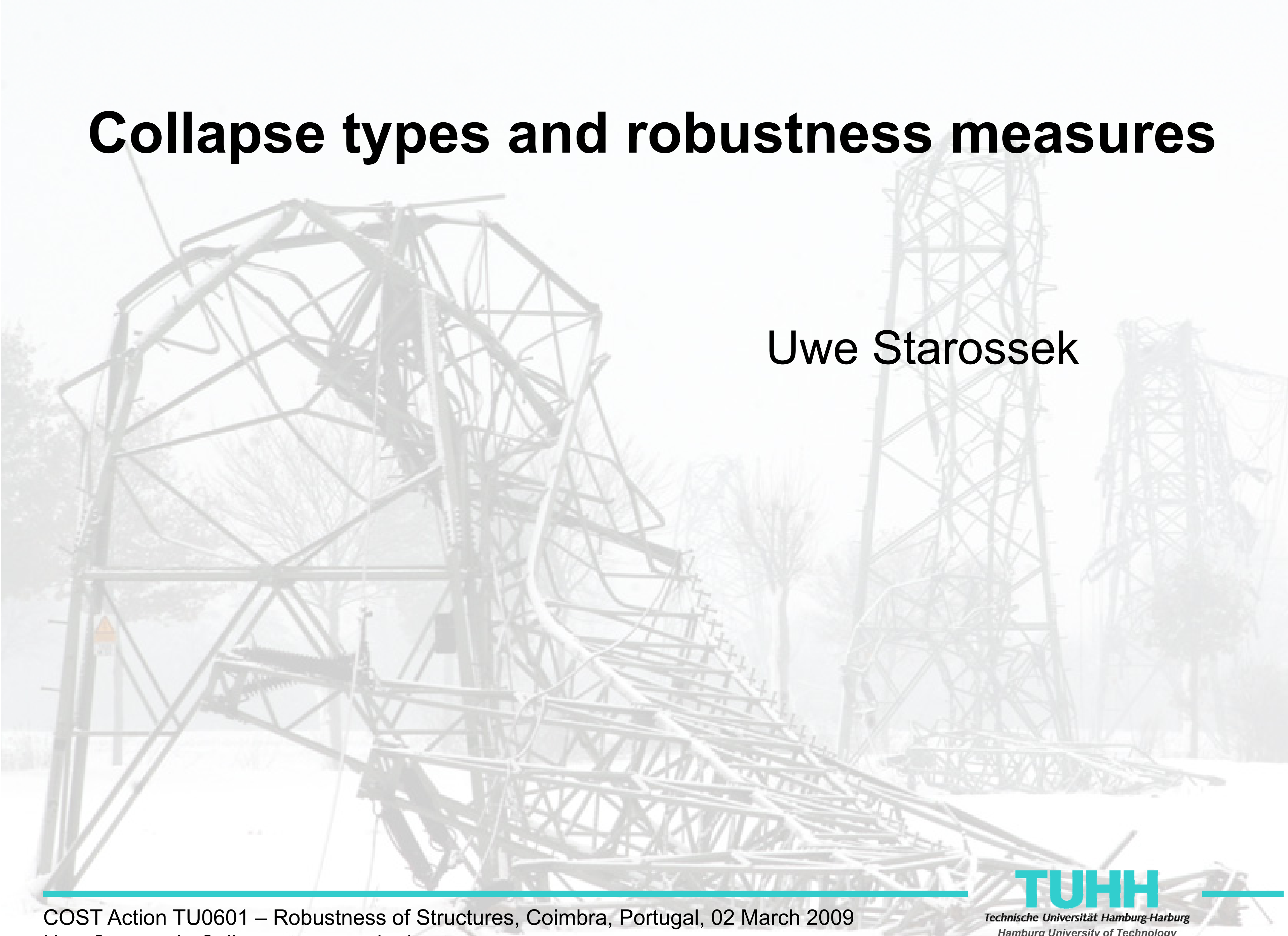
Collapse types and robustness measures



Uwe Starossek

Disproportionate collapse …

… is characterized by a distinct *disproportion* between cause and effect, i.e., between the *triggering event* and the resulting widespread collapse.

