Generation of combinations to consider in the structural calculation

XC Ingeniería Estructural

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1 Introduction

This Appendix has the object of defining the actions, weighting coefficients and the combination of actions which shall be taken into account when designing structures.

Checking the structures through design is the most used method to guarantee their safety [1].

1.1 The Limit States design method

The usual method prescribed by the codes for checking the safety of a structure is the so-called *Method of limit states*. A *limit state* is a situation in which, when exceeded, it may be considered that the structure does not fulfil one of the functions for which it has been designed.

The limit states are classified in:

- *Ultimate Limit States (ULS)*;
- *Serviceability Limit States (SLS)*, and
- *Durability Limit States (DLS)*.

1.2 Design situations

The concept of *design situation* is useful to sort the checks performed on the project or study of a structure. A design situation is a simplified representation of the reality that is amenable to analysis.

Thus, it can be considered design situations those that correspond to the different phases of construction of the structure, the normal use of the structure, its reparation, exceptional conditions, ...

For each of the design situations, it must be checked that the structure doesn't exceed any of the Limit States previously laid down in paragraph 1.1

1.3 Actions

Action is defined as any cause capable of producing stress states in a structure, or modifying the existing one. Weight coefficients can be different according to the codes that apply for verification of the different structural elements (IAP, EHE, Eurocodes,. . .).

1.4 Working life

The working life of a structure is the period of time from the end of its execution, during which must maintain the requirements of security and functionality of project and an acceptable aesthetic appearance. During that period it will require conservation in accordance with the maintenance plan established for that purpose.

The design working life depends on the type of structure and must be fixed by the Owners at the start of the design. In any case its duration will be lower than that indicated in the regulations applicable or, in the absence of these, than the values laid down in Table 1.

When a structure consists of different members, different working life values may be adopted for such members, always in accordance with the type and characteristics of the construction thereof.

[1] Other procedures are also acceptable such as the reduced model tests, full-scale tests of the structure or its elements, extrapolation of the behaviour of similar structures, . . .

Type of structure	**Design working life**
Temporary structures (*)	3 to 10 years (*)
Replaceable structural elements that are not part of the main structure (eg, handrails, pipe supports)	10 to 25 years
Agricultural or industrial buildings (or installations) and maritime works	15 to 50 years
Residential buildings or offices, bridges or crossings of a total length of less than 10 meters and civil engineering structures (except maritime works) having a low or average economic impact	50 years
Public buildings, health and education.	75 years
Monumental buildings or having a special importance	100 years
Bridges of total length equal to or greater than 10 meters and other civil engineering structures of high economic impact	100 years
(*)In accordance with the purpose of the structure (temporary exposure, etc.). Under no circumstances shall structures with a design working life greater than 10 years be regarded as temporary structures.	

Table 1: Design working life of the various types of structure (according reference [2]).

1.5 Risk level

The level of risk of an infrastructure defines the consequences of a structural failure during its construction or service (public building, private store, bridge, ...)

1.6 Control level

Regardless of the rigor with which the checking calculations of the structure are made during the project, its safety also depend on careful construction of it. Different standards establish the influence that the level of control during the execution of the work has on safety factors to be used in the execution of the same.

1.7 Combination of actions

When designing a structure or a structural member by the limit state method, load combinations shall be considered as the sum of the products of the load effect corresponding to the basic value of each load and the load factor.

Load factors shall be determined appropriately considering the limit state, the target reliability index, the variability in the load effect of each load and resistance, the probability of load coincidence, etc.

1.8 Verification of the structure

From the discussion in the previous sections, the verification procedure of the structure will consist of performing the following tasks:

1. identify the design situations to be considered when checking the structure;

2. identify the load criterions hypotheses for each of those design situations;

3. define the combinations of actions to be considered when checking the ULS and SLS, depending on:
   (a) materials composing the structure or the element to check: rolled steel, reinforced concrete, wood, ...;
   (b) risk level of the infrastructure
   (c) level of control with which the construction work is performed;
   (d) design situation (persistent, transient or accidental)
4. obtain the calculation value of the effect of actions for each combination.
5. verify all the limit states.

2 Actions

An action is a set of forces applied to the structure or a set of imposed deformations or accelerations, that has an effect on structural members (e.g. internal force, moment, stress, strain) or on the whole structure (e.g. defection, rotation)

2.1 Classification of actions

Actions can be classified by their variation over time, their nature, their origin, their spatial variation, ...

2.1.1 By their nature

- **Direct actions**: loads applied to the structure (e.g. self-weight, dead load, live load, ...)
- **Indirect actions**: imposed deformations or accelerations caused for example by temperature changes, moisture variation,...

2.1.2 By their variation over time

Actions shall be classified by their variation in time, by reference to their *service life*[2], as follows:

- **Permanent actions G**: actions that are likely to act throughout a given reference period and for which the variation in magnitude with time is negligible, or for which the variation is always in the same direction (monotonic) until the action attains a certain limit value, e.g. self-weight of structures, fixed equipment and road surfacing, and indirect actions caused by shrinkage and uneven settlement.
- **Permanents of a non-constant value G***: are those which act at any time but whose magnitude is non constant. This group include those actions whose variation is a function of elapsed time and are produced in a single direction, tending towards a certain limit value (rheological actions, pretensioning, subsidence of the ground under the foundations, ...). They also include other actions originating from the ground whose magnitude does not vary as a function of time but as a function of the interaction between the ground and the structure (for example, thrusts on vertical elements).
- **Variables Q**: action for which the variation in magnitude with time is neither negligible nor monotonic. E.g. imposed loads on building floors, beams and roofs, wind actions or snow loads.

