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Verification of a new prototype design of bogie monorail frame with variation of static loading

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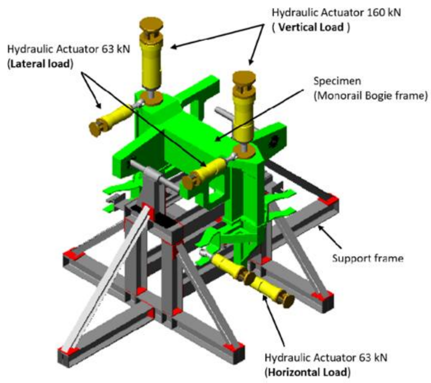
This article contributes to: 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; SUSTAINABLE DEVELOPMENT GOALS



Highlights:
- The strength of the newly designed monorail bogie frame has been analyzed and validated
- The monorail structure bogie frame prototype made from JIS SS 400 steel material was tested with a static load of 16.5 tons
- Static test results show a maximum strain value of 479 microstrain or equivalent to a stress value of 100.54 MPa

Abstract
The purpose of this study was to analyze and validate the strength of a new design monorail bogie frame. The 33 tons capacity of passenger train is supported by two bogie frames, in which each bogie frame structure should support 16.5 tons train load. A bogie frame prototype of monorail structure made of steel material JIS SS 400 was tested with 16.5 tons of static loading. Static test results showed the maximum strain value was 479 microstrain or equivalent to a stress value of 100.54 MPa. The experimental stress value was still far below the yield stress value of the material of 245 MPa. Based on the results of static testing, the design of the monorail bogie frame structure meets strength criteria and safety requirements.

Keywords: Bogie frame; Monorail; Static load, Microstrain

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1. Introduction

Monorail train is a single rail that runs on the rubber tires on a single rail beam track (straddle-beam monorails) or hangs on the rail beam (suspended monorail) [1], [2]. Monorail is an urban transportation that operates in some countries like Germany, Japan, China, Malaysia, United States, and others. Monorail offers various advantages such as less land needed, able to adjust narrow curve relatively, uphill tracks, and no crossing tracks because the lines are above the land (elevated) [3]–[6]. Monorail train is one of mass transportation vehicles in urban areas that has not been developed in Indonesia until today. Monorail train divides into two main parts of structures, lower part structure that is bogie frame and upper part structure that is train body or usually called carbody [7]. Monorail bogie frame structure is made from iron plate that is joined by welding and must be able to hold static loads and fatigue during operation [8], [9]. Meanwhile, car body structure is designed using light and strong construction materials such as extraction aluminum and hybrid technology, the structures from steel concrete composite materials. In this research, monorail bogie structure materials use steel JIS SS 400 with plate property in **Table 1** which is joined by welding process [10]–[12].

Component structures in monorail bogie structure consist of frame, tire wheel, electric motor drive, and monorail beam as shown in **Figure 1**. The research stages are begun by making the model as it shown in **Figure 2**, optimizing the design result, prototyping, static testing and analyzing the

Table 1. Mechanical Properties material JIS SS400

Material Properties	Value
Modulus of Elasticity	210 GPa
Poisson's Ratio	0.3
Density	7.8 e-6 kg/mm^3
Yield Strength	245 MPa
Ultimate Strength	400 MPa

