

INTERNATIONAL STANDARD

**ISO
10252**

First edition
2020-02

Bases for design of structures — Accidental actions

Bases du calcul des constructions — Actions accidentelles



Reference number
ISO 10252:2020(E)
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Published in Switzerland

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces and other actions*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides requirements and guidelines for the design and assessment of structures in relation to the possible occurrence of accidental actions induced by human activities. Fire and man-made earthquake, however, are not included.

This document is fully aligned with ISO 2394 and gives information for risk informed decision making and semi-probabilistic design and assessment. Like in most modern codes nowadays, attention is given to explicit modelling of hazard scenarios as well as to more implicit safety measurements following from robustness requirements.

This document aims at promoting harmonization of design practice internationally and unification between the respective codes and standards such as for actions and resistance for the respective structural materials.

The principles and appropriate instruments to ensure adequate levels of reliability provide for special classes of structures or projects where the common experience base need to be extended in a rational manner.

The informative annexes included in this document provide support for the interpretation and the use of the principles contained in the normative clauses.

Bases for design of structures — Accidental actions

1 Scope

Accidental actions can be subdivided into accidental actions with a natural cause and accidental actions due to human activities. This document applies to reliability based and risk informed decision making for the design and assessment of structures subject to accidental actions due to human activities. However, fires and human-made earthquakes are not included.

The information presented in this document is intended for buildings and civil engineering works, regardless of the nature of their application and the use or combination of materials. The application of this document can require additional elements or elaboration in special cases.

This document is intended to serve as a basis for those committees that are responsible for the task of preparing International Standards, national standards or codes of practice in accordance with given objectives and context in a particular country. Where relevant, it can also be applied directly to specific cases.

This document describes how the principles of risk and reliability can be utilized to support decisions related to the design and assessment of structures subject to accidental actions and systems involving structures during all the phases of their service life. For the general principles of risk informed design and assessment, it is intended that ISO 2394 be considered.

The application of this document necessitates knowledge beyond that which it contains. It is the responsibility of the user to ensure that this knowledge is available and applied.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the editions cited here apply. For undated references, the latest editions of the referenced documents (including any amendments) apply.

ISO 2394:2015, *General principles on reliability for structures*

ISO 8930, *General principles on reliability for structures — Vocabulary*

3 Terms and definitions

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

For the purposes of this document, the terms and definitions given in ISO 2394 and ISO 8930 and the following apply.

3.1

barriers and shock absorbers

objects or structural devices intended to absorb part of the impact energy in order to protect the structure

3.2

burning velocity

rate of flame propagation relative to the velocity of the unburned dust, gas or vapour that is ahead of it

3.3
deflagration

propagation of a combustion zone at a velocity that is lower than the speed of sound in the unreacted medium

3.4
detonation

propagation of a combustion zone at a velocity that is greater than the speed of sound in the unreacted medium

3.5
dynamic load

time variant load or action that causes significant dynamic effects in the structure or in structural elements

Note 1 to entry: This means that the acceleration is not negligible; as a consequence, equations of motion should be used instead of equations of equilibrium.

Note 2 to entry: In the case of impact, the dynamic load represents a force on an associated contact area at the point of impact.

3.6
equivalent static load

alternative and usually conservative representation of a *dynamic load* ([3.6](#)) suitable for a static structural analysis

3.7
explosion

physical and/or chemical process of abrupt release of energy leading to short pressure waves of very high intensity

3.8
flame propagation

speed of a flame front relative to a fixed reference point

3.9
impact

event occurring when one object comes into contact with another one, where the contact force is of short duration

3.10
impacting object

vehicle, ship, etc. colliding with a structure

3.11
key element

structural member upon which the stability of a part of remainder of the structure depends

3.12
local damage

localised failure of a part of a structure that is severely disabled by an accidental event

3.13
unidentified action

accidental action or event that is unknown or unforeseen and cannot be considered by explicit analysis in the design or assessment

3.14**venting panel**

non-structural part of the enclosure (wall, floor, ceiling) with limited resistance that is intended to relieve the developing pressure from *deflagration* (3.4) in order to reduce pressure on other parts of the building

4 Symbols and abbreviated terms**4.1 General**

The symbols listed in this clause are used generally throughout the document. Symbols which are used only in one section are explained there and not listed here. All the symbols are based on ISO 3898.

4.2 Latin upper case letters

A	accidental action, (cross sectional) area
A_d	design value of an accidental action
D	diameter
E	modulus of elasticity, action effect, energy
E_{kin}	kinetic energy
E_{def}	deformation energy
F	action, load in general, collision force
F_R	frictional impact force
H	height
K_G	deflagration index of a gas cloud
K_{St}	deflagration index of a dust cloud
L	length
P	probability
P_f	probability of failure
P_{ft}	target probability of failure
P_s	probability of survival
R	resistance
T	temperature, period of time
T_e	period of time to be considered in a damaged situation
T_{ref}	reference period of time
U	severity (magnitude) of the source of an action

4.3 Latin lower case letters

a	acceleration, geometric parameter
b	geometric parameter
c	wave propagation speed
f	the event of failure, material strength parameter
$f_X(x)$	probability density function of X with dummy variable x
$g(X, t)$	limit state function
h	height
h_a	height of the application area of a collision force
i	impulse per unit of area resulting from explosion
k	stiffness
l	length
m	mass
p	momentum (impulse); pressure
p_{stat}	static activation pressure that activates a vent opening when the pressure is increased slowly
r	distance parameter
r_F	reduction factor
t	time
u	displacement;
u_o	maximum possible displacement (crumble length of impacting object)
v	velocity

4.4 Greek letters

Δ	interval
β	reliability index
β_t	target reliability index
ε	strain
γ	partial factor
γ_f	partial factors for actions
λ	rate of relevant events

μ	friction coefficient
ρ	mass density
σ	stress

4.5 Subscripts

i, j	index of basic variable
k	characteristic value
d	design value
l	leading action
max	maximum value (often in time)
o	initial (reference) value
p	plastic
rep	representative value
x, y, z	coordinate directions
y	yield (material)

5 General principles and conceptual approach

5.1 Types of accidental actions

Accidental actions due to human activities shall be considered in the design and assessment of buildings and other civil engineering structures. These actions include but are not limited to:

- Impact from vehicles, trains and tramways, ships, aircrafts, helicopters, forklift trucks, falling materials (rockfall, debris flow, dropped objects from cranes), machine related impacts like toppling cranes, wind turbines, parts detached from a rotary machine, blades detached from turbines, etc.;
- Internal and external explosions due to various sources like gas, dust, TNT, dynamite, etc.;
- Unidentified actions following from:
 - errors in design, errors during construction, service and operation and errors associated with maintenance and repair activities,
 - acts such as sabotage, vandalism, terrorism, etc. and their consequences.

Unidentified actions may be taken into account by specifying the resulting damage to the structure.

Design and assessment decisions related to the occurrence of accidental actions shall be made in accordance with the principles in ISO 2394.

This document shall, for a limited set of relevant actions, provide dedicated information on incident scenarios, load and resistance models, protection systems and calculation procedures.

NOTE Depending on the local circumstances, other actions can also require attention, as for instance avalanches, ice loading, floods resulting from storm surges, heavy rainfall or melting snow, log jams in rivers, sinkholes, etc.

Common impact actions (such as those resulting from stumbling persons, mooring of ships, etc.) should be considered as variable actions and are outside the scope of this document.

The extent and the depth of the design and analysis depend on the possible failure consequences and costs of mitigation.

5.2 Conceptual approach

5.2.1 Target reliability level

The appropriate degree of reliability shall, in accordance with ISO 2394, be selected with due regard to the possible consequences of failure, the associated expense and the level of efforts and procedures required to reduce the risk of failure and damage.

Target reliability levels for existing structures can differ substantially from those for new structures due to economic reasons. Ethical considerations, however, can impose bounds on the outcomes of an economic optimisation.

