Eurocode: Basis of structural design

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Introduction

This chapter gives a brief introduction to EN 1990, describes its main innovative features, particularly the requirements, reliability differentiation, based on the consequences of failure, limit state and actions and the choice of load combination format and safety factors by the UK national annex considering consistency of safety for all materials.

EN 1990 (Eurocode 0: Basis of structural design) is the head key code for the harmonized Structural Eurocodes. EN 1990 establishes and provides comprehensive information and guidance for all the Structural Eurocodes, the principles and requirements for safety and serviceability, and provides the basis and general principles for the structural design and verification of buildings and civil engineering structures (including bridges, towers and masts, silos and tanks etc.). EN 1990 gives guidelines for related aspects of structural reliability, durability and quality control. It is based on the limit state concept and used in conjunction with the partial factor method. Comprehensive background information is given on EN 1990 by Gulvanessian, Calgaro and Holicky [1].

As shown in Figure 0.1, EN 1990 will be used with every Eurocode part for the design of new structures, together with:

- EN 1991 (Eurocode 1: Actions on structures); and
- EN 1992 to EN 1999 (design Eurocodes 2 to 9)
This is different to the situation adopted by the present British Standard codes of practice (e.g. BS 8110, BS 5950, BS 5628 etc.) because with the design Eurocodes the requirements for achieving safety, serviceability and durability and the expressions for action effects for the verification of ultimate and serviceability limit states and their associated factors of safety are only given in EN 1990. Unlike the equivalent British Standard codes of practice the material Eurocodes (EN 1992, EN 1993, EN 1994, EN 1995, EN 1996 and EN 1999) only include clauses for design and detailing in the appropriate material and require all the material independent information for the design (e.g. safety factors for actions, load combination expressions etc.) from EN 1990.

Furthermore, construction products requiring CE marking (e.g. pre-cast concrete products, metal frame domestic houses, timber frame housing etc.) all need to use the principles and rules in EN 1990 together with the appropriate Eurocodes, thus ensuring a level playing field, as do the execution standards.

As well as being the key Eurocode in setting recommended safety levels, EN 1990 also introduces innovative aspects described as follows which encourage the design engineer to consider the safety of people in the built environment together with the responsible consideration of economy by:

- allowing reliability differentiation based on the consequences of failure;
- introducing the concept of using the representative values of actions and not only the characteristic values as used for UK codes of practice. The
loads used in the EN 1990 load combinations recognize the appropriate cases where:
- rare
- frequent, or
- quasi-permanent
occurring events are being considered with the use of an appropriate reduction coefficient ($\psi$), applied to the characteristic load values as appropriate. The use of the representative values for actions in the load combination expressions for ultimate and serviceability limit state verifications are logical and give economies for particular design situations;
- an alternative load combination format, giving the choice to the designer of using either the expressions 6.10 or 6.10a/6.10b for the combination of actions for ultimate limit state verification. This choice provides opportunities for economy especially for the heavier materials, and can provide flexibility with regard to assessment;
- the use of lower factors of safety for loads compared to British Standards. Although the effects of actions according to the Eurocodes are lower than British Standards codes for ULS and SLS verification, this should not be a concern to the industry as the EN 1990 values are based on better science and better research;
- the use of advanced analytical techniques for the designer is encouraged and the use of probabilistic methods should the designer wish to use these for the more specialist design problems.

**Principal objectives of EN 1990**

EN 1990’s principal objective is that this Eurocode sets out for every Eurocode part the principles and requirements for achieving:
- safety;
- serviceability;
- durability
of structures.

EN 1990 provides the information for safety factors for actions and the combination for action effects for the verification of both ultimate and serviceability limit states. Its rules are applicable for the design of building and civil engineering structures including bridges, masts, towers, silos, tanks, chimneys and geotechnical structures.
The requirements of EN 1990

To achieve safety, serviceability and durability for structures EN 1990 contains requirements to be adhered to by the complete Eurocode suite and construction product standards on

- fundamental requirements (safety, serviceability, resistance to fire and robustness);
- reliability management and differentiation;
- design working life;
- durability;
- quality assurance and quality control.

Each requirement is described as follows.

