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Reliability-based design optimization using optimum safety factors for large-scale problems*

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Надежность оптимизации дизайна с использованием оптимальных факторов безопасности для крупномасштабных задач***

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Introduction. Reliability-Based Design Optimization (RBDO) model reduces the structural weight in uncritical regions, does not only provide an improved design but also a higher level of confidence in the design.
Materials and Methods. The classical RBDO approach can be carried out in two separate spaces: the physical space and the normalized space. Since very many repeated researches are needed in the above two spaces, the computational time for such an optimization is a big problem. An efficient method called Optimum Safety Factor (OSF) method is developed and successfully put to use in several engineering applications.
Research Results. A numerical application on a large scale problem under fatigue loading shows the efficiency of the developed RBDO method relative to the Deterministic Design Optimization (DDO). The efficiency of the OSF method is also extended to multiple failure modes to control several output parameters, such as structural volume and damage criterion.
Discussion and Conclusions. The simplified implementation framework of the OSF strategy consists of a single optimization problem to evaluate the design point, and a direct evaluation of the optimum solution considering OSF formulations. It provides designers with efficient solutions that should be economic, satisfying a required reliability level with a reduced computing time.

Введение. Модель, основанная на оптимизации надёжности, (RBDO) уменьшает структурный вес в некритических регионах, обеспечивает не только улучшенную конструкцию, но и более высокий уровень уверенности в дизайне.
Материалы и методы. Классический подход RBDO может быть выполнен в двух отдельных пространствах: физическом пространстве и нормированном пространстве. Поскольку в вышеупомянутых двух пространствах требуется очень много повторных исследований, расчётное время для такой оптимизации является большой проблемой. Эффективный метод, называемый Optimum Safety Factor (OSF), разработан и успешно применяется к нескольким инженерным приложениям.
Результаты исследования. Численное приложение по крупномасштабной задаче при усталостной загрузке показывает эффективность разработанного метода RBDO относительно детерминированной оптимизации дизайна (DDO). Эффективность метода OSF также распространяется на несколько режимов отказоустойчивости для управления несколькими выходными параметрами, такими как структурный объем и атрибут повреждения.
Обсуждение и заключения. Упрощенная стратегия внедрения структуры OSF состоит из единственной задачи по оптимизации оценки проектной точки и прямой оценки оптимального решения с учетом составов OSF. Он предоставляет разработчикам эффективные решения, которые должны быть экономичными, удовлетворяющими требуемому уровню надежности с сокращённым расчётным временем.

Keywords: Reliability-Based Design Optimization, Structural Reliability, Safety Factors

Ключевые слова: оптимизация на основе надежности, структурная надежность, факторы безопасности

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1. Introduction

When Deterministic Design Optimization (DDO) methods are used, deterministic optimum designs are usually pushed to the design constraint boundary, leaving little or no room for tolerances (or uncertainties) in design, manufacture, and operating processes. So, deterministic optimum designs obtained without consideration of uncertainties may lead to unreliable designs, therefore calling for Reliability-Based Design Optimization (RBDO). An RBDO solution that reduces the structural weight in uncritical regions does not only provide an improved design but also a higher level of confidence in the design. The basic idea is to couple the reliability analysis with optimization problems. This coupling is a complex task, drawing on a high computing time and convergence stability, which seriously limits its applicability in real problems. To overcome these difficulties, several methods have been elaborated [1]. These methods can be classified into two categories: numerical and semi-numerical methods. An efficient numerical method called Hybrid Method is based on simultaneous solution to the reliability and the optimization problem. It has successfully reduced the computational time problem. The advantage of the hybrid method allows us to satisfy a required reliability level for different cases (static, dynamic, …), but the vector of variables here contains both deterministic and random variables. To overcome both difficulties, an efficient semi-numerical method called Optimum Safety Factor (OSF) method has been proposed to solve problems in statics [2], and also an efficient alternative semi-numerical method called Safest Point Method (SP) has been proposed to solve problem in dynamics [3]. Recently, a Robust Hybrid Method (RHM) is also developed to overcome the HM difficulties in order to solve multiaxial fatigue damage analysis problems [4]. The RHM leads to robust solution comparing with the HM, but the computing time is still a big drawback.