5.2.2 Strategies

Given the special character of accidental actions, the design approach shall focus on a combination of structural and non-structural measures to either prevent or limit:

- the occurrence of the action;
- the severity of the action;
- the effect of the action in terms of loading on the structure;
- the various direct and indirect consequences.

Direct consequences are damages caused directly by the action; indirect consequences are the result of direct damages, irrespective of the accidental action itself. The ratio between direct and indirect consequences can be seen as a measure of robustness (see ISO 2394).

In many cases, it can be economic, if not unavoidable, to accept some limited degree of direct local damage.

Special devices such as barriers and shock absorbers can be very helpful.

NOTE More information on effects of such devices is presented in [Annex C](#).

5.2.3 Identified and unidentified actions

In the case of identified accidental actions, an assessment on the basis of physical models, reliability considerations and risk analysis shall be performed, depending on the consequence class of the structure.

Since not all possible actions can be foreseen in sufficient detail, the structure shall possess an adequate degree of robustness. In the context of this document, this means that, given the occurrence of local damage or degradation due to an arbitrary accidental action, the probability of a disproportionate collapse should be limited.

5.2.4 Types of analysis

Depending on the function of the structure and the possible consequences in case of failure, the type of analysis and degree of sophistication shall be chosen, both with respect to the physical modelling and to reliability and risk aspects (see [5.3](#)).

The following types of analysis may be used, depending on the applicable risk/reliability aspects (see also ISO 2394):

- a) a full risk analysis;
- b) a probabilistic analysis based on predefined target reliability levels;
- c) semi probabilistic specifications of actions or damage characteristics.

The following types of analysis may be used, depending on the physical modelling (see also 5.4):

- a non-linear dynamic analysis, including load structure interaction;
- a non-linear structural dynamic analysis based on specified external forces or damage characteristics;
- a static structural analysis using quasi static actions or damage characteristics.

Within each of the above analysis categories, further simplifications are possible. The ultimate simplification is to develop a set of prescribed rules. In such a case, the effectiveness of these rules on a global level shall be based on experience (observations), experiments (tests) or advanced analysis procedures. In case of observations and testing, statistical uncertainty as formulated in ISO 2394 shall be accounted for.

Risk and reliability analysis should be based on statistical data as far as possible. Where that is not possible, best estimates based on engineering judgment should be made; these values can also be regarded as nominal values.

5.2.5 Classification of structures based on consequences

The classification system of ISO 2394:2015, Annex F, shall be followed. This system distinguishes 5 classes of consequences, ranging from consequences class CC 1 (predominantly insignificant material damage) to CC 5 (catastrophic losses and large number of exposed persons). The consequence class is in general a useful indicator for both the level of safety measures and the method of analysis to be applied.

5.2.6 Appropriate methods of analyses based on consequences

The extent and the depth of the analysis methods and the appropriate level of mitigation shall be chosen in accordance with the expected consequences.

An appropriate analysis method and level of mitigation shall contain, as a minimum, the following elements depending on the applicable consequence class:

- CC 1: No specific consideration of robustness.
- CC 2: Simplified analysis based on idealized action and structural performance models and/or prescriptive design/detailing rules.
- CC 3: Systematic identification of scenarios leading to structural collapse. Addressing strategies to deal with the identified scenarios. Analyses of structural performance may be based on simplified and idealized models but should be subject to justification. Prescriptive design and detailing rules may be utilized but should specifically address the identified scenarios. Reliability and risk analyses addressing direct and indirect consequences should be used as the basis for simplifications and idealizations.

- CC 4: Detailed studies and analyses of scenarios leading to structural collapses utilizing input from experts on all relevant subject matters. Such analyses include detailed assessments using dynamic and non-linear structural analyses and risk analyses rigorously addressing direct and indirect consequences.
- CC 5: Same as for CC 4 but with the addition of the involvement of an external expert/review panel for quality control.

From a reliability point of view, simplified models may always be used as long as they are conservative. Whether the degree of conservatism is acceptable or not is an economic issue to be decided by the decision maker.

NOTE The decision maker can be the owner or the competent authority.

5.3 Modelling of accidental actions

5.3.1 Identified actions

The model for extreme hazards such as explosions or collisions resulting in identified accidental actions shall be based on the following:

- a) a triggering event at some point in time and place;
- b) the amount of energy involved in the event and other relevant parameters;
- c) the physical interactions between the event, the environment and the structure, leading to the exceedance of various subsequent limit states in the structure.

All of the above three aspects shall be treated as random quantities and/or random processes as follows:

- The occurrence of the triggering event may often be modelled as events in a Poisson process of intensity $\lambda(t, x)$ per unit of volume and unit of time, t representing a point in time and x the spatial coordinates (x_1, x_2, x_3) .
- The amount of energy may be treated as a random quantity described by a (multidimensional) probability distribution.
- Finally, the physical interactions determining the details of the action and structural response may also be modelled using uncertain variables and properties.

Given these uncertainties, the probability of structural failure (for constant λ and small probabilities) can be expressed as:

$$P_f(T_{\text{ref}}) \approx \lambda T_{\text{ref}} \int_0^{\infty} P(f|U=u) f_U(u) du \quad (1)$$

where

- λ is the number of potential trigger events (e.g. vehicles passing by) per unit of time;
- T_{ref} is the reference period under consideration (usually one year or the lifetime of the structure);
- f is the failure event to be described by physical models of the structure and the environment;

$f_U(u)$ is the probability density function of the severity (energy) of the hazard, given a trigger event;

U represents the severity (magnitude, amount of available energy) of the hazard;

u is a specific value of U (dummy variable).

The probability of failure can depend on the distance between the structure and the location of the event. In that case, an explicit integration over the area or volume of interest is necessary. If there is more than one hazard, the resulting failure probabilities shall be added, taking into account possible correlations.

Failure in [Formula \(1\)](#) may refer to local or global consequences. The failure probability according to [Formula \(1\)](#) should be less than a specified annual target value, depending on the consequences.

NOTE Target values are usually set between 10^{-6} and 10^{-4} per year (see also ISO 2394).

5.3.2 Unidentified accidental actions

In the case of unidentified accidental actions, the effect of the action shall be modelled as a specific damage (for instance the removal of a specific beam or column). For the remaining part of the structure, for a relatively short period of time T_e (for instance defined as the time to evacuate people out of the building, or the time to repair), the structure shall withstand applicable actions. The corresponding conditional probability of failure shall not exceed a prescribed target reliability, as given by [Formula \(2\)](#):

$$P\{R < E \text{ in } T_e \mid \text{local damage occurred}\} \quad (2)$$

where

R is the resistance of the damaged structure after the occurrence of the unidentified accidental action;

E is the applicable action (effect) after the occurrence of the unidentified accidental action.

The target reliability in this case shall be aligned with the safety target for the building under non-accidental loading, the period T_e under consideration (hours, days or months) and the estimated probability that the local damage under consideration can develop (by causes other than those already considered in design).

NOTE Depending on the circumstances, values between 0,001 and 0,1 can be taken as appropriate.

For unconventional structures (e.g. structures with novel design concepts or using new materials), the probability of having an unspecified cause of failure should be considered as substantial. As a consequence, the target reliability value applicable to [Formula \(2\)](#) sometimes needs to be lowered.

5.3.3 Representative values for accidental actions

Based on the probabilistic approach outlined in [5.3.1](#) and [5.3.2](#), appropriate representative values for dynamic or quasi static accidental actions may be derived for use in simplified semi-probabilistic design and analysis.

NOTE Representative values for selected types of accidental actions, based on statistical or other approaches, are presented in [Annexes A](#) to [C](#).

5.4 Structural analysis involving accidental actions

The structural analysis involving an accidental action shall, to the extent appropriate for the specific problem, account for:

- severe geometrically nonlinear effects;
- nonlinear material behaviour;
- possible complete rupture of heavily exposed or minor structural elements;
- dynamic effects;
- the interaction between the action and the structure;
- the effects of protecting systems.

