Extension of Stress and Strength Interference Theory for Conceptual Design-for-Reliability

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It has been recognized that design-for-reliability (DFR) during the conceptual design stage is very challenging. There are several gaps and deficiencies hindering the DFR implementation. The first gap is due to the disconnection between the output of the conceptual design and reliability parameters needed for the reliability modeling. The second gap is between the knowledge available during the conceptual design and the information needed for reliability analysis. The state of the art design-for-reliability research and implementation are primarily based on the traditional reliability stress and strength interference theory. The research to date has mainly focused on the embodiment design-for-reliability, since they take embodiment design data as inputs and derive reliability measures of the product as results. On the other hand, the conceptual design, in general, and functional design in specific are usually nonanalytical and nonquantitative and result in little information immediately useful for a detailed reliability analysis. Our research aims to address these gaps and deficiencies and to build a bridge between the reliability research and the conceptual design research in order to realize conceptual design-for-reliability. In this paper, we first review the state of research and practice in the fields of reliability and conceptual design. Building on the previous research, we extend the traditional reliability stress and strength interference theory and develop a conceptual stress and conceptual strength interference theory (CSCSIT) that parametrizes the conceptual design space by introducing reliability related parameters into functional design. Based on CSCSIT, a practical analysis framework is proposed to support functional design-for-reliability. A functional design example is presented to demonstrate the effectiveness of CSCSIT and the proposed framework.
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1 Introduction

Both the research community and industry have been exploring design-for-reliability (DFR) methodologies for some time [1–5]. Reliability is defined as the probability that a system or component performs the intended functions under a set of specified operational conditions for a specified period of time [6–10,2]. The design-for-reliability is defined as a structured design methodology that guides design decision-making with parametric reliability models to meet quantitative reliability requirements or goals during all design phases [11]. It has been recognized that the design-for-reliability during the conceptual design stage is particularly challenging. This is because of the gap between the output of conceptual design and reliability parameters needed for reliability modeling, and the gap between the knowledge available during the conceptual design and the information needed for the reliability analysis. Conceptual design primarily deals with formulations of function structures and generations of design concepts in response to product functional requirements. It usually does not address the details of physical components. However, the reliability research and industry reliability practice on the contrary consider the detailed formations of the physical components as necessary input in a valid reliability analysis.

Despite the difficulties and challenges for the conceptual design-for-reliability, the engineering design community and the reliability engineering community are facing the situation that an increasing number of major research and development programs, especially United States government contracts, demand the reliability requirements and goals to be established before the program starts. There is a necessity to evaluate the reliability feasibility during an early program stage. For commercial projects, companies often want to know the reliability measures at an early stage of the product development so return on investment can be evaluated for the viability of the product to the marketplace. During these stages, only top-level concepts exist for the product to be developed.

In our design-for-reliability definition, we emphasize the following aspects. First, we emphasize the pro-active nature of the DFR. We advocate that design decisions should be made based on reliability as one of the selection criteria among competing design options. Second, we emphasize the use of a parametric reliability model tied with synthesizing, analyzing, and selecting design solutions, whether at a conceptual design phase or at an embodiment design phase, to meet the system reliability requirements or goals. Third, we emphasize a structured approach, which motivates us to elevate the DFR to a prescriptive design methodology from a descriptive and ad hoc one. Our research aims to address the forementioned gaps and deficiencies, and to build a bridge between the reliability research and the conceptual design research for developing a sound design-for-reliability methodology with the emphases mentioned above.

In the rest of this paper, we first review the related work in the literature and discuss the research and application gaps in detail in Sec. 2. In Sec. 3, we review the traditional stress and strength

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interference theory (SSIT). We then extend it to a conceptual stress and conceptual strength interference theory (CSCSIT) and present its parametrization details for functional design. In Sec. 4, we present a practical CSCSIT implementation framework that supports the functional design-for-reliability. In Sec. 5, we apply the framework to a functional design example to demonstrate its effectiveness. In Sec. 6, we summarize our work, discuss the limitations of our approach, and point out the future research direction.

2 Related Work and Research Gaps

In this section, we first review reliability engineering history, research, and application progress and status. We then provide an overview of research on engineering design methodology with a primary focus on the conceptual design, followed by the review of integration aspect of reliability and design related to design-for-reliability. Thereafter we will discuss and summarize the gaps observed from reliability engineering and engineering design that hinder the design-for-reliability implementation for the conceptual design-for-reliability.

2.1 Reliability Engineering. Reliability engineering was formally established after World War II in the United States to primarily address the effectiveness of war airplanes, weapon systems, and rockets. Many reliability engineering related military standards were generated since then under United States Department of Defense to guide the reliability engineering implementation [6,8,12]. Typical reliability engineering tasks [6–8] include reliability allocation and prediction, failure modes and effects analysis [12], fault tree analysis, reliability design review, reliability testing planning and data analysis, failure reporting, analysis and corrective action implementation and monitoring, and critical parts control and management. Reliability activities of early years focused on program control, program surveillance, and quality assurance and emphasized product reliability evaluation to ensure a good product after the design was completed. As such, lots of reliability efforts were on reliability demonstration and qualification test set up and analysis. It was very loosely connected with the engineering design. From a quantitative point of view, many traditional reliability analysis methods are probability and statistics based, which are drastically different from engineering design that is primarily physics based. Typical probability and statistics based reliability analysis approaches are given by Nelson [13], Lawless [14], and Bain and Englehardt [15]. The detailed statistical analysis from traditional reliability engineering mainly focuses on local failure analysis, and probability and statistical treatment of the data. Probabilistic risk assessment (PRA) and some system reliability modeling efforts have attempted to address issues of system reliability modeling [16–21]. PRA methodology uses fault trees, event trees, and event sequence diagrams as system modeling tools [16,17,21]. Xu and Dugan [22] introduced a dynamic fault tree analysis technique to supplement event trees for modeling dynamic functional interactions. Volovoi [23] used a Petri net aging token technique to model two shared load failure scenarios. Commonality of all these modeling methods, along with the traditional reliability block diagram technique, is to create a probability net using some failure propagation logic then quantify the system reliability accordingly. The probability net does not necessarily reflect the design physics, and the probability inputs to the net may not be tied with the failure physics. Overall, it might not have been an original intention but to a large extent reliability engineering in the industry practice has been primarily a postdesign assessment and quality assurance discipline, not so much a design-in reliability activity.

