Modeling Human Performance in Reinforced Concrete Beam Construction

By Mark G. Stewart[1]

Abstract: A significant portion of performance failures are due to human error in the construction stage of a structural engineering project. Statistical studies indicate that the construction of in-situ reinforced concrete elements is most prone to error, and that most errors are committed by contractors (either site staff or workmen). Results are reported herein of a survey investigating the error rate and error magnitude of contractor construction errors, and the frequency of engineering inspections and their influence on construction errors. The survey recipients were practicing structural engineers. Probabilistic models have been proposed for the distribution of error rates and error magnitudes, and include within them the influence of inspections. It was found that engineering inspections reduced the initial on-site construction error content by approximately two orders of magnitude. The models provide construction task performance information that can be incorporated into a probabilistic risk analysis of reinforced-concrete construction.

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 human error is the cause of up to 75% of structural failures (Ellingwood 1987). However, human error is also responsible for other types of performance failure; namely, management problems (cost overruns and delays), and death or injury to the public and construction workers. Available statistical data also suggest that design and construction errors are the two dominant causes (approximately 40–50% each) of these failures. It is worth emphasizing that engineering projects are responsible for approximately 10% of the gross domestic product (GDP) (Davis et al. 1989). It was also estimated that construction costs amount to approximately 90% of the total project cost (Melchers 1978), and that the cost of construction error is approximately 5% of this cost (Turkstra et al. 1983). The magnitude of the financial cost of construction error indicates that investigating the occurrence and detection of construction errors is an important area for research.

Statistical studies show that the construction of in-situ reinforced concrete buildings is most prone to error (Brown and Yin 1988; Eldukair and Ayyub 1991). The execution of this construction task is generally conducted by contractors, and it is therefore not surprising that up to 77% of all failures are attributed to errors committed by contractors (Eldukair and Ayyub 1991). In the present paper, the term contractor refers to all subcontractors, site staff, foreman, and workmen who are employed by the construction contractor or builder. Brown and Yin (1988) suggest that contractor errors are dominated by ignorance, thoughtlessness, and negligence. Such an observation is not unreasonable: construction workers are generally unskilled

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or semiskilled, work in unpleasant conditions, and often have poor motivation. These are all factors that ergonomically contribute to poor task performance, and suggests that errors are to be expected. Consequently, engineers place a very high importance on work site inspection as a measure to control construction errors (Ingles and Nawar 1983). For these reasons, the present paper will concentrate on the performance of contractors and inspecting engineers for in-situ reinforced concrete construction tasks.

It is the unpredictable nature of human behavior that may or may not lead to human error in circumstances where human error may be due to negligence (i.e., error is a discretionary act) or error-likely physiological and psychological conditions such as poor morale, time pressure, inexperience, and so forth. For the present study, a construction error is defined as a departure or deviation from construction tolerances as specified by the *Australian Concrete Structures Code AS3600* (*Australian* 1988).

It has been suggested that the human reliability analysis (HRA) approach is suitable for modeling the effect of human error in risk analysis (Swain and Guttman 1983). The principal objective of HRA is to compare the effectiveness of various error control measures. This method utilizes event-tree techniques and Monte Carlo simulation, which have been extensively used in assessing the safety of nuclear power plants and other complex technological systems ("Reactor" 1975; Swain and Guttman 1983), and for structural engineering design tasks (Stewart and Melchers 1989a). This is mainly due to the ability of these methods to produce a quantitative result (e.g., structural reliability) while incorporating the inherent variability of human performance. These ideas permit the modeling of complex systems by subdividing the system task into successive individual components (or microtasks). Each microtask models a step or operation needed in the sequence of producing a final product.

A HRA of the construction of a reinforced concrete beam initially requires an understanding of possible microtask error events; namely, their rate of occurrence (i.e., error rates), their consequences (i.e., error magnitude), and their rate of detection and correction. Typical construction errors (committed by the contractor) considered in this paper include early removal of shoring; incorrect placement, number, and size of reinforcing bars, beam depth, and beam width; and inadequate concrete mix. Each construction error influences flexural strength, serviceability, or loading; these influences may or may not be detrimental to the finished product. For the present study, a survey of professional structural engineers with construction experience was used to obtain subjective assessments of error rates and error magnitudes for the considered construction errors. This type of survey approach is referred to by Swain and Guttman (1983) as the "direct numerical estimation procedure," and is widely used for the estimation of operator error rates in nuclear power plants. The frequency of initial and subsequent (or follow-up) on-site engineering inspections and their influence on construction errors were also investigated in the same survey. Probabilistic models were then developed for the distribution of error rates and error magnitudes, and include within them the influence of inspections. The models provide construction task performance information that has been incorporated into a HRA of reinforced-concrete beam construction (Stewart 1992).

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Survey Task

Methodology

A mailed survey questionnaire approach was used for the survey task. This approach was considered adequate because the survey task (see Appendix I) was deemed to be relatively brief, and there was no need for the respondents to be in a controlled environment. Before the commencement of the survey, several structural engineers were asked to attempt the survey to ensure that there were no obvious ambiguities in the instructions or task design. The survey (with free return postage) was mailed to 300 civil engineers throughout several states in Australia. To encourage participation, the survey respondents were not required to identify themselves.