Simplified analysis can be appropriate but shall be based on proper justification.

EXAMPLE A quasi static analysis can often replace a full dynamic analysis.

In the case of impact, the most accurate result can be obtained by using an integrated model comprising the impacting body, the structure including the foundation and the protection system if applicable. As a simplification of the analysis, it may be assumed conservatively that the impact energy is fully absorbed either by the structure or by the impacting object.

In the case of an explosion, the action shall be characterized by sudden rises in air pressures and possibly wind effects. The following interaction effects shall be considered:

- the presence of the structure and/or other obstacles that can lead to reflections and turbulence and thus affect the explosion process;
- the collapse of weakened structural elements (accidentally or intended) that can lead to a change of air pressures.

For determining the material properties of the impacting object and of the structure, upper or lower characteristic values should be used, where relevant. Strain rate effects should also be taken into account, where appropriate.

When making simplifications to the analysis, a moderate level of accuracy may be deemed to be sufficient, considering the low probability of the accidental actions.

NOTE For relevant data and approaches of analysis reference is made to [Annex C](#).

6 Impact action

6.1 General

6.1.1 Sources of impact loading

This section applies to the following types of impact actions:

- road vehicles;
- trains and tramways;
- ships;
- aircrafts;
- helicopters;

- forklift trucks;
- falling and sliding materials (e.g. dropped objects, rockfall, debris).

Impact shall be considered in the design and assessment when any of the above (or other relevant) moving objects are in the immediate vicinity of the structure and significant impact forces can occur. The analysis shall be in accordance with the requirements described in [5.2](#).

Detailed guidance and information are provided in [Annex A](#).

6.1.2 Nature of the impact

During impact, the available kinetic energy of the impacting body shall be considered to be absorbed by deformation of the impacting object itself, deformation of the structure and, if applicable, its protecting systems. Impact interaction actions are usually of high energy and of short duration compared to the longest dynamic natural periods of the structure.

In order to assess the effect of the impact, next to the structural characteristics, the mass, the velocity at the time of impact, the angle of approach and the mechanical properties of the impacting body shall be considered. These parameters usually depend on the characteristics of the environment, such as the type of road or waterway, the distance, local slopes and so on.

Both the likelihood of the initiating event leading to structural damage as well as the statistical characteristics of the colliding object and the structure shall be taken into consideration.

6.1.3 Structural analysis and simplifications

6.1.3.1 In general, collision phenomena involve both the deformation of both the structure and the impacting body. To simplify the analysis, the interaction force may be found by assuming that the structure is fully rigid and the kinetic energy is absorbed and dissipated by the impacting object.

For the accidental type of impact considered in this document, the collision is a process involving (quasi) elastic-plastic deformations. Examples of a rigorous analysis of the collision phenomenon can be found in [Annex A](#). For guidance, the following simplified approaches to estimate the impact forces and durations are recommended:

- a) a plastic yield force that is constant with deformation and time;
- b) a series of constant forces, each of which having a finite duration;
- c) a plastic yield force that varies with deformation and/or time;
- d) a quasi-elastic rod or spring model, with calibrated properties.

The first approach is common for simple collisions:

- The primary inelastic response mode and its corresponding plastic, constant resisting force are determined.
- The elastic phase that precedes inelastic phase is disregarded because little energy is absorbed during the elastic phase.
- The time necessary to bring the colliding object to rest is calculated as per [Formula \(3\)](#):

$$\Delta t = m v_r / F_p \quad (3)$$

where

Δt is the time interval from start of collision to time of zero velocity of colliding object

m is the mass of colliding object

v_r is the velocity of colliding object at the start of the impact

F_p is the plastic resisting force

In order to consider (as in the second approach) a series of constant, but limited in duration, forces, the function needs to be evaluated as per [Formula \(4\)](#):

$$\frac{1}{2}mv_r^2 = \sum F_{pi}u_i \quad (4)$$

where

u_i are the extent of deformations over which the corresponding sequential plastic forces F_{pi} are applicable until the deformation at which all the kinetic energy is dissipated;

F_{pi} are the plastic resistance forces for interval i .

Then the duration of the collision can be estimated approximately by weighting the participation of the various engaged F_{pi} , or by theoretically exact calculations.

The third simplified approach involves postulating a force function that varies with deformation or time. Unfortunately, this approach requires the analyst to develop a forcing function, which can be problematic because the forcing function generally cannot be prescribed in advance. However, some guidance can be developed from the following subclauses and [Annex A](#), where results of some tests and theoretical developments are reported.

The fourth approach may be based on impact by a prismatic and homogeneous elastic rod. Given the primarily plastic nature of the impact process, the elastic model is useful only for the process up to the moment of the maximum indent. The properties of the rod should be considered as quasi-elastic quantities with values calibrated to the real highly non-linear elastic plastic behaviour.

A fully elastic rod develops an internal stress wave that travels from the striking end to the free end, and then back to the striking end, at which point the collision is complete. When using the model to describe the elastic-plastic impact, only the wave travelling from the striking end to the free end is used, neglecting however the reflected wave to simulate the irreversible nature of the deformation. With this model, the maximum resulting dynamic interaction force is given by [Formula \(5\)](#):

$$F = v_r \sqrt{k m} \quad (5)$$

where

v_r is the velocity of the rod at impact;

k is the spring stiffness of the rod (i.e., AE/L):

A is the cross-sectional area of the rod;

E is the elastic modulus of the rod;

L is the length of the rod;

m is the mass of the rod.

The travel time of the stress wave from the striking to the free end is L/c_o , where c_o is the rod wave propagation velocity as given in [Formula \(6\)](#):

$$c_o = \sqrt{(E / \rho)} \quad (6)$$

where ρ is mass density.

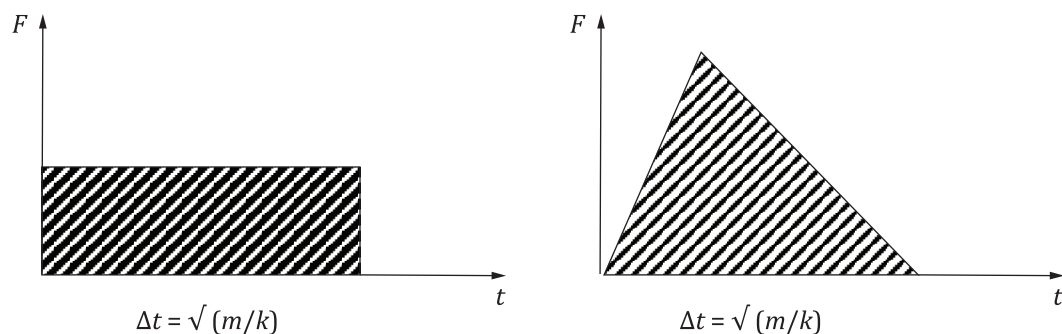
The duration of the collision is given by:

$$\Delta t = L / c_o = \sqrt{(m / k)} \quad (7)$$

NOTE 1 Guidance on appropriate values of k can be found in [A.1](#) to [A.7](#).

NOTE 2 An elastic spring model, with a rigid mass and separate spring with a stiffness constant, k , achieves the same peak force in time as the rod model. However, because the force increases over time, and is not constant as in the rod model, the time to develop the maximum force is: $\Delta t = (\pi/2) \sqrt{(m/k)}$.

NOTE 3 Refined analysis as well as experiments (see [Annex A](#)) show that the force time relation can often be represented by a triangle ([Figure 1](#)). In that case, the average value of the force follows alternatively from $m v_r / \Delta t$, where estimates for Δt can be found from [Formula \(7\)](#); in absence of other information, the duration of the impact can also be found from $\Delta t = u_o / v$, where u_o is the estimated final indent (often referred to as crumble length). In general, Δt is higher (in the elastic spring model up to a factor $\pi/2$) as the impacting body slows down during the impact process.



