INTRODUCTION

Disproportionate collapse is a complex problem for which the existing terminology and procedures are inadequate. A multitude of terms is used to describe structural characteristics and concepts in the context of disproportionate collapse. This paper attempts to make a contribution to terminology and procedures. First, it seems useful to distinguish the terms collapse resistance, robustness and vulnerability. Working definitions are suggested.

Next, the basis of current reliability-based design codes for general structures is reviewed with particular regard to their suitability to prevent disproportionate collapse. Their inadequateness regarding the prevention of disproportionate collapse is outlined.

To give immediate guidance to the practicing engineer, a pragmatic design approach is proposed in which probability-based design procedures as described in the codes are complemented by an additional assessment with particular regard to disproportionate collapse. A performance-based framework for designing against disproportionate collapse – applicable to any kind of structure, and thus also to bridges – is presented.

DISPROPORTIONATE VS. PROGRESSIVE COLLAPSE

A disproportionate collapse 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. The term progressive collapse denotes a collapse that commences with the failure of one or a few structural components and then progresses over successively affected other components.

In spite of different meanings, the terms disproportionate collapse and progressive collapse are often used interchangeably because disproportionate collapse often occurs in a progressive manner and progressive collapse can be disproportionate. The term disproportionate collapse is more appropriate in the context of design and performance because a precise definition of disproportionate requires reference to design objectives: a collapse is disproportionate if the hazard scenarios lead to an extent of damage that violates the performance objectives. The term progressive collapse is more suitable when referring to the physical phenomenon and mechanism of collapse. A progressive collapse can involve different mechanisms of collapse that depend on the type and form of a structure and its orientation in space, as well as on the triggering abnormal event (Starossek 2007, 2009).

3 PREVENT DISPROPORTIONATE COLLAPSE

The term abnormal event refers to an event that is unforeseeable or occurs with very low probability and is not considered in the ordinary design of a structure, although it may cause an initial local failure and thus trigger a disproportionate collapse.
Consider an abnormal event $E$ that acts on a structure and causes an immediate initial damage $D$. The manner in which the structure reacts to the damage $D$ is an inherent structural characteristic, which can be examined by scenario analyses of assumed cases of damage $D$ independently of specific abnormal events $E$.

The probability of disproportionate collapse as a result of an abnormal event, $P[C]$, can be broken down into its constituents according to the explanation above – that is, abnormal event, initial damage, disproportionate collapse – and represented as the product of partial probabilities (NISTIR7396 2007):

$$P[C] = P[C|D] \cdot P[D|E] \cdot P[E]$$  \hspace{1cm} (1)

In this equation, $P[E]$ denotes the probability of occurrence of an abnormal event, $E$, that affects the structure; $P[D|E]$ is the conditional probability of initial damage, $D$, in consequence of an abnormal event $E$; and $P[C|D]$ denotes the conditional probability of a disproportionate collapse of the structure, $C$, due to the initial damage $D$.

Based on Equation 1, different strategies to limit the probability of a disproportionate collapse, and thus to enhance the collapse resistance, can be identified by focusing on each of the three partial probabilities, one after the other:

- Prevent the occurrence of abnormal events. This strategy aims at reducing the probability of occurrence of abnormal events, i.e., $P[E]$, and thus the exposure of the structure.
- Prevent the occurrence of an initial damage in consequence of abnormal events. The structure is sufficiently protected or is provided with enough local resistance to withstand abnormal events without suffering damage. This strategy aims at the local element behavior. The goal of this strategy is to reduce the probability of immediate initial damage following abnormal events, i.e., $P[D|E]$, and thus the vulnerability of the structure.
- Prevent disproportionate collapse of the structure in case of an initial damage. The structure is designed so that the spread of an initial local failure remains limited – an internal property of the structure named robustness. This strategy is aimed at the global system behavior. The goal of this strategy is the reduction of the probability of collapse following a local failure, i.e., $P[C|D]$.

The above outlined design strategies are illustrated by Figure 1. Summarizing these strategies, the probability of a progressive collapse can be limited, and thus the collapse resistance can be increased, by reducing the exposure or the vulnerability of the structure or by increasing its robustness. The exposure of a structure is related to the abnormal events affecting the structure, the vulnerability depends on the individual structural components, and robustness on the whole system organization (JCSS 2008; Giuliani 2009). Influencing abnormal events, and thus the exposure, is often not within the control of the structural engineer but vulnerability and robustness are, given that they are properties of the structure. The first and the second strategy aiming at the reduction of exposure and vulnerability could be entitled “prevent failure initiation”; the third strategy aimed at enhancing robustness could be entitled “prevent failure progression”.

