# HUMAN ERROR ANALYSIS

Nowak, A.S., Collins K.R. *Reliability of structures*.
McGraw-Hill Higher Education 2000

**Human errors add considerable uncertainty** to design and construction activities, being dominant causes of structural failures.

There are **two approaches of error control**: error frequency reduction and minimization of error consequences.
Calculation check and job inspection control the quantity of errors, **sensitivity analyses identify the severity of their consequences**.

Significant human **error example - walkway collapse**
at Hyatt Regency Hotel in Kansas City.

There were two levels of walkways suspended by steel hanger bars, as shown in Figure 10.1.

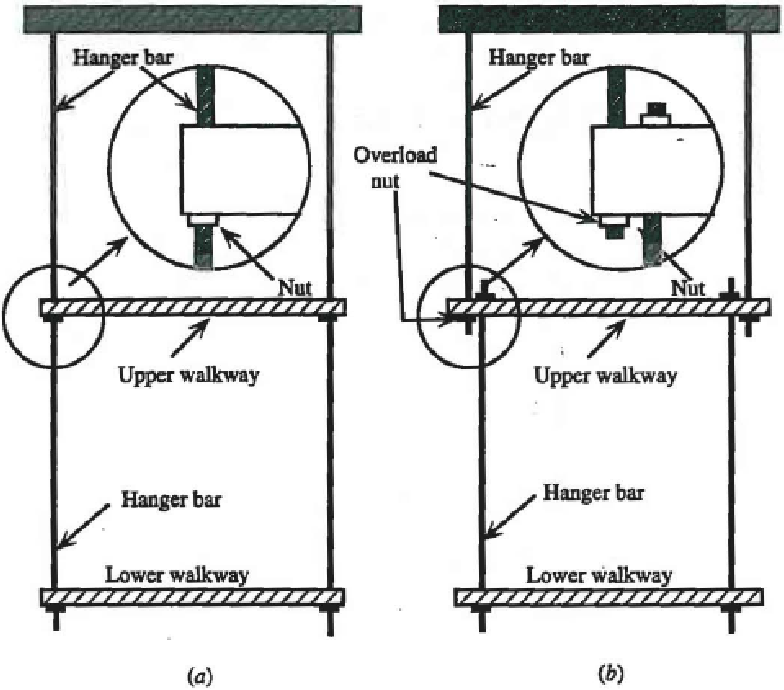
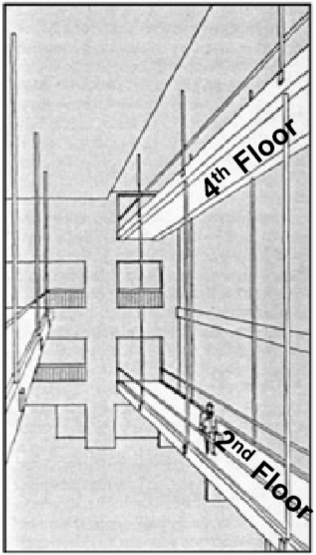


**FIGURE 10.1** Details of hotel walkway hanger bar connection. (*a*) Original design. (*b*) As-built configuration.

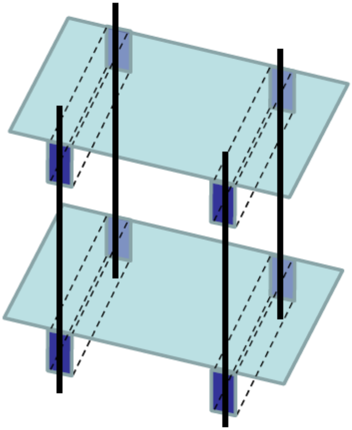
# Hyatt Regency Walkway Collapse

*Presentation by William J. Frey*

On July 17, 1981, the second and fourth story walkways of the Kansas City Hyatt Regency Hotel collapsed
**killing 114 people and seriously injuring an additional 200.**

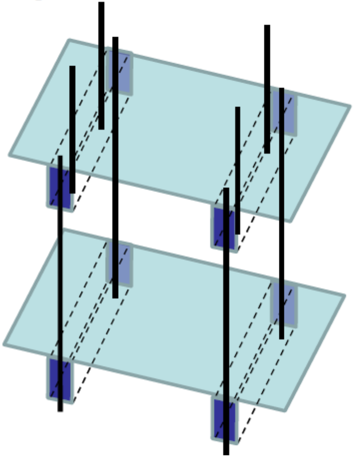


**Initial Design**



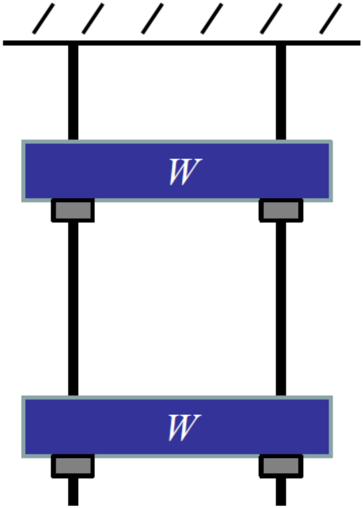
Long rods threaded
over entire length

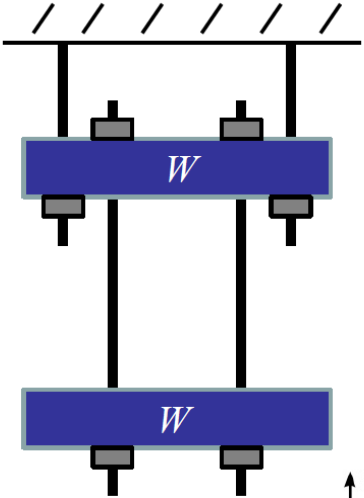
**Proposed Modification**

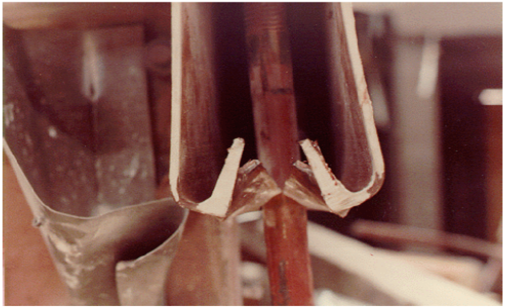


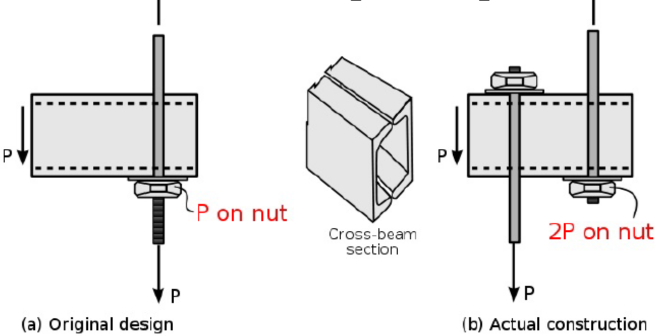
Shorter rods threaded
only near connections

- Cause:
  - “A deviation in the design in the way the rods connected the lower skywalk to the upper and the upper to the ceiling of the atrium was clearly described and zeroed in on as the ultimate cause of the accident.” Petroski: 86









(a) Original design

(b) Actual construction

**Warning Signs** (from Petroski)

- – The Atrium ceiling collapsed during construction; but a study carried out by an independent engineering firm found nothing wrong with the skywalk
- – Workers carrying loaded wheel barrows across the skywalk complained about excess vibration and swaying
- – Faulty connection recognized six times

  “Duncan assured each inquirer that replacing the single, long hanger rods with double, offset rods would not compromise the safety of the walkways.”

