A Risk-Informed Approach to the Assessment of DHC Initiation in Pressure Tubes

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Abstract

The delayed hydride cracking (DHC) of pressure tubes is a serious form of degradation in the reactor core. Flaws in pressure tubes generated by fretting or any other mechanism are potential stress raisers that could become sites of DHC initiation under right circumstances. CSA standard N285.8 recommends deterministic and probabilistic procedures for the assessment of potential for DHC initiation from planar flaws. The deterministic method is simple, but it lacks a risk-informed basis for the assessment. A full probabilistic method based on simulations is tedious to implement. This paper presents an innovative, semi-probabilistic method that bridges the gap between a simple deterministic analysis and complex simulations. In the proposed method, the deterministic assessment criterion of CSA N285.8 standard is calibrated to specified target probabilities of DHC initiation using the concept of partial factors. The main advantage of the proposed approach is that it provides a practical, risk-informed basis for DHC initiation assessment while retaining the simplicity of the deterministic method.

1. Introduction

A CANDU reactor core consists of 380-480 fuel channels. Each fuel channel consists of a pressure tube (PT) made of Zr-2.5%Nb alloy, enclosed in a calandria tube (CT) along with annulus spacers and end fittings. The growth of crack-like defects in a PT through delayed hydride cracking (DHC) is a serious degradation mechanism [1, 2] with potential to compromise the structural integrity of PT. Therefore, assessment of flaw type defects is given high priority in the fitness for service assessment of PTs.

If part-through-wall flaws are suspected in the reactor core, the DHC initiation assessment is required to access the likelihood of crack initiation and growth. The assessment is important especially when the hydrogen equivalent concentration in the PT is expected to exceed a threshold level that makes the Zr-alloy susceptible to DHC [1, 2]. From fracture mechanics point of view, the DHC initiation is avoided so long as the applied stress intensity factor (K_I) remains less than a critical value (K_{IH}) that reflects resistance of the material to DHC initiation.

Planar flaws, such as fretting flaws, can be detected through the inspection of a small number of PTs. Since the dimensions of detected flaws are known from inspection, the DHC initiation assessment for these flaws can be done with high precision or certainty. A key concern is about the prospect of DHC initiation due to un-detected flaw population in PTs that are not inspected. To provide assurance against DHC initiation in this situation, both deterministic and probabilistic methods have been specified in the CSA standard N285.8 [3].

The deterministic method of CSA N285.8 is based on comparing the upper bound applied stress intensity factor (K_I^{UB}) with the lower bound of DHC initiation toughness (K_{IH}^{LB}). To compute the upper bound value of K_I, upper bounds of flaw dimensions (a and c) are proposed, which correspond to 97.5% percentiles of a and c obtained from their respective probability distributions [3, Clause C.3.2.2.2]. The protection against DHC is demonstrated when it is shown that $K_I^{UB} < K_{IH}^{LB}$ in a bounding PT. A formal probabilistic method for DHC assessment is able to account for uncertainties associated with flaw dimensions and material properties. Here, the basic idea is to demonstrate that the probability of DHC initiation from a part-through-wall flaw is sufficiently low. This method requires probability distributions of all random variables, and it typically employs a simulation-based method for computing the probability of DHC initiation.

Although the deterministic method is based on sound engineering experience, it lacks a quantitative risk-informed basis. On the other hand, the simulation-based probabilistic method is tedious to implement due to its information-intensive and computationally demanding nature. The objective of this paper is to present an innovative, semi-probabilistic approach that bridges the gap between a simple deterministic analysis and complex probabilistic simulations. The proposed method is a probabilistic conversion of the deterministic DHC initiation assessment method by incorporating partial factors that are calibrated to an acceptable probability of DHC initiation. This approach is similar to the load and resistance factor design (LRFD) used for civil engineering structures [4, 5].

The paper is organized as follows. Section 2 summaries the deterministic DHC initiation assessment for planar flaws, as described in the CSA standard N285.8 [3]. The concepts of reliability-based calibration and partial factors are discussed in Section 3. Probabilistic formulation of DHC initiation assessment and calibration of partial factors are presented Section 4. Conclusions of this study are presented in Section 5.

