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The Stress-Strength Interference Method Applied to Fatigue Design: the Independence of the Random Variables

Menan F.[a], Adragna P-A.[a], François M.[a]*

[a]*ICD-LASMIS UMR CNRS 6281. Université de Technologie de Troyes. 12, rue Marie Curie 10000 TROYES. FRANCE*

Abstract

The use of the probabilistic analysis called Stress-Strength Interference Method (SSIM) applied to the endurance limit approach is being analyzed. Mean stress effect is often included to modify this fatigue limit. Plus, through the use of K factors, the fatigue limit is usually modified to account for the influence of loading mode, temperature, component size, corrosion, roughness... A necessary assumption of the SSIM is that stress and strength are independent. In this study, the independence of stress and strength is discussed. It appears that those variables may be in fact dependent. This error may lead to unconservative reliability predictions.

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Keywords: Fatigue design, Probabilistic analysis, Risk assessment, Stress concentration factors

1. Introduction

The Stress-Strength Interference Method (SSIM) is a broadly used statistical method, applied in many published articles [1-5]. Research work has focused on dealing with limited experimental data, knowledge of the random variables [6-8], and establishing procedures when variables follow known Probability Density Functions (P.D.F) [9-10].

* Corresponding author. Tel.: +33(0)325.71.56.57
E-mail address: manuel.francois@utt.fr

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The application of probabilistic analysis to fatigue design has been applied to numerous design procedures and loading cases, such as multiaxial fatigue [11-12], cumulative damage [13-14], vibrations [15], elasto-plastic fatigue [16-17], fracture mechanics [18-20] and the endurance limit approach [21-23].

In this study, the application of the SSIM to the endurance limit approach is analyzed. First, the application of the SSIM to the endurance limit approach is described. Then, the consistency of an important hypothesis of the SSIM, the independence between the stress and strength, will be discussed.

2. The Stress-Strength Interference Method (SSIM) applied to the endurance limit approach

2.1. The SSIM

In the SSIM (Figure 1), a stress s, mean value ms, is applied to a system defined by its strength r, mean value mr. Failure will occur if s exceeds r. Hence, the grey area in Figure 1 represents the percentage of failure, i.e, the unreliability of the component.

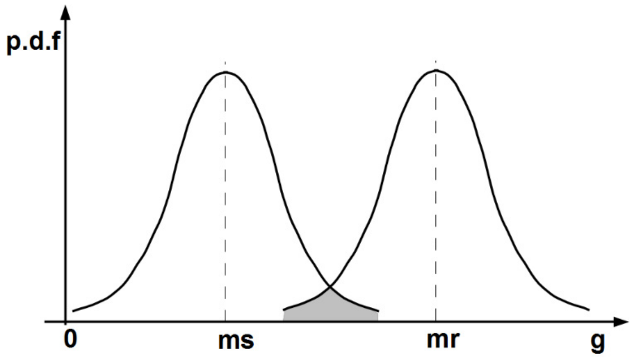

Figure 1. The Stress-Strength Interference Method. Grey area: area of failure.

2.2. Expression of stress s in the endurance limit approach

In this study, the SSIM is applied to fatigue design. The fatigue criterion utilized is the endurance limit approach.

The stress s represents the cyclic stress, i.e. the stress amplitude [5;24-25]:

$$s = \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \tag{1}$$

It should not be confused with the mean stress due to static loading defined by:

$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2} \tag{2}$$

2.3. Expression of strength r in the endurance limit approach

The strength r represents the rotating bending fatigue limit σ_d at 1.10^7 cycles [27].

2.3.1. K factors

It is assumed that the fatigue limit σ_d has been measured under rotating bending, with a small size, well-polished unnotched specimen, tested in air at 20°C, for a conventional fatigue life of 1.10^7 cycles. Variables such as the component size, environment, temperature, roughness… are taken into account thanks to K factors applied on the fatigue limit of the material [22].