4 COLLAPSE RESISTANCE

Collapse resistance – the short form for resistance against disproportionate collapse – is defined here as the insensitivity of a structure to abnormal events (Starossek 2006, 2009). A more precise definition is obtained by quantifying the defining terms insensitivity and abnormal events. This is done by referring to the design objectives, which are established in a decision-making process. Accordingly, a structure is collapse resistant if the hazard scenarios do not lead to an extent of total damage that violates the per-
formance objectives (Haberland & Starossek, in prep.).

A disproportionate collapse is avoided by ensuring collapse resistance, which is a property that depends on both local and global structural features as well as abnormal events. Collapse resistance is the overall design goal. It can be enhanced by reducing the exposure of a structure, by reducing its vulnerability, or by increasing its robustness. Collapse resistance will not be required for every structure.

5 EXPOSURE

The exposure results from the threats that possibly affect a structure during 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.

According to Bontempi et al. (2007), the threats to a structure can be grouped into physical threats and logical threats (Figure 2). The first group is named faults and encompasses all physical threats that may cause a structural failure. They can be again divided into external faults – like extreme environmental actions as well as accidental or intentional explosions or impacts – and immanent faults, that are defects of the structure – like for example an undetected crack in a steel girder. The second group is named errors and encompasses all logical threats, that is, human errors in the design, construction, and usage of the structure. In case of an error or an immanent fault, the structure is in a potentially dangerous incorrect state that may lead to failure. Failures are the manifestation of errors or faults. Some abnormal events, partly derived from Alexander (2004), are listed and classified in Table 1. The exposure of a structure can be reduced by the design method event control.

6 VULNERABILITY

Vulnerability is defined here as susceptibility of a structure to suffer immediate initial damage in case it is affected by abnormal events (Haberland & Starossek, in prep.). This definition is based on JCSS (2008) according to which vulnerability accounts for the direct consequences of an abnormal event, which are related to the element behavior. Vulnerability depends on the strength and resistance of the individual structural elements and the abnormal events affecting a structure. The vulnerability of a structure can be reduced by the design methods protecting or increased local resistance.

The definition given above is in contrast to the definition of vulnerability used in Lind (1995) and Agarwal et al. (2003) that refers to the structural behaviour following a local damage. Such a definition seems to be an antonym for robustness as defined in the next section. Employing different terms for naming the same characteristic is not generally useful. In the same vein, it can be argued that antonyms are unnecessary. So, this opens up the possibility to use the term vulnerability differently. Whereas vulnerability is related to local conditions, robustness is related to the global system behavior. The definitions of the terms vulnerability and robustness suggested here are thus clearly distinct.

7 ROBUSTNESS

Robustness is defined here as the insensitivity of a structure to initial damage (Starossek 2006, 2009). A more precise definition is obtained by quantifying the defining terms insensitivity and local failure. Again, this is done by referring to the design objectives, which are established in a decision-making process. Accordingly, a structure is robust if an initial damage as determined from the hazard scenarios does not lead to an extent of total damage that violates the performance objectives (Haberland & Starossek, in prep.).

As such, robustness is a property that depends on the structure and the amount of initial damage. If the initial damage is specified as a notional damage, 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 EN 1991-1-7 (2006) – that refers to abnormal events (see also Haberland & Starossek 2009). Such a broader conception is close to the term collapse resistance defined above.

Robustness can be enhanced by the design methods alternative load paths and segmentation. A robust structure is also collapse resistant, but not vice versa. Non-robust structures are particularly susceptible to disproportionate collapse. Nevertheless, they can be made collapse resistant by reducing the exposure and vulnerability of the structure.

8 THE INADEQUACY OF CURRENT DESIGN PROCEDURES

Modern design codes and procedures of verification are based on the probabilistic theory of reliability. Actions and resistances are statistically determined from empirical data. After choosing an allowable probability of failure, the design values for actions and resistances can be computed using probabilistic methods. Such an approach is based on a mathematically sophisticated and, as it seems, sound foundation. It is reflected in the design codes by partial safety factors and a series of load combination schemes. If the application of the ensuing code rules is often cumbersome, the design engineer might take comfort in the idea that, by working on a rational mathematical basis, a uniform safety level is reached. Even so, it turns out that such an approach fails with regard to the identification and proper treatment of a potential for disproportionate collapse. There are three reasons for this failure (Starossek 2005).