**Aftermath** Petroski

“After twenty months of investigation, the U.S. attorney and the Jackson County, Missouri, prosecutor announced jointly that they had found no evidence that either a federal or state crime was committed…” (TAMU Instructor Manual)

However in an investigation carried out by the attorney general of Missouri… Duncan, Gillum, and GCE International Inc. were found guilty of “gross negligence, misconduct and unprofessional conduct in the practice of engineering.” (TAMU Instructor Manual)

## Responsibility in Engineering

Herbert Fingarette, in Criminal Insanity, identifies legal responsibility as “response to essential relevance”

**Moral responsibility** can be formulated as moral response to essential moral relevance.

**Cognitive skills**: The ability to view a situation and identify those aspects that have moral relevance

**Volitional skills**: The ability to formulate or design actions that are morally responsive to the moral relevance in a situation

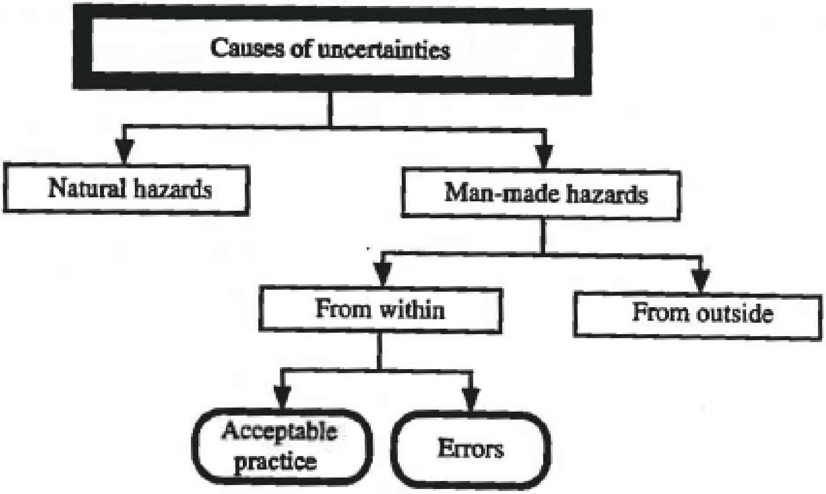
## Resources

- Hyatt Regency Kansas City Walkway Collapse" Online Ethics Center for Engineering 11/24/2010 National Academy of Engineering Accessed: Thursday, December 16, 2010 <www.onlineethics.org/Resources/Cases/24338.aspx>
- Henry Petroski (1985). To Engineer is Human: The Role of Failure in Successful Design. St. Martin’s Press: 85-97.
- http://ethics.tamu.edu/ethics/hyatt/hyatt1.htm

– http://ethics.tamu.edu/ethics/hyatt/hyatt2.htm

# Types of uncertainties

Uncertainties of the building process depend on their sources.



Error is a departure from acceptable practice

**FIGURE 10.2** Classification of uncertainties in the building process.

Two major uncertainty sources are natural and man-made hazards.

**Natural hazards** are caused by

- wind, earthquake, temperature, snow load, ice accretion,
- natural variation of structural material properties (strength, modulus of elasticity, dimensions),
- load variation (weight of people, furniture, trucks on bridges).

**Man-made hazards** may be shown their major causes:

- the building process: uncertainties due to acceptable practice (innovations, unique and new structures, new materials) and caused by **departure from acceptable practice**,
- outside the building process: fires, gas explosions, collisions.

**Comment:**

- **Practice is acceptable** if not negated by a significant number of expert engineers finds it unacceptable.
- **Common practice is not necessarily acceptable**.
- Acceptable practice is not necessarily common.
- **Departures from acceptable practice are human errors**.

# Theoretical and actual failure rates

Structural reliability theory developed considerably since the 1970s.

An improved understanding of the risk of structural failure made it possible to optimize investment by means of safety factors.

However, divergence occurs in theoretical and actual failure rates.

Computed failure probabilities for buildings and bridges lie between $10^{-6} \div 10^{-8}$ , observed values may be an order of magnitude higher.

e.g. US bridges - failure probability rate about $10^{-3} \div 10^{-5}$ annually.

Failure rates much higher for large and unique structures.

Small population – a single collapse increases overall failure rate.

The discrepancy between the theoretical and actual failure rates is due to an incomplete theoretical model.

Most failures are caused by human errors, not analyzed.

Structural failure surveys indicate human error as a major cause.

Error control - a vehicle for structural reliability improvement.

Frequency of errors reduced by inspections and checking.

Errors consequences identified using sensitivity analysis.

# The archive research

The impact of human error - two research directions: fundamental studies and frameworks for application.

**Fundamental studies** improve the understanding of error statistics, phenomenological models and heuristic models.
Their range: experimental studies of error commission, simplified mathematical models, stochastic process models.

**Frameworks for application to structural engineering** – the field of engineering science, operational research, management science.

Pragmatic approach -efficient control,
the error-prone structures introduced and identified by a framework:

- the use of fuzzy-set concepts,
- optimal time allocation for design, modelling, material testing, and inspection to reach a given target reliability,
- relation of human errors and their effects on structural reliability via sensitivity coefficients.
- structural engineering theory was dominated by the needs of quantitative analysis: determine the loads and find the stresses.

# Summing up

Human error analysis strictly linked to structural failure research.

It is a partly intuitive, partly scientific field.

Effective means to organize this knowledge to design structures or to predict structural behavior has been lacking until recently.

It has largely prevented progress in research directed toward improved frameworks for practical control of the hazard of human error.

# Error classification

**Errors** are considered with regard to

- person involved (i.e., designer, architect, draftsman, contractor, construction worker, manufacturer, user, owner),
- phase of the building process (planning, design, fabrication, transportation, construction, operation, use, demolition),
- location (office, job site, factory),
- reason (ignorance, negligence, carelessness),
- frequency or mechanism of occurrence.

Error classification with regard to **occurrence mechanism**:

- *conceptual error* - unintentional departure from the accepted practice due to insufficient knowledge,
- *error of execution* - unintentional departure from accepted practice,
- *error of intention*- intentional departure from accepted practice.

Alternative paths related to **acceptable practice** are shown in Fig. 10.3.

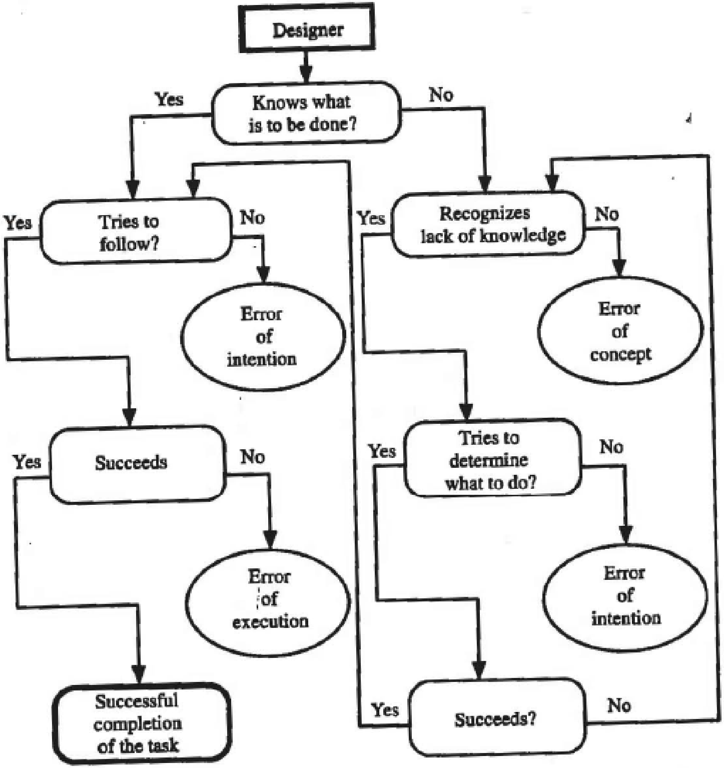


**FIGURE 10.3** Acceptable practice may follow alternative paths.

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The designer commits **conceptual errors** by the following actions:

1. Not being aware of used methods, models, tools or information,
2. Not knowing which method is the most applicable,
3. Not knowing how to use a method, model, tool or information,
4. Failing to complete the necessary actions,
5. Not knowing the acceptable level of effort or care,
6. Not knowing the possible consequences,
7. Failing to understand assumptions or limitations,
8. Using the incorrect simplifying assumptions.

**Errors of execution** include cases when the designer misread, miswrote, misdrew, misheard, misspoke, misoperated, forgot, lost, misplaced, left out, did not think of, did not hear, or did not see something.

