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Development of Methodology to Estimate the Fatigue Life of the Structure

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Abstract: In this present study, a methodology is developed to estimate the fatigue life of the structure from acquired strain data for variable amplitude loading condition. The methodology is based on the nominal stress method and the method is used creating a software module. Rainflow cycle counting method is use to extract the cycles from the strain data. Then the Palmgren-Rule is utilized to calculate cumulative damage. In addition, the fatigue life of a cantilever aluminium plate under certain loading conditions is analysed. The results are compared with the professional fatigue analysis software "N-SOFT FATIMAS".

Keywords: Fatigue, Stress Life, Variable Amplitude Loading, Life Estimation, Palmgren-miner Rule

I. INTRODUCTION

Fatigue is the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. Fatigue life estimates are often needed in engineering design, specifically in analysing trial designs to ensure resistance to cracking. A similar need exists in the troubleshooting of cracking problems that appear in prototypes or service models of machines, vehicles, and structures. That is the reason that the predictive techniques are employed for applications ranging from initial sizing through prototype development and product verification. The failure analysis, prediction, and prevention are of critical importance to the designer to achieve a success. Fatigue design is one of the observed modes of mechanical failure in practice. For this reason, fatigue becomes an obvious design consideration for many structures, such as aircraft, bridges, railroad cars, automotive suspensions and vehicle frames.

II. METHEDOLOGY

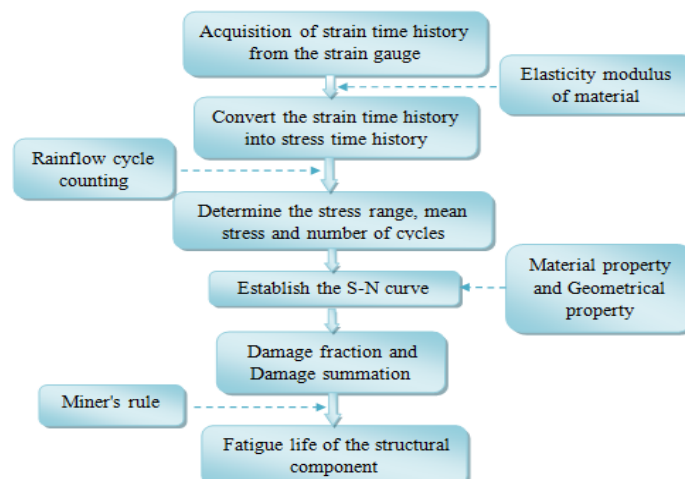


Fig.1 Sequential steps in fatigue life calculation

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The algorithm of this study is explained in the Fig.1.

The data acquisition instrument used to acquire the strain from the strain gauge mounted on required location in the structure. The strain-time data has been collected during the test is shown in the Fig.2.

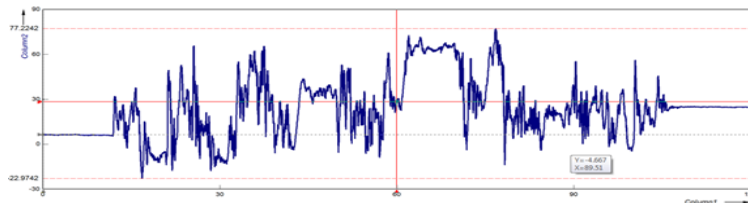


Fig.2 Strain Time data (Load spectra)

The obtained strain-time data is converted into stress-time data by using the following equation:

Stress-strain relationships

$$\sigma = E \times \epsilon$$

Rainflow cycles are counted by using computer programs. For lengthy histories, the range and mean values are often rounded off to discrete values in a range-mean matrix.

Using Modified Goodman Equation:

$$S_{ar} = \frac{S_a}{1 - \left(\frac{S_m}{S_u}\right)}$$

Where

S_a = Alternating Stress Amplitude

S_m = Mean Stress value

S_u = Ultimate tensile strength

S_{ar} = Fully reversible stress amplitude

Geometrical Details at Strain gauge Location:

Modification Factor for S_e :

1. Loading Factor C_L :

Type of Loading	Type of Material	C_L
Pure axial loading	All	0.9
Axial loading(with slight bending)	All	0.75
Bending	All	0.9
Torsion	Steel	0.9
Torsion	Cast iron	0.9

2. Surface finish C_S :

High strength steels are more adversely affected by a rough surface finish than softer steels, for this reason the surface correction factor, C_S , is strongly related to tensile strength. The surface finish correction factor is often presented on diagrams that categorize finish by means of qualitative terms such as polished, machined or forged. See Fig.3.

