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Architectural Design For Reliability

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ABSTRACT

Design-for-reliability concepts can be applied to the products of the construction industry, which includes buildings, bridges, transportation systems, dams, and other structures. The application of a systems approach to designing in reliability emphasizes the importance of incorporating uncertainty in the analyses, the benefits of optimization analyses, and the importance of integrating reliability, safety, and security.

Keywords: architectural surety, reliability, buildings, structures, design for reliability

INTRODUCTION

Reliability of buildings and other structures has been approached in the past primarily through the application of the Uniform Building Code, other applicable codes and standards, and good engineering judgment: architects and engineers for the most part know through a combination of training, experience, and intuition how to construct buildings that don't immediately fall down or wear out. On the other hand, the formal reliability techniques that are routinely applied in many other industries are not commonly used in the construction industry.* This paper considers whether design-for-reliability concepts could be applied to structures and what steps might be taken during design, construction, maintenance, and remodeling to increase architectural reliability.

DESIGN FOR RELIABILITY - BACKGROUND DISCUSSION

Definition

Design for reliability means building reliability into the design of a system rather than incorporating it after development has begun or is finished. Reliability should be considered as a design parameter early in the life cycle of a product, preferably while product requirements are being defined or during feasibility analysis. Designing in reliability does not mean that reliability issues can be ignored for the remainder of a system's life cycle. Reliability evaluation and continuous improvement should take place throughout the life cycle of a system. Figure 1 illustrates some of the activities that take place throughout a system's life cycle. The life cycle phases and activities vary depending on the type of system being analyzed.

Typical phases in the life cycle of a construction project, and the activities potentially associated with these phases, are shown in Figure 2. Reliability-related activities are included in the **surety planning** and **surety evaluation** activities. During surety planning, the analyst determines appropriate metrics and target levels for safety reliability, and security. Surety evaluation is an integrated assessment of the metrics to determine the feasibility of implementation. The metrics must be constantly reevaluated to ensure continued feasibility through the life cycle and to seize opportunities for improvement. During the disposal phase, the analyst uses surety evaluation to examine all lessons learned during the life cycle for application to new projects.

Why Do It?

The most economical approach to building a reliable system is to design in reliability early in the life cycle. The early life cycle phases typically represent the smallest portion of the total life-cycle costs borne by the supplier of a system, yet they generally present the most cost-effective opportunity to improve system reliability. As a design

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* One important exception to this comment is seismic reliability, for which there is a large body of literature.

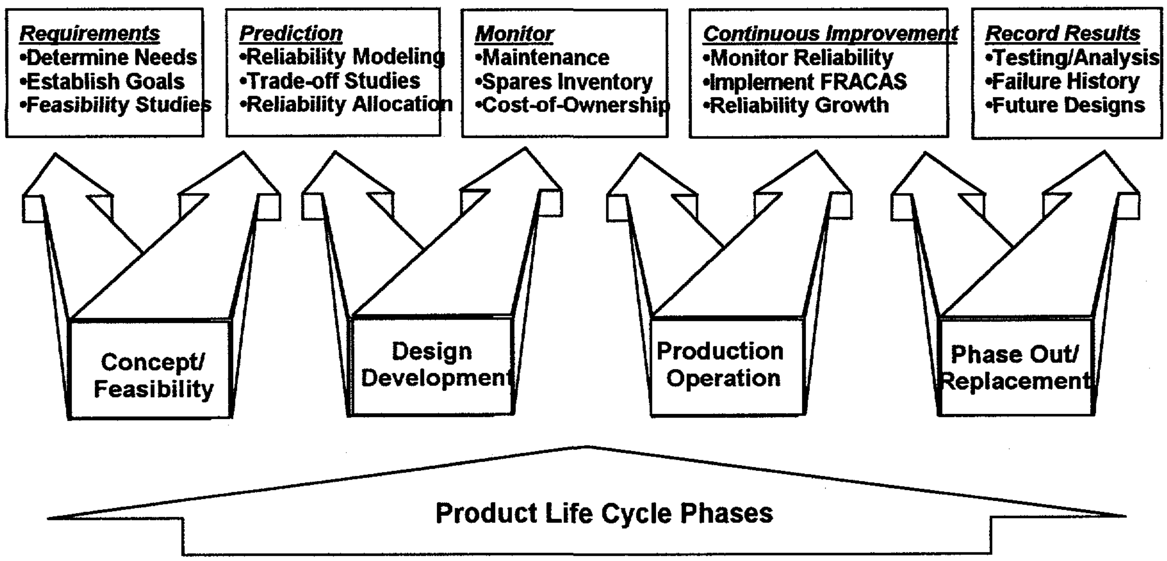

Figure 1. Typical phases and activities in the life cycle of a manufactured product.