[2]See section 1.4.

- **Accidental actions A**: action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working life. E.g. explosions, or impact from vehicles.
- **seismic action AS**: action that arises due to earthquake ground motions.

2.1.3 By their origin

- **Gravitational**: which has its origin in the earth's gravitational field (self-weight, dead load, earth pressure, ...)
- **Climatic**: whose origin is in the climate (thermal action and wind actions[3])
- **Rheological**: which has its origin in the response of material with plastic flow rather than deforming elastically when a force is applied (e.g. shrinkage of concrete).
- **Seismic**: due to earthquake ground motions.

2.1.4 By the structural response which they produce

- **static action**: action that does not cause significant acceleration of the structure or structural members;
- **dynamic action**: action that causes significant acceleration of the structure or structural members;
- **quasi-static action**: dynamic action represented by an equivalent static action in a static model.

2.1.5 By their spatial variation

- **fixed action**: action that has a fixed distribution and position over the structure or structural member such that the magnitude and direction of the action are determined unambiguously for the whole structure or structural member if this magnitude and direction are determined at one point on the structure or structural member;
- **free action**: action that may have various spatial distributions over the structure.

2.1.6 By their relation with other actions

- **Compatible actions**: two actions are compatible when it's possible for them to act simultaneously.
- **Incompatible actions**: two actions are incompatible when it's impossible for them to act at the same time (e.g. one crane acting simultaneously in two different positions).
- **Synchronous actions**: two actions are synchronous when the act necessarily together, at the same time (e.g. the braking load of a crane bridge will be synchronised with the action of the weight of the crane).

[3]thermal and wind actions can not be due to climate, such as in the case of an oven or structures subjected to the thrust of jet engines of aircraft

2.1.7 By their participation in a combination

- **Leading action**: in a combination of actions, the leading variable action is the one which produces the largest design load effect; its characteristic value is used.
- **Accompanying action**: variable action that accompanies the leading action in a combination; its characteristic value is reduced by using a factor Ψ.

2.2 Values of actions

2.2.1 Characteristic value of an action F_k

It is the principal representative value of an action; it is chosen so as to correspond to a 5% probability of not being exceeded on the unfavourable side during a "reference period" taking into account the design working life of the structure and the duration of the design situation.

2.2.2 Combination value of a variable action F_{r0}

Value chosen so that the probability that the effects caused by the combination will be exceeded is approximately the same as by the characteristic value of an individual action. It may be expressed as a determined part of the characteristic value by using a factor $\Psi_0 \leq 1$

2.2.3 Frequent value of a variable action F_{r1}

Value determined so that either the total time, within the reference period, during which it is exceeded is only a small given part of the reference period, or the frequency of it being exceeded is limited to a given value. It may be expressed as a determined part of the characteristic value by using a factor $\Psi_1 \leq 1$.

2.2.4 Quasi-permanent value of a variable action F_{r2}

Value determined so that the total period of time for which it will be exceeded is a large fraction [4] of the reference period. It may be expressed as a determined part of the characteristic value by using a factor $\Psi_1 \leq 2$.

2.2.5 Representative value F_r of the actions. Factors of simultaneity

The representative value of an action is the value of it that is used to verify the limit states. By multiplying this representative value by the the corresponding partial coefficient γ_f, the calculation value shall be obtained.

The principal representative value of the actions is their characteristic value. Usually, for permanent and accidental actions, a single representative value is considered, that matches the characteristic value ($\psi = 1$) [5]. Other representative values are considered for the variable actions, in accordance with the verification involved and the type of action:

- **Characteristic value** F_k: this value is used for leading actions in the verification of ultimate limit states in a continuous or temporary situation and of irreversible serviceability limit states.
- **Combination value** $\psi = \psi_0 F_k$ this value is used for accompanying actions in the verification of ultimate limit states in a continuous or temporary situation and of irreversible serviceability limit states.

[4] according to *Documento Nacional de Aplicación español del Eurocódigo de Hormigón (UNE ENV 1992-1-1)* more than half of the service life of the structure

[5] The IAP instruction (reference [3]) makes some exceptions to this rule)

CLIMATIC ACTIONS	ψ_0	ψ_1	ψ_2
Snow loads	0.6	0.2	0.0
Wind loads	0.6	0.5	0.0
Temperature (*non-fire*)	0.6	0.5	0.0

Table 2: Recommended values of Ψ factor for climatic actions, according to EHE

- **Frequent value** $\psi = \psi_1 F_k$: this value is used for the leading action in the verification of ultimate limit states in an accidental situations and of reversible serviceability limit states.
- **Quasi-permanent value** $\psi = \psi_2 F_k$: this value is used for accompanying actions in the verification of ultimate limit states in an accidental situation and of reversible serviceability limit states as well as in the assessment of the postponed effects.

In short, the representative value of an action depends on:

- its variation over time (G,G*,Q,A,AS);
- its participation in the combination as *leading action* or *accompanying action*;
- the type of situation (accidental, . . .);
- the origin of the load (climate, use, water, . . .).

Values of Ψ factors of simultaneity The value of the simultaneity factors ψ are different depending on the action that is involved.

According to EHE: the recommended values of factors of simultaneity ψ_0,ψ_1,ψ_2 according to the *Documento Nacional de Aplicación español del Eurocódigo de Hormigón* (UNE ENV 1992-1-1) can be seen in tables 2 y 3.