2. Reliability-Based Design Optimization

2.1 Developments

The computational cost of sequential RBDO approaches is much higher than the DDO procedure. Several developments accelerated the use of the RBDO model. The Reliability Index Approach (RIA) and the Performance Measure Approach (PMA) have been proposed [5]. Next, the sequential optimization and reliability assessment (SORA) is developed to improve the efficiency of probabilistic optimization [6]. The SORA method employs a single-loop strategy with a serial of cycles of deterministic optimization and reliability assessment. The major difficulty lies in the evaluation of the probabilistic constraints, which is prohibitively expensive and even diverges for many applications. It is clear that efforts were directed towards the development of efficient techniques to perform the reliability analysis. Here, the reliability index is computed iteratively that leads to an enormous amount of computer time in the whole design process.

2.2 Basic RBDO formulations

Traditionally, for the reliability-based design optimization procedure, two spaces are used: the physical space and the normalized space [7,8]. Therefore, the reliability-based design optimization is performed by nesting the following two problems:

1. Optimization problem:

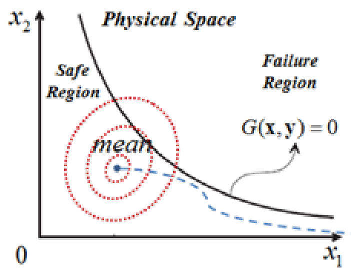
$$\begin{array}{ll} \min\limits_{\mathrm{x}} & f(\mathrm{x}) \\ \text{subject to} & g_k(\mathrm{x}) \le 0 \ , \ k = 1,...,K \\ \text{and} & \beta(\mathrm{x},\mathrm{u}) \ge \beta_t \end{array} \tag{1}$$

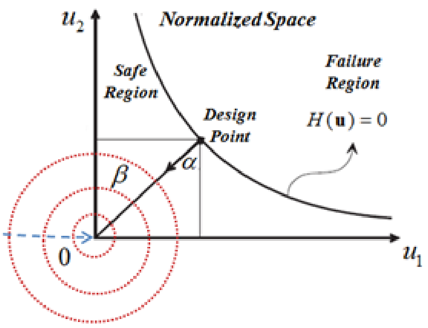
where $f(\mathrm{x})$ is the objective function, $g_k(\mathrm{x}) \le 0$ are the associated constraints, $\beta(\mathrm{x},\mathrm{u})$ is the reliability index of the structure, and β_t is the target reliability.

2. Reliability analysis: the reliability index $\beta(\mathrm{x},\mathrm{u})$ is the minimum distance between the limit state function $H(\mathbf{u})$ and the origin, see Figure 1b. This index is determined by solving the minimization problem:

$$\begin{array}{ll} \min\limits_{\mathrm{u}} & d(\mathrm{u}) \\ \text{subject to} & H(\mathrm{u}) = 0 \end{array} \tag{2}$$

where $d(\mathbf{u})$ is the distance in the normalized random space, given by $d = \sqrt{\sum u_i^{\ 2}}$, and $H(\mathbf{u})$ is the performance function (or limit state function) in the normalized space, defined such that $H(\mathbf{u}) \le 0$ implies failure, see Figure 1b. In the physical space, the image of $H(\mathbf{u})$ is the limit state function $G(\mathbf{x},\mathbf{y})$, see Figure 1a. Using the classical approach, the RBDO process is carried out in two spaces. That leads to a high computational time problem. Therefore, there is a strong need to develop efficient methods [9].





a) *b*)

Fig. 1. Physical and normalized spaces

In the field of reliability-based design optimization, we distinguish between two types of variables:

1. **The optimization variables**, which are deterministic variables to be adjusted with a view to optimizing the sizing; they represent the control parameters of the mechanical system (i.e. dimensions, materials, loads, etc.), and the probabilistic model (i.e. means and standard deviations of random variables);
2. **The random variables**, which represent the uncertainties in the system. Each of these variables is identified by the type of distribution law and the associated parameters. These variables may be the geometric dimensions, the characteristics of the material or the external loads.

