Fatigue and Damage Tolerance, Prediction of Crack Propagation on Plate Using Paris Equation and Walker Equation

Andry Renaldy Pandie[1], A.R. Yudiana[2], Hermansah[3]
{pandie-andry@ed.tmu.ac.jp[1]}

Ph.D student at Department of Aeronautics and Astronautics, Tokyo Metropolitan University, 6-6 Asahigaoka, Hino, Tokyo 191-0065, Japan[1], Department of Aerospace Engineering, Sekolah Tinggi Teknologi Adisutjipto, Yogyakarta [2,3]

Abstract. Metals subjected to repetitive stresses and loads will be damaged at certain cycle stresses which cause fracture and failure. This failure was marked by a defect. To predict the magnitude of the propagation of the crack until the failure of the structure is used the Paris equation and the Walker equation to solve it. In this article, the boundaries used to determine a structure fail with the initial crack length known to consist of limits: $a \geq 0.8W$, $\sigma_{net\ max} \geq \sigma_y$, $K_{max} \geq \sigma_y$, and $K_{\max} \geq K_{IC}$. The method used to solve this case is the study of literature and using the Matlab software whose steps are contained in the flow diagram. The material to be analyzed and predicted for the addition of cracks is the aluminum series Al-2219-T87 with geometry a (70E-3 m), W (150E-3 m), σ_{max} (20 MPa), σ_{min} (12, 13, 14, 16 MPa). After analysis, conclusions are obtained: [1]Analysis using the Walker equation gives the value of fatigue life or the number of failed cycles that are less than the Paris equation, this is because Walker takes into account the stress ratio, [2]The average percentage change in the cycle in the Paris equation starting from σ_{min} 12 to 16 is 55.52%, [3]The average percentage of cycle changes in the Walker equation starting from σ_{min} 12 to 16 is 39.28%, [4]The average percentage of cycle changes in the Paris and Walker equations starting from σ_{min} 12 to 16 is 70%, [5]Fatigue life will increase if the value of R gets closer to the value 1, 8 the structure fails when (a = 120 mm).

Keywords: Stress; Failure; Paris; Walker; Fatigue; Crack

1 Introduction

On April 28, 1988 at 1346, Boeing 737-200, N73711 aircraft operated by Aloha Airlines Inc., with flight number 243 experienced explosive decompression and failure of structures at an altitude of 24000 ft when flying from Hilo - Honolulu, Hawaii, USA. It is estimated to be 18 ft long in the skin cabin and its structure after the cabin entrance is released while flying. The area where the skin structure is released starts from the aft body station 360 to the body station 540, and the circular section starts from the top of the left side of the S-15L through the

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cabin ceiling and goes to the lower right up to the S – 10R belt window. The release of this skin causes some parts to experience minor damage, such as the leading edge of both wings, horizontal stabilizer and vertical stabilizer, inlet cowls on both engines, and first stage on the fan blades of the two engines, the start level cable that flows the fuel. Damage to the loose section indicates that failure starts from the left fuselage, where the defect propagates longitudinally in fuselage [1].

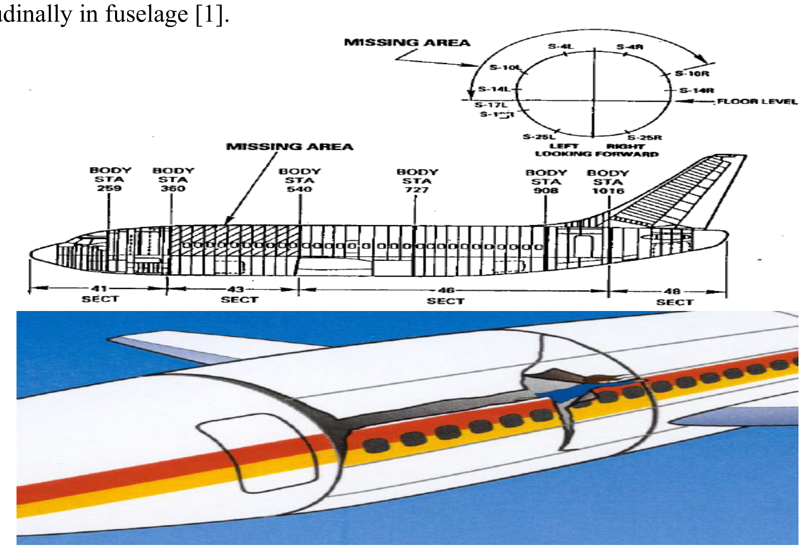

Fig. 1. Structural failure of Aloha Airlines with flight number 243 [1]