According to EAE [2] : see tables 5 y 4.

According to IAP [3]: see table 6.

2.2.6 Calculation value F_d of the actions

The calculation value of an action is obtained by multiplying its characteristic value by the corresponding partial coefficient γ_f:

$$F_d = \gamma_f \cdot F_r \tag{1}$$

The values of the coefficients γ_f takes into account one or more of the following uncertainties:

1. uncertainties in the estimation of the representative value of the actions, in fact, the characteristic value is chosen admitting a 5% probability of being exceeded during the working life of the structure;
2. uncertainties in the calculations results, due to simplifications in the models and to certain numeric errors (rounding, truncation, . . .)
3. Uncertainty in the geometric and mechanical characteristics of the built structure. During the execution of the structure some errors can be committed [6] that can make the dimensions of the sections, the position of the reinforcement, the position of the axes, the mechanical characteristics of the materials, . . . , be different from the theoretical.

[6] It is understood that these errors are within the tolerances established in the regulations

LIVE LOADS	ψ_0	ψ_1	ψ_2
Roofs			
Inaccessible or accessible only for maintenance	0.7	0.5	0.3
Accessible	by use	by use	by use
Residential buildings			
Rooms	0.7	0.5	0.3
Stairs and public accesses	0.7	0.5	0.3
Cantilevered balconies	0.7	0.5	0.3
Hotels, hospitals, prisons, . . .			
Bedrooms	0.7	0.5	0.3
Public areas, stairs and accesses	0.7	0.7	0.6
Assembly and areas	0.7	0.7	0.6
Cantilevered balconies	by use	by use	by use
Office and commercial buildings			
Private premises	0.7	0.5	0.3
Public offices	0.7	0.5	0.3
Shops	0.7	0.7	0.6
Commercial galleries, stairs and access	0.7	0.7	0.6
Storerooms	1.0	0.9	0.8
Cantilevered balconies	by use	by use	by use
Educational buildings			
Classrooms, offices and canteens	0.7	0.7	0.6
Stairs and access	0.7	0.5	0.6
Cantilevered balconies	by use	by use	by use
Churches, buildings for assembly and public performances			
Halls with fixed seatings	0.7	0.7	0.6
Halls without fixed seatings, tribunes, stairs	0.7	0.7	0.6
Cantilevered balconies	by use	by use	by use
Driveways and garages			
Traffic areas with vehicles under 30 kN in weight	0.7	0.7	0.6
Traffic areas with vehicles of 30 to 160 kN in weight	0.7	0.5	0.3

Table 3: Recommended values of Ψ factors of simultaneity for climatic loads, according to EHE

USE OF AREA	ψ_0	ψ_1	ψ_2
Domestic, residential areas	0.7	0.5	0.3
Office areas	0.7	0.5	0.3
Congregation areas	0.7	0.7	0.6
Shopping areas	0.7	0.7	0.6
Storage areas	1.0	0.9	0.8
Traffic areas, weight of vehicle $\leq 30\ kN$	0.7	0.7	0.6
Traffic areas, $30\ kN <$ weight of vehicle $\leq 160\ kN$	0.7	0.5	0.3
Inaccessible Roofs	0.0	0.0	0.0

Table 4: Recommended values of Ψ factors for buildings, according to EAE

CLIMATIC ACTIONS	ψ_0	ψ_1	ψ_2
Snow loads in buildings set over a thousand meters above sea level.	0.7	0.5	0.2
Snow loads in buildings set under a thousand meters above sea level.	0.5	0.2	0.0
Wind loads	0.6	0.2	0.0
Thermal action	0.6	0.5	0.0

Table 5: Recommended values of Ψ factors of simultaneity, according to EAE

VARIABLE ACTIONS	ψ_0	ψ_1	ψ_2
Traffic load model fatigue	1.0	1.0	1.0
Other variable actions	0.6	0.5	0.2

Table 6: Values of Ψ factors of simultaneity according to IAP.

Values of the partial coefficients The coefficients γ_f have different values in accordance with:

1. the limit state to be verified;
2. the design situation that is involved (see section 3);
3. the variation of the action over time (according to classification in 2.1.2);
4. the effect favourable o unfavourable of the action in the limit state that is verified;
5. the control level.

According to EHE: the values of the partial coefficients γ_f are specified in table 7 for serviceability limit states and in table 8 for ultimate limit states.

According to EAE: the values of the partial coefficients γ_F to be used are specified int tables 9 for serviceability limit states and in table 10 for ultimate limit states.

According to IAP: the values of the partial coefficients γ_F to be used are specified int tables 11 for serviceability limit states and in table 12 for ultimate limit states.

ACTION	EFFECT	
	favourable	unfavourable
Permanent	$\gamma_G = 1.00$	$\gamma_G = 1.00$
Prestressing (pre-tensioned concrete)	$\gamma_P = 0.95$	$\gamma_P = 1.05$
Prestressing (post-tensioned concrete)	$\gamma_P = 0.90$	$\gamma_P = 1.10$
Permanent of a non-constant value	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Variable	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
NOTATION:		
G: Permanent action. P: Prestressing. G*: Permanent action of a non-constant value. Q: Variable action. A: Accidental action.		

Table 7: Partial factor for actions in serviceability limit states according to EHE.