- $K_{roughness}$ is the fatigue limit with the component roughness divided by the fatigue limit with low roughness (smoothly polished).

$$K_{roughness} = \frac{\sigma_d(component\ roughness)}{\sigma_d(polished)} \tag{3}$$

- Elastic Finite Element Modeling provides the elastic stresses in notches, $K_t.\sigma_{nominal}$. But the fatigue limit needs to be compared with $K_f.\sigma_{nominal}$, with K_f the effective stress concentration factor. Failure will appear if:

$$K_f.\sigma_{nominal} = \sigma_d \tag{4}$$

This equation is equivalent to

$$\sigma_d \frac{K_t}{K_f} = K_t.\sigma_{nominal} \tag{5}$$

Therefore we will define

$$K_{notch} = \frac{K_t}{K_f} \tag{6}$$

and we will compare $\sigma_d.K_{notch}$ with the stresses $K_t.\sigma_{nominal}$ given by Finite Element Analysis.

- $K_{corrosion}$ is the fatigue limit in the service environment divided by the fatigue limit in air.

$$K_{corrosion} = \frac{\sigma_d(service\ environment)}{\sigma_d(air)} \tag{7}$$

- $K_{temperature}$ is the fatigue limit at the service temperature divided by the fatigue limit at 20°C.

$$K_{temperature} = \frac{\sigma_d(service\ temperature)}{\sigma_d(20°C)} \tag{8}$$

- K_{vhcf} is the fatigue limit for the desired number of cycles (> 10^7) divided by the usual fatigue limit (1.10^6-10^7 cycles for ferrous alloys [27]).

$$K_{vhcf} = \frac{\sigma_d(expected\ fatigue\ limit)}{\sigma_d(10^7 cycles)} \tag{9}$$

Other K factors can be defined to take into account the difference between bending and traction and the effect of component size [22].

2.3.2. Mean stress correction

Goodman [21] mean stress correction is chosen in this study.

Following all of the previous definitions, the expression of the strength r is

$$r = \sigma_d . K_{tractionbending} K_{size} K_{roughness} K_{notch} K_{corrosion} K_{temperature} K_{vhcf} . \left(1 - \frac{\sigma_{mean}}{R_m}\right) = \sigma_d . \left(1 - \frac{\sigma_{mean}}{R_m}\right) . \prod_i K_i \quad (10)$$

For sake of simplicity, the geometry of the structure is deterministic. In fact, geometry scatter is included in the strength scatter. The material parameters, the factors K and the stresses are normal probabilistic variables, i.e. they are defined with a mean value, a standard deviation and a given distribution law.

2.4. Failure function g

The failure function g is defined as follows, according to the SSIM: $g = r - s$ (11)

The component fails if the strength r is lower than the stress s, so the failure area is defined by g(r,s)<0 (Figure 2).

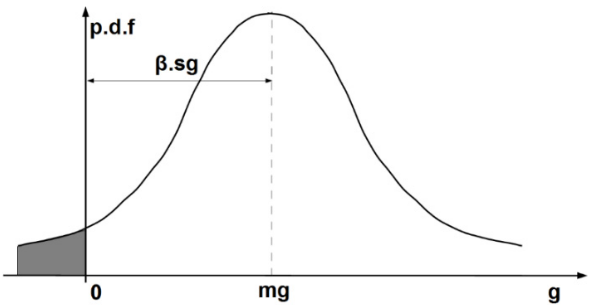

Figure 2. Failure function g and reliability index β. Grey area: percentage of failure.

The failure function g is supposed to follow a Normal Probability Density Function P.D.F, with m_g and s_g respectively mean and standard deviation of the failure function g. Thus, the unreliability P_f is the probability p that g<0, and is given by:

$$P_f = p(\mathrm{g} < 0) = \frac{1}{s_g . \sqrt{2\pi}} \int_{-\infty}^{0} e^{-1/2.\left(\frac{t-m_g}{s_g}\right)^2} . dt \quad (12)$$

3. Discussion : the independence of the random variables

3.1. The dependence between σ_a and σ_{mean}

Fatigue design is most often realized with the variables (σ_a ; σ_{mean}) or ($2.\sigma_a$; σ_{mean}) [22;24;28]. However, are the variables σ_a and σ_m independent? This will depend on the service loading.

