Optimal design of corroded reinforced concrete structures by using time-variant reliability analysis
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ABSTRACT: The design optimization of RC structures should take into account the uncertainties related to all, material properties, geometry, loading and deterioration. The Time-Variant Reliability-Based Design Optimization (TV-RBDO) consists in finding the optimal design by satisfying appropriate safety levels during the whole structure lifetime. This work proposes an efficient method for TV-RBDO, where the classical formulation is transformed into a sequence of equivalent deterministic design optimization sub-problems. This transformation is defined by the mean of optimally calibrated safety factors, linking the reliability requirement to the equivalent deterministic optimization. The proposed method is developed to account for deterioration (corrosion) and is applied to optimize a corroded RC bridge girder. The results show the effectiveness and the efficiency of the method.
2 TIME-VARIANT RELIABILITY ANALYSIS

The probabilistic models are usually used to describe the deterioration phenomena. When the time dependency affects only the degradation mechanism, where the material properties are decaying with time, the uncertainties are often modeled by random variables multiplied by deterministic functions of time describing the degradation kinetics. In this case, the problem can be treated by time-invariant reliability methods (Andrieu et al. 2002). However, there are many problems where the deterioration is influenced by phenomena that vary randomly with time, as the weather actions (i.e. temperature, relative humidity…) and loading (i.e. wind, traffic…). The stochastic processes are usually used to describe these phenomena. For these problems, the time-invariant reliability analysis is not valid.

The time-variant reliability aims at computing the probability of failure during the whole structure lifetime, when the time dependency lies in the loading and the degradation phenomena. Several approaches are addressed to assess the time-variant reliability, which can be done either by simulation techniques or by approximate approaches. Sampling methods such as the Monte Carlo simulation are computationally very expensive.

The approximate approaches are generally based on the outcrossing approach (Ditlevsen & Madsen 1996). Schall et al. (1991) have used the outcrossing approach and asymptotic integration to assess the probability of failure, which is related to the mean number of outcrossing of the random process through the limit state surface. Hagen & Tvedt (1991) suggested an original approach based on a parallel system reliability formulation for computing the outcrossing rate. This formulation is useful because it is based on time-invariant reliability tools. The PHI2 method developed by Andrieu et al. (2002) is based on this approach.

2.1 The PHI2 method

Considering the following limit state function \( G(t, X(t,\omega)) \), where \( X(t,\omega) \) denotes the set of random variables \( X_j(\omega), j = 1, \ldots, p \) and the one-dimensional random process \( X_k(t,\omega), k = p+1, \ldots, p+q \), \( t \) represents the time and \( \omega \) describes the randomness in the mechanical model. The cumulative probability of failure \( P_{f,c}(0, T_L) \) of the structure within the interval \([0, T_L]\) is given by:

\[
P_{f,c}(0, T_L) = \Pr\left[ \exists \tau \in [0, T_L] \mid G(t, X(t,\omega)) \leq 0 \right] \quad (1)
\]

where \( T_L \) is the structural lifetime; \( G(t, X(t,\omega)) > 0 \) indicates the safe domain and \( G(t, X(t,\omega)) \leq 0 \) indicates the failure domain. The cumulative probability of failure \( P_{f,c}(0, T_L) \) is bounded by (Hagen & Tvedt 1991):

\[
\max_{0 \leq \tau \leq T_L} \left[ P_{f,c}(\tau) \right] \leq P_{f,c}(0, T_L) \leq P_{f,c}(0) + \int_0^{T_L} v(t) \, dt \quad (2)
\]

where \( P_{f,c}(\tau) \) is the instantaneous probability of failure at a given time \( \tau \) and \( v(t) \) is the outcrossing rate function defined by:

\[
v(t) = \lim_{\Delta t \to 0} \frac{\Pr[A \cap B]}{\Delta t} \quad (3)
\]