The structure of airplanes, especially civil aircraft, is still largely made of metal, although now there have been developments for the use of composites whose numbers have not replaced the role of metals. Metals subject to repetitive stresses and loads will be damaged at certain cycle stresses which cause fracture and failure [2]. This failure was marked by a defect. This defect can affect the structure of the material because the material has passed through the fatigue point. Fatigue failures are the behavior of metals that fail because of repeated variable stresses with a certain value (usually under the yield stress of material), which generally occurs after a long period of usage. Fatigue failure is increasingly prominent along with technological developments, one of which is the development of aircraft which will experience repeated loads and vibrations. Repeated loads and vibrations are what increase failure in aircraft structures.

Fatigue failure arising from the structure of the aircraft must be predictable at the time of design and selection of structural materials so as not to endanger safety when operated. One of these fatigue failures can be approached using the initial cracks that occur in the structure. The initial crack that occurs will continue to increase in crack along with changes in the load / stress imposed on the structure. Therefore, it is necessary to predict the magnitude of crack propagation that occurs until the structure fails. To predict the magnitude of the propagation of the crack until the failure of the structure, the Paris equation and the Walker equation are used. In the Paris equation, the value of the stress ratio is not calculated. Whereas in the Walker equation, the stress ratio is calculated. In this article, the boundaries used to determine a structure fail with the initial crack length known to consist of limits:

a. $a \geq 0.8W$
b. $\sigma_{net\ max} \geq \sigma_y$
c. $K_{max} \geq \sigma_y$
d. $K_{max} \geq K_{IC}$

2 Method and Basic Theory

Fracture / failure is a problem that is commonly found in every structure designed and made by humans. Current structural problems are increasingly complex and need solutions to problem solving, which is evident from the large number of aircraft that have crashed due to structural failure [3]. Common causes often encountered in structural failures fall into one of the following categories:

a. Negligence during the design, construction or production and operation of the structure.
b. Determination of design or new material where the results are not as expected.

There are three basic factors that cause fatigue failure, namely the maximum tensile stress, variation or stress fluctuation, and the stress application cycle. In addition to these three basic factors, there are still several other factors that influence, namely stress concentration, corrosion, temperature, excess material, metallurgical structure, and combination stress [2]. The following is the process of basic changes that occur in structures that experience repeated stresses:

a. The beginning of crack formation - the initial formation of failure caused by scratches, dent, corrosion or impact.
b. Propagation / crack growth stage 1 (slip band crack growth) - propagation of cracks in fields having high shear stresses.
c. Crack propagation stage 2 - crack propagation in fields having high tensile stress / crack propagation perpendicular to the maximum tensile stress.
d. Ultimate ductile failure - occurs when the crack reaches a length that is large enough so that the remaining cross section / field is no longer able to withstand the load that occurs [2].

In generally there are 3 phases in damage or failure due to fatigue, namely crack initiation, crack propagation, and fracture [5]. Airplane structural components can experience loading in several variations of loads such as load fluctuations, strain fluctuations or temperature fluctuations. In fact, it is not uncommon for construction to experience combined stress or contamination with a corrosive environment which will certainly cause a construction to be more threatened by safety. In generally there are three cycles that can show a fatigue stress cycle, namely:

a. Stress fluctuations occur from zero average stress with a reversed stress cycle.
b. Stress fluctuations start above the zero average line with a repeated stress cycle.
c. Random stress cycle.

