The Case for System-Based Structural Design

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The current code approach for structural design is member-based, where designs are checked for the safety of individual members. There is very little guidance on the overall safety, design and integrity of their assemblage except broad statements regarding the need for an arrangement that provides stability to the entire structural system, along with continuity, redundancy and ductility. U.S. codes do not specify how to achieve this goal, leaving its implementation to the discretion and ability of the engineer.

Observations from actual projects show that competent structural engineers do incorporate empirical strategies to limit adverse consequences to the structural system from member failures, depending on their understanding, knowledge and experience, as well as the structure type and its vulnerability. However, there are many examples where seemingly highly redundant structures have failed due to a lack of system integrity. There are also cases where individual members that are expected to fail do not, because of interaction among members in the system. Therefore, it is of paramount importance to study structural system integrity and develop system-based design procedures, including specific code guidance to limit adverse consequences.

Measuring Structural Integrity

Efforts to pin down the structural integrity concept have been thwarted due to its elusive nature, precluding development of an objective, simple and practical metric, which is a pre-requisite for rational design of systems and comparison of alternatives. Quantification of structural integrity has also proved difficult due to the diversity of systems and the various contributing causes of initiating damage. The myriad ways in which structural integrity is influenced – from configuration, member sizes, material properties, connection types, applied loads etc. – are all captured in the structural stiffness matrix $\mathbf{K}$, where the singularity of $\mathbf{K}$ represents the extreme case of loss of general structural integrity.

Recent research has used this fact to quantify structural system integrity as a metric Δ ranging from 0-1 (higher value denoting better structural integrity), defined by the determinant $|\mathbf{K}_N|$ of the normalized stiffness matrix $\mathbf{K}_N$, where $\mathbf{K}_N$ is obtained by dividing each row of matrix $\mathbf{K}$ by the square root of the sum of squares of the terms in that row. This metric is easily computed and accounts for the contributions of configuration, geometry of members, their importance or criticality in alternative load paths, material behavior and applied loading on the structures to the system safety performance. This metric can serve as the linchpin for system-based structural design.

System-Based Design

Structural design for natural and man-made hazards or specified loads has two components: the likelihood of the postulated hazard or load event (probabilistic aspect) and what happens when such an event actually occurs (consequences). Risk is determined by the combination of these factors. System-based design would necessarily be secondary. In the primary stage, the structure would be proportioned using the current probability-inspired, member-based code provisions, including appropriate minimum joint resistance and continuity. Thereafter, the members would be examined and, if necessary, re-designed to ensure adequate structural system integrity, based on their role and importance in contributing to adverse system consequences. These consequences can be characterized in terms of collapse or any other pre-defined performance criterion.

The level of modification for a member is identified through the *Member Consequence Factor*, C_f, which accounts for its contribution to the undesirable system response. The consequence factor for the i^th^ structural member is defined as the ratio of $|\mathbf{K}_N^i|$ to $|\mathbf{K}_N|$, where $\mathbf{K}_N^i$ is the normalized stiffness matrix after removal of the i^th^ member from the system. These consequence factors for all n members range from 0 to 1; the lower the factor, the more critical the member is for system safety. A consequence factor of 0 indicates that removal of the member results in immediate structural failure.

C_f can be used as an additional partial safety factor on the resistance side of the member-based code equations for implementation of system-based structural design. It is also possible to investigate various failure strings comprised of multiple member failures (with C_f still in range 0-1) with a similar approach, except for the additional complexity involved in the calculations. In this formulation, even though overall system design is consequence-based, the design of individual members is still probability-based and all requirements in current codes would still apply, with the additional proviso for consequence factors.

Benefits

An advantage of the system-based approach is the possibility of optimizing robustness to prevent minor damages from causing disproportionately large consequences. Robustness, a subset of structural integrity, is an important property about the form and/or connectedness of the structure and a major governing factor in system behavior, but has been neglected in modern codes due to a lack of theoretical understanding of its contribution to capacity. It provides a measure of the quality of system configuration and may be obtained by separating geometrical/topological properties from material properties through decomposition of the stiffness matrix $\mathbf{K}$.

This approach provides a tool to optimize the assembly of members through innovative configurations, resulting in new designs limited only by the creativity of the designer. It is also possible to use member-based, probability-oriented design for service requirements and high-likelihood environmental events, while using consequence-oriented, system-based design for low-likelihood events (e.g., multi-hazard occurrence) to leverage the robustness property of configurations. This can reduce the design cost without compromising overall safety.

The system-based approach is also appropriate for brittle materials like glass, which fail suddenly without prior warning, or for temporary structures with limited service life. Finally, the consideration of failure consequences at the design stage helps to mitigate the impact of building misuse, or design and construction errors.▪

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References

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