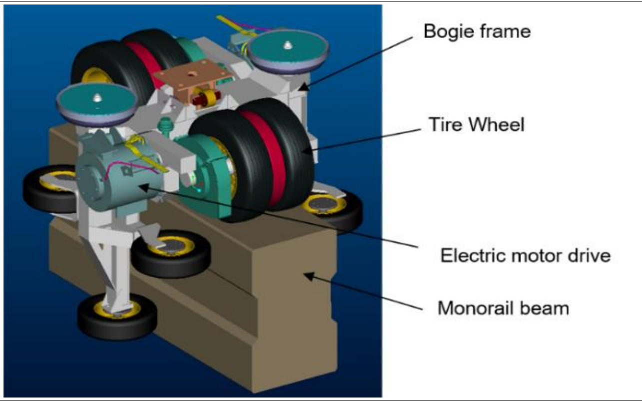

Figure 1. Component in Monorail Bogie Structures

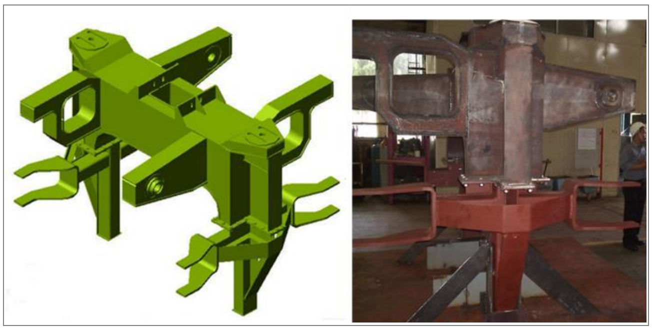

Figure 2. Monorail Bogie Frame Design and Prototype

tests result. Monorail bogie design structure modelling uses CAD software that is built in solid form. Such structure is built from steel plate component in various thicknesses and joined with fixed connection using weld method. Bogie frame model is analyzed by finite element method through CAE software. If the simulation result of finite element shows that the result does not meet requirement in term of strength, the model will be optimized in several ways by evaluating the form, dimensions and plate thickness [13]–[15].

A new train with capacity of 33 tons (323.62 kN) load is supported by two monorail bogie structure, in which the test load given to each bogie frame is 16.5 tons (161.81 kN), the same as defined by designer or manufacturer. This load magnitude is compiled from the loads representing carbody, accessories equipment, passengers, and overload factor. If the frame bogie design has passed the simulation test in which it meets the allowable stress design, then the prototype is manufactured based on the final design. Validation of the final design result was carried out by using the static test method on the prototype of the monorail bogie frame structure. The static loading method is a multiaxial load that is given through 6 hydraulic actuators that represent vertical, lateral, and longitudinal loads. Parameter measured during the test is strain with several loading cases [16]–[19].

Previous research included the design and finite element analysis of a straddle beam monorail bogie frame. Static load is a vertical, horizontal, and lateral load that includes carbody, passenger, air conditioning, seats, etc. The results of the finite element simulation show that stress values meet acceptance criteria. This research is to observe experimentally the influence of actual loading factors on the prototype bogie frame monorail made by the welding process. Shear values were obtained as measured parameters during static test loading of structure monorail bogie, then converted to be stress values.

2. Methods

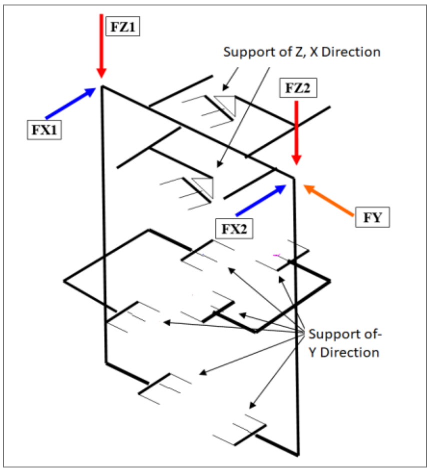

Figure 3. Free body diagram loading test

Monorail bogie frame structure must be able to hold static and dynamic loads during operation. This structure is designed optimally in order that its strength meets the material acceptance criteria [20]–[22]. The monorail bogie frame structure modeling is made by using CAD software (i.e: Solidworks) in three-dimensional solid form. Analysis of the strength of the structure is using the FEA (Finite Element Analysis) method with the help of Ansys CAE software and finite element method [23], [24].

The load values that are input into the model (shown in **Figure 3**) are obtained from the results of an analytical calculation [25], [26]. The details of the formula are presented in Eq. (1) to (4).

a. Static vertical load (F_z)

$$F_{z1.2} = \frac{(T_W + 1.2 \times P - 2 \times W_B)}{2} \quad (1)$$

b. Lateral load (F_y)

$$F_{y1.2} = \frac{k(T_W + 1.2 \times P + 2 \times W_B)}{2} \quad (2)$$

Lateral force if failure occurs so the train position unbalanced

$$F_{y3} = \frac{\sin\beta\,(T_W + 1.2 \times P + 2 \times W_B)}{2} \quad (3)$$

c. Longitudinal load (F_x)

$$F_x = (\sin\partial + \mu_{rs})(T_W + 1.2 \times P + 2 \times W_B) \quad (4)$$

In which T_w = train weight without passengers (kN), P = total passenger weight (kN), W_b = bogie weight (kN), k = dynamic factor, β = Slope angle, ∂ = incline angle, μ_{rs} = coefficient between wheel and track [27], [28].

