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Experimental study on a new prototype design of electric bus vehicle structure under torsion loading conditions

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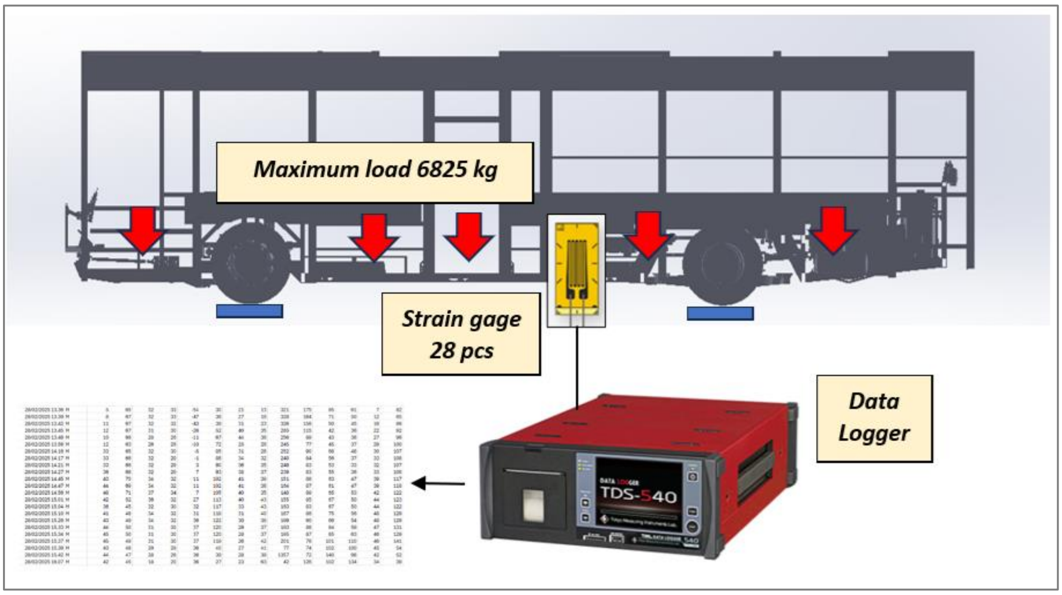

Highlights:

- The electric bus frame structure, constructed from SS 400 steel and 6061 aluminum alloy materials, has been experimentally verified under torsional loading conditions.
- The parameters in the discussion are the stress values obtained from simulation and those from experimental results.
- There is a deviation between the simulated and experimental stress values; however, both remain below the yield strength of the respective materials.

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Abstract

Vehicles commonly encounter uneven road conditions, which can lead to torsional deformation of the frame structure. The results of finite element analysis (FEA) indicate that the highest stress occurs under torsion loading conditions. To validate these simulation results, an experimental study was conducted involving static load testing under torsional loading conditions on a hybrid frame structure, composed of SS 400 carbon steel and 6061 aluminum alloy, designed for a 70-passenger electric bus. The test was performed by applying a static load of 6,825 kg as sandbags on the seating area and aisle, and supporting the frame on three wheels only. Strain measurements were recorded using 28 strain gauges: 20 on the SS 400 carbon steel underframe and 8 on the 6061 aluminum alloy structure of the side and roof frames. The total load was the weight of 70 passengers plus a 30% dynamic load factor. Experimental analysis revealed a maximum stress value of 76.42 MPa in the SS 400 carbon steel of the underframe at location 9 in the central section of the underframe. In the 6061 aluminum alloy structure, the maximum stress value of 15.56 MPa was obtained in the roof frame directly below the air conditioner unit. Overall, the measured stress values were within the elastic ranges of the materials used, demonstrating structural integrity under load. The average difference between the experimental results for stress and the finite element analysis (FEA) simulation was approximately 11.21%.