Fundamental requirements

The fundamental requirements stipulate that:

a) a structure should be designed and executed in such a way that it will, during its intended life with appropriate degrees of reliability and in an economic way:
   - sustain all actions and influences likely to occur during execution and use (safety requirement); and
   - meet the specified serviceability requirements for a structure or a structural element (serviceability requirement); and
b) in the case of fire, the structural resistance should be adequate for the required period of time;
c) a structure should be designed and executed in such a way that it will not be damaged by events such as explosion, impact or consequences of human errors, to an extent disproportionate to the original cause (robustness requirement). EN 1990 provides methods of avoiding or limiting potential damage.

Reliability differentiation

Design and execution according to the suite of the Eurocodes, together with appropriate quality control measures, will ensure an appropriate degree of
reliability for the majority of structures. EN 1990 provides guidance for adopting a different level of reliability (reliability differentiation). Additional guidance is included in an informative annex to EN 1990 *Management of structural reliability for construction works*. Calgaro and Gulvanessian [2] describe the management of structural reliability in EN 1990, where the concept of the risk background of the Eurocodes is described more comprehensively.

EN 1990 gives recommended values of partial factors applicable to actions and provides a framework for the management, at national levels, of structural reliability. Embodied in the values of the partial factors are implicit ‘acceptable’ or ‘accepted’ risk levels, which relates to the consequences of the hazard and use of the structure. Risk may be defined as:

\[
\text{Prob}(F) \times C
\]

where:

\text{Prob}(F) is the probability of the hazard occurring, and \\
C is the consequence in magnitude or extent, expressed, for example, in numbers of deaths, time or monetary units.

Partial factor design is based on the consideration of limit states which are, in most common cases, classified into ultimate and serviceability limit states idealizing undesirable phenomena. The design is such that their probability of occurrence in 50 years is less than an ‘acceptable’ value.

Figure 0.2 shows the ranges of values for probabilities for the ultimate and serviceability limit states, obtained when using EN 1990.

![Figure 0.2. Probabilities associated with limit states](image_url)
In EN 1990 the design working life is the assumed period for which a structure is to be used for its intended purpose with anticipated maintenance but without major repair being necessary. Table 0.1 taken from the UK national annex to EN 1990 gives a design working life classification.

**Design working life**

The durability of a structure is its ability to remain fit for use during the design working life given appropriate maintenance. The structure should be designed in such a way, and/or provided with protection so that no significant deterioration is likely to occur within the period between successive inspections. The need for critical parts of the structure to be available for inspection without complicated dismantling should be considered in the design. Other interrelated factors that should be considered to ensure an adequately durable structure are listed in EN 1990 and each is considered and given as follows:

a) the intended and future use of the structure;

b) the required performance criteria;
c) the expected environmental influences;


d) the composition, properties and performance of materials;

e) the choice of a structural system;


f) the shape of members and structural detailing, and buildability;

g) the quality of workmanship and level of control;


h) the particular protective measures;


i) the maintenance during the intended life.

Quality assurance and quality control

EN 1990 stipulates that appropriate quality assurance measures should be taken in order to provide a structure that corresponds to the requirements and to the assumptions made in the design by:


• definition of the reliability requirements;

• organizational measures;

• controls at the stages of design, execution, use and maintenance.

Principles of limit state design

Ultimate and serviceability limit states

EN 1990 is based on the limit state concept used in conjunction with the partial safety factor method where limit states are the states beyond which the structure no longer fulfils the relevant design criteria. Two different types of limit state are considered, namely ultimate limit state and serviceability limit state.

Based on the use of structural and load models, it has to be verified that no limit state is exceeded when relevant design values for actions, material and product properties, and geometrical data are used. This is achieved by the partial factor method.

In the partial factor method the basic variables (i.e. actions, resistances and geometrical properties) are given design values through the use of partial factors, $\psi$, and reduction coefficients, $\gamma$, of the characteristic values of variable actions (see Figure 0.3).

Design may also be based on a combination of tests and calculations, provided that the required level of reliability is achieved. Alternatively, EN 1990 allows for design directly based on probabilistic methods (see Figure 0.4).
Design situations

Design situations are sets of physical conditions representing the real conditions occurring during the execution and use of the structure, for which the design will demonstrate that relevant limit states are not exceeded.

EN 1990 stipulates that a relevant design situation needs to be selected to take account of the circumstances in which the structure may be required to fulfil its function.

Ultimate limit state verification design situations

EN 1990 classifies design situations for ultimate limit state verification as follows:

- persistent situations (conditions of normal use);
- transient situations (temporary conditions, e.g. during execution);
• accidental situations; and
• seismic situations.