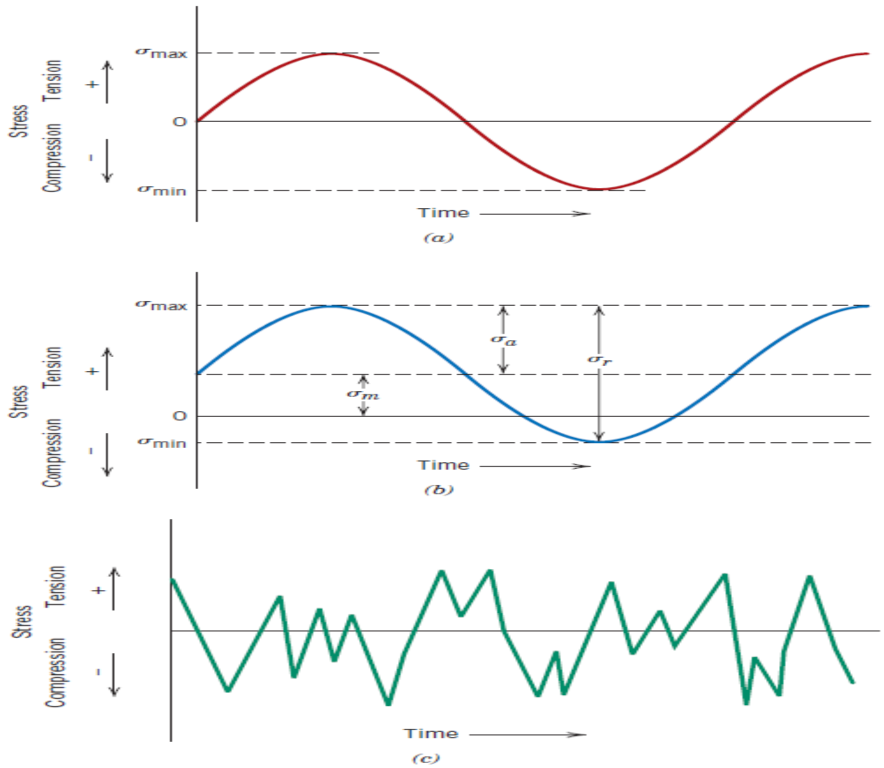

Fig. 2. Fatigue stress cycle [4]

The following equation for the stress cycle graphs above:

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{1}$$

$$\Delta\sigma = \sigma_r = \sigma_{\max} - \sigma_{\min} \tag{2}$$

$$\sigma_a = \frac{\sigma_r}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{3}$$

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{4}$$

Fatigue data is usually presented in a stress and cycle curve, where the stress is S and the cycle is N. The number of cycles is a cycle ranging from cracking to crack propagation.

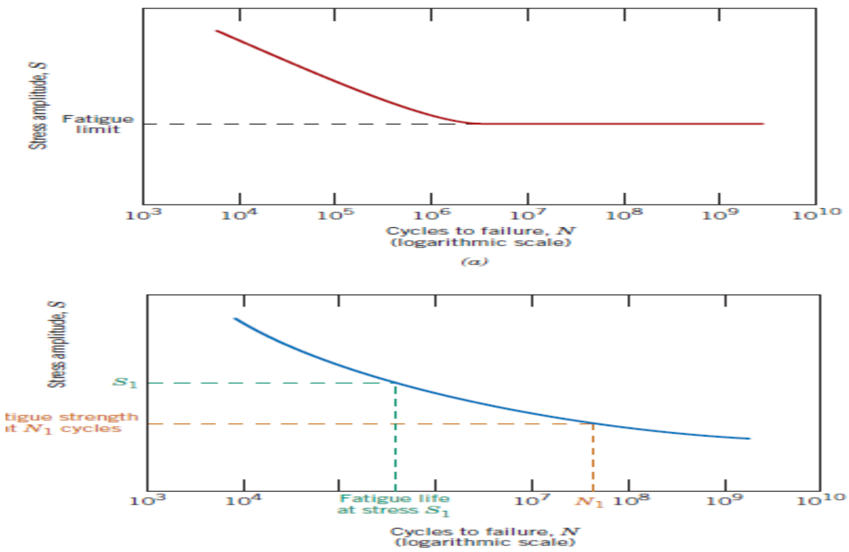

Fig. 3. S-N curve [4]

It can be seen that if the stress drops then the number of cycles for failure to increase, whereas if the stress rises, the number of cycles will decrease (Figure 3). For fatigue life itself, there are several factors that influence it, namely:

a. The stress concentration - the trigger for stress concentrations such as fillets, notches, etc. will cause a decrease in fatigue life.
b. Material dimension / size - if the size of the specimen increases, the fatigue resistance sometimes decreases. This is because fatigue failure usually starts from the surface. So, if the additional size is done then it gives the possibility of causing the existence of defects. As a result, the crack began with the defect.
c. Surface effects - fatigue resistance is strongly influenced by surface conditions. The surface conditions are surface properties such as surface treatment such as surface hardening and residual surface tension. The effects of surface finishing or surface roughness qualitatively also affect the fatigue resistance of a material. Conversely the surface hardening process can increase fatigue resistance. Residual stress, especially compressive residual stress, will provide increased fatigue resistance. This residual stress can be developed by performing plastic deformations that are not uniform in a cross section.
d. Mean stress - mean stress also affects fatigue resistance. This stress is indicated by the amplitude of the stress expressed by the stress ratio. If the tensile amplitude is equal to the amplitude of the compressive stress. If the R value tends to be positive, the fatigue resistance will decrease.

