Verification of urban light rail transit (LRT) bogie frame structure design lifetime under variable fatigue loads

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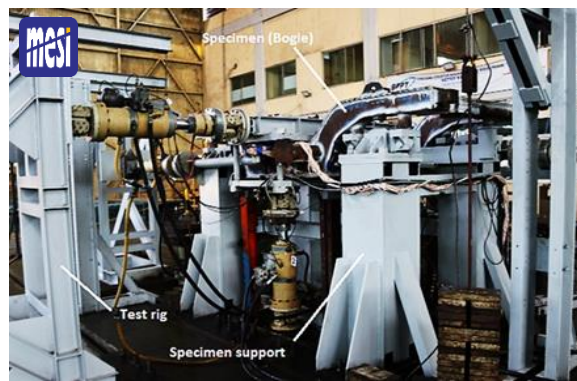[3] The Indonesian Railroad Industry (INKA), Madiun 63122, East Java, **Indonesia**
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Highlights:

- Newly bogie frame structures under various fatigue load conditions were verified experimentally.
- The bogie frame was subjected to two variable types of fatigue loads, namely driving in curves and passing points (switches).
- Non-destructive test methods in all areas of welded joints of bogie structures were reported.

Abstract

The bogie frame is the main structure of the train that supports the train's loads during its operation. These structures are subject to fatigue testing to ensure their design life is up to the required standards. The urban light rail transit (LRT) bogie frame used in the Greater Jakarta area is newly designed and manufactured by a commercial railway rolling stock manufacturer. The design lifetime of this newly designed bogie frame structure under various fatigue load conditions is verified experimentally by fatigue testing. Testing and evaluations were conducted following the EN 13749 standard and VDV recommendation. The fatigue test of the urban LRT bogie frame structure was carried out in the test hall of the BPPT Structural Strength Technology Center (B2TKS) using a combination of seven loadings. The bogie frame was subjected to two variable types of fatigue loads, namely driving in curves and passing points (switches), with 2,000,000 cycles, 4,000,000 cycles, and 6,000,000 cycles of fatigue loadings. The parameter measured on the bogie frame structure is the strain value during the test using a dynamic data logger. The stress values analyzed are the average stress and the stress amplitude and then plotted on the maximum and minimum stress curve. The bogie structure is inspected by the non-destructive test method in all areas of its welded joints. This inspection is carried out before and after the test to ensure whether there are cracks caused by fatigue loads. The results of the fatigue test on the bogie structure under the variable fatigue load conditions show that the maximum stress value of 91.71 MPa at 1,500,000 cycles, that occurs during the test, does not exceed the fatigue limit of the material, and there are no cracks in the structure after the test is carried out for up to 6,000,000 cycles.

Keywords: Bogie frame, Fatigue, Mean stress, Amplitude stress, Crack

1. Introduction

Currently, Indonesia is developing and producing an urban light rail transit (LRT) that connects the capital city of Jakarta with the nearest cities, namely Bogor, Depok, and Bekasi. This urban LRT train is a collaboration between research institutes, academics, and train manufacturer, in this case, PT. INKA (Persero) Madiun. These trains run on rails built above the ground and operate

automatically. The main structure of the train consists of a car body structure and a bogie set structure. This bogie set consists of a bogie frame, suspension, axle, and wheels.
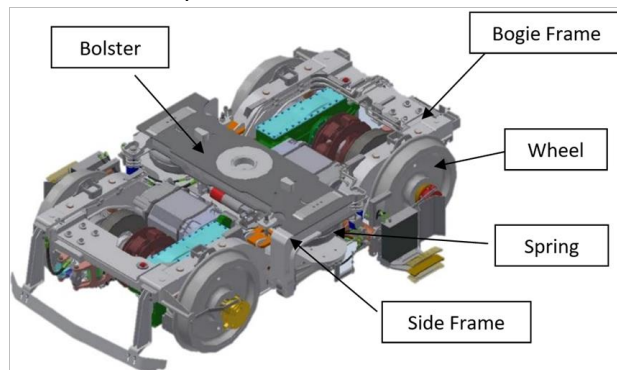
Inside-framed bogie technology is applied to the urban LRT to reduce the load and flexibility of the LRT train on its track. This bogie can be characterized by wheels that look intact from the outside due to the bogie frame and axle box installed on the inside. Meanwhile, conventional bogies have a bogie frame and axle box that are mounted on the outside and can be seen. The inside-framed bogie technology on the urban LRT is commonly referred to as a lightweight bogie. This is due to several factors, such as having a lower total weight than conventional bogies and smaller unsprung weight. The designed bogie set, showing the position of the frame, wheels, springs, as well as other components in the bogie set is shown in **Figure 1**.

Unsprung weight is the weight of the wheels and other components that are not supported by springs. If the unsprung weight gets smaller, the comfort when riding the urban LRT will be achieved. Due to its lightweight, this bogie has a smaller size than conventional bogies in Indonesia. As a result of the reduced bogie weight, the axle load (axle pressure) is low and is in accordance with the construction of the urban LRT infrastructure. The bogie has an H-shaped frame with an internally mounted end beam, as was the design of Indonesia's new LRT bogie frame seen in **Figure 2**, which will undergo full-scale fatigue testing.

Typically, the various parts of a railway bogie frame structure will utilize different grades of steel. The main structure, consisting of the side frame, T/M mounting bracket, transom support, gear mounting bracket, is made from materials with a higher yield strength (325-355 MPa), than other parts of the bogie frame, such as the transom (315 MPa) and the bracket/stiffener (245 MPa). The mainframe structure utilizes SM490A (JIS) steel plates, or its European equivalent S355J2(+N) and ST52-3, that are connected by the welding and heat-treatment process. The transom is made from STKM18B steels and stiffener from SS400 steels [1]–[4].