These errors also occur when **an individual hears and sees the proper information but does not recognize it**.

An **intentional error** may be committed for different reasons:

1. Expediency,
2. Time, money, energy savings,
3. To avoid responsibility or liability,
4. To avoid embarrassing someone else,
5. Being requested or required by supervisor, contract or regulations to complete current work or obtain future work,
6. Not being capable to do the work under accepted practice,
7. Impossible for anyone to do the work under accepted practice,
8. Designer’s acceptance of risk  recognized as unacceptable,
9. Designer’s departure from common practice without acceptable reason.

The error results may be reduced reliability (hazardous errors) or increased reliability(opulent errors).

Error consequences - from minor serviceability problems to overall collapse.

The structural performance may be affected directly or indirectly (e.g., by increasing the probability of other errors).

Resulting failure may be localized or spread to other components, leading to progressive collapse.

Error changes analytical models of structures.

They may affect loads, load-carrying capacity or the overall interpretation of behavior.

**Gross errors** cause drastic departures from assumed theoretical models (placing a beam upside down, missing the reinforcing steel).

Error classification - affected part(s) of the theoretical model:

- *Parametric errors* cause changes in statistical distribution functions of load and load-carrying capacity parameters
  Examples: use of the wrong grade of material and under- or overestimation of load
- *Modal errors* result in changes in the mode of structural behavior.
  Examples - omission of relevant failure modes from the analysis, incorrect interpretation of structural behavior.

In most structural engineering tasks design and construction errors are described by two parameters: **frequency** and **consequences.**

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Error frequency may be reduced by means of a control scheme.

Relationship: error consequences vs structural safety is defined by sensitivity functions, which may initiate the error-control strategy.

An inexperienced engineer may design are reinforced concrete slab,

his ignorance may lead to an incorrect number of steel rebars, which yields poor strength, failure and damage to the structure.

In real life the number of possible structural errors and their consequences is infinite.

A moderate number of possible consequences may be stated for each structure by means of controlling parameters in design and construction.

Sensitivity analysis can be used to determine the relationship between structural errors and the resulting service errors.

For each structural error, the sensitivity analysis can determine the impact of such an error on the load or load-carrying capacity of the structure, and consequently on its serviceability and safety.

This procedure can be applied for a structural element or for an entire structure.

# Error surveys

Actual failure rate is higher than the theoretical value (no human errors considered), but it is still very small.

The failure database is therefore limited, so it is difficult to develop reliability models that account for errors.

The available data sources include failure surveys in order to develop a profile of design and construction practices, activities and circumstances that lead to errors.

**The database of concrete structures showed that only about 10 percent of failures came from load and resistance stochastic variability, the remaining 90 percent derived mostly from design and construction errors.**

Half the errors occurred in design, the other half in construction.

Most of the design errors resulting in failure resulted from **misconception or lack of consideration of structural behavior**.

These errors were detected during the service life of structures,most resulted in serviceability problems.

Errors that resulted in a collapse are just the “tip of the iceberg” compared to the total population of errors, as seen in Figure 10.4.

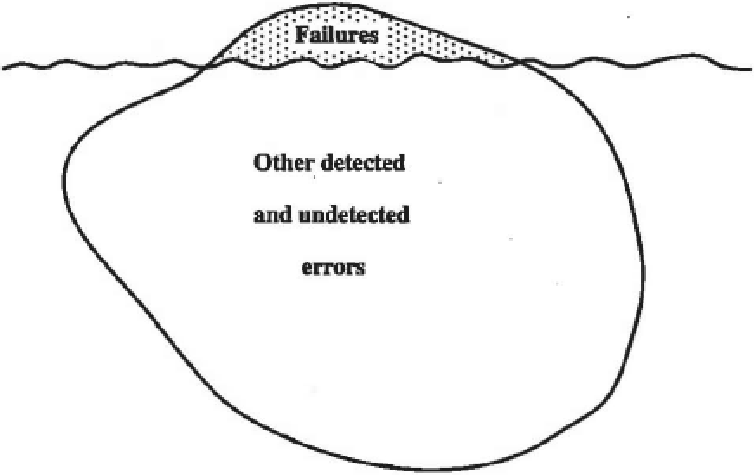

**FIGURE 10.4** Proportion of errors leading to failure relative to the total population of possible errors.

The most common error causes are: incomplete understanding of structural behaviour (design criteria, assumptions, boundary conditions), departure from typical loading cases, insufficient load analysis during construction stages, time pressure, specification ambiguity, discontinuity in design process, lack of experience, communication problems, lack of coordination, undefined goals of structural use.

Three major types of design calculations are: **manual**, **computational** and using standard **tables and charts**.

Typical errors of **hand calculations** are: calculation errors, omission of critical loading conditions, use of wrong units, incorrect code interpretation.

**Computer** output errors are difficult to detect, but it may be stated

- it is easy to add errors while updating a program,
- the design software assumptions may be unknown to the user,
- programs are sometimes not suited for some components,
- complicated codes increase the probability of errors.

In design based on **tables and charts** errors may result from misuse of tables or charts (design components not fitting the standards, elements selected not knowing design forces or loading conditions).

Identification of consequential errors is done by sensitivity analysis.

Examples of common error causes observed in surveys include:

- Incomplete understanding of structural behaviour,
- Poor judgement and inattention to the problem,
- Calculation errors that are not detected,
- Change of use (e.g. applying loads not intended for the structure),

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- Contractor interpreting design and drawings for a self-advantage,
- Organizational problems, lack of continuity,
- Attempts to fit numbers in wrong formulas,
- Misunderstood information copied from different sources,
- Inexperienced engineers, designers and inspectors,
- Poor inspection or no regulations to provide good inspectors,
- Lack of coordination between field engineers,
- Communication problems, specification ambiguity,
- Undefined goals so that a change of use may be expected,
- Little attention given to the boundary conditions and supports.
- Incomplete design, ignorance to vital actions: torsion or buckling,
- Time pressure, especially for inexperienced engineers,
- Lack of clear and well-understood design criteria,
- Complex load condition set (different for various structural parts),
- Abnormal loading,
- Use of load combination for a wrong building,
- Departure from typical causes (unusual loading such as thermal effects, tornados, missiles).

# Approach to errors

Figure 10.5 shows that failure probability depends mostly on the control of causes and consequences of errors.

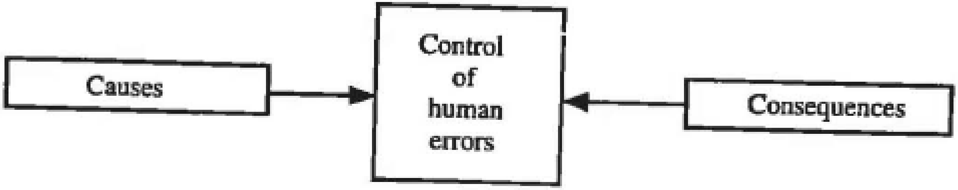


**FIGURE 10.5** An approach to controlling human error.

The causes cover frequencies of occurrence and reasons.

Frequency of errors can be reduced by inspections, calculation checking, improving the work environment, or use of special design and construction techniques.

The most important factor affecting human performance in the building process: motivation, knowledge, experience, and physiological conditions.

Consequences of errors can be controlled through the identification of the consequential errors using sensitivity analysis.

The objective of the sensitivity analysis is to relate error magnitude and structural reliability.

For each considered parameter reliability is determined corresponding to various errors.

Error consequences are usually the only ones considered, omitting the causes.

For example, the effective depth of steel reinforcement, $d$, is a critical parameter in the design of reinforced concrete beams.

To develop a sensitivity function for $d$, reliability is estimated for various possible values of $d$.

# EXAMPLE.

Sensitivity analysis concept is shown on a simple beam design.
The beam is to resist a uniformly distributed load (Fig.10.6a).