where \( A: G(t, X(t,\omega)) > 0 \) is the event where the structure is in the safe state at \( t \) and \( B: G(t+\Delta t, X(t+\Delta t,\omega)) \) is the event that the structure is in the failure domain at \( t+\Delta t \) (Figure 1). In the PHI2 method, the outcrossing rate is given by:

\[
v(t) = \frac{\Phi_2(\beta(t), -\beta(t+\Delta t); \rho_c(t, t+\Delta t))}{\Delta t} \quad (4)
\]

where \( \Phi_2(.) \) stands for the bivariate normal cumulative distribution function; \( \beta(t) \) and \( \beta(t+\Delta t) \) are the reliability indexes corresponding to the two events \( A \) and \( B \), respectively; and \( \rho \) \( (t, t+\Delta t) \) is the correlation coefficient between the two events, which is given by the sensitivities of the random variables obtained in the two time-invariant reliability analyses.
\[
\rho(t, t + \Delta t) = -a(t + \Delta t) \cdot a(t + \Delta t)
\]  \hspace{1cm} (5)

where \(a(t)\) and \(a(t + \Delta t)\) are the sensitivities of the two events \(A\) and \(B\), respectively.

The advantage of the PHI2 approach consists in the use of the FORM approximation, where the time-variant reliability problem is converted to several time-invariant reliability analyses. Figure 1 shows the concept of the PHI2 approach. In this work, the PHI2 method is used, including the improvements proposed by Sudret (2008).

2.2 Discretization of the random process

The discretization of the random process is required for time-variant reliability analysis especially when simulation methods are used. This discretization consists in representing the random process \(X(t, \omega)\) by a finite set of deterministic functions weighted by a set of random variables. Several approaches can be used, as Fourier series expansion, Karhunen-Loève expansion (Ghanem, & Spanos 2003) and EOLE approach (Expansion Optimal Linear Estimation) (Li & Der Kiureghian 1993). The method retained in the present work is the Karhunen-Loève expansion:

\[
X(t, \omega) = \mu_X + \sigma_X \sum_{i=1}^{n_{KL}} \lambda_i f_i(t) \xi_i(\omega)
\]  \hspace{1cm} (6)

where \(\mu_X\) and \(\sigma_X\) are respectively the mean and the standard deviation of the scalar Gaussian process \(X(t, \omega)\); \(\lambda_i\) and \(f_i\) are respectively the eigenvalues and the eigenfunctions of the covariance function \(\rho_{XX}(t_1, t_2)\); \(\xi_i\) is a set of independent normal variables and \(n_{KL}\) is the number of terms of the truncated discretization.

3 CLASSICAL FORMULATION OF TV-RBDO

Generally, the TV-RBDO is formulated like the RBDO problem, where the expected total cost is minimized under probabilistic constraints solved by nested optimization. The outer loop concerns the optimization and the inner loop concerns the reliability analysis leading to repeated evaluations of the performance function. This scheme leads to an expensive computation cost, where convergence and accuracy problems are observed.

\[
\min_{\mathbf{d}} C_f(\mathbf{d}) + \mathbb{E}[C_f(\mathbf{d}, \mathbf{X}, t)]
\]  \hspace{1cm} (7)

subject to

\[
P_{f,c}(\mathbf{d}, \mathbf{X}, t) \leq P^*_{f,c} \quad \forall t \in [0, T_e]
\]

\[
h_j(\mathbf{d}) \leq 0 \quad j=1, \ldots, m
\]

where \(\mathbf{d}\) is the vector of the design variables; \(\mathbf{X}\) is the vector of random variables and stochastic processes; \(\mathbb{E}[.\]\) is the expectation operator; \(C_f\) is the initial cost; \(C_f\) is the failure cost; \(P^*_{f,c}\) is the admissible probability of failure and \(h_j\) are deterministic functions, such as the lower and the upper bounds of the design variables. Kuschel & Rackwitz (2000) defined the expected cost of failure by:

\[
E[C_f(\mathbf{d}, \mathbf{X}, t)] = \int_0^{\delta(t)} f(\mathbf{d}, \mathbf{X}, t) C_f \delta(t)
\]  \hspace{1cm} (8)

where \(C_f\) is the annual failure cost; \(f(\mathbf{d}, \mathbf{X}, t)\) is the time to failure and \(\delta(t)\) is the capitalization or discount function. However, the PDF of time to failure \(f(\mathbf{d}, \mathbf{X}, t)\) is not easy to compute. An approximation proposed by Sorensen & Tarp-Johansen (2005) for instantaneous probability of failure is extended in this work for cumulative probability of failure.

