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Analysis of Dynamic Loading on Automatic People Mover System (APMS) Bogie Frame According to UIC Standard

Setyo Margo Utomo[1*], Agus Krisnowo[2], Jean Mario Valentino[3]

[1]Specialist Engineer, Center for the Assessment of Industrial in Manufacturing, Telematic & Electronic, BPPT, Indonesia
[2]Principle Engineer, Center for the Assessment of Industrial in Manufacturing, Telematic & Electronic, BPPT, Indonesia
[3] Specialist Engineer Center for Technology of Transportation & Infrastructure System, BPPT, Indonesia

***Abstract*— *The purpose of this research is to conduct numerical analysis and verification of APMS bogie frame to withstand maximum dynamic loading with finite element analysis and to conduct design modification if bogie is not achieving safety criterion and infinite life cycle. Stages of this research was collecting data and APMS bogie drawing from PT. INKA Madiun, then conduct identification of bogie model structure, which included quality validation of Solid CAD model and mesh quality valiadation, then determination of boundary conditions for dynamic loading to acquire simulation of fatigue loading analysis or fatigue of material due to dynamic loading. From 3rd load step smilation showed that alternating stress result was 75.813 MPa which is under the limit of High Cycle Fatigue, 97,36 Mpa, and safety factor 1.25 so that until this stage was still safe. Limit of material SM 490A touhgness used for bogie frame manufacturing on cycle 10^6 or High Cycle Fatigue (HCF) was 97.36 MPa.*

***Keywords*— bogie frame, dynamic load, fatigue analysis.**

I. INTRODUCTION

APMS manufactured by PT. INKA basically using monorail as a basis, which developed by adopting technology and latest design, however those APMS bogie design need to be verified for its safety and ability to withstand standard working load or crush load.

Purpose of this structural analysis was to determine and assure the limit of bogie frame strength in order to fullfil requirements prior to the testing, or generally said as design verification stage. Static analysis represents bogie frame structure behavior in certain conditions, such as cruising, side wind, braking and maneuver, whereas maximum loading in short period on frame structure from vertical load, lateral load, or longitudal load so that we can identify critical area due to maximum strain/ stress and deflection.. The result of this static analysis can be used as reference for strain gauge attachment during static test of APMS bogie prototype.

Dynamic load can be defined as time-load function. One of the result of dynamic load is fatigue load, because it can cause fatigue to material even if load is not achieving maximum limit of material yet. Most common fatigue analysis method used in railways structure is limit of endurance using nominal stress with maximum dynamic load. Saurabh et.all [1] during bogie lifetime several external forces act in the normal service loads on the bogie frame. These forces are coming from the wheel-rail contact points and from the interfaces with the car body and are generated from:

1) double sprung masses, including payload;
2) track irregularities;
3) lateral accelerations caused by curve riding;
4) longitudinal accelerations caused by traction and braking;

Kiim et al. [2] evaluated the static structural safety and durability of two composite bogie frame models using a finite element analysis. Based on the Tsai-Wu failure criterion under ten different loading conditions, durability of bogie frame were researched using Goodman diagrams. Han et al. [3] evaluated experimentally fatigue strength for bogie frame of an urban maglev train and researched fatigue and damage. Moskvitin et al. [4] studied the effect of fatigue crack growth under overload situation. Kumar et al [5] the acceleration response of front and the rear bogie with time is presented, initially the wheels of the front bogies comes in contact with the track irregularity and the vibration starts in the front bogie and latter these vibrations are shifted tothe rear bogie. The amplitude of the vehicle vibration also increased with vehicle speed.

This research focused on numerical fatigue analysis on main frame of the bogie monorel to discover dynamic loading condition at the most dominant direction-vertical translation-which will effect fatigue strength of material on APMS bogie structure according to infinite fatigue life criterion, more than 10^6 cycle of dynamic loading .

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II. RESEARCH METHOD

First step of dynamic load of bogie frame is preparing 3D solid model and assembly for validation of structural model.

Next is calculation of dynamic load according to UIC due to rollingstock movement on the track to get loading value received by bogie structure.

To represent static and dynamic load on the bogie model, the boundary conditons and free body diagram was defined.

Then making prediction of S-N diagram for bogie material as input of fatigue analysis. Fatigue simulation is runned using ANSYS software [6][7].

According to regulation of Ministry of Transportation Republic of Indonesia: PM. 37 year 2014 about Technical Specification Standard of Monorail, Bogie is a construction entity which support monorail while moving on arches railway or straight railway for stability and comfort [8].