2. Deterministic DHC initiation assessment

2.1 Method

The goal of the deterministic DHC initiation assessment approach is to demonstrate that in the event of the presence of a part-through-wall flaw and sufficient hydride concentration, DHC initiation from a part-through-wall flaw is avoided.

The deterministic criterion for DHC initiation from a planar flaw is given as

$$K_I^{UB} > K_{IH}^{LB} \tag{1}$$

The stress intensity factor (K_I) for an axial part-through-wall planar flaw located far away from the rolled joint is given in Clause A.5.2.2.2 of CSA N285.8 [3] as

$$K_I = \left[p\left(\frac{r_i}{w}+1\right)F_P\right]\sqrt{\frac{\pi a}{Q}} \tag{2}$$

where p = internal pressure in the PT in MPa, r_i = internal PT radius, w = PT wall thickness, Q = flaw shape parameter given by $Q = 1 + 1.464(a/c)^{1.65}$, a = flaw depth, c = half flaw length, F_P = geometry correction factor under the pressure loading. Depending on the range of a/c and a/w, different equations are given in Clause A.5.2.2.4 of CSA N285.8 [3] for computing F_P.

To compute the upper bound value of K_I using Eq. 2, upper bounds of flaw dimensions (a and c) are required, which correspond to 97.5% percentiles of a and c obtained from their respective probability distributions [3, Clause C.3.2.2.2]. The lower bound value of K_{IH} is given in Section D.6.2 of CSA N285.8 [3] as

$$K_{IH}^{LB} = 4.5\ MPa\sqrt{m} \tag{3}$$

The deterministic approach is further illustrated through an example in the following subsection.

2.2 Illustration

Consider the following dimensions of the PT: r_i = 52.73 mm and w = 3.8 mm. The operating pressure at full power is taken as p = 8.9 MPa. The empirical distributions of planar flaw dimensions (a and $2c$) are shown in Fig. 1, which were obtained from a sample of debris fretting flaws in a reactor core. The flaw dimensions can be fitted reasonably well with log-normal distribution. The DHC initiation toughness (K_{IH}) can be modelled as a normally distributed random variable. The distribution parameters are provided in Table 1.

Table 1 Probability distribution of flaw dimensions and K_{IH}

Variable	Distribution	Mean	Standard dev.	COV
a (mm)	Lognormal	$\mu_a = 0.1743$	$\sigma_a = 0.0761$	$\delta_a = 0.4364$
c (mm)	Lognormal	$\mu_c = 1.1669$	$\sigma_c = 0.4067$	$\delta_c = 0.3485$
K_{IH} (MPa$\sqrt{m}$)	Normal	$\mu_{K_{IH}} = 6.62$	$\sigma_{K_{IH}} = 0.911$	$\delta_{K_{IH}} = 0.1376$

The 97.5% percentiles or upper bound values of flaw dimensions are computed as a_{UB} = 0.3621 mm and c_{UB} = 1.6968 mm. Using these values, we compute, a_{UB}/c_{UB} = 0.2134 and a_{UB}/w = 0.0953. The expression for geometry factor for the range of $[0 \le a/c \le 1.0]$ and $a/w \cong 0$ is given as [3, Clause A.5.2.2.4.3]

$$F_P = \frac{2wr_o}{r_o^2 - r_i^2}\left(1.13 - 0.07\sqrt{a/c}\right) \tag{4}$$

where $r_o\left(= r_i + w\right)$ is the PT outer radius. By substituting appropriate parameters in Eq. 4 and Eq. 2, we compute F_P = 1.1358, which then lead to the upper bound stress intensity factor as

$$K_I^{UB} = 0.5398 \times p \tag{5}$$

At full power operating condition (p = 8.9 MPa), the upper bound K_I (= 4.80 MPa$\sqrt{m}$) is slightly greater than the lower bound K_{IH} (4.5 MPa$\sqrt{m}$) as shown in Fig. 2. Hence, the deterministic DHC initiation criterion is not satisfied.