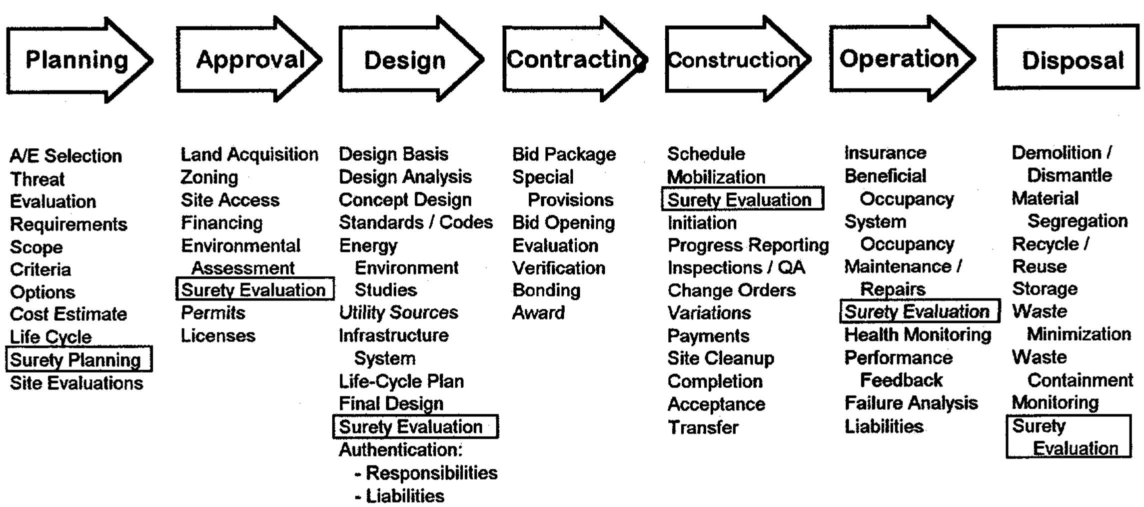

Figure 2. Typical phases and activities in the life cycle of a construction project.

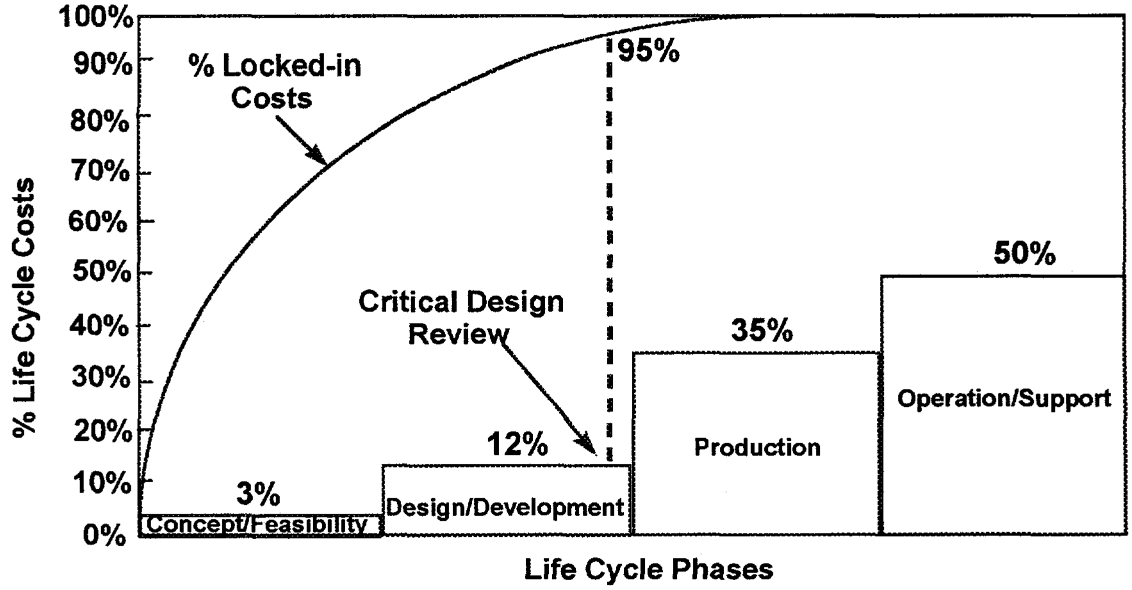

Figure 2. Typical distribution of costs over the total life cycle of a product.[1]

moves toward completion, design details become increasingly fixed, and the cost in time and dollars to correct reliability problems increases. Figure 3 shows that typically toward the end of the design and development phase of the life cycle, only about 15% of the life-cycle costs are consumed, but about 95% of the total life-cycle costs have been determined. Thus, changes made to improve reliability after design and development have little impact on overall life cycle costs, but they can be very expensive in terms of costly design changes, retrofits, service call, warranty claims, and customer goodwill. This is not meant to imply that systems already in production or in operation should be ignored in terms of improving reliability. Reliability improvement activities should continue throughout the life of the structure.

