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Simulation of Human Error in Reinforced Concrete Design

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Abstract. Available statistical data suggest that human error in design causes a significant proportion of performance failures; namely, structural failure, cost overruns, and delays. A Human Reliability Analysis (HRA) model has been developed to simulate the effect of human error on the design computations of a reinforced concrete beam. The proposed HRA model incorporates the effect of "self-corrections"; this is a process where tasks are re-evaluated if the result appears to be not within "reasonable" expectations. Calculation, table look-up, chart look-up, and table ranking microtasks were incorporated into the proposed HRA model; human perormance data are described for each of these microtasks. It was found that human error, particularly multiple errors, lead to a significant loss of structural safety.

1 Introduction

It is generally accepted that humans are the "weakest link" in the process of planning, design, construction, and utilization of an engineered structure. It is therefore not surprising that reviews of statistical data indicate that human error is the cause of up to 75% of structural failures [e.g., Ellingwood, 1987; Brown and Yin, 1988]. Human error is also responsible for other types of performance failure; namely, management problems (cost overruns and delays), and death and injury to the public user and construction workers. Available statistical data also suggest that design error causes a significant proportion (between 10% and 60%) of these failures.

It has also been observed that structural failure rates (i.e., probabilities of failure) based on statistical surveys seem much higher than those derived from analytical models by at least several orders of magnitude [e.g., Melchers, 1976]. According to Allen (1968), human error, rather than rare or extreme occurrences of high loads and/or low strengths, accounts for the discrepancy between observed and calculated failure rates. For this reason, present calculated failure rates are termed "notional" because these calculated failure rates are not the same as those observed.

Human error may be defined as an event or process that departs from commonly accepted competent professional practice. It excludes such unforeseen events as "Acts of God," variation in material properties, etc. Human errors may be broadly categorized as either slips or mistakes [Norman, 1981]. A slip was defined as an unconscious error (e.g., a calculation error) and a mistake as an error due to a deliberate or conscious action (e.g., selecting an unsuitable design loading combination). Furthermore, human error is generally caused by error-likely conditions, such as poor morale, time pressure, inexperience, etc. [Rouse, 1985]. It is therefore reasonable to assume that it is these error-likely conditions that would most likely cause "slip" errors. It is this aspect of human error that the present paper addresses.

Unfortunately, very little is known about the the causes and prevention of human error and its relationship to structural safety; nearly all the literature is qualitative rather than quantitiative. In order to understand the influence of human error, it is necessary to mathematically model the process of design, and the occurrence, consequence, and control of human error. It has been suggested that the Human Reliability Analysis (HRA) approach is suitable for modeling these effects [e.g., Swain and Guttman, 1983]. This method utilizes event-tree and fault-tree techniques, which have been extensively used in assessing the safety of nuclear power plants and other complex technological systems. It is therefore not unexpected that similar methods have been recommended for evaluating human error effects and quality control strategies for structural engineering tasks [Nessim and Jordaan, 1983; Nowak and Lind, 1985]. However, it is recognized that results obtained from HRA models can provide only an indication of the true nature of the effect of human error

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because human behavior is a complex phenomenon that is difficult to quantify. Nonetheless, HRA is particularly useful for assessing the comparative effectiveness of various error control programs.

Nessim and Jordaan (1983) developed a preliminary HRA model for design errors in a reinforced concrete beam to illustrate an error control decision theory. However, Nessim and Jordaan (1983) report that the assumptions used in the model were arbitrarily chosen, and that further research was needed to obtain appropriate human performance data. The HRA methodology has since been used to develop models to realistically simulate the effect of human error on the design loading and member design of a rafter for a steel portal frame [Stewart and Melchers, 1988; Stewart and Melchers, 1989; Stewart, 1991a]. The member design model has also been utilized to examine the effectiveness of various error control measures; namely, self-checking, detailed design checking, overview checking, and use of design aids. An optimal risk management strategy was then developed using decision theory concepts [Stewart, 1991b]. In the work reported by Stewart and Melchers (1988), verification with appropriate real-world data confirmed the validity of the HRA methodology.

In the present paper, a HRA model has been developed to simulate the effect of human error on the computations for the design of a typical reinforced concrete beam. The HRA model will be referred to herein as the "reinforced concrete design task" model. The model aims to accurately reflect all foreseeable actions that a designer takes in the design process. Although the final product is of simple form, its design is a complex task. The proposed HRA model also includes the effect of "self-corrections"; this is a process where tasks are re-evaluated if the result appears to be not within "reasonable" expectations. The following tasks were incorporated into the proposed HRA model: calculations, table look-ups, chart look-ups, and table rankings. Error rate and error magnitude distributions are described for each task. The outcomes for a reinforced concrete beam design were the member effective depth (i.e., depth to bottom reinforcement) and the amount of reinforcing steel. It was then possible to compute measures of structural resistance and structural reliability (i.e., probability of failure) from the reported results. A sensitivity analysis was conducted to ascertain the effect of error rate (and magnitude) uncertainty on the final results.