For example, the minimum stress σ_{min} in a crane would be induced by its own weight, when the crane is not working. The maximum stress would be due to its own weight + the heaviest load the crane would lift. If the weight of the crane is supposed to be deterministic, $v(\sigma_{min}) = 0$. The variance of the maximum stress is due to the variance of the load to lift. Finally, σ_{min} and σ_{max} are independent and the mean stress σ_{mean} and stress amplitude σ_a are dependent because they both depend on σ_{min} and σ_{max}. In this example, r and s deal with σ_{mean} and σ_a while they should deal with σ_{min} and σ_{max}.

On the other hand, the independent variables can be σ_{mean} and σ_a. For example, during a flight, the mean bending moment in the wing of an aircraft is considered deterministic (one can expect engine and kerosene weight and aerodynamic lift), and the small variations of the bending moment are random and centered on zero due to gusts and taxiing loads [21].

3.2. The dependence between Strength r and Stress s due to mean stress correction

In the SSIM, it has to be assumed that r and s are independent [8-10;29-33]. But if σ_{mean} and σ_a are dependent, s and r do become dependent variables.

Thus, for the variance of the failure function g, instead of: $v_1(g) = v(r) + v(s)$ (13)

One should use the following equation: $v_2(g) = v(r) + v(s) - 2.cov(r,s)$ (14)

To investigate the consequences of this observation, the reliability index β will be introduced [7;9;15-16;19;34].

$$\beta = \frac{m(g)}{\sqrt{v(g)}} \quad (15)$$

m(g) is the average failure function and is given by $m(g) = m(r) - m(s)$ (16)

β is the number of standard deviations of g between m(g) and the failure area (Figure 2). When β increases, the reliability of the component increases.

Suppose now that r and s are independent, and define

$$\beta_1 = \frac{m(g)}{\sqrt{v(r) + v(s)}} \quad (17)$$

Suppose now that r and s are dependent, and define

$$\beta_2 = \frac{m(g)}{\sqrt{v(r) + v(s) - 2.cov(r,s)}} \quad (18)$$

It is possible to calculate the term -2.cov(r,s) analytically. From equation (16) :

$$-2.cov(r,s) = \sum_i \left(\frac{\partial g}{\partial x_i}\right)^2 .v(x_i) - \sum_i \left(\frac{\partial r}{\partial x_i}\right)^2 .v(x_i) - \sum_i \left(\frac{\partial s}{\partial x_i}\right)^2 .v(x_i) \quad (19)$$

Where x_i are the random variables that define r and s, i.e. they are : σ_d, the K factors, σ_{max}, σ_{min} and Rm.

The stress s does not depend on σ_d, K factors, and Rm so for those variables, $\partial s/\partial x_i = 0$ and $\partial g/\partial x_i = \partial r/\partial x_i$.

So, after simplification of (23):

$$-2cov(r,s) = \left(\frac{\partial g}{\partial \sigma_{max}}\right)^2 . v(\sigma_{max}) - \left(\frac{\partial r}{\partial \sigma_{max}}\right)^2 . v(\sigma_{max}) - \left(\frac{\partial s}{\partial \sigma_{max}}\right)^2 . v(\sigma_{max}) + \left(\frac{\partial g}{\partial \sigma_{min}}\right)^2 . v(\sigma_{min}) - \left(\frac{\partial r}{\partial \sigma_{min}}\right)^2 . v(\sigma_{min}) - \left(\frac{\partial s}{\partial \sigma_{min}}\right)^2 . v(\sigma_{min}) \quad (20)$$

$$\left(\frac{\partial g}{\partial \sigma_{max}}\right)^2 = \left(\left(\frac{-1}{2.Rm}.\sigma_d.\prod_i Ki\right) - 1/2\right)^2 \quad (21)$$

$$\left(\frac{\partial r}{\partial \sigma_{max}}\right)^2 = \left(\frac{-1}{2.Rm}.\sigma_d.\prod_i Ki\right)^2 \quad (22)$$

$$\left(\frac{\partial s}{\partial \sigma_{max}}\right)^2 = (1/2)^2 \quad (23)$$

The three previous equations are also valid for σ_{min} instead of σ_{max}. Finally,

$$-2cov(r,s) = \frac{1}{2.Rm}.\sigma_d.\prod K_i\,.\,(v(\sigma_{max}) - v(\sigma_{min})) \quad (24)$$

The previous quation shows that if $v(\sigma_{max}) > v(\sigma_{min})$, then $-2.cov(r,s) > 0$, and

$$\sqrt{v(r) + v(s) - 2cov(r,s)} > \sqrt{v(r) + v(s)} \quad (25)$$

Consequently, if $v(\sigma_{max}) > v(\sigma_{min})$, then $\beta_2 < \beta_1$.