Serviceability limit state verification design situations

Serviceability limit states correspond to conditions beyond which specified service requirements for a structure or structural element are no longer met and the design situations concern:
• the functioning of the construction works or parts of them;
• the comfort of people; and
• the appearance.

EN 1990 recommends that the serviceability requirements should be determined in contracts and/or in the design. EN 1990 distinguishes between reversible and irreversible serviceability limit states. EN 1990 gives three expressions for serviceability design: characteristic, frequent and quasi-permanent.

Actions

Actions are sets of forces, imposed displacements or accelerations. They are classified by their variation in time as follows:
• permanent actions, G, e.g. self-weight of structures, fixed equipment and road surfacing, and indirect actions caused by shrinkage and uneven settlements;
• variable actions, Q, e.g. imposed loads on building floors, beams and roofs, wind actions or snow loads;
• accidental actions, A, e.g. explosions or impact from vehicles.

A variable action has four representative values. In decreasing order of magnitude, they are:
• characteristic value $Q_k$;
• combination value $\psi_0 Q_k$;
• frequent value $\psi_1 Q_k$;
• quasi-permanent value $\psi_2 Q_k$.

The reduction coefficients, $\psi$, are applied to the characteristic load values which are appropriate to cases where
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• combination (or Rare)
• frequent, or
• quasi-permanent

occurring events are being considered.

Verification by the partial factor method

Ultimate limit states

For the ultimate limit state verification, EN 1990 stipulates that the effects of design actions do not exceed the design resistance of the structure at the ultimate limit state; and the following ultimate limit states need to be verified.

Ultimate limit states concern the safety of people and/or the safety of structures and, in special circumstances, the protection of the contents. They are associated with collapse or with other similar forms of structural failure.

In EN 1990 the following ultimate limit states are verified, where relevant.

• EQU. Loss of static equilibrium of the structure or any part of it considered as a rigid body, where:
  – minor variations in the value or the spatial distribution of actions from a single source are significant;
  – the strengths of construction materials or ground are generally not governing.
• STR. Internal failure or excessive deformation of the structure or structural members, including footings, piles and basement walls, etc., where the strength of construction materials of the structure governs.
• GEO. Failure or excessive deformation of the ground where the strengths of soil or rock are significant in providing resistance.
• FAT. Fatigue failure of the structure or structural members. The combinations apply:
  – persistent or transient design situation (fundamental combination);
  – accidental design situation;
  – seismic design situation.

For a limit state of static equilibrium (EQU), it is verified that:

\[ E_{d,\text{dst}} \leq E_{d,\text{stb}} \]
where

\[ E_{d,\text{dest}} \] is the design value of the effect of destabilizing actions, and
\[ E_{d,\text{stb}} \] is the design value of the effect of stabilizing actions.

When considering a limit state of rupture or excessive deformation of a section, member or connection (STR and/or GEO), it is verified that:

\[ E_d \leq R_d \]

where

\[ E_d \] is the design value of the effect of actions, and
\[ R_d \] is the design value of the corresponding resistance.

Specific rules for FAT limit states are given in the design Eurocodes EN 1992 to EN 1999.

For the ultimate limit state verification, EN 1990 stipulates that the effects of design actions do not exceed the design resistance of the structure at the ultimate limit state; and the following ultimate limit states need to be verified.

**Alternative load combination expressions in EN 1990 for the persistent and transient design situations**

EN 1990 specifies three sets of alternative combination expressions for the determination of action effects, expressions 6.10, 6.10a and 6.10b, and 6.10a modified and 6.10b (see the following) for the persistent and transient design situations to be used by EN 1991 and the design Eurocodes for ultimate limit state verification, as follows:

\[
\sum_{j=1}^{G_d} \gamma_{G_d} G_{k,j} + \gamma_P^P + \gamma_{Q,1} Q_{k,1} + \sum_{i>1} \gamma_{Q,i} \psi_{0,i} Q_{k,i}
\]  

(6.10)

The procedure using expression 6.10 is denoted as case A in this paper.

For this case the combination of actions is governed by a leading variable action \( Q_{k,1} \) represented by its characteristic value and multiplied by its appropriate safety factor \( \gamma_Q \). Other variable actions \( Q_{k,i} \) for \( i > 1 \) which may act simultaneously with the leading variable action \( Q_{k,1} \) are taken into account as accompanying variable actions and are represented by their combination value, i.e. their characteristic value reduced by the relevant combination
factor, $\psi_0$, and are multiplied by the appropriate safety factor to obtain the design values.