Crack growth is the change in the length of the crack to the loading cycle that occurs. In this stage the crack grows and spreads to reach a critical size. From crack propagation data, fatigue life predictions can be developed. From the concept of fracture mechanics, the crack growth rate is expressed by $\frac{da}{dN}$ which is a function of material properties, crack length, and operating stress. Cracks start from the weakest regions, then develop along with the cycle of loading. To prevent fracture mechanics / mechanical cracking in the material, several design approaches were taken to anticipate it. These approaches include [3]:

a. The approach to using energy standards - is used when cracking occurs when the energy available for crack growth exceeds material resistance.
b. b. Approach to stress intensity - this approach is used to determine the stress distribution at the crack tip of the material. To calculate the stress distribution, it is necessary to know the value of stress intensity factor (K_I) formulated with $K_I = \sigma \sqrt{\pi a}$ (5)
c. c. Failure tolerance approach - this approach is used to predict material durability based on time variables and crack cracking mechanisms. Crack growth rate has a correlation with stress intensity factors and fracture toughness material. The crack rate is formulated with

$$\frac{da}{dN} = C(\Delta K)^m \quad (6)$$

The fatigue life of a component that has a defect, initial defect, or continuity can be predicted using fracture mechanics developed and widely used both analytically, experimentally and numerically. To evaluate a structure that has flaw, one approach is to predict the age of crack propagation. In fatigue cases, the Linear Elastic Fracture Mechanics (LEFM) method is commonly used. This is because fatigue cases occur in elastic conditions. The parameters used in LEFM consist of:

a. a. Voltage intensity factor (K_I) - the K_I value indicates the strength of a component, or the age of the crack growth and a measure of the magnitude of the stress concentration field around the crack tip. The value of K_I is a function of the crack length and working stress formulated with $K_I = Y \sigma \sqrt{\pi a}$ (7)
b. Material toughness properties (fracture toughness) K_{IC} – the K_{IC} value is the material toughness properties in resisting crack rates. The nature of the toughness of the material in static conditions is expressed as yield strength or ultimate strength. If value $K_I < K_{IC}$ it can be said that a construction is safe. And vice versa if the value of K_I approaches the value of K_{IC} or $K_I \geq K_{IC}$ it can be said that a construction will experience a failure / broken [5].

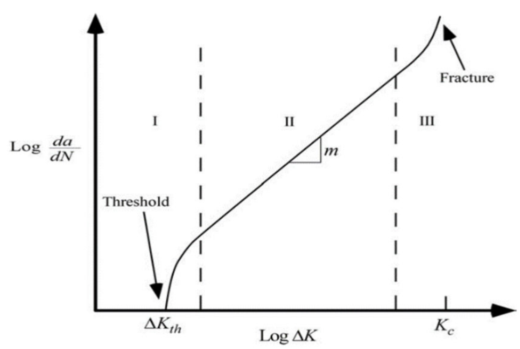

Fig. 4. Type of crack growth on metal [2]

Caption:
Region I → At the threshold, the crack does not increase
Region II → Linear region
Region III → The rate of increase in cracks will increase rapidly.

In this paper, only calculating the amount of crack propagation that occurs in region I, two equations are used, namely;

2.1 Paris Equation

In this equation, the ratio between the maximum stress and the minimum stress is not taken into account. The following are the equations used:

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \tag{8}$$

$$\Delta K_I = Y\Delta\sigma\sqrt{\pi a} \tag{9}$$

$$\Delta a = \frac{da}{dN} = C(\Delta K)^m \tag{10}$$

$$a_n = a_0 + \Delta a \tag{11}$$

2.2 Walker Equation

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{12}$$

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \tag{13}$$

$$\Delta K_I = Y\Delta\sigma\sqrt{\pi a} \tag{14}$$

$$\Delta a = \frac{da}{dn} = \frac{C(\Delta K)^m}{1-R} \tag{15}$$

$$a_n = a_0 + \Delta a \tag{16}$$

2.3 Percentage of difference between $\sigma_{\min}$ in the equation of Paris and Walker

$$\%\Delta Cycle = \frac{|\,S\sigma_A - S\sigma_B\,|}{\frac{1}{2}\times(S\sigma_A + S\sigma_B)} \times 100 \tag{17}$$

2.4 Percentage of failed cycle difference between Paris and Walker to Paris with the same R

$$\%\Delta Cycle = \frac{|\,ParisCycle - Wal\,ker\,Cycle\,|}{ParisCycle} \times 100 \tag{18}$$

3 Methodology

The material to be analyzed and predicted for the crack increase is the aluminum Al-2219-T87 series which has the following properties [6]:

Table 1. Properties Al-2219-T87

σ_y (MPa)	K_{IC} (MPa$\sqrt{m}$)	C	m
395	27.3	6.27E-11	3.3

The plate geometry is as follows:

a = 70E-3 m
W = 150E-3 m
σ_{max} = 20 MPa
σ_{min} = 12, 13, 14, 16 MPa

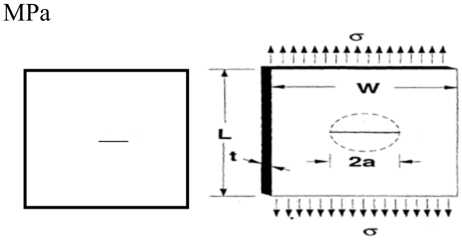

Fig. 5. Plate geometry that predicted the crack propagation

The method used in solving this case is use Matlab software whose steps are outlined in the following flow chart:

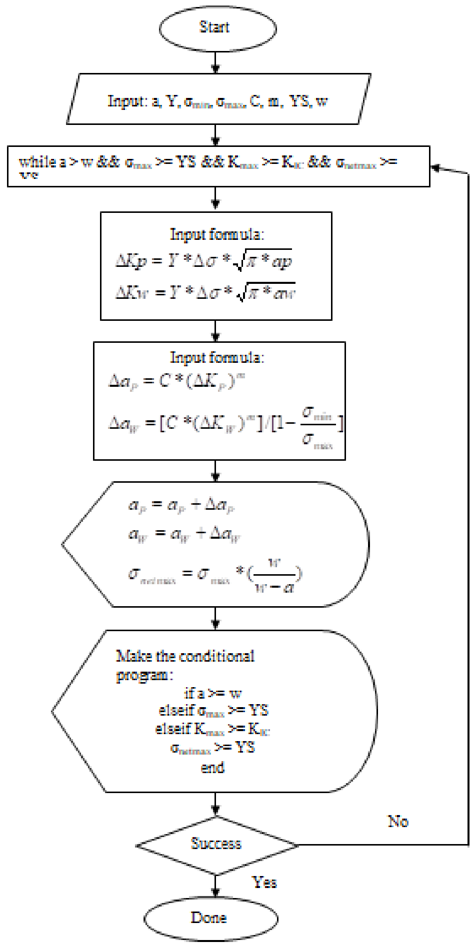

Fig. 6. Flow Chart

4 Result and Discussion

Programs that are run in Matlab use parameters:

a. a = 70E-3 m
b. W = 150E-3 m
c. σ_{max} = 20 Mpa$\sqrt{m}$
d. σ_{min} = 12, 13, 14, 16 Mpa$\sqrt{m}$
e. Y = 1
f. Every increase in cycle 2E5, the value a_n displayed
g. Properties owned by Al-2219-T87.

Based on the parameters above, the results are:

4.1 Paris Equation

Table 2. Results in the Paris equation (σ_{max} = 20 and σ_{min} = 12)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
4	0.12	1.20E+02	6,466,247

Table 3. Results in the Paris equation (σ_{max} = 20 and σ_{min} = 13)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
52	0.12	120	10,046,753

Table 4. Results in the Paris equation (σ_{max} = 20 and σ_{min} = 14)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
85	0.12	120	16,708,986

Table 5. Results in the Paris equation (σ_{max} = 20 and σ_{min} = 15)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
151	0.12	120	30,496,373

Table 6. Results in the Paris equation (σ_{max} = 20 and σ_{min} = 16)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
320	0.12	1.20E+02	63,687,065

Table 7. Difference in cycles in the Paris equation with variations of σ_{min}

No	1	2	3	4
N	6,466,247 (σ_{min} 12)	10,046,753 (σ_{min} 13)	16,708,986 (σ_{min} 14)	30,496,373 (σ_{min} 15)
N	10,046,753 (σ_{min} 13)	16,708,986 (σ_{min} 14)	30,496,373 (σ_{min} 15)	63,687,065 (σ_{min} 16)
N	3,580,506	6,662,233	13,787,387	33,190,692
N̲	($\Delta N1 + \Delta N2 + \Delta N3 + \Delta N4$) / 4 = 14,305,204.5			
%	155.372243	166.3123001	182.5148037	208.8348834
	178.2585576			