Action	Control level	Effect in persistent or transient design situations		Effect in accidental or seismic design situations	
		favourable	unfavourable	favourable	unfavourable
G	intense	$\gamma_G = 1.00$	$\gamma_G = 1.35$	$\gamma_G = 1.00$	$\gamma_G = 1.00$
	normal	$\gamma_G = 1.00$	$\gamma_G = 1.50$	$\gamma_G = 1.00$	$\gamma_G = 1.00$
	low	$\gamma_G = 1.00$	$\gamma_G = 1.60$	$\gamma_G = 1.00$	$\gamma_G = 1.00$
G*	intense	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.50$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
	normal	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.60$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
	low	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.80$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Q	intense	$\gamma_Q = 0.00$	$\gamma_Q = 1.50$	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
	normal	$\gamma_Q = 0.00$	$\gamma_Q = 1.60$	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
	low	$\gamma_Q = 0.00$	$\gamma_Q = 1.80$	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
A	-	-	-	$\gamma_A = 1.00$	$\gamma_A = 1.00$
NOTATION:					
G: Permanent action. G*: Permanent action of a non-constant value. Q: Variable action. A: Accidental action.					

Table 8: Partial factor for actions in ultimate limit states according to EHE.

ACTION	EFFECT	
	favourable	unfavourable
Permanent	$\gamma_G = 1.00$	$\gamma_G = 1.00$
Permanent of a non-constant value	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Variable	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$

Table 9: Partial factor for actions in serviceability limit states according to EAE.

Action	Effect in persistent or transient design situations		Effect in accidental or seismic design situations	
	favourable	unfavourable	favourable	unfavourable
G	$\gamma_G = 1.00$	$\gamma_G = 1.35$	$\gamma_G = 1.00$	$\gamma_G = 1.00$
G*	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.50$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Q	$\gamma_Q = 0.00$	$\gamma_Q = 1.50$	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
A	-	-	$\gamma_A = 1.00$	$\gamma_A = 1.00$
NOTATION:				
G: Permanent action. G*: Permanent action of a non-constant value. Q: Variable action. A: Accidental action.				

Table 10: Partial factor for actions in ultimate limit states according to EAE.

Action	Effect	
	favourable	unfavourable
Permanent	$\gamma_G = 1.00$	$\gamma_G = 1.00$
Internal prestressing (post-tensioned concrete) Internal prestressing (pre-tensioned concrete)	$\gamma_{P_1} = 0.9$ $\gamma_{P_1} = 0.95$	$\gamma_{P_1} = 1.1$ $\gamma_{P_1} = 1.05$
External prestressing	$\gamma_{P_2} = 1.0$	$\gamma_{P_2} = 1.0$
Other prestressing actions	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Rheological	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Thrust of the site	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Variable	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
Notation:		
G: Permanent action. P_1: Internal prestressing. P_2: External prestressing. $G*$: Permanent action of a non-constant value. Q: Variable action. A: Accidental action.		

Table 11: Partial factor for actions in serviceability limit states according to IAP.

Action	Effect in persistent or transient design situations		Effect in accidental or seismic design situations	
	favourable	unfavourable	favourable	unfavourable
Permanent	$\gamma_G = 1.00$	$\gamma_G = 1.35$	$\gamma_G = 1.00$	$\gamma_G = 1.00$
Internal prestressing	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
External prestressing	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.35$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Other prestressing actions	$\gamma_{G*} = 0.95$	$\gamma_{G*} = 1.05$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Rheological	$\gamma_{G*} = 1.0$	$\gamma_{G*} = 1.35$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Thrust of the site	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.50$	$\gamma_{G*} = 1.00$	$\gamma_{G*} = 1.00$
Variable	$\gamma_Q = 0.00$	$\gamma_Q = 1.50$	$\gamma_Q = 0.00$	$\gamma_Q = 1.00$
Accidental	-	-	$\gamma_A = 1.00$	$\gamma_A = 1.00$

Table 12: Partial factor for actions in ultimate limit states according to IAP.

3 Design situations

Design situations, that take into account the circumstances under which the structure can be required during its execution and use, shall be classified as follows:

1. Persistent design situations, which refer to the conditions of normal use.
2. transient design situations, which refer to temporary conditions applicable to the structure, e.g. during execution or repair.
3. Accidental design situations, which refer to exceptional conditions applicable to the structure or to its exposure, e.g. to fire, explosion, impact or the consequences of localised failure.

4 Level of quality control

A two level system for control during execution has been adopted:

- Intense control.
- Normal control.

As will be seen later, the partial factors for a material or a member resistance depend on the level of inspection during construction.

5 Limit states

They can be defined as those states beyond which the structure no longer fulfils the relevant design criteria.

The design of the structure will be right when:

1. it is verified that no ultimate limit state is exceeded for the design situations and load cases defined in 6.1, and
2. it is verified that no serviceability limit state is exceeded under the design situations and load cases defined in 6.2.

5.1 Ultimate limit states

They are states associated with collapse or with other similar forms of structural failure. They generally correspond to the maximum load-carrying resistance of a structure or structural member.

The following ultimate limit states shall be verified where they are relevant: - failure caused by fatigue or other time-dependent effects.

1. loss of equilibrium of the structure or any part of it, considered as a rigid body;
2. failure by excessive deformation, transformation of the structure or any part of it into a mechanism, rupture, loss of stability of the structure or any part of it, including supports and foundations;
3. failure caused by fatigue or other time-dependent effects.

5.2 Serviceability limit states

They can be defined as states that correspond to conditions beyond which specified service requirements for a structure or structural member are no longer met. These service requirements can concern:

- functionality.
- comfort.
- durability.
- aesthetics.