\[
E[C_f] = \sum_{i=1}^{n_{KL}} \frac{P_{f,c}(\mathbf{d}, \mathbf{X}, t) - P_{f,c}(\mathbf{d}, \mathbf{X}, t_{i-1})}{(1+r)^i} C_f
\]  \hspace{1cm} (9)

4 PROPOSED APPROACH FOR TV-RBDO

The classical formulation of TV-RBDO converges slowly or even fails to converge. The proposed approach is based on the concept of decoupling the reliability analysis and the optimization procedures. This decoupled concept has been largely used in RBDO problems (Royset et al. 2001, Du & Chen 2004).

In this study, the TV-RBDO problem is decoupled and transformed into a sequence of sub-problems of equivalent deterministic design optimization followed by the time-variant reliability analysis. The proposed approach called SOTVRA (Sequential Optimization and Time-Variant Reliability Analysis) approximates the objective function at each deterministic optimization on the basis of the previous time-variant reliability analysis. At the end of each deterministic optimization and time-variant reliability analysis, the optimal safety factors are calibrated on the basis of the target reliability index at the initial time and provided to the next deterministic optimization sub-problem. In other words, the safety factors link the reliability requirement to the equivalent deterministic constraints. The Figure 2 shows the different steps of the SOTVRA approach, where the principal steps are described in the following subsections.
4.1 Approximation of the objective function

The objective function of the TV-RBDO problem formulated in Equation 7 requires a time-variant reliability analysis to evaluate the expected failure cost \( E[C_f] \). In the SOTVRA approach, the objective function is approximated on the basis of the time-variant reliability analysis performed in the previous sub-problem. In this way, the reliability analysis is avoided in the optimization procedure. The objective function is approximated by a first-order Taylor expansion:

\[
\tilde{C}_f(d) = C_f + \sum_{i=1}^{n+1} \left[ P^{(k)}_{f,c}(t_i) - P^{(k)}_{f,c}(t_{i-1}) \right] + \left\{ \frac{\partial P^{(k)}_{f,c}(t_i)}{\partial d} - \frac{\partial P^{(k)}_{f,c}(t_{i-1})}{\partial d} \right\}^T (d - d^{(k)}) \frac{1}{(1+r)^t} \tag{10}
\]

where \( T \) indicates the transpose operator; \( P^{(k)}_{f,c}(t_i) \) and \( P^{(k)}_{f,c}(t_{i-1}) \) are respectively the cumulative failure probabilities at times \( t_i \) and \( t_{i-1} \) calculated at the \( k \)th sub-problem; \( d^{(k)} \) is the optimal design of the previous sub-problem; \( d \) is the current design point; \( \frac{\partial P^{(k)}_{f,c}(t_i)}{\partial d} \) and \( \frac{\partial P^{(k)}_{f,c}(t_{i-1})}{\partial d} \) are the derivatives of the cumulative failure probabilities regarding the design variables, respectively. These derivatives are calculated by using the time-variant reliability results of the previous sub-problem. The cumulative probability is approximated by the upper bound given in Equation 2.

\[
P^{(k)}_{f,c}(t_i) = P^{(k)}_{f,d}(t_{i-1}) + \int_{t_{i-1}}^{t_i} \nu(t) \, dt \tag{11}
\]

we assume that the outcrossing rate \( \nu(t) \) is constant in the interval \([t_{i-1}, t_i]\) because the step length \( \Delta t = t_i - t_{i-1} \) is small, therefore the derivation is easily obtained.