A bogie frame is the high-strength steel chassis of the bogie where each component of the bogie, either made from steel sheets, forged, or cast pieces are connected through welding. The bogie frame itself is classified by its shape, namely as Open-H, Closed-H, and Three-piece, which are determined based on its operational demand [5].

Like other railway bogie frames, when assessing the static strength of an LRT bogie frame, following the Allowable Stress Criterion, stress values from the selected measuring points must be lower than the yield limit of the base metal. The LRT bogie frame structure is formed from steel plates with EN S355J2+N material shown in Error! Reference source not found., which is joined by an electric welding process and further processed by heat treatment (normalizing) [6]. The stress occurring in the LRT bogie frame on exceptional loads should be less than the yield strength of the material used. Under the normal service loads, the mean stress and the stress amplitude are calculated on each load and they should be within the fatigue limit diagram.

Previous research has utilized finite element (FE) analysis to analyze the dynamic behavior of railway coaches as well as bogie/chassis [7], [8]. ANSYS engineering simulation and 3D design software have been commonly used in the design of railway and bullet train bogies and coaches to determine their dynamic response. By conducting a structural analysis of the bogie frame, followed by the analysis of the attachment components of the bogie frame by finite element calculation, an assessment could be made to locate

Figure 1. Urban LRT train bogie set

Figure 2. Urban LRT train bogie frame

Table 1. Mechanical Properties of materials EN S355J2+N

Parameter	Value
Modulus of Elasticity	210 GPa
Poison's Ratio	0.3
Density	7850 kg/m^3
Yield Strength	355 MPa

critical zones and surfaces, check for maximum stresses and deflections to be within the permissible limits, and verify that fatigue failures or permanent deformations do not occur during the bogie frame specified lifetime. Considering the similarity in the operating conditions of railway coaches/bogies and that of LRT, a similar approach is used in utilizing finite element analysis to assess the dynamic behavior of LRTs. Assumptions taken in the finite element modeling of the LRT bogie include [9], [10]:

- Primary and secondary suspensions are modeled as linear spring elements;
- Material properties of the steel are used entirely for the element types since the majority of the material in the bogie body is steel;
- The elastic boundary on each supporting surface is set. The X coordinate is the forward direction of the vehicle, the Y coordinate is the transverse direction, and the Z coordinate is the vertically upward direction. Each direction represents the three directional stiffness from the series of suspensions in a bogie; and
- For harmonic analysis, sinusoidal excitation is used as input. The obtained harmonic peaks are compared with eigenfrequencies in modal analysis.

The bogie structure is designed as well as possible to withstand static and dynamic loads while traveling on the rails. Therefore, the bogie structure that has been made must be tested for static, fatigue, and dynamic tests on the track which is a design requirement and evaluation of its strength. The LRT bogie frame design has gone through a structural design optimization process using finite element analysis using CAE software and has passed manufacturing quality control.

In order to prove that the design of the LRT bogie frame has met the required technical specifications, a validation plan based on the EN 13749 standard UIC Code 615-4, and the VDV Recommendation is established and carried out in a nationally accredited testing hall. Tests carried out following the validation plan also seek to evaluate the behavior of the designed bogie frame, to ensure that defects such as catastrophic rupture, permanent deformation, and fatigue cracks, do not occur during service. Relations between the associated bogie components or sub-assemblies are also evaluated, to ensure that no adverse influences are observed [11], [12]. Static tests and fatigue tests are carried out, following the technical specifications and regulations, to satisfactorily validate the LRT bogie design. The bogie frames and test frames must also be manufactured according to an equivalent set of specifications outlined in drawings, procedures, and quality plans established. Using the result of fatigue testing, the overall service life of the produced LRT bogie frame is to be ascertained, safety margins evaluated, and weak points not identified by the static tests to be detected [13]. Keeping in mind the capabilities of existing test installations in the country, these tests can only be recommended.

Therefore, the objective of this research is to utilize fatigue testing in verifying the design and manufacturing quality of the new Indonesian LRT bogie frame. Optimization to the bogie design is done through finite element analysis and numeric computation done using CAE software. The bogie frame is manufactured through welding and heat treatment is carried out to eliminate the resulting residual stress from welding. Verification is done by conducting fatigue testing with incremental loading cycles, where non-destructive testing is done after each loading cycle to check for damage or failures.

2. Materials and Method

The first stage of the design life verification is conducted by conducting a non-destructive test (NDT) on the existing LRT bogie frame specimen, to ensure that no pre-existing defect exists or to verify that sound repairs have been made on the specimens that will be tested. Strain gauges are then mounted on the frame and a dynamic data logger is installed. Fatigue testing is carried out on the specimen until it reaches 2,000,000 cycles, after which loading is stopped and non-destructive testing is carried out to confirm the absence of cracks on the specimen and verify that the specimen is undamaged. If undamaged, then loading is continued to 4,000,000 cycles and 6,000,000 cycles, each followed by non-destructive testing to check for damages due to fatigue loadings. If failures, confirmed through NDT, are found after any of the three loading cycles, then the design life verification testing is ended, and evaluations are made (see **Figure 3**).