Task Specification: Task Design

Survey recipients were requested to provide their own (i.e., expert) numerical assessment of the average error rate, and the average and maximum error magnitudes for each specified construction error type. These estimates were requested for the time of the initial engineering inspection, which is an assessment of the work done by the contractor before the inspection. The questionnaire also requested that estimates of the frequency of engineering inspections and their influence on construction errors be provided. Each assessor was asked to record their years of relevant construction site (or supervisory) experience.

The task consisted of ten typical construction error types. Error types considered in the present study are defined as:

- E1 = reduced area of tensile steel (A_{st}): reduced number or size of reinforcing bars.
- E2 = increased area of tensile steel (A_{st}).
- E3 = decreased overall depth (D).
- E4 = increased overall depth (D).
- E5 = decreased effective depth to tensile steel (d): reinforcing bars placed at reduced depth.
- E6 = increased effective depth to tensile steel (d): reinforcing bars placed at increased depth causing a reduction in cover.
- E7 = decreased beam width (B).
- E8 = increased beam width (B).
- E9 = inadequate concrete mix: concrete compressive strength (F'_c) at 28 days is less than specified strength.
- E10 = premature removal of shoring: formwork or shoring removed prior to 12-day period.

Error types E1, E5, E9, and E10 have been shown to be responsible for the majority of failures contributed to construction error (Fraczek 1979). Error types E3, E4, E7, and E8 were included because of their adverse influence on flexural strength or dead load. The remaining error types E2 and E6 are not directly detrimental to flexural strength or dead load, but are still defined as errors because they are a departure from construction tolerances and may, for example, adversely influence durability requirements.

Task Specification: Construction Tolerances

For the survey task, an error is defined as a departure from construction tolerances as specified by the *Australian Concrete Structures Code AS3600.* The specified tolerances, which were provided with the survey sheet, are:

1. Dimension/200 or 5 mm (whichever is greater) for beam width (B) and depth (D);
2. $-10, +5$ mm for effective depth to tensile reinforcing steel (d); and
3. Formwork not to be removed within 12 days of concrete placement.

These tolerances are also similar to those specified by the *Building Code Requirements for Reinforced Concrete ACI 318-83* (*Building* 1986). Naturally, the lower bound of the tolerances for the area of tensile steel (A_{st}) and concrete compressive strength (F_c') are zero deviation from the specification.

Task Specification: Error Rates and Error Magnitudes

Definitions of average error rate and error magnitude (and examples of their estimation) were provided in the survey instructions. An average error rate is the number of errors encountered divided by the total number of inspections for that error type. A list of possible error rates (expressed as fractions or decimal values) was provided in the survey sheet. Swain and Guttman (1983) suggest that error rates less than 5×10^{-5} are unlikely to exist; thus the lowest listed error rate was selected at this level. If an error is evident, the error magnitude (or error consequence) is the size of the error as a percentage of the correct (or specified) outcome. Thus, the error magnitude m_e is defined as

$$m_e = \frac{x - x_m}{x_m} \times 100\% \quad \text{(1)}$$

in which x and x_m = incorrect and correct values, respectively.

Task Specification: Engineering Inspections

In Australia, it is a regulatory requirement that engineering works be inspected and certified by a professional structural engineer at all stages of a project (*Building* 1990). This requirement generally means that the inspecting engineer must certify that the works comply with the relevant sections of the *Australian Concrete Structures Code AS3600* (*Australian* 1988). Similar inspection requirements are also required in other countries; these may either be regulatory (*Quality* 1987) or contractual (McCaffer 1989; Quinn 1984) in nature.

Inspections are typically performed by the design engineer who is familiar with the project and its design, and is therefore more likely to be able to detect deviations from the specifications (Ford 1984). Inspections are also conducted by local government building inspectors (who are not professional engineers); their function is to ensure conformance to nonstructural aspects (e.g., building clearances). In addition, a clerk of works is often appointed by the client for large sites. It is clear that there is some overlap between the duties of the inspecting engineer, local government building inspector, and clerk of works. (A clerk of works is an inspector employed by the building owner.) Nonetheless, it is assumed in the present study that the inspecting engineer is primarily responsible for inspecting the structural works.

In the present study, the term initial inspection refers to the initial visual inspection of the beam dimensions and reinforcement layout prior to the placement of concrete. It is the duty of the contractor to notify the inspecting engineer only when the site is ready to be inspected. If errors are detected, then it is the responsibility of the inspecting engineer to inform the site contractor or their representative (e.g., general foreman) so that corrections may be undertaken. Often these corrections are carried out immediately, while the inspecting engineer is still on-site. However, there are occasions in which the inspecting engineer may return to the site at a later date to check that the incorrect work has been corrected. It is this follow-up inspection that is referred to herein as the second inspection. It is also not uncommon for the engineer to inform the contractor of required corrections, and then not ensure that the errors are in fact corrected (i.e., no second inspection).