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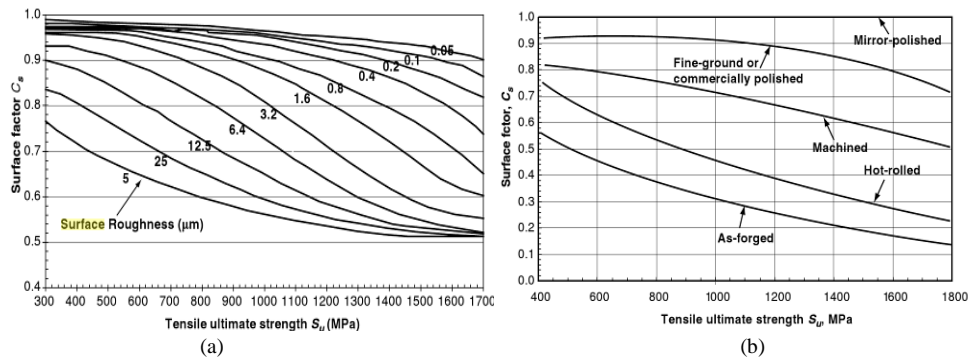


Fig.3 (a)The Effect of Surface Roughness on Surface Finish Factor, (b)Surface Finish Correction Factor for Steel Components

3. Size factor C_D :

If the diameter of the shaft is $< 8\text{mm}$:

$$C_D = 1$$

If the diameter is between 8 mm and 250 mm:

$$C_D = 1.189d^{-0.097}$$

For situations where components do not have a round cross section, an equivalent diameter, d_{eq} , can be calculated for a rectangular section width, w and thickness, t , undergoing bending from:

$$d_{eq}^2 = 0.65 \times w \times t$$

4. Reliability Factor C_R :

Using the standard normal cumulative distribution and assuming an 8 % standard deviation for both the stress and strength, an analytic expression for C_R is deduced.

$$C_R = 1 - 0.08Z_r$$

Where Z_r is the standard normal variable (defines the area under the normal distribution based on number of standard deviations from the mean).

5. Notch Correction Factor K_f :

$$K_f = 1 + (K_t - 1) \times q$$

Notch Sensitivity Factor

$$q = \frac{1}{1 + \sqrt{\frac{a}{r}}}$$

Where 'a' is the Neuber's material constant related to the grain size and 'r' is the notch root radius.

Stress at Fatigue limit

$$S_e = C_L \times C_S \times C_D \times C_R \times \frac{1}{K_f} \times S_{be}$$

Where S_{be} = Baseline fatigue limit

Modification Factor for S_{10}^3 :

1. Loading Factor C_L :

Type of Loading	Type of Material	C_L
Pure axial loading	All	0.9
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3. Notch Factor At 1000cycles:

$$q'_{1000} = \frac{K'_f - 1}{K_f - 1}$$

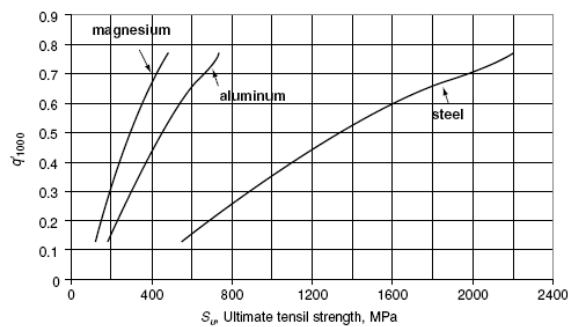


Fig.4 Empirical curves between q'_{1000} and S_u for materials such as steel, aluminium, and magnesium.

Stress at 10^3 Cycles S_{10^3} :

$$S_{10^3} = \frac{0.75 \times C_R \times S_u}{K'_f}$$

Slope of the curve (b) $= \frac{-(\log S_{10^3} - \log S_e)}{(\log N_e - \log N_{10^3})}$

Theoretical Cycles to Failure

$$N_f = N_e \times \left(\frac{S_{ar}}{S_e}\right)^{\frac{1}{b}}$$

Palmgren-miner rule for life prediction for variable amplitude loading that is completely reversed.

$$\text{Cumulative Damage } D = \sum \frac{n_{ij}}{N_{fij}}$$

$$\text{Total life at the strain gauge position} = \frac{1}{\text{Cumulative damage}}$$