2.2 Engineering Design. Various approaches have been taken toward providing a better engineering design process. The systematic design framework proposed by Pahl and Beitz [9] is a practical driven methodology that closely reflects reality and industry design practice from a design process flow perspective. The systematic treatment of the design process makes it possible for designers to manage their design activities and information more effectively. It discussed design-for-quality and used ad hoc ratings to evaluate reliability for conceptual and functional designs. Suh's axiomatic design process [24,25] provided a prescriptive way to address design detail progressions from customer needs (CNs) to function requirement (FR) formation, design parameter (DP) set up, and process variable (PV) implementation. The key ingredients of axiomatic design are the zig-zag design process and the two axioms (independence axiom and information axiom). The zig-zag process maneuvers the design progression by mapping horizontally and decomposing vertically from "what" to "how" using the independence axiom as the guides and the information axiom as the candidate concept down selection criteria. The axiomatic design process provided a systematic way for designers to generate design solutions and to make design decisions that lead to simple designs. Suh claimed that following these two axioms will greatly improve a product quality therefore reliability [25]. Altshuller's TRIZ approach [26] provided a roadmap to obtain innovative design solutions through a set of pre-established inventive principles and abstracted design solutions. The aim of the approach is to overcome technical and physical contradictions with near-ideal solutions, defined by maximizing the ratio of useful functions over undesired functions and minimizing required resources. Taguchi [27,28] systematically introduced a robust design concept, and developed an experimental based design method to achieve a robust design. Akiyama [29] presented detailed function analysis processes and techniques aimed at improving the product quality. Otto and Wood [30] discussed various techniques in product design and development that address conceptual formulation, functional design, and embodiment design issues. Stone and Wood [31] and Hirtz et al. [32] provided a set of function basis that intends to standardize and formalize function structure design, modeling, and evaluation. Hutcheson et al. [33] discussed an approach to integrate the function modeling with the behavioral modeling.

From a design process standpoint, there are three major design steps, that is, conceptual design, embodiment design and detail design [9]. We focus our interest on the conceptual design in this paper. Various text books may define the tasks of a conceptual design slightly differently. But approximately, the typical tasks [9,24,25,30] for conceptual design include the following:

1. identify all customer requirements
2. decompose and regroup the customer requirements into design requirements
3. establish functional structures
4. search for working principles and working structures
5. generate candidate conceptual design solutions
6. evaluate and down select the solutions for the down stream embodiment and detail design implementation

The above tasks are not necessarily sequential. They are actually often iterative and compounding, especially for Tasks 2, 3, and 4.

2.3 Design and Reliability Integration. It was not until the 1980s that design engineering became significantly involved in addressing reliability of the design. The early effort of the involvement was to introduce probabilistic design methodology. It quantifies randomness of engineering parameters in factor of safety calculation of stress analysis then derives the probability of failures [34,35,1]. The theoretical foundation of this approach is the stress and strength interference theory [48,4,34]. Another example of the SSIT applications was given by Kececioglu [3] who presented largely mathematical treatments of localized stress and strength interference theory implementation.

Based on SSIT, a probabilistic design analysis (PDA) methodology has been developed and has evolved significantly in the past 20–30 years [1,34–36]. The PDA methodology has been advanced

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as an important design analysis and optimization tool, called reliability based design optimization (RBDO), to support embodiment design optimization and reliability quantification. However, PDA has three limitations. The first limitation is that it only applies to embodiment designs with explicitly defined constructional structures for the reason that a probabilistic design calculation has to take detailed form design information, such as part geometries, material properties, and operating loads, as inputs [1,34–36]. The second limitation is its inapplicability in analyzing a function structure model for the mechanical stress and strength concepts are not directly applicable to the functional design. The third limitation is its limited capability to analyze a system model.

El-Haik [2] elaborated in detail how the axiomatic design methodology helps achieve a robust and six-sigma [37] quality level, and tied matrix mappings from function requirements to design parameters and process variables with reliability quantification. Wang and Jin [38] proposed to use a Bayesian Net to model function structures for relative reliability comparisons of alternative function structures. Wang and Jin [39,40] also proposed a graphical model to model and manage general engineering design and functional dependencies. To address functional design and connection of functional failures to the component failures, Grantham Lough, Stone and Tumer [41] and Stone, Tumer and Wie [42], Tumer and Stone [43] and Grantham Lough et al. [44] developed function design methods that identify failure modes and failure risks during a functional design stage and map functions to the failure modes and likelihood, based on historical similar design data and engineering knowledge. To address functional failures and their propagation, Kurtoglu and Tumer [45] proposed to analyze them with three analysis elements, which are function modeling, behavioral simulation, and failure reasoning. Krus and Grantham Lough [46] proposed to address functional failure propagation by identifying common interfaces and associated faults. Hutcheson et al. [47] analyzed the changes in functionality during transitions between critical mission events to evaluate failure effects. In summary, lots of attempts and progresses have been made to integrate reliability and design and to push reliability based design. But there is still lack of theoretically sound, seamlessly integrated, and practically implementable design-for-reliability methodology envisioned in our DFR defined in Sec. 1 across the conceptual design, embodiment design, and detail design stages.

2.4 Summary of Research and Application Gaps. First, the current conceptual design, to a large extent, is still descriptive, nonanalytical, and nonquantitative in addressing reliability. The reliability parameters are not explicitly established during the conceptual design. The outputs of a conceptual design provide a set of design concepts, function structures, working principles, and working structures, which are not immediately useful for reliability modeling because of the lack of reliability parametrization. Second, there is always a gap between the knowledge available during the conceptual design and the information needed for reliability analysis. There is a common protest and excuse from the reliability community that a valid reliability analysis cannot be performed during the conceptual design. This is because a conceptual design primarily deals with the concept formulations and function structures that respond to product functional requirements, and usually does not produce the detailed physical component information, which is considered to be necessary for a conventional reliability analysis.

During the past 10–20 years, both the engineering design and reliability engineering disciplines have advanced significantly in many areas, such as computerization of data generation, data archiving and retrieving, advanced tools, methods, and algorithm development, and automation or semi-automation of many engineering tasks. However, there is yet a significant progress to be made to address the gaps discussed above and to integrate the disciplines of reliability analysis with conceptual design.

Analyzing the details of these two gaps, we consider the first gap primarily has to be addressed from the perspective of engineering design process. The reliability parametrization has to be part of the design output embedded in the main stream design entities. The second gap has to be addressed from the reliability engineering perspective. It takes a paradigm shift for the reliability engineering to take this challenge as an opportunity for pushing the design-for-reliability upfront, starting from the conceptual design phase.

We envision a proactive design-for-reliability methodology that is built on the conceptual design research and the reliability research to close the above gaps. It starts from the conceptual design stage to drive the design to meet reliability goals while fully compatible and in line with the design synthesis, analysis, and the maturity of the design progressing through the conceptual design to the embodiment design, and to the detail design. We have started such effort by extending the traditional SSIT to the conceptual stress and conceptual strength interference theory [11]. In this paper, we elaborate more on the approach and its potential effectiveness to close the gaps discussed above.

3 Conceptual Stress and Conceptual Strength Interference Theory

In this section, we first review the traditional stress and strength interference theory. We then parametrize the conceptual design space with meaningful reliability parameters using the stress and strength concepts. With the reliability parameters defined, we introduce the definitions of the conceptual stress and the conceptual strength, and extend the traditional stress and strength interference theory to the conceptual design stage, which we call conceptual stress and conceptual strength interference theory.

