Structural Steel Design to MS EN 1993-1-1: An Introduction and Overview

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THE development of the Eurocode system has been ongoing for more than 20 years. The entire Eurocode system is divided into 10 parts, namely, EN 1990 through EN 1999. The EN 1990 and EN 1991 are the base codes from which all the other Eurocodes must refer to irrespective of the structural material used for design. The EN 1993 or Eurocode 3 (or EC3 for short) pertains to the design of steel structures for buildings and civil engineering works. This paper is an introduction and overview of the EN 1993, focusing particularly on the EN 1993-1-1 which is the sub-sub part of EN 1993. The MS EN 1993-1-1 is the Malaysian version of EN 1993-1-1.

THE STRUCTURE OF EUROCODE 3

Consistent with the Eurocode system for structural material design, EC3 complies with the principles and requirements for the safety and serviceability of structures given in the base code, namely, EN 1990 – "Basis of structural design" and EN 1991 – "Actions in Structures". In addition, EC3 is intended to be used in conjunction with several other codes such as EN 1090 – "Execution of Steel Structures" and other codes pertaining to material properties. There are six sub-parts to EC3, namely:

EN 1993-1: General rules and rules for building

EN 1993-2: Steel bridges

EN 1993-3: Towers, masts and chimneys

EN 1993-4: Silos, tanks and pipelines

EN 1993-5: Piling

EN 1993-6: Crane supporting structures

It should be noted that the rules in EN 1993-2 to EN 1993-6 supplements those of EN 1993-1. Thus, it can be said that EN 1993-1 is the base code for the design of steel structures. The EN 1993-1 in turn is sub-divided into 12 sub-parts, namely:

EN 1993-1-1: General rules and rules for buildings

EN 1993-1-2: Structural fire design

EN 1993-1-3: Cold-formed thin gage members and sheeting

EN 1993-1-4: Stainless steels

EN 1993-1-5: Plated structural elements

EN 1993-1-6: Strength and stability of shell structures

EN 1993-1-7: Strength and stability of planar plated structures transversely loaded

EN 1993-1-8: Design of joints

EN 1993-1-9: Fatigue strength of steel structures

EN 1993-1-10: Selection of steel for fracture toughness and through-thickness properties

EN 1993-1-11: Design of structures with tension components made of steel

EN 1993-1-12: Supplementary rules for high strength steel

The structure of the Eurocode system is such that duplication of information is avoided as much as possible. For this reason, cross-references of information among the various sub-parts of the codes are used extensively. For example, a steel building designer will require references to EN 1990 and EN 1991 for loads and load combinations. He or she will then require references to EN 1993-1-1 for general rules, EN 1993-1-8 for connection designs, EN 1993-1-2 to ensure compliance to fire safety and EN 1994 for the design of a steel-concrete composite floor system. Thus, the design documentation will involve references to several codes in the Eurocode system.

Unlike the BS 5950-1:2000, EN 1993-1-1 is a modern performance based code rather than a prescriptive based code. The code is intentionally kept very brief, showing only the basic and necessary background principles for steel design. Instead of providing the tabulation of design stress tables, formulas are provided. In a simplistic sense, it can be said that EN 1993-1-1 emphasises what BS 5950-1:2000 places in the appendix. There are many supports available for users who require the design stress tables from handbooks and websites.

Eurocode embraces modern technology to provide users with up-to-date information. A category of information called "Non-Conflicting and Complementary Information" or NCCI on the use of EN 1993 is available in this website (www.steel-ncci.co.uk) which provides users with the latest information about the code.

Moreover, design examples and other design aids are freely available in www.access-steel.com. The advantage of using NCCI is that any new design information can be changed readily without the necessity of issuing amendments to the code.

NATIONAL ANNEX

The unique feature of the Eurocode system is that individual countries which adopted these codes can develop their own National Annex (NA), which overrides certain specific parts of the main code. These annexes are meant to account for design conditions unique to the individual countries. An example of the parameter allowed in the NA is the minimum design temperature of steel in a particular country. The IEM-SIRIM SWO technical committee for the "Code of Practice for Design of Structural Steel" has already completed the National Annex for EN 1993-1-1, which is available for public comment since December 2009. The code will be designated MS EN 1993-1-1, the prefix "MS" being short for Malaysian Standard.

PARTIAL MATERIAL SAFETY FACTORS

Partial material safety factors, also called "gamma factors" and denoted by the symbol γ_M, are used extensively in EC3. Subscripts 0, 1 or 2 are added to further clarify the failure mode being controlled. Thus,

γ_{M0} is the partial material safety factors for yielding failure.

γ_{M1} is the partial material safety factors for buckling failure.

γ_{M2} is the partial material safety factors for fracture failure.

