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Research Paper

Bogie Frame Structure Evaluation for Light-Rail Transit (LRT) Train: A Static Testing

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Abstract

A new bogie frame of Light-Rail Transit (LRT) is having its strength of structure verified with experimental static testing according to EN 13749 standards. Static testing of bogie frame structure of LRT is performed by using a combination of seven tensile and compression loads that comprise of operational loads (normal service) and over-loads (exceptional service). Measurement parameters of bogie frame are strain and deflection values. The strain and deflection values resulted at every step of the load test were measured and monitored to further be used as analytic data. This data is then compared to the stress data of finite element analysis to check its deviation value. Testing results show the maximum stress value is 81.48 MPa on operational load, meanwhile, for exceptional load case, maximum stress is 120.96 MPa and deflection value is 1.25 mm. The maximum stress value is still below yield strength of bogie frame material S 555J2 (σ_y=355 MPa). According to testing data, structure of bogie frame LRT fulfill as the acceptance criteria.

Keywords: Light-Rail Transit (LRT); Operational loads; Over loads

Abstrak

Rangka bogie baru dari Light-Rail Transit (LRT) memiliki kekuatan struktur yang diverifikasi dengan pengujian statis secara eksperimental sesuai dengan standar EN 13749. Pengujian statis struktur rangka bogie LRT dilakukan dengan menggunakan kombinasi tujuh beban tarik dan kompresi yang terdiri dari beban operasional (servis normal) dan beban berlebih (servis luar biasa). Parameter pengukuran rangka bogie adalah nilai regangan dan defleksi. Nilai regangan dan defleksi yang dihasilkan pada setiap tahap uji beban diukur dan dimonitor untuk selanjutnya digunakan sebagai data analitik. Data ini kemudian dibandingkan dengan data tegangan analisis elemen hingga untuk memeriksa nilai deviasinya. Hasil pengujian menunjukkan nilai tegangan maksimum sebesar 81,48 MPa pada beban operasional, sedangkan untuk beban luar biasa, tegangan maksimumnya 120,96 MPa dan defleksinya 1,25 mm. Nilai tegangan maksimum masih dibawah kuat luluh material rangka bogie S 555J2 (σ_y=355 MPa). Berdasarkan data pengujian, struktur rangka bogie LRT memenuhi kriteria penerimaan.

Kata-kata kunci: Light-Rail Transit (LRT); Rangka bogie; Beban operasional; Beban berlebih

1. Introduction

One means of mass transportation that is being developed in Indonesia is the Jabodebek light rail or LRT (Light Rail Transit) which connects the capital city Jakarta with the closest cities, namely Bogor, Depok and Bekasi (**Figure 1**). This LRT train is operated automatically and controlled by the

Automatic Train Operation (ATO) operating system, through equipments supplied by the signal system provider. This mode of transportation is expected to reduce the density of passengers on highway and commuter line trains. This LRT train is designed with a maximum operating speed of 80 km/hour and a maximum carrying capacity of about 220 people in one train [1, 2].

Most of the railway vehicle studies focus on the complete design process of the key structural components of the railway carriage such as bogie frames, axles, wheels and other components, which includes design procedures, assessment methods, verification and manufacturing quality requirements [3]. The train structure is divided into two main parts, i.e. the carbody and the bogie which serve as a support for the basic frame of the carbody. The main function of the bogie (**Figure 2**) is to provide the train's flexibility to the rails so that the wheels can still follow the direction of the rail as they pass through curves. In addition, the bogie also functions to reduce the effects of shocks caused by the unevenness of the rail [4, 5].

Kim and Yoon studied the design and manufacture of a GFRP composite bogie frame to be applied to the bogie of urban subway trains. The stresses at the connection region between a cross beam and a side beam and deflection were measured and used to assess the structural safety. The stress and strain distribution for the whole bogie frame was evaluated through finite element analysis and compared with the experimental results [6]. The concept of GRP bogie was evaluated at fifth-scale model by making, instrumenting and testing two bogies. A shaker test rig has been developed for testing the whole rail vehicle at various performance conditions as well as with various suspension types to get these interactions using electro-hydraulic testing system. Several tests were performed like drop test, sweep tests, track profile test and so on to assess the properties and structural integrity of the developed bogie [7].