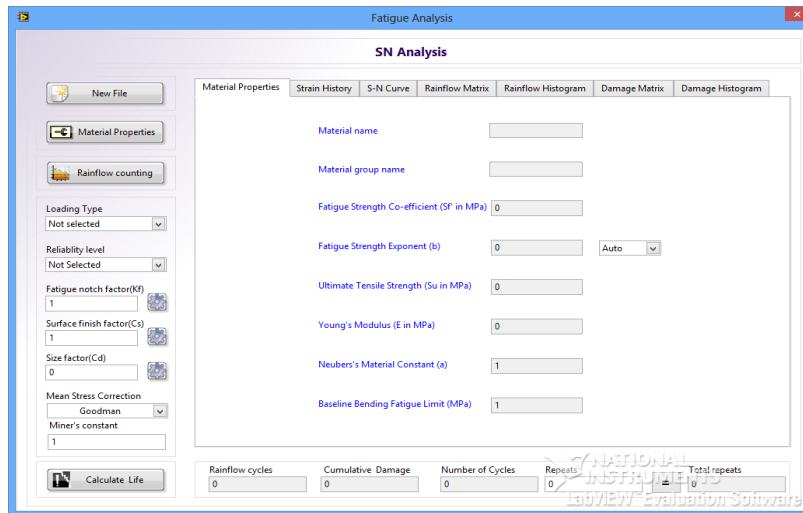
III. SOFTWARE DEVELOPMENT

The calculation whichever employed in this chapter are used in the development of the fatigue life analysis software. The Main Screen contains all main features fatigue analysis including the display option of graphs and plots in one single window. In the Main Screen the data entering options are located in the left side of the screen and Display configuration on the centre of the screen and Results are displayed at the bottom.

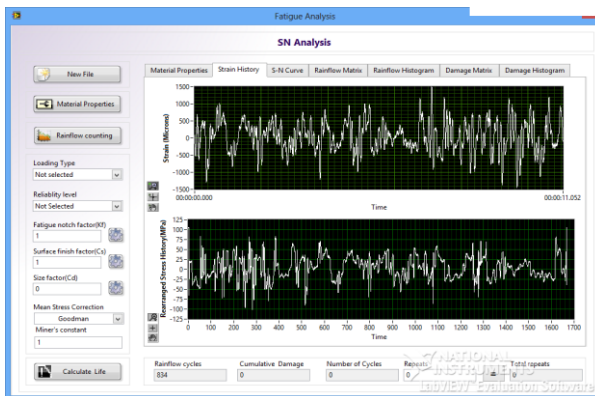
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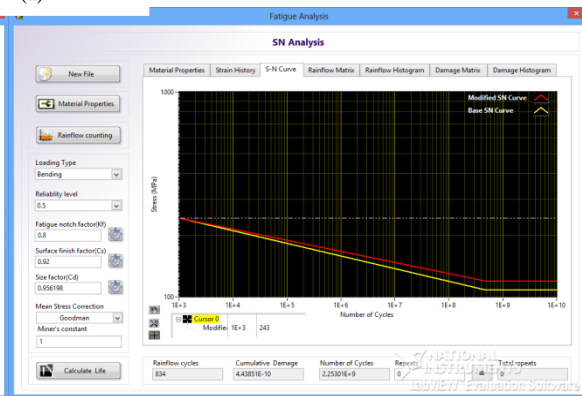
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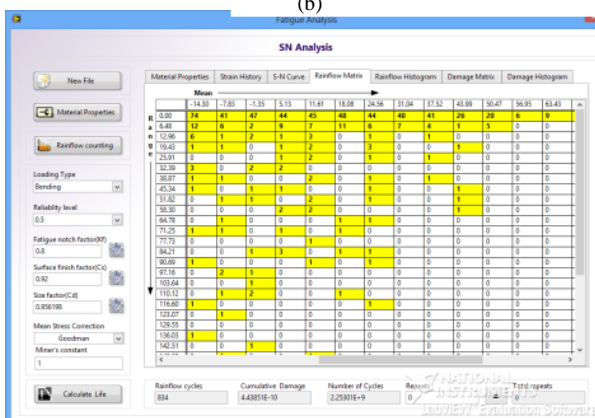
(a)



(b)