In order to quantify the described inspection process, the following three questions were included in the questionnaire, and their responses are referred to herein as A, B, and C, respectively:

1. Occasions when all detected errors are corrected on-site during the initial inspection <u>A</u> %

2. If errors are not corrected immediately:

   (*a*) Occasions when a second inspection is conducted <u>B</u> %

   (*b*) Percentage of initial errors not corrected by the time of a second inspection <u>C</u> %

A flowchart of the decision process involved in an engineering inspection (incorporating information from the survey questions) is given in Fig. 1. The quality of concrete mix and removal of shoring (error types E9 and E10, respectively) cannot be inspected by the inspecting engineer prior to concrete placement.

Analysis of Survey Data

Survey Response

A total of 50 individuals responded to the survey, although some respondents did not fully complete all sections of the survey. For the present study, an expert was defined as an individual with more than five years of professional experience. A total of 41 individuals were therefore classified as experts, and their assessments accepted for the present study. The average experience of the assessors was 17.5 years.

Average Error Rate Data

The analysis of average error rate data in the present section was conducted in accordance with the method described by Seaver and Stillwell (1983). In this method, a single point estimate of the average error rate (or human error probability) HEP_j is obtained by statistically aggregating expert assessments of average error rates

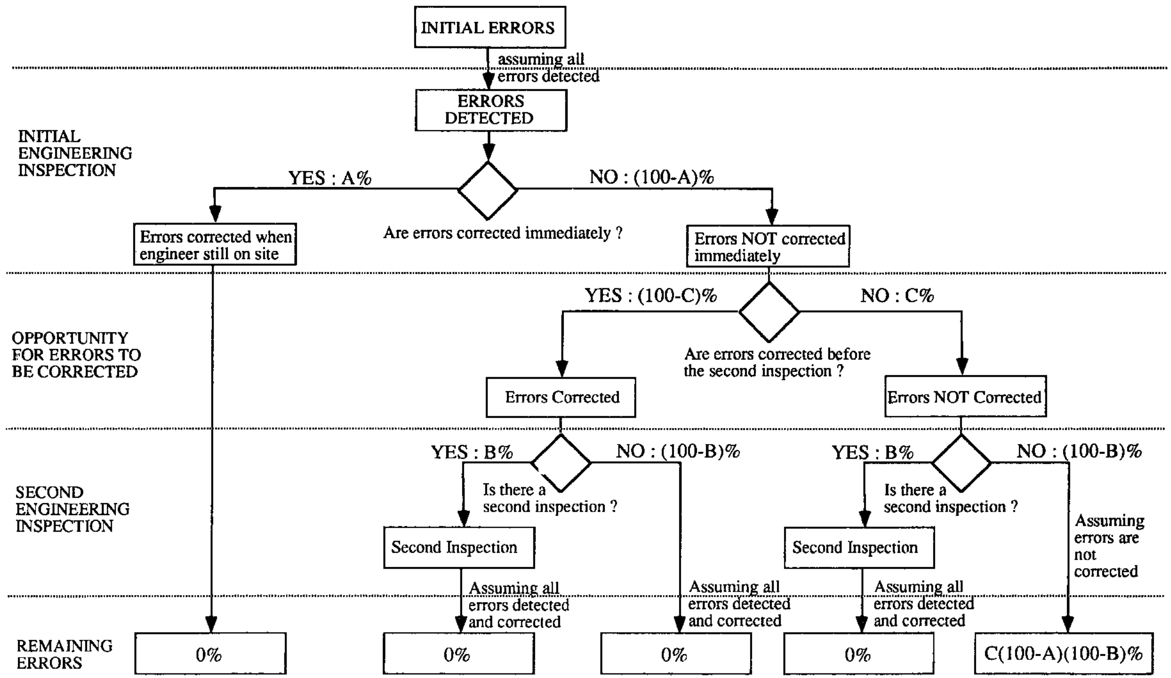

FIG. 1. Flowchart of Engineering Inspection Process

$$HEP_j = \frac{\left(\prod_{k=1}^{n} P_{jk}\right)^{1/n}}{\left(\prod_{k=1}^{n} (1 - P_{jk})\right)^{1/n} + \left(\prod_{k=1}^{n} P_{jk}\right)^{1/n}} \quad (2)$$

in which P_{jk} = recommended average error rate from expert k for error type j; and n = total number of experts. This expression represents the aggregated mean of individual expert judgments. The HEP_j's (and their upper and lower 95% confidence limits—assuming a lognormal distribution) for each error type are shown in Table 1.

The results obtained from the expert judgments will have an enhanced confidence level if there is an interjudge consistency, or agreement of assessments. The analysis of variance (ANOVA) is used to compute the intraclass correlation coefficient (R), which is a measure to assess the degree of consistency among experts (Seaver and Stillwell 1983). It has been shown by Stewart (1991) that the intraclass correlation coefficient among experts within each error type is relatively low (R = 0.12). However, the degree of consistency is statistically significant ($p < 0.01$), thus representing a significant degree of interjudge consistency.