An analysis of the strain and stress distributions in a prototype of a bogie frame was carried out using strain measurements and finite element modeling. The research performed by Liliana et al was focused on the critical stress of a bogie frame of railway carriage for the transportation of the liquid cast iron [8]. The study to evaluate the fatigue strength of the bogie frames of electric railcars, the static load test, fatigue test, and track test were performed. The load conditions occurring under the track test of Korea were compared to those of EN 13798 and the fatigue damage was assessed by applying various fatigue evaluation methods [9]. Experimental static and dynamic tests of a bogie frame for a narrow-gauge tramway according to CSN EN 13749 yielded data were done, in which the strain gauge measurements after static loading of 157 kN provided evidence of zero residual deformation in the bogie frame. The fatigue test verified the life of the bogie frame after 107 cycles under loads at increasingly higher levels [10].

The LRT bogie frame is the main structure of bogie set which is designed to withstand the loads of the car body, accessories and passengers. The structure of the bogie frame is formed from steel plate material which is connected by welding and heat treatment processes. The bogie frame material is EN S355J2 + N which has a yield stress value (σ_y) of 355 MPa (**Figure 3** and **Figure 4**) [11, 12].

Optimization of LRT bogie frame design is carried out by solid modeling which is analyzed by the finite element method using ANSYS software. The calculation of the loading applied to the bogie frame model is performed by referring to the train design specifications and the EN 13749 railway application standard [3]. According to the result from simulation in finite element analysis as shown in Figure 4, the construction of LRT bogie is safe due to the given loads and the maximum stress value of the model is under yield stress of material [13].

Figure 1. Jabodebek LRT train design

Figure 2. Bogie frame train set

Figure 3. Jabodebek LRT bogie frame structure

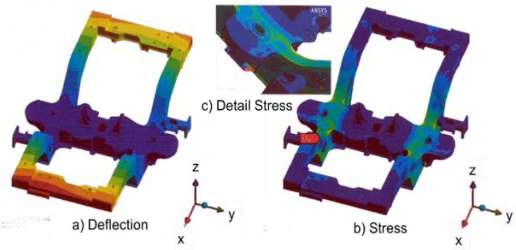


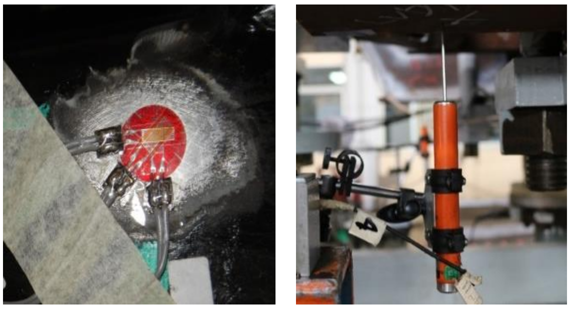
Figure 4. Finite element analysis

The structure of the bogie must be able to withstand static loading and there should not be any permanent deformation, also the bogie must be able to withstand the operational load [14]. Therefore, manufactured bogies must be verified for its strength experimentally through static testing using measuring equipment.

2. Methods

Data that can be measured experimentally in a static structure testing are the strain value using a strain gauge sensor and the deflection value using LVDT (Linear Variable Displacement Transformers) sensor as shown in **Figure 5**.

Strain is the tensile deformation divided by the original length which is a dimensionless number or expressed in percent. To get the actual stress value that occurs, the strain value is multiplied by the elastic modulus of the bogie material of 210 GPa [11]. Calculation of the average stress if the strain gauges are installed in the rosette and single form as shown in **Figure 6**.



(a) (b)

Figure 5. a. Strain gauge sensor; b. LVDT sensor

2.1. *Rosette type strain gauge*

Base on **Figure 6**, the direction sketch of strain gauge are:

ε_a = Strain direction a
ε_b = Strain direction b
ε_c = Strain direction c
φ = Angle
σ_1 = Stress 1
σ_2 = Stress 2

Rosette 45°/60° stress value is obtained by Eq.(1).

$$\sigma_{1,2} = \frac{E}{2}[(\frac{\varepsilon_a + \varepsilon_c}{1-\nu}) \pm \frac{\sqrt{2}}{1+\nu}\sqrt{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2}] \quad (1)$$

If the Poisson ratio is assumed at $\nu \approx 0.3$, hence:

$$\sigma_{1,2} = \frac{E}{1.4}[(\varepsilon_a + \varepsilon_c) \pm 0.76\sqrt{(\varepsilon_a - \varepsilon_b)^2 + (\varepsilon_b - \varepsilon_c)^2}] \quad (2)$$

The equivalent stress value is based on the Von Misses Criteria using the Eq.(3).

$$\sigma_{eq} = \sqrt{(\sigma_1{}^2 + \sigma_2{}^2 - \sigma_1\sigma_2)} \quad (3)$$