3. Optimum Safety Factor (OSF)

The Partial Safety Factors (PSF) presented in [10] use the calibration methods that need to propose some constraints during the calibration process to increase the efficiency and the accuracy. The resulting solution when using PSF may not represent a global or even local optimum. It may satisfy the required reliability level because of the efficiency of the used optimization algorithm. An efficient OSF method essentially depends on the satisfaction of the optimality conditions of the reliability index problem (2). This method provides the designer at least with a local reliability-based optimum without additional computing cost. This method has been basically developed for a normal distribution case [11]. In this work, it is generalized to be applied to a single and multiple failure cases.

3.1 Single Failure Mode (SFM)

The SFM reliability problem can be written as:

$$\beta^{SFM} = \min d(u_i) = \sqrt{u_1^2 + u_2^2 \ + \ldots + u_n^2} \quad \text{s.t.:} \quad H\left(u_1, u_2, \ldots, u_n\right) \le 0 \tag{3}$$

where $d(u_i)$ is the minimum distance between the design point and the optimal solution. And $H\left(u_i\right) \le 0$ represent the failure mode. The corresponding analytical formulation using OSF can be written as follows:

$$u_i^* = \beta_t \sqrt{\frac{\left|\dfrac{\partial G}{\partial y_i}\right|}{\sum_{j=1}^{n}\left|\dfrac{\partial G}{\partial y_j}\right|}}, \qquad i = 1, \ldots, n \tag{4}$$

where the sign of ± depends on the sign of the derivative, i.e.,

$$\frac{\partial G}{\partial y_i} > 0 \Leftrightarrow u_i^* > 1 \ \text{ and } \ \frac{\partial G}{\partial y_i} < 0 \Leftrightarrow u_i^* < 1\,, \qquad i = 1, \ldots, n$$

Formulation (4) provides different optimum values of the normalized variables at the design point and taking into account a single failure mode. In [2], a similar formulation can be found for several distributions.

3.2 Multiple Failure Mode (MFM)

Using the same OSF developments for a single failure mode [2], the MFM problem can be written as:

$$\beta^{MFM} = \min d(u_i) = \sqrt{u_1^2 + u_2^2 + \ldots + u_n^2} \text{ s.t.: } H_j\left(u_1, u_2, \ldots, u_m\right) \le 0 \tag{5}$$

$H_j\left(u_i\right) \le 0$ represent the different failure modes. The corresponding analytical formulation using OSF can be written as follows:

$$u_i^* = \pm\beta_t \sqrt{\frac{\left|\sum_{j=1}^{m} \frac{\partial G_j}{\partial y_i}\right|}{\sum_{i=1}^{n}\left|\sum_{j=1}^{m} \frac{\partial G_j}{\partial y_i}\right|}} \tag{6}$$

Formulation (6) provides different optimum values of the normalized variables at the design point and taking into account several failure modes.

3.3 OSF algorithm

The Optimum Safety Factor (OSF) algorithm can be easily implemented in three principal steps (Fig. 2). The first step is to determine the design point considering the most active constraint as a limit state function *G*(y). The optimization problem is to minimize the objective function subject to the limit state and the deterministic constraints. The resulting solution is termed the design point. The second step is to compute the safety factors using the equations (4) and (6). The third step is to calculate the optimal solution including the values of the safety factors in the computation of the values of the design variables and then determine the optimum design of the structure.