The permanent actions are taken into account with their characteristic values, and are multiplied by the load factor $\gamma_G$. Depending on whether the permanent actions act favourably or unfavourably they have different design values.

This is explained in Figure 0.5.

b) or the less favourable of the two following expressions:

$$\sum_{j=1}^N \gamma_{G,j} G_{k,j} \quad \gamma_P \quad + \quad \gamma_{Q,j} \psi_{0,j} Q_{k,j} \quad \gamma_{Q,i} Q_{k,i} \quad \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

(6.10a)

$$\sum_{j=1}^N \xi_j \gamma_{G,j} G_{k,j} \quad \gamma_P \quad + \quad \gamma_{Q,j} \psi_{0,j} Q_{k,j} \quad \gamma_{Q,i} Q_{k,i} \quad \gamma_{Q,i} \psi_{0,i} Q_{k,i}$$

(6.10b)

The procedure using expressions 6.10a and 6.10b is denoted as case B.

In expression 6.10a, there is no leading variable action: all the variable actions are taken into account with their combination value, i.e. their value is reduced by the relevant combination factor $\psi_0$. The permanent actions are taken into account as in expression 6.10, and the unfavourable permanent actions may be considered as the leading action in the combination of actions. All the actions are multiplied by the appropriate safety factors, $\gamma_G$ or $\gamma_Q$.

In expression 6.10b the combination of actions is governed by a leading variable action represented by its characteristic value as in expression 6.10 with the other variable actions being taken into account as accompanying variable actions and are represented by their combination value, i.e. their characteristic value is reduced by the appropriate combination coefficient of a variable action $\psi_0$. But the unfavourable permanent actions are taken into account
with a characteristic value reduced by a reduction factor, $\xi$, which may be considered as a combination factor.

All the actions are multiplied by the appropriate load factors, $\gamma_c$ or $\gamma_Q$. When the envelope of the two expressions showing the less favourable effects of expressions 6.10a and 6.10b is determined, generally expression 6.10a applies to members where the ratio of variable action to total action is low, i.e. for heavier structural materials, and 6.10b applies where the same ratio is high, i.e. for lighter structural materials.

c) or expression 6.10a modified to include self-weight only and expression 6.10b, as shown as follows:

\[
\sum_{j>1} \gamma_{G,j} G_{k,j} \quad \text{“+”} \quad \gamma_P P
\]

\[
\sum_{j>1} \xi \gamma_{G,j} G_{k,j} \quad \text{“+”} \quad \gamma_P P \quad \text{“+”} \quad \gamma_{Q,1} Q_{k,1} \quad \text{“+”} \quad \sum_{j>1} \gamma_{Q,j} \psi_{0,j} Q_{k,j}
\]

(6.10a, modified)

(6.10b)

The procedure using expressions 6.10a modified and 6.10b is denoted as case C. This case is very similar to case B but the first of pair expressions includes only permanent actions.

In the preceding text:

“+” implies ‘to be combined with’
\[\Sigma\] implies ‘the combined effect of’
$\xi$ is a reduction factor for unfavorable permanent actions $G$

EN 1990 allows through NDPs and the national annexes for

- the choice of which of the three combination expressions given in EN 1990 to use; and
- the specification of appropriate safety factors, $\gamma$ and combination coefficients, $\psi$ and $\xi$, for actions

which should be used nationally.

Comparison of expressions for the combination of the effects of actions between BSI structural codes of practice and EN 1990 (note that the factors of safety for permanent and variable actions are lower in EN 1990) using expression 6.10, are shown as follows.

For one variable action (imposed or wind)
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- BSI: \(1.4G_k + (1.4 \text{ or } 1.6)Q_k\)
- EN 1990: \(1.35G_k + 1.5Q_k\)

For two or more variable actions (imposed + wind)

- BSI: \(1.2G_k + 1.2Q_{kl} + 1.2Q_{k2}\)
- EN 1990: \(1.35G_k + 1.5Q_{kl} + 0.75Q_{k2}\)

where

\(G_k\) is the characteristic value for permanent actions, and
\(Q_k\) is the characteristic value for variable actions

**Choice of load combination expressions for the UK national annex to EN 1990**

Based on an investigation by Gulvanessian and Holický [3], the following two combinations have been adopted in the UK national annex for EN 1990 for buildings.