2.1. Fatigue loading

The load cases used for the bogie frame fatigue test are defined based on the loading condition of the vehicle equipped with the bogies. External dynamic loads can be designated as the results of running on the track (e.g. vertical forces due to the load carried by the vehicle, trans-
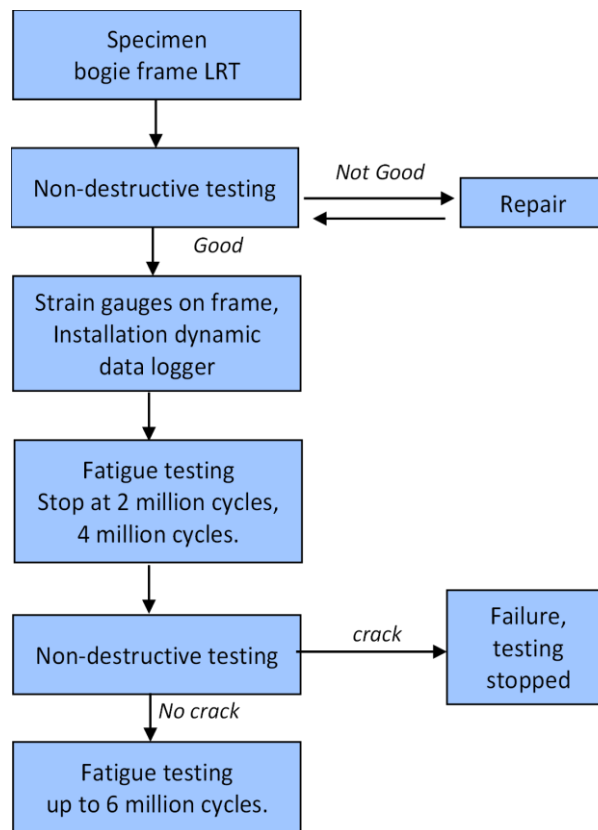
verse forces on curves or when going across points and crossings, twisting of the bogie frame because of the vehicle going over the twisted track); starts/stops and associated vehicle accelerations; loading/unloading cycles of the vehicle; lifting and jacking. The dynamic test load applied to the test object is obtained from analytical calculations according to the EN 13749 standard for railway applications.

To investigate the fatigue strength of the welded frame of LRT bogies under random loads, a load program of the dynamic bogie frame test was established. The time histories of the vertical load between the wheel and rail, the vertical and lateral loads of the air spring, the lateral stop and damper loads, and the twisting load experienced by the bogie frame were calculated. The time-load history of the relevant position of the bogie frame under different working conditions can be obtained [14], [15]. According to the UIC 615-4 regulations, the fatigue loading can be represented as the appropriate supernormal load, simulated operational load, and special operational load. Supernormal load is when the maximum load operations may occur; simulated actual operating load refers to the load operations that occur frequently; special operational load refers to the load frame by a special device caused [16]. Compared with high-speed railway passenger trains covering long distances and time, the Light-Rail Transit (LRT) trains are used to experiencing more abnormal loading due to frequent start-stops and passenger uncertainty [17].

The fatigue load condition comes from the normal service load added with an additional value of force, namely quasi-static and dynamic. The loading of fatigue load is divided into two types, namely driving in curves and passing points (switches). Calculation of loading meets Eqs. (1) to (8) [11].

Figure 3. Testing design

a. Vertical static load

$$F_{z1}, F_{z2} = \frac{m_1}{2} . g \tag{1}$$

b. Quasi-static vertical load
   Driving in curves,

$$F_{z1qs}, F_{z2qs} = \left(k_{qs} . m_1 . \left(a_{yc} + a_{ycc} \right) \right) + \left(k_{qs} .2. m_2 . \left(a_{yb} + a_{ycb} \right) \right) \tag{2}$$

   Switches,

$$F_{z1qs}, F_{z2qs} = \frac{F_w}{2} \tag{3}$$

c. Vertical dynamic load

$$F_{z1dyn}, F_{z2dyn} = \left(\frac{m_1}{2} \right) . a_{zc} \tag{4}$$

d. Transverse Quasi-static Load
   Driving in curves,

$$F_{yqs} = \left(k_{qs} . m_1 . \left(a_{yc} + a_{ycc} \right) \right) + \left(k_{qs} .2. m_2 . \left(a_{yb} + a_{ycb} \right) \right) \tag{5}$$

   Switches, Fz1qs, Fz2qs = Fw/2

$$F_{yqs} = \frac{F_w}{2} \tag{6}$$

e. Transverse dynamic Load

Driving in curves,

$$F_{ydyn} = \left(k_{dyn}.m_1.\left(a_{yc} + a_{ycc}\right)\right) + \left(k_{dyn}.2.m_2.\left(a_{yb} + a_{ycb}\right)\right) \qquad (7)$$

Switches,

$$F_{ydyn} = \left(m_1.a_{yc}\right) + \left(2.m_2.a_{yb}\right) \qquad (8)$$

Where F_{z1} = vertical static load 1, F_{z2} = vertical static load 2, F_{z1qs} = vertical quasi-static load 1, F_{z2qs} = vertical quasi-static load 2, F_{z1dyn} = vertical dynamic load 1, F_{z2dyn} = vertical dynamic load 2, F_{yqs} = load transverse quasi-static, F_{ydyn} = transverse dynamic load, m_1 = carbody load, m_2 = motor-gear box load, g = gravity, k_{qs} = quasi-static factor, a = acceleration, F_w = wind load. All loading units are in Newton (N).