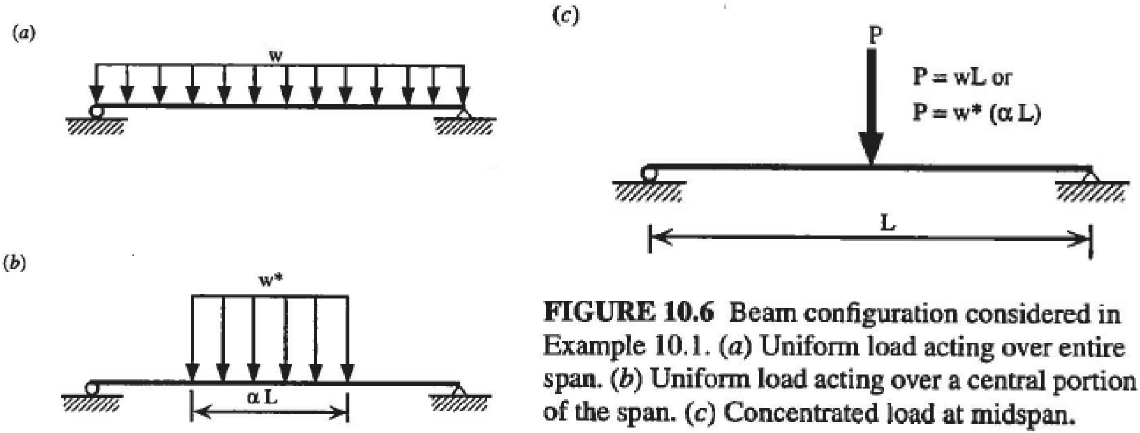


**FIGURE 10.6** Beam configuration considered in Example 10.1. (*a*) Uniform load acting over entire span. (*b*) Uniform load acting over a central portion of the span. (*c*) Concentrated load at midspan.

The calculated reliability index is $\beta = 3{,}5$.

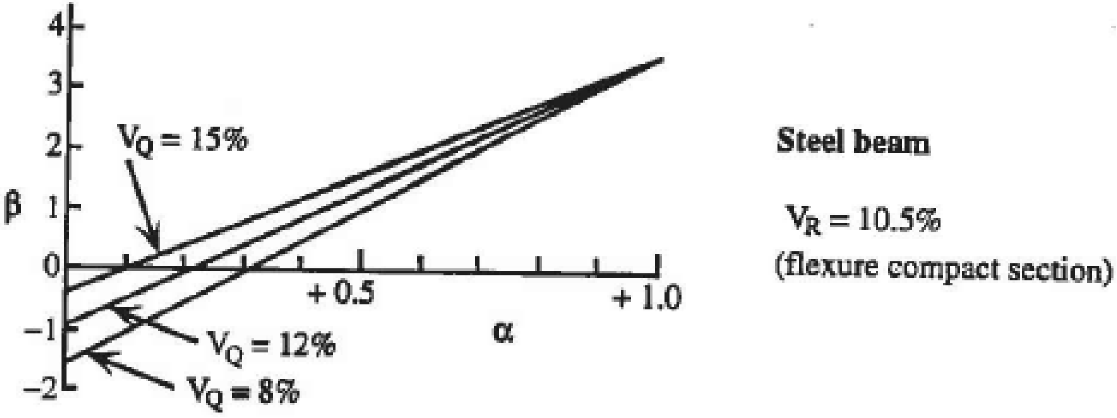
A frequent case of construction or use is the load piled in the central part of the beam (Figs.10.6b, c), rather than spread over the length.

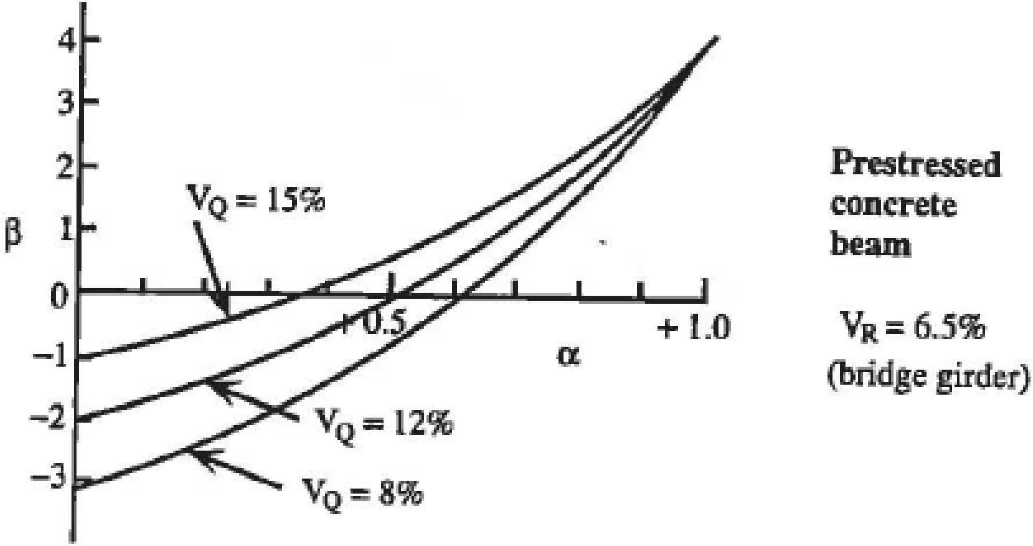
The loaded portion of the span is $\alpha L$, $0 < \alpha < 1$, $L$- beam length.

The reliability index $\beta$ for the beam is obtained for various values of $\alpha$. The case $\alpha = 1$ gives $\beta = 3.5$.

Three type of material are considered: structural steel, prestressed concrete and wood with coefficients of variation of resistance equal 0.105, 0.065, and 0.225, respectively.

Sensitivity functions are plotted in Figure 10.7 as a function of $\alpha$.




4
3
2
1
0
−1
−2
−3
β
α
+0.5
+1.0
$V_Q = 15\%$
$V_Q = 12\%$
$V_Q = 8\%$
Prestressed concrete beam
$V_R = 6.5\%$
(bridge girder)

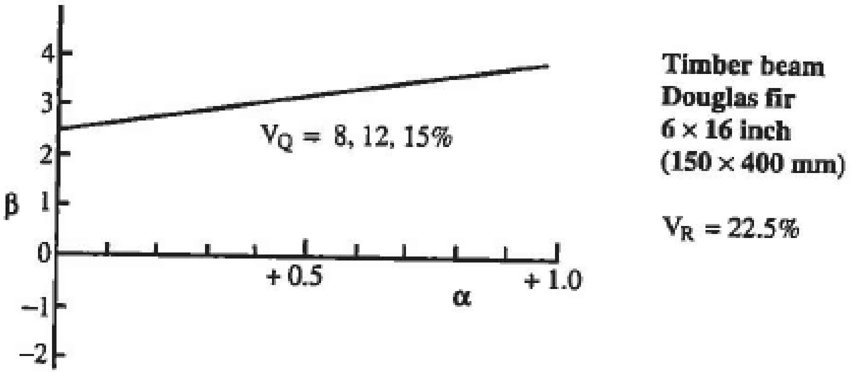


**FIGURE 10.7** Sensitivity functions for the beam considered in Example 10.1.

Three c.o.v. values of load effect are considered: 0.08, 0.12, 0.15.

The prestressed beam is mostly sensitive to load distribution errors whereas a wooden beam is least sensitive. This comes from large variation of wood strength vs. prestressed concrete or steel.

In the case of wood the uncertainty in material strength is much more significant than the uncertainty in the load.

# Sensitivity analysis

## Procedure

Sensitivity analysis is performed to identify the most important parameters affecting safety.

The basic steps in the procedure are as follows:

1. Develop a structural model, identify parameters and limit state functions,
2. Generate possible scenarios: concept, execution and intention errors,
3. Calculate reliability for each scenario,
4. Calculate the overall reliability (expected value),
5. Identify the most sensitive parameters.

This procedure is demonstrated for various structures.

# Bridge slab

Consider the bridge slab shown in Figure 10.8.

