Recommendations for Design against Disproportionate Collapse of Structures

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American Society of Civil Engineers
Structural Engineering Institute
Disproportionate Collapse Standards and Guidance Committee
Terminology and Procedures Sub-Committee
Working note to the Committee members

This document consists of recommendations and commentary. Specific content still to be developed by dedicated Sub-Committees is indicated in red and brackets. Numbers and text given in tables are intended to illustrate the possible final content of these tables and to stimulate discussion. They should be understood as placeholders for the final content to be specified by the respective Sub-Committees.

Draft April 2011 is a further development of Draft April 2010 emailed to the Disproportionate Collapse Standards and Guidance Committee on 01 May 2010. Comments referring to Draft April 2010 have been received from within and outside the Committee over the last year. These comments were discussed and mostly settled by the Terminology and Procedures Sub-Committee. Corresponding changes were implemented in this new Draft April 2011. Changes to Draft April 2010 were made in the WORD track changes mode and are visible as long as the markup option in the view menu is selected.

It follows a list of still open issues and required changes.

1. The wording of “Section C.2.22 Integrity” needs to be adapted to the new ASCE 7-10.
2. It was suggested to mention methods of risk assessment in Commentary Section C.4.4 or elsewhere.
3. It was asked if ASCE employs lawyers for checking their documents against legal risks.
4. It was suggested to include more technical information on segmentation (Section 6.6 or elsewhere).
5. It was asked if and how confidentiality should be required concerning the documentation produced in the course of the design (Section 8). For instance, information on key elements might be critical and for security reasons it might be better to keep it confidential.
# Table of Contents

- **Working note to the Committee members** ................................................................. 2

1. **Scope** .......................................................................................................................... 6

2. **Definitions** .................................................................................................................. 7
   - 2.1 Abnormal event ........................................................................................................ 7
   - 2.2 Action ........................................................................................................................ 7
   - 2.3 Alternative load paths ............................................................................................. 7
   - 2.4 Authorities ............................................................................................................... 7
   - 2.5 Client ....................................................................................................................... 7
   - 2.6 Collapse resistance ............................................................................................... 7
   - 2.7 Consequences ......................................................................................................... 8
   - 2.8 Continuity ............................................................................................................... 8
   - 2.9 Design criteria ....................................................................................................... 8
   - 2.10 Design methods ................................................................................................... 8
   - 2.11 Design objectives ............................................................................................... 8
   - 2.12 Design requirements ........................................................................................... 8
   - 2.13 Direct design ...................................................................................................... 9
   - 2.14 Disproportionate collapse .................................................................................. 9
   - 2.15 Ductility ............................................................................................................. 9
   - 2.16 Engineer ............................................................................................................. 9
   - 2.17 Event control ..................................................................................................... 9
   - 2.18 Exposure ............................................................................................................ 10
   - 2.19 Hazard scenarios .............................................................................................. 10
   - 2.20 Indirect design .................................................................................................. 10
   - 2.21 Initial damage .................................................................................................... 10
   - 2.22 Integrity ............................................................................................................. 10
   - 2.23 Key element ....................................................................................................... 10
   - 2.24 Local resistance ............................................................................................... 11
1 Scope

These recommendations concern the design for the prevention of disproportionate collapse of structures. A performance-based framework of design criteria comprising design requirements, design objectives, design methods, and verification procedures is given. It applies to the design of new structures and the retrofit design of existing structures.

C.1 Scope

In general, the design criteria are specified on a project-by-project basis by the parties involved in and affected by a given project. This specification can be based on the provisions presented here as long as they are applicable. If not, other applicable provisions can be used. The provisions given here become binding only if and only to the extent as stipulated elsewhere.

See also Sections 2.14 and 3.2.
2 Definitions

2.1 Abnormal event

An event that is unforeseeable or occurs with very low probability and is not considered in the ordinary design of a structure.

C.2.1 Abnormal event

This term refers to the abnormal conditions that might actually occur. In contrast, the abnormal conditions assumed in the design against disproportionate collapse are called hazard scenarios (see Section 5.2).

The term ordinary design encompasses all kinds of design including that for seismic loading but excluding the special considerations related to disproportionate collapse treated here.

2.2 Action

A condition that affects a structure and can be characterized by physical quantities.

C.2.2 Action

In most cases, actions are applied loads or imposed deformations or displacements. However, the definition also includes heat action (fire) and corrosive action. Abnormal events and hazard scenarios may or may not result in actions.

2.3 Alternative load paths

Alternative paths for a load to be transferred from a point of application to a point of resistance. Enable a redistribution of forces originally carried by failed components thus preventing a failure from spreading.

C.2.3 Alternative load paths

Providing alternative load paths is one of the design methods (see Sections 2.10, 6.1, and 6.5).

2.4 Authorities

The Authorities are the construction authorities that hold jurisdiction over the structure in question.

C.2.5 Client

The need to include other stakeholders derives from the indirect consequences of a collapse. For a storage structure filled with hazardous material, important bridges and tunnels, and other lifeline structures, for instance, possible indirect consequences are an impairment of public infrastructure and of civil and national defense. Examples of other stakeholders are military authorities, external local authorities, utility companies, concessionaires, financial institutions, insurance companies, permanent and transient occupants, and neighbors. Defining the collective will of the Client can require an administrative or political decision on a local, national, or international level.