\[
\frac{\partial P^{(k)}_{f,c}(t_i)}{\partial d} = \frac{\partial P^{(k)}_{f,c}(t_{i-1})}{\partial d} - \frac{\partial \beta(t_{i-1})}{\partial d} \frac{\partial \beta(t_{i-1})}{\partial d} = - \frac{\partial \Phi_2(\beta(t_{i-1}), -\beta(t_i), \rho)}{\partial d} \tag{12}
\]

with:

\[
A_i = - \varphi(-\beta(t_{i-1})) \tag{13}
\]

The term \( A_2 \) depends on the nature of the design variable \( d \). When \( d_j \) is a deterministic design variable then \( A_2 \) becomes:

\[
A_2 = - \frac{1}{\left| \nabla d_j G(u^*, t_{i-1}) \right|} \frac{\partial G(d, X, t_{i-1})}{\partial d_j} \tag{14}
\]

where \( \nabla d_j G(u^*, t_{i-1}) \) is the gradient of the limit state in the normal space at the most probable failure point \( u^* \) and at the time \( t_{i-1} \); \( \partial G/\partial d_j \) is the derivative in the physical space of the limit state regarding the design variable \( d_j \). These sensitivities are already computed in the previous time-variant reliability analysis and optimization sub-problem.

However, when \( d_j \) is the mean of the random variable \( X_j \) then:

\[
A_2 = \alpha_j (t_{i-1}) \times \left( \frac{\partial T(x_j)}{\partial d_j} \right) \tag{15}
\]

where \( \alpha_j (t_{i-1}) \) is the direction cosine of the random variable \( X_j \) at the time \( t_{i-1} \) (\( \alpha_j = \nabla_a G/\| \nabla_a G \| \)) and \( T \) is the probability transformation, where \( x = T(u) \) (e.g. if \( X_j \) is normal variable with mean \( d_j \) and standard deviation \( \sigma_j \), then \( \partial T(x_j)/\partial d_j = -1/\sigma \)).

The term \( A_3 \) is given as:

\[
A_3 = \frac{\partial \Phi_2(\beta(t_{i-1}), -\beta(t_i), \rho)}{\partial \beta(t_{i-1})} \frac{\partial \beta(t_{i-1})}{\partial d} + \frac{\partial \Phi_2(\beta(t_{i-1}), -\beta(t_i), \rho)}{\partial \beta(t_i)} \frac{\partial \beta(t_i)}{\partial d} \tag{16}
\]

It is reasonable to assume that the correlation coefficient \( \rho \) stays constant in the interval \([t_{i-1}, t_i]\).

![Figure 2. Flowchart of the proposed SOTVRA method.](image-url)
linked to the admissible failure probability $P_f$ by FORM approximation:

$$\beta_{ta}^m = \Phi^{-1}(P_f)$$  (17)

where $\Phi^{-1}$ is the inverse cumulative normal distribution. Generally, $P_f$ is given by socio-economical considerations.

The design optimization is searched at the initial time $t = 0$, where the safety factors are calibrated on the basis of the target index at this time $\beta_{ta}^{m,0}$. Figure 3 shows that $\beta_{ta}^{m,0}$ can be deduced if the profile of the structural reliability index is known. This evolution is proposed as following:

$$\beta_{ta}^{m,0} = \beta_{ta}^{m} + \sum_{i=1}^{n} \left( \Phi^{-1}(P_{f,c}(I_{t-1})) - \Phi^{-1}(P_{f,c}(I_{t})) \right)$$  (18)

4.3 Calibration of the safety factors

The safety factors link the reliability requirement to the deterministic optimization sub-problem. In this work, a probabilistic procedure is proposed to calibrate the safety factors on the basis of the target reliability index at the initial time $\beta_{ta}^{m,0}$. In this way, the design space of the next equivalent deterministic optimization sub-problem is adjusted, where the design variables are searched in order to satisfy the reliability requirement.