If r and s are supposed independent, the reliability of the component may be overestimated.

It is worth noticing that in many structures, the condition $v(\sigma_{max}) > v(\sigma_{min})$ is fulfilled. Indeed, the minimum stress if often 0 when the component is not in use, but the maximum stress is very variable.

We will now discuss other sources of statistical dependence between the variables of the failure function g.

3.3. The independence of the K factors

The K factors might also depend on each other.

For example, a corrosive environment modifies the slope of the S-N curve and therefore suppresses the fatigue limit at 1.10^7 cycles [21]. A corrosive environment will also change the slope of the S-N curve after 1.10^7 cycles (Figure 3 curve 3). This will decrease the fatigue strength at 1.10^9 cycles [21;28;35-36], and change the value of K_{vhcf}.

Thus, in air, $K_{corrosion} = \frac{\sigma_{d1}}{\sigma_{d1}} = 1$ and $K_{vhcf}(air) = \frac{\sigma_{d2}}{\sigma_{d1}} < 1$.

Whereas in a corrosive environment, $K_{corrosion} = \frac{\sigma_{d3}}{\sigma_{d1}} < 1$ and $K_{vhcf}(corrosive\ environment) = \frac{\sigma_{d4}}{\sigma_{d3}} \neq K_{vhcf}(air)$.

As a consequence, there is a dependence between $K_{corrosion}$ and K_{vhcf} : they both depend on the environment.

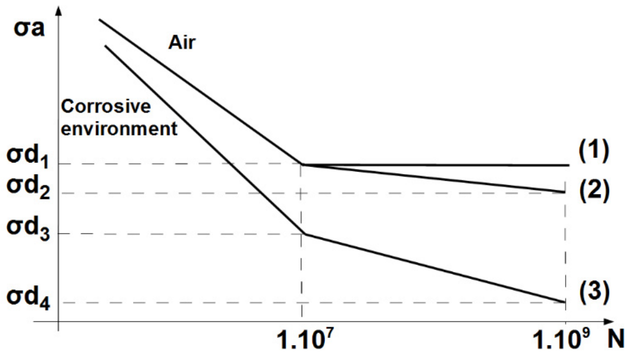

Figure 3. Typical S-N curves of ferrous alloys. (1) Theoretical curve in air, fatigue limit 1.10^7 cycles. (2) Realistic curve in air : possible decrease of fatigue strength after 1.10^7 cycles. (3) Typical curve in a corrosive environment [21;35]

Temperature also has an effect on the corrosion behavior of most materials [37]. In general, the higher the temperature, the more the metal will suffer from corrosion [37]. Therefore, $K_{temperature}$ and $K_{corrosion}$ are also correlated.

The dependence between $K_{roughness}$ and $K_{corrosion}$ can be also suspected, because the higher the roughness, the more the materiel will suffer from corrosion [38].

Some possible correlations between the K factors have been given. The point is now to investigate if ignoring them does result in conservative or unconservative predictions.

If the variables x_i are dependent,

$$v_2(g) = \sum_i \left(\frac{\partial g}{\partial x_i}\right)^2 v(x_i) + 2\sum_i \sum_j \frac{\partial g}{\partial x_i}.\frac{\partial g}{\partial x_j}.cov(x_i\,, x_j) \tag{26}$$

If the variables x_i are independent,

$$v_1(g) = \sum_i \left(\frac{\partial g}{\partial x_i}\right)^2 v(x_i) \tag{27}$$

Therefore, if $2\sum_i \sum_j \frac{\partial g}{\partial x_i}.\frac{\partial g}{\partial x_j}.cov(x_i\,, x_j) > 0$, then $v_2(g) > v_1(g)$, giving $\beta_2 < \beta_1$, and the reliability decreases.