The results of analytical calculations using the Eq. (1) to (4) show the value of the vertical static load is 91.70 kN, the lateral load is 58.73 kN and the longitudinal load is 11.40 kN. These loads are applied as load-force on the model that has been made according to the location of the loading as shown in **Figure 4**. While the boundary conditions in the form of a pedestal that located in the air spring and stabilizer area.

The design result is realized into monorail bogie frame prototype that is assembled from steel plate and joined by welding and then checked through several product quality procedures. Non-destructive test (NDT) inspection should be carried out to confirm there is no defect due to the welding process. This structure is carefully inspected by visual methods and non-destructive testing to ensure the absence of cracks and porosity in the weld area and the base metal. The next process is experimentally to verify the strength of monorail bogie structure by static testing [18]. Static test loading applied in monorail bogie frame is illustrated in vertical, lateral, and longitudinal directions refer to UIC 615-4. Vertical load is a representation of carbody, utility, accessories, and passenger weight. Lateral load occurs when train runs on the curved track, and longitudinal load is caused by the changing of speed and dynamic load [29], [30].

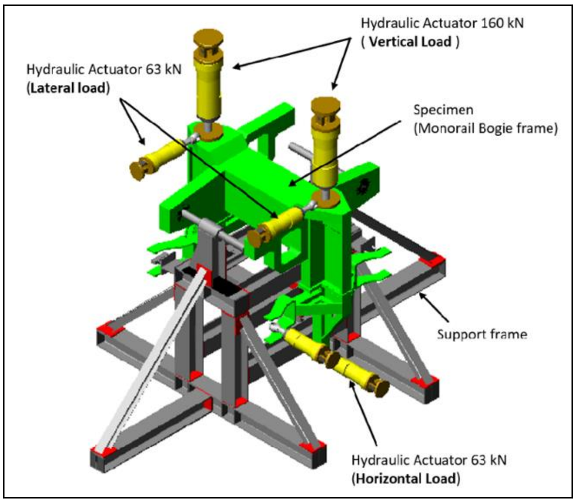

Figure 4. 3D picture of monorail frame bogie prototype static test setup

This frame structure is mounted on a support structure which is a fixed support so that translation and rotation do not occur during static testing as shown in **Figure 5**. The loading is given through several hydraulic actuators and controlled by servo valve that is connected to servo controller. Vertical static loading uses 2 actuator units with a capacity of 160 kN each to handle a load of 91.37 kN, while lateral loads use 2 actuator units with a capacity of 63 kN to handle a load of 58.73 kN. For longitudinal loads only use a single actuator with a capacity of 63 kN to handle a load of 11.40 kN.

Figure 5. Monorail frame bogie prototype static test setup

During the static testing, the loading is given through 5 hydraulic actuators and the actuator motion is controlled by using force control system (Figure 5). The bogie structure specimen is mounted on the rigid frame rig that is fastened on a strong floor. The measurement data consists of shear strain dan deflection values, in which shear strain values are obtained from 26 single type strain gauge sensors. The locations of strain gauge sensors are determined as results of FEM analysis that revealed the critical areas of monorail bogie frame [18], [19]. The test is carried out by increasing the loads gradually to reach the maximum loads and the measurement data was recorded following this process [31].

Experimental result data that can be measured in a static monorail bogie structure testing are the strain values using strain gauge sensors [19]. The sensors are connected to logger data instrument as data recording and processor. The results representing strain values will be compared to the finite element result analysis to determine the deviation values that indicate the differences between numeric simulation and experimental results.

3. Results and Discussion

Previous research was to observe the bogie frame structure with five-way static loads on four supports, while this research aims to analyze the strength of the monorail bogie frame structure with five load directions and eight support locations. The monorail bogie model analyzed using finite element analysis software Ansys is only partial or half because the model is symmetrical and has the same load on each side. The results of the computational simulation of the monorail bogie frame model using the static loading method produce stress distribution values as in Figure 6. For loading case 1 (vertical load), the maximum stress occurs in the radius area between the horizontal beam and the horizontal beam. vertical beam of 81.04 MPa. Meanwhile, for load case 2 (combined load) the maximum stress is 94.22 MPa at the same location. This stress value is still below the yield stress of the SS 400 material of 245 MPa so this model meets the acceptance criteria. Based on the results of computational simulations, this model is suitable for making a prototype and then verifying it with static testing.