The first reason lies in the consideration of local instead of global failure. Design equations for checking structural safety are usually defined and applied on a local level only (check of cross-sectional forces or element stability). Structural safety, therefore, is also accounted for only at local level. The global safety, i.e., the safety against the collapse of the entire structure or a major part thereof, is a function not only of the safety of all the elements against local failure but also of the system response to local failure. The latter influence is neglected. Different systems will respond differently to local failure. The underlying assumption that uniform reliability of a structure is reached by a uniform reliability of its elements is not generally valid. When applied to non-robust structures, such procedures produce unsafe designs.

The problem can be illustrated by means of Equation 1. The factor \( P[C|D] \) is not reflected in the verification procedures of current design codes. The probability of disproportionate collapse thus remains out of consideration. Although this deficiency is well-known to professionals familiar with reliability theory, practising engineers are often unaware of it.

The second shortcoming of current design procedures is that low-probability events (i.e., events \( E \) for which \( P[E] \) is very small) and unforeseeable incidents are not taken into account. In the context of reliability-based design, such a simplification is necessary because the supporting statistical data, derived from experience and observation, are unavailable (Alexander 2005). In the case of a non-robust structure, this simplification is unacceptable.

The third problem for the inadequacy of current design procedures is that the underlying probabilistic concept requires specification of an acceptable probability of failure. The target failure probabilities of probabilistic design codes are usually derived from calibration with previous deterministic design codes. Hence, no new societal consensus seems necessary when probabilistic design is adopted. Considering the extreme losses that can result from disproportionate collapse, however, it might be difficult to reach an informed and true societal consensus on the numerical value of the acceptable probability of such an outcome – a problem which risks of the type low probability/high consequence are typically up against. This problem can be evaded, but not solved, by not bringing the question to the attention of the public.

9 POSSIBLE IMPROVEMENTS OF CURRENT DESIGN PROCEDURES

The first problem outlined in the previous section is not inherent to reliability theory. As illustrated by Equation (1) and further outlined by Ellingwood & Dusenberry (2005), it is in principle possible to account for disproportionate collapse within a probabilistic framework. The difficulty arises from practical limitations that appear when the theory is applied to actual structures: The system response to local failure needs to be examined. This response involves large deformations and displacements, separation of structural elements, falling elements striking other parts of the structure, and other kinds of interaction which all require a fully nonlinear dynamic analysis in the time domain. Even the precise modelling of such scenarios is difficult because some structural properties, such as the behaviour of joints under failure loading, are not well established yet. These difficulties are compounded by the need to consider many initial damage scenarios and by the fact that, due to the nonlinear dependencies appearing here, small errors in the modelling assumptions can produce large deviations in the computational outcome. Even a deterministic analysis of the system response to local failure poses tremendous difficulties. A probabilistic analysis of that response and the computation of global safety would add further di-
dimensions of difficulty and, apart from special cases, seems out of reach of today’s analysis resources.

If such analysis becomes feasible in the future, one could attempt to consider the influence of the system response to local failure by an additional partial safety factor on the resistance side of the design equations, thereby maintaining the framework of current design procedures. This factor would take a value of one for robust structures and a value smaller than one for non-robust structures. Provisions in some codes aim in this direction. In these cases, however, the reduction of the design value of resistance of non-robust structures is based on judgment rather than on thorough probabilistic analysis.

The second and third problems outlined in the previous section are fundamental challenges to purely reliability-based design. If the low probability of an event that leads to local failure can add up to a large probability of global failure, then that quantity needs to be known. Also, if societal consensus on the acceptable probability of a catastrophic event cannot be reached, another basic ingredient to a numerical probabilistic computation would be missing.

10 PRAGMATIC DESIGN APPROACH

It follows from the preceding discussion that the shortcomings of current design procedures are both fundamental and practical in nature, and can only partly be overcome within the framework of reliability theory. The possibilities of improvement which do exist are not yet explored today and might prove insufficient in the future. Still, immediate guidance is needed on how to design a collapse-resistant structure. The following pragmatic approach for tackling this task is suggested (Starossek 2007, 2009).

On the one hand, the design procedures as specified in current codes are applied. They are based on reliability theory which is reflected in the codes by partial safety factors and load combination schemes. Where necessary and possible, as for instance concerning the risk of ship impact on major bridges, this code-based design is complemented by direct probabilistic analysis and risk assessment.