Triggering events are *accidental circumstances* that lead to local actions or a local lack of resistance …

… that cause *initial local failure*.

Disproportionate collapse …

… mostly commences with the failure of one or a few structural components and then *progresses* over successive other components.

Therefore, the terms `disproportionate collapse´ and `progressive collapses´ are often used synonymously.

design objectives	→	disproportionate collapse
collapse mechanism	→	progressive collapse

Two definitions

► **collapse resistance**

= insensitivity to accidental circumstances
(the design goal)

► **robustness**

= insensitivity to local failure
(a strategy for achieving the design goal)

► *insensitivity*, *local failure*, *accidental circumstances* are quantified by the design objectives which need to be predetermined in a decision-making process

Inadequacy of current design methods

► reliability-based design

$$P(C) = P(C|L) \cdot P(L|E) \cdot P(E)$$

- ► $P(C)$ = probability of a collapse, C, due to an event, E
- ► $P(E)$ = probability of occurrence of E
- ► $P(L|E)$ = probability of local failure, L, given the occurrence of E
- ► $P(C|L)$ = probability of collapse given the occurrence of L

- ► factor $P(C|L)$ is not reflected in current design codes
- ► could be considered by a system partial safety factor

Pragmatic design approach

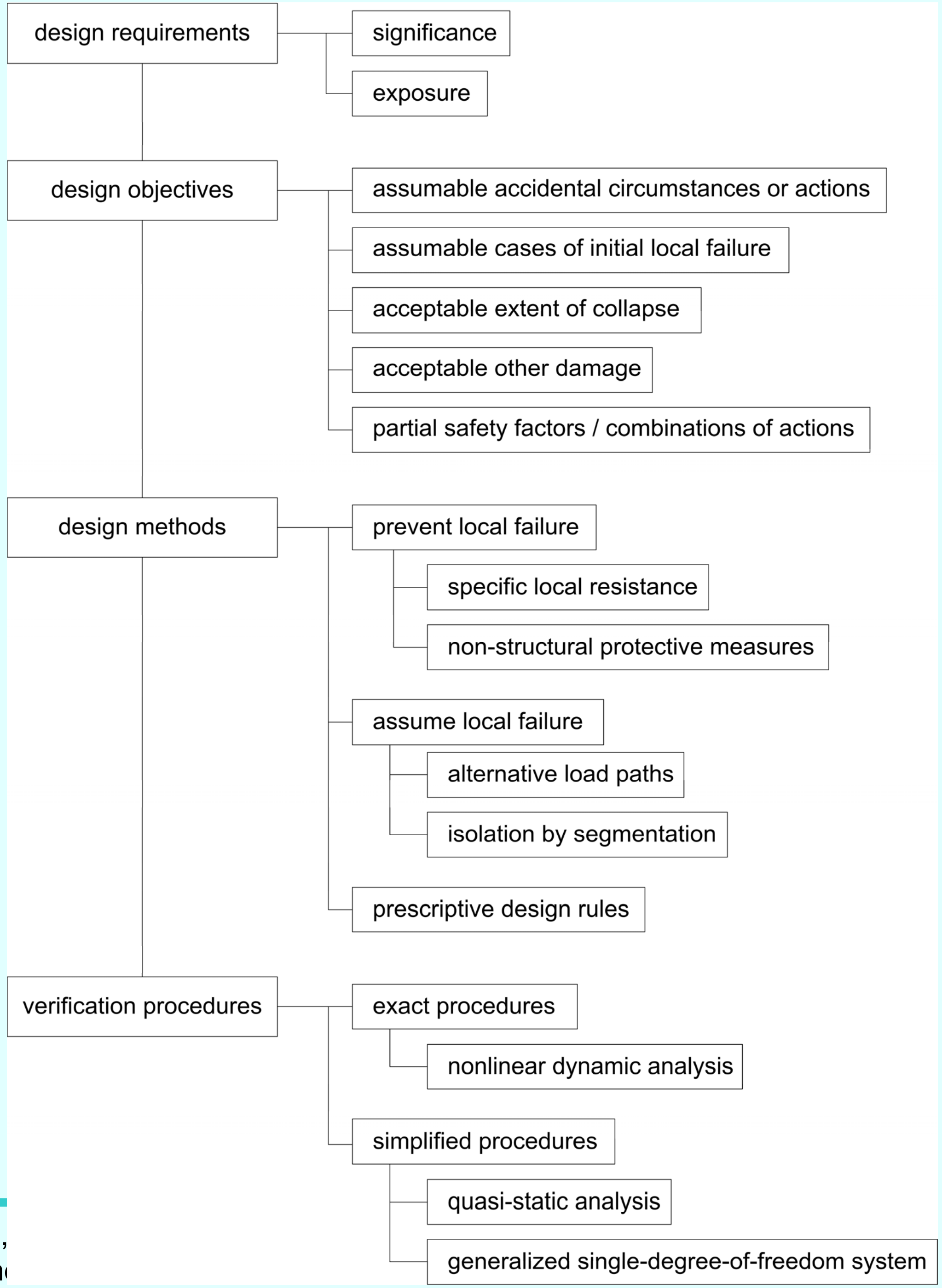
► as a starting point, the design procedures of current codes are retained

