available.

For Class B reclaimed steel, the design parameters are those from EN 1993 [4]. For reliability differentiation, the partial factors for load combinations may be modified by the coefficient K_{FI} , e.g. $K_{FI} = 1.0$ for Consequences class CC2 and $K_{FI} = 1.1$ for CC3 [58]. Class B material complies with the material performance requirements through material testing (see also Section 4.4.1), and have approved quality assurance by testing.

Finally, reclaimed steel material should be classified as C if it remains unidentified steel, free of damaging defects, and may be permitted to be used for structures or members that do not require CE marking. In this situation, it should be assumed that the steel is of the weakest grade of structural steel in use at the time of construction.

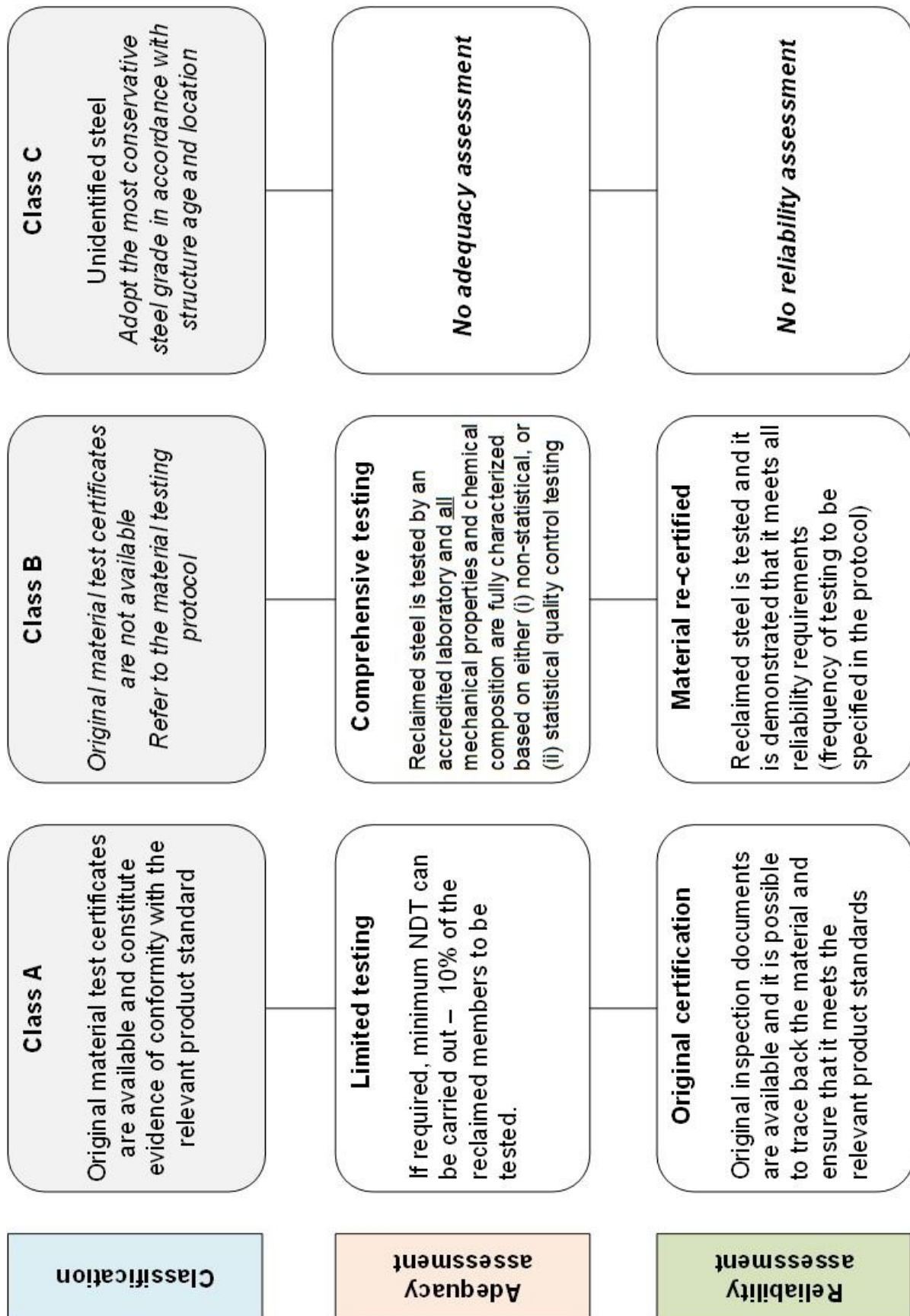


Figure 12. Overall framework for classification of reclaimed steel material and design parameters

4.4 Potential issues related to CE marking

CE marking applies to the manufacture of structural steel components, which are produced from constituent products (i.e. steel sections, mechanical fasteners and welding consumables). The properties of supplied constituent products have to be documented in a way that enables them to be compared to the specified properties and ensure that they conform to the relevant product standard. These documents include inspection certificates, test reports, declaration of compliance as relevant for structural steels so that their provenance is fully established.

4.4.1 Properties of reclaimed steel

EN 1090-2:2018 [3] for the execution (erection and fabrication) of steel structures has recently been revised and submitted for formal vote. Although the Standard does not mention the possibility of specifying reclaimed structural steel, it now clearly states the following regarding nonconforming structural steel for constituent products:

If constituent products that are not covered by product standards, their properties shall be specified. The relevant properties to be specified shall be taken from the following list:

- a) Strength (yield and tensile),*
- b) Elongation,*
- c) Stress reduction of area requirements (STRA), if required,*
- d) Tolerances on dimensions and shapes,*
- e) Impact strength or toughness, if required,*
- f) Heat treatment delivery condition,*
- g) Through-thickness requirements (Z-quality), if required,*
- h) Limits on internal discontinuities or cracks in zones to be welded, if required.*

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 [59], or,*
- A maximum limit for the carbon equivalent of the steel, or,*
- A declaration of its chemical composition in sufficient detail for its carbon equivalent to be calculated.*

The structural engineer should then specify a testing programme from the above list, bearing in mind that it is not mandatory to fully characterise all relevant properties.

The number of tests and sampling locations will depend on the particular circumstances and should ultimately be decided by the engineer taking account of factors including:

- The likely variation in material properties within and between parts of the structure,
- The probable critical members' locations,
- The possible errors in the test procedure and associated deviations in the results obtained,
- The fact that different techniques may measure properties of different volumes.

Materials evaluation usually involves a combination of on-site NDT and laboratory analysis or testing of samples using DT taken from the structure. EN 10025-1:2004 [60] states that, for “new” steels, the following samples shall be taken from one sample product of each test unit:

- One sample for tensile testing,
- One sample sufficient for one set of six impact test pieces if the impact test is required for the quality, as specified in EN 10025-2:2004 [8] (or any other relevant part of EN 10025).

The procedure generally consists of the following parts:

1. Batching the products: categorise members by groups, e.g. according to size. Assign a unique identifier to each member in each group, e.g. using consecutive integer identifiers.
2. Sampling within each lot: select samples of members for testing. Samples are selected randomly: each member of the lot has the same probability of being sampled.
3. Testing the samples using destructive techniques.
4. Statistical judgement of the results.
5. Decision regarding acceptance.

The quality control can be (i) total, or (ii) statistical. The statistical control is usually adequate, unless it is not possible to provide a statistically adequate sampling. Other cases exist that may justify total control, e.g. different material grades are found within the same group, or in cases where material re-certification is required.

Total quality control

If the control is total, every reclaimed steel product is tested, using a combination of NDT and DT. The acceptance rules imply that some of statistical analysis of results, which can be judged as good (accepted) or bad (not accepted). This requires the specification of some kind of accepted measurement error. The statistical parameter “Coefficient of Variation” (CoV) is representative of the dispersion of results within a population and is proposed to be used as an acceptance rule.

Statistical quality control

If the control is statistical, only a limited number of products are tested. The proposed minimum sample size for each group is summarised in Table 6 and it follows the recommendations given in FEMA-352 [61]. The number of products to select for testing and required to provide a statistically adequate sample essentially depends on (i) the total number of products in the group, and (ii) the error that is accepted. In this work, the acceptance rule is based on the coefficient of variation of the data set of direct measured values. For example, for strength the JCSS probabilistic model code proposes CoV of 0.07 for the yield strength and 0.04 for tensile strength [62].

Table 6. Minimum sample size

Number of products in group	Minimum sample size		Number of products in group	Minimum sample size	
6	3	50%	200	30	15%
10	4	40%	300	40	13%
15	5	33%	400	50	13%
20	6	30%	500	60	12%
30	8	27%	750	75	10%
40	10	25%	1000	100	10%
50	12	24%	1250	110	9%
75	16	21%	1500	125	8%
100	20	20%	2000	150	8%

For other numbers in the group use linear interpolation between values given, rounding up to the next highest integer.

The number of products in each group to be tested for a specific property is the same, for both DT and NDT, unlike the case of total testing. The NDT locations for material sampling can be taken as those in Figure 13.

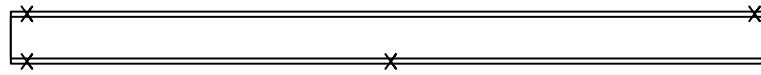


Figure 13. Suggested NDT locations for material sampling

4.4.2 Traceability

Reclaimed structural steel products for use in new design situations has to be traceable to a CE marked Type 3.1 or Type 2.2 Inspection Certificate [63], see EN 1090-2:2018 [3], which are essentially documents that contain the chemical and mechanical properties of the steel and assures that the steel product meets the specified properties. This poses some problems when the original material certificates are not available, and, as a consequence, the material has to be re-certified. This implies classification of material as class B, see above.

5. Evaluation of reusability: constituent products

5.1 General

A constituent product in the *reuse* context represents an individual element extracted from an existing structure selected for disassembly, and then reused as a *new* product for erection and fabrication of another structure, e.g. hot-rolled and cold-formed steel profiles. Such product will need a new Declaration of Performance (DoP) according to the corresponding harmonized standard because it will be marketed as new product.

Constituent products have to conform to the appropriate standards from Table 7 and Table 8. Rolled steel sections, plates, and bars used as members have to be supplied with dimensions and tolerances that comply with the standards from Table 7, while structural hollow sections with those listed in Table 8. The steel qualities shall be in accordance with the requirements as given in Table 9. The values in this table are based on EN 1993-1-10:2005 [65] assuming steelwork to be welded generally with detail being “moderate” and the presence of tensile stress. Alternatively, a fracture mechanics approach that conforms to the recommendations given in EN 1993-1-10 may be used to determine the toughness requirements.

Table 7. Rolled steel sections, plates or bar: material and dimension standards

Form	Dimensions	Tolerances	Material quality	
			Non-alloy steels	Weathering steels
I and H sections	EN 10365 [66]	EN 10034 [67]	EN 10025-2 [8]	EN 10025-5 [69]
Channels	EN 10365 [66]	EN 10279 [68]		
Rolled asymmetric beams	See manufacturers' information			
Angles	EN 10056-1 [70]	EN 10056-2 [71]		
Rolled Tees	EN 10055 [72]	EN 10055 [72]		
Plates (reversing mill)	-	EN 10029 [73]		
Plates (cut from coil)	-	EN 10051 [74]		
Steel grades S235, S275, S355 and S450. The steel grades S235 and S275 may be supplied in qualities JR, J0 and J2. The steel grade S355 may be supplied in qualities JR, J0, J2 and K2. The steel grade S450 is supplied in quality J0.				
Steel grades S235 and S355. The steel grade S235 may be supplied in qualities J0W and J2W. The steel grade S355 may be supplied in qualities J0W, J0WP, J2W, J2WP and K2W.				
The scope of EN 10029 covers plates of 3 mm up to 250 mm rolled in a reversing mill process, whereas EN 10051 covers plates up to 25 mm de-coiled continuously hot-rolled uncoated flat products.				

The steel qualities shall be in accordance with the requirements as given in Table 9. The values in this table are based on EN 1993-1-10:2005 [65] assuming steelwork to be welded generally with detail being “moderate” and the presence of tensile stress. Alternatively, a fracture mechanics approach that conforms to the recommendations given in EN 1993-1-10 [65] may be used to determine the toughness requirements.

Table 8. Structural hollow sections: material and dimension standards

Form	Dimensions and tolerances	Material quality
Hollow sections (hot finished)	EN 10210-2 [75]	EN 10210-1 [76]
Hollow sections (cold-formed)	EN 10219-2 [77]	EN 10219-1 [78]
Hollow sections for use in constructional steelwork (both hot finished and cold-formed) are supplied in steel grade S235 in quality JRH, steel grade S275 in qualities J0H and J2H, and S355 in qualities J0H, J2H, and K2H. Note: Selection of either EN 10210 or EN 10219 specifies whether structural hollow sections are to be hot finished or cold-formed. Hot finished structural hollow sections to EN 10210 cannot be directly replaced with cold-formed structural hollow sections to EN 10219 as the properties do not correspond directly.		