- Expression 6.10 with \(\gamma_G = 1.35\) and \(\gamma_Q = 1.5\)
- Expressions 6.10a and 6.10b with \(\gamma_G = 1.35, \gamma_Q = 1.5\) and \(\xi = 0.925\)

All recommended \(\gamma\) and \(\psi\) (except \(\psi_0\) for wind actions, where in the UK national annex \(\psi_0 = 0.5\)) values have been adopted by the UK national annex for EN 1990, and are generally being adopted by most CEN Member States.

For bridges only the use of expression 6.10 is permitted.

**Load combination expressions in EN 1990 for accidental design situations**

For the ultimate limit states verification for accidental design situations, EN 1990 requires the following combination expression to be investigated:

\[ \sum_{j \geq 1} G_{k,j} \text{“+” } P \text{“+” } A_d \text{“+” } (\psi_{1,1} \text{ or } \psi_{2,1})Q_{k,1} \text{“+” } \sum_{i \geq 1} \psi_{2,i}Q_{k,i} \]

The choice between \(\psi_{1,1}Q_{k,1}\) or \(\psi_{2,1}Q_{k,1}\) should be related to the relevant accidental design situation (impact, fire or survival after an accidental event or situation). In the UK national annex to EN 1990, \(\psi_{1,1}Q_{k,1}\) is chosen.
The combinations of actions for accidental design situations should either
- involve an explicit accidental action $A$ (fire or impact); or
- refer to a situation after an accidental event ($A = 0$).

For fire situations, apart from the temperature effect on the material properties, $A_d$ should represent the design value of the indirect thermal action due to fire.

The expression for the accidental design situation specifies factors of safety of unity both for the self-weight and the accidental action $A_d$ and a frequent or quasi-permanent value for the leading variable action. The philosophy behind this is the recognition that an accident on a building or construction works is a very rare event (although when it does occur the consequences may be severe) and hence EN 1990 provides an economic solution.

**Serviceability limit states**

For the serviceability limit states verification, EN 1990 stipulates that:

$$E_d \leq C_d \quad (6.13)$$

where

- $C_d$ is the limiting design value of the relevant serviceability criterion, and
- $E_d$ is the design value of the effects of actions specified in the serviceability criterion, determined on the basis of the relevant combination.

**Combination of actions for the serviceability limit states**

For the serviceability limit states verification, EN 1990 requires the three following combinations to be investigated:

a) The characteristic (rare) combination used mainly in those cases when exceedance of a limit state causes a permanent local damage or permanent unacceptable deformation.

$$\sum_{j \geq 1} G_{k,j} + P_k + Q_{k,1} + \sum_{l \geq 1} \psi_{0,l} Q_{k,l} \quad (6.14b)$$
b) The frequent combinations used mainly in those cases when exceedance of a limit state causes local damage, large deformations or vibrations which are temporary.

\[ \sum_{j=1}^{\infty} G_{k,j} \left( + \right) P \left( + \right) \psi_{1,1} Q_{k,1} \left( + \right) \sum_{i=1}^{\infty} \psi_{2,i} Q_{k,i} \]  
(6.15b)

c) The quasi-permanent combinations used mainly when long term effects are of importance.

\[ \sum_{j=1}^{\infty} G_{k,j} \left( + \right) P \left( + \right) \sum_{i=1}^{\infty} \psi_{2,i} Q_{k,i} \]  
(6.16b)

Partial factors for serviceability limit states

Unless otherwise stated (e.g. in EN 1991 to 1999), the partial factors for serviceability limit states are equal to 1.0. \( \psi \) factors are given in Table 1.3 in the chapter on Eurocode 1 in this book.

Conclusions

EN 1990 is a fully operative code and the concept of a fully operative material-independent code is new to the European design engineer. It is certainly not a code that should be read once and then placed on the bookshelf. It is the key Eurocode that sets the requirements for design, material, product and execution standards. EN 1990 needs to be fully understood as it is key to designing structures that have an acceptable level of safety and economy, with opportunities for innovation.

A course and a designers guide for EN 1990 are available in the UK through Thomas Telford Ltd. of the Institution of Civil Engineers.

Regarding implementation of EN 1990 in the UK, EN 1990 was published in April 2002 and the UK national annex for buildings was published in 2004. The UK national annex for bridges is due in 2009.

References