3.1 Traditional Stress and Strength Interference Theory (SSIT). Disney et al. [48] and Kapur and Lamberson [4] introduced and discussed a fundamental reliability theory—the SSIT. It basically states that a failure occurs when the stress, in general, exceeds or equals the strength. Mathematically, the theory presents the failure probability (P_f) of the system as the probability that the stress exceeds the strength

$$P_f = P(\text{stress} \geq \text{strength})$$

or equivalently the reliability (R) is the probability that the stress is less than the strength

$$R = P(\text{stress} < \text{strength})$$

The original meaning of the stress and strength is purely in the mechanical sense, that is, the stress represents the mechanical loads and forces, while the strength represents the material strength of the physical part that can undertake the loads to perform its intended function. Figure 1 illustrates the concept. Equation (1) presents the mathematical formula for the case of single parameter stress and single parameter strength variable situation

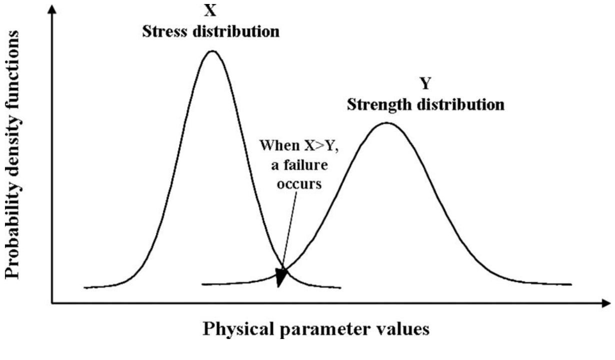

Fig. 1 Stress and strength interference diagram

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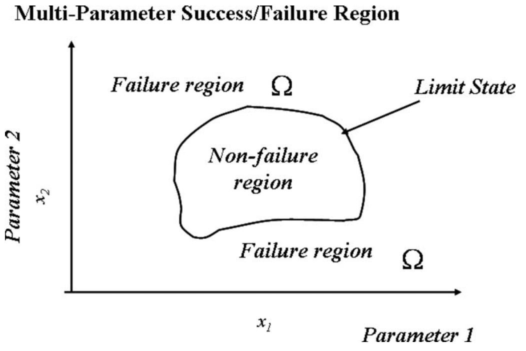

Fig. 2 Multiparameter stress and strength interference theory—limit state violation

$$P_f = P(X \geq Y) = \int_{-\infty}^{+\infty} f_y(y) \left[\int_{y}^{+\infty} f_x(x) dx \right] dy \tag{1}$$

Here, $f_x(x)$ represents the probability density function (pdf) of the stress random variable, and $f_y(y)$ represents the pdf of the strength random variable.

We can also present SSIT in terms of reliability, R

$$R = P(X < Y) = \int_{-\infty}^{+\infty} f_y(y) \left[\int_{-\infty}^{y} f_x(x) dx \right] dy \tag{2}$$

For the case of multiple parameter stress and strength, the single failure threshold value becomes multidimensional, which is called the limit state function. Figure 2 illustrates the two parameter stress and strength variable case. Basically, the stress and strength interference theory states that a failure occurs when the Parameter 1 and Parameter 2 pair (x_1,x_2) falls outside the limit state curve.

Mathematically, P_f can be represented by

$$P_f = \int\int_{(x_1,x_2)\in\Omega} f(x_1,x_2)dx_1dx_2 \tag{3}$$

Here, $f(x_1,x_2)$ represents the joint probability density function of the random variable x_1 and x_2. Ω is the failure region and "$(x_1,x_2) \in \Omega$" means (x_1,x_2) falls within Ω.

3.2 Reliability Parametrization for Conceptual Design Synthesis and Analysis. In order to introduce the conceptual stress and conceptual strength, we need to parametrize the conceptual design synthesis and analysis from a reliability standpoint. During the phase of the conceptual design, designers study the customer requirements then translate the customer requirements into a set of functional requirements. As the design synthesis progresses, the top-level functional requirements are decomposed, and energy (E), material (M), and signal (S) flows are identified. A function structure is established. As the design further progresses to the stage of formation of working principles and constructional structures, a stress function, based on the design configuration and physics laws, is generated. This stress function is then compared with the strength, which is the ability that the form structure undertakes the stress to perform the required functions successfully. The strength can be represented by a factor of safety (FS) multiplied by a stress value from the stress function. The system is considered to fail if the strength of the construction form is less than the stress imposed. We formulate the above discussion with the following matrix representations.

For the energy flow parameter vector,

$$E = [e_1,e_2, \ldots ,e_{ke}]^T$$

For the material flow parameter vector,

$$M = [m_1,m_2, \ldots ,m_{km}]^T$$

For the signal flow parameter vector,

$$S = [s_1,s_2, \ldots ,s_{ks}]^T$$

To simplify the notations, we combine the E, M, and S vectors together to form an EMS vector V with the elements $v_1,v_2, \ldots ,v_k$

$$\begin{aligned} V &= [E^T,M^T,S^T]^T = [e_1,e_2, \ldots ,e_{ke},m_1,m_2, \ldots ,m_{km},s_1,s_2, \ldots ,s_{ks}]^T \\ &\equiv [v_1,v_2, \ldots ,v_k]^T \end{aligned} \tag{4}$$

The stress function $F_{ste}=F(V)$.

Notice that F_{ste} can be a vector. We then linearize F_{ste} as a first order approximation of V, we get

$$F_{ste} = A \times V \tag{5}$$

Equation (5) is a linear mapping from EMS flow parameters to the stress function. A is the mapping matrix. Its elements are the partial derivatives of F_{ste} over V's elements. For a simple case of one-dimensional F_{ste}, we have

$$F_{ste} = A \times V = \sum_{i=1}^{k} \frac{\partial F}{\partial V_i} v_i \tag{6}$$

From the stress function F_{ste} to the strength function F_{stn}, the factor of safety is used to relate each other

$$F_{stn} = B \times G(F_{ste}) \tag{7}$$

Here B is the factor of safety matrix, a diagonal matrix with the diagonal elements as the factors of safety for the corresponding stress function elements. $G(F_{ste})$ is a function of F_{ste} and is usually a percentile of the random variable function F_{ste}. For a simple case of one-dimensional stress and strength, we have

$$F_{stn} = b \cdot G(F_{ste}) \tag{8}$$

Here b is a scalar representing the factor of safety for the one-dimensional stress and strength variable situation.

If $G(F_{ste})$ is given as the x percentile of F_{ste}, denoted as $F_{ste,x}$, we get

$$F_{stn} = b \cdot F_{ste,x} \tag{9}$$

The reliability function R, from the stress and strength interference theory, is given by the following:

$$R = \text{probability}(F_{stn} > F_{ste}) = \text{probability}(B \times G(F_{ste}) \geq F_{ste}) \tag{10}$$

For the one-dimensional case, we have

$$R = \text{probability}(b \cdot F_{ste,x} > F_{ste}) \tag{11}$$

Failure probability, P_f, is given by

$$P_f = 1 - R = \text{probability}(b \cdot F_{ste,x} \leq F_{ste}) \tag{12}$$

3.3 Conceptual Stress and Conceptual Strength for the Functional Design. Based on the above discussion and Eqs. (4)–(12), we introduce the following definitions of the conceptual stress and the conceptual strength for the functional design.

