Chapter 2

# Basis of structural design

*'EN 1990 ... is the head document of the Eurocode suite and describes the principles and requirements for safety, serviceability and durability of structures'*[1]

## 2.1 Contents of the Eurocode

*Eurocode – Basis of structural design*[2] is divided into six sections and four annexes (A-D), as shown in **Figure 12**. In this diagram, the size of each segment of the pie is proportional to the number of paragraphs in the relevant section.

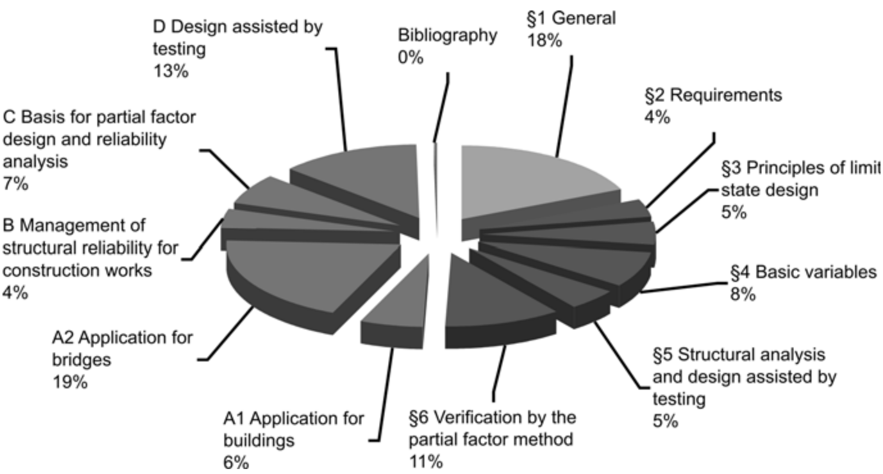


***Figure 12**. Contents of the Eurocode*

EN 1990 describes the basis for the design and verification of buildings and civil engineering works, including geotechnical aspects, and gives guidance for assessing their structural reliability (see **Figure 13**). It covers the design of repairs and alterations to existing construction and assessing the impact of changes in use. Because of their special nature, some construction works (such as nuclear installations and dams) may need to be designed to provisions other than those given in EN 1990.

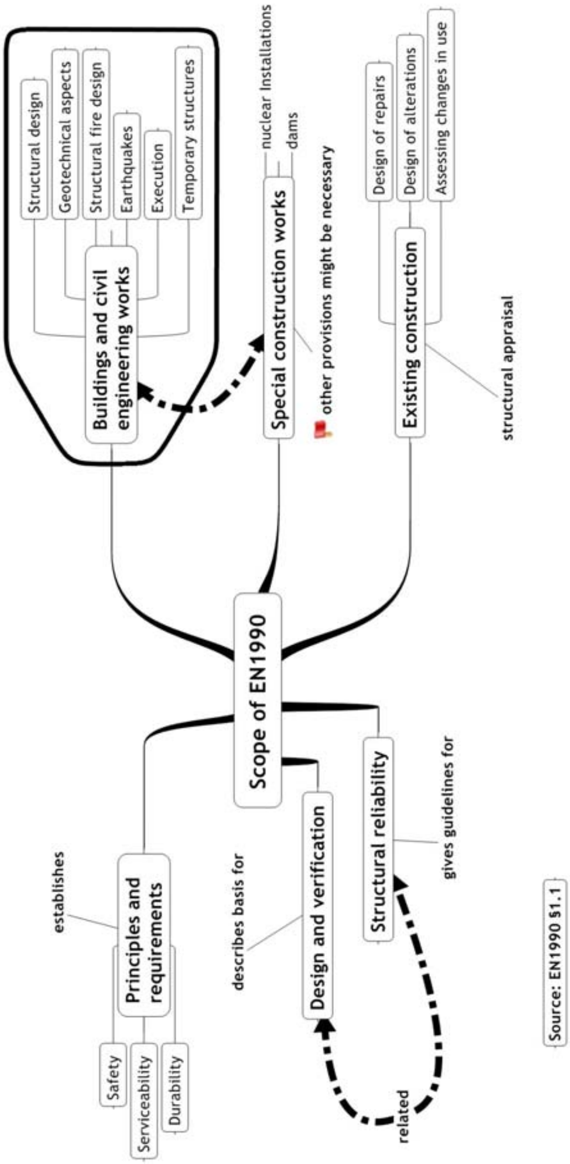


***Figure 13***. *Scope of EN 1990, Basic of structural design*

## 2.2 Requirements

The basic requirements of a structure are to sustain all likely actions and influences, to remain fit for purpose, and to have adequate structural resistance, durability, and serviceability. These requirements must be met for the structure's entire design working life, including construction.