With reference to Table 1, the error rates are highest (approximately 0.02–0.03) for the following tasks: installation of reduced area of tensile steel reinforcement, decreased effective depth to reinforcement, and premature removal of shoring or formwork. This finding suggests that the error types most likely to occur are those that generally result in reduced costs (or savings in time) to the contractor. For example, it is more likely that less steel reinforcing will be installed than it is that more steel reinforcing will be installed.

The observation that the error rate is lowest for inadequate concrete mix (i.e., lower f'_c) may be somewhat misleading). For example, it is unlikely that laboratory results of concrete compressive strengths are known only to the contractor (who is generally the client), and therefore the engineer is often not in a position to make an informed assessment of concrete compressive strengths.

It is not possible to compare the error rates given in Table 1 with other

TABLE 1. Summary Statistics of Error Rate Data (Parameters for Error Rate Model)

	Initial Errors				Errors Remaining After Inspections	
Error type (1)	Lower 95% confidence level (2)	$\tilde{m}_o$ (HEP_j) (3)	Upper 95% confidence level (4)	EF_o (5)	$\tilde{m}_i$ (6)	EF_i (7)
Reduced A_{st}	0.0123	0.0218	0.386	5	0.000373	12.08
Increased A_{st}	0.057	0.0114	0.0227	5	0.000195	12.08
Decreased beam depth	0.0067	0.0125	0.0231	5	0.000214	12.08
Increased beam depth	0.0064	0.0124	0.0242	5	0.000212	12.08
Decreased effective depth	0.0171	0.0296	0.0513	5	0.000506	12.08
Increased effective depth	0.0107	0.0188	0.0330	5	0.000321	12.08
Decreased beam width	0.0045	0.0081	0.0147	3	0.000139	9.00
Increased beam width	0.0044	0.0083	0.0158	3	0.000142	9.00
Inadequate concrete mix	0.0026	0.0049	0.0094	3	0.004900	3.00
Premature removal of shoring	0.0116	0.0271	0.0634	5	0.027100	5.00

studies. To date, comprehensive error rate data has been obtained only for psychomotor and cognitive tasks such as those required for the operation and maintenance of nuclear power and chemical plants (Swain and Guttman, 1983).

Error Magnitude Data

The analysis of the error magnitude data was conducted in a similar manner to the average error rates. The aggregated mean of the expert judgments for the average (BE) and worst (UB) error magnitudes are denoted herein as λ_{BE} and λ_{UB}, respectively, and are shown in Table 2 for all error types. Their upper and lower 95% confidence limits are also shown in Table 2. The values of λ_{BE} and λ_{UB} will later be used as parameters of the lognormal probability distribution of error magnitudes. The intraclass correlation coefficients among the experts were 0.33 and 0.40 for the average worst error magnitude data, respectively (Stewart 1991). This finding again indicates that the degree of interjudge consistency is statistically significant ($p < 0.01$).

It may be observed from Table 2 that the largest λ_{BE} and λ_{UB} values occur for error type E10 (premature removal of shoring). The next largest error magnitudes relate to the installation of additional or reduced tensile steel reinforcing, and a reduction in concrete compressive strength. The error magnitudes for the remaining error types are lower in value, and are of similar size. It is of some concern that the error magnitudes are greatest for error types that most adversely influence flexural strength. This suggests that inspecting authorities should concentrate their attention on those particular error types. In current practice, on-site inspectors generally do place the most importance (and effort) on checking the location and quantity of reinforcement, and concrete quality and the removal of shoring are covered in some detail in codes of practice. This correlation between error types with large assessed error magnitudes and the importance placed by the profession on their control provides some verification of the validity of the collected data.

Engineering Inspection Data

The responses to the three engineering inspection questions were analyzed in a manner similar to that used for the average error rate and error mag-

TABLE 2. Summary Statistics of Error Magnitude Data (Parameters for Error Magnitude Model)

Error type (1)	Average Error Magnitude (BE)			Worst Error Magnitude (UB)		
	Lower 95% confidence level (2)	λ_{BE} (3)	Upper 95% confidence level (4)	Lower 95% confidence level (5)	λ_{UB} (6)	Upper 95% confidence level (7)
Reduced A_{st}	−11.11	−14.30	−18.41	−57.65	−82.22	−100.00
Increased A_{st}	11.08	15.16	20.75	45.29	69.22	100.00
Decreased beam depth	−5.79	−7.68	−10.19	−15.82	−20.49	−26.54
Increased beam depth	4.86	6.62	9.01	14.68	19.53	25.98
Decreased effective depth	−5.44	−7.10	−9.28	−15.14	−21.14	−29.50
Increased effective depth	4.80	6.27	8.19	11.96	16.60	23.04
Decreased beam width	−4.03	−5.24	−6.81	−10.89	−14.54	−19.41
Increased beam width	3.95	5.22	6.89	−12.08	16.52	22.59
Inadequate concrete mix	−7.51	−9.58	−12.22	−28.03	−38.01	−51.56
Premature removal of shoring	−17.78	−22.19	−27.70	−57.03	−73.14	−93.79

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nitude data. Stewart (1991) has shown that there was no significant statistical difference between expert judgments ($p < 0.01$), thus indicating interjudge consistency. The aggregated mean and its upper and lower 95% confidence limits are shown in Table 3, for all three inspection questions.