2.5 Client

The Client is understood here to be the collective of the owner of the structure and other stakeholders affected by its possible collapse.

C.2.6 Collapse resistance

Collapse resistance is a property that depends on the
collapse resistant if abnormal events do not lead to disproportionate collapse.

A precise definition requires reference to specified design objectives: a structure is collapse resistant if the hazard scenarios affecting the structure do not lead to an extent of damage that violates the performance objectives. The hazard scenarios affecting the structure, referred to in this definition, do not include hazard scenarios averted by event control.

2.7 Consequences
The consequences of the collapse of a structure.

2.8 Continuity
Uninterrupted connectivity between structural components.

2.9 Design criteria
The design criteria form the framework for performance-based design. They consist of design requirements, design objectives, design methods, and verification procedures.

2.10 Design methods
Methods that aim at preventing disproportionate collapse of a structure.

2.11 Design objectives
Design objectives are the basis of direct design. They comprise hazard scenarios, performance objectives, and applicable combinations of actions and safety factors.

2.12 Design requirements
Specification of whether design against disproportionate collapse is required for a structure and the abnormal events. A robust structure is collapse resistant because an initial damage does not spread disproportionately (see Section 2.34). A non-robust structure can be made collapse resistant by reducing its vulnerability to prevent or lessen initial damage (see Section 2.43). See also Figure 2.

A disproportionate collapse can be prevented by providing collapse resistance or by reducing the exposure (event control).

C.2.7 Consequences
Being all-embracing, this term refers to the sum of all direct and indirect losses resulting from a collapse (see Commentary Section C.4.3).

The consequences are one of the conditions from which the design requirements are derived (see Section 4).

C.2.8 Continuity
Extraordinary load-transfer mechanisms, such as catenary action, can be enabled by continuity. In this way, the redundancy and robustness of a structure can be increased. However, an increase of robustness can also be achieved by a break of continuity at segment borders.

C.2.9 Design criteria
See Sections 1 and 3.

The definition of design criteria used in this document can differ from definitions used elsewhere.

C.2.10 Design methods
The design methods are specified as part of the design criteria (see Sections 3 and 6).

The available design methods are event control, protection, local resistance, alternative load paths, and segmentation.

C.2.11 Design objectives
The design objectives are specified as part of the design criteria (see Sections 3 and 5).

The definition of design objectives used in this document can differ from definitions used elsewhere.

C.2.12 Design requirements
The design requirements are specified as part of the design criteria (see Sections 3 and 4).
and, if yes, specification of the level of requirements on design objectives, design methods, and verification methods.

### 2.13 Direct design

The terms direct and indirect design categorize approaches for designing collapse-resistant structures: (a) direct design explicitly provides collapse resistance by demonstrating that the structure meets specified performance objectives when specified hazard scenarios occur and affect the structure; (b) indirect design aims at increasing the collapse resistance of a structure implicitly by incorporating consensus-approved design features; this is done by applying prescriptive design rules and thus without explicit consideration of hazard scenarios and without demonstrating that performance objectives are met.

### 2.14 Disproportionate collapse

A collapse that is characterized by a pronounced disproportion between a relatively minor event and the ensuing collapse of a major part or the whole of a structure.

A precise definition requires reference to specified design objectives: a collapse is disproportionate if the hazard scenarios lead to an extent of damage that violates the performance objectives.

### 2.15 Ductility

The ability of a structural component or structure to sustain large plastic deformations without rupture.

### 2.16 Engineer

The Engineer is the person or entity responsible for the design of the structure and of any external structural measures of protection. This responsibility extends to both the construction stages and the completed state of structure and structural measures of protection.

### 2.17 Event control

Reducing the probability of occurrence and the intensity of abnormal events through non-structural
2.18 Exposure

The exposure is the set of abnormal events that possibly affect a structure during construction and lifetime and are not considered in ordinary structural design.

C.2.18 Exposure

The exposure of a structure is one of the conditions from which the design requirements are derived (see Section 4).

The disproportionate collapse of a structure can be prevented by reducing its exposure which in turn can be achieved by event control (see Section 2.17). See also Figure 2.

2.19 Hazard scenarios

The abnormal conditions to be assumed in design to occur during construction and lifetime of a structure.

C.2.19 Hazard scenarios

The hazard scenarios are specified as part of the design objectives (see Section 5).

2.20 Indirect design

See Section 2.13.

C.2.20 Indirect design

2.21 Initial damage

The damage to a structure that can be ascribed directly to an abnormal event (without resorting to the response of the structure as a whole) or a notional damage as determined from the hazard scenarios.

C.2.21 Initial damage

An initial damage results in a reduction (sectional weakening) or a complete loss (component failure) of the load-carrying capacity of a part of the structure. It is usually locally limited.

2.22 Integrity

This term has occasionally been used in the past to denote robustness as defined in Section 2.34. It is recommended to discontinue the usage of this term in this sense.

C.2.22 Integrity

The term general structural integrity has been defined as the property of being able “to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage” [1]. This corresponds to the term robustness as defined in Section 2.34. However, the term integrity is used only occasionally to denote this particular meaning. Furthermore, it could also be defined in a different manner more in line with general usage, namely as the wholeness and intactness of a structure. Integrity would thus refer to the state of a structure and not to its behavior. It is therefore recommended to discontinue the usage of the term integrity in the firstly mentioned sense and to use the term robustness instead.