Bogie frame is a constructuin designed to support coach from loadings. Frame must meet some requirements such as having strength and high rigidity to vertical, lateral and longitudinal without having permanent deformation and defect (crack) on the critical point of loading.

Bogie is supported on two main wheel which is wheel to support vertical direction load (z-axes fixed) and railway mover on longitudinal direction (x-axis fixed) and six side wheel as support for lateral direction (y-axis fixed). Material used for this bogie is SM 490A (JIS G3106). Steel SM490A is rolled steel commonly used in engineering, specifically on welded structure. SM 490A is having equality on the classification of JIS G3106 standard and ASTM A 572. Mechanical properties of the material as follows [9] :

Modulus young	: 210 GPa
Elongation	: 17%
Yield strength	: 325 MPa
Ultimate tensile strength	: 490 MPa
Poisson Ratio	: 0.3

III. RESULT AND ANALYSIS

Dynamic load can be defined as load-time function. Dynamic load can be classified as two kind of loading, which is impact and fluctuating/ alternating load, or can be named fatigue load, since it can cause fatigue on material even if the load is yet to achieve maximum limit of material strength. Fluctuating load is a load working on an object/ material with constant, variable and random amplitudo.

Fatigue analysis conducted to discover structural strength to cyclic or repeated loading so that remaining life of the structure can be obtained. A structure can be considered safe if service life from the calculation is longer than design life planned. Design life of a component or product is a period of time of a component or product is expected by designer to work on parameters defined; or in another words life expectancy of a component or product. Design life can be adjusted during the stage of design planning.

3.1. S-N Diagram

S-N Curve is a fatigue characteristic which generally used from a material that suffered repetitive stress with the same value. This curve is obtained from stell speciment test that given repetitive load with N cycle until failure occured. "N" is inversely proportional to span of stress "S". According to Juvinal, S-N Curve of a material can be predicted by calculate some of correction constant factor such as Loading constant (C_L), Dimension constant (C_D), Surface condition constant (C_S), Stress Consentration factor Cycle 10^3 (k_f') and Stress Consentration facto on cycle 10^6 (k_f). S-N diagram for material SM 490A can be predicted by calculating values for S'_n , K_f , K'_f , *alternating stress* on cycle 10^3 and cycle 10^6.

Value of S'_n :

$$S'_n = 0{,}5\ S_u$$
$$= 0{,}5\ .\ 490\ \text{MPa} = 245\ \text{MPa}$$

Value of K_f :

$$K_f = 1 + (K_t - 1) q C_s$$
$$= 1 + (3 - 1) 0{,}4 . 0{,}68$$
$$= 1{,}54$$

Value of K'_f :

$$K'_f = r\left(K_f - 1\right) + 1$$
$$= 0.1\,(1.54 - 1) + 1$$
$$= 1{,}054$$

Alternating stress on cycle 10^3 :

$$S = {0.9 \times S_u}/{K'_f}$$

S = 0,9 x S_u / K_f'

$$= {0.9 \times 490}/{1{,}054}$$
$$= 418.40\ \text{MPa}$$

Alternating stress on cycle 10^6 :

$$S_n = S'_n \times C_L \times C_D \times C_S / K_f$$
$$= 245 \times 0{,}9 \times 1 \times 0{,}68 / 1{,}54$$
$$= 97.36\ \text{MPa}$$

After obtained result of calculation for endurance limit at Cycle 10^3 or limit Low Cycle Fatigue (LCF) as big as 418.40 MPa and cycle 10^6 or limit High Cycle Fatigue (HCF) 97.36 MPa, the result can be plotted to S-N Curve. Those S-N Curve prediction can be seen below:

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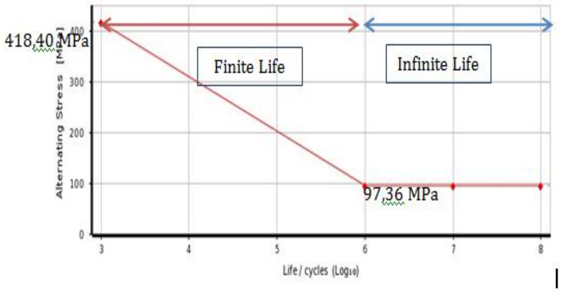

Fig.1: SN Curve Predicton for Material SM 490 A

3.2. Fatigue Loads

On conducting analysis, the most important thing is material definition used and forces assumption and boundary condition assumption which represent actual condition in a structure. Bellow is a modelling of forces and boundary condition for simulation:

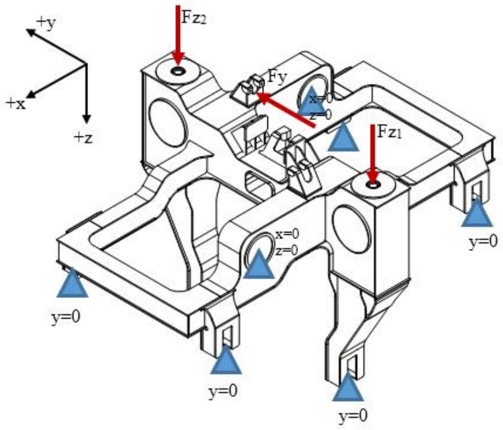

Fig.2: Forces Modelling and Boundary Condition of APMS Bogie

Definition of working loads based on UIC 615-4 while trainset is running:

- Vertical test load per bogie:

$$F_z(N) = \frac{g}{2n_b}(m_v + 1{,}2C_2 - n_b m^+)$$

- Transverse test load per bogie:

$$F_y(N) = 0{,}5(F_z + 0{,}5m^+ g)$$

Notation and definition of load above:

n_b = *number of bogies = 4*
n_e = *number of wheelset per bogie=2*
m^+ (kg) = *bogie weight = 1000 kg*
m_v (kg) = *empty weight of vehicle* = 12,000 kg.
C_2 = loading weight = 17,897 kg.
g = gravitation

According to UIC 615-4, calculation of forces for fatigue test can be conduct using formulas and step as follows:

1) Vertical Forces:
   - Static Component:
     $F_{zs1} = F_{zs2} = F_z = 36145.43$ N
   - Quasi static component:
     $F_{zq1} = F_{zq2} = \pm\alpha F_z = 3614.54$ N
   - Dynamic component:
     $F_{zd1} = F_{zd2} = \pm\beta F_z = 7229$ N

2) Transverse Forces:
   - *Quasi static component:*
     $F_{yq} = \pm$ 0,25. $(F_z + 0.5m^+.g)$ = 10262.61 N
   - *Dynamic component:*
     $F_{yd} = \pm$ 0,25. $(F_z + 0.5m^+.g)$ = 10262.61 N

3) Testing can be conduct in 3 stages, according to the increase of loading level as showed in figure 3, as follows:
   - Loading stages 1 : 2 x 10^6 cycles;
   - Loading Stages 2 : 2 x 10^6 cycles, with loading factor multiplied with 1.2;
   - Loading Stages 3 : 2 x 10^6 cycles, with loading factor multiplied with 1.4;

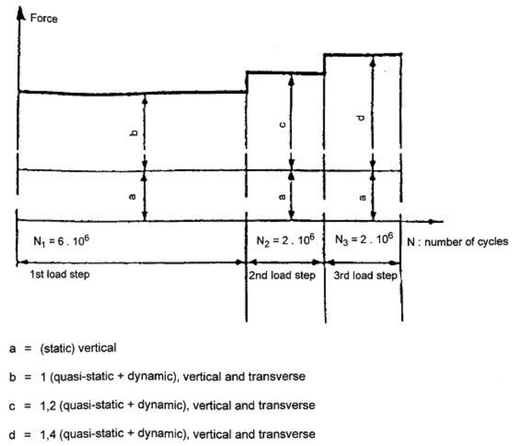

Fig.3: Fatigue Test Procedure

So can be obtained:

a. 1st load step:
   - Vertical load: 46989.07 N
   - Transverse load: 20525.22 N

b. 2nd load step:
   - Vertical load: 56386.88 N
   - Transverse load: 24630.26 N

c. 3rd load step:
   - Vertical load: 65784.69 N
   - Transverse load: 28735.3 N

3.3. Fatigue Strength Simulation

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Fatigue strength on this test evaluated using Goodman mean stress correction theory, because Goodman theory is empirically considered closest to the actual condition if compared to Soderberg Theory which is conservative as well as Gerber Theory. Loading type used in this simulation is zero based.