The structure must not suffer disproportionate damage owing to adverse events, such as explosions, impact, or human error. The events to be taken into account are those agreed with client and relevant authorities.

In addition, the design must avoid or limit potential damage by reducing, avoiding, or eliminating hazards. This can be achieved by tying structural members together, avoiding collapse without warning (e.g. by employing structural redundancy and providing ductility), and designing for the accidental removal of a structural member.

The *design working life* is the

> *assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary.* *[EN 1990 §1.5.2.8]*

**Figure 14** compares the design working life of various structures according to EN 1990 (dark lines) with the modifications made to these time periods by the UK National Annex to EN 1990 (lighter lines). The most significant change is the extension of Category 5 to 120 years – although this only really affects fatigue calculations.

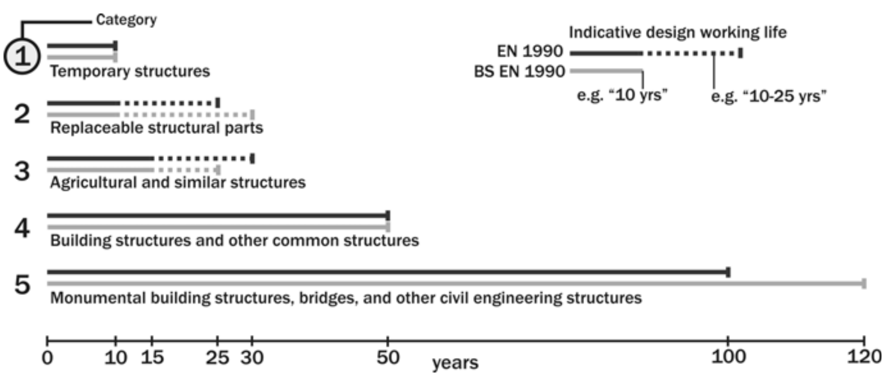


***Figure 14**. Design working life of various structures*

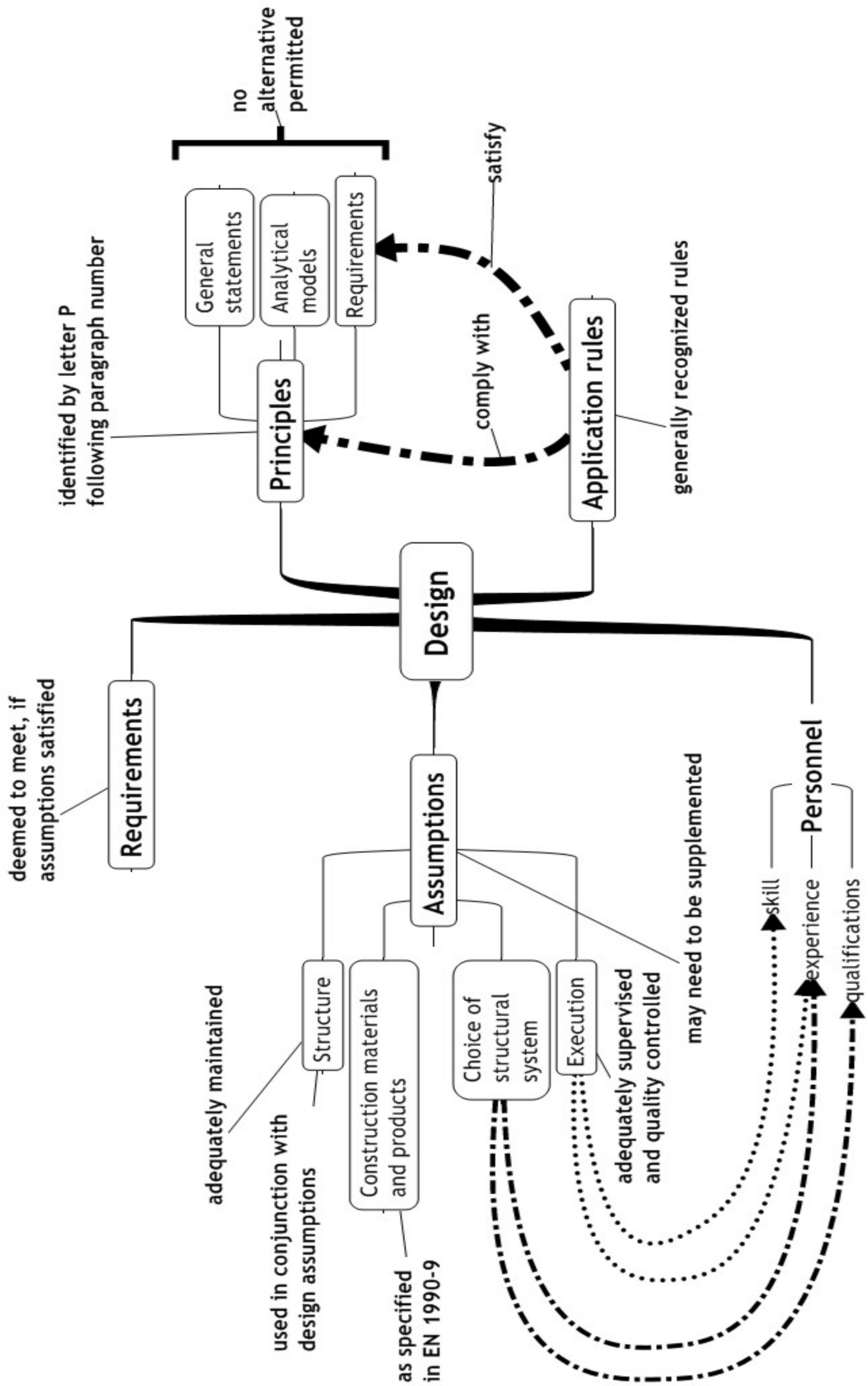


***Figure 15***. *Design according to the Eurocode*

## 2.3 Assumptions

EN 1990 makes important assumptions about the way structures are designed and executed (see **Figure 15**).

It is assumed that people with appropriate qualifications, skill, and experience will choose the structural system, design the structure, and construct the works. It is also assumed that construction will be adequately supervised and quality controlled; and the structure will be adequately maintained and used in accordance with the design assumptions.

Because they vary from country to country, EN 1990 gives no guidance as to what 'appropriate' qualifications are needed to perform these tasks. Likewise 'adequate' supervision and control is not further defined in the Eurocode.

## 2.4 Principles and Application Rules

A distinctive feature of the Structural Eurocodes is the separation of paragraphs into Principles and Application Rules (see **Figure 15**).