It is also generally recognized that human error is the primary cause of accidens and failure in other complex technological systems, such as nuclear power plants and offshore oil/gas platforms [Rouse and Rouse, 1983]. Risk studies are now required to be conducted by these industries. Therefore, even though the present paper is orientated towards structural engineering design, it is likely that the reported methodology and results will be appropriate to other design-orientated disciplines in engineering.

2 Description of "Reinforced Concrete Design Task" Model

2.1 *Design Task*

The design task considered in the present study is the design of a reainforced concrete beam (without compressive and shear reinforcement, and of rectangular cross section). It is assumed that the bean is supporting design dead (g) and live loads (q) of 3.8 kPa and 3.0 kPa, respectively (i.e., typical loads for a reinforced concrete floor slab), and that the beam length (L) and width (b) are known. The design is to be in accordance with the Australian Concrete Structures Code AS3600-1988. The nominal design resistance $R_{NOM} = M^*/\emptyset$ where M^* is the design action that results from the combination of dead and live loads and $\emptyset = 0.8$ [Standard Association of Australia, 1988]. In a realistic design process, the designer aims to produce a design outcome such that its member structural resistance (R_U) exceeds the nominal design resistance (R_{NOM}). The outcome for the design is the effective depth to steel reinforcing (d) and the amount of reinforcing steel (A_{st}) (see Fig. 1). A discretization of design outcomes occurs because the selection of the capacity to be provided is made from a limited range of beam depths (assumed rounded to next highest 50 mm—e.g., 450 mm, 500 mm, etc.) and cross-sectional areas of reinforcing steel (governed by number and diameter of manufactured bars).

2.2 *Methodology*

The mathematical modeling used to simulate human error was developed from event-tree methodology. This enables complex systems (or macrotasks) to be divided into successive individual components (or microtasks). Each microtask models a step or operation needed in the sequence of producing a final product.

Monte-Carlo simulation will be the main operational tool for the HRA. It may be visualized as a set of repeated experiments that are performed artifically by a computer. No feasible technique is available by which solutions to the present complex system problem can be obtained by hand. Further, computer simulation techniques are extremely flex-

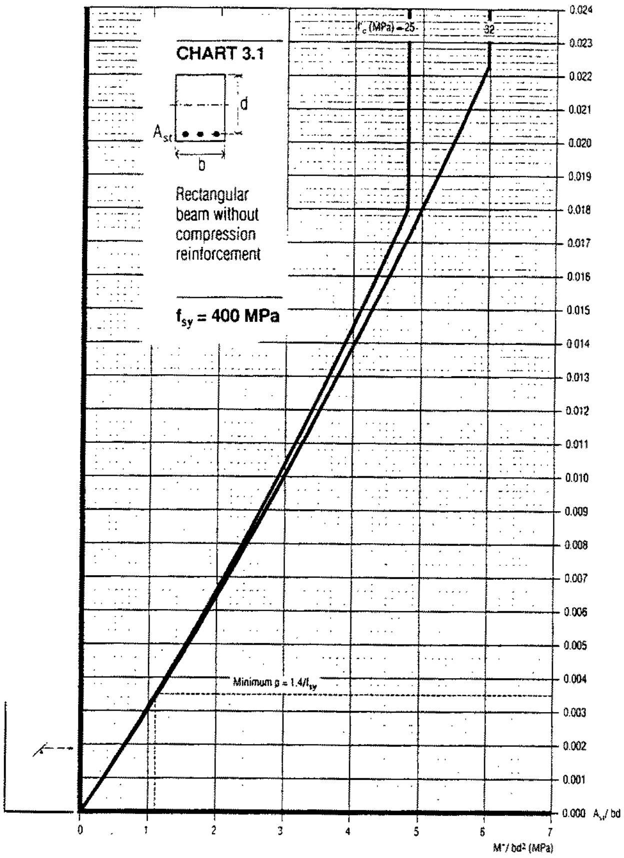

Fig. 1. Design chart for selecting A_{st}/bd [CCAA, 1989].

ible in allowing the effects of varying input paramters to be evaluated. For the proposed model, the procedure is as follows: at each node of an event-tree a random variable for error rate is generated and compared with the given error rate for the operation represented by the node. This enables a binary decision (either "error-included" or "error-free") to be made at this node. The same process is repeated at subsequent nodes. By working through successive steps an outcome is produced; the progression through the event-tree from the start to the finish is termed a "design cycle" or "run." For example, a section of an event-tree for a calculation microtask (i.e., $a = M^*/bd^2$) is shown in Fig. 2.