► on the other hand, an additional assessment for ensuring collapse resistance is carried out

- ► not based on reliability theory but on judgment and design objectives that are established deterministically in a decision-making process

- ► analyses are similarly carried out deterministically

additional assessment for ensuring collapse resistance*)



*) For more detail, see:

U. Starossek: “Progressive collapse of structures: Nomenclature and procedures.” Structural Engineering International, May 2007.

U. Starossek: *Progressive collapse of structures*. Thomas Telford Publishing, June 2009.

Measures of robustness

► applications

- ► evaluation
- ► optimization
- ► regulation
- ► system partial safety factors

Measures of robustness

► requirements

- ► expressiveness
- ► objectivity
- ► simplicity
- ► calculability
- ► generality

Typology of progressive collapse

► pancake-type collapse

pancake-type collapse of a 10-story building
triggered by an earthquake (Islamabad, 2005)

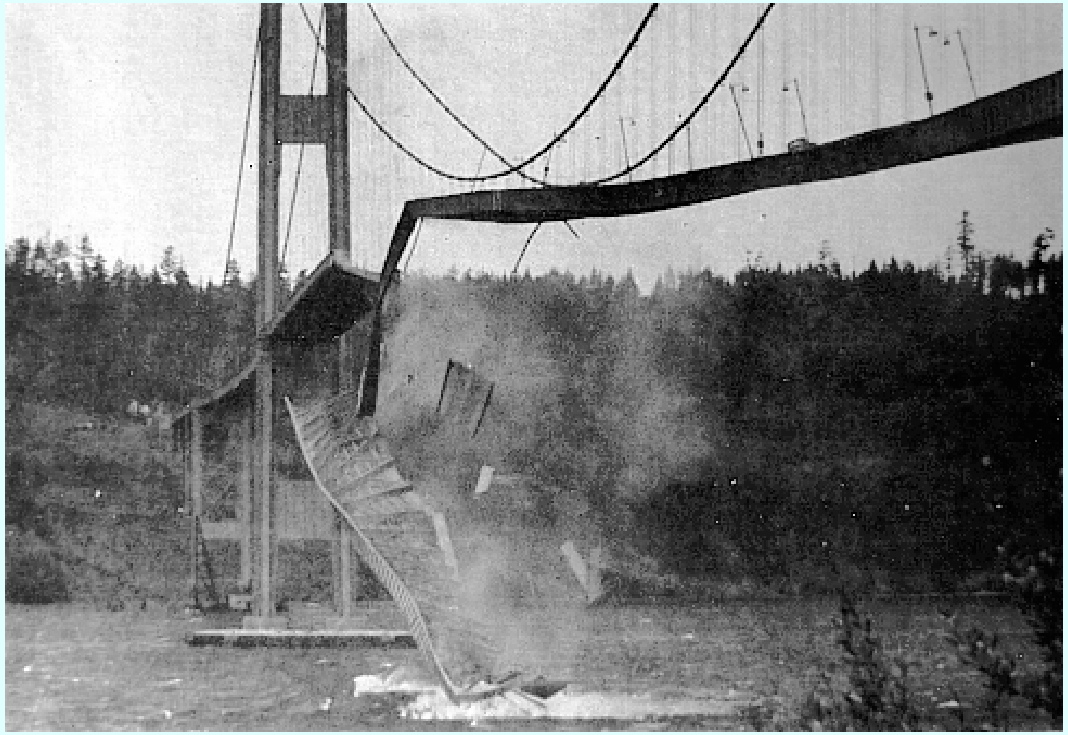
Typology of progressive collapse

► domino-type collapse

domino-type collapse of overhead transmission line towers
triggered by ice accretion (Germany, 2005)

Typology of progressive collapse

► zipper-type collapse



zipper-type collapse of the Tacoma Narrows Bridge
triggered by wind-induced vibrations (1940)

Typology of progressive collapse

► pancake-type collapse

pancake-type collapse of a 10-story building
triggered by an earthquake (Islamabad, 2005)

Typology of progressive collapse

► pancake-type collapse

- ► initial failure of vertical load-bearing elements
- ► separation and fall, in a vertical rigid-body motion, of components
- ► transformation of gravitational energy into kinetic energy
- ► impact of falling structural components on the remaining structure
- ► failure of other vertical load-bearing elements due to the impact loading
- ► failure progression in the vertical direction

- ► principal forces in the failing elements, propagating action, and direction of failure propagation are parallel (i.e. vertical)
- ► structural system is characterized by series primary load transfer

Typology of progressive collapse

action resulting from the failure of one component and leading to the failure of one or more further components

- ► principal forces in the failing elements, propagating action, and direction of failure propagation are parallel (i.e. vertical)

Typology of progressive collapse

► domino-type collapse

domino-type collapse of overhead transmission line towers triggered by ice accretion (Germany, 2005)