> *Design which employs the Principles and Application Rules is deemed to meet the requirements provided the assumptions given in EN 1990 to EN 1999 are satisfied.* *[EN 1990 §1.3(1)]*

Principles – identified by the letter 'P' after their paragraph numbers – are general statements and definitions that must be followed, requirements that must be met, and analytical models that must be used. The English verb that appears in Principles is 'shall'. *[EN 1990 §1.4(2) & (3)]*

Application Rules – identified by the absence of a letter after their paragraph numbers – are generally recognized rules that comply with the Principles and satisfy their requirements. English verbs that appear in Application Rules include 'may', 'should', 'can', etc. *[EN 1990 §1.4(4)]*

## 2.5 Principles of limit state design

The Structural Eurocodes are based on limit state principles, in which a distinction is made between ultimate and serviceability limit states.

Ultimate limit states are concerned with the safety of people and the structure. Examples of ultimate limit states include loss of equilibrium, excessive deformation, rupture, loss of stability, transformation of the structure into a mechanism, and fatigue.

Serviceability limit states are concerned with the functioning of the structure under normal use, the comfort of people, and the appearance of the construction works. Serviceability limit states may be reversible (e.g. deflection) or irreversible (e.g. yield).

Limit state design involves verifying that relevant limit states are not exceeded in any specified design situation (see Section 2.6). Verifications are performed using structural and load models, the details of which are established from three basic variables: actions, material properties, and geometrical data. Actions are classified according to their duration and combined in different proportions for each design situation.

**Figure 16** illustrates the relationship between these various elements of limit state design.

## 2.6 Design situations

Design situations are conditions in which the structure finds itself at different moments in its working life.