In response to question A, the respondents indicated that all detected errors were corrected on-site (during the initial inspection) on approximately 48% of occasions. The immediate correction of errors is dependent upon the type of error, effort required to correct the error, and the time remaining before concrete placement. However, the size of the response indicates that a significant proportion of errors are minor and can be rectified (e.g., by adding a reinforcing bar) while the inspecting engineer is still on-site.

If the errors were not corrected immediately under the supervision of the inspecting engineer, then on approximately 47% of occasions a second inspection was conducted. This incidence is also highly dependent upon the type and severity of the error. A minor error may not warrant a second inspection if the contractor (or foreman) has been notified about its existence. On the other hand, the inspecting engineer may conduct a second inspection if the correction of the error was based upon specific detailed instructions, if the error was particularly severe, or if the inspecting engineer was not confident about the overall quality of work on the site. In current practice, it is not uncommon for the inspecting engineer to issue a structural certificate subject to written instructions specifying the occurrence of errors and the need for their correction. Furthermore, a survey respondent commented that the standard fee schedule of an inspecting engineer typically does not allow for multiple inspections, an important factor that limits the incidence of second inspections. This observation is supported by Ford (1984), who suggests that engineers do not negotiate a sufficient fee for inspections.

In response to question C, it was indicated that approximately 6% of initial detected errors were not corrected by the time of a second inspection. In an ideal situation, the percentage of uncorrected errors should equal zero. In an engineering context, it is the duty of the contractor to ensure that the finished work complies accurately with the contract specifications (e.g., construct a reinforced concrete beam according to structural drawings). There can be little justification for not complying to structural drawings or the instructions of the inspecting engineer concerning the correction of errors. However, it has been suggested that poor contractor performance may be due to the changing role of the general foreman (involvement with work sequences and coordinating the various subtrades has overshadowed their supervisory role), poor literacy skills of construction workers, and other factors that influence task performance (Jubelin 1983; Moody 1986). It is beyond the scope of the present paper to investigate these factors.

What happens to the uncorrected errors if a second inspection is not conducted can only be a matter for speculation. Nonetheless, it is unlikely

TABLE 3. Summary Statistics of Inspection Data

Inspection question (1)	Lower 95% confidence level (2)	Aggregated mean (3)	Upper 95% confidence level (4)
A	34.57	47.81	66.12
B	34.80	47.05	63.62
C	4.22	6.20	9.11

that the 6% of remaining errors will be corrected before the placement of concrete. Therefore, if it assumed that these errors are not corrected, then it follows that the proportion of remaining errors after the engineering inspections is $\tilde{m}_{pi}$ = C(100-A)(100-B), see Fig. 1. It can then be computed that the aggregated mean proportion of remaining errors (denoted as $\tilde{m}_{pi}$) will be approximately $0.52 \times 0.53 \times 0.06 \approx 1.7\%$ of the initial average error rate (i.e., 98.3% of errors are corrected); see Table 3. It is this proportion of uncorrected (but previously detected) errors that may be caused by the negligence, thoughtlessness, or ignorance of the contractors. Nonetheless, this is a relatively low proportion of remaining errors, and would tend to suggest that the current engineering inspection processes may be adequate. On the other hand, it has been shown by Stewart (1992) that these remaining errors can lead to significant losses of structural safety.

Finally, it has been assumed herein that the efficiency of error detection is constant for all error types. In practice, however, the inspecting engineer may be more concerned about errors that lead to a loss of flexural strength; thus the checking efficiency may be higher for these critical error types. It should also be emphasized that the inspecting engineer is not the only inspector of structural works; local government building inspectors, clerk of works, and others may detect these uncorrected errors during the process of their involvement with the project. It was also assumed in the present study that all contractor errors are detected by the inspecting engineer; an assumption that may be somewhat optimistic. This is clearly an area for future research.

Modeling Distribution of Error Rates

Initial Errors

It might be expected that the error rate for a specific task will vary from individual to individual. 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 lognormal 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, nuclear power plants ("Reactor" 1975).

The HEP_j values computed from the expert judgments (see Table 1) may be defined as single point best estimates for each error type j. For the present study, the best estimate is used as the median value of the lognormal distribution of error rates. This approach has been recommended by Apostolakis (1982), Swain and Guttman (1983), and others. The use of the median has some basis with experimental psychology, in which assessors tend to bias their estimates of mean values toward the median (Peterson and Miller 1964). Furthermore, the use of the median is conservative, since the mean of the lognormal distribution is always greater than the median.