On the other hand, additional measures with particular regard to collapse resistance are taken. The procedure is further described in the following section. It is not necessarily based on reliability theory but rather on judgment and a decision-making process. Structural analyses are carried out deterministically. This approach is called pragmatic because it lacks the stringency of a purely mathematical basis. Nevertheless, it enables the engineer to adequately address disproportionate collapse in the sense that safety and economy are reasonably balanced and the required structural analysis remains tractable.

Figure 3. Framework for designing collapse-resistant structures

11 FRAMEWORK FOR DESIGNING COLLAPSE-RESISTANT STRUCTURES

In the following, a performance-based framework for designing collapse-resistant structures is suggested (Haberland & Starossek, in prep.). Note that some elements of the framework suggested here have been implemented in a number of standards and guidelines already (GSA 2003; EN 1991-1-7 2006; UFC 4-023-03 2005), although not with the same degree of generality, consistency, and completeness.

In the assessment and the improvement of a structural design with respect to disproportionate collapse, design criteria are of importance. They are organized into design requirements, design objectives, design methods, and verification procedures (Figure 3). The design criteria should generally be established according to codified provisions as long as these exist and are applicable. If applicable design criteria are unavailable in codified form, they must be agreed upon on a project-by-project basis by the contracting and other affected parties and approved by the construction authorities. Such an agreement
requires a decision-making process supported by specialist consultants. For major projects, a project-related agreement on design criteria will be the rule rather than the exception.

For illustrating this framework, the Confederation Bridge, Canada is used as an example. This structure is a prestressed concrete girder bridge that crosses the Northumberland Strait between Prince Edward Island and the Canadian mainland. The bridge is a two-lane road bridge and opened after about three years of construction in the spring of 1997. The bridge is 12910 m long, and consists of 43 main spans and shorter approach spans on both sides of the main spans (Figure 4). The cross section of the superstructure is a mono-cellular box with deck slab cantilevers. The maximum width of the girder is about 11 m and the girder depth changes continuously from 14 m at the piers to 4.5 m at midspan.

Each typical pier balances two cantilever beams of 95 m length; the cantilevers of two adjacent piers support a 60 m drop-in girder; this configuration results in a span length of 250 m. In every second main span, the cantilever beams and the drop-in girders are rigidly connected, thus creating a series of two-column portal frames. In the other main spans, the connections are made by hinges at both sides of the drop-in girder. This configuration has arisen from extensive investigations of the structural behavior following the sudden failure of a main bridge pier.

11.1 Design requirements

The first step in the design process is to establish the design requirements. In particular, the question of whether collapse resistance is necessary must be clarified. The answer depends on the significance of the structure with respect to the consequences of a collapse, including the immediate material and immaterial losses but also indirect consequences such as impairment of the infrastructure. Another criterion is the structure’s degree of exposure to abnormal events, such as deliberate damage and assault (malicious action), accidents, and natural disasters. Collapse resistance will not be required for every structure.

If collapse resistance is found necessary, it can be so to varying degrees. The significance and exposure of a structure can thus serve to establish a classification of structures. The classification can be used to specify design objectives and to select design and verification methods used within the design process. For instance, structures could be classified into four groups according to the degree of necessity of col-
collapse resistance and thus the level of requirements. Structures of the no-requirements class do not require an additional assessment or specific measures with respect to collapse resistance. Structures of the basic-requirements class can be designed using indirect design, whereas structures of the high-requirements and very-high-requirements classes are designed using direct design in a non-threat-specific or threat-specific manner.

11.2 Design objectives

If collapse resistance is deemed necessary, the design objectives must be specified. They comprise hazard scenarios, performance objectives, and applicable combinations of actions and safety factors, which together serve as a basis of a performance-based design. Hazard scenarios are the abnormal conditions to be assumed in the design to affect the structure during construction and lifetime. In a threat-specific approach, they are specific abnormal events. In a non-threat-specific approach, they are notional actions or notional damage, without regard to the cause. Threat-specific design requires the identification and quantification of all abnormal events 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 Confederation Bridge, for instance, the hazard scenario considered was the notional failure of a main bridge pier (pier B or C in Figure 5; note that a preliminary design is shown in which the drop-in girders have hinges on one side only) (Stauros 1999). Even if this hazard scenario is inspired by the possibility of ship collisions or exceptionally large ice forces, it is part of a non-threat-specific approach in that the triggering abnormal condition could be anything else as well.