2.23 Key element

A structural component (or a part of the structure)

C.2.23 Key element

Examples of possible key elements are a building column,
that meets two conditions: (a) it is not larger than the structural part assumed to initially fail as determined from the hazard scenarios; (b) its failure leads to further damage that violates the performance objectives.

2.24 Local resistance
An increase or confirmation of adequacy of local structural resistance. Prevents or reduces initial damage that could otherwise lead to disproportionate collapse.

2.25 Non-structural methods
See Section 2.40.

2.26 Non-threat-specific design
See Section 2.41.

2.27 Performance objectives
The acceptable response of a structure to the hazard scenarios.

2.28 Prescribed local resistance
A local increase or confirmation of adequacy of structural resistance implemented as an indirect design measure.

2.29 Prescriptive design rules
Consensus-approved features of indirect design that have been codified in standards and guidelines or specified for a particular project.

2.30 Progressive collapse
A collapse that commences with the failure of one or a few structural components and then progresses over successively affected other components.

a pier of a continuous bridge, a cable in a cable-supported structure, an individual anchor of an anchored retaining wall, certain areas of the subsoil, and components of temporary bracing or shoring during construction.

C.2.24 Local resistance
Providing local resistance is one of the design methods (see Sections 2.10, 6.1 and 6.4). Within direct design, this is called specific local resistance (see Section 2.39). Within indirect design, this is called prescribed local resistance (see Section 2.28).

C.2.27 Performance objectives
The performance objectives are specified as part of the design objectives (see Section 5).

The definition of performance objectives used in this document can differ from definitions used elsewhere.

C.2.28 Prescribed local resistance
Prescribed local resistance is the indirect-design version of the design method local resistance described in Section 2.24. Instead of prescribed local resistance, the term enhanced local resistance has occasionally been used in the past.

C.2.29 Prescriptive design rules
See Section 6.8.

C.2.30 Progressive collapse
See Commentary Section C.2.14.

There are various types of progressive collapse that differ with respect to the mechanism of collapse and the propagating action such as pancake-type collapse, zipper-type collapse, domino-type collapse, section-type collapse, instability-type collapse, and mixed-type collapse. Different kinds of structures can be susceptible to different types of progressive collapse.
2.31 Propagating action

An action that in the course of a progressive collapse results from the failure of one structural component and leads to the failure of one or more further structural components.

C.2.31 Propagating action

The type of progressive collapse is characterized by the propagating action (see Commentary Section C.2.30).

2.32 Protection

Mitigating the effect of abnormal events through external structural measures. Prevents or reduces initial damage that could otherwise lead to disproportionate collapse.

C.2.32 Protection

Providing protection is one of the design methods (see Sections 2.10, 6.1, and 6.3).

Protection is a structural method and, therefore, different from event control, which is a non-structural method (see Section 2.17). Nevertheless, the classification of a measure as protection or event control may be difficult in practice.

2.33 Redundancy

Availability of alternative load paths.

C.2.33 Redundancy

See Section 2.3.

Redundancy is one possibility to enhance robustness. Both terms denote different properties of the structure though and should be clearly distinguished.

2.34 Robustness

Insensitivity to initial damage. A structure is robust if an initial damage does not lead to disproportionate collapse.

A precise definition requires reference to specified design objectives: a structure is robust if an initial damage as determined from the hazard scenarios does not lead to an extent of damage that violates the performance objectives.

C.2.34 Robustness

Robustness is a property that depends on the structure and the location and amount of initial damage. If the initial damage is specified as a notional damage (see Section 2.41), its cause is immaterial and robustness becomes a purely structural property. This is in contrast to a broader definition of robustness – as it is given, for instance, in Eurocode 1 [2] – that refers to abnormal events. Such a broader conception is close to the term collapse resistance defined in 2.6.

A robust structure is collapse resistant but not vice-versa (see Section 2.6). Robustness can be achieved by alternative load paths (see Section 2.3) or segmentation (see Section 2.37). See also Figure 2.

2.35 Segment

A part of the structure delimited by dedicated segment borders. In case of a failure within a segment, the failure is limited to this segment and no forces are transmitted to, or displacements are imposed on, adjacent segments that could lead to the failure of the adjacent segments.

C.2.36 Segment border

See Section 2.37 and Commentary Section C.6.6.

A border of a segment of a structure at which a failure within the segment is isolated from the
remaining structure and thus brought to a halt.

2.37 Segmentation

Segmenting a structure by dedicated segment borders to isolate a failure that occurs in a segment within that segment thus preventing a failure from spreading.

C.2.37 Segmentation

Segmentation is one of the design methods (see Sections 2.10, 6.1, and 6.6).

Instead of segmentation, the term compartmentation (or compartmentalization) has occasionally been used in the past. This term originates from fire engineering where it denotes the division of a structure into fire compartments to confine a fire to the compartment of origin. Despite the functional similarity of both terms, the purposes and structural means are different. It is therefore recommended to discontinue the usage of the term compartmentation for denoting a design method against disproportionate collapse and to use the term segmentation instead.

2.38 Significance

The significance of a structure is determined by the consequences of its collapse.

C.2.38 Significance

The significance of a structure is one of the conditions from which the design requirements are derived (see Section 4).

2.39 Specific local resistance

A local increase or confirmation of adequacy of structural resistance implemented as a direct design measure.