A distribution of human performance cannot be derived solely from a single point estimate (i.e., median); it is also necessary to derive a measure of dispersion (i.e., variance) for the lognormal distribution. The variance represents the uncertainty that may be due to imprecise knowledge (e.g., variation in the estimate of the median), and the inherent variation of human performance due to differing ability, personal characteristics, 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 variance may be represented by an error factor (EF), which is expressed as

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$$EF = \sqrt{\frac{Pr(F_{90th})}{Pr(F_{10th})}} \quad \text{(3)}$$

in which $Pr(F_{10th}$ and $Pr(F_{90th})$ are the 10th and 90th percentiles, respectively, of the lognormal distribution of human performance (Apostolakis 1982). Hence the standard deviation σ_0 of the lognormal distribution of error rates prior to any engineering inspections is $\ln(EF_0)/1.2817$. General guidelines for estimating an error factor have been provided by Swain and Guttman (1983) for operator tasks in nuclear power plants conducted under routine circumstances (and assuming interjudge consistency among the experts), see Table 4. In the absence of other guidelines, it is proposed that the error factors given in Table 4 be applied to the tasks considered in the present study. A distribution of error rates for error type E1 (reduced area of tensile reinforcement) is shown in Fig. 2, for the parameters given in Table 1.

Errors Remaining after Engineering Inspections

It is now of interest to examine the influence of engineering inspections on the distribution of error rates. In other words, this section refers to the errors that are included in the finished work. The aggregated mean of the proportion of remaining errors ($\tilde{m}_{p_i}$) not corrected after inspections was obtained from the survey data (Table 3). The proportion of remaining errors may be represented as a lognormal distribution to indicate variation in quality control across all construction sites. It has been shown in the present paper that $\tilde{m}_{p_i}$ = (100-A)(100-B)C (i.e., the product of the three engineering inspection survey responses). Thus, the standard deviation σ_{p_i} is

$$\sigma_{p_i} = \frac{\ln(EF_{p_i})}{1.2817} = \sqrt{\frac{\{\ln(EF_{100\text{-A}})\}^2 + \{\ln(EF_{100\text{-B}})\}^2 + \{\ln(EF_C)\}^2}{1.2817^2}} \quad \text{(4)}$$

in which $EF_{100\text{-A}}$, $EF_{100\text{-B}}$, and EF_C = error factors for responses A, B, and C, respectively. If it is assumed that $EF_{100\text{-A}} = EF_{100\text{-B}} = EF_C = 3.0$, then it follows that $\sigma_{p_i} = 1.48$ (i.e., $EF_{p_i} = 6.70$). It then follows that the median $\tilde{m}_i$ and standard deviation σ_i of the distribution of error rates for errors remaining after the engineering inspections are

$$\tilde{m}_i = \tilde{m}_o \times \tilde{m}_{p_i} \quad \text{(5)}$$

$$\sigma_i = \sqrt{\sigma_o^2 + \sigma_{p_i}^2} \quad \text{(6)}$$

respectively. Table 1 shows the computed values for these parameters, for all error types E1 to E8. For example, the distribution of error rates prior to and after initial engineering inspections for error type E1 is shown in Fig. 2.

It is observed that the best estimate error rates of errors remaining after the engineering inspections is relatively low. However, the error rate for

TABLE 4. Guidelines for Estimating Error Factor

Estimated HEP_i (1)	Error factor (EF) (2)
<0.001	10
0.001 to 0.01	3
>0.01	5

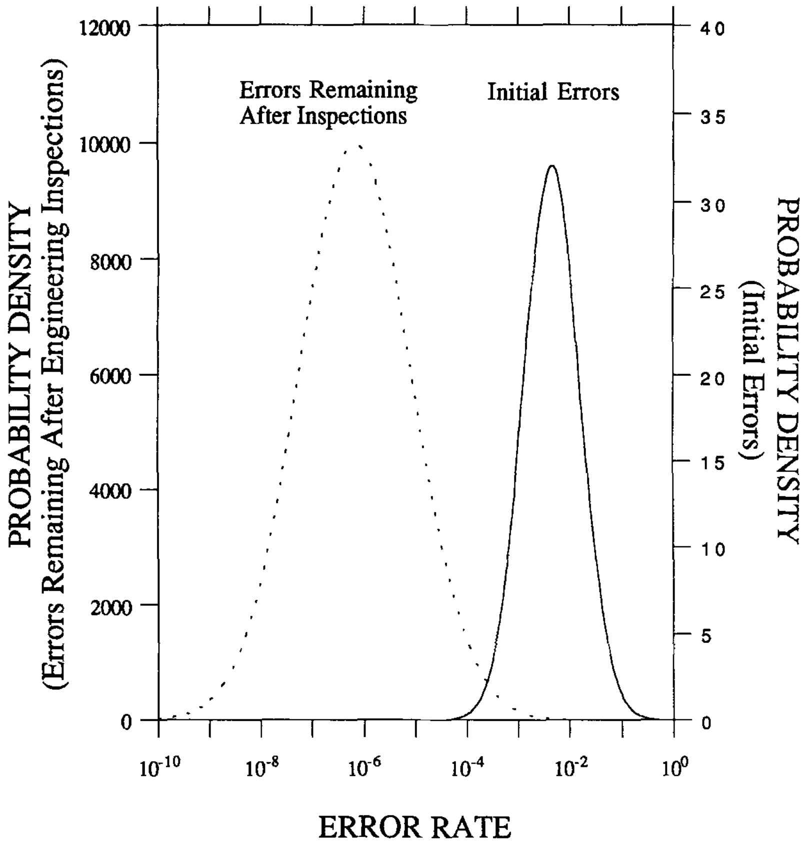

FIG. 2. Distribution of Error Rates for Error Type E1

an individual may vary above or below this value. With reference to Fig. 2, for example, the distribution of error rates for an individual after inspections varies from 10^{-10} to 10^{-2}. It is the high error rates, albeit with a low probability of occurrence, that significantly influence structural reliability (Stewart 1992).