Keywords: Electric bus; Torsion; Strain gauge; Stress

1. Introduction

With the sustainable approach to alleviating transportation emission problems and global ecosystem degradation, electric vehicles have become quite popular within the past couple of years [1], [2]. Electric buses have zero emission tail pipes and provide services that help in the shift towards a tender public transport system. They are powered by batteries or overhead wires unlike diesel buses that primary use fossil fuels as their power source. This makes them eco-friendly which is very crucial for public transportation systems because buses are used regularly by large parts of the population [3], [4], [5], [6]. The electric bus frame houses one of the most powerful batteries in the transportation industry. It is one of the components that enable the vehicle's operational range, but because it is also one of the heaviest components, it needs to be carefully positioned [7]. Recent research has shown that the most optimal positions for the battery is on top of the roof, underneath the floor or towards the rear of the bus. The increased weight of the bus can lead to operational inefficiency, however when positioned correctly, they enable to the bus to increase the distance it travels on a single charge [8], [9]. The battery of an electric bus can be placed on the roof, under the floor, or at the rear of the bus [10]. The electric bus chassis is typically ordered for electric buses with careful consideration of the weight and location of the battery. To minimize the total weight, the electric bus framework structure is typically constructed from light materials such as aluminum alloy, magnesium alloy, fiber, or composite materials [11], [12], [13].

A lightweight frame is essential for an electric bus as it significantly enhances the vehicle's efficiency and performance [14]. A bus that consumes less energy is necessary, hence a lighter bus that uses less energy to operate, which helps the bus range and conserves battery usage. A hybrid frame structure is utilized to enhance the strength, weight, and durability of the electric bus through the use of aluminum alloys and carbon steel [15], [16]. Optimization of the electric bus frame structure is normally done through finite element analysis (FEA) on the frame model to find its response under operating loads by utilizing CAE software. Typical operating conditions of the bus for normal operations include full vertical load, horizontal bending, torsion conditions, instantaneous cornering, and emergency braking [17], [18]. Severe testing and certification of the car body structure are important to ensure the safety and reliability of electric buses. Static load testing is among the most frequent methods of assessing the structural behavior of automobile frames under the influence of gravity and other external forces [19].

A 70-passenger electric bus featuring a hybrid frame composed of aluminum alloy and carbon steel has been developed. The side frame and roof are made of 6061 aluminum alloy, while the lower frame is constructed from carbon steel. According to the results of a finite element simulation conducted using Ansys software across four load cases, the maximum stress occurs under torsional loading. However, the stress value remains within the elastic range, well below the material's yield strength. This research aims to validate the hybrid frame structure (SS 400 carbon steel and 6061 aluminum alloy) through static load testing, specifically focusing on the torsional load case.

2. Methods

The subject of this research is an electric bus constructed using a combination of 6061 aluminum alloy for the side frame and roof, and SS 400 carbon steel for the underframe. The bus has dimensions of 12,000 mm in length, 2,500 mm in width, and 3,700 mm in height. It is designed as an urban passenger transport vehicle with a maximum capacity of 70 passengers. The bus is fully equipped with an electric motor drive system, inverter, battery, air conditioning, seats, and other essential components, resulting in a total weight of approximately 13,000 kg, as shown in **Figure 1**. The underframe structure is fabricated from SS 400 carbon steel, utilizing square tube profiles with dimensions of 120 × 60 mm (6 mm thickness), 60 × 60 mm (4 mm thickness), and 50 × 30 mm (3 mm thickness). All frame components are welded together, followed by a thorough inspection to ensure the welds meet the required specifications.

The side frame and roof structure of the electric bus are fabricated from 6061 aluminum alloy through an extrusion process. This material was selected due to its favorable strength-to-weight ratio and excellent corrosion resistance, both of which contribute significantly to minimizing the

Figure 1. A new prototype of a 70-passenger capacity electric bus

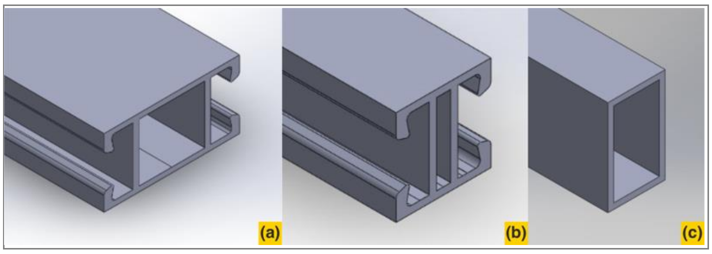

Figure 2. (a), (b) Profile type of aluminum alloy 6061; (c) Carbon steel SS 400

Table 1. JIS G3101 SS 400 mechanical properties

Properties	Value
Density	7860 kg/m^3
Yield strength	245 MPa
Ultimate tensile strength	400 MPa
Modulus of Elasticity	190-210 GPa
Poisson rasio	0.26

Table 2. Aluminum alloy 6061 mechanical properties

Properties	Value
Density	2700 kg/m^3
Yield strength	276 MPa
Ultimate tensile strength	310 MPa
Modulus of Elasticity	68.9 GPa
Poisson ratio	0.33

overall mass of the vehicle and enhancing its energy efficiency. The connections between components of the aluminum frame are secured using bracket plates and bolted joints, including the interfaces between the aluminum alloy frame and the square tube underframe. **Figure 2** illustrates the specific type of 6061 aluminum alloy employed in the electric bus frame structure. The mechanical properties of SS 400 carbon steel and 6061 aluminum alloy are summarized in **Table 1** and **Table 2**, respectively.