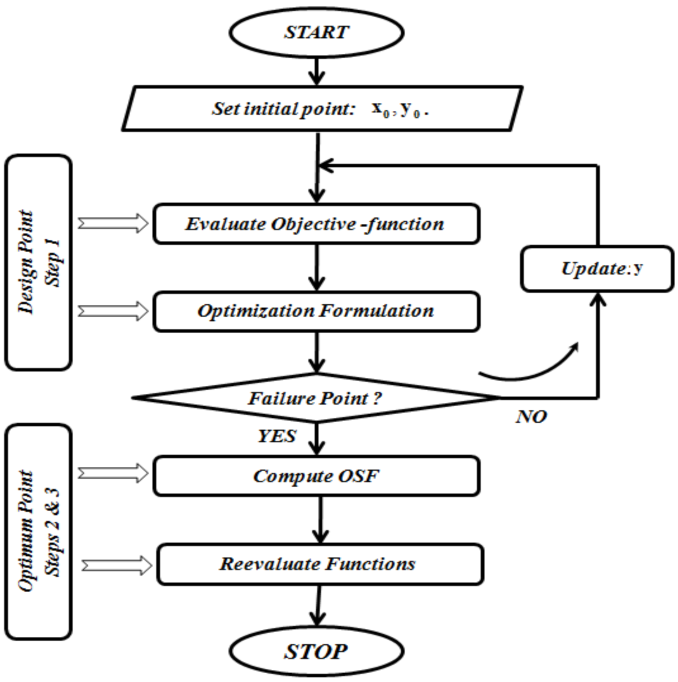
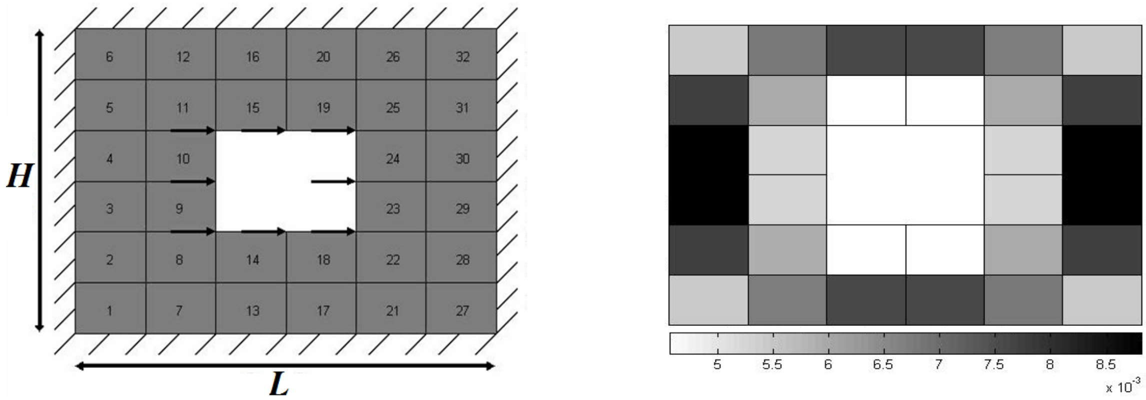


Fig. 2. OSF algorithm

4. Numerical Application

The objective of this application is to show the advantage of the RBDO by OSF relative to the DDO when dealing with SFM and MFM. The corresponding material properties are: Young's modulus E = 206.8GPa, Poisson's ratio ν = 0.29 and density ρ = 7820 kg/m^3. The endurance limits for the reversed tension stress and torsion stress f-1 and t-1 stated after 2.106 cycles are equal to 252MPa and 182MPa, respectively. For more details about the fatigue data and methods of this example, the interested reader can refer to [12]. The length and the height of the studied plate are: L=0.14 m and H=0.1 m, respectively (Fig. 3a). In finite element analysis, the plate is supposed simply fixed on its four edges and is modelled by 32 eight-node square elements which produce no out-of-plane stress (Fig. 3b). Here, the thickness of each element T_i is considered as a random variable and its mean as a deterministic variable that leads to 32 deterministic variables and 32 random variables.



a *b*

Fig. 3:
a - Dimensions of the perforated plate and
b - Thickness distribution for resulting optimum design

The objective of the DDO procedure is to minimize the volume subject to the fatigue damage constraints. Here, we consider a global safety factor $S_f = 1.25$ applied to the damage $D_{\max}$ and based on the engineering experience. The RBDO procedure cannot control not only the reliability level but several output parameters. In [2], the reliability level has been controlled considering a target reliability level, however, here we seek to control the other output parameters such as the structural volume and the damage criterion.

