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STRESS-STRENGTH INTERFERENCE ANALYSIS OF AISI 4140 STEEL UNDER CONSTRAINED THERMAL EXPANSION USING MONTE-CARLO SIMULATION

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ABSTRACT
Material properties and stresses acting on machine parts are not point values but are statistically distributed. Consequently, it is possible for stress and strength distributions to overlap, exposing weaker materials to stresses greater than their strengths, leading to failure. A Monte Carlo simulation was conducted on AISI 4140 steel subjected to constrained thermal expansion using practical statistical distributions of material properties and environmental variables. The probability of failure of constrained and unstrained AISI 4140 steels were compared and the results showed a lower probability of failure for the latter. The results also showed that at low to moderate stress levels, mechanical load and thermal stress had relatively similar impact on the probability of failure. However, at high stress levels, the effect of mechanical load was predominant.

INTRODUCTION
Engineering materials fail when the stress acting on them exceeds their strength [1]. These stresses can be from applied loads and/or residual stresses from various phenomena that create a metastable state such as lattice defects, cold work, heat treatment, welding, and constrained mechanical and thermal deformations.
For ductile materials like steel, failure occurs when stress exceeds yield strength, thus leading to permanent plastic deformations [1] that cause change of shape and dimensions. The yield strength of different types of steels and the stresses that they are exposed to are not fixed numbers but vary [2][3][4]. While the former is due to material variations and time-dependent deterioration, the latter results from different loading cycles [5]. These variations of stress and strength follow various statistical distributions as shown in Figure 1.

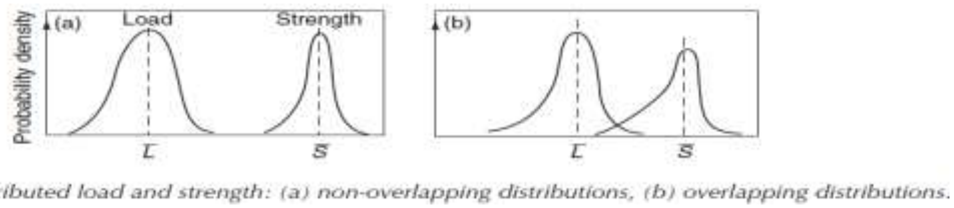

Figure 1: Statistically distributed stress and strength (Adapted from O'Connor, P.D.T and Kleyner, A. [3])

Consequently, it is possible for the right tail of the stress distribution to overlap with the left tail of the strength distribution as shown in Figure 1, resulting in failure. The area bounded by both overlapping curves gives the probability of this failure. Thus, it is possible to determine the probability of failure of a material if the distributions of its strength and stress over its useful life are known. Results from this analysis could inform the safety factor to be used, equipment derating, the duration of the useful life and selection of maintenance strategies.

Given the randomness in stress and strength values and the corresponding uncertainties in stress-strength interference analysis, Monte-Carlo simulations would be useful in modelling this phenomenon [3]. For this, stress and strength values that follow known statistical distributions from historical data are randomly generated, design margins are determined and the probability of negative safety margins which represent failures is computed.

This study is carried out on AISI 4140 steel, a low alloy steel that contains Chromium, Manganese, and Molybdenum, because it has a wide range of engineering applications, due to its high fatigue strength, toughness, torsional strength, and abrasion and impact resistance [6]. Some of its engineering applications include rotating machine elements such as gears, shafts, axles, to mention but a few [6]. Some of these machine parts work above room temperature, under cyclic loads and constrained deformation.

This study aims to determine the probability of failure of AISI 4140 steel subjected to mechanical load and residual thermal stress, at different safety factors.

MATERIALS AND METHODS

Input and Output Variables

The output variable for the Monte-Carlo simulation is the Design Margin of the material,

$$DM = \sigma_y - \sigma_T \qquad 1$$

where DM is the Design Margin, σ_y is the Yield Strength and σ_T is the Total Stress.