It is however possible to reach the same target reliability level by infinite ways of setting the safety factors. Nevertheless, only one combination of the safety factors verifies the target safety and minimizes the performance function. Besides, the minimum structural performance that satisfies the target reliability avoids over-designing of structures. In other words, the proposed procedure aims at searching for the safety factors corresponding to the target reliability level $\beta_{ta}^{m,0}$ by minimizing the structural performance function. This procedure is formulated as:

$$\min_{\gamma^k} G(d, \gamma^k x_m, t = 0)$$  (19)

s.t.  $\Phi^{-1}(F_X(\gamma^k x_m)) = \beta_{ta}^{m,0}$

where $F_X$ is the cumulative distribution of the random variables $X$; $\gamma^k$ is the vector of safety factors at the $k$th sub-problem and $x_m$ is the vector of characteristic values of the random variables, which are taken as the median value. When the design variables are the means of random variables, the shift factors $\Delta_d$ are defined in order to take into account this situation. The vector $\Delta_d$ is given by:

$$\Delta_d^{(k)} = d^{(k)}(\gamma^{(k)} - 1)$$  (20)

where $d^{(k)}$ is the optimal design point obtained in the $k$th deterministic design optimization and $\gamma^{(k)}$ are the optimal safety factors of the random variables $X_d$ which are the design variables $d$. The updated safety factors $\gamma^{(k)}$ and $\Delta_d^{(k)}$ are provided to the next deterministic optimization sub-problem.

4.4 Implementation and Convergence criteria

The proposed approach SOTVRA and the classical TV-RBDO method are implemented in a computer program using the MATLAB environment, which contains a very useful optimization toolbox. The SQP (Sequential Quadratic Programming) method is used to solve the optimization problem. The convergence criteria are formulated by the absolute changes in design variables, the relative changes in the objective function and the constraint verification. The tolerance of these termination conditions is fixed to $10^{-3}$ and the maximum number of iterations is fixed to 100.

5 APPLICATION

Consider the RC girder in Figure 4 with rectangular cross-section, subjected to uniform live load. This application aims at searching for the optimal design for concrete cross-section defined by $h$ and $b$, steel area $A_s$ and the depth of the reinforcement cover $c$. The structure is designed by the classical TV-RBDO (Equation 7) and SOTVRA methods. The failure probability of the optimal design should be always less than the admissible probability $P_f = 7.23 \times 10^{-5}$ during the whole structure lifetime. This admissible probability corresponds to the target reliability index $\beta_{ta}^{m,0} = 3.8$ and the lifetime $T_l$ of the structure is fixed to 50 years. The annual failure cost is supposed proportional to the initial cost, i.e. $C_f = 100 \times C_l$. Where $C_l$ is the initial cost calculated from the concrete, steel and formwork costs.

$$C_l = bh L_s C_{con} + \rho_s C_{sl} L_s A_s + C_{inv} (2h + b)$$  (21)

where $C_{con}$, $C_{sl}$ and $C_{inv}$ are respectively the unit cost of concrete, steel and formwork taken to 150.5 €/m³, 1.46 €/kg and 47 €/m²; $\rho_s = 7850$ kg/m³ is the unit weight of steel; $L_s$ and $L_l$ are respectively the total beam length and the length of steel bars.
The operational life of the RC girder is affected by steel corrosion induced by chloride ingress. In saturated conditions, chloride ingress into concrete matrix can be simplified as a diffusion problem modeled by Frick’s second law (Tuutti 1982). The time to corrosion initiation $t_{ini}$ is the time at which a threshold concentration of chlorides that induces corrosion $C_{th}$ reaches the cover depth:

$$t_{ini} = \frac{c^2}{4D_{ct}} \left[ \text{erf}^{-1} \left( \frac{1}{C_{th}} \right) \right]^2 \tag{22}$$