Users of the code will recognise immediately that a particular provision is controlling buckling failure mode if γ_{M1} is present, which is very useful for the fundamental understanding of the structural behaviour. Suggested values of these gamma factors are given in EC3 but individual countries may change their values in the NA. It should be mentioned that the BS 5950-1 (2000) also uses partial material safety factors, except that these factors are built into and not explicitly indicated in the design equations. A hallmark of EN 1993 is the transparent nature of their design equations, where these factors as well as other design principles are clearly indicated.

MATERIAL PROPERTIES

The designation for structural steel as specified in the Eurocode for hot rolled steel (EN 10210 & EN 10025) as well as cold form steel (EN 10219) are shown in Table 1 and 2 respectively. The yield and tensile stresses mentioned in the table are for material thickness less than 40mm.

The EN 1993-1-1 is particularly concerned with ductility in the structural steel material, and several provisions are placed in the material properties to achieve minimum ductility including Charpy impact value, ratios of ultimate to yield stress, ratios of ultimate to yield strain as well as minimum elongation.

It is compulsory in EN 1993 for all steel to have a guaranteed minimum Charpy Impact value (generally 27 Joules). The temperature which the Charpy test is done is designated by the "J" value following the steel grade shown in Table 2. Specifically,

JR denotes Charpy test carried out at 20 Celsius (room temperature)

JO denotes Charpy test carried out at 0 Celsius

J2 denotes Charpy test carried out at -20 Celsius

For steel structures constructed in Malaysia, a JR designation is generally sufficient.

The variation in yield stress with respect to the material thickness up to 80 mm in accordance to EN10025 is shown in Table 3a for Grade S275 steel and Table 3b for Grad 355 steel. It can be seen that between a thickness of 16mm and 40mm as well as between a thickness of 63mm and 80mm, the Eurocode has a higher steel grade compared to that in the corresponding British Standard.

The higher yield stress will not lead to substantially different load carrying capacities. However, it aids considerably the design process since the majority of the available sections are less than 40mm thick and a constant yield stress can be used for these sections.

Table 1: Hot-rolled steel for UB & UC

EN 10025		
Grade	Yield Stress (MPa)	Tensile Stress (MPa)
S275 JR S275 JO S275 J2	275	430
S355 JR S355 JO S355 J2	355	510

Table 2: Cold-form steel for hollow section

EN 10219		
Grade	Yield Stress (MPa)	Tensile Stress (MPa)
S235 JRH	235	360 – 510
S275 JOH S275 J2H	275	410 – 580
S355 JOH S355 J2H	355	470 – 680

Table 3a: Material yield strength (Mild Steel)

	EN 10025	BS 5950
	S 275	S275
Thickness [mm]	Yield Stress [MPa]	
t ≤ 16	275	275
16 < t ≤ 40	275	265
40 < t ≤ 63	255	255
63 < t ≤ 80	255	245

Table 3b: Material yield strength (High Strength Steel)

	EN 10025	BS 5950
	S 355	S355
Thickness [mm]	Yield Stress [MPa]	
t ≤ 16	275	275
16 < t ≤ 40	275	265
40 < t ≤ 63	255	255
63 < t ≤ 80	255	245

The Young's modulus allowed in Eurocode is about 2.5% higher than that in the BS 5950 as shown in Table 4.

Table 4: Young's modulus and Poisson ratio

	EN 1993	BS 5950
Young's modulus [MPa]	210000	205000
Poisson ratio	0.3	0.3

Eurocode recognised that modern steel production technique using fine grain steel will result in a ultimate to yield stress ratio that is lower than that of the conventional steel production process. The minimum ductility requirements based on tension tests are shown in Table 5.

Table 5: Ductility requirements for EN 1993

Ultimate to Yield stress ratio	1.1
Ultimate to Yield strain ratio	15
Elongation at failure	15%

It should be mentioned that individual countries can revise this requirement in their NA, and this has been done in the British Standard National Annex as well as in the Malaysian National Annex.

GLOBAL ANALYSIS AND STRUCTURAL STABILITY

In the EC3, the structural stability of a building frame can be carried out by one of the following methods:

a) Individual stability checks of equivalent members using appropriate buckling lengths.
b) Combined global analysis (generally second order elastic analysis) and individual stability checks of members.
c) Totally by global analysis (generally second order inelastic analysis).

Almost all design codes provide information for methods (a) and (b). However, EC3 is probably among the first code to provide guides for method (c). The second order inelastic analysis refers to the technique whereby the analysis and strength of a member or frame are determined directly and simultaneously without reference to the design strength equations in the code. Such analysis requires input for modelling the global and local imperfections, inelastic material properties, second order effects, and failure limits among many others. This input information is provided by the EC3.