The model therefore contains branches of an event-tree that sequentially spread out; hence, many possibile paths through the event-tree lead to the final result. Only one path leads to the completely "correct" or "error-free" result. By replicating the design cycle many times so that most combinations of foreseeable human error consequences (or branches in the event-tree) can be evaluated, distributions of outcomes can be inferred. In the present case, the outcomes are the member effective depth and amount of reinforcing steel. Estimates of struc-

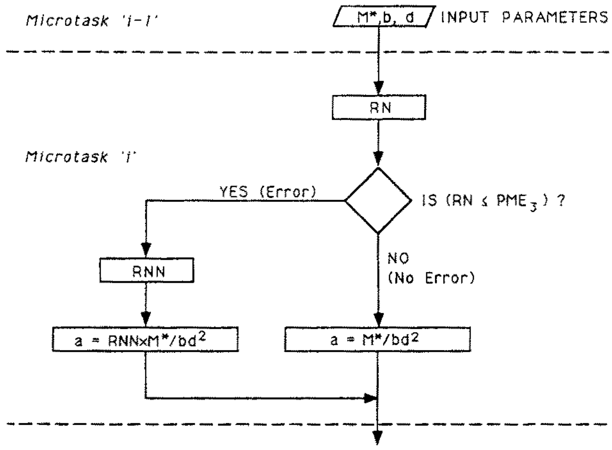

Fig. 2. Section of event-tree for a calculation microtask. RN, random number; RNN, magnitude of calculation error; and PME_3, error rate for calculation microtask.

tural resistance (or strength) and structural reliability can then be calculated for each outcome. The computation of structural reliability is obtained by standard computational procedures [e.g., Melchers, 1987], with statistical load and resistance parameters provided by Pham (1985) and Ellingwood et al. (1980), respectively.

The designer must proceed through the following steps in the design cycle:

Step 1. Select deflection limit (Δ/L) from table in AS3600.
2. Select deflection constant (k_2) from table in AS3600.
3. Select short-term live load factor (ψ_s) from table in AS3600.
4. Select long-term live load factor (ψ_l) from table in AS3600.
5. Calculate effective design load $F_{def} = (1.0 + k_{cs})g + (\psi_s + k_{cs}\psi_l)q$, where $k_{cs} = 2.0$ [AS3600].
6. Calculate minimum effect depth

$$d_{min} = \frac{L}{\left[\dfrac{k_1 \cdot (\Delta/L) \cdot b \cdot E_c}{k_2 \cdot F_{def}}\right]^{1/3}}$$

from the deemed to comply span-to-depth ratio serviceability requirement in AS3600.
7. Round-up d_{min} to next highest 50 mm to give d, then $D = d + 50$ mm.
8. Calculate $a = M^*/bd^2$.
9. Refer to standard chart that plots reinforcement ratio ($p = A_{st}/bd$) as a function of "a," and look-up the value of "p" [CCAA, 1989] (See Fig. 1).

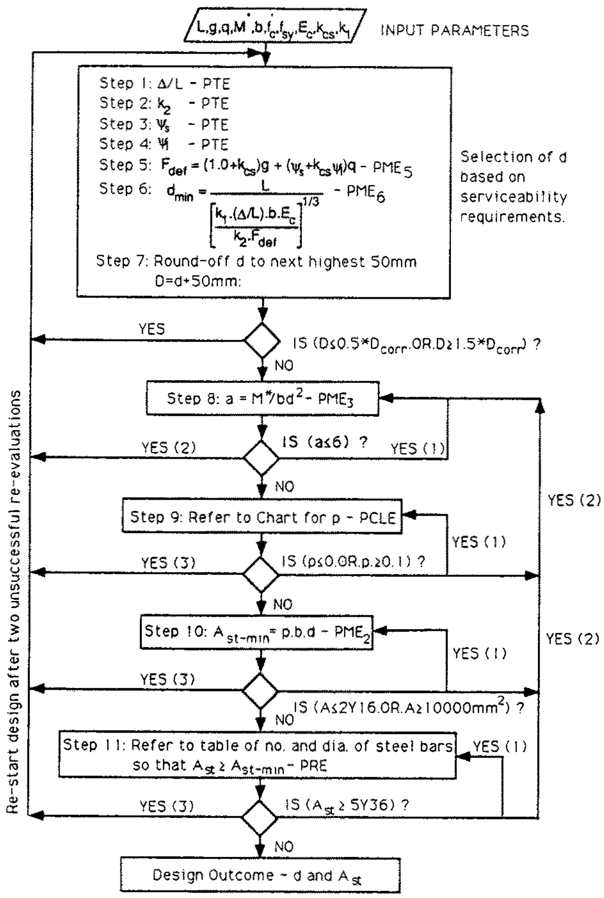

Fig. 3. Flowchart of design cycle showing process of "self-corrections." Note: (1), (2) and (3) refer to successive occasions when computed result appears to be not "reasonable." See Table 1 for definitions of PTE, PME_j, PCLE, and PRE.