Typology of progressive collapse

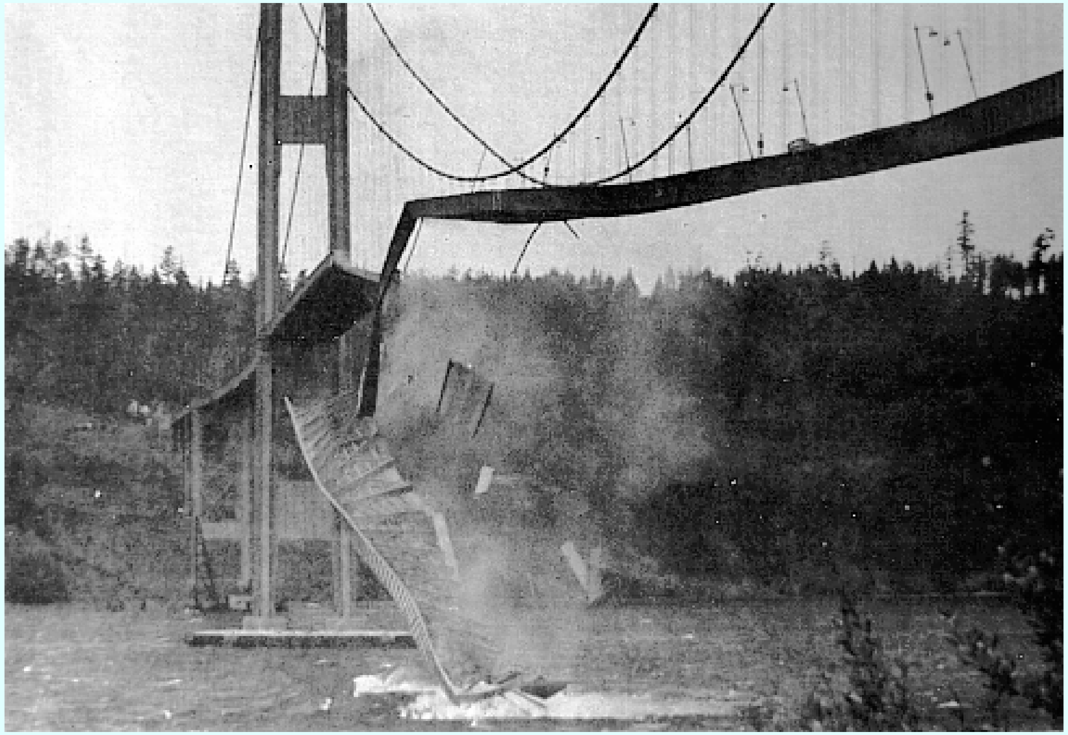
► domino-type collapse

- ► initial overturning of one element which can be an individual structure
- ► fall of that element in an angular rigid-body motion around a bottom edge
- ► transformation of gravitational energy into kinetic energy
- ► abrupt deceleration of the motion of the element through sudden activation of other elements during direct impact or effected by mediating elements
- ► overturning of the suddenly activated other elements due to the (static and dynamic) horizontal force from the decelerated element
- ► failure progression in the horizontal direction

- ► principal forces in the failing elements (prior to failure) are orthogonal to the propagating action and the direction of failure propagation
- ► elements constitute a parallel load transfer system

Typology of progressive collapse

► zipper-type collapse



zipper-type collapse of the Tacoma Narrows Bridge
triggered by wind-induced vibrations (1940)

Typology of progressive collapse

► zipper-type collapse

- ► initial failure of one or a few structural elements
- ► redistribution of forces of these elements in the remaining structure
- ► impulsive loading due to the suddenness of the initial failure
- ► dynamic response of the remaining structure to that impulsive loading
- ► static and dynamic force concentration and failure of other elements
- ► failure progression in a direction transverse to the principal forces

- ► direction of principal forces in failing elements and propagating action is orthogonal to the direction of failure propagation
- ► structural system is characterized by parallel primary load transfer

Typology of progressive collapse *)

- ► pancake-type collapse → impact class
- ► domino-type collapse → impact class
- ► zipper-type collapse → redistribution class
- ► section-type collapse → redistribution class
- ► instability-type collapse
- ► mixed-type collapse

*) For more detail, see:

U. Starossek: "Typology of progressive collapse." Engineering Structures, Sept. 2007.

Measures of robustness

► based on damage

$$R_{\mathrm{d}} = 1 - \frac{p}{p_{\mathrm{lim}}}$$

► R_{d} = damage-based measure of robustness

► p = maximum total damage resulting from the assumable initial damage

► p_{lim} = acceptable total damage

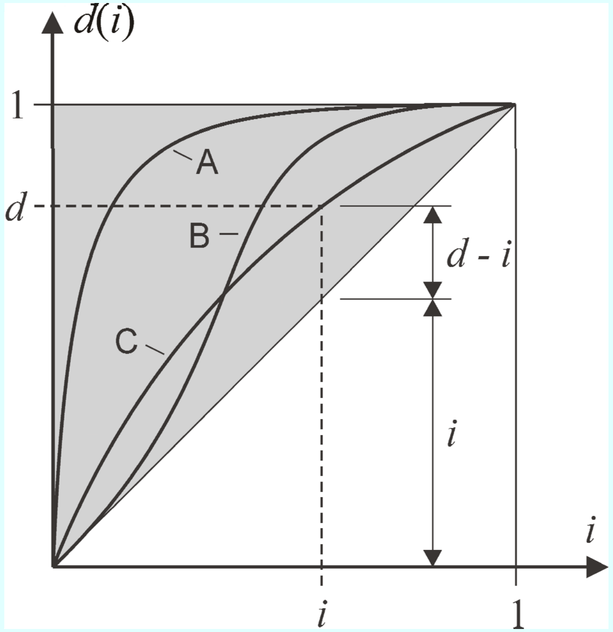
► a value of one indicates perfect robustness; negative values indicate that the design objectives are not met

► measure is expressive and objective within the context of given design objectives

Measures of robustness

► based on damage

$$R_{\mathrm{d,int}} = 1 - 2\int_0^1 \left[d(i) - i\right] di$$



► $R_{\mathrm{d,int}}$ = integral damage-based measure of robustness

► d = maximum total damage resulting from and including an initial damage of extent i (dimensionless)

► A: non-robust structure

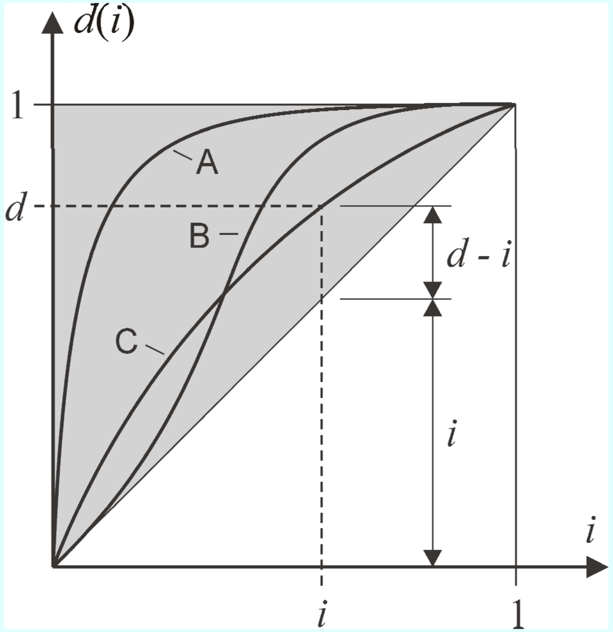
► B: relatively robust structure

► C: structure of intermediate robustness

Measures of robustness

► based on damage

$$R_{d,int} = 1 - 2\int_0^1 \left[d(i) - i\right] di$$



► $R_{d,int}$ = integral damage-based measure of robustness

► d = maximum total damage resulting from and including an initial damage of extent i (dimensionless)

► a value of one indicates maximum possible robustness; a value of zero indicates total lack of robustness

► damage-based measures are difficult to calculate because failure progression after initial damage needs to be analyzed

Measures of robustness

► based on stiffness

$$R_{\mathrm{s}} = \min_{j} \frac{\det \mathbf{K}_j}{\det \mathbf{K}_0}$$

- ► R_{s} = stiffness-based measure of robustness
- ► $\mathbf{K}_j$ = active system stiffness matrix of structure after removing a structural element or constraint *j*
- ► $\mathbf{K}_0$ = active system stiffness matrix of intact structure

- ► measure does not correlate well with structural response of modified systems → the measure is not expressive
- ► however, stiffness-based measures are simple and calculable; improved formulations that are expressive are therefore sought

Measures of robustness

► based on stiffness

$$R_s = \min_j \frac{\det \mathbf{K}_j}{\det \mathbf{K}_0}$$

► R_s = stiffness-based measure of robustness

► $\mathbf{K}_j$ = active system stiffness matrix of structure after removing a structural element or constraint j