DEFINITION 1. *Conceptual stress* (*CSte*). *Given EMS flow vector* $V=[v_1,v_2, \ldots ,v_k]^T$ *of a function event within the function structure, the conceptual stress of the function event, CSte, is defined as*

$$CSte = \sum_{i=1}^{k} c_i v_i \tag{13}$$

Here c_i *is a set of constants that will be determined during a conceptual design phase. In the following sections, we will explain what* c_i *represents and their implications to the design-for-reliability.* ■

DEFINITION 2. *Conceptual strength function* (*CStn*), *determinis-*

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tic case. Given the conceptual stress (*CSte*) *of a function event within the function structure defined in Eq. (13), the conceptual strength* (*CStn*) *of the function event is defined as*

$$CStn = b \cdot CSte_{x\_\text{percentile}} \tag{14a}$$

Here b is a constant that will also be determined during the conceptual design phase. We call b a conceptual factor of safety. Later we will discuss the relationship of the conceptual factor of safety with a real factor of safety and its implications to the design-for-reliability. $CSte_{x\_\text{percentile}}$ *is a high tail end percentile of the conceptual stress function (x usually takes on 90 or 95). The x value will also be determined during the conceptual design. It is obvious that the CStn defined in Eq. (14a) is a deterministic value. In order to accommodate future embodiment design-for-reliability that deals with not only the mean value but also with the variability of the strength variable, we extend the definition of CStn from deterministic to probabilistic as follows.*

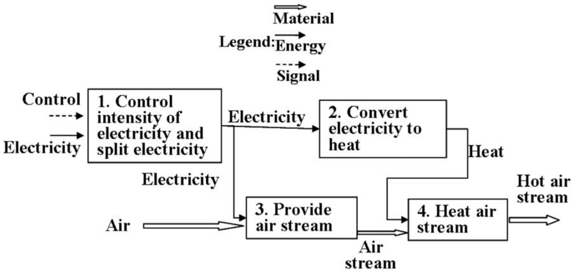
DEFINITION 2a. *Conceptual strength function* (*CStn*), *probabilistic case. Given the conceptual stress* (*CSte*) *of a function event within the function structure defined in Eq. (13), the conceptual strength* (*CStn*) *of the function event is defined as a random variable with*

$$CStn_{y\_\text{percentile}} = b \cdot CSte_{x\_\text{percentile}} \tag{14b}$$

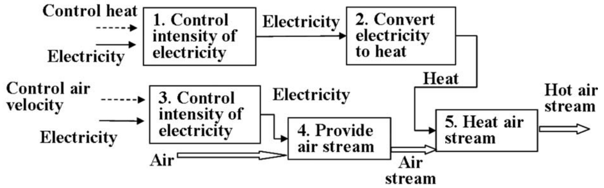
$$CStn_{50\_\text{percentile}} = CStn_{y\_\text{percentile}} \times EF_{50/y} \tag{14c}$$

$CSte_{x\_\text{percentile}}$ and b in Eqs. (14*b*) and (14*c*) are the same as in Eq. (14*a*). $CStn_{50\_\text{percentile}}$ is the 50 percentile of the strength random variable. $CStn_{y\_\text{percentile}}$ is a y percentile of the strength random variable (y is on the low tail end, usually 5 or 10). $Ef_{50/y}$ is the error factor, which is defined as the ratio of the 50 percentile of the strength random variable and y percentile ($EF_{50/y}$ is always ≥ 1, since $y \leq 50\%$). It is obvious, from Eqs. (14*a*)–(14*c*), that when $EF_{50/y}$ becomes 1, *CStn* diminishes to a single value therefore *CStn* becomes deterministic. Definition 2a extends the deterministic strength function to a probabilistic random function, while Definition 2 is just a special case of Definition 2a.

As we have seen before, a real stress is defined as a physical load that is imposed on a physical part. It is usually represented by engineering parameters such as temperature, pressure, force, flow rate, or a function of them. During a conceptual and functional design phase, constructional form structure does not exist. Therefore, we do not know what kind of physical stress will be applied to a potential constructional form that may accommodate the embodiment design of a particular function event. However, every function within the function structure takes some combination of energy, material, and signal as its input. The function, based on the energy conservation law, has to output a combination of energy, material, and signal. Therefore, it is natural to choose the conceptual stress as a function of energy, material, and signal. The simplest choice is a linear function. But we choose the linear function not just for the simplicity. The conceptual stress as chosen, will be naturally transitioned to a real stress as the design evolves from a conceptual design to an embodiment design, as a detailed stress function is established (just take partial derivatives of the stress function over v_i and substitute the constant c_i with the partial derivatives). For the conceptual strength, we can think of it as the ability that a potential constructional form will undertake the input of the function, which is the conceptual stress, and successfully complete the intended functions. Therefore we measure the conceptual strength using a probabilistic random variable function, which separates from the conceptual stress function by a conceptual factor of safety b. This b value is the ratio of a low tail end percentile of the conceptual strength probabilistic random function and a high tail end percentile of the conceptual stress probabilistic random function, as defined in Eq. (14*b*). The conceptual factor of safety, b, becomes the real factor of safety, when the design evolves into an embodiment design, as a conventional stress analysis is performed. The choice of the high tail end percentile of the conceptual stress (usually 90 percentile or 95 percentile) and the low tail end percentile of the conceptual strength (usually 5 percentile or 10 percentile), is often governed by the design team's analysis policy. By defining the conceptual stress and conceptual strength this way, we provide an analysis framework that is embedded in the synthesis process. The framework is grounded on the reliability concept of the stress and strength interference, therefore many existing reliability tools and methods can be potentially used. It also naturally connects the conceptual stress and the conceptual strength to real stress and real strength, and provides a possibility of seamless transition from the conceptual design-for-reliability to the embodiment design-for-reliability.



(a) Function Structure 1



(b) Function Structure 2

Fig. 3 Function structures of hair dryer design

Throughout this paper, we will use the hair dryer functional design example from Ref. [38] to illustrate the application of the conceptual stress and the conceptual strength. Figures 3(*a*) and 3(*b*) present two competing function structures of the hair dryer. The objectives are to evaluate and compare two alternative function design candidates, and to provide the design-for-reliability guidance and actions for a follow-on embodiment design. Here we first apply the conceptual stress and the conceptual strength to these function structures. For the simplicity of the discussion, we consider the conceptual strength function is deterministic. Therefore Eq. (14*a*) is used to define the conceptual strengths. Table 1 presents the conceptual stress and conceptual strength formulas for all functions. Section 5 will discuss how to establish all to-be-determined parameter values and their implications to design-for-reliability.

3.4 Conceptual Failure Analysis.

To put the concepts of conceptual stress and conceptual strength under the reliability perspective, and to lay down the foundation for the conceptual stress and conceptual strength interference theory, we present our view of conceptual failure analysis. This is an extension of a general real failure analysis from the embodiment design phase to the conceptual design phase. To help the discussion, we first introduce the definitions of function fault and failure.