Two types of loading are given to the static test, namely a simulated load when the monorail runs on a straight track (loading case 1) and another load when the monorail turns at a certain radius (loading case 2). The load on the straight track is simulated when the monorail train receives a normal load consisting of the weight of the train and passengers which is simulated as a vertical load (F_z). Other loading cases are when the train makes a turn where the vertical (F_z), lateral (F_y) and longitudinal (F_x) forces work. The values of these forces were obtained through a load analysis with reference to formula 1 for vertical loads, formula 2 for lateral loads and formula 3 for longitudinal loads [7], [32]. From the results of the finite element analysis in Figure 6, it can be estimated the locations of 10 critical points to determine the stress values from the measurements using 26 strain gauges which are then compared to the results of the finite element analysis.

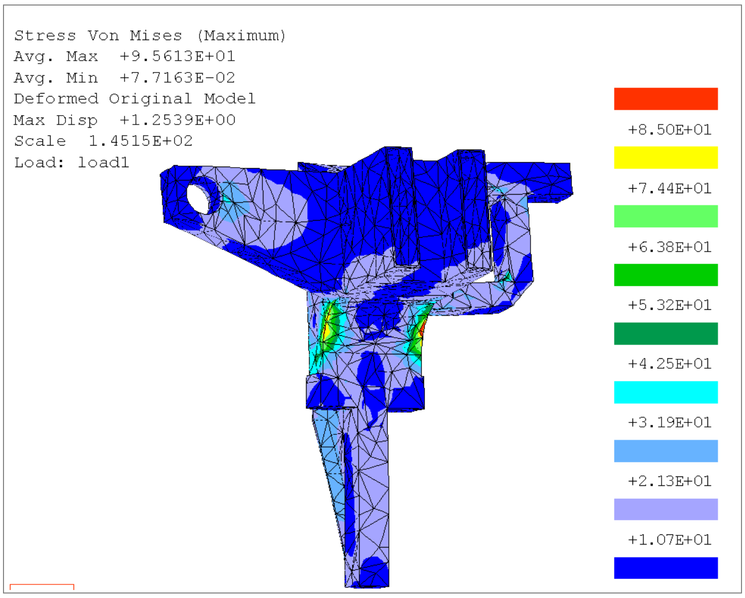

Figure 6. Stress distribution in monorail frame bogie model for load case 2 (combine load)

Comparation of test analysis and finite element is shown in Table 2 and Table 3, where in the table column 3 is the strain values, column 4 is the test stress values, column 5 is the FEM stresses and column 6 is the deviations. Based on the data on the Table 2 and Table 3, The actual stress that occurs during the static test in case 1 ranges from 12.35 MPa to 90.69 MPa, meanwhile in case 2, stress range that occurs is 17.53 MPa to 100.54 MPa.

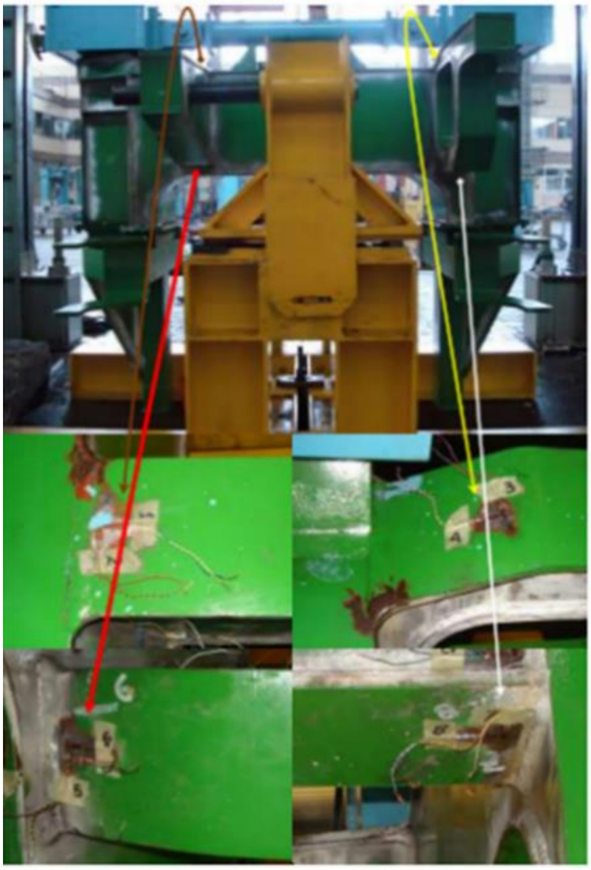

Figure 7. The most critical point (strain gauge nr. 6)