The verification of serviceability limit states should be based on criteria concerning the following aspects :

1. deformations that affect:
    - the appearance,
    - the comfort of users, or
    - the functioning of the structure (including the functioning of machines or services),

   or that cause damage to finishes or non-structural members;
2. vibrations
    - that cause discomfort to people, or
    - that limit the functional effectiveness of the structure;
3. damage that is likely to adversely affect
    - the appearance,
    - the durability, or
    - the functioning of the structure.

6 Combination of actions

When the verification of a structure is carried out by the partial factor method, it shall be verified than, in all relevant design situations, no relevant limit state is exceeded when design values for actions or effects of actions and resistances are used in the design models.

In order to eliminate the combinations that are not possible (or do not make sense), the following criteria will be considered:

- When an action is involved in a combination, none of its incompatible actions will be involved in that combination.
- When an action is involved in a combination, all of its synchronous actions must be involved in that combination [7]

In what follows, we will consider any structure, under the following actions:

- n_G permanent actions: G_i[8].

[7]See synchronous action and compatible action definitions in section 2.1.6.
[8]The subscript refers to each of permanent actions on the structure G_1, G_2, G_3, G_4, $\ldots$, G_{n_G}

- n_{G*} permanent actions of a non-constant value: $G*_j$.
- n_Q variable actions: Q_l.
- n_A accidental actions: Q_m.
- n_{AS} seismic actions: Q_n.

6.1 Combinations of actions for ultimate limit states

For the selected design situations and the relevant ultimate limit states the individual actions for the critical load cases should be combined as detailed in this section.

6.1.1 Combinations of actions for persistent or transient design situations

For each variable action, a group of combinations with this action as *leading variable action* will be considered [9].

$$\sum_{i=1}^{n_G} \gamma_G \cdot G_{k,i} + \sum_{j=1}^{n_{G*}} \gamma_{G*} \cdot G*_{k,j} + \gamma_Q \cdot Q_{k,d} + \sum_{l=1}^{d-1} \gamma_Q \cdot Q_{r0,l} + \sum_{l=d+1}^{n_Q} \gamma_Q \cdot Q_{r0,l} \tag{2}$$

where:

$\gamma_G \cdot G_{k,i}$: design value of the permanent action i, obtained from its characteristic value ;

$\gamma_{G*} \cdot G*_{k,j}$: design value of the permanent action of a non-constant value j, obtained from its characteristic value;

$\gamma_Q \cdot Q_{k,d}$: design value of the leading variable action d, obtained from its characteristic value;

$\gamma_Q \cdot Q_{r0,l}$: design value of la variable action l, obtained from its accompanying value.

Number of combinations to be considered: According to section 2.2.6:

- The permanent actions, in ULS combinations corresponding to persistent or transient design situations, will have two non-zero partial factors.
- In the same case, the permanent actions of a non-constant value will have two non-zero partial factors that, in some cases, can be equal (see the case of internal prestressing on the table 12).
- The variable actions will have a single non-zero partial factor.

therefore, assuming that:

n_{G2} is the number of permanent actions that have two different partial factors;

n_{G1} is the number of permanent actions that have a single partial factor[10];

n_{G*2} is the number of permanent actions of a non-constant value that have two different partial factors;

n_{G*1} the number of permanent actions of a non-constant value that have a single partial factor, and

[9] See section 2.1.7.
[10] Because both factors are equal.

n_Q is the number of variable actions, all of then have a single partial factor.

If, by now, incompatibility or synchronicity of actions is ignored, for each variable action we'll have:

- $2^{n_{G2}}$ combinations of permanent actions in the set $G2$;
- 1 combination of permanent actions in the set $G1$;
- $2^{n_{G*2}}$ combinations of permanent actions in the set $G*2$;
- 1 combination of permanent actions in the set $G*1$, and
- 2^{n_Q-1} combinations of accompanying variable actions.

As, for each leading action two partial factors must be considered, the total number of combinations $n_{comb,spt}$ for persistent or transient design situations will be equal to the cartesian product of the previous combinations by $2^{n_{Qd}}$, where Qd is the number of variable actions that can be leading:

$$n_{comb,ULS,spt} = 2^{n_{G2}} \cdot 2^{n_{G*2}} \cdot 2^{n_Q-1} \cdot 2^{n_{Qd}} = 2^{n_{G2}+n_{G*2}+n_Q+n_{Qd}-1} \quad (3)$$

Among these combinations, those that are incompatibles must be eliminated.
For synchronic actions, the following procedure can be followed:
Let a be a synchronic action of the action b:

1. a is eliminated from the list of variable actions;
2. the action $a+b$ is added to the list of variable actions;
3. incompatibility between $a+b$ and b actions is set.

6.1.2 Combinations of actions for accidental design situations

For each variable action Q_l, n_A combinations with that action as leading are formed.

$$\sum_{i=1}^{n_G} \gamma_G \cdot G_{k,i} + \sum_{j=1}^{n_{G*}} \gamma_{G*} \cdot G*_{k,j} + A_{k,m} + \gamma_Q \cdot Q_{r1,d} + \sum_{l=1}^{d-1} \gamma_Q \cdot Q_{r2,l} + \sum_{l=d+1}^{n_Q} \gamma_Q \cdot Q_{r2,l} \quad (4)$$

where:

$A_{k,m}$: design value of the accidental action m, obtained from its characteristic value;

$\gamma_Q \cdot Q_{r1,d}$: design value of the leading variable action d, obtained from its representative frequent value;

$\gamma_Q \cdot Q_{r2,l}$: design value of la variable action l, obtained from its representative quasi-permanent value.