Table 9. Maximum thickness, in [mm]

Steel-work	S235			S275			S355		
	JR	J0	J2	JR	J0	J2	JR	J0	J2
Internal	45	82.5	115	40	70	102.5	22.5	45	67.5
External	26.5	67.5	97.5	22.5	60	85	12.5	37.5	55

5.2 Selection and acceptance criteria

The following procedure is proposed for verification of the reusability of steel members as constituent products, in the scope of the current project:

1. Documentation showing the location and building structure where the members were recovered from, including date of construction of original building, should be provided.
2. All products to be reused should come from a building structure erected after 1970 that was not exposed to extensive dynamic loading and other severe conditions, e.g. fire. Possible damages of structural members (e.g. earthquake history or fire history, according to the recordings of the owner), design specification, and the inspection certificate, should be evaluated.
3. All surfaces should be visually inspected, to ensure that the steel surfaces are free of rust, and that there is no corrosion (elements need to be visually exposed, therefore fire protection, if present, needs to be removed). In the case of structural hollow sections, the weld seam has to be inspected and it has to be demonstrated that there are no defects.
4. Members from reclaimed steel should not include welded or bolted splices along the length and should not have holes in the vicinity (say within 100 mm), of locations where new holes are to be drilled in the member.
5. Sectional dimensions (if not known) should be measured and sections classified according to Table 7 and Table 8. Three locations along the members for comparison against nominal values should be selected.
6. For open cross-sections (wide flange H- and I-beams), EN 10034 [67] specifies tolerances on shape dimensions of structural steel universal beams and columns. At the level of cross-

section, the following tolerances have to be measured: height of cross-section, flange width, web thickness, flange thickness, out-of-squareness, and web off-centre. Flange thickness should be measured at 3 quarter points along the member, each at top left half-flange and bottom right half-flange, and web thickness should be measured at 3 quarter points along beam central axis.

7. For closed cross-sections, e.g. Circular Hollow Sections (CHS) and Rectangular Hollow Sections (RHS), EN 10219-2 [77] specifies tolerances on shape dimensions of cold-formed structural hollow sections, while EN 10210-2 [75] specifies tolerances on shape dimensions of hot finished ones. At the level of cross-section, the following tolerances should be observed: outside dimensions (CHS and RHS), thickness (CHS and RHS), out-of-roundness (for CHS), concavity/convexity (for RHS), and squareness of sides (for RHS).
8. Tolerances on the member straightness should comply with EN 1090-2 [3] and tolerances on twist, for CHS and RHS should comply with EN 10219-2. Tolerances on older sections may be different and therefore supplementary measures may be required, e.g. see, as an exemplification, Table 10 for the UK and Romania.

Table 10. Geometrical tolerances for individual members, e.g. UK, Romania

Section	Straightness tolerances			
	Dorman Long [82]	NSSS [83]	STAS 767/0-88 [84]	EN 1090-2 [3]
Beam	$L/960$	$L/1000$ or 3 mm	$L/1000$, but max. 15 mm	$L/1000$
Columns up to 13.72 m	$L/960$	$L/1000$ or 3 mm	$L/1000$, but max. 15 mm	$L/1000$
Columns over 13.72 m	$9.5 \text{ mm} + L/960$	$L/1000$ or 3 mm	$L/1000$, but max. 15 mm	$L/1000$

9. Members from reclaimed steel should not have areas of accelerated localised corrosion or showing other evidence of localised section loss. The members should have a smooth surface. However, bumps, cavities, or shallow longitudinal grooves resulting from the manufacturing process are permissible, provided the remaining thickness is within tolerance. Surface defects may be removed by grinding provided that the thickness(es) of the cross-section after the repair is not less than the minimum permissible thickness. If the actual dimension after blasting/grinding fails to meet the nominal dimensions minus the nominal tolerance, the section should be relegated to the next lighter section.
10. Diffuse necking is not permitted in any cross-section, e.g. connections areas and elements in tension.
11. If the existing painting contains toxic substances (e.g. lead, cadmium and/or asbestos), remove existing coatings and surface scaling by preparing the surfaces to EN ISO 8501-1:2017 [79]. Steel paint that contains lead carbonate and lead sulphate can be encapsulated with other paint.
12. Reclaimed sections which are beyond economic repair/reconditioning shall be scrapped.

The inspection documents (or test certificates) constitute sufficient evidence that the mill product satisfies a required grade and quality. At the steel manufacturing plant, the quality control system

puts markings in the form of stamped numbers or letters on each length or batch of products so that it can be traced back to its particular cast and manufacturing route up to the point of assembling members. The inspection document for each batch of steel is the most important document to the steel manufacturer, the fabricator, the erector, and to the subsequent purchaser of the finished component or structure. In addition to the chemical composition and mechanical properties, the inspection document should also record details of the steelmaking route and any heat treatments applied to the material by the steel manufacturer.

Steel that is not readily identifiable as to grade has to be tested to determine conformity to standards. A sampling protocol has to be established in order to provide the adequate knowledge of the materials needed for reliable evaluation. Unidentified reclaimed steel may be used in non-safety critical structures, e.g. agricultural buildings.

The information presented below represents a starting point for producing a specification for reclaimed structural steel. The overall framework for verification of the reusability of a constituent product is shown in Figure 14. All reclaimed steel should be certified to the section properties and classified according to the system proposed in Section 4 of this document.

The overall framework for verification of the reusability of a constituent product is presented in Figure 14. There are three available options for reclaimed constituent products:

- **Option 1:** The original documentation exists, and the elements can be identified/confirmed according to the product standards. All surfaces are free of rust. Minimum measurements to confirm the section and length tolerances are needed.
- **Option 2:** The original documentation is missing. Reclaimed steel elements are measured to obtain the actual dimensions and thicknesses. Detailed measurements are taken to confirm the section and length tolerances. All surfaces are checked against rust.
- **Option 3:** The reclaimed steel elements do not meet the tolerances and are beyond the economic repair. These elements may be used as non-structural elements or should be sent to the scrap.

In case of Option 1 and Option 2, if the reclaimed steel material corresponds to the classification in Figure 12 from Section 4, i.e. Class A and Class B, and the acceptance criteria from above are fulfilled, then the fabricated steelwork can be CE marked according to EN 1090-1:2009 [80].

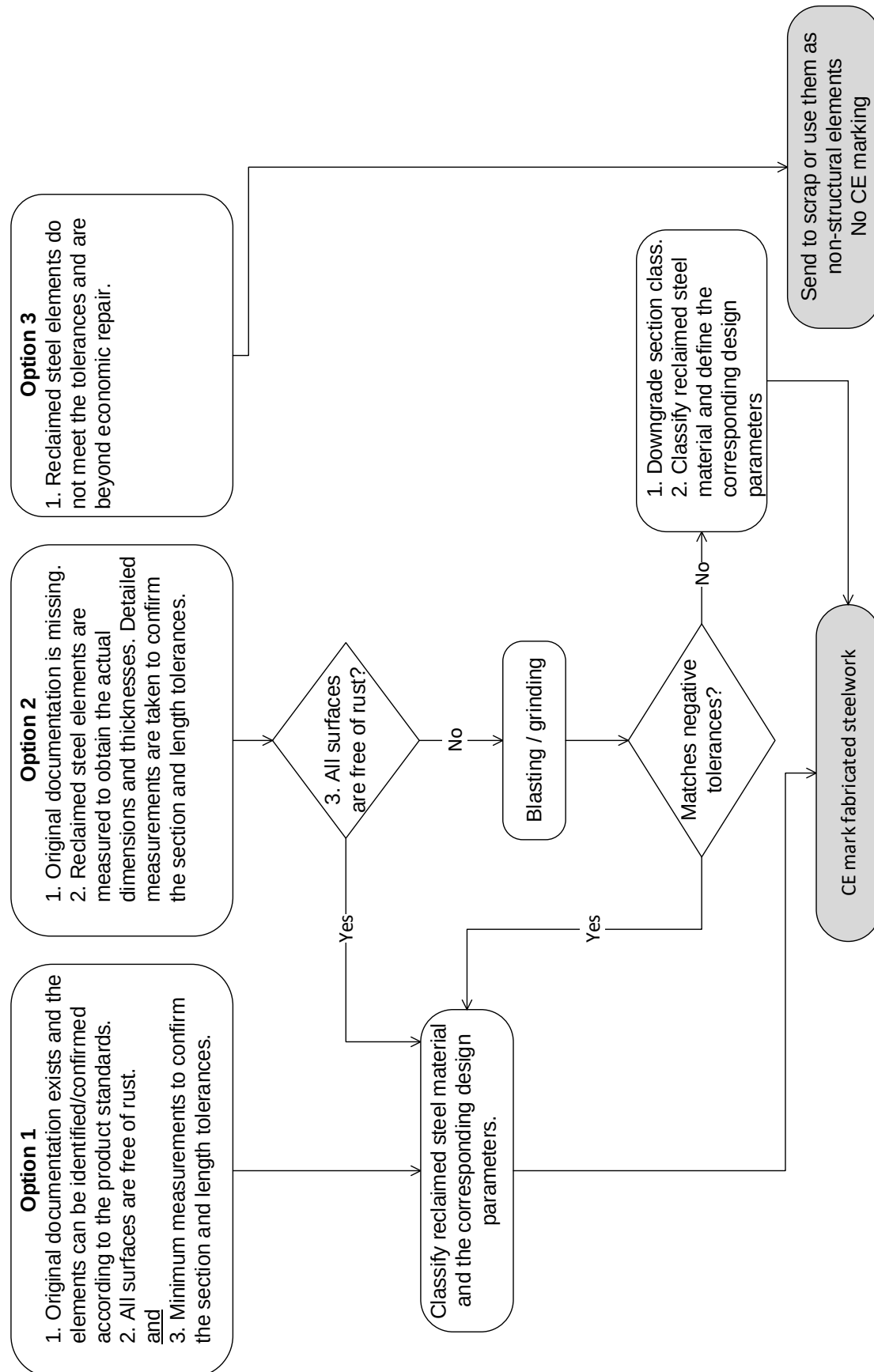


Figure 14. Overall framework for verification of the reusability of individual members

5.3 Potential issues related to CE marking

CE Marking for all construction products, covered by a harmonised European standard or conforming to a European Technical Assessment became mandatory on 1 July 2013. For fabricated structural steelwork, CE Marking became mandatory on 1 July 2014. This represents a major development for engineers, contractors and steelwork specialists and it demands careful attention to the new obligations imposed.

CE Marking demonstrates compliance with the appropriate manufacturing standard for a product. Under the Construction Products Regulation (CPR), new legal obligations have been placed on manufacturers, distributors and importers of construction products used within the EU to CE Mark their products where they are covered by either a harmonised standard or European Technical Assessment (ETA). This applies not only to constituent products (such as steel beams, bolts etc.) but also to fabricated elements and systems made from both CE Marked and non-CE marked products.

A CE Mark indicates that a product is consistent with its Declaration of Performance (DoP) as made by the manufacturer. CE Marking can be either affixed to the product, issued with accompanying documentation or made available on demand through electronic means. By making a DoP, the importer, distributor or manufacturer is assuming legal responsibility for the conformity of the product with its declared performance.

There are two forms of CE Marking, which are applicable to structural steelwork:

- Material and product standards – relating to the manufacture and properties of the product,
- Execution standards – relating to the design and manufacture of load bearing components and structures.

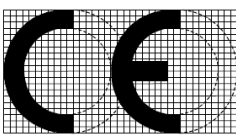
If not available for reclaimed steel, the process for certification must be repeated and the Declaration of Performance must accompany the products.

The constituent products should be evaluated by checking (i) geometry, (ii) structural steel products, see Section 4, and (iii) durability. EN 1090-1 [59] refers to the methods and instruments to be used to check that the geometry of the constituent products complies with all tolerances.

Figure 15(a) shows an example of CE marking of a constituent product, in this case, a cold-formed structural hollow section. It was issued by SSAB and it contains (i) the CE mark and underneath a four digit number which is the number of the Notified Body that assessed SSAB for CE marking, (ii) the grade and quality of the steel material, (iii) the mechanical and chemical properties of the section, (iv) tolerances on dimensions and shape, and (v) durability (indirect) evaluation by specifying surface protection requirements. The constituent products should be evaluated by checking (i) geometry, (ii) structural steel products and (iii) durability. Figure 15(b) shows a similar example of CE marking of constituent product, i.e. hot-rolled structural steel products. EN 1090-1 [59] refers the methods and instruments to be used to check that the geometry of the constituent products complies with all tolerances.

 0416	
SSAB SSAB Europe Oy, Harvialantie 420, 13300 Hämeenlinna 07 ref. S235JRH_20150812	
EN 10219-1:2006 Cold formed welded structural hollow section:	
EN 10219-1:2006	S235JRH
Essential characteristics:	
Yield strength $R_{p0.2}$ min	235
Tensile strength R_m $T < 3$ mm	360-510
Tensile strength R_m $T \geq 3$ mm	360-510
Elongation A% min*	24
Impact strength min J / Temp	27 / -20 °C
Weldability CEV max	0.35
Tolerances on dimensions and shape	EN 10219-2, Clause 6
Durability	Suitable for hot dip galvanizing
*For section sizes $D/T < 15$ (round) and $(B+H)/2T < 12,5$ (square and rectangular) the minimum elongation is reduced by 2	

(a)

 01234	
Any Co Ltd, PO Box 21, B-1050 03 01234-CPD-00234	
EN 10025-1	
Hot rolled structural steel products.	
Intended uses: Building constructions or civil engineering.	
Tolerances on dimensions and shape: Plate EN 10029 Class A	
Elongation	: Steel S355J0 – EN 10025-2
Tensile strength	
Yield strength	
Impact strength	
Weldability	
Durability: No performance determined	
Regulated substance: No performance determined	

(b)

Figure 15. Template and example of CE marking of constituent products

6. Evaluation of reusability: structural components or entire primary structure

6.1 General

Steel structures and steel construction products are, in general, highly demountable. Provided that attention is given to deconstruction at the design stage, there is no technical reason why nearly all the steel building stock should not be regarded as components for future use in new applications. Some industrial sectors commonly reuse steel structures and cladding components.

The steel construction sector has a great deal to offer sustainable development, including reuse, design for deconstruction, etc. Like other industrial activities, steel construction works for continuously improvement in terms of sustainability. The following guiding principles can be emphasized [85]:

- Use whole-life thinking, best value considerations and high-quality information to inform your decision making;
- Design for flexibility to extend building lifetimes and, where possible, further extend the life of buildings by renovation and refurbishment;
- Design and construct with maximum speed and minimum disruption around the site;
- Design to minimize operational impacts (e.g. energy use);
- Design for demountability, to encourage future reuse and recycling of products and materials;
- Engage with organizations within the supply chain about sustainable development;
- Select responsible contractors who have embraced sustainable development principles.