Key

- F interaction force
- t time
- Δt time interval
- m mass of the colliding object
- k stiffness of colliding object

Figure 1 — Schematic pulse shapes in case of a colliding object hitting a rigid, immovable structure

NOTE 4 The models in this clause give dynamic elastic force values on the outer surface of the structure. Within the structure, these forces can give rise to dynamic effects in structural components, depending on the duration of the load. In the absence of a dynamic analysis, the dynamic amplification factor for elastic response can be assumed to be equal to 1,4.

6.1.3.2 An alternative upper bound can be found when the structure dissipates all energy and the colliding object is considered rigid.

If the structure is designed to absorb the impact energy by plastic deformations, provision should be made so that its ductility is sufficient to absorb the total kinetic energy $\frac{1}{2} m v_r^2$ of the colliding object. In

the limit case of rigid-plastic response of the structure, the above requirement is satisfied if [Formula \(8\)](#) is verified:

$$(1/2)mv_r^2 \leq F_p u_0 \quad (8)$$

where

- F_p is the plastic strength of the structure, i.e. the limit value of the static force F ;
 u_0 is the maximum displacement (deformation capacity) of the point of impact that the structure can undergo, often referred to as crumble length.

NOTE Shear deformation at concentrated forces or near supports is often decisive for the limit on deformation capacity, at least in part because shear failure generally is brittle. When brittle failure modes govern, analysts often increase the assumed impact energy or reduce the crumble length in order to compensate for uncertainties.

In the case of protection by barriers, the formulae should be changed accordingly. See also [Annex C](#).

6.2 Impact from specific causes

6.2.1 Impact from road vehicles

A distinction shall be made between several types of roads, such as highways, local roads, urban roads and parking areas. Each of these road types has a typical distribution for traffic type, traffic intensity, driving velocity, vehicle mass, etc. The traffic type shall also be decisive for the location and size of the impact area on structural elements.

In general, actions in the driving direction (on the traffic way) and the direction perpendicular shall be considered. Road vehicle impact shall be taken into account for road crossing bridges, tunnels and buildings situated close to driveways; in some cases, it is also important to consider vehicles operating inside buildings.

For detailed information on distributions and resulting representative actions, see [A.1](#).

6.2.2 Impact from derailed trains

The effects of derailed trains shall be taken into account for buildings and structures in the vicinity of the railway. Derailing can also affect the superstructure supporting the railroad; effects on the superstructure from derailed rail traffic under or on the approach to a structure need not generally be taken into account as long as no collision with vertical elements is involved.

NOTE Derailment and dislocations of trains on bridge decks are outside the scope of this document.

In general, both loads in the driving direction and in the direction perpendicular to it should be considered.

For detailed information on distributions and resulting representative actions, see [A.2](#).

6.2.3 Impact from ships

Accidental actions due to collisions from ships shall be determined taking account, amongst other factors, the type and dimensions of the waterway, the flood conditions, the type and draught of vessels and their impact behaviour, and the type of the structures and their energy dissipation characteristics.

The effects of hydrodynamic added mass shall be taken into account; in some empirical calculation models, this can already have been done implicitly.

Bow, stern and broad side impact should be considered where relevant. Bow impact should be considered for the main sailing direction with a maximum deviation of 30°.

The action due to impact should be represented by a frontal force, a lateral force with a component acting perpendicularly to the frontal impact force and a friction component parallel to the surface of the structure.

The position and area over which the impact force is applied depend upon the geometry of the structure and the size and geometry (e.g. with or without bulb) of the vessel, the vessel draught and trim, and tidal variations. The vertical range of the point of impact shall account for consistently unfavourable conditions for the vessels sailing in the area.

The forces on a superstructure should be determined by taking account of the height of the structure and the types of ship that can be sailing in the vicinity. In general, the force on the superstructure of the bridge is limited by the yield strength of the ships' superstructure.

Under certain conditions, it can be necessary to assume that the ship is lifted over an abutment or foundation block prior to colliding with columns.

For detailed information on distributions and resulting representative actions, see [A.3](#).

6.2.4 Impact from aircraft

Impact loads from aircraft shall be taken into account for relatively high rise buildings located near airports. Details of the analysis and safety measures to be considered taken should depend on the importance and the strategic value of the building.

For detailed guidance, see [A.4](#).

6.2.5 Impact from helicopters

For buildings with roofs designated as a landing pad for helicopters, an emergency landing (helicopter fall (bad landing) in [A.5](#)) force shall be taken into account.

For detailed guidance, see [A.5](#).

6.2.6 Impact from forklift trucks

Impact loads from forklift trucks for buildings in which forklift trucks are operating shall be taken into account.

For detailed guidance, see [A.6](#).

6.2.7 Other types of impact

For many structures, in particular off shore, dropped objects can form a hazard for roofs and pipelines. In addition, blades and loose parts detached from machinery and equipment, snow (avalanches) and falling rocks can cause serious damage. Where relevant, such impact actions shall be considered.

For further information, see [A.7](#).

7 Explosion

7.1 General

7.1.1 Explosion types to be considered

Explosions shall be considered in design and/or assessment of buildings and civil engineering works relevant to transport (bridges, tunnels, jetties) where exposure to explosive material and serious consequences can be anticipated.

The origin of an explosion can be of a chemical or physical nature. Chemical explosions can result from:

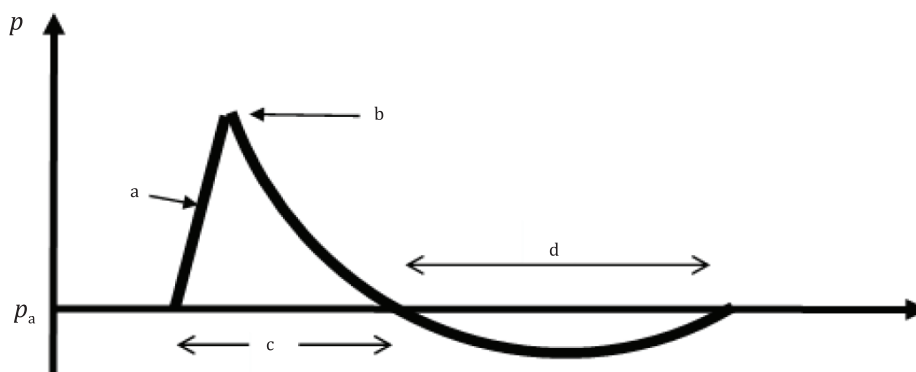
- natural gas and other explosive gases in buildings (piped gas or in gas in cylinders), tanks or transport vehicles (road tankers, tank wagons and ships);
- dust in buildings;
- high energy explosives (e.g. TNT or dynamite in storage or during transport).

An example where an explosion of physical origin can occur is a steam pressure vessel. This type of explosion is considered to be outside the scope of this document.

NOTE A BLEVE (boiled liquid expanded vapour explosion) starts as a physical explosion, but can develop into a chemical explosion.

7.1.2 Nature and schematisation of explosion loading

In an explosion, a very large amount of energy is released in a very short time. The energy can be released via pressure, temperature, radiation and flying debris. [Figure 2](#) gives a characteristic pressure time relation for an explosion.



Key

- p pressure
- p_a atmospheric pressure
- t time
- a Rise time.
- b Peak pressure.
- c Positive phase.
- d Negative phase.

Figure 2 — Typical pressure time relation for a vapour explosion

The likelihood of attaining a certain explosion pressure shall be based on:

- a) the probability of the presence of explosive material/equipment, its amount and location;
- b) the probability of direct or delayed ignition;
- d) the characteristics of the structure under consideration.