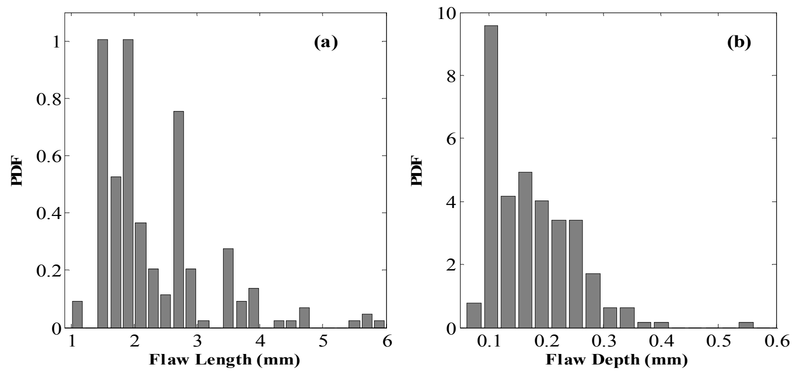

Figure 1 Sample distributions of (a) flaw length and (b) flaw depth

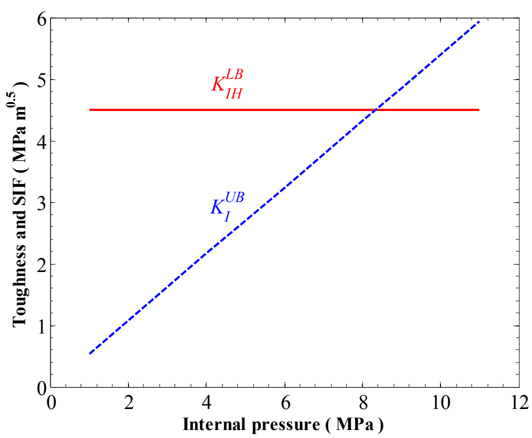

Figure 2 Illustration of deterministic DHC initiation assessment

2.3 Remarks

Although the deterministic assessment is attractive due to its simplicity, its interpretation in the context of modern risk-informed regulatory framework is ambiguous. The deterministic assessment has basically binary outcomes, '*acceptable*' (Safe) or '*not acceptable*' (Fail), with no reference to associated conservatism or safety level. In reality, the associated variables a and c are distributed quantities or random variables. Because of this, estimates of K_I is necessarily a distributed quantities. The deterministic assessment criterion compares the lowers bound K_{IH} with upper bound K_I which is computed using heuristically assigned percentiles to a and c. Therefore, this comparison does not provide any risk insight. In other words, even if the deterministic condition is satisfied i.e. $K_{IH}^{LB} > K_I^{UB}$, the implied reliability level is unknown, because the current deterministic criterion is not formally calibrated to a specific reliability level. The method proposed in this paper, based on the concept of reliability-based calibration, overcomes this limitation.

3. Concept of reliability-based calibration

As an alternative to a fully probabilistic approach for quantifying reliability, a deterministic equation can be developed for design or assessment of structural components. In this equation, all random variables are replaced by their specific percentile values that are determined for a specified reliability level. This can be explained further by considering a simple stress (*S*) strength (*R*) reliability problem, in which the failure condition is defined by the limit state function: $G(R,S) = R - S$. The failure event is: $G(R,S) \leq 0$. Consider a standard case in which *R* and *S* are independent, normally distributed random variables with means μ_R and μ_S, standard deviations σ_R and σ_S. The coefficient of variations (COVs) of *R* and *S* given by, $\delta = \sigma/\mu$, are δ_R and δ_S respectively. The probability of failure can be computed [4, 5] as

$$P_f = P[G(R,S) \leq 0] = P[(R-S) \leq 0] = \Phi(-\beta) \tag{6}$$

where Φ is the standard normal cumulative distribution function and β is the reliability index given as

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{7}$$

The reliability index can be rewritten in terms of non-dimensional variables as

$$\beta = \frac{\lambda - 1}{\sqrt{\delta_R^2 \lambda^2 + \delta_S^2}} \tag{8}$$

where $\lambda\left(= \mu_R/\mu_S\right)$ is known as central safety factor.