The data analysis of the test results, as presented in both **Table 2** and **Table 3**, reveals crucial insights into the structural behavior under various conditions. It is evident that the area around the joint radius connecting the vertical and horizontal beams, specifically at the single strain gauge position number 6 (as illustrated in **Figure 7**), experiences the highest stress levels. This finding is of paramount significance as it directly impacts the structural integrity of the assembly. The maximum recorded strain value stands at 479 microstrain, equivalent to a substantial stress level of 100.54 MPa, and this condition is observed when a combination of vertical, lateral, and horizontal forces is applied (as outlined in **Table 3**). Importantly, this stress level remains comfortably below the material's yield stress threshold of 245 MPa, ensuring the safety and reliability of the structure. However, it's worth noting that there are notable discrepancies between the test results and the finite element simulations. These discrepancies can be attributed to a range of factors that manifest during the manufacturing process. Factors such as plate cutting, welding techniques, and the overall quality control procedures in production contribute to the observed deviations. As a result, a comprehensive assessment of these factors is imperative to minimize these deviations and enhance the accuracy of future structural analyses and designs. By addressing these manufacturing challenges, it is possible to create structures that not only meet the safety requirements but also provide a more precise alignment between the real-world test results and the finite element simulations.

Table 2. Load Case 1 (Vertical Force)

Nr.	Nr. of SG	Strain (microstrain)	Stress Actual (MPa)	Stress FEM (MPa)	Deviation (%)
1	1	121	25.41	23.24	9.34
2	2	118	24.85	22.39	10.99
3	5	160	33.59	29.93	12.23
4	6	422	90.69	81.04	11.91
5	10	61	12.84	11.79	8.91
6	12	64	13.42	12.11	10.82
7	19	59	12.35	11.07	11.56
8	24	95	19.97	18.16	9.97
9	25	358	75.15	70.51	6.58
10	26	299	62.89	58.47	7.56

Table 3. Load Case 2 (Vertical Force, Lateral Force and Horizontal Force)

Nr.	Nr. of SG	Strain (microstrain)	Stress Actual (MPa)	Stress FEM (MPa)	Deviation (%)
1	1	169	35.47	32.74	8.34
2	2	157	32.89	30.32	8.48
3	5	273	57.42	53.41	7.51
4	6	479	100.54	94.22	6.71
5	10	84	17.63	15.19	16.06
6	12	76	16.03	14.67	9.27
7	19	83	17.53	13.24	32.40
8	24	124	25.97	22.31	16.41
9	25	377	79.18	74.45	6.35
10	26	304	63.87	59.86	6.70

4. Conclusion

The new design of a monorail bogie frame made of SS400 material plates is analyzed using the finite element method and validated by static testing using the loading given by 5 hydraulic actuator units. The loading given to the static test consists of two conditions, namely the vertical load and a combination of vertical, lateral, and horizontal loading. From the results of the finite element analysis of the monorail bogie frame structure, it is possible to estimate the location of the strain sensor measuring point to obtain the stress value which will be compared with the von misses stress value resulting from the finite element method computational simulation. The maximum stress value of the measurement results is 100.54 MPa in the same critical area from the computational simulation results. The stress value from the test results gives an estimated static load safety value of 2.43. This value indicates that the prototype design of this monorail bogie frame can be produced, and it is recommended to use materials that are resistant to fatigue loads.

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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.

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References

[1] J. Zhou, Z. Du, Z. Yang, and Z. Xu, "Dynamics Study of Straddle-Type Monorail Vehicle with Single-Axle Bogies-Based Full-Scale Rigid-Flexible Coupling Dynamic Model," *IEEE Access*, vol. 7, pp. 110249–110257, 2019, doi: 10.1109/ACCESS.2019.2933991.

[2] J. Zhou, Z. Du, and Z. Yang, "Dynamic response of the full-scale straddle-type monorail vehicles with single-axle bogies," *Mechanika*, vol. 25, no. 1, pp. 17–24, 2019, doi: 10.5755/j01.mech.25.1.21931.