► $\mathbf{K}_0$ = active system stiffness matrix of intact structure

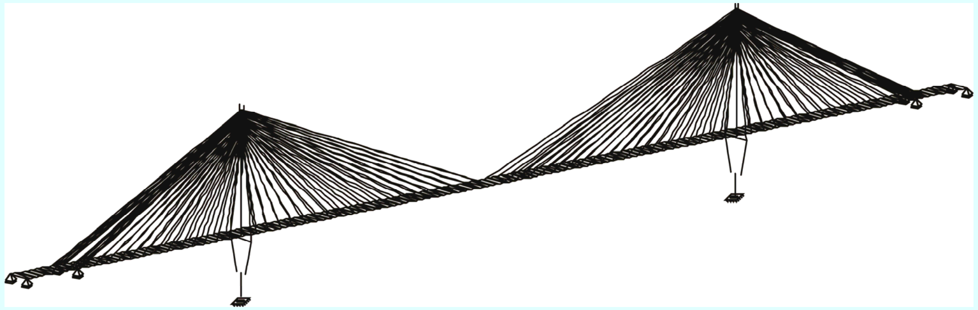
► such measures relate to load redistribution capability of structure

► improved formulations possibly applicable to zipper-type collapse

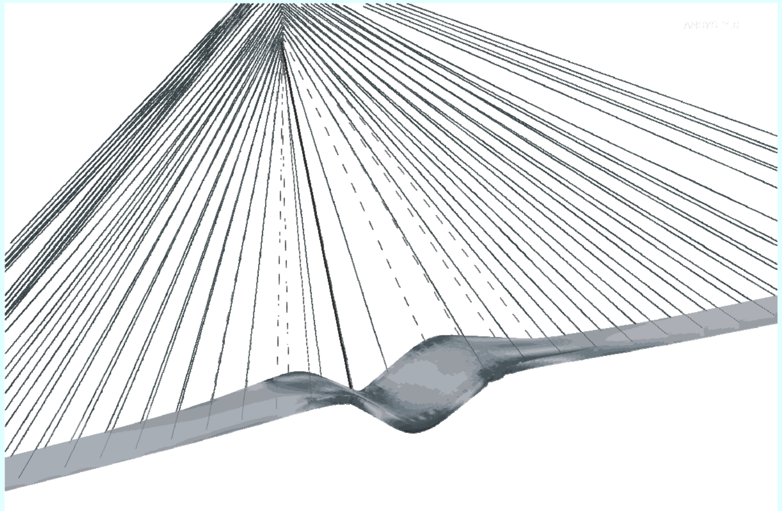
► inapplicable to collapses governed by impact forces, i.e., pancake-type and domino-type collapses

Measures of robustness

► based on stiffness



cable loss in cable-stayed bridge resulting in zipper-type or instability-type collapse