The basic idea behind the reliability-based design is to replace random variables in the limit state function by their factored nominal values in terms of partial factors. Partial factors are scaling factors that scale the nominal values of the random variables to the design point coordinates [4, 5]. For illustration, the nominal values of strength and stress variables are taken as their mean values. The partial factors for target reliability index β_T are then derived as

$$\gamma_R = \frac{r^*}{\mu_R} = 1 - \frac{\delta_R^2 \beta_T}{\sqrt{\delta_R^2 + \left(\delta_S/\lambda\right)^2}}, \quad \gamma_S = \frac{s^*}{\mu_S} = 1 + \frac{\delta_S^2 \beta_T}{\sqrt{\delta_S^2 + \left(\delta_R \lambda\right)^2}} \tag{9}$$

As shown in Eq. 9, a partial factor is a function of COVs and the central safety factor λ and is invariant to the mean values of random variables. For given COVs and a target reliability index β_T, substituting the value of λ used in Eq. 8 into Eq. 9 allows the calibration of partial factors. Using partial factors the limit state equation can be written as

$$g(R,S) = \gamma_R \mu_R - \gamma_S \mu_S = 0 \tag{10}$$

The partial factors are pre-calibrated such that a system satisfying Eq. 10 would achieve a target reliability index of β_T. Then $\gamma_R \mu_R$ and $\gamma_S \mu_S$ can be considered as the probabilistic bounds of *R* and *S*, respectively. Eq. 10 provides a basis for design, i.e. the calculation of μ_R for a specified μ_S, or vice-versa. This approach is referred to as LRFD in structural engineering [4, 5]. It is preferable compared to a full probabilistic analysis, since it retains the simplicity of the deterministic design yet at the same time satisfies a quantitative reliability target. The process of calibration of partial factors is exact for limit state functions involving linear combinations of normally distributed random variables. In case of nonlinear limit states and non-normal random variables, approximate methods have been developed [4]. This approach has been applied to nuclear piping [6], containment structures [7], concrete columns [8], welded offshore structures [9], and recently to leak-before-break assessment [10].

4. Probabilistic formulation of DHC initiation analysis

In principle, the probability of DHC initiation event (C_{in}) can be estimated as

$$\mathrm{P}[C_{in}] = \mathrm{P}[C_{in}|H] \times \mathrm{P}[H] \tag{11}$$

where *H* denotes the event that the hydrogen concentration is sufficiently high to allow DHC initiation.

The CANDU industry has developed detailed, full-scale simulation models in which flaws and the hydrogen content (H_{eq}) are simulated for each PT in the reactor core. Then DHC initiation is assessed for each simulated flaw, when H_{eq} exceeds a threshold. By repeating flaw simulations for a large number of times, the probability of DHC initiation in a specified operating period is computed.

This section describes a simpler approach. First, the conditional probability of DHC initiation $\mathrm{P}[C_{in}|H]$ can be computed using first order reliability (FORM) method [4, 5]. Secondly, the probability of hydrogen content exceeding a threshold, $\mathrm{P}[H]$, can be estimated from the hydrogen uptake model for a specific reactor. The probability of DHC initiation can be finally computed from Eq. 11. The proposed approach is simplified by recognizing that the hydrogen uptake process is independent of the flaw generation mechanisms. Thus, the DHC assessment can be based on only conditional probability of initiation $\mathrm{P}[C_{in}|H]$.

4.1 General approach

The conditional probability of DHC initiation given the occurrence of *H*, $\mathrm{P}[C_{in}|H]$, can be written as

$$\mathrm{P}[C_{in}|H] = \mathrm{P}[K_{IH} - K_I \leq 0] \tag{12}$$

The applied stress intensity factor is a function of random flaw dimensions. The DHC initiation toughness (K_{IH}) is also a random variable due to variability associated with the microstructure of alloy. To compute the conditional probability of DHC initiation given in Eq. 12, a limit state function is introduced as

$$G(K_{IH}, a, c) = K_{IH} - K_I(a, c) \tag{13}$$

Note that $G(K_{IH}, a, c) \leq 0$ defines the event of DHC initiation.