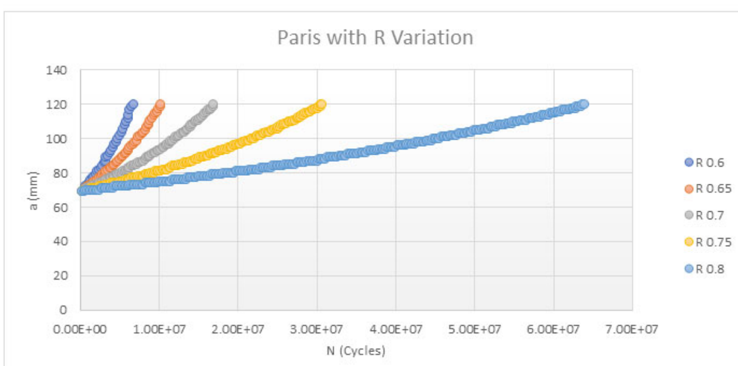

Fig. 7. Graph a vs N of Paris equations with variations of σ_{max}

From table 2-7, the results in Matlab, and Figure 7, it is found that:

a. The greater the value of σ_{min} or the closer to σ_{max}, the greater the fatigue life of the material. Thus, it is endeavored that $\Delta\sigma$ is not too large.
b. Every increase in one σ_{min} then the number of cycles that increase is twice that of the previous cycle (the cycle increases almost 100%).
c. The average cycle change from σ_{min} 12 to 16 is 14,305,204.5 times, with an average percentage of 178.2585576%.
d. The structure will fail under conditions $a \geq 0.8W$

4.2 Walker Equation

Table 8. Results in the Walker equation (σ_{max} = 20 and σ_{min} = 12)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
14	0.12	1.20E+02	2,586,499

Table 9. Results in the Walker equation (σ_{max} = 20 and σ_{min} = 13)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
19	0.12	120	3,516,364

Table 10. Results in the Walker equation (σ_{max} = 20 and σ_{min} = 14)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
27	0.12	120	5,012,696

Table 11. Results in the Walker equation (σ_{max} = 20 and σ_{min} = 15)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
40	0.12	120	7,624,094

Table 12. Results in the Walker equation (σ_{max} = 20 and σ_{min} = 16)

No	a_n (m)	a_n (mm)	N (Cycle)
1	7.00E-02	70	0.00E+00
65	0.12	1.20E+02	12,737,414

Table 13. Difference in cycles in the Walker equation with variations of σ_{min}

No	1	2	3	4
N	2,586,499 (σ_{min} 12)	3,516,364 (σ_{min} 13)	5,012,696 (σ_{min} 14)	7,624,094 (σ_{min} 15)
N	3,516,364 (σ_{min} 13)	5,012,696 (σ_{min} 14)	7,624,094 (σ_{min} 15)	12,737,414 (σ_{min} 16)
ΔN	929,865	1,496,332	2,611,398	5,113,320
$\underline{N}$	(ΔN1 + ΔN2 + ΔN3 + ΔN4) / 4 = 2,537,728.75			
%	135.9507195	142.5533875	152.095679	167.0679034
	149.41692			

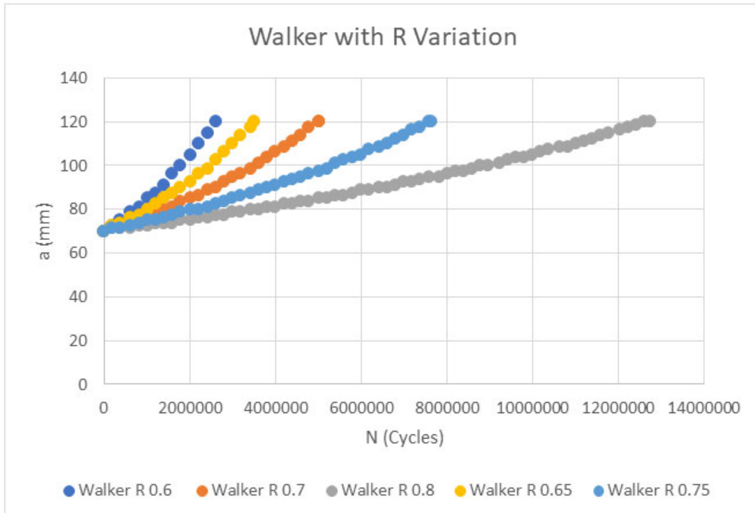

Fig. 8. Graph a vs N Walker equation with $\sigma_{max} = 20$ and variation R

From table 8-13, the results in Matlab, and figure 8, it is found that:

a. The greater the value of σ_{min} or the closer to σ_{max}, the greater the fatigue life of the material. Thus, it is endeavored that $\Delta\sigma$ is not too large.

b. Every increase in one σ_{min} then the number of cycles that increase is twice that of the previous cycle (the cycle increases almost 100%).