► improved formulations possibly applicable to zipper-type collapse

Measures of robustness

► based on energy

$$R_\mathrm{e} = 1 - \max_j \frac{E_{\mathrm{r},j}}{E_{\mathrm{f},k}}$$

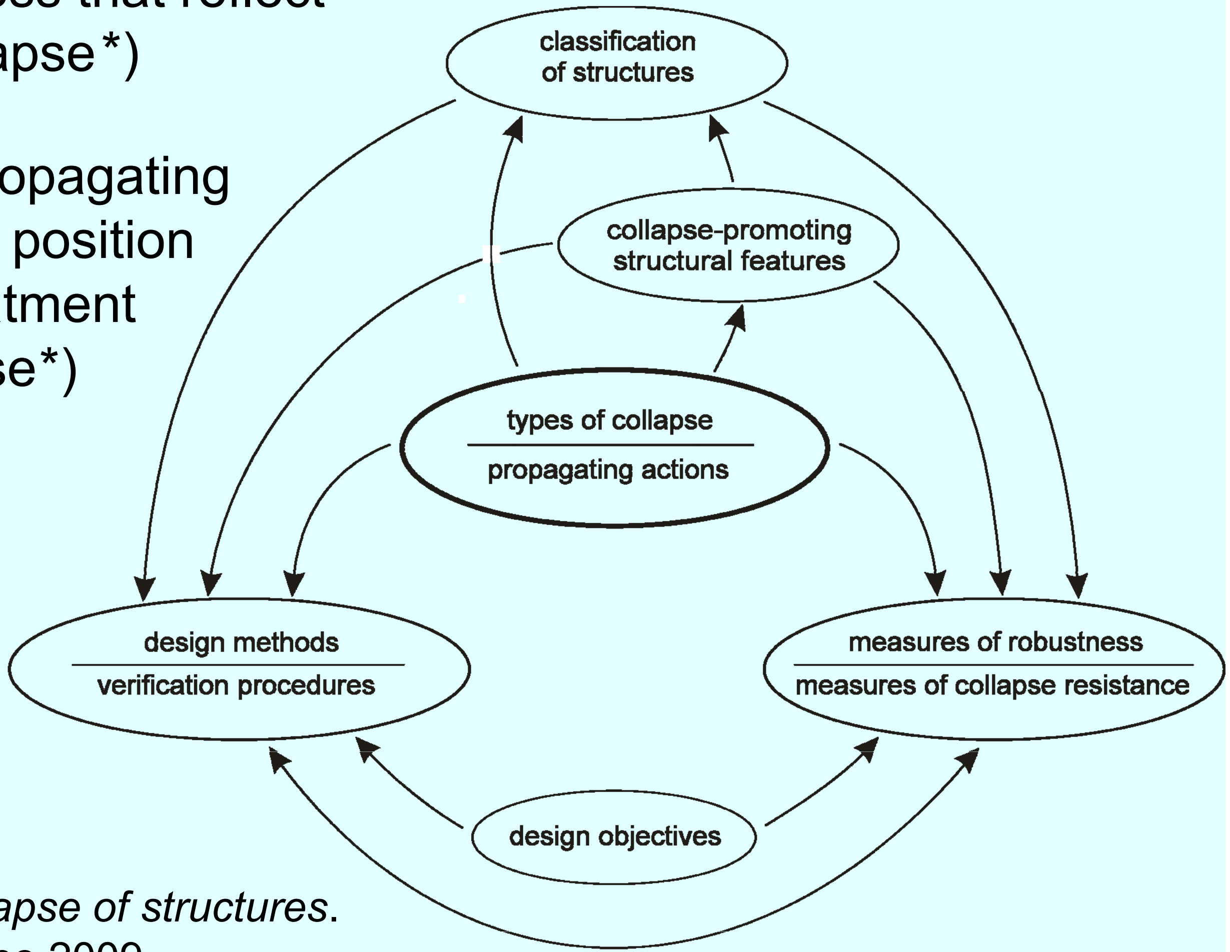
- ► R_e = energy-based measure of robustness
- ► $E_{\mathrm{r},j}$ = energy released during initial failure of structural element *j* and contributing to damaging a subsequently affected element *k*
- ► $E_{\mathrm{f},k}$ = energy required for failure of subsequently affected element *k*

- ► a value of one indicates perfect robustness; negative values indicate failure progression
- ► $E_{\mathrm{r},j}$ generally difficult to calculate
- ► possibly applicable to collapses governed by <u>impact</u> forces

Collapse types and robustness measures

► different kinds of structures can best be described by differently defined measures of robustness that reflect different types of collapse*)

► collapse types and propagating actions hold a central position in the conceptual treatment of progressive collapse*)



*) For more detail, see:

U. Starossek: *Progressive collapse of structures*. Thomas Telford Publishing, June 2009.

Summary

- ► a terminology and a pragmatic approach for designing against disproportionate collapse have been suggested
- ► a typology has been presented on which the conceptual treatment of progressive collapse can be based
- ► this has been exemplified by a discussion of measures of robustness

Thank you!