Now we present an analytical formulation of the limit state function. Substituting for F_P from Eq. 4 into Eq. 2 results in the following expression for applied stress intensity factor

$$K_I(a, c) = p\,\frac{2\;w\;r_o}{r_o^2 - r_i^2}\left(\frac{r_i}{w} + 1\right) f(a, c) \tag{14}$$

where $f(a, c)$ is a function of random variable *a* and *c* given as

$$f(a, c) = \left(1.13 - 0.07\sqrt{\frac{a}{c}}\right)\sqrt{\frac{\pi\;a}{1 + 1.464(a/c)^{1.65}}} \tag{15}$$

In order to apply a semi-analytical method of reliability computation, the function $f(a, c)$ is fitted with a more simple linear functional relation given as

$$f(a, c) = 0.0135 + 0.0828 \times a - 0.0013 \times c \tag{16}$$

Figure 3 shows that the linear form of $f(a, c)$ given by Eq. 16 is a highly accurate approximation of the analytical relation Eq. 15. Using Eqs. 14 and 16, the limit state function for DHC initiation (Eq. 13) can be written as

$$G(K_{IH},\, a,\, c) = K_{IH} - d_I \times (0.0135 + 0.0828\,a - 0.0013\,c) \tag{17}$$

where d_1 is a deterministic design constant given as

$$d_1 = p\,\frac{2\;w\;r_o}{r_o^2 - r_i^2}\left(\frac{r_i}{w} + 1\right) \tag{18}$$

For sake of illustration, Fig. 4 compares the distributions of K_{IH} and K_I at full power operating condition, which were obtained by simulation. An overlap between the two distributions implies that there is a finite probability of DHC initiation. The probability of DHC initiation was computed by FORM method using the limit state function Eq. 17. At the full power operating condition (*p* = 8.9 MPa), the probability of DHC initiation is estimated as 1.494×10^{-2} and other details including design points and sensitivity coefficients are given in Table 2. The design points represent the most likely combination of flaw dimensions and K_{IH}

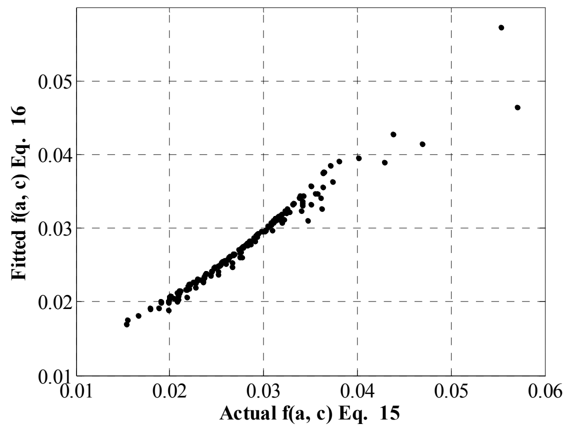

Figure 3 Linear regression fitting of function $f(a,c)$

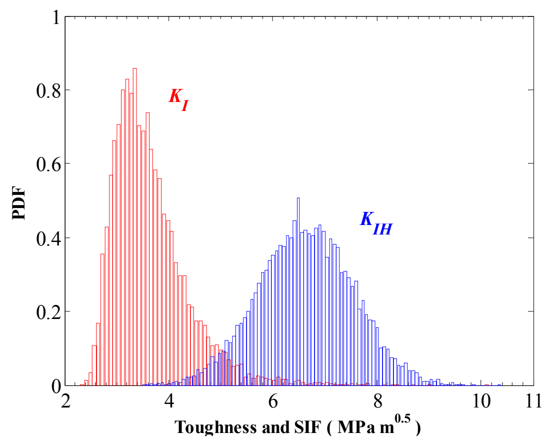

Figure 4 Distributions of K_{IH} and K_I (p = 8.9 MPa)

Table 2 Results of $\mathrm{P}[C_{in}|H]$

Failure Probability	1.494×10^{-2}
Design point, a^*	0.354 mm
Design point, c^*	1.075 mm
Design point, k^*_{IH}	5.677 MPa$\sqrt{}$m
a^* percentile	97.18 %
c^* percentile	47.06 %
k^*_{IH} percentile	15.02 %
Sensitivity coefficient, α_a	0.8783
Sensitivity coefficient, α_c	-0.0340
Sensitivity coefficient, $\alpha_{k_{IH}}$	-0.4769

that would result in DHC initiation and can be interpreted as the probabilistic bounds of the variables. Table 2 gives the design point values of the random variables as: k^*_{IH} = 5.67, a^* = 0.354 mm and c^* = 1.075 mm. The FORM analysis also provides sensitivity of a random variable to the probability of DHC initiation. For example, the flaw depth has the highest influence (sensitivity coefficient α_a = 0.87), followed by that of K_{IH} . It is interesting that flaw length has fairly small influence (α_c = -0.03).