The following characteristics shall be considered:

- The fuel involved in an explosion can be a combustible gas (or vapour), a mist of combustible liquid, a combustible dust, a high-energy explosive or some combination of these.
- Gaseous fuels have a lower flammability limit (LFL) and an upper flammability limit (UFL). Between these limits for the fuel air ratios, ignition is possible and combustion takes place. The maximum explosion pressure is reached at the so-called stoichiometric mixture.
- The free air pressure following the ignition depends on the amount of available energy and the distance from the location of the explosion. Obstacles in the vicinity of the blast source can have a significant effect on the blast wave in some cases; in particular where the obstacle is situated inside the vapour cloud at the moment of ignition. For explosions inside structures (interior explosions), the venting conditions determine, to a large extent, the final explosion pressures.
- Ignitions of gasses and dust in confined spaces and high-energy explosives normally cause detonations that can be characterized by very rapid pressure increases that decay quickly, and heat-induced expansion of gases that effectively cause “winds”, followed by a lower-intensity negative pressure phase. Ignition of unconfined gas and dust usually results in deflagration, characterized by somewhat lower magnitude positive and negative pressure phases and longer pressure build-up and decay durations. In long tubes like tunnels, conditions can lead to a detonation process where internal ignition is by pressure. This can lead to much higher pressures.

7.1.3 Structural analysis and simplifications

In addition to the general information given in [Clause 5](#), the following analysis features and simplifications shall be applicable to explosions. The positive pressure phase is of interest for most applications and shall be taken into account. The negative pressure phase can be neglected in most applications due to its lower magnitude, and its direction generally acting back toward the explosion point, over areas that have already been exposed to the higher positive pressures. Negative phase loadings can sometimes be important for structures that require elastic response when negative phase coupling with natural modes can be important, and when rebound failures of components are to be avoided.

For many applications, the explosion action can be described with sufficient accuracy by the combination of two parameters: the peak pressure and the duration of the pressure wave or the peak pressure and the impulse.

Explosion pressures may be assumed to be uniform over the length of structural elements. Exceptions occur for detonations near to structural elements, for which there can be significant decreases in pressures at more distant points along a member, and for near-range explosions when the structural element is very near to or within the fire ball of the explosion. In these latter cases, loading histories can be very complex.

Brittle failure modes should be avoided for most explosion resistant designs, since many designs rely on ductility to dissipate energy and compensate for uncertain blast pressures. Non-ductile failure modes, such as buckling and shear at component extremities, should be avoided.

Since the rise time for blast loads is normally much shorter than the longest natural period of structural elements, the load is dynamic or impulsive. Therefore, the use of dynamic analyses to determine structural response should be considered. In some cases, single-degree-of-freedom structural elements subjected to blast loads that are taken to be uniform along their lengths can be assessed following basic theories that predict response as a function of load duration and intensity, natural frequency of the

element, and the amount of post-yielding behaviour to be allowed. For other systems, and in particular for multi-degree-of-freedom systems, advanced non-linear computer analyses are usually applied.

7.2 Explosions of various types

7.2.1 Interior explosions

Interior explosions due to dust, gas or vapour shall be considered wherever dust in large quantities can be present and where gases are burned, regulated, transported or stored. The explosion pressure depends primarily on the type of explosive substance, the concentration and uniformity of the dust, gas or vapour air mixture, the ignition source, the presence of obstacles in the enclosure, the size, the shape and the strength of the enclosure and the state of loading in which the explosion occurs, and the amount of venting or pressure release that can be available. The explosive pressure should be assumed to act effectively simultaneously on all of the bounding surfaces of the enclosure in which the explosion occurs.

High energy explosives shall be considered wherever present. When detonated inside structures, they generate very rapid, short-term impulse pressures, followed by build-up of pressurized hot gasses released by the combustion of the explosive material. The geometry of the compartment and the potential for venting through openings and by release of blast panels shall be accounted for in determining the pressure history on any component.

NOTE More information on models for interior explosion loading can be found in [Annex B](#).

7.2.2 Exterior explosion

Exterior explosions can result from transport and storage of explosive materials and shall be considered wherever present in close proximity to a building. It is in particular a common threat to buildings inside or just outside industrial areas that use or manufacture combustible or explosive materials. Exterior explosions also include intentional bomb attacks.

When estimating the pressures, the following shall be taken into account:

- Exterior explosions of gases, vapours and dust generally yield relatively low (but not necessarily negligible) pressures, unless the pre-explosion explosive cloud envelopes a volume that is congested with volumes of components, equipment and mechanical systems. In the latter case, there can be sufficient confinement to yield pressures that tend toward those associated with interior explosions.
- In any case, the magnitudes of the loads depend on the type and concentration of explosive material, the location and configuration of the structure under consideration relative to the explosive cloud or high-energy explosive, and the presence of intervening structure that can impact pressure magnitudes.

NOTE Detailed guidance on models for exterior explosion loading is provided in [Annex B](#).

7.2.3 Explosions in tunnels

Explosions in road tunnels shall be considered when vehicles with dangerous materials like LPG or explosives are to be expected. In tunnels, explosion pressures can become very high and even detonations cannot be completely excluded.

NOTE Detailed guidance on models for explosions in tunnels is provided in [B.2](#).

7.2.4 Dust explosions

Flammable dust explosions shall be taken into account in the design of buildings and other civil engineering works where combustible dust can accumulate on places unlikely to be cleaned in a regular way and ignitions sources can be expected to be present as a consequence of industrial activities.

NOTE Detailed guidance on modelling of dust explosions is provided in [B.3](#).

7.2.5 High energy explosions

High-energy explosions shall be considered in the vicinity of structures where explosives are fabricated, stored, handled and transported.

NOTE Detailed guidance on models of high energy explosions is provided in relevant parts of [B.1](#) and [B.4](#).

8 Unidentified actions

8.1 General

A structure shall be designed against "unidentified" accidental actions, in addition to "identified" accidental actions (see also [5.1](#)). Unidentified actions can include human errors in design, construction and use. Requirements to the response of the structure to unidentified actions should, as far as possible, be similar as to identified accidental actions, that is that damage (or damage increase) is accepted as long it is not disproportionate to the original cause. The process to achieve this is known as design for robustness.

Unidentified actions are intended to be used as a substitute for hazards and situations that cannot be foreseen in detail or at all. For the purpose of this document, unidentified actions shall be considered in one of the two following ways:

- by defining their negative effect on the structure such as a partial or total reduction of the structural capacity of one or more elements as indicated in [8.2](#);
- by specifying notional actions as indicated in [8.3](#).

Unidentified actions as provided in this clause may also be used as a simplification of identified actions when a detailed analysis is considered to be unnecessarily laborious.

NOTE 1 The unidentified actions to be taken into account as well as the requirements with respect to the response are to some extent arbitrary and depend on an agreement with the client and regulatory authority. This includes the periods for safe evacuation and rescue operations.

NOTE 2 Detailed guidance is provided in [Annex C](#).

8.2 Notional removal of or damage to elements

As indicated in [5.3](#) and [8.1](#), the nature and impact of an unforeseen action cannot be described in detail but, as a meaningful substitute action, a certain degree of reasonable damage may be defined instead.

In particular, the notional removal of a single load bearing member (column, beam or floor) in the structure may be specified. The structure shall then be checked to ensure that upon the notional removal of each element the structure remains stable and that any local damage does not exceed a certain limit.

For buildings that are not frame buildings, the equivalent member to be removed shall be:

- in a reinforced concrete wall, a length not exceeding $2,25 h$, where h is the storey height;
- in an external masonry, timber or steel stud wall, the length measured between lateral supports provided by other vertical building components (e.g. columns or transverse partition walls);
- in an internal masonry wall or timber or steel stud wall, a length not exceeding $2,25 h$, where h is the storey height.

NOTE These criteria have been taken from Eurocode EN 1991-1-7.

Where the structural form justifies it, more than one member of one type or a combination of types can be removed as notional action. This may be the case if they are very closely spaced such that it is very

likely that an unidentified action results in them all suffering damage simultaneously. In the case of a transfer beam, its notional removal requires columns supported by it to be removed simultaneously.