10. Calculate $A_{st} = p \times b \times d$.
11. Select number and size of reinforcing bars from a table of bar areas.

A flowchart describing the design cycle is shown in Fig. 3. With refeernce to Fig. 3 it is also noted that the design cycle includes within it a mechanism for "self-correction" of results to ascetain whether the results appear reasonable. This "self-correction" is a process where the designer would re-evaluate some or all prior tasks until the results was within "reasonable" limits. In the present case, if a result is deemed not "reasonable," then the "self-correction" process is as follows: (1) the designer would first re-evaluate the prior microtask; (2) if the re-evaluated result still appears not "reasonable" then it is assumed that the designer would then go back several microtasks and re-evaluate these in the sequence in which they occur; and (3) if no error can be found, then the designer may restart the design sequence from the beginning. The precise definition of what constitutes "reasonable limits" is highly subjective; however, the limits as shown in Fig. 3 are not considered to be unrealistic.

The following assumptions were also made in the development of the design task model:

1. Each event was statistically independent of all other events
2. The designer completed the sequence of events in the order given above
3. The designer referred to the relevant design code rules, tables, and charts
4. An error of omission could not occur without terminating the design process
5. Completion of a "self-correction" process (i.e., re-evaluation of prior microtasks) would only occur when the updated result was consistent with the previously evaluated result. If the results differ, then the microtask would be successively re-evaluated until successive results were of similar magnitude. This implies that the designer has confidence in the accepted microtask result before proceeding to the next microtask
6. Total beam depth (D = d + 50 mm) was only deemed "acceptable" if it was within the limits of ±50% of what an "error-free" design would have produced
7. Minimum and maximum allowable steel reinforcement (A_{st}) is 2Y16 and 5Y36 bars, respectively [Standard Association of Australia, 1988]

Each step in the design cycle consisted of one or more of the following microtasks; numerical calculation, table look-up, chart look-up, and table ranking. Human performance (i.e., error rate and error magnitude) probabilistic models are therefore required for each microtask. These are now described in detail.

2.3 *Microtask Human Performance Models*

2.3.1 Distribution of error rates. It might be expected that the error rate for a specific task will not be constant, but will vary from individual to individual. The variation in error rates may thus be represented by a probability distribution. Swain and Guttman (1983) suggest that the performance of skilled persons tends to bunch up toward the low error rates on a distribution of error rates. For this reason, the log-normal distribution is recommended for modeling human performance data. This distribution is widely used to model component and operator error rates for HRA studies; for example, of nuclear power plants [RSS, 1975].

A distribution of error rates requires an estimate

Table 1. Summary of average microtask error rates

Microtask error		Error rate
PRE	Table ranking	0.0135
PTE	Table look-up	0.0126
PCLE	Chart look-up	0.0200
PME_1	One-step calculation	0.0128
PME_2	Two-step calculation	0.0256
PME_3	Three-step calculation	0.0384
PME_5	Five-step calculation	0.0640
PME_6	Six-step calculation	0.0768

of the mean and a measure of dispersion (i.e., variance) for the log-normal distribution. The mean or average error rate has been obtained from survey data and appropriate literature (see Table 1); these are described in the following sections. However, measures of variance are not available from these data sources. The variance represents the inherent variation of error due to differing ability, personal characheristics, work environments, and other factors that affect task performance. It is beyond the scope of the present paper to attempt to isolate these performance-shaping factors. However, a convenient measure of uncertainty may be represented by an "error factor" (EF) which is expressed as

$$EF = \sqrt{\frac{Pr(F_{90th})}{Pr(F_{10th})}} \qquad (1)$$

where $Pr(F_{10th})$ and $Pr(F_{90th})$ are the error rates corresponding to the 10th and 90th percentiles, respectively, of the distribution of error rates [Apostolakis, 1982]. Thus, the standard deviation of the lognormal distribution is $\sigma = \ln(EF)/1.2817$.

Swain and Guttman (1983) have estimated that an error factor of either 3.0 or 5.0 is appropriate for operator tasks in nuclear power plants conducted under routine circumstances. In the absence of other guidelines, it is proposed that an error factor of EF = 3 be applied to the tasks considered in the present study. For example, the influence of the error factor on the distribution of chart look-up error rates is shown in Fig. 4, for EF = 0.0, 3.0, and 5.0.