For a material under mechanical and residual thermal stress, the Total Stress,

$$\sigma_T = \sigma_L + E\alpha(T_2 - T_1) \qquad 2$$

where σ_L is the stress due to the mechanical load, E is the Young's Modulus, α is the Coefficient of Thermal Expansivity, T_2 is the final temperature and T_1 is the initial temperature.

Assuming $T_1 = 298K$ and substituting Equation 2 in Equation 1,

$$DM = \sigma_y - [\sigma_L + E\alpha(T_2 - 298)] \qquad 3$$

Equation 3 will be used for the Monte-Carlo simulations. With DM as the output variable, σ_T, σ_L, E, α and T_2 will be the input variables.

A limited amount of research has been carried out on the statistical distribution of Yield Strength of steel. Nonetheless, according to the few available papers, the Yield Strength, Young's Modulus, the Coefficient of Thermal Expansivity of steel and the applied stress all followed normal distributions [7][8][9].

For Hot Rolled (HR) S355MC steel, steel grades of Yield Strength greater than 380 MPa, S235JR steel, S355J2+N steel, S550MC steel and different stainless steel grades, the Yield Strength had coefficients of variance of 4.4% [8], 5% [10], 13% [5], 17% [5], 5.3% [5] and 5.6 – 6% [7] respectively. Thus, for this study, a coefficient of variance of 6% will be used because it is about the average of the reported data.

The coefficient of variance of the Young's Modulus reported by different researchers range from 1-3% [11], 1.9-4.5% [12], 2.4-3.4% [13], 6% [4], 10.5% [14] and 13.2% [5]. Consequently, a coefficient of variance of 13.2% will be used for the Young's Modulus because the steel in the study [5] is the most similar to AISI 4140 in composition and properties.

The Coefficient of Thermal Expansivity will be assigned a coefficient of variance of 6%.

Stress on the other hand will be assigned a coefficient of variance of 15%.

A triangular distribution of temperature will be used because this variable depends on the environment and varies for different applications. The minimum, mean and upper temperatures used are 25°C, 100°C and 300°C. The temperatures were selected such that significant changes to the microstructure would not occur and the mechanical properties would remain constant.

The Monte-Carlo simulation was conducted with 10,000 iterations.

Safety factors are used during design to ensure that the minimum material strength is always greater than the maximum expected stress. Mathematically, Safety Factor,

$$SF = \frac{\sigma_{y\,\min}}{\sigma_{L\,\max}}, \qquad 4$$

where $\sigma_{y\,min}$ is the minimum value of Yield Strength from its statistical distribution and σ_{Lmax} is the maximum value of mechanical stress from its statistical distribution. The following levels of mechanical stress will be simulated, 50 MPa, 100 MPa, 150 MPa, 200 MPa, 250 MPa, 300 MPa, 350 MPa, 400 MPa, 450 MPa and 500 MPa. These correspond to different values of Safety Factor.

Since most of the variables follow the normal distribution and their coefficient of variance are known, their minimum and maximum values can be determined. Their mean values are the nominal values reported in literature.

The coefficient of variance (COV),

$$COV = \frac{Variance}{Mean} \qquad 5$$

Table 1 summarizes the input data the Monte Carlo simulation.

Table 1: AISI 4140 steel input data for the Monte Carlo simulations

Variable	Mean	Coefficient of Variance (%)	Minimum Value	Maximum Value
Yield Strength (MPa)	417	17	294.4	539.6
Stress (MPa)	Varied	15	Varied	Varied
Young’s Modulus (MPa)	655,000	13.2	231,346	1,078,654
Coefficient of Thermal Expansivity (m/m K)	0.000001	6	0.0000007	0.0000013
Final Temperature (K)	373	---	298	373

Table 2 summarizes the input data for the stress levels used in the Monte Carlo simulation.

Table 2: Stress data for Monte Carlo simulation

Mean Stress (MPa)	Coefficient of Variance (%)	Minimum Value (MPa)	Maximum Value (MPa)
50	15	13.3	86.8
100	15	26.5	173.5
150	15	39.8	260.3
200	15	53	347
250	15	66.3	433.8
300	15	79.5	520.5
350	15	92.8	607.3
400	15	106	694
450	15	119.3	780.8
500	15	132.5	867.5

RESULTS AND DISCUSSIONS

The results of the Monte Carlo simulations are summarized in Table 3 and Figure 2.