C.2.39 Specific local resistance

Specific local resistance is the direct-design version of the design method local resistance described in Section 2.24.

2.40 Structural methods

Structural methods aim at preventing a disproportionate collapse through the structural design of the structure itself (internal methods) or of external structural measures of protection, thus enhancing collapse resistance. In contrast, non-structural methods aim at preventing abnormal events from affecting a structure, thus reducing the exposure, without requiring a structural design for this purpose.

C.2.40 Structural methods

Protection, local resistance, alternative load paths, and segmentation are structural methods. Event control is a non-structural method. Structural methods can be implemented within a direct or indirect design approach (see Sections 6.7 and 6.8). Internal methods apply to the design of the structure itself. External structural methods (protection) apply to the structural design of additional auxiliary components or structures that are not components of the structure itself.

2.41 Threat-specific design

The terms threat-specific and non-threat-specific design categorize the manner hazard scenarios are specified: (a) threat-specific design is based on specific threats that possibly occur (specific abnormal events); (b) non-threat-specific design is based on the assumption of notional actions or notional damage.

C.2.41 Threat-specific design

Direct design can be based on threat-specific or non-threat-specific hazard scenarios. Indirect design is not based on hazard scenarios and therefore is neither threat-specific nor non-threat-specific (see Section 6.8). Event control is threat-specific (see Section 6.2).

2.42 Verification procedures

Procedures for demonstrating that specified performance objectives are met when specified

C.2.42 Verification procedures

The verification procedures are specified as part of the design criteria (see Sections 3 and 7).
hazard scenarios occur. Used in the context of direct design and event control

2.43 Vulnerability

Susceptibility of a structure to suffer initial damage when affected by abnormal events.

C.2.43 Vulnerability

This definition is based on Ref. [3] according to which vulnerability accounts for the direct consequences of an abnormal event, which are related to the component behavior.

A structure can be made collapse resistant (see Section 2.6) by reducing its vulnerability which in turn can be achieved by protection (see Section 2.32) or local resistance (see Section 2.24). See also Figure 2.
3 Design criteria

3.1 General

The design criteria form the framework for performance-based design against disproportionate collapse. They consist of design requirements, design objectives, design methods, and verification procedures.

C.3.1 General

See also Section 1.

The framework suggested here is illustrated in Figure 1.

3.2 Specification of design criteria

In general, the design criteria are specified on a project-by-project basis by the Client and the Engineer and approved by the Authorities as further detailed below. This specification can be based on the provisions of Sections 4 to 7 if applicable. If not, other applicable provisions can be used. The provisions of Sections 4 to 7 become binding only if and only to the extent as stipulated by the Authorities or by law.

C.3.2 Specification of design criteria

Due to the complexity and diversity inherent in major structures, a project-related specification of design criteria is required for such structures. Such a specification entails a decision-making process possibly supported by specialist consultants. The various parties involved in and affected by a given project (i.e. Client, Engineer, and Authorities) are assigned different responsibilities in specifying the design criteria (see Sections 4.4, 5.6, 6.10, 7.4).

In some cases, the design criteria can be established on the basis of a classification of structures. Such a classification is outlined below. It is anticipated, however, that a generally binding specification of design criteria on the basis of a classification of structures will at best be possible for small to medium-sized structures.

Some of the design criteria listed here have been codified for specific types of structures: Eurocode 1 [2], General Services Administration guidelines for federal office buildings [4], Unified Facilities Criteria for Department of Defense projects [5], Approved Document A of the UK Building Regulations [6], Post-Tensioning Institute recommendations for stay cable design, testing and installation [7].
Figure 1: Design criteria: framework for design against disproportionate collapse
4 Design requirements

4.1 General

The design requirements specify whether design against disproportionate collapse is required for a structure. If such a design is required, they can specify the level of requirements on design objectives, design methods, and verification methods.

The design requirements are usually based on the exposure and the significance of a structure.

4.2 Exposure

The exposure results from the threats that possibly affect a structure during its construction and lifetime. In the context of disproportionate collapse, only the threats not considered in the ordinary design of a structure are of interest. When they occur they are called abnormal events.

C.4.2 Exposure

Abnormal events result from physical threats (faults) or logical threats (errors) [8]. The first group can be divided into external physical threats (extreme environmental action, accidental or intentional explosion or impact, fire) and immanent physical threats (undetected defects of the structure). The second group encompasses errors in the design, construction, and usage of the structure.

Concerning intentional physical threats, a structure is particularly exposed when it is significant, is perceived as important, or symbolizes major institutions. This is the case for landmark structures, public buildings, major bridges and tunnels, and other lifeline structures.

A list and classification of possible abnormal events is given in Table 1 [to be revised and completed by the Requirements and Objectives Sub-Committee].

4.3 Significance

The significance of a structure is determined by the consequences of its collapse.

C.4.3 Significance

The consequences of a collapse are the sum of all direct and indirect losses. They go beyond the immediate human and material losses and include indirect consequences such as impairment of public infrastructure and of civil and national defense.

A list and classification of possible consequences is given in Table 2 [to be drafted by the Requirements and Objectives Sub-Committee].

4.4 Specification of design requirements

The design requirements are specified by the Client and approved by the Authorities. This specification can be based on the classification suggested in Table 3 if applicable or on other applicable provisions.

