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Correlation and difference between stoll criterion and damage integral model for burn evaluation of thermal protective clothing

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ABSTRACT

Empirical Stoll criterion and the damage integral model are two methods that are often used for burn injury prediction in the evaluation of thermal protective clothing. As researchers have previously reported different burn results from these two methods, a quantitative analysis on the correlation and difference between them is conducted by numerical simulation and experimental studies. By introducing and calculating the factor of accumulated energy on the skin surface, the Stoll criterion, the damage integral model and experimental cases are correlated on the same scale, to allow for comparisons. Results showed that there is discrepancy between the simulated burn curve and Stoll curve before a material test begins. Also, the non-rectangular heat shape beneath fabrics was found to accelerate skin burn injury. As the Stoll curve assumes constant heat intensity, it underestimates the severity of burn injury. It is suggested that every damage integral model should be calibrated with empirical burn data before application. Once it reaches good agreement with the empirical burn data, it will promise more realistic predictions in material tests, as the realistic heat boundary is used.

1. Introduction

Potential fire risks are present in both natural [1] and urban cases [2], for instance post-earthquake [3], and from chemical fireballs [4]. Even with protection from the utilization of flame-resistant materials, human skin is likely to get injured due to thermal stimulation [5,6]. Many methods are available to predict this burn injury, such as Moritz and Henriques [7], Buettner [8], Stoll and Chianta [9], Morse et al. [10], Mehta and Wong [11] and Takata [12]. Among these methods, two methods are now widely used by researchers [13–15] and employed as standards. One is the empirical burn criterion created by Stoll and Chianta [9] and the other is the damage integral model based on the bio-heat transfer model and Henriques equation.

Even though different standards all aim to serve the same purpose of evaluating thermal protective clothing and materials, each adopt different burn injury prediction methods. For instance, for the evaluation of unsteady-state heat transfer (ASTM F2703, ISO9151) and radiant heat performance (ASTM F2702, ISO6942) of flame resistant materials, the empirical Stoll criterion is adopted. While on the other hand, for measuring the stored energy of firefighter's protective clothing systems (ASTM F2731) and the evaluation of flame resistant clothing using instrumented manikin (ASTM F1930, ISO13506), the damage integral model is adopted. However, researchers have reported different burn results using these two prediction methods. Song et al. [16] evaluated firefighter clothing composites exposed to various heat conditions and observed large differences in predicted burn time when different methods were used. This difference ranged from 3 to 5 s in flash fire exposures and up to 10–25 s in lower heat intensity exposures.

Stoll and Chianta [9] also reminded users that when applying their data, it was absolutely essential that the heat pulse used be rectangular, while also, in their experimental studies, the constant heat exposure and unclothed human skin are used [17]. It is obvious that once clothing fabric is placed between heat source and human skin, the heat pulse on skin surface will be different. In Fig. 1, Holcombe and Hoschke [18] showed the instantaneous heat flux beneath different fabrics, together with the original burn threshold curve developed by Stoll and Chianta [9]. They pointed out that in no case does the heat pulse under the fabrics approach the rectangular profile, which is required for the burn threshold. Similar heat flux profiles can also be found elsewhere [19]. The damage integral model, however, is based on the skin temperature field and Henriques equation, thus it is more flexible for various heat shape profiles [16].

Some researchers [16,18] made hypotheses that the heat flux shape

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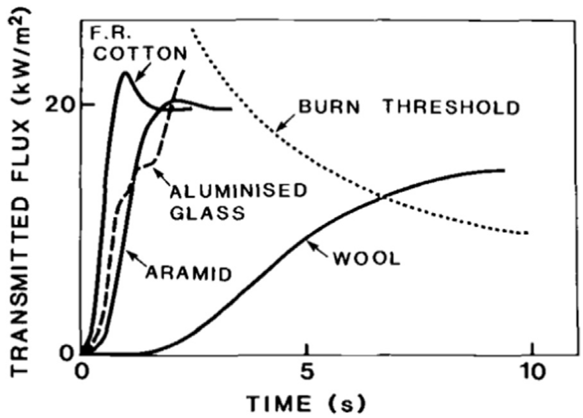

Fig. 1. The non-rectangular character of heat flux profiles beneath different fabrics [18].

could be the possible reason for the difference between the Stoll criterion and the damage integral methods. But none of them gave convincing data to clarify how the real heat flux shape from experimentation influences the burn prediction. This is due to the lack of a way to correlate these two methods on the same scale. The difficulty of the correlation is due to the fact that the studies by Stoll and Chianta [9] are based on in-vivo human experimental data while the damage integral model is based on a mathematical model validated by ex-vivo animal experiments. In our study, we introduced and calculated the factor of accumulated energy on the skin surface when burn is induced. By calculating this factor, the Stoll curve, the damage integral method and the experimental cases can be correlated and compared directly on the same scale. In this way, the influence of real heat flux shape could be examined and differences between these two prediction methods before and after material tests could also be clarified.