DEFINITION 3. *Function fault. Given a function f with input flows* $V_i=\{v_{i1},\ldots,v_{ik}\}$ *and output flows* $V_o=\{v_{o1},\ldots,v_{ol}\}$ *such that the desired range of* $V_o=f(V_i)\pm\Delta_f$, *there is a functional fault if the function is in its undesired state, i.e., the output flow V falls under the following range:* $V<f(V_i)-\Delta_f$, *or* $V>f(V_i)+\Delta_f$. ■

DEFINITION 4. *Function failure. A function failure of a given function f is defined as the termination of the ability of the function to realize its required function* V_o. ■

From the above definitions, we can see that a function fault is

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Table 1 Conceptual stress and conceptual strength for hair dryer design

Fn	Function Structure 1		Function Structure 2	
	Conceptual stress	Conceptual strength	Conceptual stress	Conceptual strength
F_1	$CSte_{1,1}=c_{11,1}s_{1,1}+c_{12,1}e_{1,1}$	$CStn_{1,1}=b_{1,1}\times CSte_{1,1,x}$	$CSte_{1,2}=c_{11,2}s_{1,2}+c_{12,2}e_{1,2}$	$CStn_{1,2}=b_{1,2}\times CSte_{1,2,x}$
F_2	$CSte_{2,1}=c_{21,1}e_{2,1}$	$CStn_{2,1}=b_{2,1}\times CSte_{2,1,x}$	$CSte_{2,2}=c_{21,2}e_{2,2}$	$CStn_{2,2}=b_{2,2}\times CSte_{2,2,x}$
F_3	$CSte_{3,1}=c_{31,1}m_{3,1}+c_{32,1}e_{3,1}$	$CStn_{3,1}=b_{3,1}\times CSte_{3,1,x}$	$CSte_{3,2}=c_{31,2}s_{3,2}+c_{32,2}e_{3,2}$	$CStn_{3,2}=b_{3,2}\times CSte_{3,2,x}$
F_4	$CSte_{4,1}=c_{41,1}m_{4,1}+c_{42,1}e_{4,1}$	$CStn_{4,1}=b_{4,1}\times CSte_{4,1,x}$	$CSte_{4,2}=c_{41,2}m_{4,2}+c_{42,2}e_{4,2}$	$CStn_{4,2}=b_{4,2}\times CSte_{4,2,x}$
F_5			$CSte_{5,2}=c_{51,2}m_{5,2}+c_{52,2}e_{5,2}$	$CStn_{5,2}=b_{5,2}\times CSte_{5,2,x}$

Nomenclature:
$s_{i,j}$–signal flow for the *i*th function of function structure *j*
$e_{i,j}$–energy flow for the *i*th function of function structure *j*
$m_{i,j}$–material flow for the *i*th function of function structure *j*

not necessarily a function failure. It may or may not lead to a function failure. Often times, the analysis of how a function fault propagates to a function failure can be very difficult. A top-level function failure is the failure of the system.

The first question we ask during a failure analysis is what can go wrong for a technical system. Since during the conceptual design phase, we often only have function structure information. The failure analysis at this stage of design must deal with function faults and function failures as defined above. Utilizing the conceptual stress and conceptual strength concepts, we analyze the following possible failure scenarios.

Case 1. The conceptual stress is bigger than what is assumed such that the corresponding function(s) cannot perform as expected. In the hair dryer example, if the voltage of the electricity getting into the function "Convert the intensity of the electricity" is twice as assumed, the function "control" probably would not perform adequately. The root cause of such failure can be an uncertainty or wrong assumption in the stress, or a more complicated case that is due to dependency of multiple function events that causes the perturbation of the stress, or the most complicate situation that is unknown/unpredictable function fault propagation.

Case 2. The conceptual strength is less than what is designed. This is the case that the incoming stress is within nominal design range, while the potential constructional structure and forms are incapable of dealing with the stress. The root causes of this failure scenario can be underdesign (bad embodiment design), or underbuild (bad manufacturing). In the air dryer example, if the physical entity that embodies the function "Convert the intensity of the electricity" is not strong enough, it probably would not be able to take the electric load.

Case 3. A function design has a loophole or a sneak circuit condition [49] that leads to one of the following situations:

1. subfunctions do not cover the higher-level function
2. function interactions and/or dependencies introduce an unexpected prohibition of execution of a required function

For Case 1, the root cause is a function design failure. The function design either does not decompose a top-level function adequately to subfunctions, or some necessary subfunctions do not exist. For Case 2, it is simply an inherent design difficulty for the function design. There are some research attempts to analyze this type of failures [34,42–46], but there are lot to do to reach the point that this type of failures can be predicted, analyzed, and therefore prevented during a conceptual design phase for a complex technical system.

Case 4. A function fault propagates to a function failure. This is also associated with functional interactions, integrations, and dependencies. This type of failures is also difficult to analyze because a functional fault is not easy to define, the boundary of abnormality and normality of the functional performance often cannot be locally and explicitly determined, and the propagation paths and propagation physics can be very dynamic and difficult to simulate and analyze.

For Case 3 or Case 4, the ultimate failure phenomenon still can be attributed to overstress or understrength, as described in the failure scenario categories 1 and 2, but in a more general sense, which is incompatibility of the stress and the strength. For these cases, the faulty stress or faulty strength can be a complex function of several local stresses or strengths.

Case 5. A fault of function structure or construction form leads to an unexpected harmful or useless function, regardless of whether all required functions perform adequately or not. The former can be a safety concern, and the later is about waste of energy or reduction in efficiency. This can be due to a function design loophole, complex and unpredictable functional fault propagation, an embodiment design deficiency, a manufacturing error, or, more generally, a combination of all. From a physics failure standpoint, it is the case that energy equilibrium does not obey the desired intention. Energy, material, and signal flows go somewhere else and not as intended. From the stress and strength interference perspective, some fault occurs somewhere in the chain of functional events, either on the stress or on strength side or on both, triggering the harmful or useless function; however, the adverse effect may not be to the extent affecting the nominally designed functional performance.

The conceptual stress and conceptual strength interference approach, presented in Sec. 3.5, can potentially handle all five failure cases discussed above.

3.5 Toward a Conceptual Stress and Conceptual Strength Interference Theory (CSCSIT).

Following the SSIT [48,34,4], CSCSIT is intended to be a reliability theory that evaluates functional failures and provides guidance for design decision-making during the conceptual design stage. In CSCSIT, we define that a failure occurs when the conceptual stress exceeds the conceptual strength for any of the function events. Therefore, the failure probability ($P_{f,i}$) for the function i of the function structure is given by

$$P_{f,i} = \text{probability}(CSte_i \geq CStn_i) \tag{15}$$

Here $CSte_i$ is the conceptual stress and $CStn_i$ is the conceptual strength for the *i*th function of the function structure, as defined by Eqs. (13) and (14*a*) or Eqs. (14*b*) and (14*c*), respectively.