ULTIMATE LIMIT STATES

Design strength at ultimate limit states can be categorised into four groups, namely, resistance of cross-sections, buckling of members, buckling of frames and uniform built-up compression members. Except for buckling of frames, the design guides for determining the ultimate limit states of the other categories are covered under ultimate limit states. The buckling of frames, together with section classification, are covered under global analysis.

The design tables for beam buckling and column buckling widely found in BS 5950 are conspicuously absent from the MS EN 1993-1-1. This absence is understandable as the code mainly covers the design principles used. Such tables can be generated from the design principles or found in handbooks. Also, MS EN 1993-1-1 makes references to other parts or sub-parts of the Eurocode so as not to repeat the information. Thus, shear lag and block shear in tension member design are covered by EN 1993-1-8 as these phenomenon are considered (and rightly so) as connection behaviours.

It is interesting to note that EC3 always starts a section with the general philosophy. For example, in shear resistance design,

$$\frac{V_{Ed}}{V_{c,Rd}} \leq 1.0$$

Where V_{Ed} is the design value of shear force and $V_{c,Rd}$ the design shear resistance. While the above requirement is obvious, it is necessary for completeness as a legal document. Subsequently, the code provides the design guide for shear resistance as

$$V_{c,Rd} = V_{pl,Rd} = \frac{A_v (f_y/\sqrt{3})}{\gamma_{M0}}$$

Note the clarity of subscript and the transparency of the principles used in the above equation. The subscript 'pl' informs that plastic (and not the elastic) resistance is considered. The use of the term $(f_y/\sqrt{3})$ instead of $(0.6f_y)$ informs of the yield criteria used in the shear resistance. The use of the material partial safety factor (γ_{m0}) is clear even though the value might be unity. Such clarity and transparency are repeated throughout the code, and extremely useful for the understanding of the design code especially for the international community.

A particularly complex area in the MS EN 1993-1-1 is in the provision for buckling resistance for combined bending and axial compression. The expression for this provision is

$$\frac{N_{Ed}}{\chi_y \frac{N_{RK}}{\gamma_{M1}}} + k_{yy}\frac{M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}} + k_{yz}\frac{M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}} \le 1$$

$$\frac{N_{Ed}}{\chi_z \frac{N_{RK}}{\gamma_{M1}}} + k_{zy}\frac{M_{y,Ed}}{\chi_{LT}\frac{M_{y,Rk}}{\gamma_{M1}}} + k_{zz}\frac{M_{z,Ed}}{\frac{M_{z,Rk}}{\gamma_{M1}}} \le 1$$

Briefly, the first term refers to the axial capacity and the last two terms refer to bending capacities in the y and z axis respectively. The term χ is the reduction factor due to axial or lateral torsional buckling. The complexity of the above formula lies in the expression for interaction factors k_{yy}, k_{yz}, k_{zy} and k_{zz} which are too complicated to use in routine hand calculations. This is one area where the use of NCCI is very effective. Conservative simplifications for the above factors can be found Ref. (5) and (6).

NATIONAL ANNEX TO MS EN 1993-1-1

The National Annex to MS EN 1993-1-1 is modelled after the National Annex to BS EN 1993-1-1 with few changes as highlighted in this section.

Other Steel Products (NA 2.3)

This NA permits other steel products to be used besides those listed in the MS EN 1993-1-1, provided they satisfy the ductility and weldability requirements. This is particularly important for Malaysia where our steel products can come from many sources that are not necessarily based in Europe. The NA permits SIRIM Berhad Malaysia (SIRIM) or the Institution of Engineers, Malaysia (IEM) to list steel products that are deemed to satisfy the requirements of MS EN 1993-1-1 in the NCCI.

Ductility Requirements (NA 2.5)

The comparison for ultimate to yield stress and strain ratios are shown in the table below.

		Elastic	Plastic	Plastic
	EN 1993-1-1	MS EN 1993-1-1 & BS EN 1993-1-1		BS 5950
Ultimate to Yield stress ratio	1.10	1.10	1.15	1.2
Ultimate to Yield strain ratio	15	15	20	20
Elongation at failure	15%	15%	15%	15%

This NA makes a clear distinction between the ductility ratios for elastic and plastic analysis whereas the only limits for plastic design are placed on the ductility requirements under BS 5950. As mentioned, the use of modern fine grain steel permits the use of lower ultimate to yield stress ratio for plastic design.

Fracture Toughness (NA 2.6)

Steel buildings in Malaysia are not likely to be subjected to temperature below 20 degrees Celsius (room temperature) except for cold store rooms, highland areas and other similar cold areas. For this reason, it is only necessary to specify "JR" in the material grade specification.