4.2 Proposed DHC initiation assessment model

The following equation is proposed for the assessment of DHC initiation due to planar flaws:

$$G_{DHC}(\mu_{K_{IH}}, \mu_{K_I}) = \gamma_{K_{IH}}\ \mu_{K_{IH}} - d_1\ (0.0135 + 0.0828\ \gamma_a\mu_a - 0.0013\ \gamma_c\mu_c) \qquad (19)$$

where d_1 is a design constant defined in Eq. 18.

This equation is developed by incorporating the partial factors associated with random variables into the limit state equation for DHC initiation (Eq. 17). Partial factors associated with random variables a, c and K_{IH} are denoted as γ_a, γ_c, and $\gamma_{K_{IH}}$, respectively.

The probability distributions given in Table 1 are used to calibrate the partial factors. Note that an "acceptable" value of probability of DHC initiation is not specified in the literature. Therefore, partial factors were calibrated to the conditional probability of initiation in a range of 10^{-2} to 10^{-4}. Results of calibration are presented in Fig. 5. Additional information including design points are presented in Table 3.

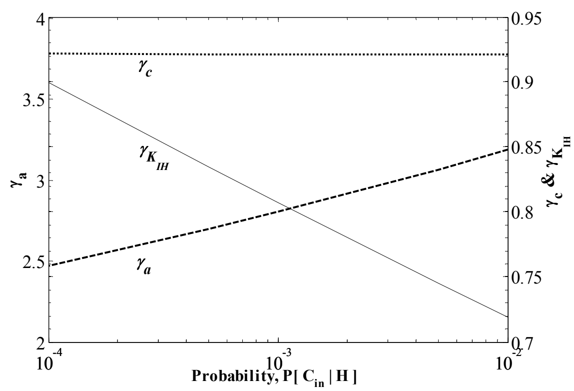

Figure 5 Partial factors versus target conditional probability of DHC initiation

Table 3: Results of calibration of partial factors

$P[C_{in}\|H]$	a^*	c^*	k^*_{IH}	$a^*\%$	$c^*\%$	$k^*_{IH}\%$	γ_a	γ_c	$\gamma_{K_{IH}}$
10^{-2}	0.375	1.074	5.613	97.96%	47.03%	13.46%	2.153	0.921	0.848
10^{-3}	0.499	1.074	5.297	99.68%	47.02%	7.32%	2.861	0.921	0.800
10^{-4}	0.628	1.076	5.020	99.95%	47.15%	3.95%	3.601	0.922	0.758

4.3 Discussion

As shown in Table 3, the partial factor for flaw depth (a) increases rapidly from 2.153 to 3.601 and the probabilistic bound varies from 97.96% to 99.95% percentile as the target probability is increased from 10^{-2} to 10^{-4}. For target probability 10^{-2} the probabilistic bound for a corresponds to 97.96% of the distribution which is fairly close to 97.5% percentile as specified in CSA N285.8 [3].

The partial factor for half flaw length (c) is almost a constant (= 0.92) irrespective of the probability level. The percentile level of the probabilistic bound is also a constant at 47%. The probabilistic bound is almost equal to median of half flaw length (c), whereas CSA N285.8 [3] specifies 97.5% percentile as an upper bound.

The partial factor for K_{IH} varies in a relatively narrow range, 0.9 to 0.7, and corresponding percentile levels vary from 13% to 4%. The probabilistic lower bound for K_{IH} varies from 5.02 to 5.613 ($\mathrm{MPa}\sqrt{\mathrm{m}}$), which is somewhat higher the lower bound 4.5 $\mathrm{MPa}\sqrt{\mathrm{m}}$ specified in CSA N285.8 [3]. The CSA lower bound corresponds to 1% percentile of K_{IH} distribution with parameters given in Table 1.