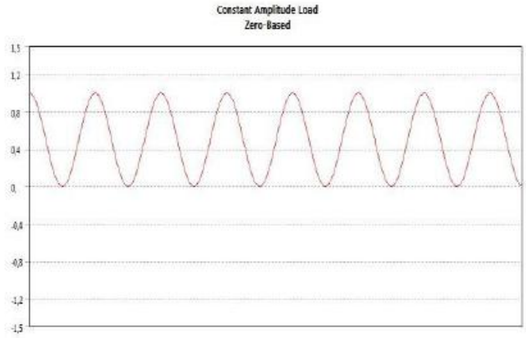

Fig.4: Zero Based Loading Type

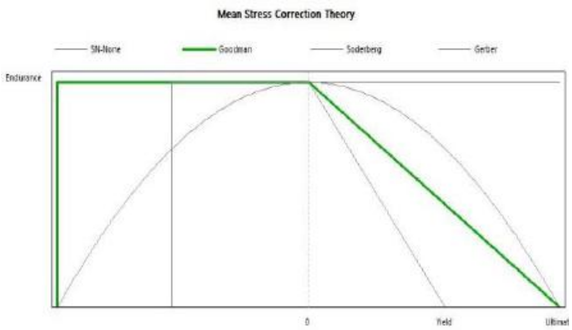

Fig.5: Goodman Mean Stress Correction Theory

These following figures is the result of fatigue test using ANSYS, and can be obtained data as follows:

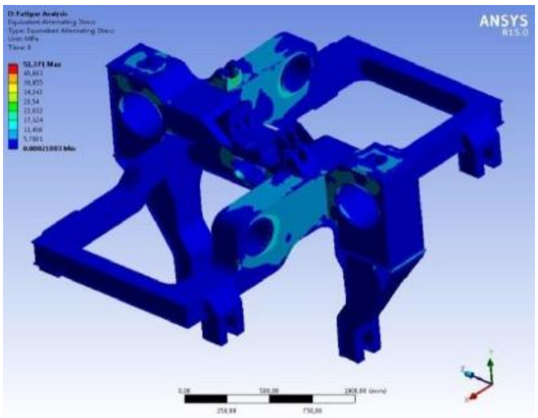

Fig.6: Alternating Stress on 1st Load Step

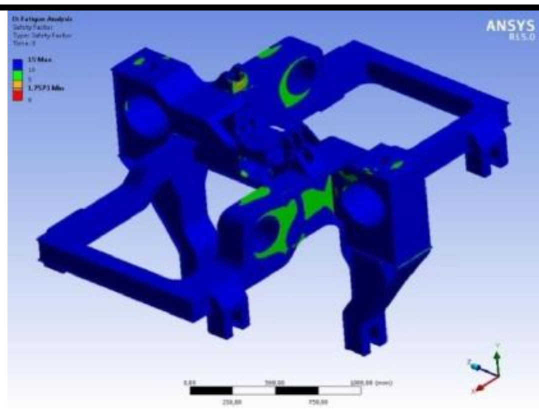

Fig.7: Safety Factor on 1st Load Step

From 1st load step simulation result, can be obtained result of alternating stress is 51.371 MPa which is still below limit of High Cycle Fatigue (HCF) 97.36 MPa, and safety factor 1.75, thus on this stage can be considered safe and can be continued to 2nd load step with multiplier for vertical load dan transverse load is 1.2.

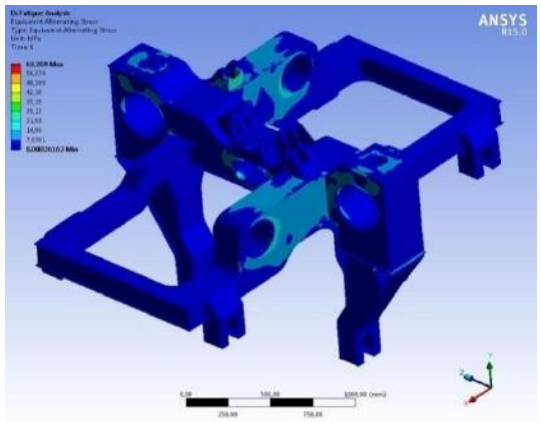

Fig.1: Alternating Stress on 2nd Load Step

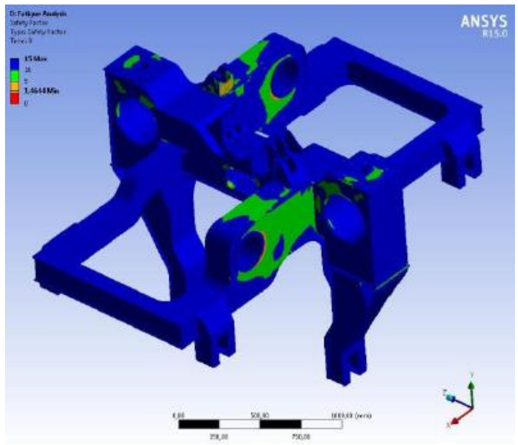

Fig.9: Safety Factor on 2nd Load Step

From the simulation of 2nd load step, can be obtained result of alternating stress is 63.269 MPa which is still below limit of High Cycle Fatigue (HCF) 97.36 MPa, and safety factor 1.46, thus at this stage still considered safe,

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and can be continued to 3rd load step with multiplier factor for vertical load and transverse load is 1.4.