Although reliability improvements made early in the life cycle can increase initial costs to the builder, they generally result in lower support costs for the manufacturer and lower operational costs for the consumer.

Another aspect of designing for reliability is *designing for maintainability*. One method of enhancing reliability is to enhance the repairability or maintainability of a system. This is particularly important for buildings or systems where life extension is considered, or where upgrades or improvements are important. A question that is frequently asked in light of the World Trade Center and Oklahoma City bombings is whether we can afford to replace many of our critical infrastructures. The answer is probably not. Thus, it becomes important to design structures for ease of repair, maintenance or upgrading.

Why a System-Level Focus?

Field reliability data on complex systems indicate that the primary causes of failures are not component failures, but rather are system-level deficiencies in design, manufacturing, or requirements definition.[2] Data indicate that part failures account for only about 15% of system failures; 85% are due to system-level problems associated with design and manufacturing. As a result, reliability assessments based primarily on component reliability do not adequately represent system-level reliability. The National Research Council's Evaluation of NASA's safety analysis of the Challenger accident included criticisms of their lack of an emphasis on *systems* analysis, their failure to adopt established *probabilistic risk assessment* methods, and their lack of *uncertainty analysis.*[3]

A system-level reliability focus is a top-down approach that starts very early in system design. Prediction and analysis are used at every stage of design to identify problems in meeting system requirements and to correct these problems as early as possible.

A system-level focus applies *optimization techniques* to determine such things as optimal target reliabilities for design and upgrades for structures. Such approaches have been proposed for formulating cost-effective risk-based criteria for the design and upgrading of structures with special reference to earthquake protection. (Target reliabilities [or acceptable risks] for damage control and human safety are determined on the basis of minimum expected life-cycle cost, from which risk-consistent criteria for design or upgrading are developed.) This approach has been illustrated for a specific class of reinforced concrete buildings in Mexico City.[4]

A systems approach also recognizes that most reliability problems involve *decision making under uncertainty.* Decisions are evaluated in terms of their effects on system reliability. Although it is clear that the reliability of a system is known with certainty only after it has been used until it is worn out and its failure history has been faithfully recorded, design for reliability is a cost-effective step toward increasing the time period of reliable performance.

DESIGNING RELIABLE STRUCTURES

What does it mean for a structure to be reliable? Our society tends to associate "reliability" with products whose life spans are relatively limited: automobiles, appliances, electronic equipment, industrial machinery, and so on. Buildings and other structures, in contrast, typically have life spans measured in decades. We define a reliable structure to be one that can continue to serve its original function (or a closely related function) for at least the design lifetime without a significant increase in maintenance and repair costs. Thus a reliable building is one in which

- failures of major structural components (such as the foundation) do not occur,
- maintenance schedules for major non-structural components (such as the roof finishing materials or facade) are determined by component lifetimes, not by secondary effects of other structural failures,
- heating, cooling, and ventilation continue to function efficiently without increasing energy usage,
- electrical and plumbing systems can be maintained and repaired easily and inexpensively, and
- renovation and modernization can be accomplished without major structural modifications.

In an unreliable building, the foundations shift, causing the walls to crack and the roof to sag; energy usage increases; maintenance and repair costs are high; and renovation and modernization are not cost effective.

How might the reliability concepts discussed above be applied to the design and construction of buildings, bridges, transportation systems, dams, and other structures? The initial steps of the process are clear. First, long-term structural reliability must be included as a design parameter along with other basic considerations such as function, size, and location.

Second, the design phase must include a systems analysis. The systems analysis should be a holistic examination of both component reliability and the interactions of components. It should consider the construction processes to be used and the environment the structure must function in after construction is complete. The systems analysis should result in an allocation of construction resources in such a way that overall reliability is enhanced. For example, components that directly or indirectly support the function of several other components could be singled out for higher-grade construction materials, while components that do not support multiple functions or are likely to be replaced for cosmetic reasons could be candidates for cost savings. The systems analysis should also consider ease of maintenance and repair. Components with moving parts (e.g., heating systems) or with short lifetimes due to high usage (e.g., elevators) should be designed in such a way that they are readily accessible for maintenance and repair without removing walls or furnishings or inconveniencing occupants. Finally, the possibility that major new systems (e.g., fiber optics) may have to be installed at a later time should be considered and the design be made flexible enough to accommodate such upgrades.

The results of the systems analysis should be used in a comprehensive reexamination of the design to ensure that appropriate emphasis has been give to lifetime reliability of the structure. At this point the design can be optimized to achieve a proper allocation of reliability and cost. Uncertainty and sensitivity analysis allow the designer to make informed decisions about the potential impacts of inadequate data.

CONCLUSION

Design-for-reliability concepts can be applied to buildings, bridges, transportation systems, dams, and other structures. The use of these concepts could have the dual benefits of lowering life-cycle costs by reducing the necessity for maintenance and repair and of enhancing the safety and security of the structure's users.

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