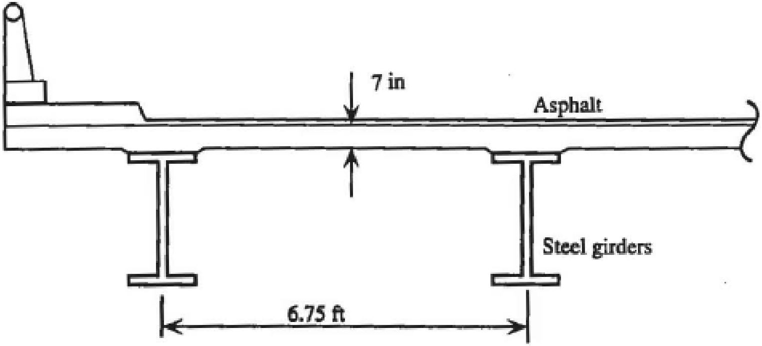


**FIGURE 10.8** Bridge slab.

The major design parameters are
$s$ – spacing between rebars,
$d$ – effective depth,
$f_c'$ – strength of concrete,
$D$– dead load,
$L$ – live load,
$I$ – impact.

The design (nominal) parameter values are enlisted below (British-American units):

Concrete strength, $f_c' = 3000$ psi

Rebars, $f_y = 40$ ksi (No.6 bars at $s = 7.5$ in)

AASHTO moment-carrying capacity = 10.9 k-ft

Effective depth, $d = 4.7$ in

Dead load moment = 0.40 k-ft

Live load moment = 3.30 k-ft

Impact = 1.00 k-ft

Statistical data:

$$\mu_D = 1.05 D_n; \qquad V_D = 0.08$$

$$\mu_L = 1.58 L_n; \qquad V_L = 0.11$$

$$\mu_I = 1.05 D_n; \qquad V_I = 0.45$$

$$\mu_R = 1.07 R_n; \qquad V_R = 0.11$$

The reliability index is obtained from the formula

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{0.1}$$

The resulting sensitivity functions are shown in Figure 10.9.

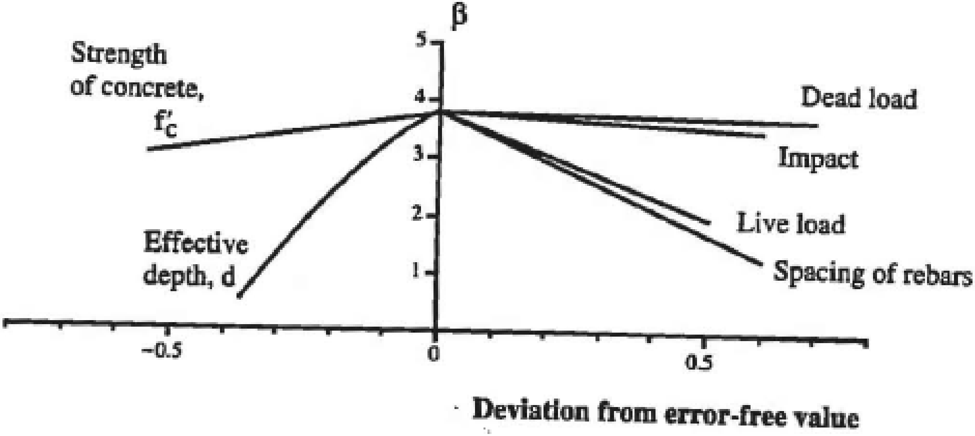


**FIGURE 10.9** Sensitivity function for bridge slab shown in Figure 10.8.

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# Beam-to-column connection

A steel beam-to-column connection is taken, shown in Fig. 10.10.

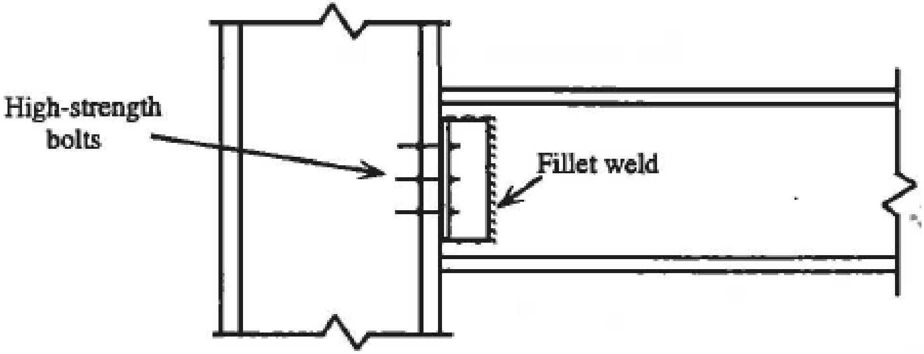

**FIGURE 10.10** Steel beam-to-column connection.

Fillet welds and bolts are chosen for the structure.

The following parameters are considered: angle thickness, number of bolts, bolt diameter, shear strength of the bolt, shear strength of the weld, dead load and live load.

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The statistical data are

$$D = L$$

$$\lambda_D = 1.0; \qquad V_D = 0.10$$

$$\lambda_L = 0.85; \qquad V_L = 0.20$$

$$\mu_R = 2.93(D + L); \qquad V_R = 0.185 \text{ for filled weld}$$

$$\mu_R = 3.00(D + L); \qquad V_R = 0.10 \text{ for A325 bolds}$$

$$\mu_R = 2.51(D + L); \qquad V_R = 0.07 \text{ for A490 bolds}$$

Sensitivity functions are presented in Figures 10.11 and 10.12.

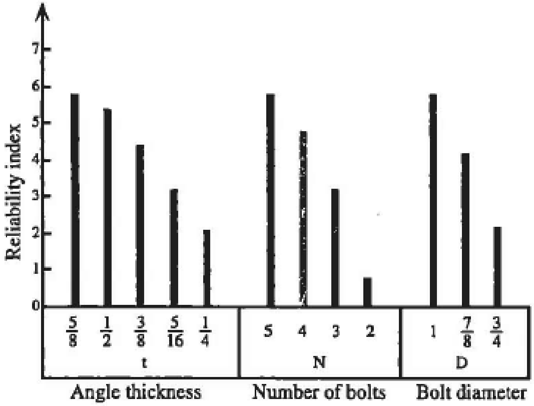

**FIGURE 10.11** Sensitivity functions for beam-to-column connection. Sensitivity to information on bolts is shown.

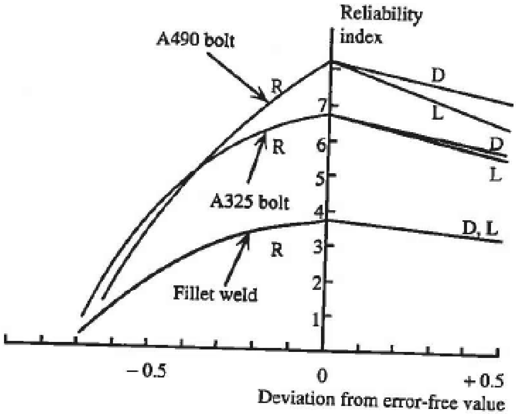

**FIGURE 10.12** Sensitivity functions for beam-to-column connection considering both bolts and welds.

# Timber bridge deck

A stringer deck is considered as shown in Figure 10.13.

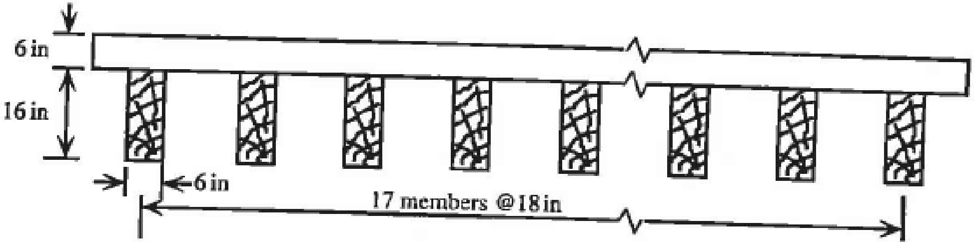

FIGURE 10.13 Timber bridge deck.

It is assumed that Hem-Fir select structural timber is used.

Dimensions and stringer spacing given in Figure 10.13 limit the  maximum span (AASHTO specifications, 1992) to 12.5 ft.