c. The average change of cycles starting from σ_{min} 12 to 16 is 2,537,728.75 times with the percentage change in average 149.41692%.

d. The structure will fail under conditions $a \geq 0.8W$

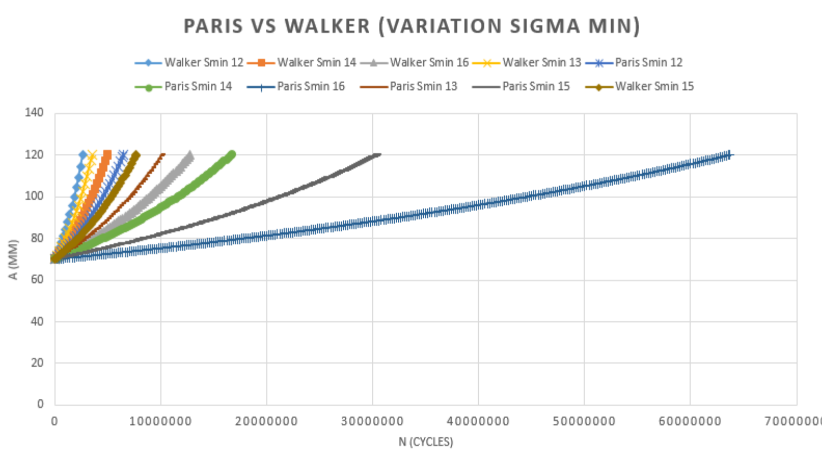

Fig. 9. Paris vs Walker graph with variations of σ_{min}

Table 14. Difference in cycles in the Paris and Walker equations with variations of σ_{min}

σ_{min}	12	13	14	15	16
Paris	6,466,247	10,046,753	16,708,986	30,496,373	63,687,065
Walker	2,586,499	3,516,364	5,012,696	7,624,094	12,737,414
ΔN	3,879,748	6,530,389	11,696,290	22,872,279	50,949,651
N	(ΔN1 + ΔN2 + ΔN3 + ΔN4) / 5 = 19,185,671.4				
%	(6,466,247 / 2,586,499) * 100 = 250	285.7142	333.3333	400	500
	353.8095				

From figure 9 and table 14 it is found:

a. The number of cycles in the Walker equation is less than the number of cycles in the Paris equation. This is because the Walker equation takes into account the effect of stress ratio.

b. Every increase in one σ_{min} then the number of cycles that increase is twice that of the previous cycle (the cycle increases almost 100%).

c. The average cycle difference in the two equations with the same σ_{min} value is 19,185,671.4, and the average percentage is 353.8095% (table 14).

5 Conclusion

After analysis, conclusions are obtained:

a. Analysis using the Walker equation gives less fatigue life compared to the Paris equation, this is because Walker takes into account the stress ratio.

b. Analysis using the Walker equation is better because it provides predictions of fatigue life that are close to accurate because more variables are involved when compared to the Paris equation.

c. The average cycle change in the Paris equation starting from σ_{min} 12 to 16 is 14,305,204.5 times, with an average percentage of 178.2585576%.

d. The average cycle change in the Walker equation starting from σ_{min} 12 to 16 is 2,537,728.75 times with a percentage change in the average of 149.41692%.

e. The average cycle difference in the two equations with the same σ_{min} value is 19,185,671.4, and the average percentage is 353.8095%.

f. Each increase in one σ_{min}, the number of cycles that increase is twice that of the previous cycle (the cycle increases almost 100%) for each equation.

g. The greater the value of R (with a note that is varied only σ_{min}), the fatigue life will be longer. Fatigue life will increase if the value of R gets closer to the value 1.

h. The structure will fail with $a \geq 0.8W$ (a = 120 mm).

List of Symbols

No	Symbol	Annotation
1	a, a_0	half the initial crack length
2	a_n	half the crack length in a certain cycle
3	W	half width plate
4	K_{max}	maximum stress intensity factor
5	K_{IC}	fracture toughness of material
6	σ_y	limit stress that is still safe for material
7	σ_{max}	maximum stress
8	σ_{min}	minimum stress
9	σ_m	mean stress
10	$\Delta\sigma$, σ_r	range of stress
11	σ_a	stress amplitude
12	R	stress ratio
13	$\frac{da}{dN}$	crack growth rate
14	Y	form factor of the structure
15	*C* and *m*	constant properties in the material
16	N	cycle
17	$\underline{N}$	cycle average
18	ΔN	difference or cycle change