Moreover, for the K factors, $\frac{\partial g}{\partial Ki} = \frac{1}{Ki}\sigma_d \prod_j K_j.(1 - \frac{\sigma_{max}+\sigma_{min}}{2.Rm}) > 0$, so the sign of $\partial g/(\partial K_i).\partial g/(\partial K_j).cov(K_i,K_j)$ will depend on the sign of $cov(K_i,K_j)$.

The term $cov(K_i,K_j)$ will be positive if K_i and K_j vary in a similar way, for instance if K_i increases when K_j increases.

From a physical viewpoint, this correlation between two K factors is possible:

- $K_{corrosion}$ and K_{vhcf} will both decrease in a corrosive environment (Figure 3). Thus, $cov(K_{corrosion},K_{vhcf})$ will be positive and the term $\partial g/\partial K_{corrosion}.\partial g/(\partial K_{vhcf}).cov(K_{corrosion},K_{vhcf})$ will increase the variance of g. Consequently, neglecting the covariance of $K_{corrosion}$ and K_{vhcf} results in unconservative predictions.

- When temperature increases in a corrosive environment, the corrosion will be more active. Therefore, when $K_{temperature}$ decreases, $K_{corrosion}$ decreases. Thus, cov($K_{temperature}$,$K_{corrosion}$) is positive and ignoring this covariance may result in unconservative predictions.

Dependencies can also be found between the K factors and Rm. For instance, $K_{roughness}$ and K_{notch} factors are given as a function of Rm [22;39] so they are dependent variables. Similarly, Rm depends on the service temperature, so Rm and $K_{temperature}$ are dependent variables.

A complete analysis of these dependence is beyond the scope of the present paper.

3.4. Is the endurance limit approach appropriate for probabilistic fatigue?

It has been shown above that correlations can be found between the random variables of the failure function g, due to

- the dependence between σ_a and σ_{mean}
- the mean stress correction
- the K factors.

Thus, the endurance limit approach may not offer a relevant framework for probabilistic analysis.

One question arises: could we ignore the covariances? Experimental campaigns found in the literature would enable estimating this covariances, a matrix of variance-covariance could be established and serve as a basis in simulations such as Monte-Carlo [40]. This work looks endless and it seems relevant to estimate the possible influence of the dependence of the random variables. This will be done in the next part of this paper throughout a case study.

4. Case study : fatigue design of a component made of quenched and tempered Cr-Mo steel

Consider a circular cross section, notched component. The minimum stress in the component is 0 (its own weight is negligible). Thus, σ_{min} and σ_{max} are independent. Stress s and strength r are defined with equations (3) and (13).

4.1. Estimation of P.D.F, average and standard deviation of the random variables

Rm and the K factors are supposed here to be independent. The parameters values are listed in table 1.

A normal P.D.F is assumed for Rm [5], with mean value 1025 MPa [41] and standard deviation 35 MPa [39]. The rotating bending fatigue limit is assumed to follow a normal P.D.F, mean value 398MPa [41]. Coefficient of variation will be 0.1 [22;33].

The triangular P.D.F is chosen for the K factors (Figure 4) in order to bound the possible values. Indeed, the authors wish to avoid that K factors get higher than 1, which could be physically odd (except for K_{notch}). It should be reminded that for an unsymmetrical P.D.F, the most probable value called peak is distinct from the average value.

The average and variance of a triangular P.D.F are given by:

$$m = \frac{min + peak + max}{3} \tag{28}$$

$$v = \frac{min^2 + peak^2 + max^2 - min.max - min.peak - max.peak}{18} \tag{29}$$

Table 1. Values of the parameters for the case study.