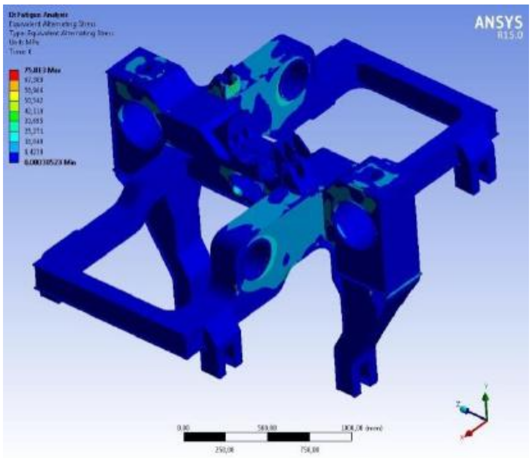

Fig.10: Alternating Stress on 3rd Load Step

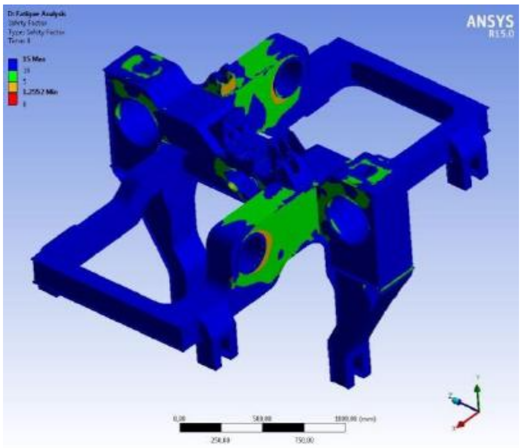

Fig.11: Safety Factor on 3rd Load Step

From the simulation of 3rd load step, can be obtained result of alternating stress is 75.813 MPa which is still below limit of High Cycle Fatigue (HCF) 97.36 MPa, and safety factor 1.25, thus at this stage still considered safe. Following table is summary for the fatigue test above:

Table.1: Result of Fatigue Test

Load Step	Cycle	Alternating Stress (MPa)	Safety Factor
1	6×10^6	51.371	1.75
2	2×10^6	63.269	1.46
3	2×10^6	75.813	1.25

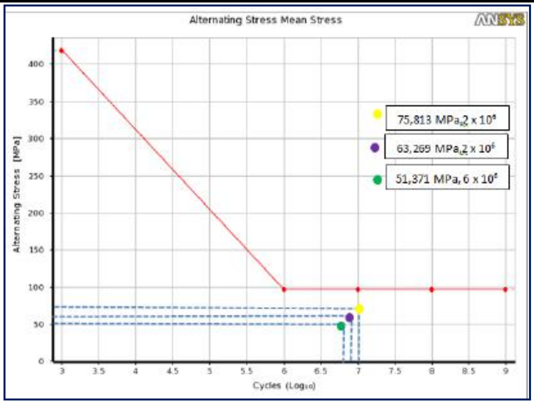

Fig.12: Fatigue Life APMS Bogie

From the result of fatigue test above, if the result of alternating stress is plotted to S-N Diagram prediction of material SM 490A, can be concluded that bogie frame was able to withstand loading according to UIC 615-4 Standard, until life cycle above $1e^7$, so can be considered having infinite life.

IV. CONCLUSION

Endurance limit of SM 490A used for bogie frame manufacturing on cycle 10^3 or limit for Low Cycle Fatigue (LCF) is 418.40 MPa and on cycle 10^6 or limit for High Cycle Fatigue (HCF) is 97.36 MPa.

From 1st load step simulation result, can be obtained result of alternating stress is 51.371 MPa which is still below the limits of High Cycle Fatigue (HCF) 97.36 MPa, and safety factor 1.75, thus until this stage is still considered safe.

From the 2nd load simulation step, can be obtained alternating stress is 63.269 MPa which is still below the limit of High Cycle Fatigue (HCF) is 97.36 MPa, and safety factor 1.46, so until this stage is still considered safe.

From the 3rd load simulation step, can be obtained alternating stress is 75.813 MPa which is still below the limit of High Cycle Fatigue (HCF) is 97,36 MPa, and safety factor 1.25, so until this stage is still considered safe.

APMS bogie frame able to withstand loading according to UIC 615-4 Standard, until lifetime above $1e^7$ cycle, thus can be considered having infinite life.

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