The test loads represent the load cases driving in curve and passing point as shown in **Figure 4**. Following BOStrab VDV Recommendation, the relation between the load case driving in curve and the load case passing points shouldbe 2:1. Both the load case driving in curve and the load case passing point consist of a right-hand curve and a left-hand curve. Each right-hand or left-hand curve has 15 load cycles in the vertical direction. The minimum load collective according to **Figure 4** is repeated and thefatigue test loading program is executed. Based on the results of the standard analytical calculation EN 13749 with the input, the magnitudes of the force applied to the fatigue test consist of driving conditions in the curve (**Figure 5**) and passing point conditions/switches (**Figure 6**). During actual testing, fatigue loadings following the conditions in **Figure 5** and **Figure 6** are simulated.
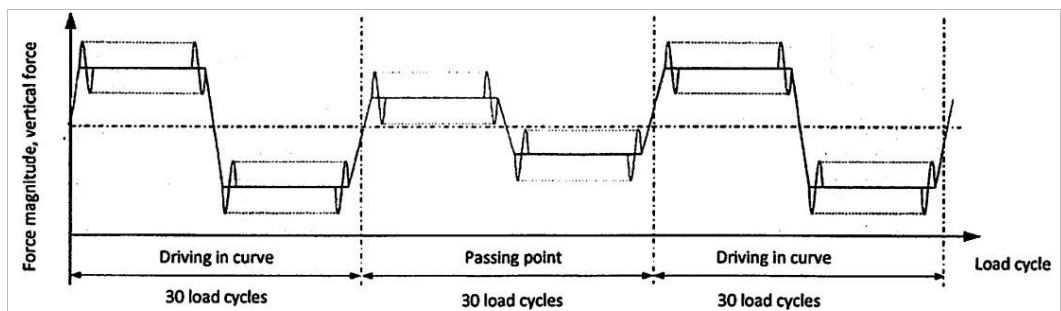

Figure 4.
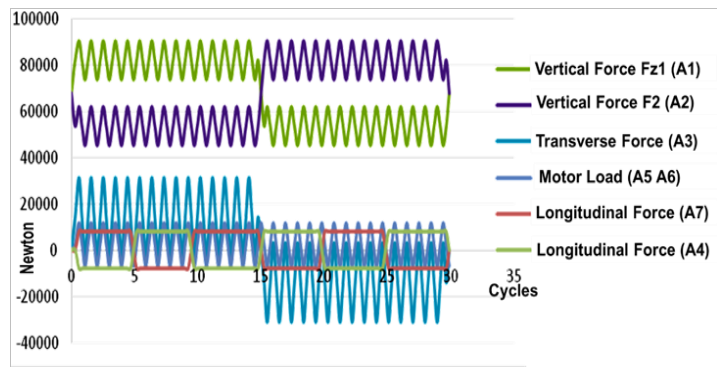Fatigue test model with two types of loading [12]

Figure 5.
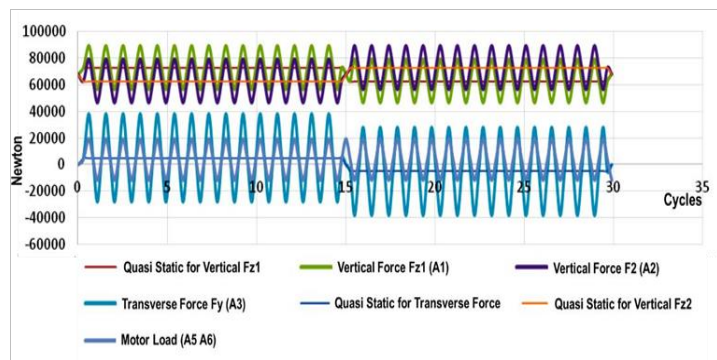Simulation of fatigue loading conditions driving in curve

Figure 6.
Simulation of fatigue loading conditions passing point (switches)

The loading value itself is a summation of the static, quasi-static, and dynamic loadings experienced. The maximum and minimum loading value is obtained based on analytical calculation following Eqs. (1)-(8). Fatigue test loading program for bogie frame consists of two load levels (**Figure 7**):

▪ load level 1, which consists of 4×10^6 load cycles of vertical and transverse forces with static, quasi-static and dynamic force components; and
▪ load level 2, which consists of 2×10^6 load cycles, the main load amplitudes of which are increased by factor 1.2 as against load level 1.
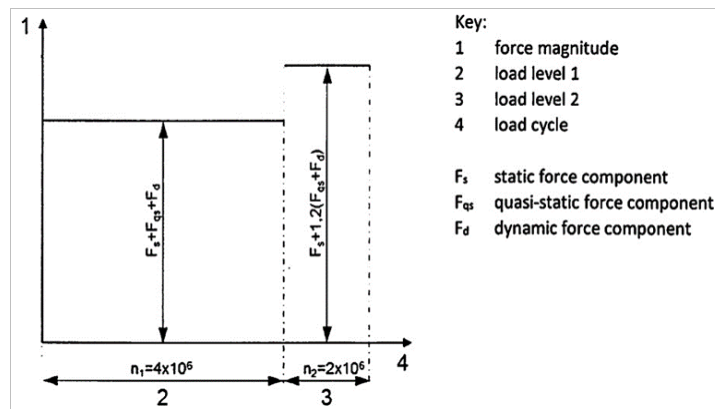
Figure 7.
Fatigue testing stage [12]

An additional case during fatigue testing is the condition of the bogie structure that experiences twisting. The test scheme in the twist condition is to add a plate to one of the supports were based on the results of analytical calculations, the plate thickness is 2.7 mm or 0.5% of the horizontal distance. The acceptance criteria for fatigue test results based on the VDV standard are the absence of cracks in the bogie structure during the test up to 4,000,000 cycles and the maximum allowable cracking is 2 mm during fatigue testing cycles of 4,000,000 to 6,000,000 cycles. Inspection of cracks on the surface of the bogie structure using the non-destructive test method.

2.2. Experimental Execution

Before installing the new LRT bogie frame on the testing machine, the bogie structure must be inspected to ensure no initial damages or cracks on the test specimen caused by welding or other machining processes. In this case, the inspection is carried out using a non- destructive test method, in which the method uses Magnetic Particle Inspection (MPI) and examines on all-welded plate joint areas (**Figure 8**).