C.4.4 Specification of design requirements

Structures can be classified according to their exposure and significance. The resulting classes of structures can be linked to levels of requirements. Such a classification is suggested in Table 3 [to be revised and completed by the Requirements and Objectives Sub-Committee]. No requirements indicates that design against disproportionate collapse is not required.
Specifying design requirements is not intrinsically an engineering problem. It can be supported by professionals but must reflect the will of the owner, the concern of other stakeholders affected by a possible collapse, and public opinion, which is represented by the collective will of Client and Authorities. Therefore, the classification suggested in Table 3 is a non-binding orientation guidance. It becomes binding only if expressly stipulated.

Table 1: List and classification of abnormal events

<table>
<thead>
<tr>
<th>Faults</th>
<th>External</th>
<th>Man-made (accidental or intentional)</th>
<th>Impact (car, train, ship, aircraft, missile)</th>
<th>Explosion (gas, explosives)</th>
<th>Fire</th>
<th>Excessive loading (live load)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Environmental</td>
<td>Earthquake</td>
<td>Extreme wind forces</td>
<td>Heavy snow fall (excessive roof loads)</td>
<td>Floods (scour)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Immanent</td>
<td>Lack of strength</td>
<td>Cracks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errors</td>
<td></td>
<td>Errors</td>
<td>Design errors</td>
<td>Construction errors</td>
<td>Usage errors</td>
<td></td>
</tr>
</tbody>
</table>

[To be revised and completed by the Requirements and Objectives Sub-Committee.]

Table 2: List and classification of consequences

[To be drafted by the Requirements and Objectives Sub-Committee.]
### Table 3: Classification of structures and design requirements

<table>
<thead>
<tr>
<th>Basis of classification</th>
<th>Classification of structures</th>
<th>Examples of structures</th>
<th>Requirement level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significance low</td>
<td>Structures whose failure does not result in major human or material losses.</td>
<td>Buildings rarely occupied by humans. Short bridges on secondary roads.</td>
<td>1 No requirements</td>
</tr>
<tr>
<td>Significance medium</td>
<td>Structures whose failure results in limited human or material losses.</td>
<td>Buildings with up to 50 occupants. Bridges and tunnels of up to 100 m length and up to four lanes.</td>
<td>2 Basic requirements</td>
</tr>
<tr>
<td>Exposure or significance high</td>
<td>Structures which are highly exposed or whose failure results in major human or material losses.</td>
<td>Embassy and military buildings. Structures and clusters of structures with up to 1000 occupants. Bridges and tunnels of up to 1000 m length and up to six lanes.</td>
<td>3 High requirements</td>
</tr>
<tr>
<td>Exposure and significance high</td>
<td>Structures which are highly exposed and whose failure results in major human or material losses.</td>
<td>Lifeline structures. Buildings in which hazardous products are stored or processed. Structures and clusters of structures with more than 1000 occupants. Bridges and tunnels of more than 1000 m length or more than six lanes.</td>
<td>4 Very high requirements</td>
</tr>
</tbody>
</table>

[To be revised and completed by the Requirements and Objectives Sub-Committee.]
5 Design objectives

5.1 General

Design objectives are the basis of direct design. They comprise hazard scenarios, performance objectives, and applicable combinations of actions and safety factors.

5.2 Hazard scenarios

The hazard scenarios are the abnormal conditions to be assumed in the design to occur during the construction and lifetime of a structure.

They can be specified as specific abnormal events, as notional actions or as notional damage. Notional damage is typically specified as cases of initial local failure.

C.5.2 Hazard scenarios

In threat-specific design, the hazard scenarios are specific abnormal events. In non-threat-specific design, they are notional actions or notional damage.

The abnormal conditions possibly affecting a structure can differ substantially from project to project. Therefore, it is difficult to specify the hazard scenarios in a standardized manner, in particular when threat-specific design is used.

Threat-specific design requires the identification and quantification of all threats possibly affecting the structure and the ensuing effects on it. These input data are likely to be incomplete and imprecise because some threats remain unpredictable. Threat-specific design, if used, should therefore be complemented by elements of non-threat-specific design, in particular by the assumption of notional damage. For the same reason, preference should normally be given to non-threat-specific design, possibly complemented by elements of threat-specific design.

With respect to notional damage, the applicable design methods are limited to alternative load paths and segmentation (see Section 6). When the performance objective that no initial damage shall occur is specified (see Commentary Section C.5.3), notional damage cannot be specified as a hazard scenario and only the design methods event control, protection, and local resistance are applicable.

Initial local failure is usually assumed to be a sudden failure of a connection or a structural component section.

5.3 Performance objectives

The performance objectives are the acceptable response of a structure to the hazard scenarios.

They are typically specified as acceptable extent of collapse and acceptable other damage.

C.5.3 Performance objectives

The performance objectives can be defined on a global level, that is, as acceptable extent of collapse and acceptable other damage, or on a local level, for instance, as acceptable rotation of plastic hinges.

Other damage includes damage to the non-collapsed remaining structure, damage to the surroundings, and indirect losses resulting from an impairment of public infrastructure and of civil and national defense. The acceptable extent of collapse and the acceptable other damage can be combined in the term acceptable
5.4 Combinations of actions and safety factors

The combinations of actions and safety factors to be applied in analytical verifications pertaining to direct design must be specified.