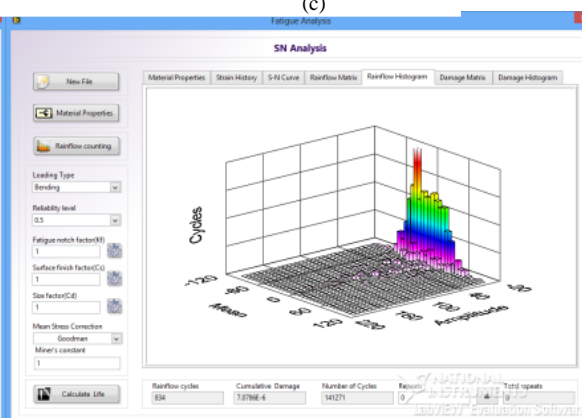


(c)



Mean	-14.39	-1.35	11.81	18.88	24.46	31.04	37.52	43.99	50.47	56.95	63.43
0.00	14	41	47	44	43	48	44	40	26	28	0
0.48	12	6	2	6	7	15	6	7	4	5	0
15.86	16	1	2	1	1	0	1	0	1	0	0
19.43	1	0	1	2	0	3	0	0	1	0	0
25.91	0	0	1	2	0	6	0	0	0	0	0
33.39	0	0	2	2	0	0	0	0	0	0	0
38.87	1	1	0	2	0	1	0	0	0	0	0
45.34	0	0	0	0	0	1	0	0	1	0	0
51.82	0	1	1	2	0	1	0	0	1	0	0
58.30	0	0	0	2	0	0	0	0	1	0	0
64.78	0	0	0	0	0	0	0	0	0	0	0
71.25	1	1	0	1	0	0	0	0	0	0	0
77.73	0	0	0	0	1	0	0	0	0	0	0
84.20	0	0	0	0	0	0	0	0	0	0	0
90.68	1	0	0	1	0	1	0	0	0	0	0
97.15	0	0	0	0	0	0	0	0	0	0	0
103.64	0	0	0	0	0	0	0	0	0	0	0
110.12	0	1	2	0	0	1	0	0	0	0	0
116.60	1	0	0	0	0	0	0	0	0	0	0
123.07	0	0	0	0	0	0	0	0	0	0	0
129.55	0	0	0	0	0	0	0	0	0	0	0
136.03	1	0	0	0	0	0	0	0	0	0	0
142.51	0	0	0	0	0	0	0	0	0	0	0
148.99	0	0	0	0	0	0	0	0	0	0	0

(d)

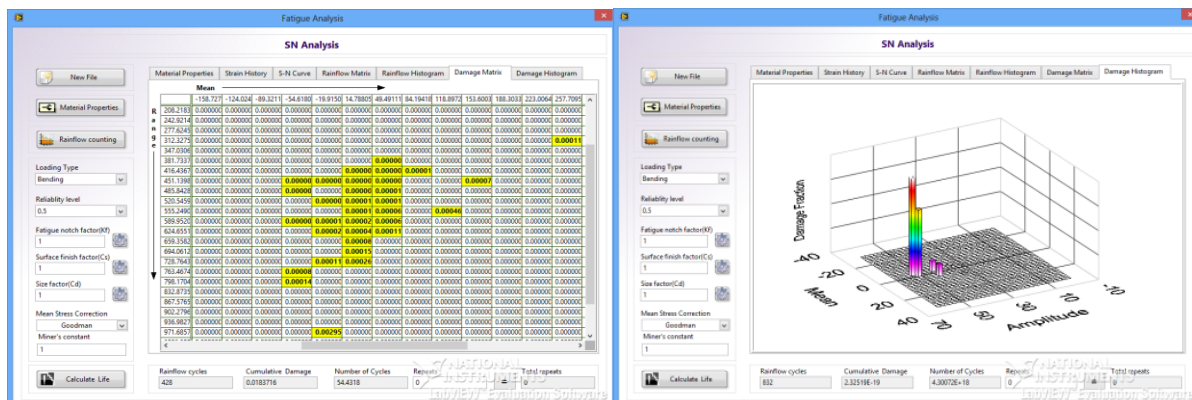


(e)

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(f)

(g)

Fig.5. (a) Main Screen, (b) Strain time data display screen, (c) S-N Curve Display, (d) Damage Fraction Matrix, (e) Damage Fraction Histogram, (f) Rainflow Cycle Count Matrix, (g) Rainflow Cycle Count Histogram

IV. VALIDATION OF THE METHOD

VALIDATION 1: Fatigue life of the eight sample strain histories are estimated using the current developed fatigue analysis software and "N-SOFT FATIMAS". The results are then comparing with results of "N-SOFT FATIMAS" for eight test sample signal.