According to EN1090-2 a component represents part of a steel structure, which may itself be an assembly of several smaller components. A steel structure represents an organized combination of connected components designed to carry loads and provide adequate rigidity.

To facilitate greater reuse, it is important that designers not only use steel but also do what they can to optimise future reuse. Steps that can take to maximise the opportunity for reusing structural steel include [86]:

- Use bolted connections instead of welded joints to allow the structure to be easily disassembled;
- Use standard connection details including bolt sizes and spacing of holes;
- Ensure easy and permanent access to connections;
- Where feasible, try to ensure that the steel is free from coatings or coverings that will prevent visual assessment of the condition of the steel;
- Minimise the use of fixings to structural steel elements that require welding, drilling holes, or fixing, by using clamped fittings where possible;
- Identify the origin and properties of the component for example by bar-coding or e-tagging or stamping and keep an inventory of products;
- Use long-span beams as they are more likely to allow flexibility of use and to be reusable by cutting the beam to a new length.

Figure 16 presents the overall framework for reuse process of a steel structure or structural components parts of it.

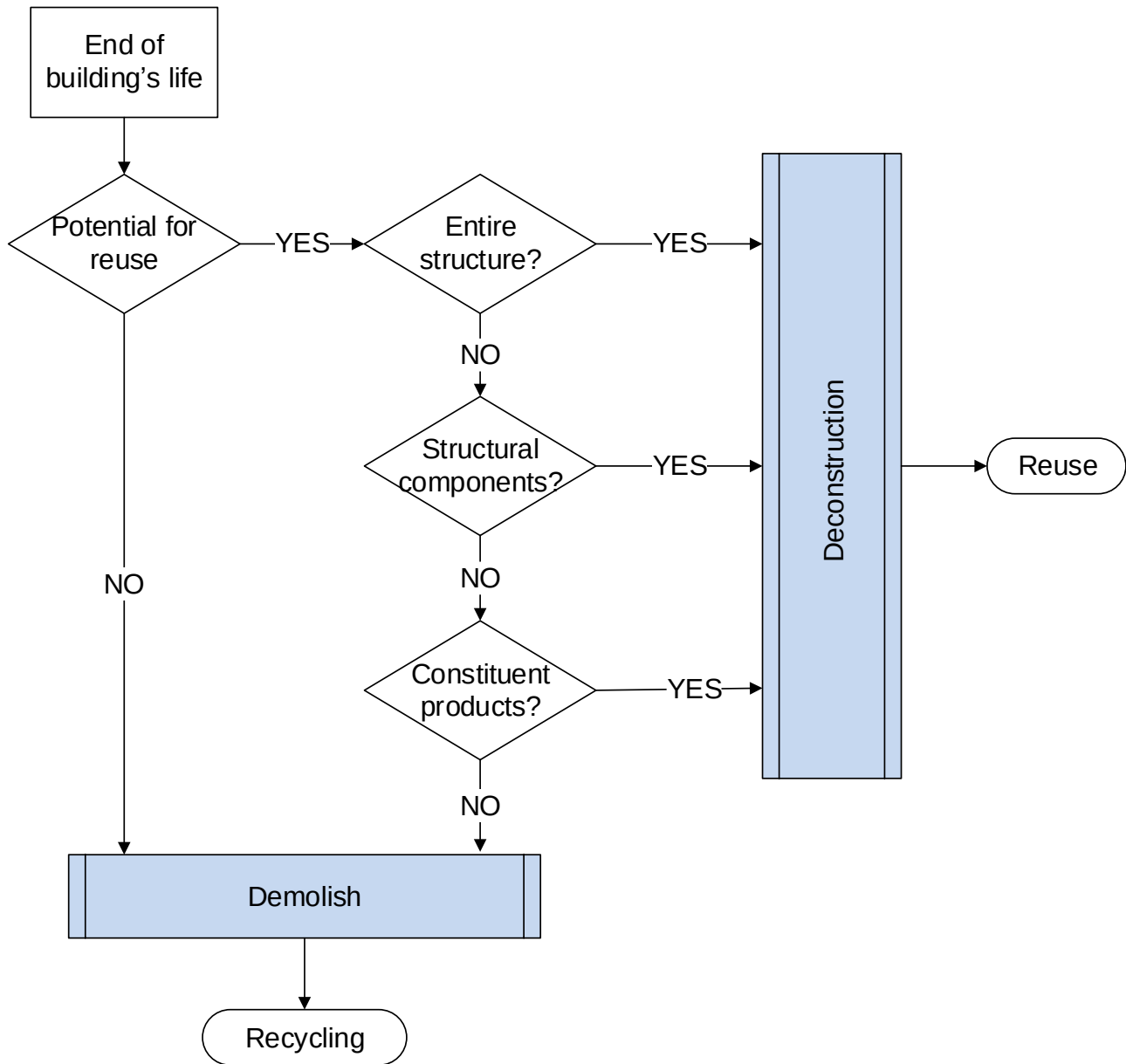


Figure 16. Overall framework for reuse process of steel structure/components

6.2 Selection and acceptance criteria for reclaimed structural components or entire primary structure

The following selection and acceptance criteria for reuse of a steel component, i.e. part of a structure, or entire primary structure, in the scope of the current project is proposed:

- The structural components or entire primary structure should be a part of a single-storey steel building. The building structure should have been erected after 1970 and should have not been exposed to extensive dynamic loading and other extreme actions.

- Each element shall be dismantled in the reverse order of construction. Elements providing lateral stability shall not be dismantled prior to the removal of the main elements or prior to the installation of the temporary bracing.
- Structural steel components shall be packed, handled and transported in a safe manner, so that permanent deformation does not occur, and surface damage is minimised. Products that have been handled or stored in a way or for a length of time that could have led to significant deterioration shall be checked before use, to ensure that they still comply with the relevant product standard.
- First, the individual structural members are evaluated, see Section 5. The term “evaluation”, in this context, is as defined in EN 1090-1:

The term 'evaluation method' is used for all kinds of methods used to demonstrate compliance with the requirements, e.g. physical testing, measurements of geometry and structural calculations whether assisted or not by physical testing.

- The reclaimed steel components should not have areas of accelerated localised corrosion or show other evidence of localised section loss. If corrosion affects the characteristics of the components, they should be redesigned according to the new dimensions or, if are beyond economic repair/reconditioning, shall be scrapped.
- For all reused components, or entire primary structure, documentation showing the location and building structure where the components were recovered from, including date of construction of original building, should be provided.
- All reclaimed steel should be certified to the section properties and classified according to the system proposed in Section 4 of this document.
- Careful visual inspection of every reclaimed member, and assessment against the tolerances should ensure that the element has not undergone plastic deformations and therefore the residual strains, and reserves of ductility, are no different to that of ‘new’ steel. All dimensions (if the initial drawings are missing) of the components/structure shall be measured to check they meet all the tolerances, at the level of cross-section, member and/or structure. Cross-section dimensions have to comply with EN 10034 [67] for wide flange H- and I- members, EN 10219-2 [77] specifies tolerances on shape dimensions of cold-formed structural hollow sections, while EN 10210-2 [75] specifies tolerances on shape dimensions of hot finished ones. Straightness of all members need to comply with the tolerances given in EN 1090-2 [3]. The structural component or module or the primary structure should comply with the geometric tolerances in Annex B of EN 1090-2 [3] (see B.2 manufacturing tolerances and B.3 for erection tolerances).
- All welds should be 100% visually inspected throughout their entire length for surface imperfections in accordance with EN ISO 17637:2016 [81]. The visual inspection should be carried before any other NDT inspection. If surface imperfections are detected, additional surface testing by liquid penetrant testing or magnetic particle inspection should be carried out on the inspected weld. Generally, ultrasonic testing or radiographic testing applies to butt welds and liquid penetrant testing or magnetic particle inspection applies to fillet welds.

- Bolts from the previous application should not be reused. They can be reused for secondary structure or for non-structural applications.
- If the existing painting contains toxic substances (e.g. lead, cadmium and / or asbestos), remove existing coatings and surface scaling by preparing the surfaces to EN ISO 8501-1 [79]. Steel paint that contains lead carbonate and lead sulphate can be encapsulated with other paint.
- The reused steel component/detail/structural component or module/primary structure can be CE marked to EN 1090-1 [80].

Reclaimed steel structural components, detail, module, or primary structure can be CE marked according to EN 1090-1. Nevertheless, some degree of uncertainty is inevitably associated with the use of reclaimed steelwork. The overall framework for verification of the reusability of components, or entire primary structures is presented in Figure 17.

The flowchart in Figure 17 identifies three possible classes, after checking the eligibility and compliance with tolerances in EN 1090-2:

- Class RSC1: the structural component has not been CE marked in the first life and has to be certified as a new structural component/structure. Deep investigations are necessarily for this Class - steel materials meet performance requirements through extensive testing;
- Class RSC2: the structural component has been CE marked in the first life according to EN 1090-1 and the original documentation is available. Each component should be reassessed to confirm the compliance with EN1090-2 and the harmonised standards. Steel materials meet performance requirements through limited testing (see Figure 12) and with approved quality assurance from original certificates. The welding has to pass the visual and other NDT inspection. The reclaimed structural component can be reused in designed according to EN 1993-1-1 with some restrictions: (i) plastic global analysis is not recommended when reclaimed steel is reused; (ii) a conservative value of the γ_{M1} safety factor is recommended to address possible uncertainties as the assessment processes are likely to be less reliable than those undertaken for the new steel structural components.
- Class RSC3: the structural component has been CE marked in the first life according to EN 1090-1, but in this case an existing CE marking is not available. The structural components have to conform with EN 1090-2 standard. In general, steel materials and welding can be evaluated through limited material testing and certified. The reclaimed structural component can be reused in designed according to EN 1993-1-1 with the same restrictions as for Class RSC2.

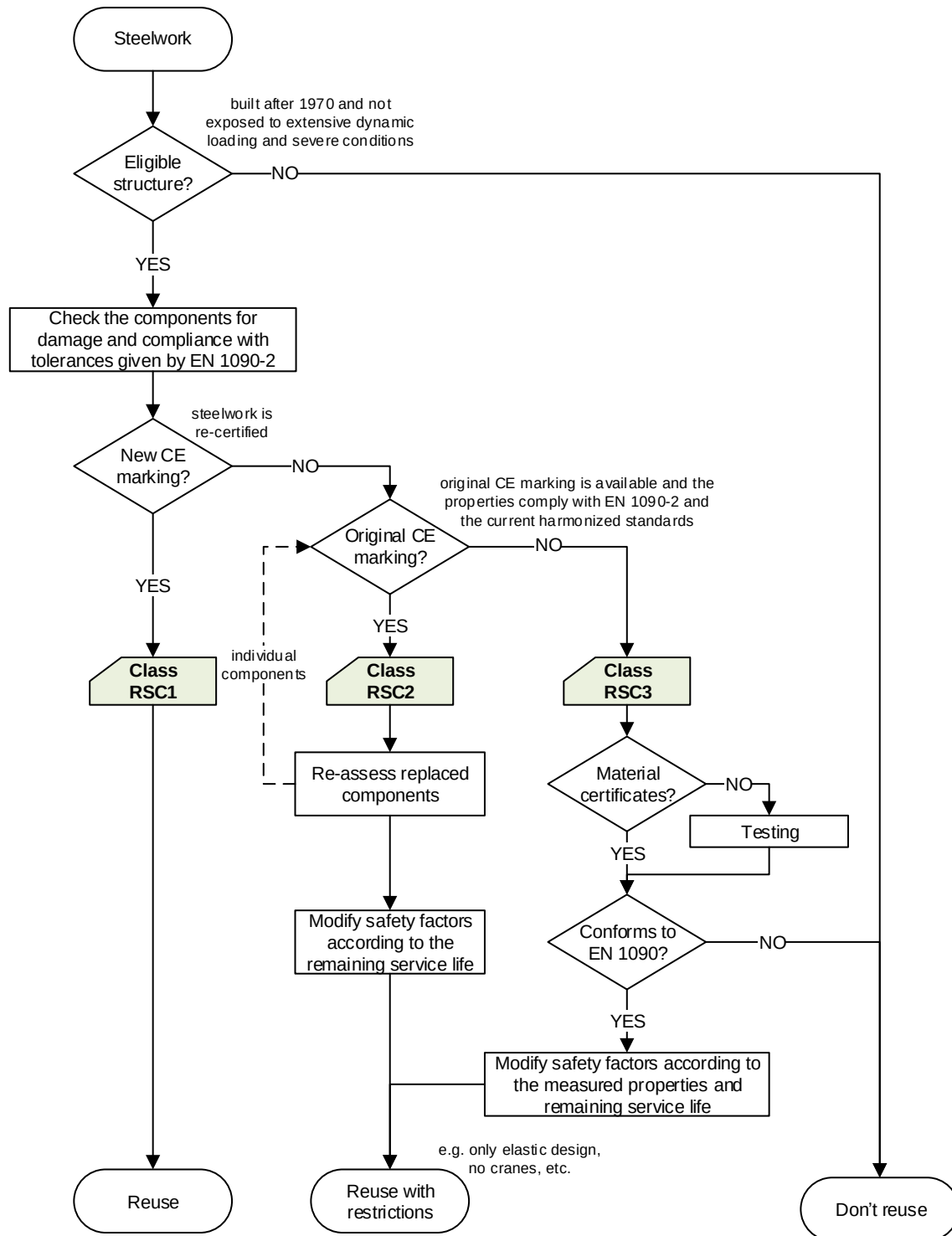


Figure 17. Overall framework for verification of the reusability of components or entire primary structures

6.3 Potential issues related to CE marking

6.3.1 Execution class

The execution class required for the steelwork is a reliability differentiator for providing choice of quality, testing and qualification requirements.