The major parameters considered include MOR (modulus of rupture), MOE (modulus of elasticity), dead load and live load.

It is assumed that MORand MOE are partially correlated.

Reliability analysis is performed using Monte Carlo simulations.

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The basic procedure is as follows:

1. MOR and MOE are generated for each stringer,
2. Stress in each stringer is calculated using the finite strip method (Bakht and Jaeger, 1985),
3. The ratio of MOR-to-actual stress is calculated for each stringer, the minimum ratio is saved for each run,
4. Distributions of minimum ratios are plotted on normal probability paper, the index $\beta$ is determined.

The MOE of the deck planks affects the stiffness of these planks and hence influences the lateral load distribution.

The sensitivity functions are shown graphically in Figure 10.14.

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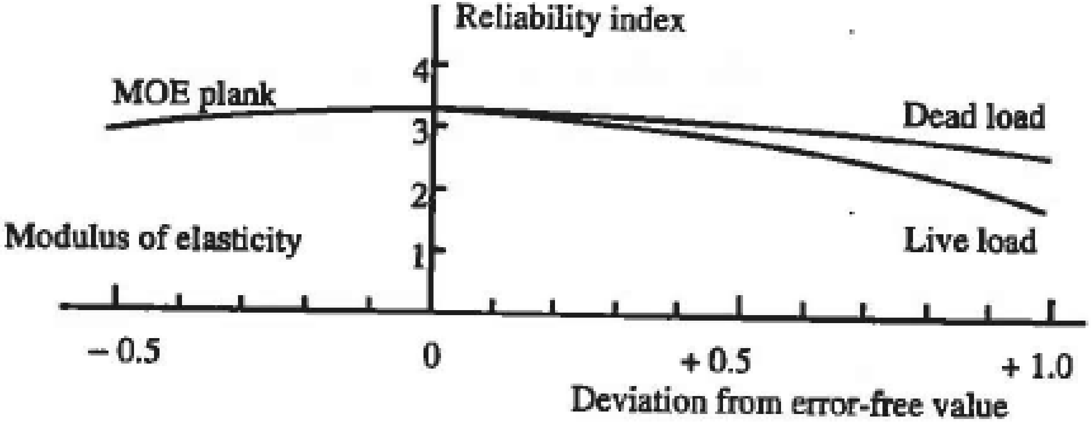

**FIGURE 10.14** Sensitivity functions for timber bridge deck.

# Partially Rigid Frame Structure

A partially rigid frame structure is shown in Figure 10.15.

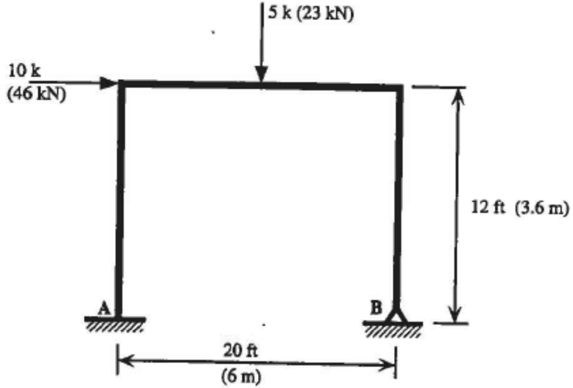

**FIGURE 10.15** Partially rigid frame structure.

The effect of boundary condition change at *A* is considered for a fully fixed / partially fixed support conversion.
Reliability index is computed for both cases.
The fully fixed support at *A* results in $\beta = 2.7$
the partially fixed support at *A* gives $\beta = 2.0$.

# Rigid frame structure

The rigid frame structure shown in Figure 10.16 is considered.

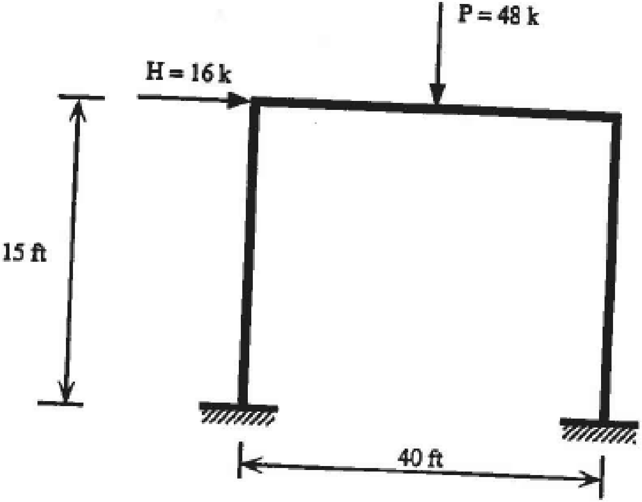

**FIGURE 10.16** Simple rigid frame structure.

Three parameters are considered: vertical force $P$ (gravity load), horizontal force $H$ (wind) and plastic moment $M_p$ (resistance).
Statistical load and resistance parameters are shown in Table 10.1.

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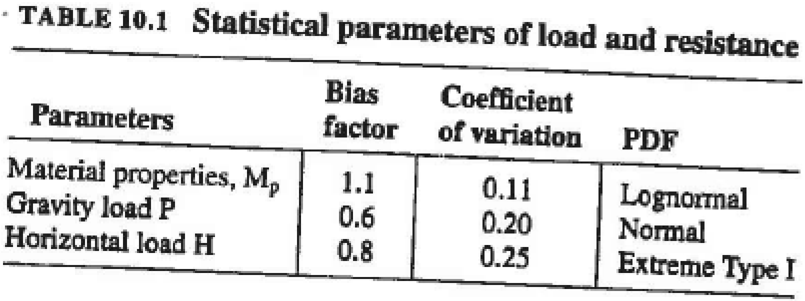

**TABLE 10.1 Statistical parameters of load and resistance**

| Parameters | Bias factor | Coefficient of variation | PDF |
|---|---|---|---|
| Material properties, $M_p$ | 1.1 | 0.11 | Lognormal |
| Gravity load P | 0.6 | 0.20 | Normal |
| Horizontal load H | 0.8 | 0.25 | Extreme Type I |

Sensitivity functions are presented graphically in Figure 10.17.

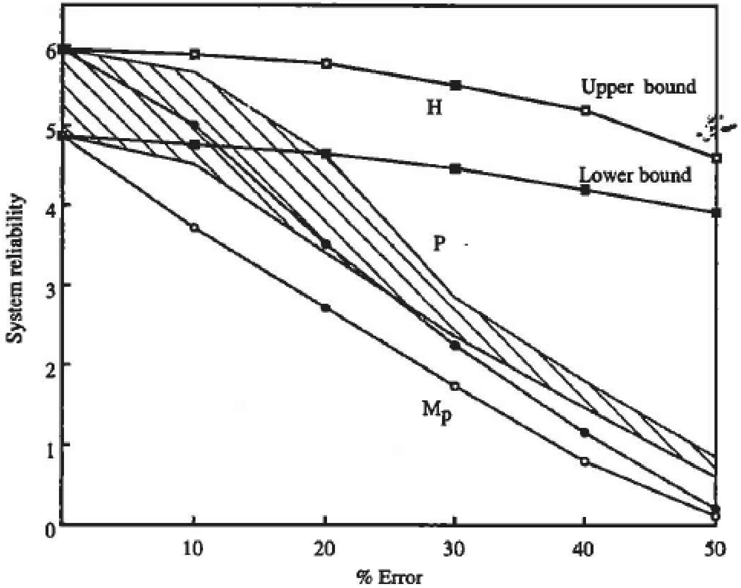

**FIGURE 10.17** Sensitivity of system reliability of frame structure due to errors in load and resistance parameters.

Various degrees of correlation are considered between the calculated upper and lower bounds for the reliability index.

# Noncompositesteel bridge girder

A noncomposite steel bridge girder is considered, its parameters are:
Span = 18 m
W36×210 girders spaced at 2.4 m
Yield strength, $F_y$ = 250 MPa
Slab thickness = 180 mm
Concrete strength, $f_c'$ = 21 MPa
Sensitivity functions are presented graphically in Figure 10.18.