The method of structural analysis used should be commensurate with that used in structural design against identified accidental actions and the method of notional member removal (i.e. whether quasi-static or sudden and causing dynamic effects).

8.3 Notional loads on key elements

As an alternative to the procedure in 8.2, key elements may be designed against the specified notional unidentified actions. The standardized notional action is a uniformly distributed load of 34 kN/m².

NOTE 1 This criterion has been taken from Eurocode EN 1991-1-7.

The unidentified action should be applied in the vertical and both horizontal directions (in one direction at a time) to the member and any attached components while giving due regard to the ultimate strength of such components and their connections.

NOTE 2 A key element is a critical member in the absence of which the structure can become damaged to an intolerable extent. In principle, the most obvious critical elements are the columns.

8.4 Risk-based design for unidentified accidental actions

As the unidentified accidental actions are not quantified in intensity and likelihood of occurrence, a risk assessment based on an assumed state of damage should be carried out. This assessment should determine the risks, conditional on a structural element having failed. The tolerable conditional risk shall be greater (e.g. two orders of magnitude) than the value of the unconditional risk chosen for risks corresponding to identified accidental actions.

NOTE 1 A higher tolerable limit can be used for tolerable conditional risk from unidentified actions because the generally low probability of occurrence of the unidentified actions reduces the non-conditional risk. For example, for a probability of occurrence of 1/100 in the period considered (say the life time), the total risk is equal to the unconditional risk divided by 100.

NOTE 2 The tolerable conditional risk level can be determined based on the tolerable unconditional risk level and the potential likelihood of unidentified accidental actions that can be determined based on expert engineering judgment.

For individual projects, communication with local authorities in an early stage of the design is recommended.

Annex A (informative)

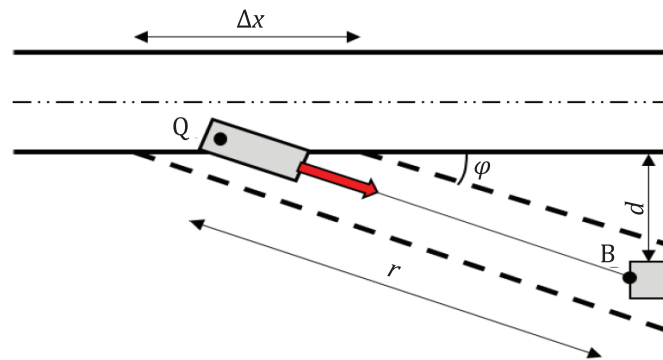
Guidance for detailed impact analysis

A.1 Impact from road vehicles

A.1.1 Impact model

The basic design situation for vehicle impact is given in [Figure A.1](#). The impact force should be determined taking into account the local characteristics of the road, the traffic and the terrain. The object B may be a building, a bridge pier or for instance any protective structure.

A vehicle leaves the intended course at point Q with velocity v_0 and under an angle φ . A structure B or structural member in the vicinity of the roadway at distance r is hit with velocity v_r .



NOTE See [Formula \(A.1\)](#) for designation.

Figure A.1 — Vehicle impact scenario

The probability that there is a collision during a period of time, T , can be approximated by:

$$P_c(T) = n T \lambda \Delta x P(v_0^2 > 2ar) \quad (\text{A.1})$$

where

- n traffic intensity (depending on local circumstances);
- λ vehicle failure intensity (number of road leaving incidents per vehicle km);
- T period of time under consideration;
- Δx part of the road from where collisions can be expected (see [Figure A1](#));
- v_0 velocity of vehicle;
- a deceleration of the vehicle after leaving the road;

- r $d/\sin \varphi$ = the distance from "leaving point" to "impact point";
 d distance from the structural element to the road;
 φ angle between vehicle trajectory and road axis.

In case of a lorry impacting a structural member, the velocity v_r at impact may be determined using [Formula \(A.2\)](#):

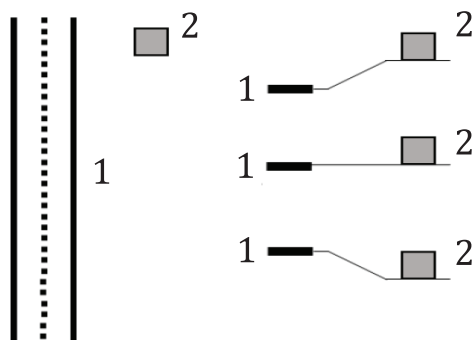
$$v_r = \sqrt{(v_0^2 - 2ar)} = v_0 \sqrt{(1 - d/d_b)} \quad (\text{for } d < d_b) \quad (\text{A.2})$$

where

- v_0 is the velocity of the lorry leaving the trafficked lane;
 a is the average deceleration of the lorry after leaving the trafficked lane;
 d_b is the projection of the braking distance r_b : $d_b = r_b \sin \varphi = (v_0/2a) \sin \varphi$.

The value of d_b may be multiplied by 0,6 for uphill slopes and by 1,6 for downhill slopes (see [Figure A.2](#)).

The probability of having an impact force F exceeding a value X is the same as in [Formula \(A.1\)](#), but with $P(F(m, k, v_r) > X)$ instead of $P(v^2 > 2ar)$, where for $F(\cdot)$ any suitable impact model may be taken.



Key

- 1 road
2 structure

Figure A.2 — Uphill and downhill slopes

The traffic intensity and the vehicle failure intensity (number of times a car flies off the road per km of driving) should be estimated on the basis of national or regional statistics, taking care of local circumstances like grades, curvatures, road condition and speed limits. An indicative value for λ on highways is:

$$\lambda = 10^{-7} \text{ per km running of vehicle} \quad (\text{A.3})$$

Further indicative probabilistic information for the basic variables (partly based on statistical data and partly on engineering judgement^[1]) is given in [Table A.1](#).

The actual impact on the structure for given values of mass, velocity, etc. follows from advanced or simplified models as described in [Clause 6](#).

Given a target reliability $\beta = 4,0$ for a reference period T of 50 years, [Table A.2](#)^[1] gives recommended design values for some of the input parameters and the resulting impact forces.

Table A.1 — Indicative data for probabilistic collision force calculation

Variable	Designation	Probability distribution	Mean value	Standard deviation
v_o	Vehicle velocity			
	— highway	Lognormal	80 km/h	10 km/h
	— urban area	Lognormal	40 km/h	8 km/h
	— courtyard	Lognormal	15 km/h	5 km/h
	— parking garage	Lognormal	5 km/h	5 km/h
a	Deceleration (on the ground)	Lognormal	4,0 m/s ²	1,3 m/s ²
m	Vehicle mass — lorry	Normal	20 000 kg	12 000 kg
m	Vehicle mass — car	—	1 500 kg	—
k	Vehicle stiffness	Deterministic	300 kN/m	—
φ	Angle	Raleigh	10° (1:6)	10° (1:6)

Table A.2 — Design values for vehicle mass, velocity and horizontal dynamic impact force F_0

Type of road	Mass m kg	Velocity v_o km/h	Deceleration a m/s ²	Impact force ^a F kN	Duration ^a Δt s	Distance ^a d_b ^a m
Motorways	30 000	90	3	2 400	0,3	20
Urban areas ^b	30 000	50	3	1 300	0,3	10
Courtyards	1 500	20	3	120	0,1	2
— cars only	30 000	15	3	500	0,3	2
— all vehicles						
Parking garages	1 500	10	3	60	0,1	1
— cars only						

^a Based on [Formula \(A.2\)](#) and [Formula \(5\)](#) with $v_r = v_o$.

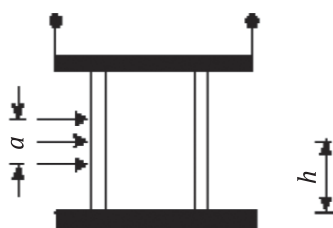
^b Road in areas where the speed limit is 50 km/h.
Only almost horizontal terrain is considered.