This research employs two methodologies. The first approach involves the use of the finite element method (FEM) with the assistance of Ansys software, while the second approach is experimental, utilizing static loading tests on an electric bus specimen. Finite Element Analysis (FEA) is a numerical technique used to solve complex engineering problems by dividing a structure into smaller, simpler components known as finite elements. Each element is analyzed independently, and the results are then assembled to predict the overall behavior of the structure under various conditions. The Eq. (1) and Eq. (2) are finite element equations which applied to compute the beam element responses.

$$f = [k].\{u\} \tag{1}$$

$$k = \frac{A.E}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{2}$$

where, f = force vector, k = element stiffness matrix, u = nodal vector or displacement, A = cross-sectional area, E = modulus of elasticity, L =beam length.

The loading scenario for this study involves a torsional condition, where the bus is supported by three wheels while one wheel remains free. Torsional load on an electric bus refers to the twisting force applied to the vehicle's chassis or structural components due to external loads, road conditions, and dynamic forces during operation as shown in **Figure 3** and **Table 3**. This torsional loading condition was selected because it represents one of the most critical scenarios, where the bus is fully loaded and supported by only three wheels, as shown in **Figure 4** free-body diagram. In this setup, the front-left wheel is left unconstrained. The results from the finite element analysis show the stress distri-

Table 3. Load on an electric bus

Number	Component	Weight (kg)
1	Body plate	582
2	Glass	230
3	Passenger seats	500
4	Electric motor	100
5	Electric component	200
6	Air Conditioner	250
7	Battery (9 packs)	1305
8	Passenger and bag	5250
Total weight		8417
Total weight + Dynamic factor (1.3g)		10492.10

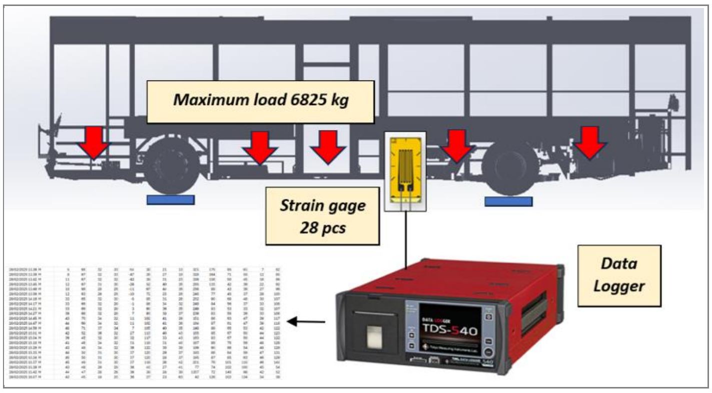

Figure 3. Schematic diagram of experimental loading on the electric bus

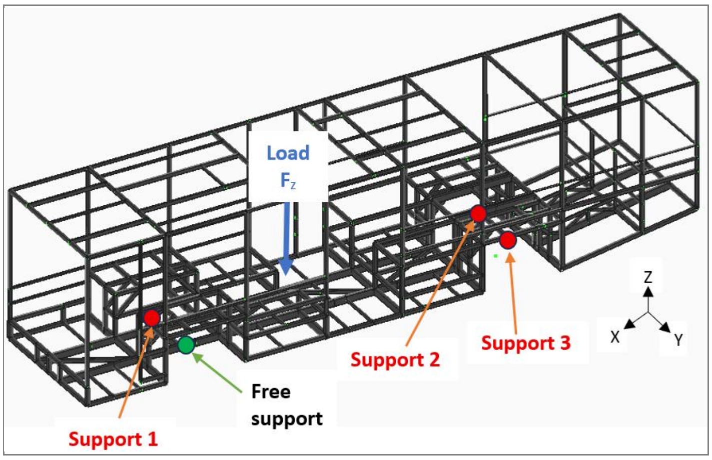

Figure 4. Free-body diagram

bution on the frame structure under torsional loading. The electric bus has four wheels, with wheels numbered 1, 3, and 4 constrained to prevent both translation and rotation along the x-axis and y-axis. In contrast, wheel number two is free to translate along the z-axis. The mathematical formula for shear stress induced by the torsional condition is provided in Eq. (3) to Eq. (5). Where, τ = shear stress (Pa), T = torque (N.m), r = outer radius of the shaft or beam (m), J = polar moment of inertia (m^4), B = outer side length, b = inner side length.