The basis for CE marking is that the manufacturer declares that its products meet specified performance characteristics that are defined as essential to the application of the products in the field of construction.

For any project, the required quality of fabrication or Execution Class (EXC) must be specified. EN 1090-2: requires the Execution Class to be specified for the works as a whole, an individual component and a detail of a component. In some cases, the Execution Class for the structure, the components and the details will be the same while in other cases the Execution Class for the component and the details may be different to that for the whole structure.

EN 1090-2 specifies requirements, which are mostly independent of the type and shape of the steel structure (e.g. buildings, bridges, plated or latticed components) including structures subjected to fatigue or seismic actions. Certain requirements are differentiated in terms of execution classes. Execution Class is defined as a classified set of requirements specified for the execution of the works as a whole, of an individual component or of a detail of a component.

According to EN 1090-2 there are four classes EXC1, which is the least onerous to EXC4, which is the most onerous. For the four execution classes EXC1 to EXC4 requirement strictness increases from EXC1 to EXC3 with EXC4 being based on EXC3 with further project specific requirements. It is down to the designer to select the EXC required for the structure, an individual component or a particular detail of a component. EN 1090-2 states that EXC2 should apply if no execution Class is specified.

The selection of the execution Class should be based on the following three factors:

- the required reliability;
- the type of structure, component or detail; and
- the type of loading for which the structure, component or detail is designed.

In terms of reliability management, the selection of execution Class should be based on either the required consequences Class (CC) or the reliability Class (RC) or both. The concepts of reliability Class and consequences Class are defined in EN 1990 [59].

In terms of the type of loading applied to a steel structure or component or detail, the selection of execution Class should be based on whether the structure or component or detail is designed for static actions, quasi-static actions, fatigue actions or seismic actions.

The selection of execution Class (EXC) should be based on Table 11.

Table 11. Selection of execution Class (EXC)

Reliability Class (RC) or Consequence Class (CC)	Type of loading	
	Static, quasi-static or seismic DCL ^a	Fatigue or seismic DCM or DCH ^a
RC3 or CC3	EXC3 ^c	EXC3 ^c
RC2 or CC2	EXC2	EXC3
RC1 or CC1	EXC1	EXC2
^a Seismic ductility classes are defined in EN 1998-1: Low = DCL; Medium = DCM; High = DCH. ^b See EN 1993-1-9. ^c EXC4 may be specified for structures with extreme consequences of structural failure.		

If the required execution Class for particular components and/or details is different from that applicable to the structure in general, then these components and/or details should be clearly identified.

The National Annexes may specify the choice of execution Class in terms of types of components or details. The following is recommended:

If EXC1 is selected for a structure, then EXC2 should apply to the following types of component:

- a) welded components manufactured from steel products of grade S355 and above;*
- b) welded components essential for structural integrity that are assembled by welding on the construction site;*
- c) welded components of CHS lattice girders requiring end profile cuts;*
- d) components with hot forming during manufacturing or receiving thermic treatment during manufacturing.*

Specification of a higher execution Class for the execution of a structure or component or detail should not be used to justify the use of lower partial factors for resistance in the design of that structure or component or detail.

PROGRESS Project focuses on the reuse of single-storey steel buildings and their components. The reused components can be framed on *Consequences Class* CC1 or CC2 according to Annex A of EN 1993-1-1, for static, quasi-static or seismic DCL type of loading. Consequently, Execution Class 2 (EXC2) is the most appropriate for the majority of single-storey industrial buildings.

Reclaimed steel structural components must clearly be treated differently, as it might have been manufactured to a withdrawn standard and is most unlikely to have any documented test results from time of manufacture. EN 1090-2 sanctions the use of other materials by stating that: "If constituent products that are not covered by the standards listed are to be used, their properties are to be specified". There will be no difference in the fabrication processes, procedures, standards or tolerances for either new steel or reclaimed steel. It is therefore appropriate that reclaimed structural steel components can be CE Marked in accordance with EN 1090. In addition to careful control of the structural components, material properties must be declared according to EN 1090-2.

Special care is needed if existing connections are to be re-used. In particular, any welding should be subject to careful inspection and test. Visual inspection of 100% of the welds is recommended.

Specification of EXC may not always be sufficient alone for the differentiation of the acceptance criteria and the extent of inspection for welds /details of different importance or criticality. This may result in the following:

- a) the acceptance criteria may become too onerous for welds that are not important;
- b) the extent of specified inspection may become too large for welds that are not important;
- c) the specified inspection may miss the critical locations.

The use of weld inspection classes (WICs) may be useful in directing the scope and percentage extent of supplementary testing according to the criticality of the weld. This may be beneficial both from a safety aspect and from an economic point of view as unnecessary inspection and repair may be avoided. The initial choice of weld inspection classes (WICs) should take into account the likelihood that defects would arise for particular weld configurations (e.g. welds to be executed in difficult conditions such as overhead welds, site welds, welds for temporary attachments). Subsequently, the weld inspection classes (WICs) may be reduced based on experience in production.

If weld inspection classes are to be used based on the following criteria for selection:

- a) utilization for fatigue;
- b) consequence of failure of weld for the structure;
- c) direction, type and level of stresses.

Annex A.3 of EN 1090-2 [3] lists requirements specific to each of the execution classes referenced in this European Standard. “Nr” in the Table means: No specific requirement in the text.

In order to apply CE mark for reused structural components, the reused structure need to follow the protocol for CE marking appropriating the qualification of welding procedures and welding personnel and the inspection.

In case of reclaimed components or entire primary structure, the contractor or the holder of the stock, is responsible for specifying the EXC for the structure (the works as a whole) and for components and details, where it is appropriate to specify an Execution Class different to that specified for the structure. Where different, the Execution Class for a component or detail should not be lower than that specified for the works as a whole. The EXC for a component or detail should be clearly identified in the new specification if it is different to the Execution Class for the structure.

The organisation holding the reclaimed structural components or entire primary structure has important responsibilities involving the examination and testing of the steelwork, keeping of comprehensive records and formal declarations of material properties when the reclaimed structural components or entire primary structure is distributed into the supply chain.

When reclaimed structural components or entire primary structure is distributed into the supply chain, it must be accompanied by a formal declaration, following the requirements of EN 1090-2. The declaration must make clear which properties have been assumed, and which have been determined by test.

The contractor or the stockholder has to draw up the product technical documentation required by the Regulation for the assessment of the product's conformity to the relevant requirements. Together with the EC Declaration of Performance, the technical documentation must be made available when requested by the appropriate authorities.

The contractor or the stockholder of components falling within EXC2, 3 and 4 must have, or have access to, a Responsible Welding Co-ordinator (RWC) and all welding must be controlled by the RWC.

The Declaration of Performance (DoP) is a legal declaration made by the contractor or the stockholder that the product was manufactured in accordance with, and conforms to, the requirements of the standard EN 1090-1. The contractor, his authorised representative or the stockholder must produce a DoP before placing the product on the market.

The following properties shall be declared:

- geometrical data (tolerances in dimensions and shape);
- weldability – If required, if not "No performance determined (NPD)" may be declared;
- fracture toughness of structural steel products;
- reaction to fire – To be declared that the materials are classified as Class A1; or if a coating with organic content larger than 1%, the relevant class of the organic content;
- release of cadmium and its compounds – "NPD" to be declared;
- emission of radioactivity – "NPD" to be declared;
- durability – To be declared according to component specification;
- execution class (EXC);
- reference to component specification.

The contractor or the stockholder is responsible for creating a CE Mark and applying it to their product. It must be affixed visibly, legibly and indelibly on one or more of the following locations: the product, an attached label, the packaging, on the accompanying commercial documentation (such as delivery note) or in a technical specification.

The format of the CE Mark, as well as the information that needs to be included to ensure traceability, is detailed in the Annex ZA of EN 1090-1 and presented in Figure 18.

 01234
AnyCo Ltd, PO Box 21, B-1050 18 01234-CPD-00234
EN 1090-1 Rafter of a steel portal frame – M 123 Tolerances on geometrical data: EN 1090-2. Weldability: Steel S235J0 according to EN 10025-2. Fracture toughness: 27 J at 0°C. Reaction to fire: Material classified: Class A1. Release of cadmium: NPD. Emission of radioactivity: NPD. Durability: Surface preparation according to EN 1090-2, preparation grade P3. Surface painted according to EN ISO 12944-5, S.1.09. Structural characteristics: Design: NPD. Manufacturing: According to component specification CS-034/2006, and EN 1090-2, execution class EXC2.

Figure 18. Proposal of CE marking information of product properties by material properties and geometrical data

7. Secondary steelwork elements

7.1 Structural components and materials

Purlins and side rails are usually proprietary cold-rolled thin gauge galvanised sections. Currently, Z-, C- and Σ - sections are used as purlins or rails, the manufacturers offering design data in terms of load/span tables or software. Purlins and side rails acting as secondary beams supported by primary beams (e.g. rafters) or columns are often restrained by the building envelope (e.g. trapezoidal sheeting, cassettes, sandwich panels, etc.).

The shape and sign of the bending moment diagram is depending not only on the type of loading, gravity or uplift, but also on the support conditions of the purlin, which can be simply supported or continuous over two or more spans. When it is continuous, the purlin may have uniform cross-section in the span and over the support, or stepped cross-sections, by overlapping the profiles over the supports. In the latter case, the Z-sections can be selected to adapt the purlin capacity to the moment variation along the member, and also to the transverse load demand at the supports.

Each manufacturer produces its own specific shapes, the depths ranging from 100 to 350 mm and thicknesses from 0.8 to 3.2 mm. These purlins are usually suitable for frame spacings between 4 to 9 m and purlin spacing between 1.2 to 2.5 m.

All steels used for cold-formed steel members and profiled sheeting shall be suitable for cold-forming and, if relevant, for welding. Steels used for members and sheets to be galvanized should also be suitable for galvanizing.

Steels specified in Table 12 conform to harmonized product standards, while steel presented in Table 13 conform to EN or ISO product standards. EN1993-1-3:2006 [87] is applicable to the materials listed in both Tables. For other steels the suitability for cold-forming shall be demonstrated by a bend test in accordance with EN ISO 7438 [88] or by an equivalent test.

Table 12. Standards and type of steels suitably for cold-forming conform to harmonized product standards

Type of steel	Standard	Grade
Hot-rolled products of non-alloy structural steels	EN 10025-2 [8]	S 235
Part 2: Technical delivery conditions for non-alloy structural steels		S 275
		S 355
		S 460
Hot-rolled products of structural steels	EN 10025-3 [89]	S 275 N
Part 3: Technical delivery conditions for normalized/ normalized rolled weldable fine grain structural steels		S 355 N
		S 420 N
		S 460 N
		S 275 NL
		S 355 NL
		S 420 NL
	S 460 NL	

Hot-rolled products of structural steels	EN 10025-4 [90]	S 275 M S 355 M S 420 M S 460 M S 275 ML S 355 ML S 420 ML S 460 ML
Part 4: Technical delivery conditions for thermomechanical rolled weldable fine grain structural steels		

Table 13. Standards and type of steels suitably for cold-forming conform to EN or ISO product standards

Type of steel	Standard	Grade
Cold reduced steel sheet of structural quality	ISO 4997 [91]	CR 220 CR 250 CR 320
Hot-rolled flat products made of high yield strength steels for cold-forming - Part 2: Delivery conditions for thermomechanically rolled steels	EN 10149-2 [92]	S 315 MC S 355 MC S 420 MC S 460 MC S 500 MC S 550 MC S 600 MC S 650 MC S 700 MC
Hot-rolled flat products made of high yield strength steels for cold-forming – Part 3: Delivery conditions for normalized or normalized rolled steels	EN 10149-3 [93]	S 260 NC S 315 NC S 355 NC S 420 NC
Cold-rolled flat products made of high yield strength micro-alloyed steels for cold-forming	EN 10268 [94]	HC260LA HC300LA HC340LA HC380LA HC420LA
Continuously hot-dip coated steel flat products for construction	EN 10346 [95]	S220GD+Z, +ZF, +ZA, +ZM, +AZ S250GD+ Z, +ZF, +ZA, +ZM, +AZ, +AS S280GD+ Z, +ZF, +ZA, +ZM, +AZ, +AS S320GD+ Z, +ZF, +ZA, +ZM, +AZ, +AS S350GD+ Z, +ZF, +ZA, +ZM, +AZ, +AS S390GD+Z, +ZF, +ZA, +ZM, +AZ S420GD+ Z, +ZF, +ZA, +ZM, +AZ S450GD+Z, +ZF, +ZA, +ZM, +AZ

Continuously hot-dip coated steel flat products of steel with high proof stress for cold-forming	EN 10346 [95]	HX260LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX300LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX340LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX380LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX420LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX460LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS HX500LAD+Z, +ZF, +ZA, +ZM, +AZ, +AS
Continuously hot-dip coated steel flat products of low carbon steels for cold-forming	EN 10346 [95]	DX51D+Z, +ZF, +ZA, +ZM, +AZ, +AS DX52D+Z, +ZF, +ZA, +ZM, +AZ, +AS DX53D+Z, +ZF, +ZA, +ZM, +AZ, +AS

A list of corresponding former national designations is presented in Table 14.

Table 14. Standards and for national designations of steel for cold-forming

STAS 9485-80	NF A 36-401-69 A 36-301-71	DIN 1623-72 1614-74	BS 1449; Part 1; 1972	ASTM SAE	JTS G 3131-77 G 3141-77	GOST 4041-71 9045-70	ISO
A1	TC	St 12 (1.0330)	CR 4	A 366/1012	Cls. 1 SPCC	BG (08 kp)	CR2; CR22; CR27
A2	E	St 13 (1.0333)	CR 3-CR 2	A 619/1008	Cls. 2 SPCD	CB (08 ps)	CR3; CR23; CR3ZE
A3	ES	St 14 (1.0333)	CR	A 620/1006 1008	Cls. 3 SPCFN	OCB (08 ps)	

Figure 19 shows typical support and overlapping arrangements for purlins. Z- and C- section fabricators usually offer design tables for such arrangements for various loading cases.