In normal use, the structure is in a *persistent* situation; under temporary conditions, such as when it is being built or repaired, the structure is in a *transient* situation; under exceptional conditions, such as during a fire or explosion, the structure is in an *accidental* situation or (if caused by an earthquake) a *seismic* situation. *[EN 1990 §3.2(2)P]*

Society is willing to accept that fires and explosions may lead to building damage – necessitating repair – whereas snow and wind should not. None of these events must lead to collapse. The Structural Eurocodes define partial factors for accidental and seismic situations (i.e. exceptional conditions which are unlikely to occur) that are typically 1.0. These factors are considerably lower than those specified for persistent and transient situations (conditions which are more likely to occur), typically 1.2-1.5. The development of different design situations helps to determine what level of reliability the design requires and what actions need to be considered as part of that design situation.

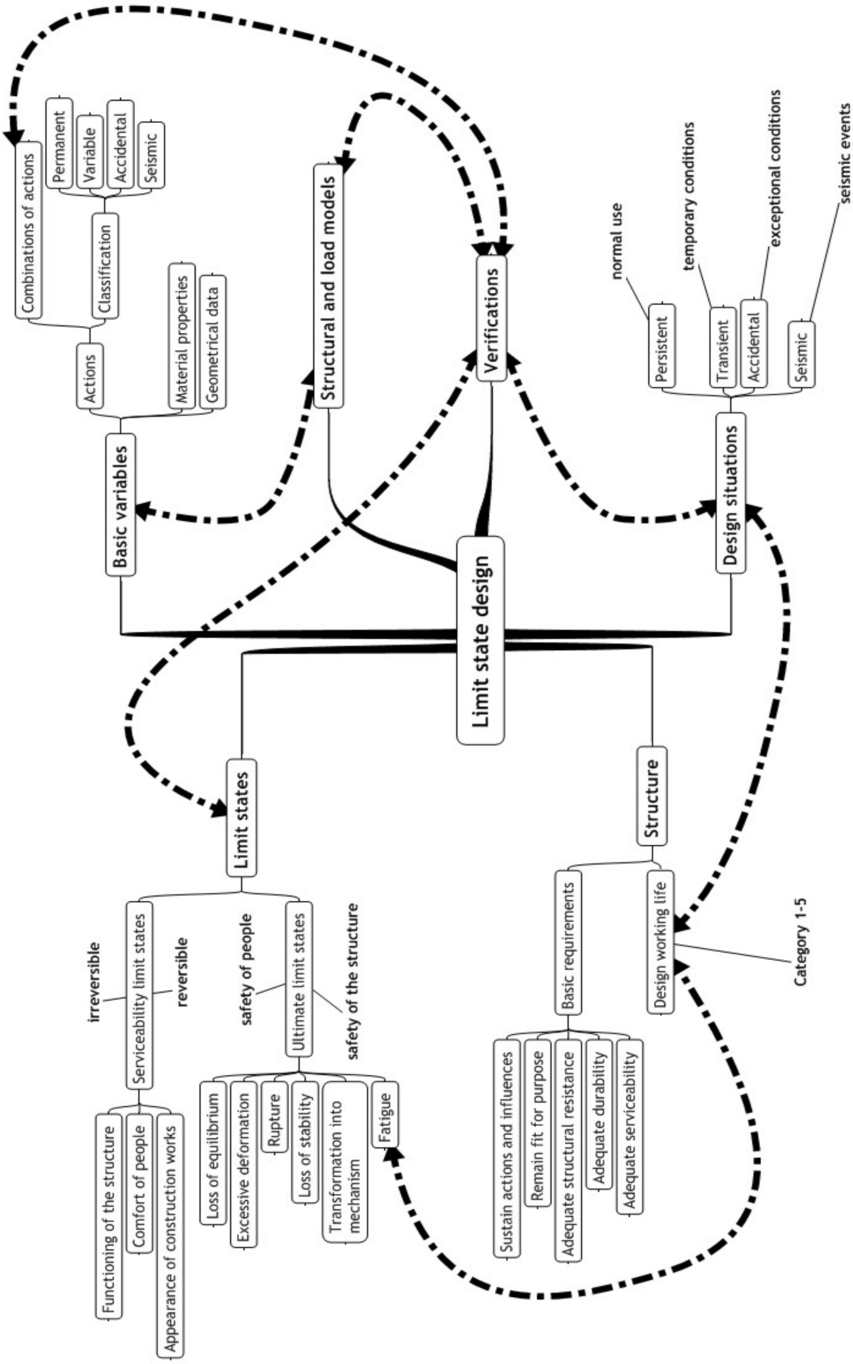


***Figure 16**. Overview of limit state design*

## 2.7 Ultimate limit states

Ultimate limit states (ULSs) are concerned with the safety of people and the structure. *[EN 1990 §3.3(1)P]*