where $D_{ct}$ is the chloride diffusion coefficient in concrete; erf(.) is the error function and $C_{th}$ is the chloride surface concentration. After $t_{ini}$, the corrosion of reinforcement is controlled by a well-known electrochemical process. Corrosion can be quantified in terms of corrosion current density $i_{corr}$, also called corrosion rate. This parameter measures general or uniform loss of metal and relates corrosion current with section reduction. A corrosion rate of $i_{corr} = 1 \mu A/cm^2$, corresponds to a section loss of 11.6 $\mu m/yr$ (Jones 1992). By assuming uniform corrosion (Figure 5), the diameter reduction $\phi(t)$ in $mm$ at time $t$ is computed as:

$$\phi(t) = \phi_0 - 0.0232 \int_{t_{ini}}^{t} i_{corr}(t) \, dt \tag{23}$$

where $\phi_0$, is the initial diameter of the bar in $mm$, and $i_{corr}(t)$ must be given in $\mu A/cm^2$. Equation 23 is only valid if uniform corrosion is assumed; however, chloride-induced corrosion is typically characterized by highly localized corrosion (i.e. pitting corrosion). According to González et al. (1995), the maximum penetration of pitting corrosion is about four to eight times that of the uniform corrosion. If the ratio between pitting and uniform corrosion depth is related by a factor $\alpha$, the reduction in diameter at time $t$, for pitting corrosion becomes (Figure 5):

$$\phi_p(t) = \phi_0 - 0.01166\alpha \int_{t_{ini}}^{t} i_{corr}(t) \, dt \tag{24}$$

Based on the work of González et al. (1995), Stewart (2004) found that for a 125 $mm$ length of reinforcing bar, the parameter $\alpha$ follows a Gumbel distribution with mean of 5.65 and coefficient of variation of 0.22. By using Equations 23-24, it is possible to compute the effective reinforcement area of the bars i.e. $A_e(t)=\pi \phi(t)^2/4$, and subsequently, to evaluate the loss of capacity of a RC beam. Thus, the limit state function can be written:

$$G(d,X,t) = M_u(d,X,t) - M_{app} \tag{25}$$

where $M_{app}$ is the applied moment and $M_u(d,X,t)$ the ultimate moment given by:

$$M_u(t) = A_s(t) f_y (h-c) \left( 1 - \frac{0.59 A_s(t) f_y}{b(h-c) f_y} \right) \tag{26}$$

where $f_c$ and $f_y$ are respectively the concrete compressive strength and the steel yield stress, assumed as random variables. The statistical data of the random variables are detailed in Table 1. The applied moment is considered as Gaussian process with mean of 882 $kN.m$ and coefficient of variation of 0.25. The autocorrelation function of this random process is assumed as:

$$\rho_{SS}(t_1,t_2) = \exp \left[ -\left( \frac{t_1-t_2}{L_c} \right)^2 \right] \tag{27}$$

where $L_c$ is the length correlation fixed to 1 year. The time-variant reliability analysis is carried out by using a step length of 0.1 years. Figure 6 shows some trajectories of the random process $M_{app}$ generated by using 10 terms of the the Karhunen-Loève expansion.

**Figure 4.** Rectangular RC bridge girder.

**Figure 5.** Diameter of bar as function of time (a) uniform corrosion (b) pitting corrosion.

**Table 1.** Statistical data of random variables (Bastidas et al. 2007).

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>C.V</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_c$ (MPa)</td>
<td>30</td>
<td>0.15</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$f_y$ (MPa)</td>
<td>500</td>
<td>0.10</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$C_{th}$</td>
<td>0.37</td>
<td>0.11</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$C_l$</td>
<td>2</td>
<td>0.30</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$D_{ct}$ cm$^3$/s</td>
<td>1.62x10$^{-8}$</td>
<td>0.31</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$i_{corr}$ $\mu A/cm^2$</td>
<td>2</td>
<td>0.30</td>
<td>Lognormal</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>5.65</td>
<td>0.22</td>
<td>Gumbel</td>
</tr>
</tbody>
</table>

The design variables $h$, $b$, $A$, and $c$ are the means of normal random variables with coefficient of variation of 0.03. The initial design point, the lower and the upper bounds of design variables are detailed in Table 2.