Number of combinations to be considered: it results the same number of combinations for each sum than in the case solved in the paragraph 6.1.1 (see 3 expression), though, in this case, the representative values of the variable actions are other ones. If, as usual, the partial factors for seismic actions are equal for favourable and unfavourable actions, it suffices to multiply by the number of accidental actions n_A.

$$n_{comb,ULS,acc} = 2^{n_{G2}+n_{G*2}+n_Q+n_{Qd}-1} \cdot n_A \quad (5)$$

For incompatible actions, the procedure provided for in section 6.1.1 is applicable.

6.1.3 Combinations of actions for seismic design situations

For each seismic action one combination will be formed:

$$\sum_{i=1}^{n_G} \gamma_G \cdot G_{k,i} + \sum_{j=1}^{n_{G*}} \gamma_{G*} \cdot G*_{k,j} + AS_{k,n} + \sum_{l=1}^{n_Q} \gamma_Q \cdot Q_{r2,l} \tag{6}$$

where:

$A_{k,m}$ is the design value of the accidental action m, and

$\gamma_Q \cdot Q_{r2,l}$ is the design value of the variable action l, obtained from its representative quasi-permanent value.

Number of combinations to be considered:

$$n_{comb,ULS,sism} = 2^{n_{G2}+n_{G*2}+n_Q} \cdot n_{AS} \tag{7}$$

For incompatible actions, the procedure provided for in section 6.1.1 is applicable.

6.2 Combinations of actions for serviceability limit states

For the selected design situations and the relevant serviceability limit states the individual actions for the critical load cases should be combined as detailed in this section.

6.2.1 Rare combinations:

For each variable action, one combination with this action as *leading variable action* will be considered.

$$\sum_{i=1}^{n_G} G_{k,i} + \sum_{j=1}^{n_{G*}} G*_{k,j} + Q_{k,d} + \sum_{l=1}^{d-1} Q_{r0,l} + \sum_{l=d+1}^{n_Q} Q_{r0,l} \tag{8}$$

In a general case, with no incompatible or concomitant combinations, the following combinations will be formed (see notation in section 6.1.1):

$$n_{comb,SLS,pf} = 2^{n_{G2}+n_{G*2}+n_Q+n_{Qd}-1} \tag{9}$$

Since the partial factors are for serviceability limit states, the sets $G2$ y $G*2$ generally will not match those for ultimate limit states. Given that in many cases both partial factors are equal to the unity, the cardinality of these sets will be much lower than the equivalent in paragraph 6.1.1.

For incompatible actions, the procedure provided for in section 6.1.1 is applicable.

6.2.2 Frequent combinations:

For each variable action, one combination in which this action acts as *leading* will be formed.

$$\sum_{i=1}^{n_G} G_{k,i} + \sum_{j=1}^{n_{G*}} G*_{k,j} + Q_{r1,d} + \sum_{l=1}^{d-1} Q_{r2,l} + \sum_{l=d+1}^{n_Q} Q_{r2,l} \tag{10}$$

the number of combinations will be the same as the precedent case, since only the combination factors can vary.

6.2.3 Quasi-permanent combinations:

$$\sum_{i=1}^{n_G} G_{k,i} + \sum_{j=1}^{n_{G*}} G*_{k,j} + \sum_{l=1}^{n_Q} Q_{r2,l} \tag{11}$$

the number of combinations will be:

$$n_{comb,SLS,cp} = 2^{n_{G2}+n_{G*2}+n_Q} \tag{12}$$

6.3 Combinations to be considered in the calculation

According to the discussion in the previous sections, the number of combinations for a general calculations will be the following:

Ultimate limit states	number of combinations
Persistent or transient design situations	$2^{(n_G+n_{G*}+n_Q)} \cdot n_Q$
Accidental design situations	$2^{(n_G+n_{G*}+n_Q)} \cdot n_Q \cdot n_A$
Seismic design situations	$2^{(n_G+n_{G*}+n_Q)} \cdot n_{AS}$
Total ULS	$2^{(n_G+n_{G*}+n_Q)} \cdot (n_Q(1+n_A)+n_{AS})$
Serviceability limit states	
Rare combinations	n_Q
Frequent combinations	n_Q
Quasi-permanent combination	1
Total SLS	$2n_Q+1$
Total combinations	$\mathbf{2^{(n_G+n_{G*}+n_Q)} \cdot (n_Q(1+n_A)+n_{AS})+2n_Q+1}$

For example, if we had:

- 2 permanent actions;
- 1 permanent action of a non-constant value;
- 3 variable actions;
- 1 accidental action, and
- 2 seismic actions

the number of combinations will be:

Ultimate limit states	number of combinations
Persistent or transient design situations	$2^{(2+1+3)} \times 3 = 192$
Accidental design situations	$2^{(2+1+3)} \times 3 \times 1 = 192$
Seismic design situations	$2^{(2+1+3)} \times 2 = 128$
Total ULS	$2^{(2+1+3)} \times (3 \times (1+1)+2) = 512$
Serviceability limit states	
Rare combinations	3
Frequent combinations	3
Quasi-permanent combination	1
Total SLS	$6+1=7$
Total combinations	**519**

6.4 Algorithm to write the complete list of combinations

6.4.1 Combinations for ultimate limit states

Each of the sums in expressions (2),(4) y (6) appears as follows:

$$\sum_{i=1}^{n} \gamma_f \cdot F_{r,i} \tag{13}$$

For each action F_i the partial factor can take two values, depending on the effect favourable or unfavourable of the action[11] .