For an effective design, when spans are around 6.0 m to 7.0 m, continuous purlins are usually made with sections lapped and bolted at intermediate supports. Alternatively, double-sections can be used for strengthening the purlin at intermediate supports (see Figure 20).

As seen, sheeting itself can be used as a continuous restraint system to prevent lateral and torsional deformations of purlins. To be effective, such restraint systems must possess sufficient translational and rotational stiffness. When the restraint by sheeting is not fully effective, non-continuous or discrete lateral bracing devices, spaced along the purlins can be used.

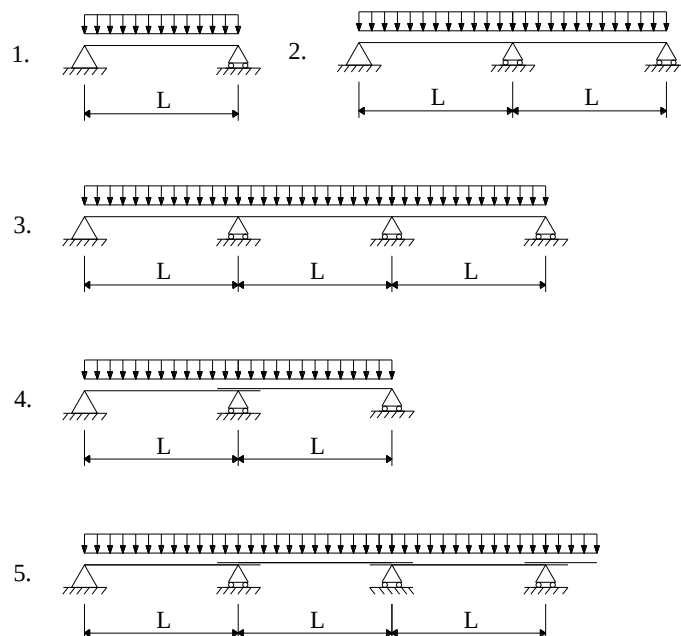


Figure 19. Support and overlap arrangements for purlins

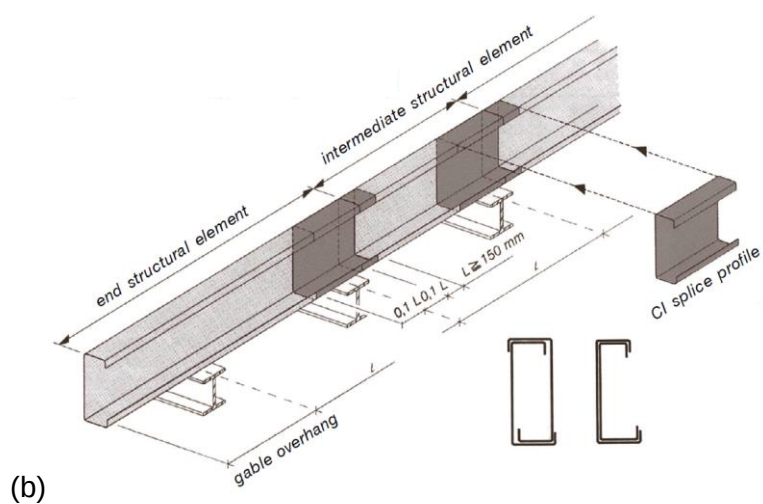
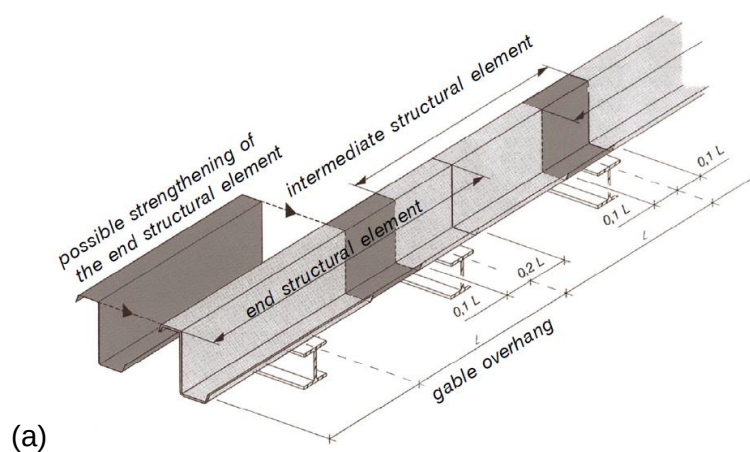


Figure 20. Double-sections or splices of Z- and C-purlins or rails [96]

The main factor governing the corrosion resistance of cold-formed steel sections is the type and thickness of the protective treatment applied to the steel rather than the base metal thickness. Cold-formed steel has the advantage that the protective coatings can be applied to the strip during manufacture and before roll forming. Consequently, galvanised strip can be passed through the rolls and requires no further treatment. Steel profiles are typically hot dip galvanised with 275 gram of zinc per square meter (Zn 275), corresponding to a zinc thickness of 20 μm on each side. The galvanising layer is sufficient to protect the steel profiles against corrosion during the entire life of a building, if constructed in the correct manner. The most severe effects of corrosion on the steel occur during transport and outdoors storage. When making holes in hot dip galvanised steel framing members, normally no treatment is needed afterwards since the zinc layer possesses a healing effect, i.e. transfers to unprotected surfaces. Hot dip galvanising is sufficient to protect the steel profiles against corrosion during the life of a building. The service life of hot dip galvanised steel studs was studied by British Steel and others [97]. The loss in zinc weight will be around 0.1 g/m² per year indoors. A similar study was also carried out for steel floors above crawl spaces with plastic sheeting on the ground. Results showed that a zinc weight of 275 g/m² is sufficient to provide a durability of around 100 years.

7.2 Design criteria

In Europe, the ECCS Committee TC7 originally produced the European Recommendations for the design of light gauge steel members in 1987 [98], followed by ENV1993-1-3:1996 [99]. This European document has been further developed and published in 2006 as the European Standard Eurocode 3: *Design of steel structures. Part 1-3: General Rules. Supplementary rules for cold-formed thin gauge members and sheeting* [87]. EN1993-1-3:2006 represents the unified European Code for cold-formed steel design and contains specific provisions for structural applications using cold-formed steel products made from coated or uncoated thin gauge hot or cold-rolled sheet and strip. It is intended to be used for the design of buildings or civil engineering works in conjunction with EN1993-1-1:2003 and EN1993-1-5:2006. EN1993-1-3 permits only design by the limit states method (LSD).

EN1993-1-3 includes in Chapter 10 design criteria for the following particular applications:

- Beams restrained by sheeting;
- Linear trays restrained by sheeting;
- Stressed skin design;
- Perforated sheeting.

The design provisions for these particular applications are often complex but may be useful for design engineers since they include detailed methodologies not available in other standards or specifications.

As application support of this code, the European Convention for Constructional Steel Work, ECCS, published in 2008 “Worked examples according to EN1993-1-3” [101]. Previously, in 2000, ECCS also edited worked examples on the same topic [100].

In 1995 the European Convention for Constructional Steelwork – ECCS published the *European Recommendations for the Application of Metal Sheeting acting as a Diaphragm* [102].

Cold-forming technology makes available production of unusual sectional configurations. However, from the point of view of structural design, the analysis and design of such unusual members may be very complex. Structural systems formed by different cold-formed sections connected to each other (like purlins and sheeting, for instance) can also lead to complex design situations, not entirely covered by design code procedures. Of course, numerical FEM analysis is always available, but for many practical situations, modelling can be very complicate. For such complex design problems, modern design codes permit the use of testing procedures to evaluate structural performances. Testing can be used either to replace design by calculation or combined with calculation. Only officially accredited laboratories, by competent authorities, are allowed to perform such tests and to delivery relevant certificates.

7.3 Selection and acceptance criteria

The following selection and acceptance criteria are proposed for assessing the reusability of secondary steelwork, i.e. purlins and side rails, in the scope of the current project:

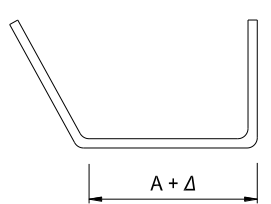
1. The structural components (member composing the secondary structural system) or the secondary structural system, should be a part of a single storey steel building and should have not been exposed to any extreme actions.
2. Each element shall be dismantled in the reverse order of construction. Elements providing lateral stability shall not be dismantled prior to the removal of the main elements or prior to the installation of the temporary bracing.
3. Structural steel components shall be packed, handled and transported in a safe manner, so that permanent deformation does not occur, and surface damage is minimised. Products that have been handled or stored in a way or for a length of time that could have led to significant deterioration shall be checked before use, to ensure that they still comply with the relevant product standard.
4. First, the individual structural members are evaluated according to EN 1090-1:2009 [80].
5. All reclaimed steel should be certified to the section properties and classified according to the system proposed in Section 4 of this document.
6. All dimensions (if the initial drawings are missing) of the components/structure shall be measured to check they meet the tolerances, at the level of cross-section, member, or structural system (see EN 1090-4). All measurements to verify the cross-sectional shape and dimensions, shall be carried out at a distance of at least 250 mm from the end of the sections to exclude any influence of end-flare on measured results. The thickness of the section shall be measured on the flat sides of the section. Straightness and twisting of a section shall be checked over the entire length of a section resting on a flat base. The length shall be measured along the centreline of the largest surface.
 - a. Essential and functional manufacturing tolerances for press braked or folded members are presented in Table 15.
 - b. For roll formed members EN 10162 [103] applies. The minus tolerance on the height of the lip of the edge stiffeners shall conform to the following: (1) the minus tolerance

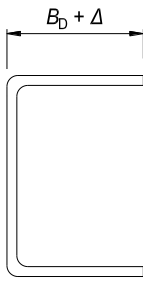
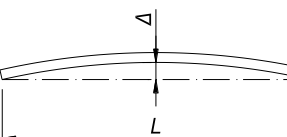
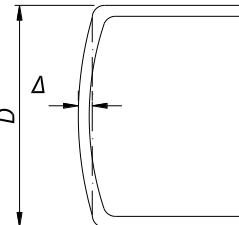
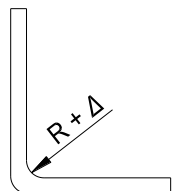
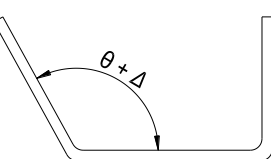
on the height of the lip of each individual edge stiffener shall not be larger than 10% of the nominal lip height, with a maximum of minus 2 mm; (2) the average tolerance on the height of the lip of all the edge stiffeners in each cross-section along the member length shall not be larger than half of the permitted minus tolerance for outside dimensions limited by one radius and a free edge. Positive tolerance is a functional tolerance.

- c. The thickness may be measured at any point located more than 40 mm from the edges. The tolerances on thickness shall be as given in Tables 1 to 4 of EN10143 [111] and apply over the whole length.

7. Bolts from the previous application can be reused.
8. The product surface shall be visually inspected for verification of conformance with the requirements in 7.4 to 7.6 of EN10346 [95]. Possible coating finishes are given in *Table 16*. The coating surface can vary and change to a dark appearance by oxidation. Due to aging of the coating a certain cracking of the surface can appear. The available coating masses should conform with Table 11 of EN10346. NDT tests have to be performed to check the coating thickness. If necessarily the methods described in Annex A (Z, ZF, ZA and AZ) or Annex B (AS) of EN10346 shall be used.
9. The reused steel component/ structural component can be CE marked according to EN 1090-1:2009

Table 15. Essential and functional manufacturing tolerances press braked or folded members

No.	Criterion	Parameter	Permitted deviation Δ		
			Essential	Functional	
				Class 1	Class 2
1	Internal element width: 	Width A between bends:	$\Delta = A/50$ (no positive value given)		
		$t < 3 \text{ mm}$: Length $< 7 \text{ m}$		$\Delta = \pm 3 \text{ mm}$	$\Delta = \pm 2 \text{ mm}$
		$t < 3 \text{ mm}$: Length $\geq 7 \text{ m}$		$\Delta = -3 \text{ mm} / +5 \text{ mm}$	$\Delta = -2 \text{ mm} / +4 \text{ mm}$
		$t \geq 3 \text{ mm}$: Length $< 7 \text{ m}$		$\Delta = \pm 5 \text{ mm}$	$\Delta = \pm 3 \text{ mm}$
		$t \geq 3 \text{ mm}$: Length $\geq 7 \text{ m}$		$\Delta = -5 \text{ mm} / +9 \text{ mm}$	$\Delta = -3 \text{ mm} / +6 \text{ mm}$
2	Outstand element width:	Width B_D between a bend and a free edge:	$\Delta = B_D/80$ (no positive value given)		
		Mill edge: $t < 3 \text{ mm}$		$\Delta = \pm 6 \text{ mm}$	$\Delta = -2 \text{ mm} / +4 \text{ mm}$
		Mill edge: $t \geq 3 \text{ mm}$		$\Delta = \pm 6 \text{ mm}$	$\Delta = -3 \text{ mm} / +5 \text{ mm}$
		Sheared edge: $t < 3 \text{ mm}$		$\Delta = \pm 5 \text{ mm}$	$\Delta = -1 \text{ mm} / +3 \text{ mm}$

		Sheared edge: $t \geq 3 \text{ mm}$		$\Delta = \pm 5 \text{ mm}$	$\Delta = -2 \text{ mm} / +4 \text{ mm}$
3	Straightness for components to be used unrestrained: 	Deviation Δ from straightness	$\Delta = \pm L/750$	-	-
4		Convexity or concavity	-	$\Delta = \pm D/50$	$\Delta = \pm D/100$
5		Internal bend radius R	-	$\Delta = \pm 2 \text{ mm}$	$\Delta = \pm 1 \text{ mm}$
6		Angle θ between adjacent components	-	$\Delta = \pm 3^\circ$	$\Delta = \pm 2^\circ$

NOTE: B_D is the width of the flange – theoretical requirement used for static calculations.