C.5.4 Combinations of actions and safety factors

In ordinary design, this specification is mathematically derived from the requirement to achieve a uniform level of safety. This is not currently possible in the context of disproportionate collapse. A reasonable level of safety can nevertheless be achieved by using reasonable combinations of actions and safety factors.

It is suggested that the actions determined from the hazard scenarios and actions resulting from an initial damage be combined with dead load, live load, and environmental loads. Actions determined from the hazard scenarios are notional actions or actions resulting directly from specific abnormal events (and not averted by event control). Actions resulting from initial damage are related to the transfer of elastic or gravitational potential energy stored in the structure. Examples are forces originally carried by failed components that are redistributed into the remaining structure and forces caused by the impact of separated and falling components on the remaining structure.

It is suggested that stricter safety factors be required when disproportionate collapse is intended to be prevented by specific local resistance (see Commentary Section C.6.4).

5.5 Sets of design objectives

The design objectives can be specified as sets or functions of interrelated data.

C.5.5 Sets of design objectives

When the design objectives are specified as more than one set of data, the performance objectives can be specified differently for hazard scenarios of different kind or extent. Such dependency can be expressed by a number of sets of design objectives or by functional relationships. An example for the latter is to specify the acceptable extent of collapse as a multiple of the (notional) initial damage. The extent of collapse and the initial damage can be quantified by referring to the affected masses, volumes, floor areas...
5.6 Specification of design objectives

The design objectives are specified by the Client and approved by the Authorities. This specification can be based on the provisions suggested in Table 4, Table 5, and Table 6 if applicable or on other applicable provisions.

The list of specified hazard scenarios shall be expanded on the request of the Engineer.

C.5.6 Specification of design objectives

Client and Authorities will normally seek engineering advice when specifying and approving design objectives. This advice can be provided by in-house or external professionals. These professionals are normally, but not necessarily, different from the Engineer as defined in Section 2.16.

The design objectives can be established depending on the level of requirements. Corresponding design objectives are suggested in Table 4, Table 5, and Table 6 [to be revised and completed by the Requirements and Objectives Sub-Committee]. The level of requirement in these tables can be determined from the classification of structures suggested in Table 3 if applicable. It is suggested that direct design can be used for requirement level 2 and is required for requirement levels 3 and 4 (see Commentary Section C.6.10). Table 4, Table 5, and Table 6 therefore only refer to these levels.

For the reasons outlined in Commentary Sections C.5.2, C.5.3, C.5.4, the provisions suggested in Table 4, Table 5, and Table 6 are intended to serve as a non-binding orientation guidance. They become binding only if expressly stipulated.

The list of specified hazard scenarios shall be expanded on the request of the Engineer because they can depend on the structural properties of the structure. For instance, key elements that become apparent only during design can be accounted for in this manner. While the selection of the size of notional damage is the responsibility of Client and Authorities, the opinion of the Engineer shall be considered concerning the locations of notional damage. Alternatively, only the size of notional damage is specified as a hazard scenario.
### Table 4: Hazard scenarios depending on the level of requirements

<table>
<thead>
<tr>
<th>Requirement level</th>
<th>Notional actions</th>
<th>Notional damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Basic requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 High requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Very high requirements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

[To be revised and completed by the Requirements and Objectives Sub-Committee.]

### Table 5: Performance objectives depending on the level of requirements

<table>
<thead>
<tr>
<th>Requirement level</th>
<th>Acceptable extent of collapse</th>
<th>Acceptable other damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Basic requirements</td>
<td>10 % of the structure in terms of masses, volumes, or floor area (in buildings).</td>
<td>A cost equivalent of 10 % of the construction costs of the structure.</td>
</tr>
<tr>
<td>3 High requirements</td>
<td>10 % of the structure in terms of masses, volumes, or floor area (in buildings).</td>
<td>A cost equivalent of 10 % of the construction costs of the structure but not more than USD 20 M.</td>
</tr>
<tr>
<td>4 Very high requirements</td>
<td>5 % of the structure in terms of masses, volumes, or floor area (in buildings).</td>
<td>A cost equivalent of 5 % of the construction costs of the structure but not more than USD 20 M.</td>
</tr>
</tbody>
</table>

[To be revised and completed by the Requirements and Objectives Sub-Committee.]
Table 6: Combinations of actions and safety factors depending on the level of requirements

<table>
<thead>
<tr>
<th>Requirement level</th>
<th>Design method</th>
<th>Combinations of actions and load safety factors</th>
<th>Resistance safety factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Basic requirements</td>
<td>Specific local resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3 HSA + 1.1 IDA + (0.95 or 1.1) DL + 0.7 LL + 0.2 EL</td>
<td>Concrete: 0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternative load paths</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.1 HSA + 1.1 IDA + (0.95 or 1.1) DL + 0.7 LL + 0.2 EL</td>
<td>Concrete: 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segmentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>High requirements</td>
<td>Specific local resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5 HSA + 1.1 IDA + (0.95 or 1.1) DL + 0.7 LL + 0.2 EL</td>
<td>Concrete: 0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternative load paths</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.2 HSA + 1.1 IDA + (0.95 or 1.1) DL + 0.7 LL + 0.2 EL</td>
<td>Concrete: 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segmentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Very high requirements</td>
<td>Specific local resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.7 HSA + 1.3 IDA + (0.9 or 1.3) DL + 1.0 LL + 0.3 EL</td>
<td>Concrete: 0.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alternative load paths</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3 HSA + 1.3 IDA + (0.9 or 1.3) DL + 1.0 LL + 0.3 EL</td>
<td>Concrete: 0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