The design value of the action $F_{r,i}$ depends on:

- its variation in time (G,G*,A,A,AS);
- its role in the combination, as leading or accompanying action;
- if there is or not accidental actions in the combination;
- the nature of the action (climatic or live loads).

in any case, for any combination, the value of $F_{r,i}$ is known.

Moreover, the value of n is known for each sum.

Following this, the summands of (13) correspond to the variations with repetition [12] of two elements [13] taken n by n.

To write the variations with repetition of expression (13), proceed as follows:

Let $\gamma_{\mathbf{f}_v}$ be the row vector whose components are the partial factors of the variation v ($1 \leq v \leq 2^n$):

$$\gamma_{\mathbf{f}_v} = [\gamma_{f,1}, \gamma_{f,2}, \cdots, \gamma_{f,i}, \cdots, \gamma_{f,n}] \tag{14}$$

that's to say, the element $\gamma_{f,i}$ is the partial factor (favourable or unfavourable) of action $F_{r,i}$.

Let $\mathbf{F_r}$ be the column vector whose components are the actions $F_{r,i}$ of the expression (13):

$$\mathbf{F_r}^T = [F_{r,1}, F_{r,2}, \cdots, F_{r,i}, \cdots, F_{r,n}] \tag{15}$$

then, the expression (13) is equivalent to the scalar product:

$$\sum_{i=1}^{n} \gamma_f \cdot F_{r,i} = \gamma_{\mathbf{f}_v} \cdot \mathbf{F_r} \tag{16}$$

and it must be formed as many scalar products as variations with repetition can be arranged, that's to say, 2^n.

Let $S_{F,v}$ be the sum that corresponds to variation v,

$$S_{F_r,v} = \gamma_{\mathbf{f}_v} \cdot \mathbf{F_r} \tag{17}$$

then each of sums (2),(4) and (6) gives rise to set of variations:

[11] We assume a priory unknown the effect favourable or unfavourable of the action for the limit state and structural element in analysed

[12] The variations with repetition of n elements taken k by k are the arranged groups formed by k elements from A (which may be repeated)

[13] The partial factors corresponding to favourable and unfavourable effects

$$S_{F_r,1} = \gamma_{\mathbf{f}\,1} \cdot \mathbf{F_r}$$
$$S_{F_r,2} = \gamma_{\mathbf{f}\,2} \cdot \mathbf{F_r}$$
$$\cdots$$
$$S_{F_r,v} = \gamma_{\mathbf{f}\,v} \cdot \mathbf{F_r}$$
$$\cdots$$
$$S_{F_r,n_F} = \gamma_{\mathbf{f}\,n_F} \cdot \mathbf{F_r}$$

where n_F is the number of actions in each case, that's to say n_G, n_{G*}, n_Q, n_A, or n_{AS}.

Therefore, the summands (2),(4) and (6) will be one of the following scalar products:

- Summand corresponding to permanent actions: S_{G_r,v_G} $(1 \leq v_G \leq 2^{n_G})$.
- Summand corresponding to permanent actions of a non-constant value: $S_{G*_r,v_{G*}}$ $(1 \leq v_{G*} \leq 2^{n_{G*}})$.
- Summand corresponding to variable actions: S_{Q_r,v_Q} $(1 \leq v_Q \leq 2^{n_Q})$.
- Summand corresponding to accidental actions: S_{A_r,v_A} $(1 \leq v_A \leq 2^{n_A})$.
- Summand corresponding to seismic actions: $S_{AS_r,v_{AS}}$ $(1 \leq v_{AS} \leq 2^{n_{AS}})$.

Combinations of actions for persistent or transient design situations With this notation, the expression (2) can be written as follows:

$$CQ_{v_G,v_{G*},v_Q,d} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r0,d},v_Q} \tag{18}$$

where:

v_G is the variation corresponding to the permanent actions;

v_{G*} is the variation corresponding to the permanent actions of a non-constant value;

v_Q is the variation corresponding to the variable actions;

d is the index that corresponds to the leading variable action, and

$\mathbf{Q}_{r0,d}$ is the vector $[Q_{r0,1}, Q_{r0,2}, \cdots, Q_{r0,d-1},\ Q_{k,d},\ Q_{r0,d+1}, \cdots, Q_{r0,n_Q}]$

Combinations of actions for accidental design situations Similarly, the expression (4) can be written as follows:

$$CA_{v_G,v_{G*},v_Q,d,m} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r2,d},v_Q} + A_{k,m} \tag{19}$$

where:

v_G is the variation corresponding to the permanent actions;

v_{G*} is the Variation corresponding to the permanent actions of a non-constant value;

v_Q is the variation corresponding to the variable actions;

d is the index corresponding to the leading variable action;

$\mathbf{Q}_{r2,d}$ is the vector $[Q_{r2,1}, Q_{r2,2}, \cdots, Q_{r2,d-1},\ Q_{r1,d},\ Q_{r2,d+1}, \cdots, Q_{r2,n_Q}]$;

m is the index that corresponds to the accidental action considered, and

$A_{k,m}$ is the design value of the accidental action m.