A.1.2 Practical guidance

A.1.2.1 Impact area

In the absence of further information, the collision force F from lorries may be applied at any height h between 0,5 m to 1,5 m above the level of the carriageway or higher where certain types of protective barriers are provided (see [Figure A.3](#)). The recommended application area is $a = 0,5$ m (height) by 1,50 m (width) or the member width, whichever is the smaller.

For impact from cars, the collision force F may be applied at $h = 0,50$ m above the level of the carriageway. The recommended application area is $a = 0,25$ m (height) by 1,50 m (width) or the member width, whichever is the smaller.

**Key**

- a* height of the recommended force application area, ranging from 0,25 m (cars) to 0,50 m (lorries)
- h* location of the resulting collision force *F*, i.e. the height above the level of the carriageway, ranging from 0,50 m (cars) to 1,50 m (lorries)

Figure A.3 — Collision force on supporting substructures near traffic lanes for bridges and supporting structures for buildings

A.1.2.2 Forces on superstructures

Design values for actions due to impact from lorries and/or loads carried by the lorries on members of the superstructure should be defined unless adequate clearances or suitable protection measures to avoid impact are provided. The recommended value for adequate clearance, excluding future re-surfacing of the roadway under the bridge, to avoid impact is in the range of 1 m above the legal limit value.

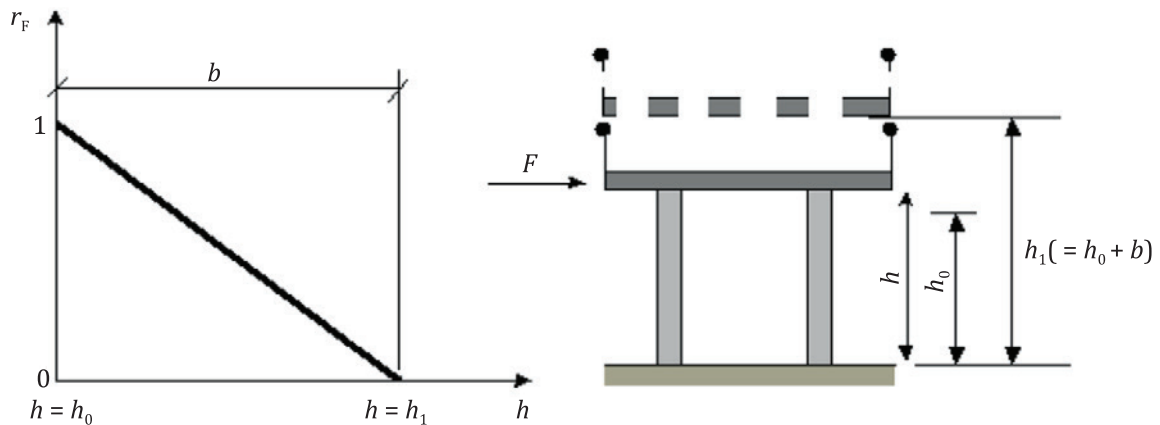
Table A.3 — Indicative equivalent horizontal static design forces due to impact on superstructures

Category of traffic	Equivalent static design force, F_{dx}^a
	kN
Motorways and country national and main roads	500
Country roads in rural area	375
Roads in urban area	250
Courtyards and parking garages	75
^a x = direction of normal travel.	

On vertical surfaces, the indicative design impact forces are equal to the equivalent static design forces due to impact given in [Table A.3](#).

For $h_0 \leq h \leq h_1$, these values may be multiplied by a reduction factor r_F . A recommendation is given in [Figure A.4](#).

On the underside surfaces of bridge decks, the same impact forces as above with an upward inclination sometimes have to be taken into account: the conditions of impact may depend on local circumstances. The recommended value of upward inclination is 10° ; see [Figure A.5](#).

**Key**

r_F multiplication (reduction) factor for the impact force F depending on the value of h

F impact force

h physical clearance between the road surface and the underside of the bridge deck

h_0 minimum height of clearance between the road surface and the underside of the bridge deck below which a full impact on the superstructure needs to be taken into account

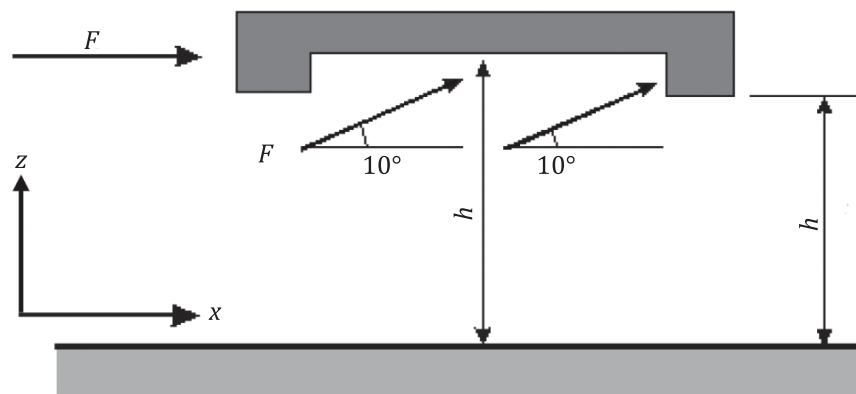
The recommended value of h_0 is the legal truck limit plus 0,1 m.

h_1 maximum value of the clearance between the road surface and the underside of the bridge deck

For values of h_1 and above, the impact force F may be left out of consideration.

b $b = h_1 - h_0$. The recommended value for b is 1,0 m. A reduction factor r_F for F is allowed for values of b between 0 m and 1 m, i.e. between h_0 and h_1

Figure A.4 — Recommended value of the factor r_F for vehicular collision forces on bridge decks

**Key**

x direction of traffic

z vertical direction

h height of the bridge from the road surface measured to either the soffit or the structural members

F collision forces

**Figure A.5 — Impact force on members of the superstructure
(y is perpendicular to the paper)**

In determining the value of h , allowance should be made for any foreseeable future reduction caused by the resurfacing of the roadway under the bridge.

Where appropriate, horizontal forces perpendicular to the direction of normal travel, F_{dy} , should also be taken into account. It is recommended that these forces do not act simultaneously with the actions resulting from traffic in the driving direction.

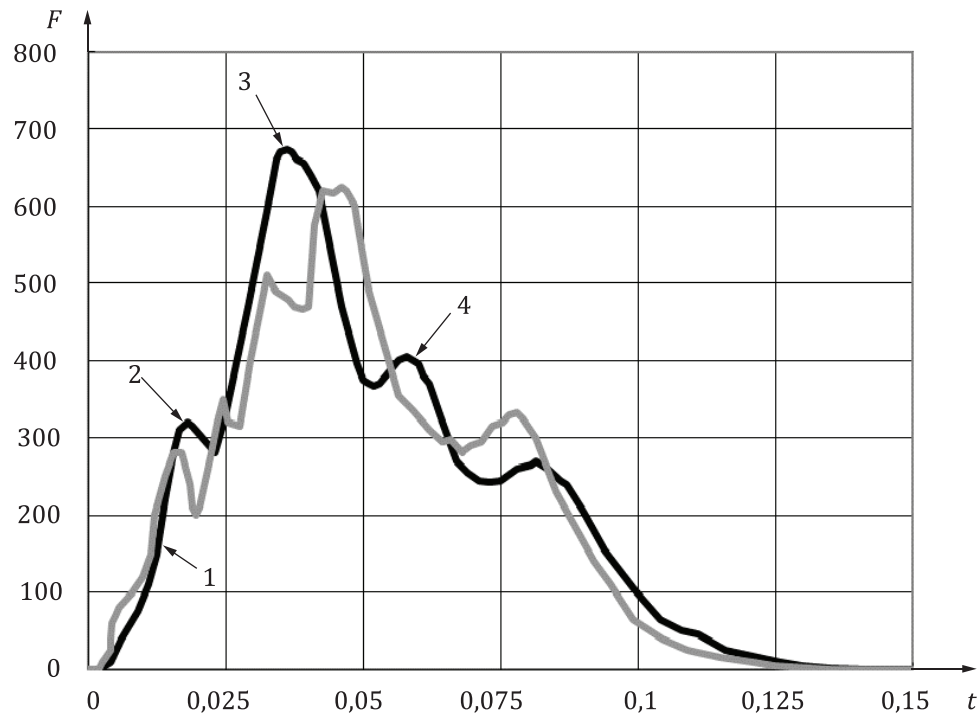
A.1.3 Example of an impact force calculation

A.1.3.1 Impact force versus time based on measured values

For a standard-sized vehicle, the actual impact values measured during the frontal impact tests can be available. The impact force when a standard-sized vehicle of a given weight hits a building with the given impact velocity can be estimated. The load versus time curve in the impact direction obtained from an actual frontal impact test is shown in [Figure A.6](#)^[2]. The black line in the figure indicates the measured values of the impact force, and the grey line indicates the FEM simulation results of a frontal impact test.