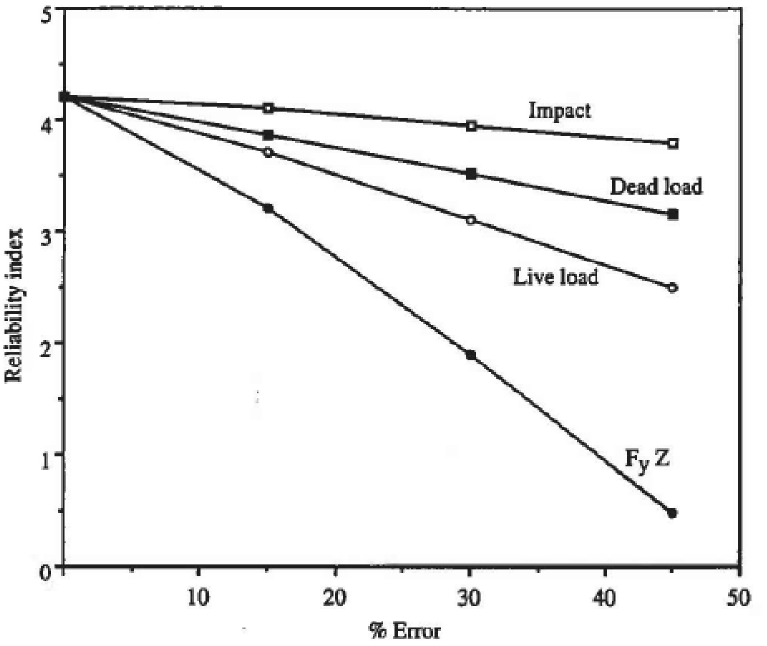

FIGURE 10.18 Sensitivity functions for noncomposite steel girder.

# Composite steel bridge girder

A composite steel bridge girder is considered, its parameters are:
Span = 18 m
W33×130 girders spaced at 2.4 m
Yield strength, $F_y$ = 250 MPa
Slab thickness = 180 mm
Concrete strength, $f_c'$ = 21 MPa
Sensitivity functions are presented graphically in Figure 10.19.

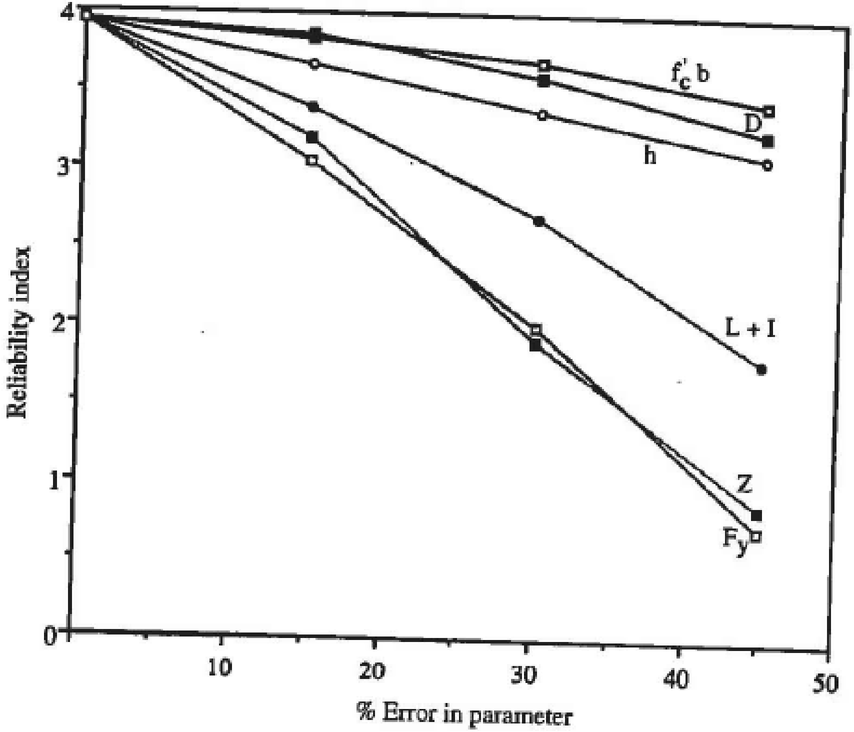

**FIGURE 10.19** Sensitivity functions for a composite steel girder.

...

# Reinforced concrete T-beam

A reinforced concrete T-Beam is considered, its parameters are:
Span = 18 m
Beam effective depth = 915 mm
Beams spaced at 2.4 m
Yield strength, $F_y$ = 275 MPa
Concrete slab strength, $f_c'$ = 21 MPa
Sensitivity functions are presented graphically in Figure 10.20.

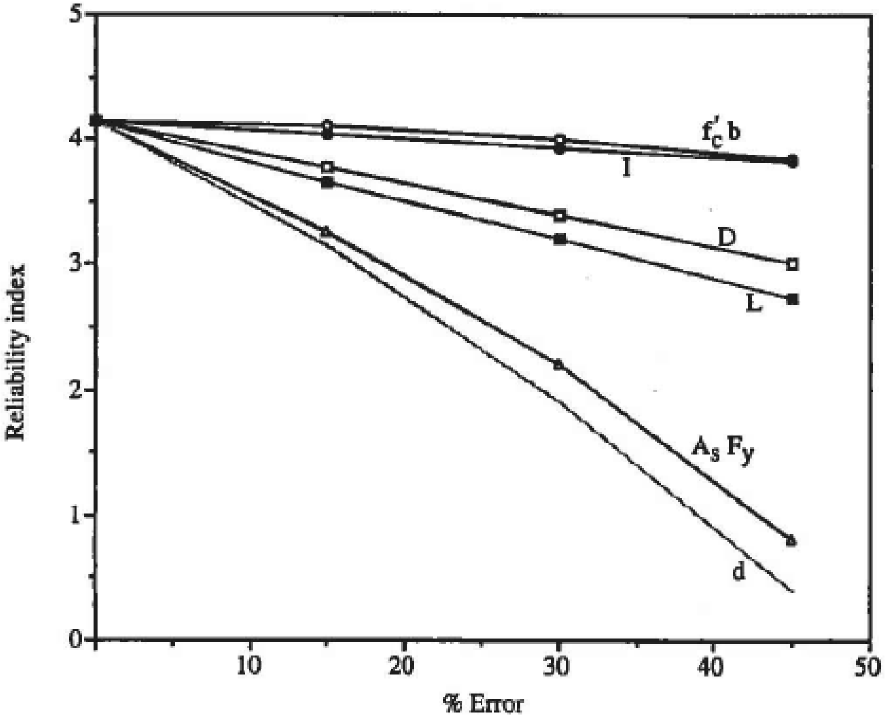

**FIGURE 10.20** Sensitivity functions for reinforced concrete T-beam.

# Prestressedconcrete bridge girder

A prestressed concrete bridge girder (AASHTO type) is considered, itsparameters are:

Span = 18m

$f_{pu}$ = 1860 MPa

Slab thickness = 180 mm

Concrete strength for girder, $f_c'$ = 28 MPa

Concrete strength for slab, $f_c'$ = 21 MPa

Sensitivity functions are presented graphically in Figure 10.21.