[3] E. Adawy and M. Amr, "Monorail System as Urban Sustainable Transit in Alexandria," *ERJ. Engineering Research Journal*, vol. 40, no. 4, pp. 349–357, 2017, doi: 10.21608/erjm.2017.66361.

[4] T. Ahmed, M. Salem, A. Saad, and A. R. Alaqqad, "Improving the Traffic Flow in Hot Arid Climate Areas by Implementing a Monorail Light Rail Transit System: Case of Kuwait," *American Journal of Engineering and Applied Sciences*, vol. 14, no. 1, pp. 103–111, 2021, doi: 10.3844/ajeassp.2021.103.111.

[5] T. Kuwabara, M. Hiraishi, K. Goda, S. Okamoto, A. Ito, and Y. Sugita, "New solution for urban traffic: Small-type monorail system," *Hitachi Review*, vol. 50, no. 4, pp. 139–143, 2001, doi: 10.1061/40766(174)65.

[6] P. E. Timan, "Why Monorail Systems Provide a Great Solution for Metropolitan Areas," *Urban Rail Transit*, vol. 1, no. 1, pp. 13–25, 2015, doi: 10.1007/s40864-015-0001-1.

[7] J. Zhou, Z. Du, Z. Yang, and Z. Xu, "Curving performance of straddle-type monorail vehicle with single-axle bogies based on spatial multi-body dynamic analysis," *Mechanika*, vol. 27, no. 2, pp. 148–154, 2021, doi: 10.5755/J02.MECH.22930.

[8] J. K. Ren, Q. Y. Chen, J. Chen, and Z. Y. Liu, "On mechanical properties of welded joint in novel high-mn cryogenic steel in terms of microstructural evolution and solute segregation," *Metals*, vol. 10, no. 4, 2020, doi: 10.3390/met10040478.

[9] Y. Ogawa, T. Horita, N. Iwatani, K. Kadoi, D. Shiozawa, and T. Sakagami, "Evaluation of fatigue strength based on dissipated energy for laser welds," *Infrared Physics and Technology*, vol. 125, no. January, p. 104288, 2022, doi: 10.1016/j.infrared.2022.104288.

[10] A. S. Baskoro, M. A. Amat, and M. F. Arifardi, "Investigation Effect of ECR's Thickness and Initial Value of Resistance Spot Welding Simulation using 2-Dimensional Thermo-Electric Coupled," *Evergreen*, vol. 8, no. 4, pp. 821–828, 2021, doi: 10.5109/4742127.

[11] A. E. Öberg and E. Åstrand, "Variation in welding procedure specification approach and its effect on productivity," *Procedia Manufacturing*, vol. 25, pp. 412–417, 2018, doi: 10.1016/j.promfg.2018.06.111.

[12] L. H. Shah and M. Ishak, "Review of research progress on aluminum-steel dissimilar welding," *Materials and Manufacturing Processes*, vol. 29, no. 8, pp. 928–933, 2014, doi: 10.1080/10426914.2014.880461.

[13] J. Zou, B. Chen, S. Zhan, C. Huang, and X. Wang, "Theoretical Derivation of Gauges for Straddle-type Monorail Vehicle," *Journal of Physics: Conference Series*, vol. 1910, no. 1, 2021, doi: 10.1088/1742-6596/1910/1/012052.

[14] D. W. Karmiadji *et al.*, "Verification of urban light rail transit (LRT) bogie frame structure design lifetime under variable fatigue loads," *Mechanical Engineering for Society and Industry*, vol. 2, no. 1, pp. 42–53, 2022, doi: 10.31603/mesi.6938.

[15] Kiran S. Phad and A. Hamilton, "Experimental Investigation of Friction Coefficient and Wear of sheet metals used for Automobile Chassis," *Evergreen*, vol. 9, no. 4, pp. 1067–1075, 2022, doi: 10.5109/6625719.

[16] A. T. Raheem, A. R. A. Aziz, S. A. Zulkifli, A. T. Rahem, and W. B. Ayandotun, "Development, Validation, and Performance Evaluation of An Air-Driven Free-Piston Linear Expander Numerical Model," *Evergreen*, vol. 9, no. 1, pp. 72–85, 2022, doi: 10.5109/4774218.

[17] V. Singh, Vinod Singh Yadav, M. Kumar, and N. Kumar, "Optimization and Validation of Solar Pump Performance by MATLAB Simulink and RSM," *Evergreen*, vol. 9, no. 4, pp. 1110–1125, 2022, doi: 10.5109/6625723.