Modeling Distribution of Error Magnitudes

The distribution of error magnitudes for each error type is derived in a manner not dissimilar to the methodology adopted for error rates. It has been stated previously that the lognormal distribution is recommended for modeling human performance data. For this reason, the distribution of error magnitudes will also be modeled by the lognormal distribution. The lognormal distribution of error magnitudes m_e is computed by using the best estimate λ_{BE} as the median, and the maximum estimate λ_{UB} as the 90th percentile upper bound; thus the standard deviation σ_{me} of the lognormal distribution is $\ln(\lambda_{UB}/\lambda_{BE})/1.2817$. Note that $-100 \leq m_e \leq 0$ for error types E1, E3, E5, E7, E9, and E10, and $0 \leq m_e \leq \infty$ for error types E2, E4, E6, and E8. This is a censored distribution at $m_e = -100\%$ for error types that can result in an error of omission. This is an important consideration, because approximately 30% of survey respondents indicated that the worst error magnitude that they had witnessed was the omission of tensile steel reinforcing (error type E1), and 5% responded that zero concrete compressive strength (error type E9) was the worst. It may also be necessary to truncate the proposed distributions at error magnitudes equivalent to the maximum or minimum allowable construction tolerances or at other realistic maximum or minimum values (e.g., formed beam depth must be greater than, say, 100 mm). A distribution of error magnitudes is shown in Fig. 3, for error types E1 and E2 (area of reinforcing steel). The statistical uncertainties of the parameters λ_{BE} and λ_{UB} are considered to be not statistically significant due to interjudge consistency, and are thus ignored.

It has been reported by Stewart and Melchers (1989b) that the effectiveness of design checking is dependent upon the size of the error. It is likely

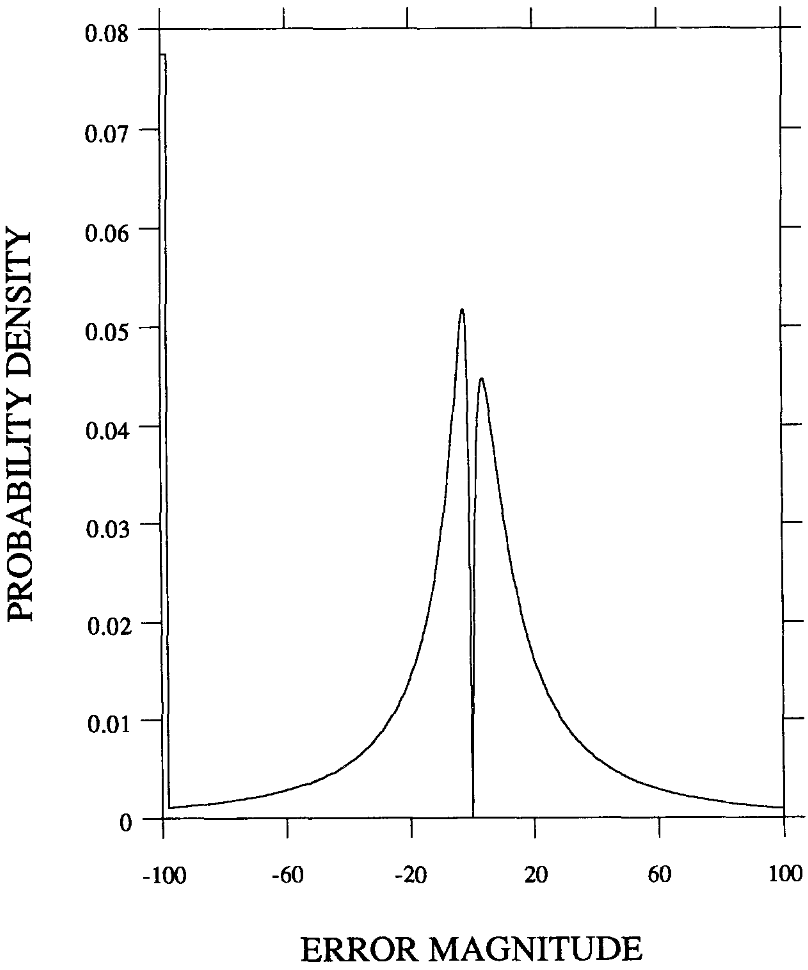

FIG. 3. Distribution of Error Magnitudes for Error Types E1 and E2

that this observation is relevant to the inspection of construction tasks. For example, it may be that larger errors are detected more often than smaller errors, hence the distribution of error magnitudes would be more skewed to lower error magnitudes as a result of engineering inspections. However, in the absence of any appropriate quantitative information, it is simply assumed that the distribution of error magnitude will remain unchanged after the detection and correction of errors.