The principle of this method is to generate magnetic flux in the article to be examined, with the flux lines running along the surface at right angles to the suspected defect. Where the flux lines approach a discontinuity, they will stray out into the air at the mouth of the crack. The crack edge becomes magnetic attractive poles North and South. These have the power to attract finely divided particles of magnetic material such as iron fillings. Usually, these particles are of an oxide of iron in the size range 20 to 30 microns and are suspended in a liquid which provides mobility for the particles on the surface of the test piece, assisting their migration to the crack edges [18]. The inspection not only detects those defects which are not normally visible to the unaided eye, but also renders easily visible those defects which would otherwise require scrutiny of the surface [19].

The following step is to install strain measurement sensors at several locations of the bogie frame structure. The strain sensor uses a strain gauge mounted on the point to be measured and is connected to a dynamic data logger. The maximum benefit from strain gauge measurements can only be obtained when a correctly assembled measuring system is allied with a thorough knowledge of the factors governing the strength and elasticity of materials. The only physical sign of loading is the mechanical deformation due to the load, and it is this deformation that can be measured by the strain gauge [20].

Figure 8.
Magnetic NDT inspection of particles before fatigue testing

The stress in a material balanced with an applied external force can be considered a combination of more than one simple stress. In other words, these stresses can be divided into simple stress in the respective axial directions; however, measurement with ordinary strain gauges is restricted to the plane strain (**Figure 9a**). When strain is generated on the surface of the material and the principal direction of the strain and its extent are unknown, the principal strain, stress, and their directions and shearing strain and stress can be obtained by measuring the strains in three directions over the surface (**Figure 9b**). To simplify calculation, the relative angle in the three directions is determined as maximum and minimum principal stress and maximum shearing stress [21]. The experimentally measured data at the time of bogie frame testing are the strain values under driving in curves and switches conditions.
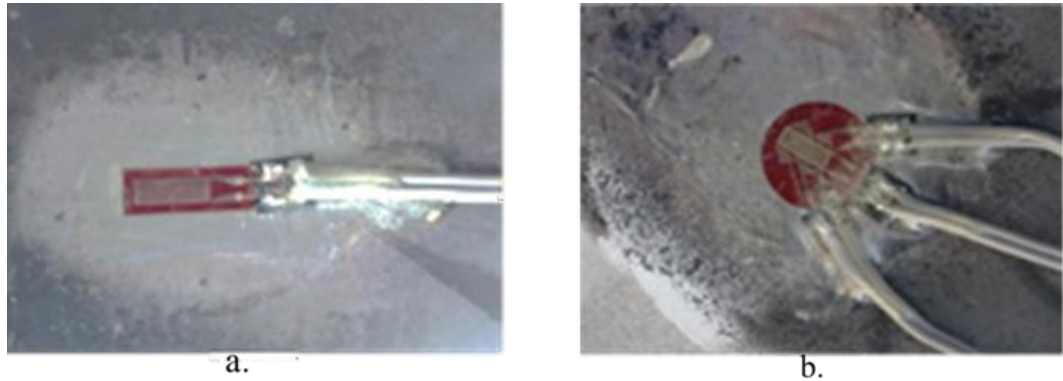

Figure 9.
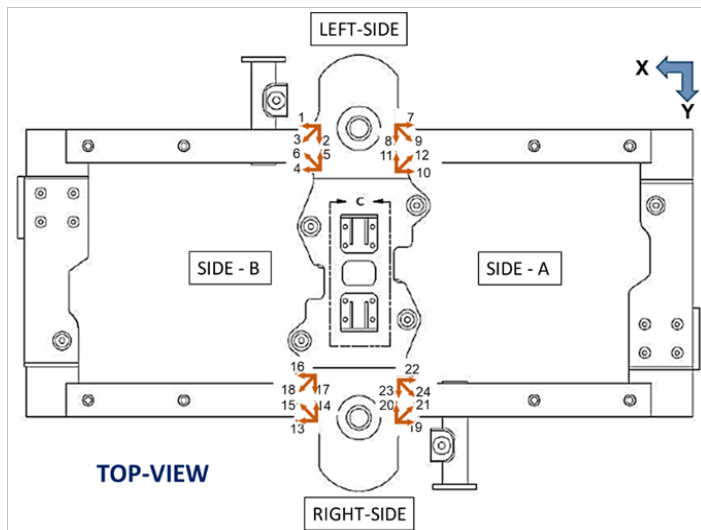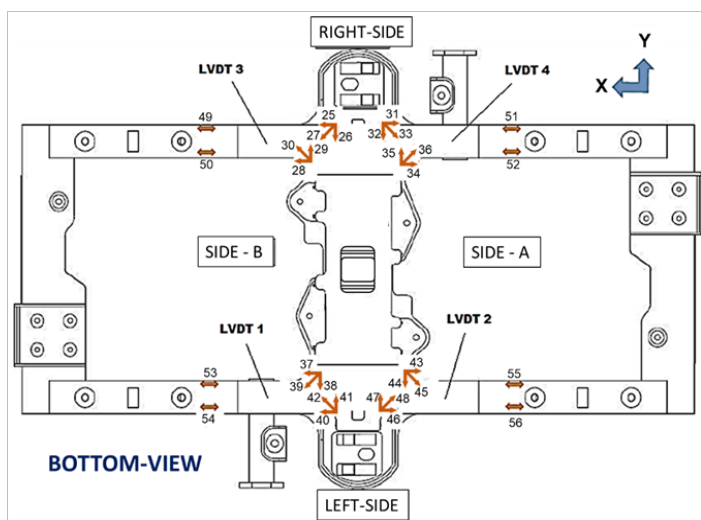Single type strain gauge (a) and Rosette type strain gauge (b)

Figure 10.
Top view of strain gauge installation location

The data can be obtained through 16 rosette and 8 single strain gauges located on the top frame specimen as shown in **Figure 10** and bottom frame in **Figure 11**. The data logger records the strain data as much as 56 strains, in which the data include 16 x 3 (rosette gauges) plus 8 single gauges. These strain data are converted to principal stresses expressing the stress where the strain gauges are located.