$$\tau = \frac{T.r}{J} \tag{3}$$

$$J = J_x + J_y \tag{4}$$

$$J = \frac{1}{6}(BH^3 - bh^3) + \frac{1}{6}(HB^3 - hb^3) \tag{5}$$

This electric bus has been fully fabricated, meaning that all loads, including the electric motor, battery, inverter, air conditioning, seats, and other components, are already supported by its hybrid frame structure. The frame structure has already received the equipment loads, resulting in initial stress before testing begins. To determine the magnitude of the stress occurring in the frame structure, a finite element analysis was conducted on the bus structure with its equipment load under torsional conditions. Furthermore, experimental verification on the electric bus through static loading tests weighing 70 passengers where the weight of passenger and luggage was around 75 kg per person, resulting in a total load of 5,250 kg. The full load is added with a dynamic factor of 30 percent (1.3 g) [20], giving a total load of 6,825 kg. The test load used in this static load test consists of 136.5 sandbags, each weighing 50 kg. The test load was gradually applied to the electric bus, with loading beginning at all seats and then continuing on the aisle.

Structural stress monitoring during testing is conducted by installing strain gauge sensors on the underframe, side frame, and roof frame. The working principle of a strain gauge sensor is to measure the strain or deformation in a material caused by external forces, either tensile or compressive in nature. A total quantity of twenty strain gauges (numbers 1-20) are installed on the carbon steel SS 400 underframe, while eight strain gauges (numbers 21-28) are placed on the aluminum alloy 6061 side frame and roof frame as shown in **Figure 5**. The strain gauge used for carbon steel SS400 material is TML Type FLA-6-11, while the strain gauge used for aluminum material is TML Type FLA-5-23. The signals from all strain gauge and LVDT sensors are processed and stored in the TML 540 Data Logger as shown in **Figure 6**.

3. Results and Discussion

3.1. FEM Simulation Results

There were previous research studies which studied the structural behavior of a hybrid electric bus frame composed of carbon steel SS 400 and aluminum alloy 6061 under various loading conditions using finite element analysis (FEA) through Ansys software. The results validated

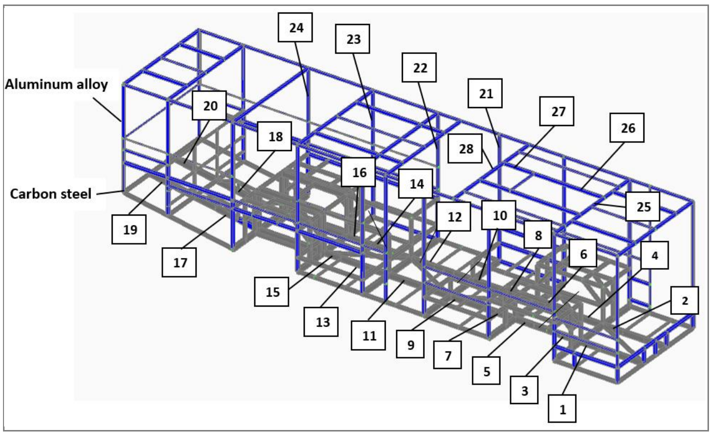

Figure 5. Location of strain measurement points

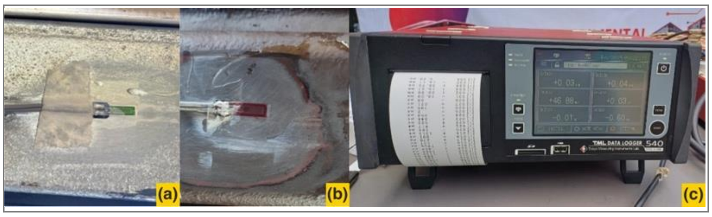

Figure 6. Location of strain measurement points:
(a) Atrain gauge on aluminum alloy;
(b) Strain gauge on carbon steel;
(c) Data Logger TML

that the highest amounts of stresses in the frame occured under torsion loading conditions. To validate the simulation results, a physical torque load test was subsequently performed on the hybrid bus frame structure. In the FEA model, the bus frame was represented by shell elements, with carbon steel SS 400 being utilized for the underframe and aluminum alloy 6061 for the side and roof frame members. All loads imposed were positioned to their actual locations on the vehicle. The simulation was performed under two significant loading conditions:

Tare load condition: This condition represents the scenario in which the electric bus frame supports the weight of various components, including the battery, motor, inverter, air conditioning system, seats, body panels, glass, electrical components, cables, and other accessories. The total weight under the tare load condition is 3,167 kg.

Full load condition: This condition represents the scenario in which the electric bus frame supports both the weight of the equipment and the load from up to 70 passengers. The total weight under the full load condition, with a dynamic factor of 30%, is 6,825 kg.

In this simulation, the constrained load was supported by only three wheels, with the front-left wheel left unconstrained to allow free movement. The remaining three wheels were constrained to prevent both translation and rotation. The following are the finite element method (FEM) simulation results for the two loading conditions (refer to **Figure 7**).

The maximum stress value from the finite element analysis (FEA) under tare load and static loading conditions is 13.97 MPa, occurring at the top frame of the air conditioner. Under full load conditions, the maximum stress value increases to 230.11 MPa and is concentrated in the vicinity of the underframe position around the front right wheel position. Both stress levels are under SS 400 carbon steel's yield strength, therefore meeting the structural design requirements and avoiding any plastic deformation in the structure. Referring to the simulation data, the stress values obtained from the finite element analysis (FEA) at designated points on the main frame, where strain gauges are mounted are summarized in **Table 4**.

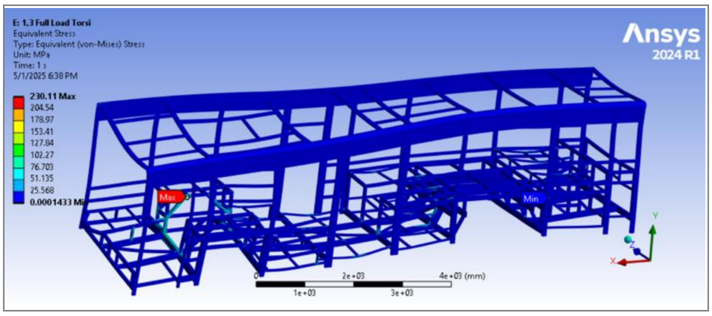

Figure 7. Stress distribution under 1.3 full load

3.2. Results of Static Load Test

Prior to the commencement of testing, the strain gauge sensors were calibrated and set to zero to ensure accurate measurements. The load test was performed by progressively applying sandbag weights onto the bus structure, as illustrated in **Figure 10**. The initial loading phase involved placing weights on all passenger seats, followed by the distribution of additional loads along the aisle. Strain measurements were recorded at the completion of each loading stage. The loading sequence was incrementally increased from 1000 kg to 6825 kg, in stages of 1000 kg, 2000 kg, 3000 kg, 4000 kg, 5000 kg, 6000 kg, 6500 kg, and finally 6825 kg (**Table 5**). **Figure 8** shows the full loading condition with sandbags inside the bus interior during the testing. The corresponding stress values were obtained by multiplying the measured strain values by the elastic modulus of the respective material. The stress values presented in **Table 4** represent a combination of experimental measure-

Table 4. Simulation stress value on the tare load and full load condition

Position	Stress (MPa) Tare load condition	Stress (MPa) Full load condition
1	2.28	10.44
2	2.72	5.49
3	4.58	19.52
4	1.86	7.23
5	7.91	29.25
6	1.16	4.55
7	5.26	38.08
8	4.00	15.22
9	2.08	6.89
10	1.53	19.56
11	3.31	19.23
12	3.71	17.14
13	5.79	15.10
14	6.23	19.02
15	5.45	20.06
16	5.51	31.12
17	2.37	5.48
18	2.49	5.51
19	0.39	1.01
20	0.39	0.79
21	0.28	4.22
22	1.10	5.95
23	1.80	8.58
24	1.83	3.39
25	13.97	6.72
26	13.46	9.33
27	8.81	3.45
28	12.90	4.85