And the system failure probability, $P_{f,s}$, for the function structure, is given by

$$P_{f,s} = \text{probability}(Cste_1 \geq CStn_1 \cup Cste_2 \geq CStn_2 \cup \ldots Cste_k \geq CStn_k) \tag{16}$$

Here K is the total number of the functions of the function structure. The symbol $\cup$ represents the union of the probability events $\{CSte_1 > CStn_1\}, \{CSte_2 > CStn_2\}, \ldots, \{CSte_k > CStn_k\}$.

We can also represent Eqs. (15) and (16) in terms of reliability as follows:

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$$R_i = \text{probability}(CSte_i < CStn_i) \tag{17}$$

$$R_s = \text{probability}(CSte_1 < CStn_1 \cap Cste_2 < CStn_2 \cap \ldots Cste_k < CStn_k) \tag{18}$$

Here R_i is the reliability for the ith function of the function structure, and R_s is the system reliability for the function structure. The symbol $\cap$ represents the intersection of the probability events $\{CSte_1 < CStn_1\}, \{CSte_2 < CStn_2\}, \ldots, CSte_k < CStn_k\}$.

4 A CSCSIT Implementation Framework

Our initial CSCSIT framework is composed of a set of conceptual parameters that CSCSIT requires, a number of conceptual design-for-reliability wants, and the steps through which a functional design-for-reliability can be practically implemented. The following are the elements of the framework.

For the CSCSIT parameter list,

- function structures that provide EMS (energy, material and signal) flow paths
- EMS parameters flowing in and out of each function
- probability distributions of EMS parameters
- coefficients of the conceptual stress, c_i, in Eq. (13)
- the x percentile value of the conceptual stress in Eq. (14*a*)
- the conceptual factor of safety value b in the conceptual strength equation (14*a*)
- the y percentile value in the conceptual strength equation (14*b*)
- error factor, $EF_{50/y}$ in Eq. (14*c*)

For the conceptual design-for-reliability wants,

- evaluate reliability of the function structure quantitatively
- identify function structure weak spots and analyze reliability sensitivity
- evaluate competing designs for relative reliability comparison
- identify risky items as actions for embodiment risk-based design

For CSCSIT framework and implementation steps,

1. define the function structure
2. list EMS parameters for each function from function structure graph
3. establish the coefficients of the conceptual stress function (c_i)
4. estimate or assign probability distributions for EMS parameters
5. assign x percentile value of the conceptual stress, the conceptual factor of safety (b value), y percentile value of the conceptual strength, and error factor, $Ef_{50/y}$, for each function
6. establish a simulation model to evaluate Eq. (16) or Eq. (18)
7. run the simulation model and investigate and summarize the simulation results
8. conduct sensitivity analyses if needed
9. recommend design-for-reliability and risk-based design actions

We briefly describe each of the steps as follows.

Step 1. Define the function structure. The candidate function structures are generated based on the customer requirements, design team's experience, physical principles and limits, and engineering common senses. Lots of research works have provided a base for the function structure generation. For example, the works of Stone and Wood [31] and Hirtz et al. [32] on the development of functional basis and its application provide a very good starting point for establishing a function structure and a promising roadmap for standardizing function taxonomy. As we reviewed the related research work in Sec. 2, we pointed out the gap between the functional modeling and reliability modeling. Our CSCSIT is such an attempt that is based on the functional modeling research and reliability research to address the gap, and potentially to help improve the function modeling so that it can provide a reliability parametrized function modeling structure.

Step 2. List EMS parameters for each function. These parameters are listed in the function structure diagram or can be derived from the function description. This approach requires the function structure development identifies all possible and independent EMS parameters explicitly.

Step 3. Establish the coefficients of the conceptual stress functions (c_i). As mentioned earlier, c_i will be evolved to partial derivatives of the real stress function over the EMS parameters. But at the conceptual design stage, we do not have the stress functions. One nice feature of the CSCSIT is that only relative ratings matter for all the c_i since both conceptual stress and conceptual strength functions contain the c_i constants and failure probability calculation of $P(CSte \geq CStn)$ is not affected by the absolute magnitude of c_i. This makes it easier to determine c_i. Several methods can be used to establish c_i. Even though the stress function is undefined, the engineering and physics knowledge from the function definition probably provides enough data and information to derive approximate c_i. Some similar functions from existing designs may also provide useful data. In cases where existing data are limited, we can always use the survey method, i.e., to survey the design team experts to obtain the relative importance ratings of all EMS parameters then convert them to c_i. This set of importance measures, c_i, represents the design team's best knowledge on the EMS parameters. It can also represent the team's desire to design the system with predetermined c_i as preferred ratings of all c_i for design-for-reliability. To perform design-for-reliability analysis, we cannot wait until all the data are available for the design to proceed. Sometimes subjective assessment of c_i becomes the only viable way and a necessary step to move design forward. As the design progresses to a working structure and form structure formulation, c_i will be updated iteratively and eventually will converge to the partial derivatives of the real stress function. It is natural that a subjective desire and objective data or evidence converge during a progressive design cycle toward a final design and a final product.

Step 4. Estimate or assign probability distributions for EMS parameters. Either physics boundary of the system, some constraints, system specifications, or energy and mass conservation laws will tell us or allow us to derive the limits of EMS parameters. For the parameter probability distribution, we assign a normal distribution for symmetric bell shape distribution, and a lognormal, gamma, Weibull, or beta distribution for a skewed distribution. The distribution parameters, such as mean, standard deviation, and location, can be anchored to the parameter limits. The distribution choice usually is not sensitive to the analysis results, and the difference is often within the noise level under the context of the conceptual design. A sensitivity analysis can always be conducted to investigate the sensitivity of the distribution selection, if needed. If it turns out that the distribution selection significantly affects the results, more analysis effort can be devoted to carefully select the distribution which grounds on some physical rationales, such as right-skewness or left-skewness, upper side bounded or lower side bounded, etc. If EMS parameters are not physically or statistically independent, dependency relationships need to be defined using physics models or experimental or historical data.

Step 5. Assign x percentile value of the conceptual stress, the conceptual factor of safety (b value), y percentile value of the conceptual strength, and error factor, $EF_{50/y}$. For the real stress and strength interference analysis, the x percentile, b, and y percentile values are usually defined in the design team's analysis policy manual. These values should be used as starting point for CSCSIT analysis, which follows the consistent analysis policy

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Table 2 ***$EF_{50/5}$* as function of *cv* for normal distribution**

cv	0%	10%	20%	30%	40%	50%
$EF_{50/5}$	1.0	1.2	1.5	2.0	2.9	5.6

within the design team. As we mentioned earlier, the x percentile generally takes on a high tail end percentile of the stress function (95 percentile or 90 percentile), and the y percentile generally takes on a low tail end percentile of the strength function (5 percentile or 10 percentile). The conceptual factor of safety (b value) takes the minimum factor of safety defined in the design team's analysis policy manual. $EF_{50/y}$ measures the dispersion of the strength distribution. It is unknown during the conceptual design stage since construction forms do not exist. However, this is another parameter that serves the purpose of transitioning from conceptual design-for-reliability to embodiment design-for-reliability. $EF_{50/y}$ is defined as the ratio of 50 percentile of the strength distribution over the y percentile of the distribution. As we mentioned earlier, $EF_{50/y}=1$ means the distribution shrinks to a single point so the strength distribution becomes a single deterministic point. Table 2 will help us to select $EF_{50/5}$ value for the case $y=5$ percentile, based on the knowledge or desire of the coefficient of variation (cv) of the distribution.