Table 16. Possible coating finishes according to EN10346 [95]

Coating type	Description according to EN10346	Characteristics according to EN10346
Z	application of a zinc coating by immersing the prepared strip in a molten bath of zinc	The zinc content is at least 99%.
ZF	application of a zinc-iron coating by immersing the prepared strip in a molten bath of zinc and a subsequent annealing	The zinc content of the bath is at least 99%. The annealing produces an iron-zinc coating with an iron content of normally 8 % to 12 %.

ZA	application of a zinc-aluminium coating by immersing the prepared strip in a molten bath of zinc-aluminium	The composition of the bath is approximately 5% aluminium, small amounts of mischmetal and the balance zinc.
ZM	application of a zinc-magnesium coating by immersing the prepared strip in a molten bath of zinc-aluminium-magnesium	The composition of the bath is sum of aluminium and magnesium from 1,5 % to 8 %, containing minimum of 0,2 % magnesium and the balance zinc.
AZ	application of an aluminium-zinc coating by immersing the prepared strip in a molten bath of aluminium-zinc-silicon	The composition of the bath is 55% of aluminium, 1,6% of silicon and the balance zinc.
AS	application of an aluminium-silicon coating by immersing the prepared strip in a molten bath of aluminium-silicon	The composition of the bath is 8 % to 11 % silicon and the balance aluminium.

8. Claddings

8.1 Sandwich panels claddings

This chapter considers metal faced insulated sandwich panels only.

Panels consist of three main components, i.e. (1) outer metal facing, (2) core of insulation material and (3) internal metal facing. Panels used for the external roofs and walls of buildings can vary in thickness from 30 to 150 mm according to use and age. Panels used for internal walls/linings and ceilings can vary in thickness from 50 to 300 mm according to use; degree of temperature control (e.g. cold stores) etc.

The metal facings protect the core insulation and provide other useful functions, e.g. weather tightness; moisture barrier; hygienic surface: fire protection etc. At the edges, the metal facings are usually profiled to form an interlocking joint. The majority of metal facings are profiled from sheet steel and can be flat or lightly profiled as used for wall panels, or deeply profiled as used for all roof panels and some wall panels. Most steel facings normally have a PVC (Polyvinylchloride coating) or PVDF (Polyvinylidene fluoride paint coating) or other paint coating for protection against weather or other environments and a thin paint finish on the alternate facing.

Insulating cores is the component of an Insulated panel that most affects disposal of panels at end of life. The central core can be made of various insulating materials like PUR), Polyisocyanurate (PIR) and Phenolic Foam (PF) and are manufactured using blowing agents that are retained in a closed cell structure to create a highly efficient insulant. PUR/PIR is the most efficient and commonly used core material for insulated panels, used in over 90% of all panels. In case of PIR, all panels produced since 1/1/2004 are non-ODS (ozone depleting substances).) cores are used in a small number of wall panels on the external walls of buildings. Internally MW panels are used in certain applications for walls, ceilings and as internal compartment walls. Polystyrene (PS) has been used as a core material for over 40 years almost entirely for panels used internally and especially within the Cold Stores Industry. Phenolic Foam is a rarely used core material in panels for specific projects, used on internal walls and ceilings.

Panels are secured by external fixings to the building's secondary steelwork. The fixings are either visible or may be covered by a flashing or cover strip and can be readily removed.

The panel industry has developed a range of mechanical handling techniques and crane lifting devices that enable panels to be safely placed or removed from the roofs and walls of buildings. These can be of equal value to Demolition Contractors. The advantage of mechanical handling equipment goes beyond the health and safety aspects of on-site handling and lifting. These techniques also offer significant time savings and earlier project completion, reduced labour costs and the reduced likelihood of damage to panels.

As background documents for designing sandwich panel structures, the text book prepared by the International Council for Building Research, Studies and Documentations (CIB), Commission W58, titled "Lightweight Sandwich Construction" [104] and the recent European Recommendations for Sandwich Panels [105], edited by a Joint Working Group composed of the ECCS Technical Committee TC 7.9 and CIB working commission W56, are recommended.

Studies into the re-use of insulated panels [108] have indicated that the potential for reuse from both an economic and technical point of view can be limited by some factors. Reuse is always the preferred option but if this is not possible these panels are often suitable for processing through conventional shredder plants once they have reached the end of their useful life.

8.2 Selection and acceptance criteria

Herein rules are given for evaluating the potential for reusing sandwich panels, dismantled after being in use for a considerable amount of time. The reason for dismantling the panels should be a change of the use of the building, not a failure in the panels. For the evaluation of safety aspects for reuse, the rules in EN 1990 (safety factors) and rules in harmonized product standard EN 14509 [107] for type testing essential properties are used. Type testing is used in EN 14509 as name for the testing where the declared values for all essential characteristics are done and following rules in EN 14509. A basic requirement for a limited amount of testing is that the name of manufacturer is known and a copy of original declared values (values given by the manufacturer) is available. This might limit the use of reduced testing program for panels older than 25 years, because of the lack of commonly known rules, unless they have been produced under national type approvals with an existing type testing and third party control. For other cases, a full testing program following rules in EN 14509 is recommended.

The mechanical panel properties to be declared and to be determined based on Type Testing are according to EN 14509:

- wrinkling strength;
- shear strength and shear module;
- creep coefficient (for permanent loads only);
- compression strength and compression module;
- tensile strength and tensile module;
- durability properties;
- tolerances.

For further processing the reference level of mechanical properties are the values declared by the manufacturer at the time of delivery of the panels. This reference level is further called as zero level.

The evaluation of the possible degradation of the panel mechanical properties is first evaluated by comparing the level of cross panel tensile strength to the zero level. If considerable degradation (over 10% lower characteristic value compared to the declared value) is noticed, the panel shear strength and compression strength is tested. The characteristic value of the panel shear strength determined on panels sampled from the panels dismantled is the value used for design when reusing the panels. The other properties used by design are the mean value of the shear modulus measured from the panels to be reused.

For wrinkling strength and compression strength and module the originally declared values are reduced with the ratio of the characteristic shear strength to the originally declared shear strength. This procedure is evaluated to be conservative as the experience is that the ageing is affecting mostly cross panel tensile strength and panel shear strength. Results from testing dismantled panels at the end of 90'ies indicate that the ageing rate of wrinkling strength is approximatively the half of the ageing in shear strength.

The level of material safety factors is suggested to be the same as determined based on original type tests. In principle a lower level could be possible as the expected lifetime of the panels to be reused is lower than when originally installed. As there is little knowledge on this behaviour today, the original material safety values are suggested to be used.

It is suggested to test samples taken from dismantled panels for testing cross panel tensile strength as specified in EN 14509, chapter A.1. The number of samples should be at least 3, preferable 10. The density of the samples is measured from samples taken close to the samples for tensile strength.

Tensile strength and density

The characteristic value of tensile strength is compared to originally declared value. If there is degradation in the level of less than 10%, the panels can be reused using the originally declared properties for all mechanical strength properties. If the degradation is more than 10% a set of samples for testing shear strength and module and compression strength and module should be taken. At least 3 samples each should be taken, preferably 5 for shear and 10 for compression tests.

Shear strength

The shear strength and shear module are tested for the samples taken from the dismantled panels. If the degradation in tensile strength is not more than 10%, one shear test has to be performed. The test result shall be at least the same as the declared value. The full range of tests is performed if the cross panel tensile strength has degradation more than 10% compared to original declared tensile strength. The characteristic value is calculated for the shear strength. This value is used for the design of the panels to be reused.

Compression strength

The compression strength is tested for the samples taken from the dismantled panels. The tests are performed if the cross panel tensile strength has degradation more than 10% compared to original declared tensile strength. The characteristic value is calculated for the compression strength. This value is used for the design of the panels to be reused.

Bending moment/wrinkling strength

For the bending moment or wrinkling strength, the originally declared value can be used if the tensile strength has degradation less than 10%. If the degradation is higher either the wrinkling strength is reduced with the same ratio as the shear strength is in comparison to the originally declared shear strength, or the wrinkling strength is tested for panels sampled from the dismantled panels. The characteristic value of test results is then used in design when reusing the panels.

Material safety factors

The material safety values determined by the original type testing is used. Alternatively, the safety values determined from the tests on dismantled panels can be used calculated as given in EN 14509, chapter A16 [107].

Durability properties

Need of repeating testing of durability is actual only if there is degradation of tensile strength more than 10%. In that case only the short-term durability testing (14 days, see EN 14509 Annex B, clause B.2.4, for all other core types than mineral wool and 7 days for mineral wool core, see EN 14509 Annex B, clause B.3.4) shall be done. For panels with core of mineral wool the degradation shall be less than 15% and for all other types less than 17%.

Tolerances

The tolerances are visually inspected and if deviation noticed checked that the panels are fit for reuse.

Thermal behaviour

In case of PU panels, if there is reduction in closed cells ratio (see ISO 4590) and change in density less than 10%, the thermal conductivity shall be retested and a new design value shall be determined (EN14509, clause A.10).

Fire safety

Only panels with core materials with fire retardants shall be retested for the small flame behaviour. This is to check that the effect of fire retardants is still active. Otherwise a reclassification might be needed. The panels are fit for use where fulfilling the requirements in the project for reuse.

8.3 Certification for reuse

Table 17 summarizes the evaluation procedure to be used for reuse of sandwich panels.

Table 17. Summary on evaluation procedure for reuse of sandwich panels according to EN 14509

Mechanical strength Testing cross panel tensile strength 3 samples a minimum (EN 14509, A.1): Calculate characteristic result for tensile strength Testing one sample for shear strength (EN 14509, A.3 or A.4)	
Evaluation: Tensile strength $\geq 0,9^*$ Declared value of Tensile strength and Shear strength $\geq$ Declared value of Shear strength	If YES; No further testing. All declared values for mechanical strength can be used
	If NO; New declared values to be determined with a test program according to EN 14509 for -Tensile strength, -Compression strength, -Shear strength. The wrinkling strength is reduced with same amount that shear strength is reduced.
Durability	
Tensile strength $\geq 0,9^*$	If YES; No further testing; panels are fit for use

Declared value of Tensile strength	If NO; <u>MW panels:</u> The 7 days testing (see EN 14509 clause B.3.4) is to be done. The reduction in tensile strength after ageing shall not exceed 15 % of the mean value of the tensile strength in ambient temperature <u>For all other panel type</u> the procedure in EN 14509 Annex B.2 is followed so that the panels are tested 14 days in the temperature as described in B.2.4. The reduction in tensile strength after ageing shall not exceed 17% of the mean value of the tensile strength in ambient temperature
Tolerances; damages evaluated by visual inspection	If no serious damages or faults found; Panel can be reused
	If serious damages are found causing weakness in strength, in insulation behaviour or tightness of joints then those panels are rejected
Moisture content	If no notable wetness of core material found the panels can be reused
Thermal behaviour	
For PUR panels: Closed cell ratio $\geq 0,9^*$ closed cell ratio by type testing and change in density less than 10%	If YES; no further testing; original thermal conductivity value can be used If NO; new test for determining thermal conductivity is to be done following rules in EN 14509, chapter A.10.
Fire safety	Small flame tests (see EN 14509 clause C.1.2) to be done with core material including fire retardants. The classification is checked and if needed reclassified. The panels are fit for use where fulfilling the requirements in the project for reuse.

Another big challenge is to reuse sandwich panels taking into account the initial holes used for fixing them to the secondary structure. A solution could be the “new to old concept” [108], which means the cladding of existing old façade with new lightweight cladding system. The cladding system in the investigation (the existing one) has been a traditional system based on thin-walled cold-formed purlin profiles and sheeting/sandwich panel, which are fixed to the external face using mechanical screw fastenings. In practice, there are a large variety of light-weight components on the market and thus, the traditional system provides many possibilities for further developments. The second cladding system (the new one) used in the investigations consisted of additional sandwich panels, which are fixed to the external face of the ordinary wall panel with screws and rivets, with or without spacers. This new system provides further benefits because of additional thermal insulation power and air and water tightness. It consists of fewer amounts of components and thus, may provide an effective alternative to retrofitting. In both cases mechanical properties of the solutions have to be studied to show the benefits and risks for further development work.

8.4 Built-up or single layer claddings

The built-up roof cladding using two layers (inner / outer) of trapezoidal sheet hiding the purlin system in between is described in Figure 21.