Table 3: Results of the Monte Carlo simulations

Safety Factor	Mean of Design Margin	Standard Deviation of Design Margin	Minimum Design Margin	Maximum Design Margin	Probability of Failure (%)	Probability of Failure (%) Without Thermal Stress
3.4	303.3	43.2	129.6	435.9	0	0
1.7	231	63.1	-124.2	415.9	0	0
1.13	181.6	64.1	-111.6	372.3	1	0
0.85	132.3	67.4	-150.2	355.1	4	0
0.68	81.9	71.2	-244.4	318.1	12	0
0.57	32.3	74.9	-275.7	263.3	32	1
0.48	-18.1	80	-383.1	244.2	57	12
0.42	-68.5	85.3	-413.1	208.5	79	40
0.38	-117.8	91.2	-530.2	212.7	91	68
0.34	-166.8	95.8	-573.4	175.7	96	96

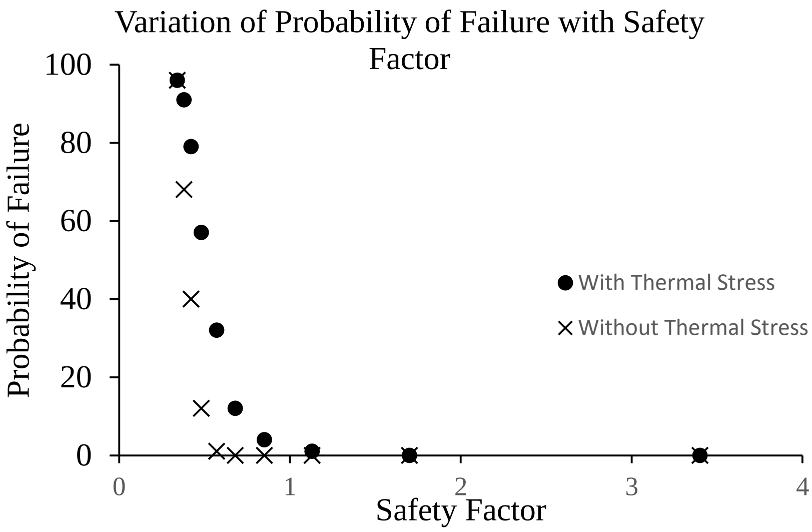

Figure 2: Variation of Probability of Failure with Safety Factor

The results show that the lower the Safety Factor, the higher the probability of failure. With a Safety Factor of 0.34, the probability of failure with and without the effects of thermal stresses is 96%. This is because with a safety factor so little, the total stress predominantly comprises of the mechanical load and the thermal stresses are relatively negligible.

More so, with a Safety Factor of at least 1.7, no failure was recorded in the constrained AISI 4140 steel. This value was much lower for the unconstrained material, about 0.68. This shows that the contribution of thermal stresses could be relatively significant at low to moderate stress levels, thus, values of safety factors that would sufficiently prevent failures in unconstrained materials could be grossly insufficient for the same material subjected to constrained expansion. Consequently, ignoring the effects of thermal stresses in constrained parts during design could be very disastrous.

Below the above-mentioned Safety Factor values, there exists a possibility that a weaker AISI 4140 steel material can be exposed to a stress greater than its yield strength, leading to unacceptable material failures. This probability increases rapidly for small reductions in the Safety Factor as we drop below 0.48.

CONCLUSIONS

AISI 4140 steel subjected to mechanical and residual thermal stress will likely suffer permanent plastic deformation and fail when the Safety Factor is less than 1.7.

At low to moderate stress levels, the individual impact of residual thermal stresses and mechanical loads on the probability of failure are relatively significant.

At higher stress levels, the influence of residual thermal stresses on the probability of failure is insignificant compared to that of mechanical load.

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