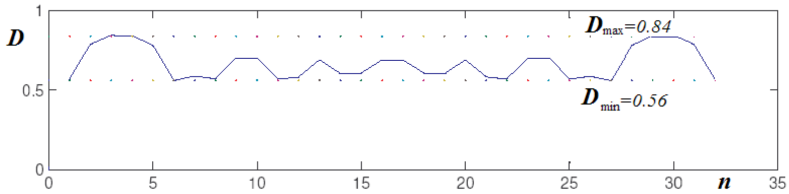
The DDO and RBDO results in table (1) show that the DDO cannot provide the designer with a required reliability level while RBDO by OSF allow controlling the safety levels. According to the problems 3 and 5, the value of the global safety factor is applied to the upper damage limit $D_U = 1$ to be $S_f = 1.25$. This way the allowable damage will be: $D_w = 0.8$. The standard deviations are considered as proportional of the mean values: $\sigma_i = 0.5 m_i$, *i=1,...,32.* After having optimized the structure, the resulting DDO volume (Table 1) was found to be V_{DDO}=*105.64*cm^3. The corresponding reliability index was found to be: $\beta_{DDO} = 2.73$. This resulting value does not belong to the standard structural engineering norm $\beta_{DDO} = 2.73 \notin [3-4.25]$. However, for the same optimum volume, the RBDO for multiple failure modes (using 5 and 6) provides the designer with a more reliable optimum structure with $\beta_{RBDO^v} = 3.64$. Figures 4a and b show the interval of the damage distribution of all structure thickness for DDO and RBDO in the same volume $V_{DDO} \approx V_{RBDO}{}^v$. The resulting damage distribution interval of RBDO by OSF [0.52,0.8] is better than the resulting one by DDO [0.4,0.8]. While Figures 4b and c show the interval of the damage distribution of all structure thickness for DDO and RBDO for the same maximum damage values $D_{DDO}=D_{RBDO}{}^v=0.8$. The RBDO by OSF provides the designer with an optimum structure with an increase 7% but more reliable by 45% relative to the resulting structure by DDO ($\beta_{RBDO^D} = 3.78 > \beta_{DDO} = 2.73$). Here, the resulting damage distribution interval of RBDO by OSF [0.56,0.84] is also better than the resulting one by DDO [0.4,0.8]. Thus, when obtaining a better damage distribution interval, the volume is reduced in the non-critical structural regions that leads to economic and reliable designs.