$EF_{50/5}$ values in Table 2 are derived from the following formula:

$$EF_{50/5} \equiv \frac{50\_\text{percentile}}{5\_\text{percentile}} = \frac{\mu}{\mu - 1.645\sigma} = \frac{1}{1 - 1.645cv} \qquad (19)$$

Here μ is the mean of the distribution (for normal distribution, the mean equals the 50 percentile), and σ is the standard deviation of the distribution. cv is the coefficient of variation of the distribution, which is equal to σ/μ.

$EF_{50/5}$ can be used as a sensitivity analysis and trade study parameter during CSCSIT analysis. When the design progresses to the embodiment design, it will guide the embodiment design-for-reliability that addresses the variability due to the strength parameters.

Step 6. Establish a simulation model to evaluate Eqs. (16) and (18). For this paper, we use the CRYSTAL BALL [50] simulation tool to build the model and to estimate $P_{f,s}$ or R_s in Eqs. (16) and (18) for a CSCSIT illustration. Recognizing Eqs. (16) and (18) can be very difficult to evaluate just by simulations, we intend to devote a research effort to quantify $P_{f,s}$ or R_s with the combination of analytical approximation modeling and computer simulations.

For Steps 7–9, we will illustrate them with the example in Sec. 5.

5 Case Example

To demonstrate the efficacy of our proposed CSCSIT framework, we apply it to the hair dryer example discussed previously. Figures 3(*a*) and 3(*b*) present two competing function structures. Table 3 lists all EMS parameters for each of the function structures. The EMS parameters can be determined by reading from the function structure graphs of Fig. 3.

Table 3 **EMS parameters for the hair dryer function design**

N	Function Structure 1		Function Structure 2	
	Inlet	Outlet	Inlet	Outlet
1	Control Signal -Signal Type -Magnitude Electricity -Voltage -Current	Electricity -Voltage -Current	Control Signal -Signal type -Magnitude Electricity -Voltage -Current	Electricity -Voltage -Current
2	Electricity -Voltage -Current	Heat -Enthalpy	Electricity -Voltage -Current	Heat -Enthalpy
3	Electricity -Voltage -Current Air -Temperature -Velocity	Air -Temperature -Velocity	Control Signal -Signal type -Magnitude Electricity -Voltage -Current	Electricity -Voltage -Current
4	Heat -Enthalpy AIR -Temperature -Velocity	Air -Temperature -Velocity	Air -Temperature -Velocity Electricity -Voltage -Current	Air -Temperature -Velocity
5			Heat -Enthalpy Air -Temperature -Velocity	Air -Temperature -Velocity

As we mentioned early, the design team should decide what the c_i (i.e., coefficients of the conceptual stress functions) should be based on the engineering data available, team's knowledge, desire, and/or preference of relative importance of the EMS parameters. For the illustrative purpose, we chose to ignore the c_i for signal and air (i.e., $c_i=0$ for signal and air flows). So we only have one constant left for each function for both inlet and outlet EMS flows. So $c_i=1$ for all remaining c_i. (Remember c_i is about relative importance. Since only one c_i is left, any nonzero value can be assigned that will not affect the CSCSIT analysis results.) Table 1 provides all conceptual stress and conceptual strength functions. For the probability distributions, we assign normal distributions to all EMS parameters with means and standard deviations following energy and mass conservation laws. For Function Structure 1, Function 1 has a subfunction "split." We assign a uniform distribution for the electricity flow distribution to the downstream Functions 2 and 3. For the x percentile of the conceptual stress random function, we chose the x percentile as 95 percentile. For the conceptual factor of safety values, we use $b=1.1$ as a starting value. For the conceptual strength variables, we consider them to be deterministic for the convenience of illustration of this example so $Ef_{50/y}=1$. As we mentioned early, all these values can be determined either based on experience, engineering knowledge, historical data, or the design team's policy. All are the inputs to the simulation model, and all can be changed easily as sensitivity analysis parameters. We establish a computer simulation model using the CRYSTAL BALL simulation tool. Before we present the simulation results, we list the following assumptions for this analysis.

- Strength variable is treated as deterministic, and its variability is not counted (this means this simulation does not count variability in design parameters and process variables).
- All EMS parameters are statistically independent.
- Failure is defined as a failure to perform any desired function, measured by

$$P_{f,s} = \text{probability}(Cste_1 \geq CStn_1 \cup Cste_2 \geq CStn_2 \cup \ldots Cste_k \geq CStn_k)$$

So for Function Structure 1, failure of any one or more of the four functions leads to a system failure. For Function Structure 2, failure of any one or more of the five functions leads to a system failure.

We should point out, these assumptions are listed for correctly understanding and interpreting the result of this specific analysis.

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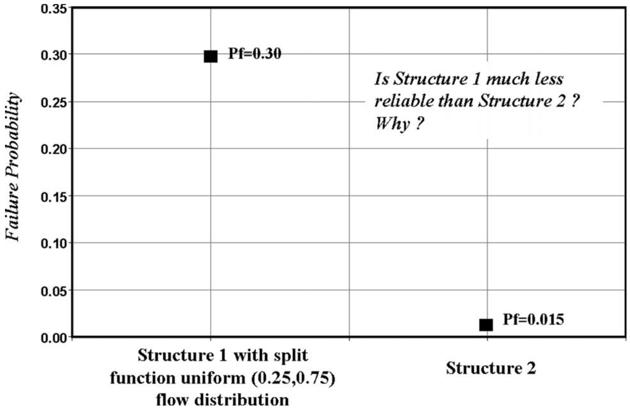

Fig. 4 Hair dryer failure probability

None of these assumptions impair the CSCSIT implementation. Conversely, assumption variations will help CSCSIT to refine detailed modeling treatment techniques. For example, for the case that not all EMS parameters are statistically independent, a computer simulation can assign statistical correlations among correlated parameters based on available historical or experimental data or engineering knowledge.

Figure 4 presents the result showing the failure probability comparison between Function Structures 1 and 2. It shows that Function Structure 2 is much more reliable than Function Structure 1 (about 20 times more). Why? We can look into the individual failure probabilities of Function Structure 1, which are shown in Fig. 5.