In the present context, the specified target probability serves as a conservative upper bound. The reason is that the target probability in the current analysis is a conditional probability ($\mathrm{P}[C_{in}|H]$), which does not account for the probability of presence of sufficient hydrogen concentration. Thus, $\mathrm{P}[C_{in}|H] < \mathrm{P}[C_{in}]$, as $\mathrm{P}[H] < 1$.

4.4 Effect of COV of flaw dimensions

The partial factors given in Table 3 and Fig. 5 were calibrated for a specific set of COVs of flaw depth and half length: δ_a= 0.4364, δ_c= 0.3485. It is however possible that flaw samples collected from different reactors may have COV values different than that used in the present calibration. Therefore, the sensitivity of COVs of flaw dimensions to partial factors is investigated in this section. Note that the COV of K_{IH} ($\delta_{K_{IH}}$= 0.1376) is considered as a constant, as it reflects the variability associated with toughness of Zr alloy.

It is found that the partial factors γ_a and $\gamma_{K_{IH}}$ are insensitive to the COV of flaw half length c (δ_c). This statement is also supported by the fact that the flaw length has fairly small influence on the DHC initiation probability, since the sensitivity co-efficient (Table 2) associated with c is very small (α_c= -0.03). The COV of flaw depth has major influence on γ_a, as shown by results given in Fig. 6 for a target conditional probability of DHC initiation of 10^{-2}. The factor $\gamma_{K_{IH}}$ varies modestly from 0.7 to 0.9 and γ_a varies from 1 to 2.5 as the COV of a is increases from 0.1 to 0.5. The factor γ_c depends on the COV of c and a, and it varies from 0.98 to 0.8 for different COV values. A detailed table of calibrated partial factors can be prepared to support DHC assessment.

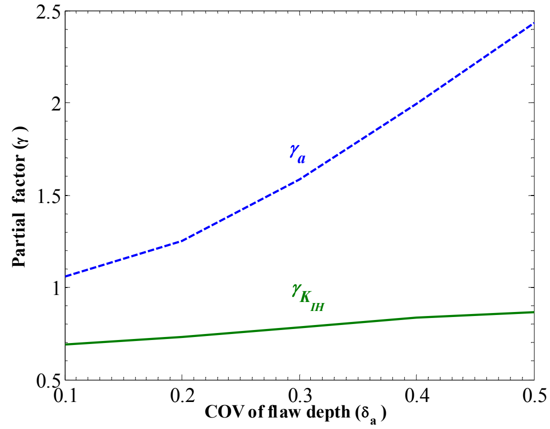

Figure 6 Partial factors γ_a and $\gamma_{K_{IH}}$ for a target conditional probability of 10^{-2}.

5. Conclusions

This paper presents a new innovative semi-probabilistic method for flaw assessment in which the deterministic DHC initiation criterion of CSA Standard N285.8 is calibrated to a target probability using the concept of partial factors. The main advantage of the proposed approach is that it retains the simplicity of deterministic method, yet it provides a practical risk-informed basis for the DHC initiation assessment. This paper formulates the limit state function for DHC initiation assessment and computes partial factors for flaw dimensions and K_{IH} using the first order reliability method. This proposed approach is generic and it can be employed to probabilistic assessment with respect to other limit states of performance.

This paper presents concepts underlying the process of calibrating a deterministic criterion to a specified probability level. The conversion is based on replacing the random variables by probabilistic bounds determined from a formal reliability analysis. A probabilistic bound (or design point) is obtained as a product of the nominal value of the random variable (such as mean) with the calibrated partial factor. Since the calibration process accounts for interaction among random variables and their sensitivity to the assessment criterion, probabilistic bounds are consistent with a specified reliability level, whereas bounds chosen heuristically or based on experience will lack this consistency.

The variability associated flaw depth and the target (or acceptable) conditional probability of DHC initiation are the dominant factors in the calibration of partial factors. For a target probability of 10^{-2}, probabilistic bounds for flaw depth and length correspond to 98% percentile and median, respectively. The probabilistic lower bound for K_{IH} (= 5.6 $\mathrm{MPa}\sqrt{\mathrm{m}}$) corresponds to 14% percentile. A detailed table of partial factors has been prepared for the ease of practical applications of this method.

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