2.3.2 Calculation microtask. For the present study, a calculation is defined as a discrete number of mathematical operations on a set of numbers leading to a recorded result. This involves the use of any combinations of the four most commonly used operational functions (+, −, ×, ÷) required in the design where the number of operational functions used defines the number of steps in the calculation. It was assumed by Melchers (1984) that rounding-

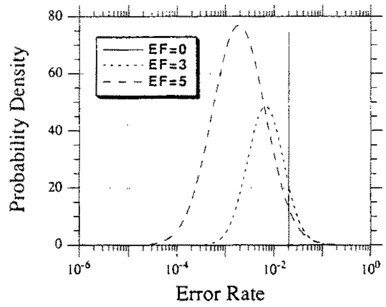

Fig. 4. Effect of error factor (EF) on the distribution of error rates.

off could account for a variation of the correct calculated result by up to 2.5%; any value above this was deemed a gross error.

It has been shown by Melchers and Harrington (1984) that there is an approximately linear relationship between the error rate and the number of calculation steps. Thus, the average calculation error rate for j calculation steps is

$$PME_j = j \times PME_1 \qquad (2)$$

where PME_1 is the average error rate for a one-step calculation (e.g., a + b). From a survey conducted among undergraduate engineering students, a representative value of $PME_1 = 0.0128$ has been derived [Melchers, 1984]. Kasprzyk and coworkers (1979), and Agate and Drury (1980) have reported similar error rates and linearity trends.

Gross errors in a calculation were considered to consist of (1) calculation gross errors (random variation in error) and (2) decimal gross errors (errors of orders of magnitude, e.g., 10^{-2}, 10^{3}). A compound probability distribution of error magnitudes has been proposed by Melchers and Harrington (1984), where error magnitude is defined as the incorrect result divided by the correct value. The distribution of error magnitude for a one-step calculation is shown in Fig. 5.

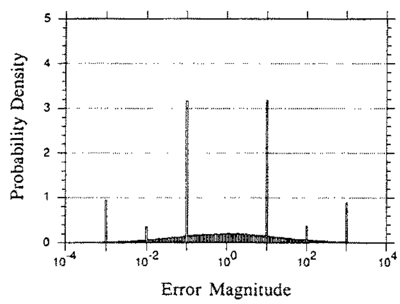

Fig. 5. Distribution of calculation error magnitudes [Melchers and Harrington, 1984].

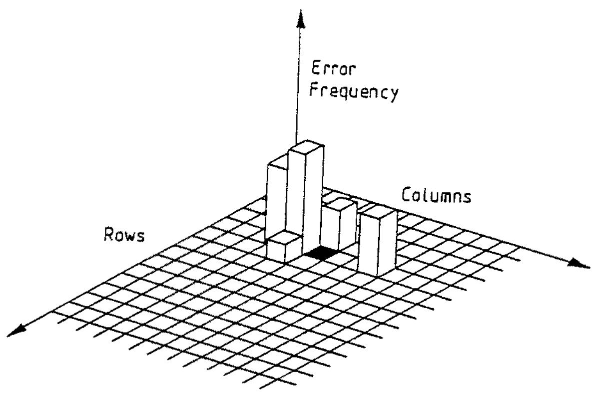

Fig. 6. Frequency distribution of table look-up errors [Melchers, 1984].

2.3.3 Table look-up microtask. This microtask is defined as the ability of a designer to look-up a specific given value from a table of values. Wherever possible, the frequency distribution of errors used was that shown in Fig. 6 [Melchers, 1984]. Equal error frequencies were given to all adjacent values of the specific given value if this value occurred in the first or last row or column. The average error rate for a table look-up is estimated to be 0.0126 [Melchers, 1984], and is assumed the same for all table formats. Research conducted by Wright (1968) indicates similar table look-up error rates.

2.3.4 Chart look-up microtask. For the present study, the designer would use a chart to determine the amount of reinforcing steel required for a given design moment and member dimensions (M^*/bd) (see Fig. 1). For a given ratio of M^*/bd^2, the designer starts at the horizontal axis, moves vertically up to the graph line and then across to the vertical axis where the area of reinforcing steel (expressed as a fraction of concrete area) is given. Beeby and Taylor (1973) have conducted several surveys of professional engineers on the performance of designers when using this and other design charts. A gross error was defined to occur when the recorded result differed by more than 3% from the correct result. Using this criterion, Beeby and Taylor (1973) observed an average error rate of 0.02 for the type of design chart considered in the present study. No information was reported about the distribution of error magnitudes, therefore for convenience, it is assumed that the distribution of error magnitudes will be the same as that used for calculation errors.

2.3.5 Table ranking microtask. This task is defined as comparing tabulated numerical values and then selecting the correct value corresponding to a specific ranking instruction. On such task is the selection of steel reinforcing that has an area greater than or equal to a specified minimum (or nominal) calculated area from a table of bar areas. The average error rate for this ranking microtask is 0.0135 [Melchers, 1984].