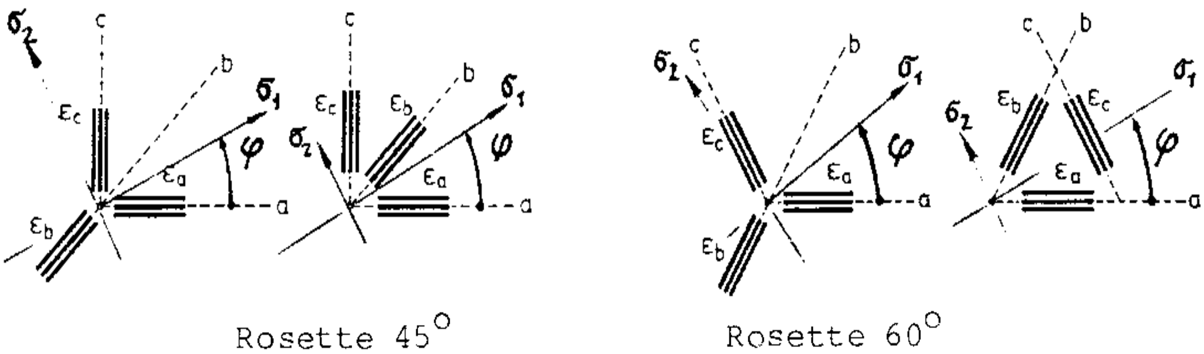


Figure 6. Illustration of rosette strain gauge angle [15]

2.2. *Single type strain gauge*

The calculation of stress with a single type strain gauge is presented in Eq.(4) as follows.

$$\sigma = E.\varepsilon \quad (4)$$

where:

σ = Stress (MPa)

E = Elasticity Modulus (MPa)

ε = Strain (μm/m)

The test object in the form of the LRT bogie frame structure is placed on the support structure as a vertical support at four air spring mount locations as shown in **Figure 7**. Static loading is located at 7 structural locations based on the results of loading calculations referring to the EN 13749 standard [3]. The vertical load in the form of the weight of the carbody pressing the bogie frame structure uses 2 hydraulic actuators with a capacity of 160 kN, while the vertical load of the motor uses 2 units of hydraulic actuator with a capacity of 63 kN. Lateral loads that simulate rolling force using 1 hydraulic actuator unit with a capacity of 100 kN. Horizontal load, which represents the force due to braking, uses 2 hydraulic actuators with a capacity of 100 kN. All static force of hydraulic actuators are controlled by servo motor and servocontroller.

In the bogie frame test object, 66 units of strain gauge sensors and 4 units of LVDT (**Figure 8**) were installed. The number of rosette-type strain gauges are 16 units and single-type strain gages are 18 units, spread over an area that is predicted to have a critical value based on the finite element simulation results. The sensors are connected to the data logger as a device to convert the signal into data in the form of strain value (microstrain) and the amount of deflection (millimeters). The display results in the form of strain and displacement data can be printed and stored in the memory contained in the data logger.

Based on EN 13749 standard [3], static testing can be categorized into four types of loading, i.e.:

1. Exceptional load test with switches condition (**Table 1**).
2. Exceptional load test with running through curves condition (**Table 2**).
3. Normal service load test with switches condition (**Table 3**).
4. Normal service load test with running through curves condition (**Table 4**).