Figure 8. Sandbag load inside the electric bus

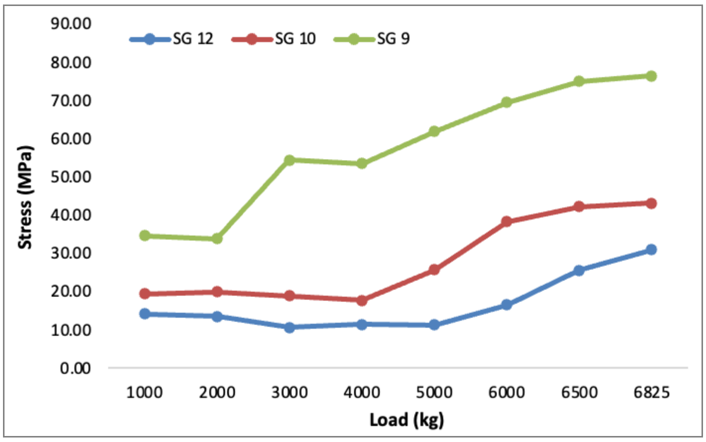

Figure 9. The three largest stress values of carbon steel SS 400

ments and finite element simulation results under the tare load condition, wherein the bus frame is fully assembled with all components, including the battery, electric motor, wall panels, glass, accessories, and other structural elements.

In general, the experimental measurements demonstrate that the stress is directly proportional to the applied load. The experimental results reveal that the maximum stress occurs under a peak applied load of 6,825 kg. In the underframe structure fabricated from SS 400 carbon steel, the highest stress is observed at strain gauge No. 9, positioned at the center-bottom of the frame, with a measured value of 76.42 MPa. The obtained stress value remains below the yield strength of SS 400 carbon steel material, which is 245 MPa, indicating that the material is still within the elastic deformation region. The stress analysis of the frame constructed from Aluminum alloy 6061 indicated that the highest stress was observed at strain gauge No. 28, which is positioned on the rooftop section of the frame. The measured stress at this point was 15.56 MPa. This value remains significantly below the yield strength of the material aluminum alloy, which is 276 MPa, indicating that the structure is operating within the elastic region and no permanent deformation is expected under the current loading conditions.

Figure 9 and Figure 10 present the plotted graphs of the maximum stress values at three strain gauge measurement points for carbon steel SS400 and aluminum alloy 6061 materials. Figure 11 illustrates that, in 12 out of 28 measurement points, the

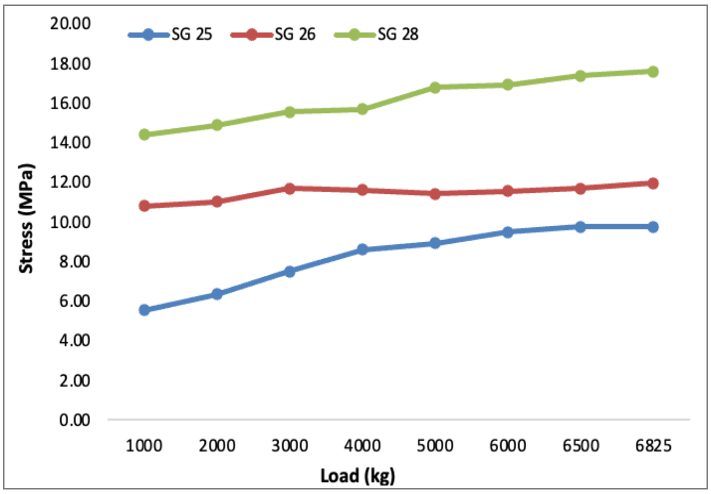

Figure 10. The three largest stress values of Aluminum alloy 6061

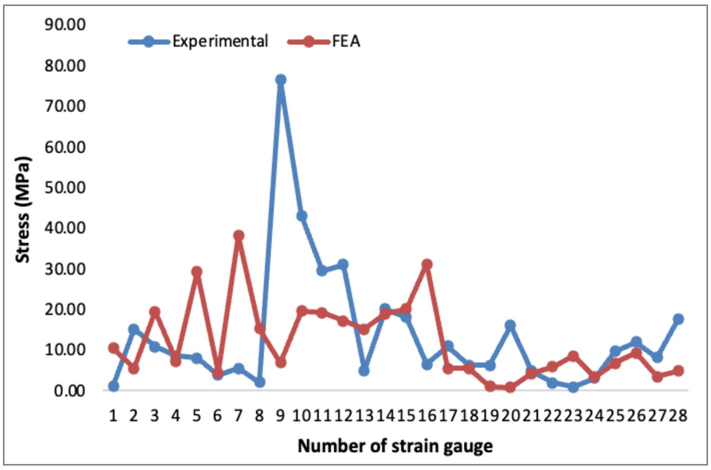

Figure 11. Stress values comparison experimental vs Finite Element Analysis (FEA)