Finishing the specimen preparation with no initial crack and setting the strain gauges on the designated location, then the bogie frame structure of the urban LRT is placed on the support structure as vertical support at four locations of the air spring mounts as shown in **Figure 12**. To realize the test setup was established the test arrangement demonstrated in **Figure 12** which the bogie frame is supported by specimen supports and the load actuators are held by test rigs.

Figure 11.
Bottom view of strain gauge installation location
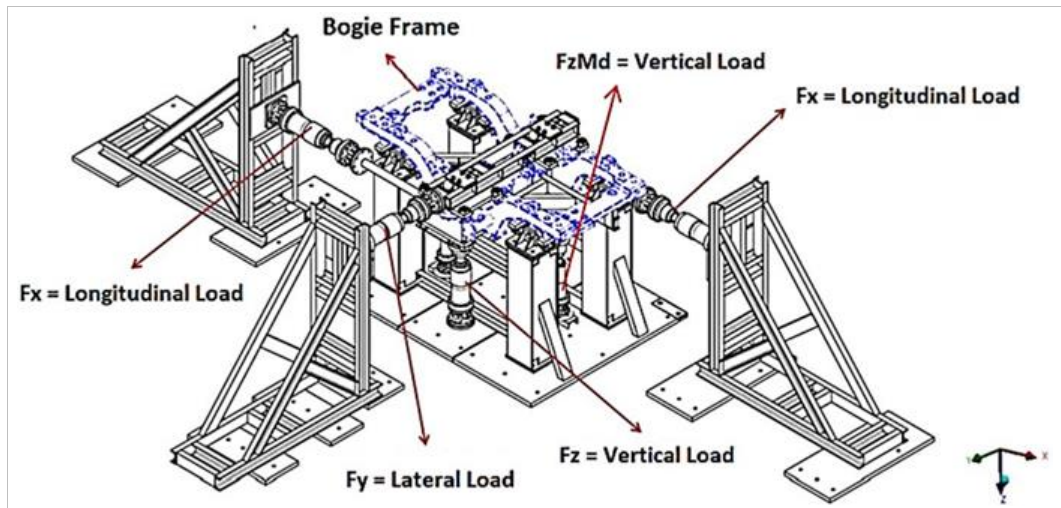
Figure 12. The urban LRT bogie frame test up

The test loads representing the load cases driving in curve and passing point are located at 7 locations of the structure based on the calculation results of loading which refer to the EN 13749 standard [11]. The vertical load in the form of the weight of the car body pressing the bogie frame structure uses 2 hydraulic actuators with a capacity of 160 kN, while the vertical load on the motor uses 2 hydraulic actuators with a capacity of 63 kN. Lateral load that simulates rolling force using 1 unit of the hydraulic actuator with a capacity of 100 kN. The horizontal load is a representation of the force due to braking using 2 units of hydraulic actuators with a capacity of 100 kN. All dynamic forces of hydraulic actuators are controlled by servo motors and servo controllers (see **Figure 13**).
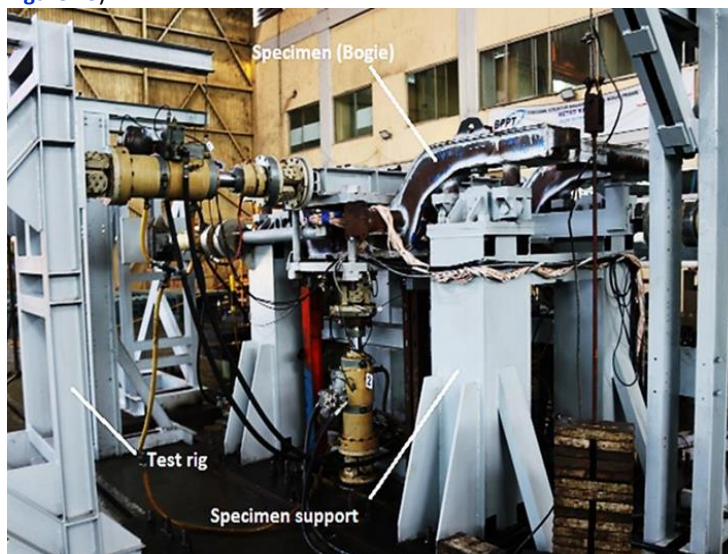
Figure 13. The experimental test the urban LRT bogie frame

Prior to running the dynamic fatigue test, all strain sensors that have been installed on the bogie structure are ensured to function properly and then set to a zero value (zero setting). Fatigue test loading is carried out following the sequence of the loading spectrum, namely driving in a curve – passing point (switches) – driving in a curve, with a total of 30 cycles for each condition (**Figure 4**, **Figure 5**, and **Figure 6**) .

Strain data is recorded at the time of initial loading and continued at the number of loading cycles in every multiple of 250,000 cycles until it reached 6,000,000 cycles. Each record contains 56 strain data from 16 rosette gauges or 16 x 3 data and 8 single strain gauges. Measurement data retrieval is carried out at a predetermined number of cycles in the form of a data strain block for 90 seconds. The strain value of each strain gauges is converted into the principal stresses and expressed as maximum and minimum stresses [21].