Table 2. Average number of errors for an "error-included" member design

Microtask error		Before self-corrections	After self-corrections
PRE	Table ranking	0.0119	0.0118
PTE	Table look-up	0.0503	0.0352
PCLE	Chart look-up	0.0184	0.0022
PME_2	Two-step calculation	0.0235	0.0050
PME_3	Three-step calculation	0.0377	0.0041
PME_5	Five-step calculation	0.0653	0.0120
PME_6	Six-step calculation	0.0783	0.0057
Total		0.2854	0.0760

3 Model Evaluation

In what follows, the Monte Carlo simulation analysis of the "reinforced concrete design task model" will be referred to as the "design process simulation." The results of a design without human error will be referred herein as an "error-free" design (microtask error rates equal to zero) and one with realistic or average human error content as an "error-included" design. Clearly, an "error-free" design may occur only as a consequence of a very efficient error detection and control program. Design process simulations were conducted for a tributary area of A_t = 50 m^s, beam width of 400 mm, and member spans from 4–20 m.

3.1 Error Frequency

Errors were categorized as (1) total number of errors committed in the process of the design (including those that are eventually self-corrected) and (2) errors in the final design (i.e., after self-corrections). The error frequency (i.e., average number of errors in a design cycle) as obtained from a typical "error-included" design process simulation is given in Table 2, for each microtask and for a member span of 10 m. It is observed that the influence of "realistic" self-corrections reduces the error frequency from approximately 0.28 to 0.08 errors per design. Furthermore, calculation and chart look-up microtasks appear to be self-corrected more frequently than the other microtasks. This is not surprising, since errors in these microtasks may lead to error magnitudes of

Table 3. Percentage of errors per "error-included" member design and failure probabilities

Number of errors per design	Before self-corrections	After self-corrections	
0	85.84	92.84	0.911E-3
1	11.79	6.60	0.449E-1
2	1.83	0.50	0.120
3	0.38	0.05	0.213
4	0.10	0.01	0.190
5	0.03	0.00	0.000
6	0.01	0.00	0.000
7	0.01	0.00	0.000
8	0.01	0.00	0.000
Weighted mean			0.446E-2

several orders of magnitude. Hence, it is more likely that some "incorrect" results would appear to be not "reasonable" and the microtask then re-evaluated. The composition of the final error content (i.e., after "self-corrections") is then approximately 46% table look-up errors, 35% calculation errors, 15% table ranking errors, and 3% chart look-up errors.

To obtain information about the incidence of multiple errors the error frequency was also represented as the number of errors committed for each design cycle (see Table 3). The data shows that the percentage of error-free designs increases from approximately 86% to 93% as a result of "self-corrections." Not surprisingly, it is also observed also that the percentage of multiple errors reduces when "self-corrections" are assumed to occur.

In the following section, the effects of such errors on structural resistance and structural reliability of a designed member is examined.

3.2 Structural Resistance

Figure 7 shows typical histograms of the distribution of structural resistances (R_U) for "error-free" and "error-included" design process simulations, for a member span of 10 m. Note that the "error-free" design process simulation produces a limited range of "correct" design outcomes (and hence structural resistances). This is due to (1) the "rounding-off" in calculations and (2) the discretization of design outcomes. With reference to Fig. 7 it is also observed that the minimum structural resistance is nonzero, but is a value that corresponds to a member with minimum "realistic" design outcomes (see Section 2.2). Figure 7 also shows that most design process simulations (even with errors) produce correctly sized members; the selection of an undersized or oversized member is a relatively rare event.

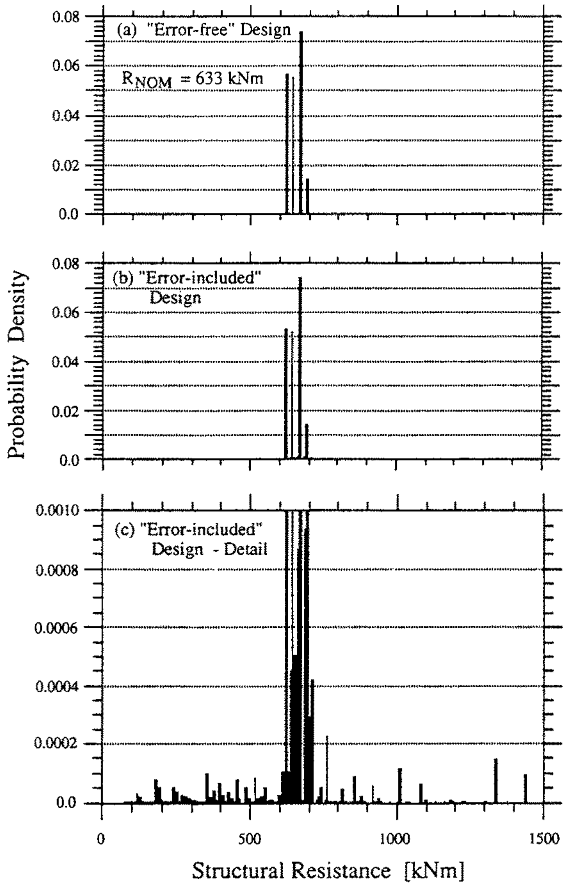

Fig. 7. Distribution of structural resistances for designed members.