Combinations for seismic design situations Similarly, the expression (6) can be written as follows:

$$CS_{v_G,v_{G*},v_Q,n} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r2},v_Q} + AS_{k,n} \tag{20}$$

where

v_G is the variation corresponding to the permanent actions;

v_{G*} is the variation corresponding to the permanent actions of a non-constant value;

v_Q is the variation corresponding to the variable actions;

$\mathbf{Q}_{r2}$ is the vector $[Q_{r2,1}, Q_{r2,2}, \cdots, Q_{r2,n_Q}]$;

n is the index of the seismic action considered, and

$AS_{k,n}$ is the design value of the seismic action n.

Calculation algorithm The proposed algorithm for writing all the combinations for ultimate limit states is as follows:

1. calculation of all the variations corresponding to actions G: γ_{g,v_G} $(1 \leq v_G \leq 2^{n_G})$
2. calculation of all the variations corresponding to actions G*: $\gamma_{g*,v_{G*}}$ $(1 \leq v_{G*} \leq 2^{n_{G*}})$
3. calculation of all the variations corresponding to actions Q: γ_{q,v_Q} $(1 \leq v_Q \leq 2^{n_Q})$
4. from $d = 1$ to $d = n_q$
   (a) calculation of all the combinations $CQ_{v_G,v_{G*},v_Q,d}$.
5. from $d = 1$ to $d = n_Q$
   (a) from $m = 1$ to $m = n_A$
      i. calculation of all the combinations $CA_{v_G,v_{G*},v_Q,d,m}$.
6. from $n = 1$ to $n = n_{AS}$
   (a) calculation of all the combinations $CS_{v_G,v_{G*},v_Q,n}$.
7. end

refinement of step 4a:

1. from $v_G = 1$ to $v_G = 2^{n_G}$
   (a) calculate S_{G_k,v_G}
   (b) from $v_{G*} = 1$ to $v_{G*} = 2^{n_{G*}}$
      i. calculate $S_{G*_k,v_{G*}}$
      ii. from $v_Q = 1$ to $v_Q = 2^{n_Q}$
         A. calculate $S_{Q_{r0,d},v_Q}$
         B. calculate $CQ_{v_G,v_{G*},v_Q,d} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r0,d},v_Q}$
2. end

refinement of step 5(a)i:

1. from $v_G = 1$ to $v_G = 2^{n_G}$

   (a) calculate S_{G_k,v_G}
   (b) from $v_{G*} = 1$ to $v_{G*} = 2^{n_{G*}}$
      i. calculate $S_{G*_k,v_{G*}}$
      ii. from $v_Q = 1$ to $v_Q = 2^{n_Q}$
         A. calculate $S_{Q_{r2,d},v_Q}$.
         B. calculate $CA_{v_G,v_{G*},v_Q,d,m} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r2,d},v_Q} + A_{k,m}$

2. end

refinement of step 6a:

1. from $v_G = 1$ to $v_G = 2^{n_G}$
   (a) calculate S_{G_k,v_G}
   (b) from $v_{G*} = 1$ to $v_{G*} = 2^{n_{G*}}$
      i. calculate $S_{G*_k,v_{G*}}$
      ii. from $v_Q = 1$ to $v_Q = 2^{n_Q}$
         A. calculate S_{Q_{r2},v_Q}.
         B. calculate $CS_{v_G,v_{G*},v_Q,n} = S_{G_k,v_G} + S_{G*_k,v_{G*}} + S_{Q_{r2},v_Q} + AS_{k,n}$

2. end

6.4.2 Combinations for serviceability limit states

Taking into account the partial factors for serviceability limit states, if:

$$S_{G_k} = \sum_{i=1}^{n_G} G_{k,i} \tag{21}$$

$$S_{G*_k} = \sum_{j=1}^{n_{G*}} G*_{k,j} \tag{22}$$

$$S_{Q_{r0},d} = \sum_{l=1}^{d-1} Q_{r0,l} + Q_{k,d} + \sum_{l=d+1}^{n_Q} Q_{r0,l} \tag{23}$$

$$S_{Q_{r2},d} = \sum_{l=1}^{d-1} Q_{r2,l} + Q_{r1,d} + \sum_{l=d+1}^{n_Q} Q_{r2,l} \tag{24}$$

and

$$S_{Q_{r2}} = \sum_{l=1}^{n_Q} Q_{r2,l} \tag{25}$$

then: the n_Q rare combinations will be:

$$CPF_d = S_{G_k} + S_{G*_k} + S_{Q_{r0},d} \tag{26}$$

the n_Q frequent combinations will be:

$$CF_d = S_{G_k} + S_{G*_k} + S_{Q_{r2},d} \tag{27}$$

and the quasi-permanent combination will be:

$$CCP = S_{G_k} + S_{G*_k} + S_{Q_{r2}} \tag{28}$$

Calculation algorithm The calculation algorithm of all the combinations for serviceability limit states would be expressed as follows:

1. calculation of S_{G_k}
2. calculation of S_{G*_k}
3. from $d = 1$ to $d = n_Q$
   (a) calculate $S_{Q_{r0},d}$
   (b) calculate $CPF_d = S_{G_k} + S_{G*_k} + S_{Q_{r0},d}$
4. from $d = 1$ to $d = n_Q$
   (a) calculate $S_{Q_{r2},d}$
   (b) calculate $CF_d = S_{G_k} + S_{G*_k} + S_{Q_{r2},d}$
5. calculation of $S_{Q_{r2}}$
6. calculate $CCP = S_{G_k} + S_{G*_k} + S_{Q_{r2}}$
7. end

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