When the cycle reaches a value of 2,000,000, the test is stopped, and the bogie structure is examined with a non-destructive test to see the possibility of cracks that occur in the structure. The test will be continued for up to 4,000,000 cycles if no structure is damaged/cracked due to its fatigue load. The load applied in cycles of 2,000,000 – 4,000,000 is the same as the previous loading simulation. Inspections on the structure will be carried out after the 4,000,000 cycles are completed by the non-destructive test method. Fatigue testing is continued in cycles of 4,000,000 - 6,000,000 with an additional load of 20% of the Quasi-static load and the dynamic load. After completion of the test, the structure will be lowered from its support to be examined in detail for the possibility of cracks in critical areas, especially the welded connection area of the bogie structure [2], [22]–[24].

3. Results and Discussion

The measurement data is expressed in the form of curves of the maximum and minimum stress values of each strain gauge and grouped by referring to the location of the strain gauges shown in **Figure 10** and **Figure 11**. The stress data is divided into 3 groups of measuring points, namely 1 group of stress data values from the location of the measuring point of 8 single strain gauges, 1 group of 8 rosette gauges measuring points at the top of the bogie frame (**Figure 10**) and the third group is the value of stress from the 8-point rosette gauges at the bottom of the bogie frame (**Figure 11**).

Group 1 which consists of 8 single strain gauges has maximum and minimum stress values as shown in **Figure 14**. Meanwhile, Groups 2 and 3 each consist of 8 rosette gauges at loca- tions of top and bottom parts of the bogie structure have maximum and minimum stress values as shown in **Figure 15** and **Figure 16**. The measurement data shows that the maximum stress values at the single strain gauges position are relatively higher than the stress values at the rosette gauges location. Likewise, the minimum values, where the single strain gauges loca- tion are lower than the rosette location.

The highest stress value occurs at strain gauge 49 with a tensile stress value of 91.71 MPa when the number of cycles is 1,500,000 and the lowest value at strain gauge 54 is the com- pressive stress -52.25 MPa when the number of cycles is 5,000,000 (**Figure 11** and **Figure 14**). The illustration of the maximum stress values of strain gauge 49 and the minimum stresses of strain gauge 54 during dynamic loading is shown in **Figure 17**. The two curves illustrate that during loading the maximum stress values on strain gauges 49 and the minimum stress values on strain gauge 54 vary and are unstable.

In group 2 which consists of 8 rosette gauges at the top of the bogie frame (**Figure 10**), the highest principal or maximum stress value occurs in rosette gauge no 4, a combination of strain gauges no 10, 11 and 12. The highest tensile stress value equals to 64.94 MPa at 1,500,000 cycles. Meanwhile, the lowest minimum stress was recorded from rosette gauge no 2 which consisted of strain gauges no 4, 5 and 6 with a compressive stress value of -5.04 MPa for a total of 4.500.000 cycles (**Figure 15**).

Group 3 which consists of 8 rosette strain gauges at the bottom of the bogie frame (**Figure 11**) has the highest principal or maximum stress value at rosette strain gauge no 10 combined from strain gauges no 28, 29 and 30 with the highest tensile stress value is 65.28 MPa at number of cycles 1,500,000. Meanwhile, the lowest minimum stress was recorded from ro- sette strain gauge no 15 consisting of strain gauges no 43, 44 and 45 with a compressive stress value of -3.566 MPa for a total of 4.500.000 cycles (**Figure 16**).
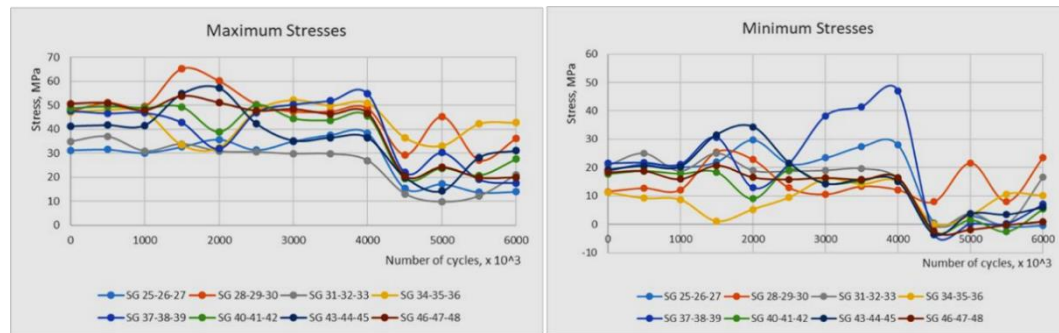