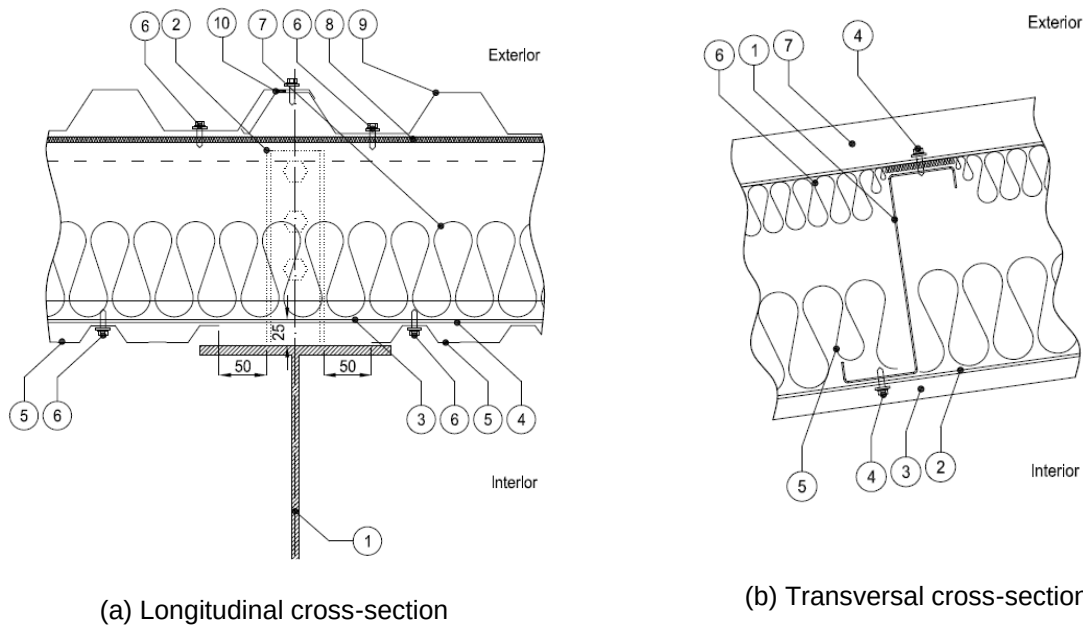


Figure 21. Longitudinal and transversal cross-section for built-up roof cladding

The relevant items on the transversal cross-section, in Figure 21(b), are:

- (1) thin-walled cold-formed Z purlin located between outer and inner sheeting;
- (2) vapour barrier;
- (3) inner trapezoidal sheet installed transversally to the purlin;
- (4) self-drilling self-taping fastener;
- (5) thermal insulation of mineral wool;
- (6) upper layer of cashier mineral wool;
- (7) outer trapezoidal sheeting installed transversally to the purlin (carrying climatic loads).

The longitudinal cross-section (see Figure 21(a)) presents the same items as before plus the rafter (1) which supports the purlins working as a continuous beams.

The built-up wall cladding using two layers (inner / outer) of trapezoidal sheet hiding the side rails (girts) system in between is described in Figure 22.

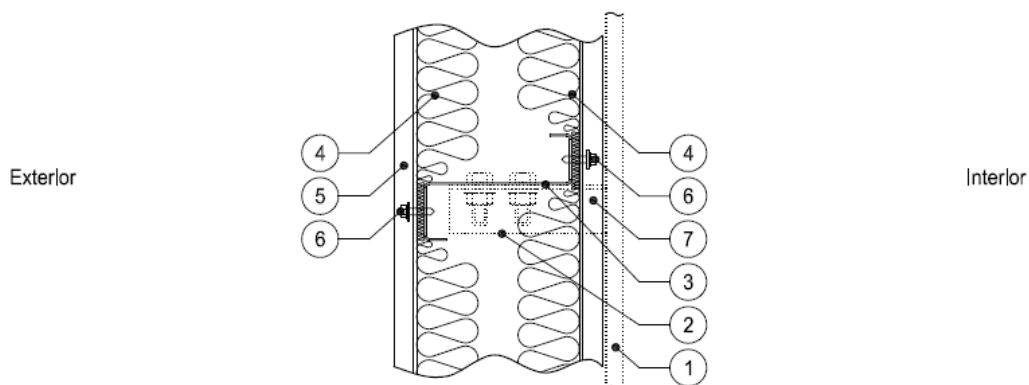


Figure 22. Transverse cross-section of built-up wall cladding (detail)

The relevant items on the transversal cross-section are:

1. primary steel structure (column);
1. cantilever welded on the primary structure to provide side-rail support;
2. side rail (thin-walled cold-formed Z profile with overlapping working as continuous beam);
3. thermal insulation of mineral wool;
4. outer thin walled trapezoidal sheet;
5. self-drilling self-taping fastener;
6. inner thin walled trapezoidal sheet.

Liner trays are thin-walled cold-formed steel profiles (see *Figure 23*) used to build SSSB wall cladding without providing a secondary structure.

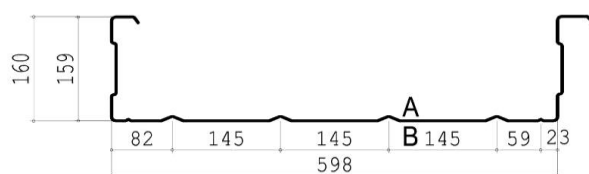


Figure 23. Example of liner tray thin-walled cold-formed profile

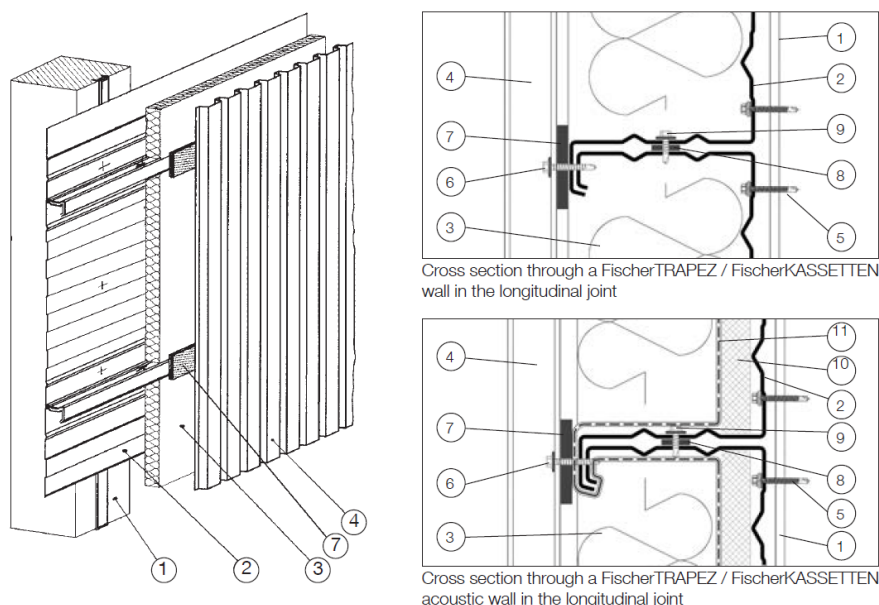


Figure 24. Wall cladding using liner trays profiles

The system uses thin-walled cold-formed steel sections of large channel-type with two narrow flanges, two webs and one wide flange (see *Figure 23* and *Figure 24*), very frequently used in practice, to resist perpendicular uniformly distributed wind loading as well as to create a diaphragm effect which acts against horizontal wind/earthquake loading at the level of industrial building cladding. Such systems are normally built using a required number of horizontally laid, inter-connected, adjacent liner trays plus an external skin of sinusoidal or trapezoidal sheeting installed perpendicularly to their direction (with vertical corrugations). This results in a stiff metal cellular system having its inner space filled with thermal insulating material.

Self-drilling self-trading fasteners or cartridge fired bolts pins serve to fix the wide flange of the horizontal profiles on the SSSB columns (see Figure 24). The outer skin (usually made of trapezoidal steel sheet vertically installed across the narrow flanges) is fixed to the narrow flanges of the liner trays using self-drilling fasteners.

Panels and decks are made from profiled sheets and linear trays as shown in Figure 25. The depth of panels usually ranges from 20 to 200 mm, while thickness is varying from 0.4 to 1.5 mm.

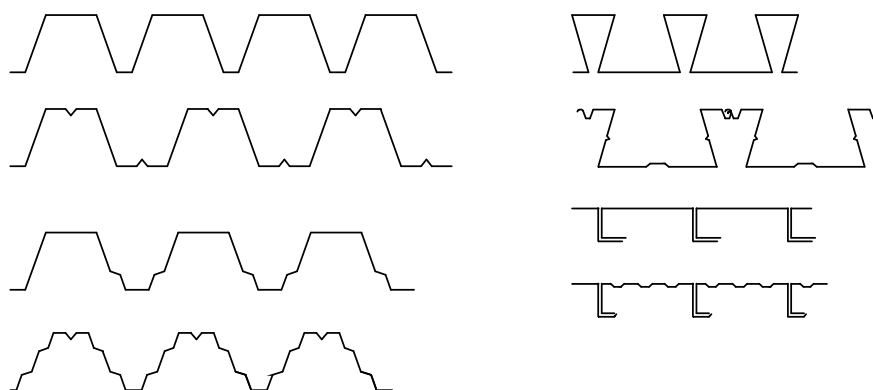


Figure 25. Profiled sheets and linear trays

The geometric tolerances on dimensional shape for continuously hot-dip metal coated steel sheet or strip shall comply with EN 10143 [111]. The thickness may be measured at any point located more than 40 mm from the edges. The tolerances on thickness shall be as given in Tables 1 to 4 of EN10143 [111] and apply over the whole length.

According to EN 1090-4, the following minimum thicknesses shall apply:

Profile steel sheets:

Decking: $t_N \geq 0.75 \text{ mm}$

Roof coverings: $t_N \geq 0.50 \text{ mm}$

Floors: $t_N \geq 0.75 \text{ mm}$

Walls and wall claddings:

Outer skin: $t_N \geq 0.50 \text{ mm}$

Single skin or inner skin: $t_N \geq 0.50 \text{ mm}$

Liner trays: $t_N \geq 0.75 \text{ mm}$

EN 508-1 [112] specifies requirements for self-supporting roofing, covering, wall cladding, lining, liner trays and tiles products for discontinuous laying made from metallic coated steel sheet with or without additional coatings. Sheets intended to be used with insulation and membranes are also covered.

EN 10169 [113] specifies performance requirements for continuously organic coated (coil coated) steel flat products. The more common coating materials used for organic coated flat products, together with their coating thickness (dry film thickness) are given in Annex B of EN 10169. Table 1 of EN 10169 gives a summary of the main properties of coil coated flat products.

The test unit consists of maximum 20 t or a fraction of 20 t of organic coated steel flat products corresponding to a substrate stemming from the same master coil and an organic coating of the same nature, appearance and thickness.

One series of tests shall be carried out per test unit for verification of:

- coating thickness;
- colour and gloss;
- adhesive strength/product flexibility;
- freedom of defects.

Permitted deviations for essential and functional tolerances for cold-formed profiled sheets are given in Annex D.2 of EN 1090-4. The tests for the various coating processes/coatings and corrosivity categories listed in Table E.8 of EN 1090-4.

The provisions in EN 13523-1 shall apply to the determination of the coating thickness. Measurement of the coating thickness ($\geq 150 \mu\text{m}$) of PVC plastisol with an outside micrometre is permitted. At least five individual measurements shall be made at each measuring point. The mean value shall then be determined from the measurements.

However, the success rate of reclaiming cold-formed profiled sheets is likely to be much lower in comparison with primary hot-rolled steelwork. This is due to the fact that, at least the external profiled sheets used for cladding are usually fixed with a considerable number of connectors. The internal profiled sheets or liner trays can be reused in future applications.

9. Integration of reclaimed steel in different reuse scenarios

There are three possible ways for the reuse of the main structure: (i) the entire primary and/or secondary structure, (ii) components of the primary (e.g. trusses or 2D portal frame, rafters, columns) and components of the secondary structure or envelope, and (iii) constituent products (IPE, HEA, HEB, RHS, CHS profiles, as Z-, C- or Σ - cold-formed steel profiles).

Purlins and side rails can be reused for the same or smaller span and/or spacing or combinations (e.g. smaller span - greater spacing). If they are treated as continuous with overlapping, either the overlapping should be considered higher either should be cut to the new dimensions. They can be framed in reuse cases (ii) or (iii) from above.

There are also three locational scenarios:

- Reuse in-situ, i.e. the components are retained and not deconstructed;
- Reuse on the same site, i.e. the components are deconstructed and re-erected either in the same configuration and/or same or different location;
- Reuse on a different site.

Examples of these scenarios are presented in D1.1 [109].

Table 18 and Figure 26 present possible ways for integration of reclaimed steel, from entire structure to structural component or to constituent products, integrating the steps from the above Sections 5 to 8.