Initial Local Bow Imperfections (NA 2.11)

In most cases, equations for design buckling checks already account for the initial local bow effects, hence the imperfection values for the bow can be safely ignored. However, these imperfection values can be important for certain types of analysis or when different methods are used for the design buckling checks. Two choices are available, namely, the use of Table 5.1 in the MS EN 1993-1-1 or to back calculate the initial local bow values from the respective design buckling checks equations. Use of the former is much simpler compared to that of the latter, however, the latter conforms more closely to the design buckling equations. The NA to BS EN 1993-1-1 uses the latter whereas other countries, such as Hungary, allow both options to be used. The NA to MS En 1993-1-1 also permits both options to be used.

Partial Safety Factors (NA 2.15)

The following table compares the material partial factors γ_{M2} (for fracture).

	EN 1993-1-1	BS EN 1993-1-1	MS EN 1993-1-1	BS 5950
γ_{M2}	1.25	1.15	1.20	1.20

The γ_{M2} factor serves two purposes, namely, contributes to the overall reliability of the design (which can be loosely thought of as factor of safety) as well as to ensure that the ductile yielding failure occurs before the onset of the more brittle fracture failure. In the context of reliability, BS5950 cannot be compared directly with the other codes as the load factor used is different. However, the use of γ_{M2} = 1.2 in the MS EN will result in higher reliability as compared to BS EN which uses γ_{M2} = 1.15. More importantly, the use of γ_{M2} = 1.2 retains the benefit of ensuring yielding failure over fracture failure as currently imposed indirectly by the BS 5950. This is also particularly important when seismic load is considered in EN 1998 by a separate sub-committee.

Modificaton Factor f (NA 2.18)

The modification factor f allows for redistribution of moment between lateral restraints for buckling checks of rolled beams or equivalent welded beams, thus allowing for an increase in the beam buckling capacity. The amount of redistribution permitted depends on the moment diagram between the restraints, which is accounted for

by the use of the correction factor k_c. Two approaches can be used to calculate k_c, namely, the use of Table 6.6 in MS EN 1993-1-1 or the use of

$$k_c = \frac{1}{\sqrt{C_1}}$$

Where

$$C_1 = \frac{M_{cr} \text{ for actual bending moment diagram}}{M_{cr} \text{ for a uniform bending moment diagram}}$$

And C_1 is given in references in NA.4 or Ref. (7). The factor C_1 is also analogous to the m_{LT} factor in BS5950.

The use of Table 6.6 for k_c is conservative. The use of the above equation will generally result in similar values for k_c as that in Table 6.6 for common loading situations such as uniform or point load at mid-span or members with end moments only. However, the values for k_c for more complicated loading situations (such as combined end moments and transverse load between spans) are not covered by Table 6.6 and can only be obtained using the above equations. The NA to MS 1993-1-1 permits the use of either Table 6.6 or the above equation.

NA.4 References to Non-contradictory complementary information (NCCI)

References to NCCI include SIRIM and IEM in case there are NCCI published that are particular to the local steel construction industry. ■

REFERENCE

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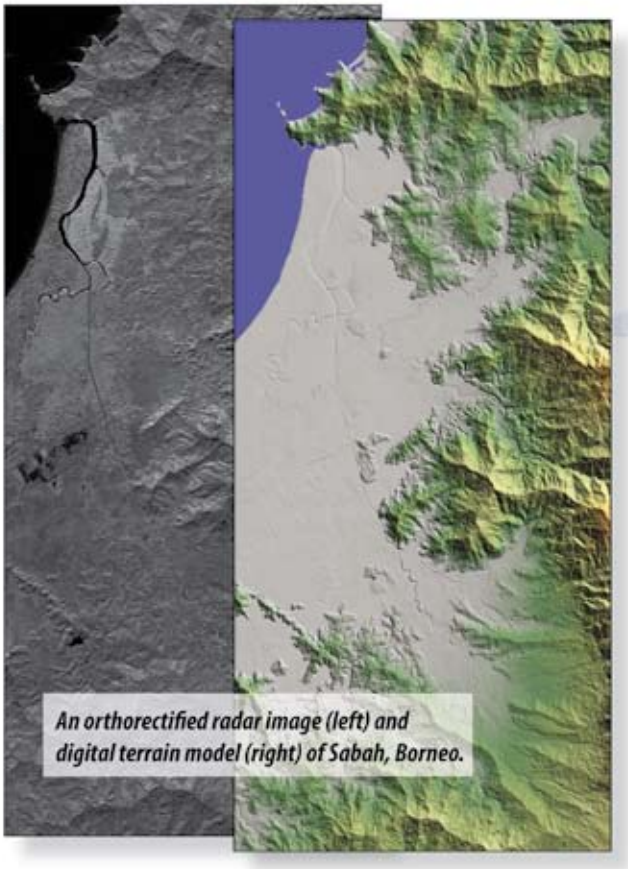
An orthorectified radar image (left) and digital terrain model (right) of Sabah, Borneo.