3.3 Structural Reliability

An estimate of structural reliability was computed from each value of structural resistance (i.e., for each design cycle) using conventional design code calibration methods [e.g., Melcher, 1987]. Therefore, histograms of the distribution of probabilities of failure were derived from the "error-free" and "error-included" histograms of structural resistance. A typical histogram of failure probabilities is shown in Fig. 8, for a member span of 10 m. The mean probabilities of failure for both the "error-free" ($\bar{p}_{f0}$) and "error-included" ($\bar{p}_{fE}$) design process simulations could then be calculated and are presented in Table 4, for member lengths from 4–20 m. The tabulated probabilities of failure are generally consistent for most member spans. The slight variation between the $\bar{p}_{f0}$ values occurs because the ratio of R_U/R_{NOM} (i.e., a measure of the degree of oversizing) is nonuniform. Oversizing is due to the discretization of design outcomes where the actual structural resistance of the member (R_U) is always

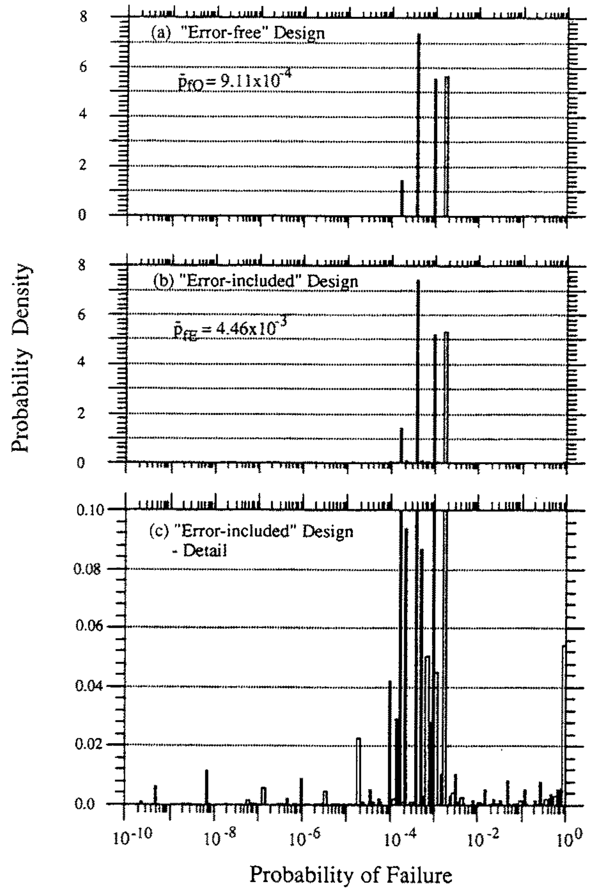

Fig. 8. Distribution of failure probabilities for designed members.

greater than the required minimum structural resistance (R_{NOM}). Table 4 also shows the relative loss of structural safety ($\bar{p}_{fE}/\bar{p}_{f0}$) for each member span. The relative loss of structural safety varies from approximately 3.8–8.9; all of which constitutes a significant loss of structural safety. This result is to be expected.

It is observed from Figs. 7 and 8 that it is the selection of members with a structural resistance less than R_{NOM} that significantly reduces structural reliability, and that in rare cases the probability of failure approaches certitude. It therefore appears that error control strategies (e.g., independent design checking, design aids) should concentrate on the amelioration of these low frequency/high consequence events; this is an area for further research. However, it should be noted that not all human errors are detrimental to structural safety; Fig. 8 also shows that some errors produce designs with extremely low probabilities of failure. For this reason, it is important to study the distribution of failure probabilities, as summary statistics (e.g., mean, variance) may be misleading to a decision-maker.