Performance objectives specify the acceptable response of the structure to the hazard scenarios. They 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 infrastructure and of civil and national defense. In the context of performance-based design, global performance objectives are generally more meaningful. Local performance objectives can serve as simplified and substitute criteria for achieving global objectives.

For the Confederation Bridge, the performance objective “acceptable extent of collapse” was stipulated in consultation with the supervising authority, Public Works Canada. A collapse starting at some location within the bridge must not trespass defined collapse boundaries, that is, pier D and hinge H1 in Figure 5. This corresponds to a collapsed bridge length of about 700 m out of a total bridge length of 12910 m (Stauros 1999).

11.3 Design methods

In the next step, appropriate design methods for ensuring collapse resistance should be selected. The available design methods are event control, protection, increased local resistance, alternative load paths, and segmentation. Event control reduces the exposure of a structure by averting abnormal events. The protection method reduces its vulnerability by mitigating the effect of abnormal events. The local-resistance method reduces vulnerability by locally increasing structural resistance. The alternative-paths method enhances the robustness of a structure by providing the capability of redistributing forces originally carried by failed elements. And the segmentation method enhances the robustness of a structure by isolating the failing part of a structure from the remaining structure by dedicated segment borders. While the first two of these methods are non-structural methods, the latter three are structural methods. Structural methods can be implemented within a direct or indirect design approach.

Direct design aims at explicitly ensuring collapse resistance by demonstrating that the structure meets specified performance objectives when subjected to specified hazard scenarios. Indirect design, on the other hand, aims at increasing the collapse resistance of a structure implicitly by incorporating consensus-approved design features; this is done without consideration of hazard scenarios and without demonstrating that performance objectives are met. Such features can be codified in standards and guidelines as prescriptive design rules. The prescriptive design rules codified so far are detailing rules that intend to provide tension ties, to enable catenary action, or to ensure ductility in building structures. These measures aim at providing increased local resistance or alternative load paths.

The adequacy of the design method depends on the type and requirement classification of a structure and the design objectives.

For the Confederation Bridge, the specified hazard scenario was the notional failure of a main pier. The alternate-paths method or the segmentation method could be used to cope with this kind of hazard scenario. Using the alternate-paths method would require designing a prestressed concrete frame with the double-span length of 500 m – arguably a vain endeavor even if resorting to catenary action. The design method chosen was segmentation. A collapsing section of the bridge is thus isolated from the remaining structure by dedicated
segment borders (pier D and hinge H1 in Figure 5) which were stipulated based on the performance objectives.

Note that although the overall performance-based framework more naturally entails direct design, a recourse to indirect design is still an option in certain cases within that framework. For structures of high exposure or significance, however, direct design is preferable to indirect design for both economical and safety reasons (Starossek 2009).

11.4 Verification procedures

Finally, suitable verification procedures need to be selected and performed when direct design methods are used. Verification procedures are used to demonstrate that a structure meets specified performance objectives when subjected to specified hazard scenarios. Verification procedures of varying degrees of accuracy can be performed, which are selected depending on the requirement classification of a structure and the design objectives.

12 CONCLUSIONS

Disproportionate collapse is prevented by ensuring collapse resistance, a property defined as the insensitivity of a structure to abnormal events. Collapse resistance can be achieved by reducing the exposure of a structure or by reducing its vulnerability – two measures that aim at preventing failure initiation – or by increasing its robustness – a measure that aims at preventing failure progression. The exposure results from abnormal events; the vulnerability of a structure is its susceptibility to suffer immediate initial damage when affected by abnormal events; and robustness is its insensitivity to such initial damage.

The basis of current reliability-based design codes for general structures is reviewed with particular regard to their suitability to prevent disproportionate collapse. Their inadequateness regarding the prevention of disproportionate collapse is outlined. To give immediate guidance to the practicing engineer, a pragmatic design approach is proposed in which probability-based design procedures as described in the codes are complemented by an additional assessment and design measures with particular regard to disproportionate collapse.

Therefore, a performance-based framework for designing against disproportionate collapse – applicable to any kind of structure – is suggested, in which the procedures currently used are complemented by an additional assessment to ensure collapse resistance. A set of corresponding design criteria is presented. These include design requirements, design objectives, design strategies, and verification procedures.

Codification is moving towards such an approach already. This paper shows how these efforts can be continued to lead to a clearer description of design criteria and to a precise and consistent use of language.

REFERENCES