[18] D. W. Karmiadji, B. Haryanto, O. Ivano, M. Perkasa, and A. R. Farid, "Bogie Frame Structure Evaluation for Light-Rail Transit (LRT) Train: A Static Testing," *Automotive Experiences*, vol. 4, no. 1, pp. 36–43, 2021, doi: 10.31603/ae.v3i3.4252.

[19] D. W. Karmiadji, M. Gozali, A. Anwar, H. Purnomo, M. Setiyo, and R. Junid, "Evaluation of Operational Loading of the Light-Rail Transit (LRT) in Capital Region, Indonesia," *Automotive Experiences*, vol. 3, no. 3, pp. 104–114, 2020, doi: 10.31603/ae.v3i3.3882.

[20] Z. Yang, Z. Du, Z. Xu, J. Zhou, and Z. Hou, "Research on dynamic behavior of train dynamic model of straddle-type monorail," *Noise and Vibration Worldwide*, vol. 51, no. 11, pp. 195–207, 2020, doi: 10.1177/0957456520947998.

[21] L. Xin, Z. Du, J. Zhou, Z. Yang, and Z. Xu, "Study on dynamic response of straddle-type monorail vehicle with single-axle bogie under curve condition," *Mechanika*, vol. 27, no. 2, pp. 122–129, 2021, doi: 10.5755/J02.MECH.25319.

[22] L. Wei, J. Zeng, C. Huang, Q. Wang, and W. Shen, "Experimental and numerical investigations on longitudinal vibration of suspended monorail trains induced by bogie pitching motion," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 236, no. 4, pp. 418–433, 2022, doi: 10.1177/09544097211023626.

[23] S. L. S. Chauhan and S. C. Bhaduri, "Structural analysis of a four-bar linkage mechanism of prosthetic knee joint using finite element method," *Evergreen*, vol. 7, no. 2, pp. 209–215, 2020, doi: 10.5109/4055220.

[24] G. Prayogo, D. A. Sumarsono, Sugiharto, and A. S. Auzani, "Analysis of the Traction Wheel Torque of the Straddle Monorail Negotiating a Curved Track Using the Finite Element Method," *International Journal of Mechatronics and Applied Mechanics*, vol. 2022, no. 12, pp. 182–189, 2022, doi: 10.17683/ijomam/issue12.27.

[25] Z. Ansari, "Design and Analysis of Railway Casnub Bogie Using Fem," *International Journal on Mechanical Engineering and Robotics (IJMER)*, vol. 4, no. 4, pp. 68–72, 2016.

[26] N. R. Veerabhadraiah, "' DESIGN And Analysis of A Bogie Truck ' Department of Mechanical Engineering The Oxford College of Engineering," no. June 2014, 2015, doi: 10.13140/RG.2.1.1721.0961.

[27] Y. Jiang, W. Zhong, P. Wu, J. Zeng, Y. Zhang, and S. Wang, "Prediction of wheel wear of different types of articulated monorail based on co-simulation of MATLAB and UM software," *Advances in Mechanical Engineering*, vol. 11, no. 6, pp. 1–13, 2019, doi: 10.1177/1687814019856841.

[28] Z. Xu, Z. Du, Z. Yang, and L. Chen, “Research on Vertical Coupling Dynamics of Monorail Vehicle at Finger-Band,” *Urban Rail Transit*, vol. 3, no. 3, pp. 142–148, 2017, doi: 10.1007/s40864-017-0065-1.

[29] W.-K. Kim and S.-T. Won, “A Study on The Load Test of Bogie for Monorail-Type LRT,” *Proceedings of the KSR Conference*, vol. 10a, pp. 939–950, 2011, https://koreascience.kr/article/CFKO201132164225636.page.

[30] U. 615-4, “Motive Power Units Bogies and Running Gear Bogie Frame Structure Tests.” International Union of Railways, p. 2nd Edition, 2003.

[31] J. Tittel, M. Kepka, and P. Heller, “Static and dynamic testing of a bogie,” *IOP Conference Series: Materials Science and Engineering*, vol. 723, no. 1, pp. 1–6, 2020, doi: 10.1088/1757-899X/723/1/012031.

[32] J. Tomas H Orihuela, “Design of Monorail Systems,” no. 74, pp. 1–20.