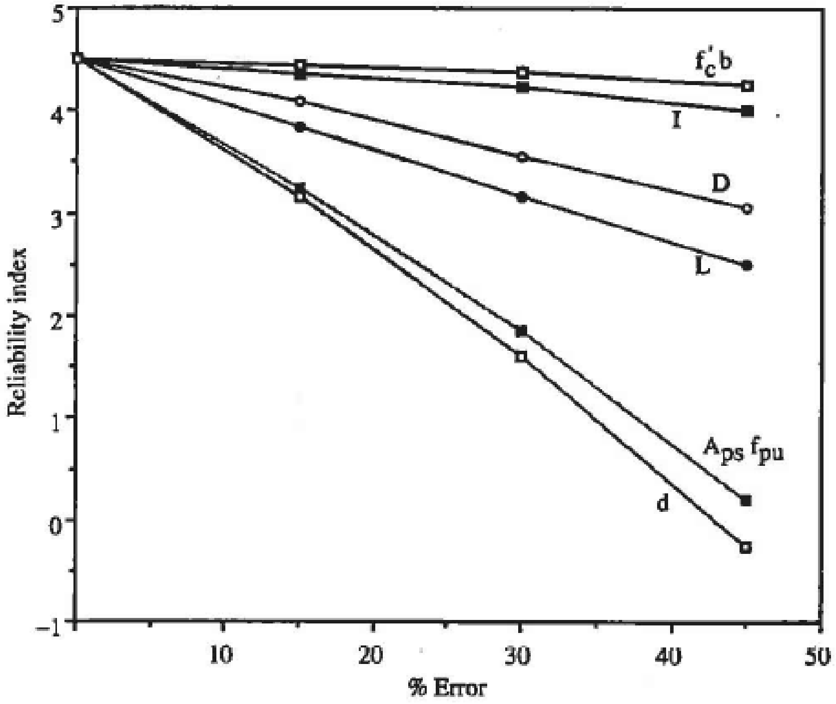

FIGURE 10.21 Sensitivity functions for prestressed concrete girder.

# Composite steel bridge system

A composite steel girder bridge is considered, its parameters are:
Span = 18m
W33×130 girders spaced at 2.4 m
Yield strength, $F_y$ = 250 MPa
Slab thickness = 180 mm
Concrete slab strength = 21 MPa.

System reliability analysis is performed to determine reliability index for the entire system.
Sensitivity functions are presented graphically in Figure 10.22.

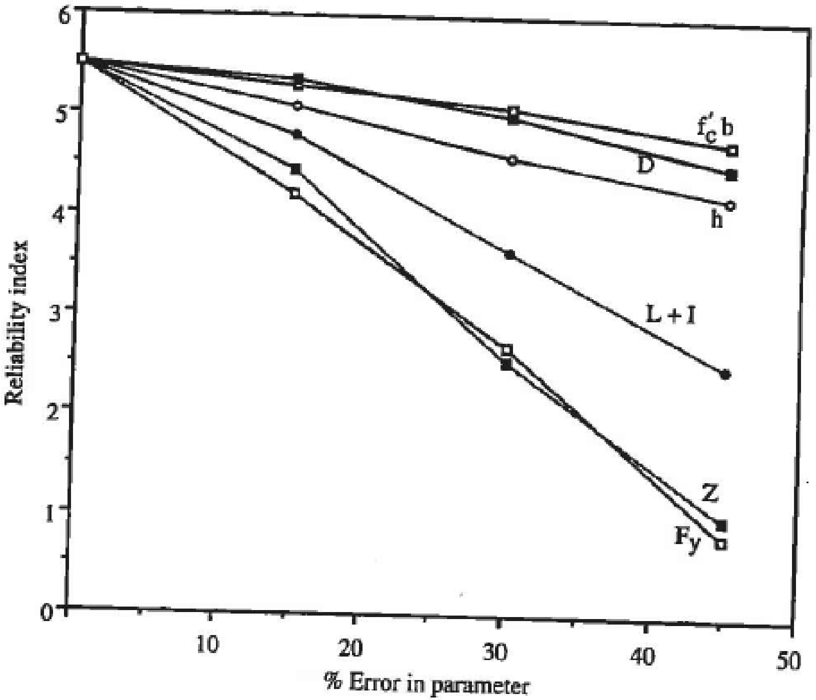

**FIGURE 10.22** Sensitivity functions for composite steel girder bridge.

# OTHER APPROACHES

Important errors affecting structural performance and reliability are identified by failure tree (event tree) and fault tree analysis.

A ***failure tree***(event tree) diagram is a schematic graph showing possible consequences of a particular event – the initiating event.

For any possible consequence one or more intermediate events must occur between the initiating event and the expected consequence.

Therefore, each path of the ***failure tree*** diagram represents one possible scenario of events leading to a particular consequence.

A ***failure tree*** (event tree) diagram shows the possible consequences due to the occurrence of the undesirable event.

This idea is illustrated in Figure 10.23.

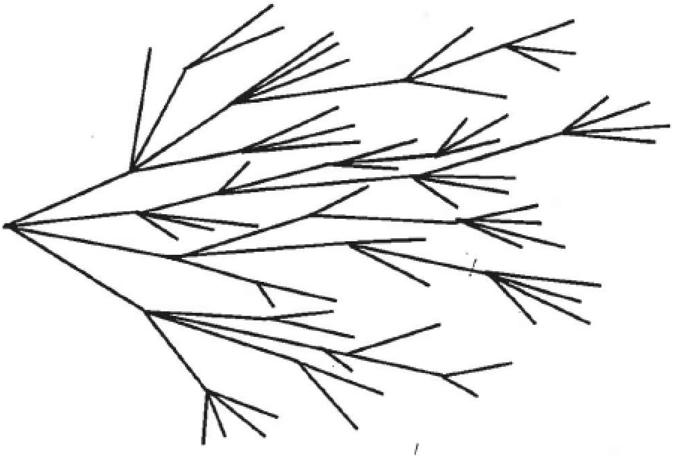

FIGURE 10.23 A schematic diagram of a failure tree.

*A **fault tree*** diagram shows how a particularly significant event(the top event) may occur, given possible fault (error) scenarios.

Thus a **fault tree** focuses on the potential ***causes*** of an event, and a **failure tree** (event tree) focuses on *consequences* of an event.

Figure 10.24 is a typical fault tree diagram.

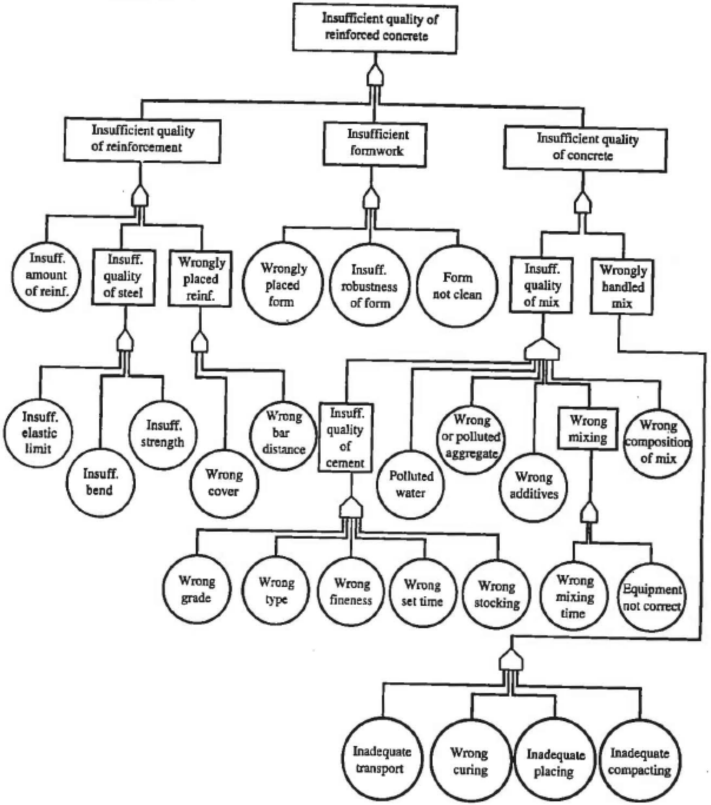

**FIGURE 10.24** A fault tree for a reinforced concrete structure. (from Task Group I, Comite European du Beton, 1983).

## Conclusions

Human error is the major cause of structural failure.

Structural reliability depends largely on controlling the causes of errors and minimizing their consequences.

Optimization of error control requires identifying the most frequent errors with their possible consequences.

Surveys identify the causes and frequency of errors,

sensitivity analysis is efficient in identifying error consequences, both actions provide means for error control measures.

Thus strategy development for a design office may be developed, focusing attention on errors of severe outcomes.

Great effect on the office organization may be achieved,
by means of selection of design and construction procedures.

The probability of error occurrence can be controlled by checking, inspection, monitoring, foolproof design and proof loading.

The damage extent can be controlled by safety factors, fail-safe design and performance monitoring.