2. Numerical study

2.1. Empirical criterion and damage integral model

2.1.1. Stoll curve

Originally, the Stoll criterion is the relationship between a constant heat flux and time to 2nd degree burns. However, when the heat flux beneath the protective fabric is not constant, therefore the original Stoll criterion is not applicable. In application, this relationship between heat flux and the time to 2nd degree burn is converted to the relationship between the temperature rises of the sensor and time to 2nd degree burn which is known as the Stoll curve [16,20]. In recent years, as new sensors are developed, an energy form of the Stoll curve is suggested by related ASTM standards [21–23]. This energy form of the Stoll curve is the relationship between the accumulated energy on the skin surface and 2nd degree burn time. Detailed discussion about the Stoll criterion and the Stoll curve can be found in our previous study [24]. In this study, the energy form of the Stoll curve is introduced and used, as the energy equivalent data is applicable to a numerical study where no sensor is used.

2.1.2. Damage integral method

More and more sophisticated models of heat transfer [25] and skin burn injury [26,27] have been introduced in recent years, two of which have won world-wide attention and high recognition. One model proposed by Torvi in 1992 [28] is popular among investigators [16,29]and is also suggested in the appendix of the standard ISO13506-08 [30]. On the other hand, ASTM's simple but very effective model can also predict skin burn. The simplicity of this model is due to use of the heat conduction equation to simulate skin temperature field in which parameters were obtained using numerical optimization techniques [31] to calculate back from the Stoll and Greene experiments. In the present study, Torvi's model is used for two reasons: firstly to make easy comparisons with the study of Song et al. [16] where Torvi's model [16] is also selected; and secondly, as ASTM's model is back calculated one from Stoll's data, it won't be able to show the possible differences in a comprehensive way.

Torvi's model was developed in MATLAB with the temperature field of skin being described as the simplified Pennes bio-heat transfer equation as Eq. (1).

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} + \omega_b \rho_b C_{p,b}(T_b - T) \tag{1}$$

Where ρ, C_p, k and T are the density, specific heat, thermal conductivity, and temperature of skin tissue, respectively; ρ_b, $C_{p,b}$, T_b are the density, specific heat, and temperature of the blood, respectively; ω_b is the blood perfusion rate per unit volume.

The initial and boundary conditions are as shown in Eqs. (2)–(5) below:

$$T(x,\ t=0) = T_i(x,\ t=0,\ (0 \le x \le L) \tag{2}$$

$$q(x=0,\ t) = q(t),\ (0 \le_t \le_{t\,\exp}) \tag{3}$$

$$q(x=0,\ t) = 0,\ (t > t_{\exp}) \tag{4}$$

$$T(x=L,\ t) = T_c = 37°C,\ (t \ge 0) \tag{5}$$

Where t_{exp} is the exposure time and *q(t)* represents heat flux incident on skin surface which will be defined respectively in different cases. The initial conditions of the skin T_i *(x,t=0)* are represented by a linear temperature distribution from the epidermis surface (32.5 °C) to the subcutaneous base (37 °C).

This partial differential equation can be solved using the finite element method by calling the pdepe function in MATLAB. The grid size used is 0.00001 m with a time step of 0.01 s [32] while thermo-physical properties of the skin are obtained from Torvi [28].

Once the temperature field of skin is solved, time to 2nd and 3rd degree burn were determined when the integral parameter Ω reaches 1.0 at two depths respectively (epidermis–dermis interface and dermis-subcutaneous tissue interface) calculated by Eq. (6). Parameters in the integral equation can be found in [31].

$$\Omega = \int_0^t P\exp(-\Delta E/RT)dt \tag{6}$$

Where Ω is the burn injury parameter; *P*,*exp*, *R* is pre-exponential term, natural exponential, and the universal gas constant respectively; ΔE and T is the activation energy and absolute temperature of skin; t is the total time for which T is above 44 °C.

For the validation of Torvi's model, the simulations of Torvi's study derived from literature [33], were reproduced within our model. As shown in Tables 1 and 2, time to both 2nd and 3rd degree burn predicted by our model are in good agreement with Torvi.

2.2. Numerical simulation

In order to correlate the Stoll curve and the damage integral model on the same scale, the accumulated energy on skin surface when 2nd degree burn is reduced is calculated using the damage integral model.

Table 1
Model validation results for second degree burn.

Heat flux (kW/m^2)	Exposure time (s)	Time to 2° Burn (s)		Deviation
		Torvi	Present	
10.4	120	9.4	9.54	1.50%
24	3	2.78	2.79	0.40%
41.6	3	1.3	1.28	−1.50%
83.2	3	0.54	0.51	−5.60%
166.4	3	0.24	0.23	−4.20%