experimentally obtained stress values were lower than those predicted by the Finite Element Analysis (FEA). In the remaining 16 points, the experimental stress values exceeded the FEA results, with an average deviation of approximately 11.21%. The relatively high stress deviation can be attributed to the current FEA model of the electric bus frame being constructed using beam elements, which exhibit lower structural stiffness compared to models developed with shell or plate elements. This study places greater emphasis on the actual stress results obtained experimentally using strain gauge sensors, where all 28 measured stress values were found to be below the yield strength of the material. These experimental findings can serve as reference data for optimizing the structural design of hybrid electric buses to reduce vehicle weight and thereby enhance energy efficiency.

Table 5. Experimental stress value (MPa)

Number	Load (kg)						
Strain gauge	1000	2000	3000	4000	5000	6000	6500
1	11.10	11.31	9.21	4.80	4.80	3.33	2.07
2	13.64	17.42	16.58	15.95	16.79	16.37	15.74
3	12.14	11.72	11.30	10.04	11.09	11.30	11.09
4	8.12	8.58	7.95	7.32	8.16	8.79	9.00
5	13.58	10.22	8.54	5.81	2.45	3.43	6.58
6	24.89	22.58	20.06	16.28	12.08	7.46	5.36
7	13.66	13.87	12.82	10.51	13.66	9.67	6.73
8	13.03	12.19	11.35	9.46	11.35	6.73	3.58
9	34.63	33.79	54.37	53.53	61.93	69.49	74.95
10	19.38	20.01	18.96	17.70	25.68	38.28	42.27
11	17.38	16.54	14.44	12.76	12.13	23.26	28.72
12	14.21	13.58	10.64	11.48	11.27	16.52	25.55
13	15.03	13.98	12.51	11.88	10.41	7.26	5.37
14	32.06	30.80	28.70	27.23	25.55	23.45	20.93
15	8.81	11.33	6.92	27.71	32.12	28.34	20.36
16	17.48	17.69	17.27	15.80	14.33	10.97	8.03
17	11.61	11.82	11.61	11.40	11.40	11.19	10.98
18	9.42	8.79	8.16	7.32	7.32	7.11	6.69
19	9.21	10.26	9.42	8.37	8.16	7.53	6.90
20	10.45	11.77	11.89	12.54	14.52	15.13	15.76
21	3.61	4.36	4.09	3.75	3.68	3.14	4.16
22	-3.18	-2.57	-1.48	-0.26	-0.40	0.62	1.37
23	-0.72	-0.24	-0.18	0.50	1.18	1.12	1.05
24	3.66	4.34	4.07	4.75	5.02	4.34	3.73
25	5.54	6.35	7.51	8.60	8.94	9.48	9.75
26	10.81	11.01	11.69	11.62	11.42	11.69	11.96
27	7.38	7.65	8.20	8.20	8.26	8.26	8.26
28	14.40	14.88	15.69	16.78	16.92	17.39	17.60

4. Conclusion

The structural frame of the hybrid electric bus, which is composed of a combination of SS 400 carbon steel on the underframe and 6061 Aluminum alloy on the side and roof frames, has been analyzed using Finite Element Analysis (FEA) and validated through experimental testing. Torsional loading conditions were selected for the analysis, as this scenario produces the highest stress levels. A full load of 6,825 kg was applied with support provided at only three-wheel locations, while one wheel remained unloaded. The results of the static torsion test showed that the highest stress in SS 400 carbon steel underframe was 76.42 MPa. In the aluminum alloy 6061 frame, the maximum stress occurred in the rooftop section supporting the air conditioning unit, with a value of 15.56 MPa. These findings indicate that the 70-passenger electric bus prototype, with its hybrid structural frame, satisfies structural safety requirements. Furthermore, the results indicate that design optimization is a feasible approach for developing lighter and safer alternative structures.

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

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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