Variable	P.D.F	Min	Peak	Max	Average	s	cv	(dr/dxi)²	Weight (%)
σ_d (MPa)	Normal	278,6	398	517,40	398	39,8	0,10	1,83E-01	30,6
$K_{traction/bending}$	Triangle	0,75	0,90	1,00	0,88	0,05	0,06	3,72E+04	10,3
$K_{size\ effect}$	Triangle	0,60	0,80	1,00	0,80	0,08	0,10	4,54E+04	31,8
$K_{roughness}$	Triangle	0,70	0,80	0,90	0,80	0,04	0,05	4,54E+04	7,96
K_{notch}	Triangle	1,00	1,05	1,10	1,05	0,02	0,02	2,63E+04	1,15
$K_{corrosion}$	Triangle	0,90	1,00	1,00	0,97	0,02	0,02	3,11E+04	1,82
$K_{temperature}$	Triangle	0,66	0,90	0,90	0,82	0,06	0,07	4,32E+04	14,5
K_{vhcf}	Triangle	0,90	1,00	1,00	0,97	0,02	0,02	3,11E+04	1,82
R_m (MPa)	Normal	/	1025	/	1025	35	0,034	7,42E-09	0,00
σ_{min} (MPa)	Deterministic	0	0	0	0	0	0	7,80E-03	0,00

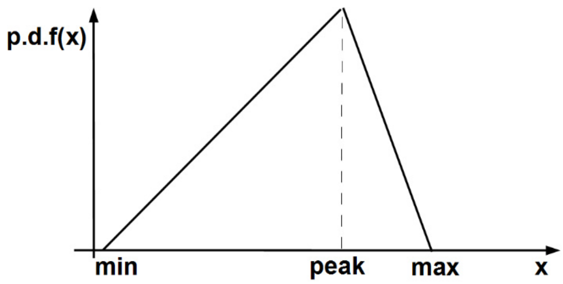

Figure 4. Triangular P.D.F. The peak is the most probable value of the P.D.F.

$K_{traction/bending}$ will have a peak value equal to 0.9 [22]. $K_{size\ effect}$ will have a peak value equal to 0.8 and a coefficient of variation of 0.1 [22;39]. The peak value of the factor $K_{roughness}$ is determined using [39]. The coefficient of variation is chosen from [22]. Minimum, peak and maximum value of K_{notch} are estimated with [39], for steel with 1000 < Rm < 2000 MPa. Values for $K_{corrosion}$ have been arbitrarily chosen.

Maximum temperature is 250°C. $K_{temperature}$ can be estimated with $K_{temperature} = 3100 / (2460+9.T)$ [42-43]. This gives $K_{temperature}$(250°C) = 0.66. On the other hand, $K_{temperature}$(250°C) = 0.9, based on Young's modulus variation [28]. Cr-Mo steel is expected to be less sensitive to high temperature than conventional steel. So the peak and maximum value of $K_{temperature}$ will be 0.9, and the minimum value will be 0.66.

The component must resist 2.10^9 cycles. The rotating bending fatigue limits of ferrous alloys are usually given for 1.10^7 cycles [27;44]. Bayraktar *et al*. observe a reduction of 0.9 for various ferrous alloys between 1.10^7 cycles and 1.10^9 cycles [44]. Pyttel *et al*. [45] observe no decrease of the rotating bending fatigue limit on notched specimens made of quenched and tempered 42CrMoS4 steel up to 1.10^9 cycles at load ratio R = 0 and -1. In this study the component is notched, so the minimum value of K_{vhcf} will be 0.9, and the peak and maximum value will be 1.

Minimum stress σ_{min} is deterministic so $v(\sigma_{min}) = 0$. The variance of σ_{max}, $v(\sigma_{max})$, is a variable.

4.2. Influence of the K factors

The weight (equation given below) of a variable x_i provides an estimation of its influence on the variance of r. The total weight of the K factors does not seem negligible compared to the weight of the fatigue limit σ_d (Table 1). As a consequence, it may be necessary to consider the covariances between the K factors.

$$weight(\%) = 100.\frac{\left(\frac{\partial r}{\partial x_i}\right)^2 v(x_i)}{\Sigma_i\left(\frac{\partial r}{\partial x_i}\right)^2 v(x_i)} \tag{30}$$

4.3. Estimation of the unreliability Pf as a function of the maximum stress variance

Whether r and s are independent or dependent, the mean value of g is: $m(g) = m(r) - m(s)$ (31)

For the sake of simplicity, the variables x_i of Table 1 are considered independent (as the estimation of covariance is not realized in this case study).