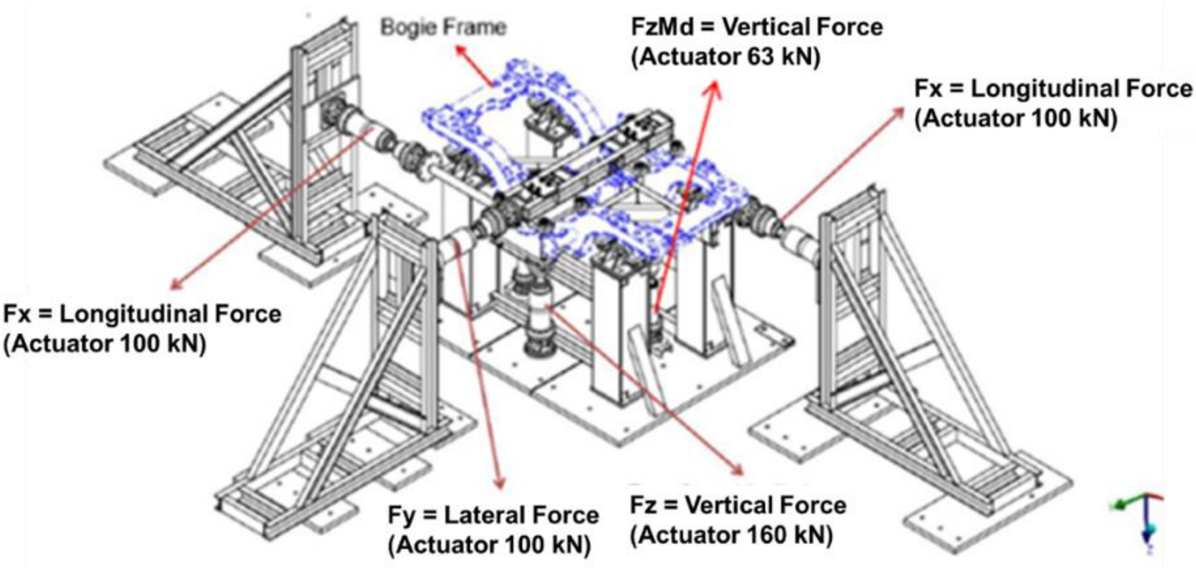


Figure 7. The static test arrangement of LRT bogie frame

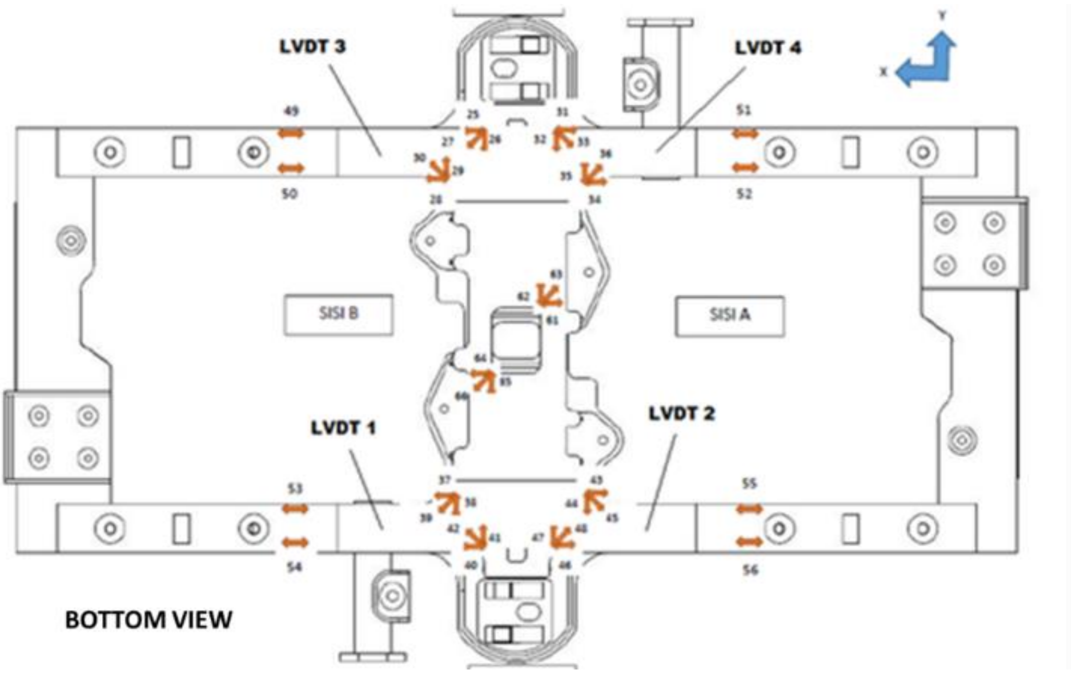


Figure 8. Sample of strain gauge dan LVDT installation location

Table 1. Load of exceptional static testing with switches condition

Case Number	Vertical Load 1 & 2 (N)	Transversal Load 3 (N)	Vertical Load 5 & 6 (N)	Longitudinal Load 4 & 7 (N)
1	112117	-	22099	-
2	112117	67418	22099	-
3	112117	-67418	22099	-
4	112117	-	22099	15328
5	112117	-	22099	-15328
6	112117	-	22099	97086
7	112117	-	22099	-97086

Table 2. Load of exceptional static testing with running through curves condition

Case Number	Vertical Load 1 & 2 (N)	Transversal Load 3 (N)	Vertical Load 5 & 6 (N)	Longitudinal Load 4 & 7 (N)
1	98325	-	13999	-
2	98325	79632	13999	-
3	98325	-79632	13999	-
4	98325	-	13999	15328
5	98325	-	13999	-15328
6	98325	-	13999	97086
7	98325	-	13999	-97086