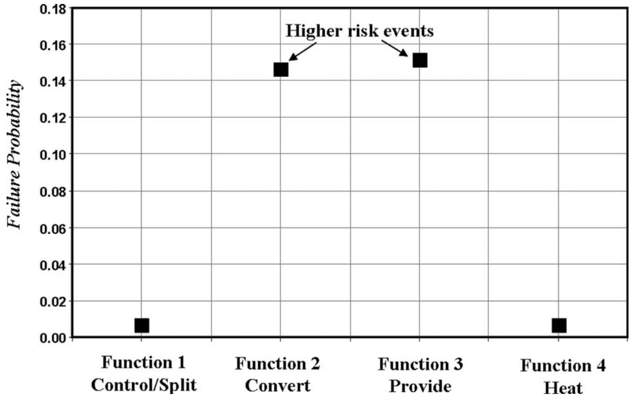

Fig. 5 Individual event failure probability for Function Structure 1

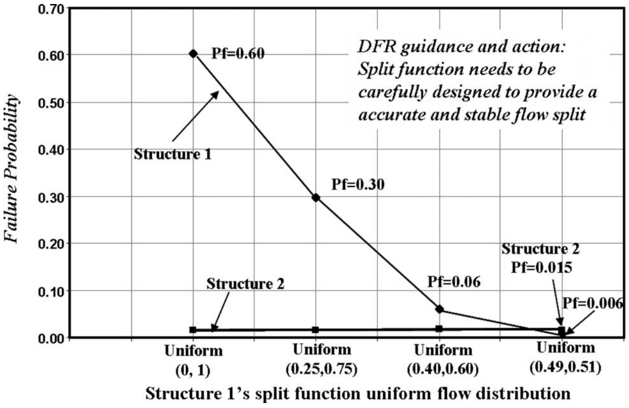

Fig. 6 Failure probability of Function Structure 1 as function of split function variability

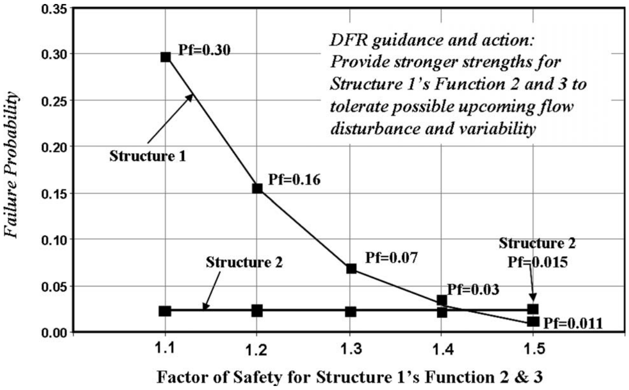

Fig. 7 Failure probability of Function Structure 1 as function of increased factor of safety for Functions 2 and 3

Figure 5 points out Function 2 and Function 3 are higher risk items for Function Structure 1. This is due to the electricity flow disturbance and variability from upstream Function 1's split function. Figure 6 shows the sensitivity of flow split stability on the system failure probability. It indicates that, the more the electricity flow splits accurately and steadily, the more reliable the system. When the flow splits 50%/50% exactly as intended, Function Structure 1 is actually more reliable than Function Structure 2. The cause of unreliability of Function Structure 1 is the split function's uncertainty and variability. *How do we fix the problem to prevent failures?* There are two ways. One way is to carefully design the split function and to tightly control the split uncertainty and variability as Fig. 6 suggests. Another way is to enhance the strengths of the downstream Functions 2 and 3 such that they can tolerate more electricity variation. Figure 7 shows the sensitivity how failure probability changes when we enhance the strengths of Functions 2 and 3 with increased factor of safety from 1.1 to 1.5. When the factor of safety is increased to 1.5 for these two functions, the failure probability of Function Structure 1 is reduced to about the same level as Function Structure 2. We can also consider extending our analysis from the deterministic strength variables to probabilistic distributions such that we can reduce failure probability by adjusting distribution means and spreads.

To summarize the results, Function Structure 2 is more reliable than Function Structure 1 unless we pay a greater attention to Structure 1's split function design and embodiment implementation, or alternatively pay extra cost to address "higher risk items" that is to enhance the downstream functions' strengths. The result provides a clear roadmap for design-for-reliability and pinpoints specific design actions to address higher risk items for reliability improvement. It quantifies reliability deltas for alternative design improvement options, which is very valuable information for a design team to make benefit-cost trade decision. This example shows the CSCSIT methodology enables us to satisfy all DFR wants outlined in Sec. 4 with only conceptual design data available. It illustrates its potential to close the gap between the output of the conceptual design and reliability parameters needed for the reliability modeling, and the gap between the knowledge available during the conceptual design and information needed for the reliability analysis.

6 Concluding Remarks

A major challenge for bringing design-for-reliability to the early stage of engineering design is how one can derive reliability implications based on the limited conceptual design information. The review of existing research from both engineering design and reliability engineering reveals the significant gaps to realize that goal. We introduced the concepts of conceptual stress and concep-

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tual strength based on the function design research and the reliability research, and parametrized the conceptual design space with reliability meaningful parameters. We extended the traditional reliability stress and strength interference theory to the conceptual stress and conceptual strength interference theory and applied it to the function design. With CSCSIT, we can assess how the selection of functions and the arrangement of the function structure may impact the overall system reliability for possible embodiments. The assessment not only allows designers to compare alternative function structures but also provides critical information that can be used to guide follow-on embodiment designs in terms of acceptable reliability ranges of function fulfillment. We developed a CSCSIT implementation framework that supports the conceptual design-for-reliability and also naturally bridges the function design-for-reliability with the embodiment design-for-reliability. Based on the reliability parametrization, the computer simulation model allows us to model functional flow paths of the EMS flows, and quantify the probability of flow anomaly threshold violation therefore calculating the system reliability. The illustrative example demonstrates the potential efficacy and easiness of the CSCSIT methodology and its implementation.

Though CSCSIT has made a significant progress toward addressing the conceptual design-for-reliability, there are several limitations in its implementation. The first limitation is its reliance on the completeness and adequacy of the function structure. In order to accurately predict the system reliability, the function structure has to reflect the function failure physics, which may not be an easy task. The second limitation is the reliability modeling of CSCSIT. Though the attempt has been made in our approach to parametrize the conceptual design space with meaningful reliability parameters, the consistency across all functions within the function structure may not be easily achieved. Both the evaluation and ways to achieve the consistency need to be explored. The third limitation is the failure probability calculation. Using computer simulation, as in the illustrative example in the paper, to compute the failure probability may not be viable for some practical conceptual design applications. Future research is needed to address the applicability of such calculations.

The introduction of CSCSIT brings many research opportunities to further substantiate and enhance the conceptual design-for-reliability. In addition to addressing the limitations discussed above, our future research will further define CSCSIT parametrization details (e.g., defining conceptual stress and conceptual strength parameters relevant to various conceptual and function design entities) and to fill in the research gaps between the current function modeling and the CSCSIT implementation. Other potential research areas are to devise reliability algorithms and optimization methods for conceptual design-for-reliability based on the CSCSIT framework, to develop CSCSIT methodology details that address function interactions, function fault/failure propagation, and dynamic function effects, to develop computer tools for general CSCSIT implementation, and to further enhance the link between the conceptual design-for-reliability and the embodiment design-for-reliability.

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