If one assumes that r and s are independent, one will probably use the equation below:

$$v_1(g) = v(r) + v(s) = \sum_i \left(\frac{\partial r}{\partial x_i}\right)^2 v(x_i) + \sum_i \left(\frac{\partial s}{\partial x_i}\right)^2 v(x_i) \tag{32}$$

If one assumes that r and s are dependent, the variance of the failure function g is given by:

$$v_2(g) = \sum_i \left(\frac{\partial g}{\partial x_i}\right)^2 v(x_i) \tag{33}$$

The unreliabilities P_{f1} and P_{f2} are then estimated with equation (12).

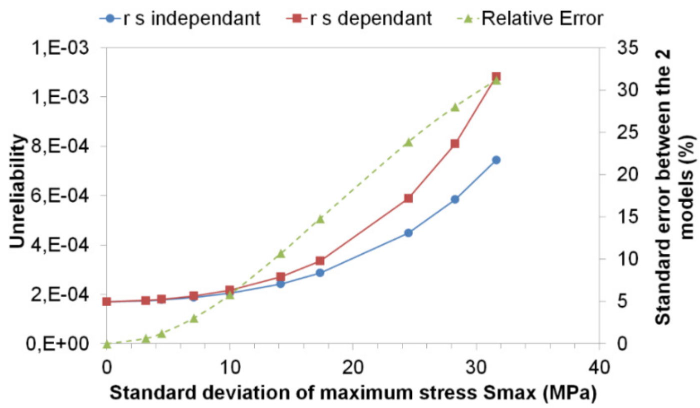

Figure 5. Unreliability as a function of the standard deviation of maximum stress considering r and s as independent variables or considering r and s as dependent variables

The relative error between the two assumptions in % is defined by

$$\varepsilon = 100.\frac{P_{f2}-P_{f1}}{P_{f2}} \tag{34}$$

In Figure 5, the unreliability is plotted against the standard deviation of σ_{max}. In the treated example, the unreliability can be increased by 30% if the dependence is not taken into account.

4.4. Dealing with the P.D.F "tails" : the concept of inherent unreliability

The values of the normal P.D.F range from -infinity to +infinity. Therefore, assuming that there is no stress in the structure (s=0), we get g = r. Negative values of the strength r are possible when using a normal P.D.F, so negative values of g become possible: the SSIM will predict a probability of failure different from zero even though the stress s is zero. This unreliability, called the inherent unreliability by Zemanick and Witt [33], has no physical meaning and illustrates the lack of precision of unbounded P.D.F.

One question arises: does the inherent unreliability influence significantly the predictions of the probabilistic model, or can it be ignored, in order to keep using the well-known normal P.D.F? In this study, the inherent unreliability is $1{,}62.10^{-8}$. This value is decades lower than the reliabilities of Figure 5 or reliabilities of the literature [31]. Thus, the negative values of the strength given by the normal P.D.F has a negligible influence.

5. Conclusion

In this study, the endurance limit approach used within the framework of probabilistic analysis has been analysed.

The following conclusions can be provided.

- For probabilistic fatigue design, it is necessary to detect the origin of the minimum, maximum and mean stresses, and use the variables that look independent, among σ_{mean}, σ_a, σ_{min} and σ_{max}.
- The SSIM applied to the endurance limit approach may provide unconservative results if it is forgotten that strength r and stress s are dependent variables, due to the mean stress correction. In the treated example, the unreliability can be increased by 30% if the dependence is not taken into account.
- Because of numerous correlations between the K factors, their suitability for probabilistic fatigue is doubtful. In a probabilistic fatigue design, roughness, corrosion, size effect…, should be included in phenomenological models, because those models deal directly with physical variables instead of using K factors. This is found, for example, in the weakest-link theory [46]. Some studies do deal with crack initiation in sound components, from a phenomenological viewpoint, within a stochastic framework [47].
- The inherent unreliability concept may be a useful tool for assessing the physical meaning of probabilistic predictions given by the SSIM. To the authors' knowledge, inherent unreliability has been rarely studied.

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