Table 1

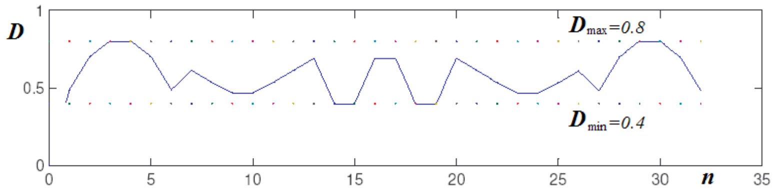
DDO and RBDO results for β^{SFM}

Parameters	Design Point	Optimum Solutions		
		$RBDO^{V}$	DDO	$RBDO^{D}$
Volume	81.9770	105.53	105.64	112.70
$D_{U\max}$	$0.9945 \approx 1$	0.84	0.8	0.8
β^{SFM}	*0*	3.64	2.73	3.78
T_1	5.5784	8.914	7.7839	9.665
T_2	7.7249	11.477	9.2979	12.434
T_3	8.7796	8.340	10.1057	8.732
T_4	8.7876	8.328	10.1055	8.718
T_5	7.7435	11.571	9.2976	12.536
T_6	5.604	9.001	7.7838	9.759
T_7	6.8081	12.024	8.6421	13.129
T_8	6.0581	8.675	8.1291	9.265
T_9	5.3822	3.715	7.5599	3.738
T_{10}	5.3866	3.745	7.5597	3.770
T_{11}	6.0644	8.678	8.1290	9.266
T_{12}	6.8267	12.063	8.6422	13.169
T_{13}	7.605	10.503	9.2265	11.214
T_{14}	4.7228	4.081	7.1685	4.157
T_{15}	4.7194	4.061	7.1689	4.136
T_{16}	7.608	10.507	9.2268	11.218
T_{17}	7.6074	10.504	9.2267	11.214
T_{18}	4.7191	4.057	7.1688	4.131
T_{19}	4.7231	4.082	7.1685	4.159
T_{20}	7.6056	10.509	9.2264	11.220
T_{21}	6.8256	12.057	8.6421	13.162
T_{22}	6.0637	8.675	8.1290	9.262
T_{23}	5.3861	3.738	7.5597	3.762
T_{24}	5.3825	3.721	7.5599	3.745
T_{25}	6.0588	8.680	8.1291	9.270
T_{26}	6.8093	12.031	8.6421	13.137
T_{27}	5.6029	8.992	7.7838	9.749
T_{28}	7.7425	11.557	9.2976	12.521
T_{29}	8.7871	8.311	10.1055	8.699
T_{30}	8.7799	8.351	10.1057	8.744
T_{31}	7.7257	11.491	9.2979	12.450
T_{32}	5.5794	8.922	7.7839	9.674

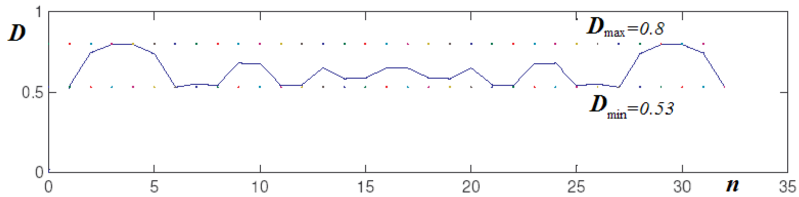
The structural reliability level is improved because the OSF-based solution essentially depends on the sensitivity study which determines the role of each parameter relative to the failure probability. For the computing time, the DDO procedure needs to solve two sequential optimization problems (1) and (2) while the RBDO by OSF can realize the operation in only one single optimization problem.



a) Optimum Solution by $RBDO^V$, Dmax=0.84 Volume=105, β =3.64, D $\in$ [0.56,0.84]



b) Optimum Solution by DDO, D_{max}=0.8, *Volume*=105, β =2.73, D $\in$ [0.4,0.8]



c) Optimum Solution by $RBDO^D$, Dmax=0.8, Volume=112, β =3.78, D $\in$ [0.53,0.8]

Figure 4. Resulting damage distribution intervals by DDO and RBDO procedures

Table 2 presents the different OSF results considering the linear and nonlinear distributions (normal, lognormal, uniform, Weilbull and Gumbel distributions), see [2], satisfying a required reliability level $\beta = 3$. The required reliability level can be considered as a given data and the algorithm converges to the optimum design that verifies the requirements (controllable designs: reliability, volume, damage …). For the computing time consumption, for a single failure mode, when using DDO procedure, two optimization processes are used (the first is to find the optimum solution and the second is to find the design point). The problem becomes much more complex for multiple failure modes where each failure mode needs a separate optimization process to find the corresponding design point. However, the RBDO by OSF needs only a single optimization process to find the design point and next the optimum solution is analytically computed using OSF-SFM or OSF-MFM formulations. The RBDO by OSF is then carried out without additional computing time because it has a single variable vector that defines the design point.