Table 4. "Error-included" and "Error-free" failure probabilities

Member span (m)	$\bar{p}_{f0}$ ("error-free")	$\bar{p}_{fE}$ ("error-included")	$\bar{p}_{fE}/\bar{p}_{f0}$
4.0	0.542E-3	0.413E-2	7.62
6.0	0.136E-2	0.524E-2	3.85
8.0	0.513E-3	0.454E-2	8.85
10.0	0.911E-3	0.446E-2	4.90
12.0	0.844E-3	0.583E-2	6.91
14.0	0.885E-3	0.530E-2	5.99
16.0	0.736E-3	0.450E-2	6.11
18.0	0.679E-3	0.450E-2	6.63
20.0	0.717E-3	0.472E-2	6.58

The influence of the number of errors per design was also investigated by obtaining the mean probabilities of failure for various error frequencies (see Table 3). Table 3 clearly shows that structural reliability decreases with the occurrence of one or more errors per design. However, multiple errors appear to be responsible for largest loss of structural safety. This is not an unexpected observation.

3.4 Sensitivity Analysis of Error Factor and Microtask Error Rates

The average microtask error rates given in Table 1 were obtained from survey data and are hence subject to some statistical uncertainty. In addition, the selection of the error factor was obtained by subjective judgement. For these reasons, a sensitivity analysis was conducted to assess the influence of uncertainty in error factor and microtask error rates on structural reliability.

In order to do this, a measure of the modification of a typical microtask error rate was defined as:

$$\Phi_m = \frac{\text{modified error rate}}{\text{average error rate}} \tag{3}$$

The sensitivity analysis involved varying the value of Φ_m and the error factor and comparing the corresponding mean probabilities of failure $\bar{p}_f$, obtained from design process simulation (see Table 5), for error factors of 0.0, 3.0, and 5.0. Table 5 shows that "error-included" designs (i.e., $\Phi_m > 0$) exhibit a gradual loss of structural safety as the error content increases and also as the error factor decreases. However, the "error-included" structural reliability for $\Phi_m = 0.25$ is approximately double that as obtained for the "error-free" design, indicating that even a very small error content causes a significant decrease in structural safety.

The results also indicate that structural reliability is not particularly sensitive to variations in error

Table 5. Sensitivity analysis of microtask error rates

Φ_m	EF = 0.0		EF = 3.0		EF = 5.0	
	$\bar{p}_f$	$\bar{p}_f/\bar{p}_{f0}$	$\bar{p}_f$	$\bar{p}_f/\bar{p}_{f0}$	$\bar{p}_f$	$\bar{p}_f/\bar{p}_{f0}$
0.00	0.911E-3	1.00	0.911E-3	1.00	0.911E-3	1.00
0.05	0.109E-2	1.20	0.111E-2	1.22	0.117E-2	1.28
0.10	0.136E-2	1.49	0.135E-2	1.48	0.133E-2	1.46
0.25	0.192E-2	2.11	0.207E-2	2.27	0.181E-2	1.99
0.50	0.322E-2	3.53	0.307E-2	3.37	0.274E-2	3.01
0.67	0.359E-2	3.94	0.320E-2	3.51	0.327E-2	3.59
1.00	0.472E-2	5.18	0.446E-2	4.90	0.386E-2	4.24
1.50	0.706E-2	7.75	0.610E-2	6.70	0.536E-2	5.88
2.00	0.957E-2	10.50	0.783E-2	8.59	0.627E-2	6.88
4.00	0.189E-1	20.75	0.132E-1	14.49	0.943E-2	10.35
10.00	0.516E-1	56.64	0.254E-1	27.88	0.166E-1	18.22
20.00	0.15000	164.65	0.430E-1	47.20	0.252E-1	27.66

rates which depart in a minor way (Φ_m = 0.5–1.5) from those given in Table 1, for error factors of 0.0, 3.0, and 5.0. It is also observed that the estimate of structural reliability decreases as the error factor increases for large values of Φ_m (i.e., $\Phi_m > 4.0$). Note that the average error rate remains unchanged, but a characteristic of the log-normal distribution is that the median decreases as the error factor increases. In other words, the probability distribution of error rates is skewed towards the lower error rate values (see Fig. 4). Hence, there is less likelihood of the occurrence of multiple errors; it has been observed in Section 3.3 that it is the occurrence of multiple errors that significantly reduces structural reliability.

Accordingly, the results and observations obtained in previous sections for the "error-included" design process simulations are not sensitive to some minor statistical uncertainty about the accuracy of the reported microtask error rates and of the selected error factor.

4 Conclusion

A HRA model has been developed to simulate the effect of human error on the design computations of a typical reinforced concrete beam. The proposed model was based on event-tree methodology and Monte-Carlo simulation, and included within it the realistic process of "self-correction" to ascertain whether the results appeared "reasonable" to the designer. Human performance data (i.e., error rate and error magnitude distributions) for calculation, table look-up, chart look-up, and ranking microtasks were also described. It was found that human error leads to a significant loss of structural safety. A sensitivity analysis found that the reported results and observations were not particularly sensitive to minor statistical uncertainty of the reported human performance data.

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