HSA = actions determined from hazard scenarios
IDA = actions resulting from initial damage
DL = dead load
LL = live load
EL = environmental load
(see Commentary Section C.5.4 for further explanations)

[To be revised and completed by the Requirements and Objectives Sub-Committee.]
6 Design methods

6.1 General

Design methods are methods that aim at preventing disproportionate collapse of a structure. The available design methods are event control and protection, which are external methods, and local resistance, alternative load paths, and segmentation, which are internal methods. Event control is a non-structural method, whereas protection and the internal methods are structural methods. Structural methods can be implemented within a direct or indirect design approach.

C.6.1 General

Internal methods apply to the design of the structure itself. External methods do not directly apply to the design of the structure itself. Protection is an external but structural method because it involves the structural design of additional auxiliary components or structures that are not components of the structure itself.

The classification of design methods suggested here is illustrated in Figure 2.

6.2 Event control

Event control reduces the probability of occurrence and the intensity of abnormal events through non-structural measures.

C.6.2 Event control

Event control reduces the exposure of a structure. The kind of abnormal event to be controlled must be anticipated for implementing event control. It is thus a threat-specific method.

Examples of event control are the control of public access to the structure, the enforcement of standoff distances, aerial surveillance, and anti-aircraft defense.

Instead of reducing the exposure of a structure as a whole, event control can focus on reducing the exposure of key elements.

6.3 Protection

Protection mitigates the effect of abnormal events through external structural measures. It prevents or reduces initial damage that could otherwise lead to disproportionate collapse.

C.6.3 Protection

Protection reduces the vulnerability of a structure. It usually focuses on the key elements of a structure.

External structural measures of protection are additional auxiliary components or structures as long as they are not components of the load-transfer system of the structure being protected.

Examples of protection are barriers, walls, and dams that resist and shield from impact, heat, and blast.

6.4 Local resistance

The local structural resistance is increased or confirmed to be adequate by this design method. It prevents or reduces initial damage that could otherwise lead to disproportionate collapse. Within direct design, this method is called specific local resistance. Within indirect design, this method is called prescribed local resistance.

C.6.4 Local resistance

Local resistance reduces the vulnerability of a structure. This method usually focuses on its key elements.

For example, building columns or bridge piers identified as key elements can be provided with local resistance.

Providing specific local resistance is based on specified hazard scenarios. These can be specific abnormal events not averted by event control (threat-specific) or notional actions (non-threat-specific). In either case, these input data are possibly imprecise. Furthermore, the failure of
6.5 Alternative load paths

Alternative load paths provide alternatives for a load to be transferred from a point of application to a point of resistance. They enable a redistribution of forces originally carried by failed components and thus prevent a failure from spreading.

6.6 Segmentation

A structure is divided into segments by dedicated segment borders by this design method. This allows a failure that occurs in a segment to be isolated within that segment and thus to prevent a failure from spreading.

6.7 Direct design

Direct design explicitly provides collapse resistance by demonstrating that specified performance objectives are met when specified hazard scenarios occur and affect the structure.

6.8 Indirect design

Indirect design aims at implicitly increasing the collapse resistance of a structure by incorporating any one key element is likely to lead to immediate disproportionate collapse (contrary to the failure of an alternative load path or a segment border). It is therefore suggested that an increased margin of safety be required when disproportionate collapse is intended to be prevented by specific local resistance (see Table 6).

Instead of prescribed local resistance, the term enhanced local resistance has occasionally been used in the past.

C.6.5 Alternative load paths

Alternative load paths enhance the robustness of a structure.

Alternative load paths can form through ordinary or extraordinary load-transfer mechanisms. Examples of the latter are the inversion of flexural load transfer (from hogging to sagging above a failing column), the transition from flexural to tensile load transfer (catenary action), and the transition from plane to spatial load transfer (in one-way slabs turning into two-way slabs). Alternative load paths can be added by increasing continuity, strength, and ductility.

C.6.6 Segmentation

Segmentation enhances the robustness of a structure.

Segment borders can produce their isolating effect by three different modes of effectiveness: (a) by accommodating large forces, that is, by high local resistance; (b) by accommodating large deformations and displacements, that is, by eliminating continuity or reducing stiffness; (c) by accommodating large forces and large displacements at the same time, which can be achieved by high ductility and results in large energy dissipation capacity.

For example, a continuous multi-span bridge can be segmented by designing selected piers as highly resistant abutment piers or by making the bridge girder discontinuous at certain intervals.

C.6.7 Direct design

For structures of high exposure or significance, direct design is preferable to indirect design. It takes into account the diversity and complexity emerging in structures and provides collapse resistance in a reasonably reliable, verifiable, and economical manner.

C.6.8 Indirect design

The verification effort required in direct design may become disproportionate for structures of low or medium
6.9 Combination of design methods

The design methods can be combined.

6.10 Specification of design methods

The structural design methods are selected by the Engineer and approved by the Authorities. This selection can be based on the provisions suggested in Table 7 if applicable or on other applicable provisions.