EN 1990 identifies three ULSs that must be verified where relevant: loss of equilibrium (EQU); failure by excessive deformation, transformation into a mechanism, rupture, or loss of stability (STR); and failure caused by fatigue or other time-related effects (FAT). (Limit states GEO, UPL, and HYD, which are relevant to geotechnical design, are discussed in Chapters 6 and 7.) These three letter acronyms are used throughout the Eurocodes as shorthand for the limit states, which, for structures, are defined more fully as follows.

### 2.7.1 Limit state EQU

Limit state EQU, dealing with static equilibrium, is defined as:

> *Loss of static equilibrium of the structure ... considered as a rigid body, where minor variations in the [actions or their distribution]... are significant, and the strengths of ... materials ... are generally not governing.*
>
> *[EN 1990 §6.4.1(1)P(a)]*

Limit state EQU does not occur when the destabilizing design effects of actions $E_{d,dst}$ are less than or equal to the stabilizing design effects $E_{d,stb}$:

$$E_{d,dst} \le E_{d,stb}$$ *[EN 1990 exp (6.7)]*

as illustrated in **Figure 17**.

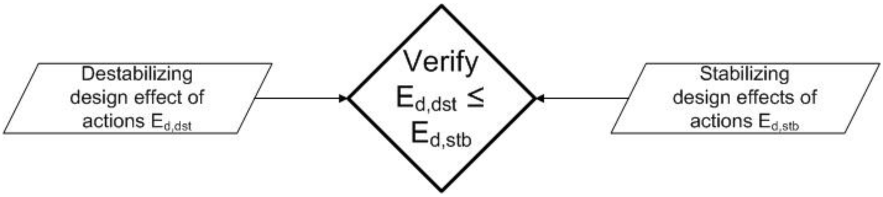


***Figure 17***. *Verification of limit state EQU*

For example, consider a motorway gantry (see **Figure 18**) subjected to a design horizontal wind load $P_d$ = 250kN acting at a height h = 7.5m above the base of the gantry. The design destabilizing (i.e. overturning) moment about the toe of the structure $M_{Ed,dst}$ is given by:

$$M_{Ed,dst} = P_d \times h = 250kN \times 7.5m = 1875kNm$$

If the design self-weight of the gantry is $W_d$ = 1600kN and its base width B = 2.5m, then the design stabilizing (i.e. restoring) moment about the toe $M_{Ed,stb}$ is:

$$M_{Ed,stb} = W_d \times \frac{B}{2} = 1600kN \times \frac{2.5m}{2} = 2000kNm$$

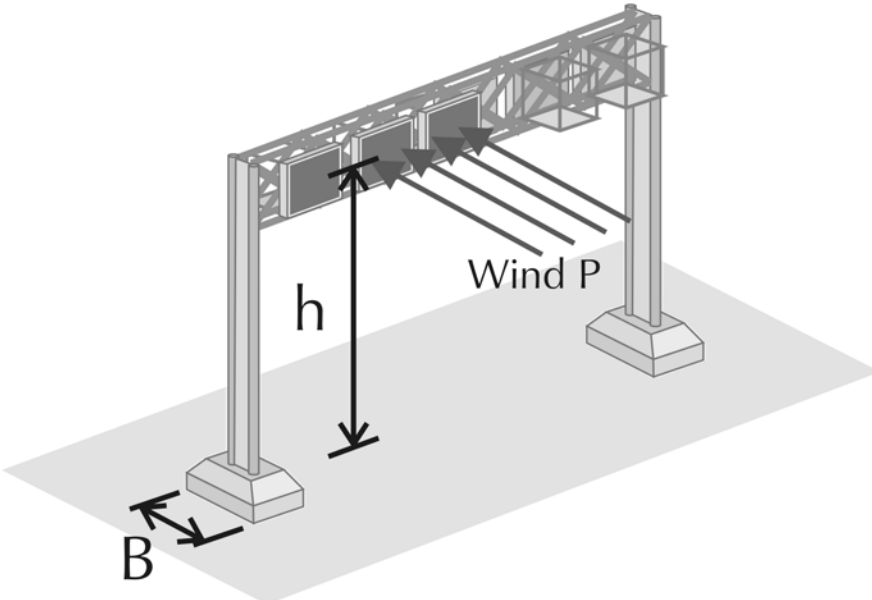


***Figure 18**. Motorway gantry subject to wind load*

Limit state EQU is therefore avoided (in the direction of the wind), since:

$$M_{Ed,dst} = 1875kNm \leq M_{Ed,stb} = 2000kNm$$

In this book, we define the 'utilization factor' for the EQU limit state as the ratio of the destabilizing and stabilizing effects:

$$\Lambda_{EQU} = \frac{E_{d,dst}}{E_{d,stb}}$$

For a structure to satisfy design requirements, it must have a utilization factor less than or equal to 100%. If $\Lambda$ exceeds 100%, although it may not necessarily lose equilibrium, the structure is less reliable than required by the Eurocodes. For the motorway gantry of **Figure 18**:

$$\Lambda_{EQU} = \frac{M_{Ed,dst}}{M_{Ed,stb}} = \frac{1875kNm}{2000kNm} = 94\%$$

### 2.7.2 Limit state STR

Limit state STR, dealing with rupture or excessive deformation, is defined as:

> *Internal failure or excessive deformation of the structure ... where the strength of construction materials ... governs.* *[EN 1990 §6.4.1(1)P(b)]*

To prevent limit state STR from occurring, design effects of actions $E_d$ must be less than or equal to the corresponding design resistance $R_d$, i.e.:

$$E_d \leq R_d$$ *[EN 1990 exp (6.8)]*

as illustrated in **Figure 19**.

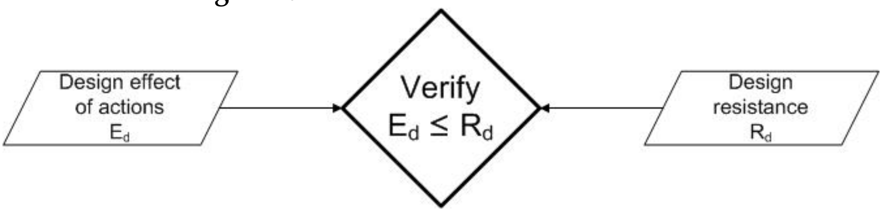


***Figure 19**. Verification of limit state STR*

Returning to the example of **Figure 18**, the bending moments induced in the motorway gantry under its self-weight are shown in **Figure 20**. If the maximum design bending moment in the structure is $M_{Ed}$ = 500 kNm and the minimum design bending resistance of the cross-section is $M_{Rd}$ = 600 kNm, then limit state STR is avoided, since:

$$M_{Ed} = 500kNm \leq M_{Rd} = 600kNm$$

In this book, we define the 'utilization factor' for the STR limit state as the ratio of the effect of actions to its corresponding resistance:

$$\Lambda_{STR} = \frac{E_d}{R_d}$$

For a structure to satisfy design requirements, it must have a utilization factor less than or equal to 100%. If Λ exceeds 100%, although it may not necessarily fail, the structure is less reliable than required by the Eurocodes. For the motorway gantry of **Figure 20**:

$$\Lambda_{STR} = \frac{M_{Ed}}{M_{Rd}} = \frac{500kNm}{600kNm} = 83\%$$

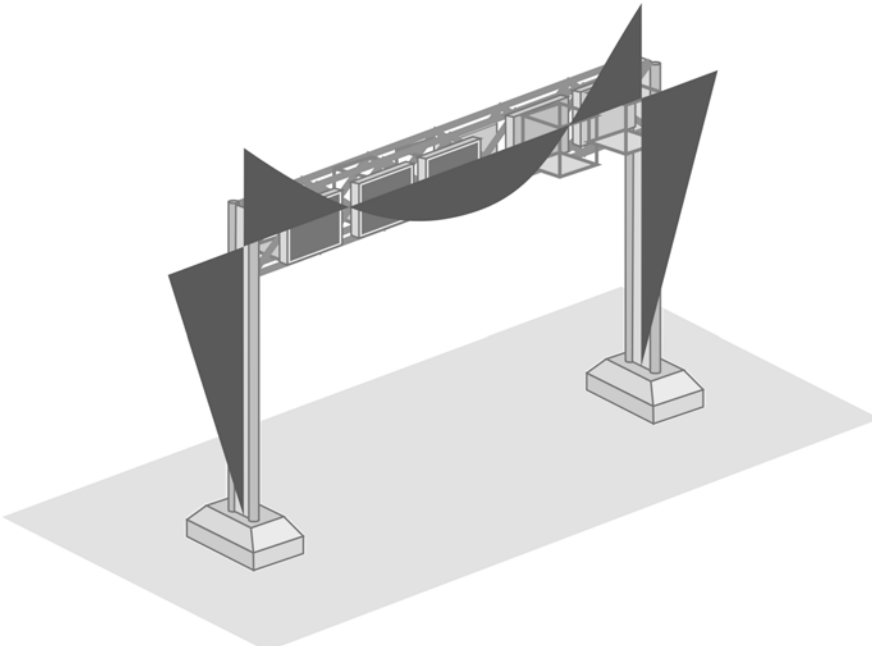

*Figure 20. Bending moments acting in the motorway gantry of* ***Figure 18***

### 2.7.3 Limit state FAT

In materials science, fatigue is the progressive and localised structural damage that occurs when a material is subjected to cyclic loading. Fatigue is mainly relevant to road and rail bridges and tall slender structures subject to wind. The subject receives particular attention in Eurocodes 1 (actions[3]), 3 (steel structures[4]), and 9 (aluminium structures[5]) but is not mentioned in Eurocode 7.

## 2.8 Serviceability limit states

Serviceability limit states (SLSs) are concerned with the functioning of the structure, the comfort of people, and the appearance of the construction works. *[EN 1990 §3.4(1)P]*

To prevent serviceability limit states from occurring, design effects of actions $E_d$ – which in this instance are entities such as settlement, distortion, strains, etc. – must be less than or equal to the corresponding limiting value of that effect $C_d$, i.e.:

$$E_d \leq C_d$$ *[EN 1990 exp (6.13)]*

as illustrated in **Figure 21**.

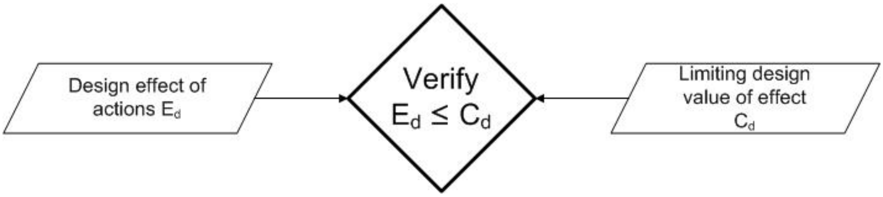


***Figure 21**. Verification of serviceability limit state (SLS)*

Returning to the example of **Figure 18**, if the maximum settlement that the gantry can tolerate is $s_{Cd}$ = 15 mm and the calculated settlement under the design actions is $s_{Ed}$ = 12 mm, then the serviceability limit state is avoided, since:

$$s_{Ed} = 12mm \le s_{Cd} = 15mm$$

In this book, we define the 'utilization factor' for the serviceability limit state as the ratio of the effect of actions to its corresponding limiting value:

$$\Lambda_{STR} = \frac{E_d}{R_d}$$

For a structure to be serviceable, it must have a utilization factor less than or equal to 100%. For the motorway gantry of **Figure 18**:

$$\Lambda_{SLS} = \frac{s_{Ed}}{s_{Cd}} = \frac{12mm}{15mm} = 80\%$$

## 2.9 Actions, combinations, and effects

The use of the word *action* to describe loads (and other entities that act like loads) reminds us of Newton's Third Law of Motion:

> *'To every action there is always opposed an equal reaction'*[6]

In Eurocode terms, the 'reaction' is known as an *effect*. That is:

$$\begin{array}{ccc} action & = & cause \\ \downarrow & \searrow & \downarrow \\ reaction & = & effect \end{array}$$

The following sub-sections explain the way in which the Structural Eurocodes define actions, combinations of actions, and the effects that arise from them.