Attachment

Coding in Matlab:

```
disp('Crack Propagation in Material Al 2219-T87 Used Paris Equation')
%Input
K1c = 27.3 %MPa(m^0.5)
m = 3.30
C = 6.27e-11
w = 150e-3 %setengah lebar material dalam m
YS = 395 %MPa
ap=input('Setengah Panjang Awal Paris=');
aw=input('Setengah Panjang Awal Walker=');
b=input('Sigma max=');
c=input('Sigma min=');
d=input('Y=');
Siklus = 0;

%Untuk Fail saat a > 0.8w maka digunakan: a0 = 70e-3 m,
%Sigma_max = 20 MPa(m^0.5), Sigma_min = 19,18,17,16, 10 MPa(m^0.5),
%Bisa juga Sigma_min = 12 MPa(m^0.5),

Kmax_Paris = (d * b * sqrt(pi * (ap)));
Sigma_net_max_Paris = b * (w / (w-ap));
Kmax_Walker = (d * b * sqrt(pi * (aw)));
```

```
Sigma_net_max_Walker = b * (w / (w-aw));

%PARIS EQUATION
Siklus = 0;
while ap < 0.8*w && b < YS && Kmax_Paris < K1c && Sigma_net_max_Paris < YS
  Delta_Sigma = (b - c);
  Kmax_Paris = (d * b * sqrt(pi * (ap)));
  Delta_K = (d * Delta_Sigma * sqrt(pi * (ap)));
  da_per_dn= (C * (Delta_K)^m);
  Delta_a = (da_per_dn);
  ap = (ap) + Delta_a;
  Siklus = Siklus + 1;
  Sigma_net_max_Paris = b * (w / (w-ap));
  A = mod (Siklus,2e5);
  if A == 0
     disp(ap)
  end
end
ap
b
Kmax_Paris
Sigma_net_max_Paris
Siklus

if ap >= 0.8*w
     disp ('Paris => Crack & Fail: a > 0.8*w')
elseif b >= YS
     disp ('Paris => Crack & Fail: b > YS')
elseif Kmax_Paris >= K1c
     disp ('Paris => Crack & Fail: Kmax > K1c')
elseif Sigma_net_max_Paris >= YS
     disp ('Paris => Crack & Fail: Sigma net max > YS')
end
%WALKER EQUATION
Siklus = 0;
          while aw < 0.8*w && b < YS && Kmax_Walker < K1c && Sigma_net_max_Walker
< YS
            R = c / b;
            Delta_Sigma = (b - c);
            Kmax_Walker = (d * b * sqrt(pi * (aw)));
            Delta_K = (d * Delta_Sigma * sqrt(pi * (aw)));
  da_per_dn= ((C * (Delta_K)^m)) / (1 - R);
  Delta_a = (da_per_dn);
  aw = (aw) + Delta_a;
  Siklus = Siklus + 1;
  Sigma_net_max_Walker = b * (w / (w-aw));
  A1 = mod (Siklus,2e5);
  if A1 == 0
```

```
    disp(aw)
  end
end
aw
b
Kmax_Walker
Sigma_net_max_Walker
Siklus

if aw >= 0.8*w
    disp ('Walker => Crack & Fail: a > 0.8*w')
elseif b >= YS
    disp ('Walker => Crack & Fail: b > YS')
elseif Kmax_Walker >= K1c
    disp ('Walker => Crack & Fail: Kmax > K1c')
elseif Sigma_net_max_Walker >= YS
    disp ('Walker => Crack & Fail: Sigma net max > YS')
end
```

References

[1] *Final Report*. NTSB/AAR-89/03. 1989. *Aircraft Accident Report — Aloha Airlines, Flight 243, Boeing 737-200, N73711, near Maui, Hawaii, April 28, 1988*. Washington DC.

[2] E. Dieter, George. *Mechanical Metallurgy*, 3rd *edition*, McGraw-Hill Inc. 1986.

[3] Anderson, T. L., *Fracture Mechanics: Fundamentals and Applications*, 3rd *edition*, CRC Press, New York. 2005.

[4] Callister, W.D., Jr. , Retwisch, D.G. *Materials Science and Engineering An Introduction*, 7th *edition*., John Wiley and Sons, New York. 2007.

[5] Chandra, H. *Linear Elastic Fracture Mechanics* (LFEM) *Fatigue*, University of Sriwijaya, Palembang. 2009.

[6] Carpinteri, Alberto, Marco Paggi. *Are the Pari's Law Parameters Dependent on Each Other?*. Atti del Conggreso IGF 19 (2-4 Juli 2007), Milan. 2007.