Analysis

The relative advantages and disadvantages of the survey methodology (i.e., direct numerical estimation procedure) have been fully described by Seaver and Stillwell (1983). In summary, the expert assessors were not judging their own performance, but the performance of contractors. It might therefore be expected that the reported assessments are less biased than if the contractors assessed their own performance. Furthermore, Seaver and Stillwell (1983) suggest that the direct numerical estimation procedure is appropriate with as few as six expert assessors. Significantly more expert assessors were used in the present study, indicating that the reported observations should have reduced statistical uncertainty due to the reduced sampling error. It is also to be expected that some of this uncertainty is unavoidable due to variation in workmanship and performance across all construction sites.

The major disadvantage of the direct numerical estimation procedure is that estimating a precise numerical value for a given task or event likelihood (e.g., error rate) is subjective. For example, it might be expected that it is generally difficult to visually observe small dimensional variations. It is also unlikely that inspecting engineers would directly measure with a tape measure beam width, beam depth, or effective depth to reinforcing. However, in the present study, it was shown that the expert assessments displayed sufficient interjudge consistency to enable the analysis of their estimates to proceed with some confidence. Nonetheless, the results described herein and the interpretations made should be seen as preliminary. Finally, results similar to those reported were obtained when the definition of expert was increased from five to ten years of experience.

Conclusion

Survey data and probabilistic models for the distribution of error rates and error magnitudes have been described for ten typical reinforced concrete construction tasks. An investigation into the frequency of initial and subsequent (or follow-up) on-site engineering inspections and their influence on construction errors was also conducted. It was found that errors are most likely to occur in tasks that are more detrimental to structural performance. The process of engineering inspections was shown to reduce the initial on-site construction error content by approximately two orders of magnitude. It was noted that the results are indicative, and subject to some statistical uncertainty.

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APPENDIX I. SURVEY

The following is a facsimile of the error rate page of the survey used in this paper.

ON COMPLETION OF TASK—PLEASE RETURN IN THE REPLY PAID ENVELOPE

Survey Task

The project for which the information is sought is concerned with the occurrence rate and relative magnitude of errors in the construction of a typical reinforced concrete beam (e.g., a floor beam). Typical error types are listed in the Table (see over). For the present task, an error is defined as a departure from construction tolerances as specified by AS3600 (see attached sheet).

I will assume that your judgment is based on your personal experience; for this reason, it is understood that your estimates will be subjective and subject to some uncertainty. Anonymity is assured since neither name nor business affiliation of the respondent is required.

For each error type, you are asked to estimate the following:

$$\text{Error Rate} = \frac{\text{number of errors}}{\text{total number of inspections}}$$

(may be expressed as a fraction or decimal value)

For example, an error rate of 0.001 (or 1/1,000) denotes one error seen for every 1,000 inspections. Error rates may vary from 0.0 ("error-free") to 1.0; however, it is unlikely that observed error rates will coincide with either of these extreme values. A list of possible error rates is provided on the survey sheet.

$$\text{Error Magnitude} = \frac{(\text{error outcome} - \text{correct outcome}) \times 100\%}{\text{correct outcome}}$$

For example, if the depth of a slab is incorrectly formed to 100 mm when it should be 125 mm; this represents an error magnitude of $[(100-125)/125] \times 100 = -20\%$. Likewise, if 4Y20 bars are installed instead of the specified 6Y20 bars, then the error magnitude is $[(4-6)/6] \times 100 = -33\%$.

(i) *Average Error Magnitude*: An average (or typical) error magnitude you would expect for each error type.

(ii) *Maximum Error Magnitude*: The maximum (or worst) error magnitude that you have witnessed for each error type.

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Appendix III. Notation

The following symbols are used in this paper:

A_{st} = cross-sectional area of reinforcing steel;
B = beam width;
BE = average error magnitude;
D = beam depth;
d = effective depth to steel reinforcing;
EF = error factor;
EF_o = error factor for distribution of initial error rates;
EF_{pi} = error factor for distribution of proportion of remaining errors;
F'_c = concrete compressive strength;
HEP_j = human error probability (i.e., error rate) for error type j;
j = error type j = 1, 10;
k = expert designation k = 1, n;
m_e = error magnitude;
$\tilde{m}_i$ = median of distribution of errors remaining after engineering inspections;
$\tilde{m}_o$ = median of the distribution of initial error rates;
$\tilde{m}_{pi}$ = aggregated mean proportion of remaining errors [= C(100-A)(100-B)];
n = number of experts;
$Pr(F_{10\text{th}})$ = 10th percentile of distribution of human performance;
$Pr(F_{90\text{th}})$ = 90th percentile of distribution of human performance;
P_{jk} = assessment from expert k for error type j;
R = intraclass correlation coefficient;
UB = worst error magnitude;
x = incorrect value;
x_m = correct value;
λ_{BE} = aggregated mean of expert judgments for average (BE) error magnitude;
λ_{UB} = aggregated mean of expert judgments for worst (UB) error magnitude;
σ_i = standard deviation of distribution of errors remaining after engineering inspections;
σ_o = standard deviation of distribution of initial error rates;
σ_{me} = standard deviation of distribution of error magnitudes; and
σ_{pi} = standard deviation of distribution of proportion of remaining errors.