The first rise in the graph is determined by the energy absorbing property of the vehicle. Repetitive interaction among various properties, including deformation, buckling and contact, of the energy absorbers results in deformations of the front part of the vehicle (1 and 2 in [Figure A.6](#)). The maximum impact force is observed when there is an impact on the engine (the stiffest structural member) during the event 3. This is the maximum impact force for the building. A deformation around the engine mount follows and the 2nd peak (4) occurs just before the engine comes in contact with the front of the cockpit. The biggest impact shock for the occupant is this 2nd peak.

The impact force versus time curve for the frontal impact of a standard-sized vehicle can be approximated to a triangular waveform which peaks during the impact on the engine ([Figure A.7](#)). The form of the triangle is determined by the maximum force $F_{\max}$, the peak time t_p , and the acting time t_{end} .

**Key** F force (kN) t time (s)

grey line measured values;

black line result of FE model simulation

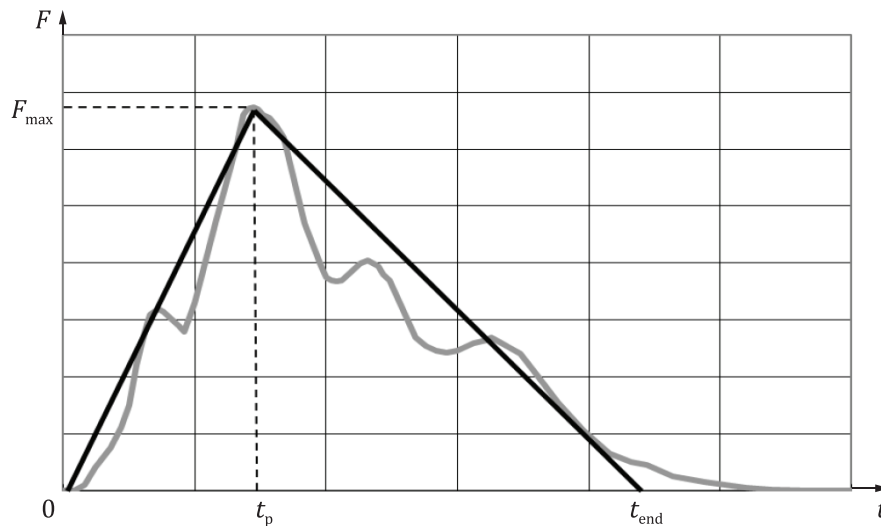
1 The initial stiffness is determined by the stiffness of the energy absorber of the body.

2 The peak due to the behavior (e.g. buckling) of energy absorbing members.

3 The peak due to the impact of the engine.

4 The peak due to the contact between the cockpit and the engine.

Figure A.6 — Example of load versus time curves in the impact direction for the frontal impact test of a standard-sized vehicle^[2]



Key

F	force (kN)
t	time (s)
$F_{\max}$	maximum force (kN)
t_p	peak time (s)
t_{end}	acting time (s)

Figure A.7 — Triangular wave approximation of the impact force versus time curve

The estimated force versus time curve for the triangular wave under the given impact conditions is obtained. The results (the maximum force $F_{\max}$, the peak time t_p , the acting time t_{end}) obtained from actual frontal impact tests are shown in [Table A.4](#). The maximum force $F_{\max}$ and the peak time t_p can be derived from the measured value in the load versus time curve for the frontal impact test. The acting time t_{end} is determined as an impulse for the load versus time curve (time integral of impact force = acting time $t_{\text{end}} \times F_{\max}/2$) which corresponds to the momentum p in the impact phenomenon (= vehicle weight $m \times$ impact velocity v):

$$t_{\text{end}} = 2p / F = 2mv / F \quad (\text{A.4})$$

The relationship between p , F , and t_p is determined by providing p as the indicator of the impact conditions, as shown in [Figures A.8](#) and [A.9](#). The square symbols in the figures indicate the results of the actual impact test and the solid lines indicate the approximated results. The relationship between p and F can be approximated using [Formula \(A.5\)](#). Similarly, the relationship between p and t_p can be approximated using [Formula \(A.6\)](#).

$$F = 23,11p + 37,45 \quad (\text{A.5})$$

$$t_p = -3,65 \times 10^{-4} p + 3,92 \times 10^{-2} \quad (\text{A.6})$$

where

F is the force given in kN;

p is the momentum in kNs;

t_p is time of the peak in s.

The maximum force is also reasonably well approximated by [Formula \(3\)](#).

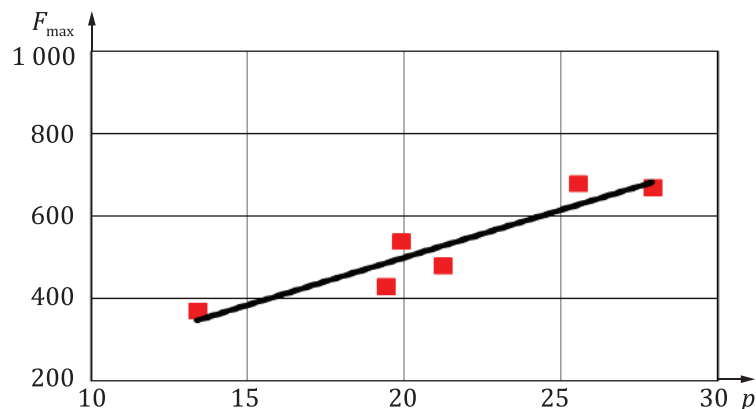
The momentum p is determined, assuming the vehicle mass m and the impact velocity v . The approximation expressions that give the estimated force F , peak time t_p , and acting time t_{end} can be determined using the momentum p as an index for the approximation [Formulae \(A.4\)](#) to [\(A.6\)](#). Finally, these parameters give the approximated impact force versus time curve for a standard-sized vehicle. The acting position of the impact force and the acting area corresponding to the height and width of the vehicle and its relative position to the building can be, consequently, determined.

Table A.4 — Results of frontal impact tests of standard-sized vehicles^[2] to ^[5]

Vehicle	Vehicle mass m t	Impact velocity v km/h	Momentum ^a p kNs	Maximum force F_{max} kN	Peak time t_p s	Acting time ^b t_{end} s
A	1,8	56,2	28	670	0,036	0,083
B	1,2	39,8	13	370	0,038	0,072
	1,3	56,3	20	540	0,031	0,074
	1,3	56,2	19	430	0,031	0,090
C	1,6	56	26	680	0,025	0,075
D	1,4	56,5	21	480	0,028	0,089

^a Momentum is given by $p=mv$, where m is the mass of the vehicle, v is the impact velocity.

^b The acting time is given by $t_{end}=2p/F_{max}$.



Key

F_{max} maximum force (kN)

p momentum (kN·s)



results of actual impact tests

Figure A.8 — Relationship between the momentum p (kN · s) and the maximum force F_{max} (kN) in a frontal impact test