VALIDATION 2: By Conducting Experiment, a cantilever aluminium plate under certain loading conditions is used as a test specimen. The fatigue behaviour of the test specimen subjected to constant loading is investigated experimentally. The acquired experimental data are then analysed using software. The strain gauge is glued on a critical point at the specimen where stress concentration exists in order to examine the life profile simulation.

V. RESULTS AND DISCUSSIONS

The Rainflow cycle counts for all sample signals are equal in both software hence we can conclude that the Rainflow cycle counting method used in this developed software is matches with n-soft. The results obtained from the four cases(Fig.6) shows that the fatigue analysis method is nearly matches with n-soft.

Test signal No.	n-soft		Present Software		% Error	Test signal No.	n-soft		Present Software		% Error
	Rainflow cycle Counts	Life in Cycles	Rainflow cycle Counts	Life in Cycles			Rainflow cycle Counts	Life in Cycles	Rainflow cycle Counts	Life in Cycles	
101	834	48321	834	40590	16.00	101	834	5916	834	5806	1.86
102	747	1.16E+05	747	94034	18.94	102	747	1.08E+04	747	10265	5.18
103	444	5.86E+05	444	322648	44.94	103	444	2.10E+04	444	20963	0.34
104	0	Failed	428	58	0.00	104	0	Failed	428	94	0.00
105	659	1.11E+05	659	97201	12.43	105	659	8.47E+03	659	8969	-5.87
106	1385	Beyond Cutoff	1385	1.88E+19	0.00	106	1385	Beyond Cutoff	1385	1.03E+13	0.00
107	834	1978	833	1816	8.19	107	834	870	833	843	3.10
108	834	833	834	773	7.20	108	834	516	834	494	4.26

(a)

(b)

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Test signal No.	n-soft		Present Software		% Error	Test signal No.	n-soft		Present Software		% Error
	Rainflow cycle Counts	Life in Cycles	Rainflow cycle Counts	Life in Cycles			Rainflow cycle Counts	Life in Cycles	Rainflow cycle Counts	Life in Cycles	
101	834	4724	834	4994	-5.72	101	834	701	834	435	37.95
102	747	8.73E+03	747	8617	1.31	102	747	1.24E+03	747	865	30.35
103	444	1.72E+04	444	17021	1.22	103	444	1.85E+03	444	1828	1.30
104	0	Failed	428	95	0.00	104	0	Failed	428	Failed	0.00
105	659	6.77E+03	659	7453	-10.12	105	659	6.03E+02	659	314	47.93
106	1385	Beyond Cutoff	1385	3.83E+12	0.00	106	1385	Beyond Cutoff	1385	3.71E+16	0.00
107	834	633	833	747	-18.01	107	0	Failed	833	Failed	0.00
108	834	127	834	470	-270.08	108	0	Failed	834	Failed	0.00

(c) (d)
Fig.6. Rainflow cycle counts and fatigue life for eight sample signal for four different conditions (a) Case I, (b) Case II, (c) Case III, (e) Case IV.

The Rainflow cycle counts are unequal in the both software because the both software uses different signal filters. The life cycles obtained from the both the software are does not match experimental cycles hence the conducted experiment failed to validated software. The reasons for the failure of experimental method are yet to be analysed.

Specimen No.	Present Software		n-soft		Experiment Results	
	Rainflow cycle Counts	Life in Cycles	Rainflow cycle Counts	Life in Cycles	Crack occurs(in cycles)	Fracture(in cycles)
1	70	4808	26	4236	7600	7834
2	38	5283	27	5458	6350	7050
3	49	2615	21	1967	5500	7040
4	41	3124	24	2712	6800	8754
5	26	2163	16	1875	4800	6400

Fig.7. Results from the experiment

VI. CONCLUSION

The present work illustrates development of fatigue analysis software based on the nominal stress method. From the study it is known that the fatigue life of the any structure is depending on the material property, geometrical definition of the required point in the structure. The estimation and selection of the factor are made easy by related graph in module from that the user can select point of curve for corresponding parameter so that the user can understand procedure of life estimation easily. The main feature of this software is the all main operations are provided in the one screen along with display of results. The results from the validation 1 (CASE I-IV) shows that the Rainflow cycle counting method is matches with the n-soft and the error of estimated fatigue life is within 20%. The results from validation 2 shows that the experiment is unable to justify the method developed and the reason for failure of experiment are yet to be identified.

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BIOGRAPHY



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