The complementary or alternative use of event control requires adequate and coordinated professional and organizational support for reliably implementing such non-structural measures and the explicit consent of the Client, the Engineer, and the Authorities.

The prescriptive design rules codified so far are detailing rules that intend to provide tension ties, to enable catenary action, or to provide ductility in building structures. These measures aim at providing local resistance or alternative load paths.

If potential alternative load paths are not provided with the strength required for a redistribution of forces, a failure spreading is possibly not prevented but promoted. Therefore, prescriptive design rules aiming at providing alternative load paths should be applied only to structures strictly within the scope of the applicable provisions or when their safety has been approved otherwise.

Prescriptive design rules for specific types of structures are suggested in Appendix A [to be drafted by the Indirect Design Sub-Committee].

The applicable structural design methods, including the respective design approaches, can be specified depending on the level of requirements. Such a specification is suggested in Table 7 [to be revised by the Requirements and Objectives Sub-Committee and the Direct Design Sub-Committee]. The level of requirement in these tables can be determined from the classification of structures suggested in Table 3 if applicable. It is suggested that no design measures be required for requirement level 1 and that direct design is required only for requirement levels 3 and 4.

Event control is normally outside the expertise and influence of the Engineer and thus requires adequate professional and organizational support. It is anticipated
that it will only be of interest for requirement levels 3 and 4, and that it will not normally be used as a stand-alone method.

Figure 2: Classification of methods for preventing disproportionate collapse (design methods)
### Table 7: Specification of Structural Design Methods

<table>
<thead>
<tr>
<th>Requirement level</th>
<th>Design approaches</th>
<th>Design methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Basic requirements</td>
<td>Indirect design (prescriptive design rules)</td>
<td>Protection</td>
</tr>
<tr>
<td></td>
<td>Direct design based on non-threat-specific hazard scenarios</td>
<td>Local resistance</td>
</tr>
<tr>
<td>3 High requirements</td>
<td>Direct design based on non-threat-specific hazard scenarios possibly complemented by threat-specific hazard scenarios</td>
<td>Protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific local resistance</td>
</tr>
<tr>
<td>4 Very high requirements</td>
<td>Direct design based on non-threat-specific hazard scenarios complemented by threat-specific hazard scenarios</td>
<td>Protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Specific local resistance</td>
</tr>
</tbody>
</table>

[To be revised by the Requirements and Objectives Sub-Committee and the Direct Design Sub-Committee.]
7 Verification procedures

7.1 General

Verification procedures are used to demonstrate that specified performance objectives are met when specified hazard scenarios occur. They are used in the context of direct design and event control.

In an analytical verification, the analysis including the modeling of hazard scenarios, structure, measures of protection, and event control should be sufficiently detailed. Specified combinations of actions and safety factors should be considered.

7.2 Detailed analysis

The required level of detail is generally high.

C.7.1 General

Verification is usually performed by analysis. In particular cases, it can be performed by model or full-scale tests.

In indirect design, verification is replaced by checking the proper application of prescriptive design rules.

C.7.2 Detailed analysis

An analytical verification generally requires non-linear dynamic analysis allowing for large displacements and non-linear material behavior, and using multi-degree-of-freedom models.

C.7.3 Simplified analysis

Simplification, where admissible, resorts to linear analysis, quasi-static analysis, and generalized single-degree-of-freedom models.

Simplified analysis can be sufficient if the failure spreading does not involve impact loading. This is not usually the case for structures susceptible to pancake-type collapse (see Commentary Section C.2.30).

[To be revised and completed by the Direct Design Subcommittee.]

C.7.4 Specification of verification procedures

It is suggested that generally detailed analysis be required. Simplified analysis can be allowed on the basis of further research into the relationship between type of structure, type of progressive collapse and propagating action, and type of structural response.

[To be revised and completed by the Direct Design Subcommittee.]
8 Documentation

8.1 General

The design criteria and the structural analysis and design with respect to disproportionate collapse shall be documented as necessary for design checking, construction, structure management, and emergency response.

8.2 Construction documents

Key elements that exist in the various construction stages and in the completed structure shall be stated in the construction documents.

8.3 Building safety provisions

The design criteria shall also be documented as part of the building safety provisions if necessary. This documentation shall include a commentary that provides efficient guidance to structure management, users, and emergency response personnel in the case of an abnormal event.

C.8.1 General

The necessity of documentation varies from project to project. It should further be specified by the Client and the Authorities.

C.8.2 Construction documents

The initial failure of any key element remaining after design is likely to lead to disproportionate collapse. To make such initial failure less probable, structural design and construction (including soil investigation) should meet enhanced requirements when key elements are concerned. In design, this is reflected by the design methods event control, protection, and local resistance. In construction, this calls for enhanced quality and safety requirements. The key elements should be stated in the construction documents to enable the Client and the Authorities to specify and to enforce such enhanced construction requirements.

The components of temporary works can be key elements. The design of such components is within the scope of these Recommendations.

C.8.3 Building safety provisions

The commentary should include, for instance, the size and location of initial damage that can safely be tolerated by the structure without leading to disproportionate collapse.

It is suggested that such documentation and commentary be required at least for requirement levels 3 and 4 (see Commentary Section C.4.4).
9 References


Appendix A: Prescriptive design rules

[Prescriptive design rules for specific and specified types of structures to be drafted by the Indirect Design Sub-Committee.]