**Table 2.** Initial design values, lower and upper bounds.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Initial value</th>
<th>Lower bound</th>
<th>Upper bound</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ (cm)</td>
<td>80</td>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>$b$ (cm)</td>
<td>60</td>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>$A$ (cm$^2$)</td>
<td>50.27</td>
<td>12.57</td>
<td>251.1</td>
</tr>
<tr>
<td>$C$ (cm)</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 3 shows that both classical TV-RBDO and SOTVRA methods lead nearly to the same expected total cost. It can also be observed that the initial cost $C_I$ and the expected failure cost $C_F$ are almost the same for both TV-RBDO methods. These results show the validity of the approximation introduced in the SOTVRA to express the objective function. From the numerical point of view, the efficiency of SOTVRA is observed, as it requires only 21s CPU compared to 603s CPU for the classical TV-RBDO approach; i.e. the computation time is divided by a factor of 28. In other words, the SOTVRA economises 96% of the computational effort. This reduction is extremely important in highly consuming finite element analyses of large-scale structures. The proposed approach requires less consumption time because it is based on the deterministic optimization procedure, already known to be numerically efficient and robust.

Table 4 indicates the optimal design obtained by both TV-RBDO approaches. The two design solutions are different. The classical TV-RBDO tends to reduce the concrete cross-section and increases the steel area. However, the SOTVRA gives other solution, where the steel area is reduced and the concrete cross-section is increased. The two solutions lead approximately towards the same expected total cost. Figure 7 shows that for both optimal solutions the reliability requirement is satisfied, where the reliability index is always higher than the target index $\beta$.

Table 5 gives the optimal safety factors at the optimal solution. Figure 8 shows that the profile of the target index $\beta_{ta}(t)$ is deduced on the basis of the structural reliability index $\beta(t)$. The target index at the initial time $\beta_{ta}(t=0)$ is improved at each sub-problem of SOTVRA, and after fourth cycles the reliability index $\beta(t)$ met the target index $\beta_{ta}(t)$ as shown in Figure 8. The optimal safety factors are calibrated from the target index at the initial time $\beta_{ta}(t=4.9)$.

It is important to notify that the random variables $\beta_{th}, C_s, Delt;i_{corr}$ and $\alpha$ play an important role in the time-variant reliability analysis only. The calibration procedure does not consider these variables because the calibration is performed at the initial time $t=0$. Furthermore, these random variables are not affected by the safety factors.
Table 7. Optimal safety factors of SOTVRA for $C_r=10^3 \times C_c$

| $\gamma_X$ | 2.00 | 1.22 | 1.26 | 2.79 | 0.4 | 1.94 | 0.01 |

Figure 8. Time-variant reliability index and target index profiles at the first four sub-problems of SOTVRA.

6 CONCLUSION

This paper proposes a decoupled approach for TV-RBDO called SOTVRA. The proposed approach consists in transforming the TV-RBDO problem into a sequence of deterministic design optimization sub-problems based on the safety factor concept. The objective function of the TV-RBDO problem is approximated at the current design point by first-order Taylor series expansion and the reliability constraints are fulfilled by optimally calibrated safety factors. The deterministic optimization is then carried out by using the approximated objective function and reliability constraints including the safety factors. Thus, the proposed method does not involve any additional function evaluations. The time-variant reliability analysis and the optimization procedures are performed sequentially until convergence.

The accuracy and the efficiency of the proposed method are shown for RC girder affected by chloride ingress. The results indicate that SOTVRA is very attractive for the following reasons: (1) its simple implementation in any general purpose optimization and finite element software; (2) the use of the safety factor concept is familiar for designers; and (3) the less consumption time allows to apply SOTVRA to large-scale structures. The robustness and the efficiency of SOTVRA lie in the fact that the time-variant reliability analysis is decoupled from the optimization process. Finally, the proposed method can be easily applied to any kind of structural durability design optimization without any loss of generality.

7 REFERENCES