Table 3. Load normal service static testing with switches condition

Case Number	Vertical Load 1 & 2 (N)	Transversal Load 3 (N)	Vertical Load 5 & 6 (N)	Longitudinal Load 4 & 7 (N)
1	67910	67910	0	19205
2	89554	79494	0	19205
3	89554	79494	37982	19205
4	56326	46266	0	19205
5	56326	46266	37982	19205
6	79494	89554	0	19205
7	79494	89554	-37982	19205
8	46266	56326	0	19205
9	46266	56326	-37982	19205

Table 4. Load of normal service static testing with running through curves condition

Case Number	Vertical Load 1 (N)	Vertical Load 2 (N)	Transversal Load 3 (N)	Vertical Load 5 & 6 (N)	Longitudinal Load 4 & 7 (N)	Twist (mm)
1	67910	67910	0	11780	0	0
2	90359	62074	0	11780	0	0
3	90359	62074	31256	11780	0	0
4	73745	45460	0	11780	0	0
5	73745	45460	31256	11780	0	0
6	62074	90359	0	11780	0	0
7	62074	90359	-31256	11780	0	0
8	45460	73745	0	11780	0	0
9	45460	73745	-31256	11780	0	0
10	90359	62074	31256	11780	0	2,7
11	73745	45460	31256	11780	0	2,7
12	62074	90359	-31256	11780	0	2,7
13	45460	73745	-31256	11780	0	2,7
14	67910	67910	0	11780	8110	0
15	67910	67910	0	11780	-8110	0

3. Result and Discussion

The measurement results were in the form of strain values at 66 strain gauge locations and deflection values at 4 LVDT locations. The value of strain is converted into stress after multiplying the modulus of elasticity of the steel material by 210 GPa, while the deflection results are shown in millimeters. From the results of data processing, as shown as **Table 5** and **Table 6**.

The stress and strain distribution for the whole GFRP composite bogie frame was evaluated through finite element analysis and compared with the experimental results [6]. The concept of GRP bogie was evaluated and test rig has been developed for testing the whole rail vehicle at various performance conditions using electro-hydraulic testing system [7]. This study develops the finite element analysis and validated through experiment supported by electro-hydraulic testing system. Some various bogie frames, such as the bogie frame of railway carriage for the transportation of the liquid cast iron [8], the bogie frames of electric railcars [9], and a railway bogie frame [10], were tested to determine the stress and strain distribution and fatigue characteristics. The static testing of the LRT bogie frame in this study is to determine the maximum stress of the specimen due to the exceptional and normal service loads.

Strength analysis for a new bogie frame LRT of motor bogie type has been done to ensure that the design can meet the requirements of a train transportation. The bogie frame must be safe from all operational loads. The analysis is initially started by geometry modeling through finite element method. By using ANSYS software, the loading condition is guided with UIC 615-4 and EN 13749 standards. The maximum stress value from FEM modelling is 290 MPa under yield stress of material (355 MPa) [13].

Based on the results of strain measurements and data processing in **Table 5** and **Table 6**, it can be seen that the maximum stress occurs during static testing with an overload of switches. The

Table 5. Maximum stress value of normal service load

Condition	Maximum stress value (MPa)	Deflection value (mm)	Strain gauge location
Switches	81.48	1.25	Number 55
Running through curves	78.75	1.05	Number 55

Table 6. Maximum stress value of exceptional load

Condition	Maximum stress value (MPa)	Deflection value (mm)	Strain gauge location
Switches	120.96	0.60	Number 55
Running through curves	111.09	0.40	Number 55

maximum stress that occurs is 120.96 MPa (576 microstrain) at the location of the strain gauge number 55 on the curved plate between the support and the middle profile of the bogie frame. The maximum stress value is still below the yield stress of S355J material of 355 Mpa [12]. While the maximum deflection value occurs in the operational load switch conditions of 1.25 mm and the value returns to zero after the release of static loads. This condition illustrates that the bogie structure is not permanently deformed.

4. Conclusion

Based on the results of the static test of the LRT bogie frame structure, the maximum stress value is 81.48 MPa on operational load case, and for exceptional load case, the maximum stress is 120.96 MPa and the deflection value is 1.25 mm. The maximum stress value is still below yield strength of bogie frame material S 555J2 (σy = 355 MPa). In regard with the requirements of the Republic of Indonesia Minister of Transportation Number Regulation No. 175 of 2015 and EN 13749, it is concluded that the structure of new Jabodebek LRT bogie frame meets the acceptance criteria, hence it is feasible for operation.

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Author's 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.

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All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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