Table 2

Linear and nonlinear RBDO result for required reliability index $\beta = 3$

Structural Parameters	Design Point	Optimum RBDO solutions				
		Normal	Lognormal	Uniform	Weibull	Gumbel
Volume	81.97	86.63	86.92	88.22	85.59	83.28
D_{max}	0.99 $\approx$ 1	0.94	0.93	0.92	0.95	0. 98
β	0	3.00	3.00	3.00	3.00	3.00
P_f	50%	$\approx$ 0.1%	$\approx$ 0.1%	$\approx$ 0.1%	$\approx$ 0.1%	$\approx$ 0.1%
T_1	5.5784	5.8679	5.8890	5.9694	5.7954	5.6604
T_2	7.7249	8.1947	8.2203	8.3520	8.0980	7.8541
T_3	8.7796	9.3409	9.3684	9.5255	9.2330	8.9342
T_4	8.7876	9.3488	9.3763	9.5334	9.2407	8.9428
T_5	7.7435	8.2130	8.2387	8.3704	8.1160	7.8739
T_6	5.6040	5.8933	5.9145	5.9949	5.8204	5.6873
T_7	6.8081	7.1965	7.2204	7.3293	7.1097	6.9176

T_8	6.0581	6.3822	6.4046	6.4950	6.3039	6.1518
T_9	5.3822	5.6633	5.6836	5.7618	5.5934	5.4579
T_{10}	5.3866	5.6677	5.6880	5.7662	5.5978	5.4625
T_{11}	6.0644	6.3885	6.4109	6.5013	6.3101	6.1584
T_{12}	6.8267	7.2148	7.2389	7.3476	7.1277	6.9374
T_{13}	7.6050	8.0591	8.0848	8.2121	7.9634	7.7337
T_{14}	4.7228	4.9483	4.9670	5.0288	4.8862	4.7866
T_{15}	4.7194	4.9451	4.9638	5.0257	4.8831	4.7830
T_{16}	7.6080	8.0621	8.0877	8.2151	7.9663	7.7369
T_{17}	7.6074	8.0615	8.0872	8.2145	7.9657	7.7362
T_{18}	4.7191	4.9448	4.9635	5.0254	4.8828	4.7827
T_{19}	4.7231	4.9486	4.9673	5.0291	4.8864	4.7869
T_{20}	7.6056	8.0597	8.0854	8.2127	7.9640	7.7343
T_{21}	6.8256	7.2137	7.2378	7.3466	7.1267	6.9362
T_{22}	6.0637	6.3878	6.4103	6.5007	6.3094	6.1577
T_{23}	5.3861	5.6672	5.6875	5.7657	5.5973	5.4620
T_{24}	5.3825	5.6636	5.6838	5.7620	5.5937	5.4583
T_{25}	6.0588	6.3828	6.4052	6.4956	6.3045	6.1525
T_{26}	6.8093	7.1976	7.2216	7.3304	7.1109	6.9189
T_{27}	5.6029	5.8922	5.9135	5.9938	5.8193	5.6861
T_{28}	7.7425	8.2121	8.2378	8.3695	8.1151	7.8729
T_{29}	8.7871	9.3483	9.3759	9.5329	9.2402	8.9422
T_{30}	8.7799	9.3412	9.3687	9.5257	9.2332	8.9345
T_{31}	7.7257	8.1954	8.2210	8.3527	8.0987	7.8550
T_{32}	5.5794	5.8689	5.8899	5.9704	5.7964	5.6615

The OSF method is shown as a distinctive tool for RBDO problems. It shows the following advantages:

- The obtained reliability-based optimum solutions should be more reliable than those obtained by DDO procedure for the same optimum volumes,
- The OSF procedure needs only a single optimization process for the design point without additional computing time because it has a single variable vector that defines the design point while the DDO procedure needs two optimization processes.
- Since the major difficulty lies in the evaluation of the probabilistic constraints, which is prohibitively expensive and even diverges for many applications, the OSF procedure provides the designer with an analytical evaluation with small computing time relative to DDO and other RBDO procedures.
- All reliability index evaluations for RBDO-MFM studies can be analytically carried out for different probabilistic distributions. There is no need to optimization processes.

7. Conclusions

The RBDO using OSF has several advantages: small number of optimization variables, good convergence stability, small computing time, satisfaction of the required reliability levels and global optima and more economic solution for the same reliability index relative to the DDO process. The OSF-MFM formulation can be applied easily to different distribution laws. In fatigue analysis, the use of the classical method leads to an extremely high computing time and also local optima.

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