Figure 14.
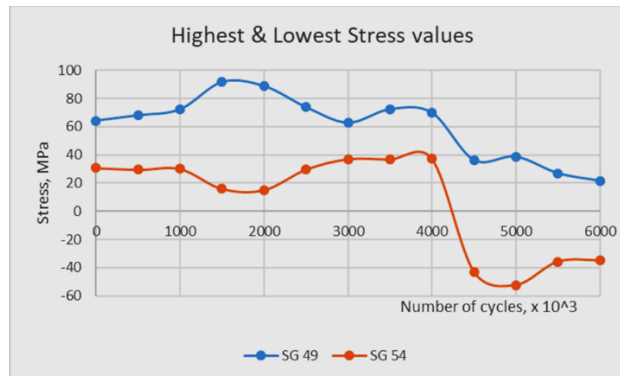Maximum and minimum stress values on 8 single strain gauges no. 49 to 56
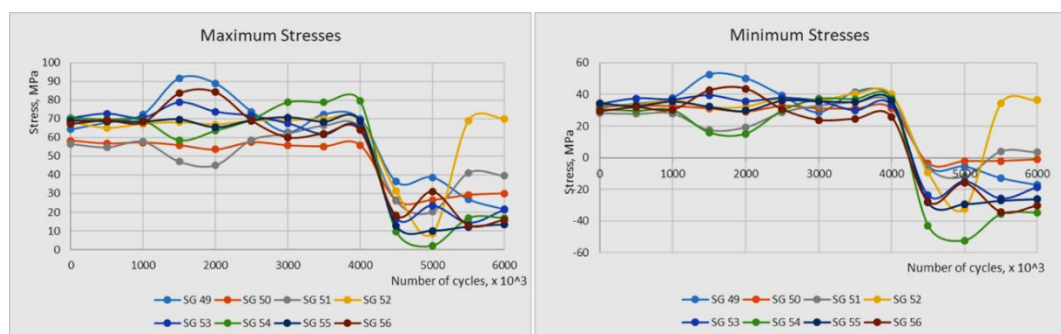
Figure 15.
Maximum and minimum stress values on 8 rosette gauges which strain gauges no. 1 to 24
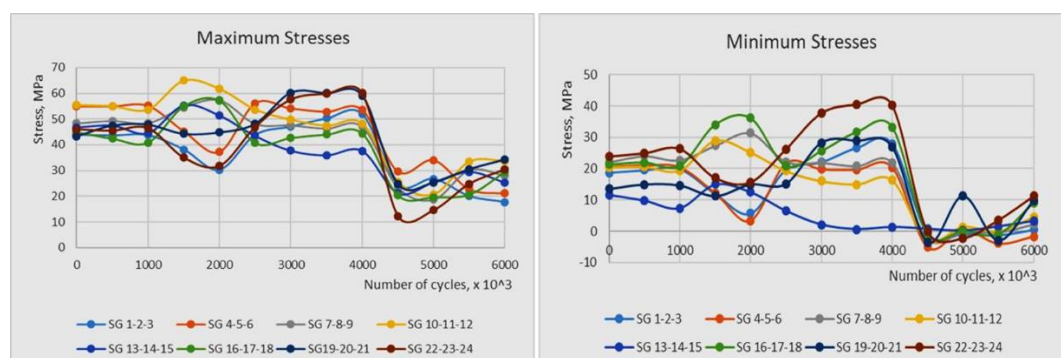
Figure 16.
Maximum and minimum stress values on 8 rosette gauges which strain gauges no. 25 to 48

Figure 17.
Maximum stress curve of SG 49 and minimum stress curve of SG 54

The measurement results in the form of stress data as shown in **Figure 14** to **Figure 17** are caused by the fatigue test loading program for bogie frame consisting of two load levels. Load level 1 consists of 4 x 106 load cycles of vertical and transverse forces with static, quasi-static and dynamic force components. Load level 2 consists of 2 x 106 load cycles, the main load am- plitudes of which are increased by factor 1.2 as against load level 1. Twist conditions to the bogie frame are added to the loading when the number of cycles reaches 4,000,000 cycles, resulting in a significant change in the stress values after 4,000,000 cycles.

The bogie structure was inspected to ensure no damages or cracks on the test specimen in the welding area of the bogie frame after 2,000,000 cycles, 4,000,000 cycles, and 6,000,000 cycles. In this case, the inspection is carried out using a non-destructive test method, in which the method uses Magnetic Particle Inspection (MPI) and examines on all-welded plate joint areas. The results of the inspection using the MPI non-destructive test method in the welding area of the bogie structure after 2,000,000 cycles, 4,000,000 cycles, and 6,000,000 cycles did not find any cracks or defects due to fatigue loading. Then it can be concluded that the structure of bogie frames of the urban LRT meets the acceptance criteria based on EN 13749 standard and VDV Recommendation [11], [12].

4. Conclusion

The LRT bogie frame design has gone through a structural design optimization process using finite element analysis using CAE software and has passed manufacturing quality control. In order to verify the result of the finite element analysis, that the design of the LRT bogie frame has met the required technical specifications, a validation plan based on the EN 13749 standard UIC Code 615-4, and the VDV recommendation is established and carried out in a nationally accredited testing hall. Seven hydraulic actuators applied multiaxial forces, which include normal service load, with the addition of quasi-static and dynamic force, to achieve fatigue load conditions. Two types of fatigue loads, namely driving in curves and passing points were applied. The fatigue test loading program for the bogie frame consisted of two load levels. Load level 1 consists of 4 x 106 load cycles of vertical and transverse forces with static, quasi-static, and dynamic force components. Load level 2 consists of 2 x 106 load cycles, the main load amplitudes of which are increased by factor 1.2 as against load level 1. Twist conditions to the bogie frame are added to the loading when the number of cycles reaches 4,000,000 cycles, resulting in a significant change in the stress values after 4,000,000 cycles. The highest stress value occurs at strain gauge 49 with a tensile stress value of 91.71MPa when the number of cycles is 1,500,000 and the lowest value at strain gauge 54 is the compressive stress -52.25 MPa when the number of cycles is 5,000,000. The fatigue testing result proved that stresses experienced by the bogie frame are well below the yield strength of the material. As an additional step in verification bogie structure was inspected to ensure no damages or cracks on the test specimen in the welding area of the bogie frame after 2,000,000 cycles, 4,000,000 cycles, and 6,000,000 cycles, using Magnetic Particle Inspection (MPI) and examines on all-welded plate joint areas. The results of the inspection using the MPI non-destructive test

method in the welding area of the bogie structure proved that there were no cracks or defects due to fatigue loading. It is thus concluded that verification of finite element analysis of bogie frame structures, could be conducted through fatigue testing following the EN 13749 standard and VDV recommendation to ensure that stress experienced in critical locations in the bogie frame is well below the material's strength. An additional MPI and examinations of the all-welded area of the bogie structure to confirm the result of the fatigue test, that the bogie frame structure designed is able to meet the LRT's design lifetime requirement.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

Availability of data and materials - All data are available from the authors.

Competing interests - The authors declare no competing interest.

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