Table 18. Integration of reclaimed steel in different reuse scenarios

Reuse case	In-situ	On same site		Relocation	
		Same configuration	Different configuration	Same configuration	Different configuration
1. Entire primary structure and/or entire secondary structure	Material (Section 4) No need for measuring dimensions to verify tolerances Visual inspection	Material (Section 4) Moderate need for measuring dimensions to verify tolerances (Section 6/7/8) Welding control	Material (Section 4) Moderate need for measuring dimensions to verify tolerances (Section 6/7/8) Welding control	Material (Section 4) Increased need for measuring dimensions to verify tolerances (Section 6/7/8)* Welding control	Material (Section 4) Increased need for measuring dimensions to verify tolerances (Section 6/7/8)* Welding control
2. Elements of the primary structure, structural components, or parts of secondary structure	Material (Section 4) No need for measuring dimensions to verify tolerances Visual inspection	Material (Section 4) Moderate need for measuring dimensions to verify tolerances (Section 6/7/8) Welding control	Material (Section 4) Moderate need for measuring dimensions to verify tolerances (Section 6/7/8) Welding control	Material (Section 4) Increased need for measuring dimensions to verify tolerances (Section 6/7/8)* Welding control	Material (Section 4) Increased need for measuring dimensions to verify tolerances (Section 6/7/8)* Welding control
Other future applications					
3. Constituent products	Material (Section 4) Increased need for measuring dimensions for tolerances (Section 5 or 7 or 8)				

* Due to transportation and manipulation

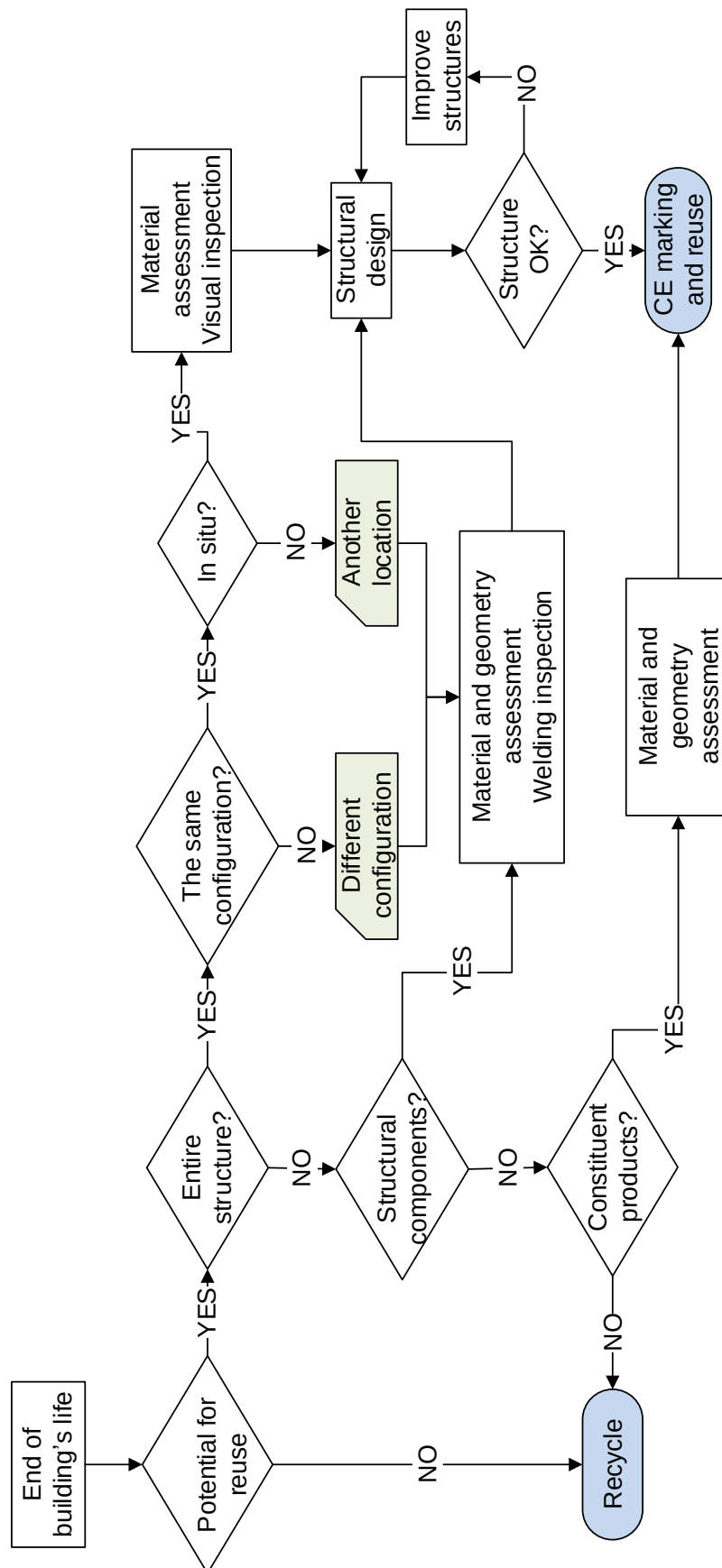


Figure 26. Integration of reclaimed steel in different reuse scenarios

In-situ reuse consists in retaining the existing structure or structural components without disassembling. If necessarily, strengthening of elements and connections, adding or removing components etc. will be done. An alternative could be deconstruction of the structure and the structural components can be then re-assembled on the same site in the original layout or different layout.

In the case of relocated reuse of the whole structure, in the same or different layout, the deconstructed structure can be either transferred directly to a new owner, sold to a stockholder or back to the producer. Alternatively, the structure can be leased by the producer/dealer and collected after the deconstruction.

The second level is relocated reuse of structural components. Similarly, as with the whole structure, components of primary or secondary structure and envelope can be reused directly, via material dealer, or their manufacturer.

Re-fabrication of individual components by using constituent products represent the third level. Usually, the individual components cannot be used in the same design configuration they need to be remanufactured (usually involving separation of different materials, welded parts and so on). The modification of the constituent product can be done by the product manufacturer, material dealer, or demolition contractor and then sold to the manufacturer or dealer.

10. Summary and conclusions

The environmental advantages of reusing reclaimed structural steel are considerable, compared to the common practice of recycling by re-melting scrap. There are also potential cost savings compared to the use of new steel.

PROGRESS Project focuses on single-storey buildings, and within this project, the reuse scenarios can be broadly divided into three categories: (i) the entire primary and/or secondary structure, (ii) components of the primary (e.g. trusses or 2D portal frame, rafters, columns) and components of the secondary structure or envelope, and (iii) constituent products (IPE, HEA, HEB, RHS, CHS profiles, as Z-, C- or Σ - cold-formed steel profiles), and may involve or not relocation.

The goal of the present document was to summarize the phenomena influencing reusability of structural steel as a material and the steel-based components in order to establish a scientific basis for the development of future verification and approval procedures.

First, material properties (based on Task 2.3) and acceptability criteria (in terms of geometrical imperfections, based on Task 2.4) were investigated to enable or limit the potential reuse of these components and classification of reusing situations are proposed, with associated acceptability criteria for the steel products.

The reuse of reclaimed steel is limited to:

- Steelwork erected after 1970;
- Steelwork which has not been subject to fatigue, e.g. not reclaimed from bridges;
- Steelwork from structures which have not experienced extreme loads;
- Steelwork which has not been subject to significant strains, e.g. plastic hinges;
- Steelwork without significant loss of sections' dimensions due to corrosion;
- Steelwork which has not been exposed to high temperature.

The important aspect in selecting the structure/members for reuse is they should come from damage-free building structures, i.e. structural members that have not been subjected to extreme events outside the code limits (e.g. large-scale earthquakes, extreme winds, extreme drifted snow etc.). The main common extreme events that can appear in the life of single-storey steel buildings are (i) ageing due to various actions, (ii) fatigue, and (iii) fire.

Single storey steel structures undergo no major changes in time, except for rust and plastic deformations. Rust problems can be avoided by means of appropriate corrosion protection. Plastic deformations from loading cannot always be avoided and may cause partial damage in structural members, identifying two types of strain aging: (i) static strain ageing, e.g. foundation settlement, where material properties change after plastic deformation, and (ii) dynamic strain ageing, e.g. large-scale earthquakes, where material properties change during the deformation. Strain ageing mainly affects the mechanical characteristics as follows: (i) the yield strength measured after ageing is higher, (ii) the ultimate strength can also increase, and (iii) ductility and percentage reduction of area after fracture decrease.

In case of fatigue, crane runway girders are fatigue-prone structures, implying a higher concentration of loads and a smaller fatigue endurance of the structural elements supporting the crane, in conjunction with stress concentration and crack initiation due to the technological process of manufacturing

the structural elements and their components. The assessment of the reliability of an existing structure aims at producing the evidence that it will function safely over a specified residual service life.

The effect of creep on steel structures is exhibited during a fire event, when the elevated temperatures are affecting the building and the structure is loaded or the element subjected to fire is restrained. Although, if the failure does not occur, the creep allows large displacements to be produced. After cooling the structure will keep residual displacements as well as residual stresses which are difficult to be estimated.

All structural steel reclaimed for reuse, is to be inspected and tested.

Quantification of the material properties and assessment of the condition of the structure, or structural components is essential to evaluate structural reusability.

The test regime, non-destructive or destructive testing, number and location of tests, is intended to allow the necessary material properties according to EN 1090-2 clause 5.1 to be declared. Non-destructive testing should prevail, as much as possible. Materials can be classified upon completion of these assessments.

In the first part (related to Task 2.3 the classification was necessary to establish whether the reclaimed steel material should be allowed for structural use to EN 1993 with or without any restriction. Reclaimed steel materials should be classified into the following classes:

- Class A: steel materials that meet performance requirements through essential material testing and with approved quality assurance from original certificates,
- Class B: steel materials that meet all performance requirements through extensive material testing and with approved quality assurance, i.e. certificates of compliancy to the relevant European Product Standards, by re-certification,
- Class C: steel materials classified as the most conservative grade in accordance with structure age and location.

This material characteristics declared under CE marking procedures are designed to ensure that the material is as specified in design. When using reclaimed steel, the design is based on the material properties (either tested or based on conservative assumptions), maintaining the relationship between the design assumptions and material resistance with an adequate level of reliability.

The second part (related to Task 2.4) concentrates on acceptability criteria of (i) constituent products (IPE, HEA, HEB, RHS, CHS profiles – Section 5, as Z-, C- or Σ - cold-formed steel profiles – Section 7), (ii) the entire primary and/or secondary structure, structural components of the primary (e.g. trusses or 2D portal frame, rafters, columns – Section 6) and components of the secondary structure (Section 7) or envelope (Section 8).

The overall framework for verification of the reusability of a constituent product can be done by three available options:

- Option 1: The original documentation exists, and the elements can be identified/confirmed according to the product standards. All surfaces are free of rust. Minimum measurements to confirm the section and length tolerances are needed.
- Option 2: The original documentation is missing. Reclaimed steel elements are measured to obtain the actual dimensions and thicknesses. Detailed measurements are taken to confirm the section and length tolerances. All surfaces are checked against rust.

- Option 3: The reclaimed steel elements do not meet the tolerances and are beyond the economic repair. These elements can be used as non-structural elements or can be sent to the scrap.

In case of Option 1 and Option 2, if the reclaimed steel material corresponds to the classification in Section 4, i.e. Class A and Class B, and the acceptance criteria are fulfilled, then the fabricated steelwork can be CE marked according to EN 1090-1:2009.

Reclaimed steel structural components must clearly be treated differently, as it might have been manufactured to a withdrawn standard and is most unlikely to have any documented test results from time of manufacture. EN 1090-2 sanctions the use of other materials by stating that: "If constituent products that are not covered by the standards listed are to be used, their properties are to be specified". There will be no difference in the fabrication processes, procedures, standards or tolerances for either new steel or reclaimed steel. It is therefore appropriate that reclaimed structural steel components can be CE Marked in accordance with EN 1090. In addition to careful control of the structural components, material properties must be declared according to EN 1090-2.

Reclaimed steel structural components, detail, module, or primary structure can be CE marked according to EN 1090-1. Nevertheless, some degree of uncertainty is inevitably associated with the use of reclaimed steelwork. The overall framework for verification of the reusability of components, or entire primary structures can be framed in three possible classes, after checking the eligibility and compliance with tolerances in EN 1090-2:

- Class RSC1: the structural component has not been CE marked in the first life and has to be certified as a new structural component/structure. Deep investigations are necessary for this Class - steel materials meet performance requirements through extensive testing;
- Class RSC2: the structural component has been CE marked in the first life according to EN 1090-1 and the original documentation is available. Each component should be reassessed to confirm the compliance with EN1090-2 and the harmonised standards. The reclaimed structural component can be reused in designed according to EN 1993-1-1 with some restrictions: (i) plastic global analysis is not recommended when reclaimed steel is reused; (ii) a conservative value of the γ_{M1} safety factor is recommended to address possible uncertainties as the assessment processes are likely to be less reliable than those undertaken for the new steel structural components.
- Class RSC3: the structural component has been CE marked in the first life according to EN 1090-1, but in this case an existing CE marking is not available. The structural components have to conform with EN 1090-2 standard. In general, steel materials and welding can be evaluated through limited material testing and certified. The reclaimed structural component can be reused in designed according to EN 1993-1-1 with the same restrictions as for Class RSC2.

Also, the following aspects should be considered:

- the chance of being able to remove a component without damage depends particularly on the installation method and building typology;
- if dismantling is very time-consuming, the component may no longer pay for itself;
- the cleaning and reconditioning could mainly take place in adequate spaces, as there is usually no time and little space available on the construction sites;
- the structural components identified as reusable, in principle, must meet the corresponding demands presented in sections 4 to 8 of the present document;

- in what concerns the building envelopes they should be energy-positive, adaptable, affordable, environmental, healthy, intelligent and durable. The envelope is essential in ensuring the comfort and energy savings of the system taken as a whole and has to provide as much as possible a uniform “wrapping” of the steel structure in order to avoid and/or control thermal bridging.

PROGRESS Project focuses on the reuse of single-storey steel buildings and their components. The reused components can be framed on *Consequences Class* CC1 or CC2 according to Annex A of EN 1993-1-1, for static, quasi-static or seismic DCL type of loading. Consequently, Execution Class 2 (EXC2) is the most appropriate for the majority of single-storey industrial buildings.

The present document highlights that re-certified and re-fabricated reclaimed structural steelwork can be CE Marked in accordance with EN 1090. There are no differences in the fabrication processes, procedures, standards or tolerances for either new steel or reclaimed steel. It is therefore appropriate that re-fabricated, reclaimed structural steelwork can be CE Marked in accordance with EN 1090.

At the building systems level, kit constructions offer the greatest opportunities for reuse. From this point of view industrial single-storey steel buildings can be regarded as the best solutions. Portal frames typically use hot-rolled I-section beams and columns for the roof rafters and supporting columns or built-up welded cross-sections, although thin-walled cold-formed steel sections may be adequate for small span structures. The usual span of these structures is in the range of 12 m to 40 m; however smaller/larger spans are also possible. Portal frames come in a variety of different shapes and sizes, with flat and pitched roofs. Large variety of framing systems exists on the market, offering standard solutions, where the structure consists of columns and rafters made of welded or hot-rolled profiles, purlins and rails of cold-formed galvanized profiles. Portal frames can be deconstructed from the building and refurbished and reused on the same or an alternative building. At a much larger scale, complete steel buildings can be reused.

Recommended solutions for reuse designing of steel framed buildings are:

- regularity in distances;
- load increasing so the building can be removed to more demanding location;
- regularity in cross-sections, material grades and connections;
- end- and base plates bolted to columns;
- simple connection details bolted to main components or welded to existing plates;
- all system components shall be prefabricated in a factory and presented to users on a system catalogue.

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