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CONDITIONS RELATED TO THE ROOF STRUCTURE STRENGTH OF BUSES POWERED BY NATURAL GAS AND FUEL CELLS

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1. Introduction

Modern public transport is increasingly turning to cleaner energy solutions such as compressed natural gas (CNG) or biomethane and hydrogen fuel cells. These technologies help reduce air pollution and greenhouse gas emissions, making buses more sustainable compared to traditional diesel vehicles. However, the use of alternative fuels also creates new engineering challenges, especially in relation to vehicle safety and structural design [1-3].

One important issue is the strength of the bus roof. In many CNG and fuel cell buses, heavy storage tanks or fuel cell systems are installed on the roof. This additional load changes how forces are distributed across the vehicle and may influence how the structure behaves during accidents, such as rollovers. Ensuring that the roof can safely carry these components while still protecting passengers is therefore a critical part of bus design.

This paper examines the conditions that affect roof structure strength in buses powered by CNG. It focuses on how roof-mounted components influence mechanical performance, safety compliance, and overall reliability. The regulations UN ECE 110R [4] and UN ECE 115R [5] more closely define the technical requirements for the installation and homologation of natural gas devices and equipment. The aim of presented researches is to contribute to the development of safer and more efficient bus designs that support sustainable public transport.

The presented calculation methods are also applicable to fuel cell and battery electric buses.

2. Methods for calculating the roof structure strength of the buses powered by CNG

From the perspective of safety and equipment installation rules for gas systems, the requirements that vehicles powered by natural gas must meet are defined by the ECE regulations [4, 5]:

- ✓ UN ECE 110R - Uniform provisions concerning the approval of specific equipment for motor vehicles using natural gas and vehicles equipped with specific natural gas equipment regarding installation.
- ✓ UN ECE 115R - Uniform provisions concerning the approval of vehicles originally approved for a primary fuel, which are subsequently equipped with specific equipment for natural gas propulsion, regarding the installation of such equipment.

CNG tanks are fastened to the bus structure according to the manufacturer's instructions, without direct contact with metal parts, and in accordance with the technical requirements of UN ECE 115R for volumes up to 150 liters.

CNG tanks with a volume greater than 150 liters, when full, must withstand the appropriate deceleration or acceleration without deformation of the tank, the supports, or the part of the bus structure where the tanks are mounted, Table 1.

Table 1. Accelerations that CNG tanks must absorb.

Categories of buses	M2	M3
The acceleration of a bus:		
- in the driving direction	20 × g	6.6 × g
- perpendicular to the driving direction	5 × g	
- g (gravitational acceleration)		

This requirement may also be verified by calculation, in accordance with the conditions defined by the aforementioned standards.

2.1 Bus roof structure model

The FEM model of the bus structure was created in Simcenter Femap program and includes the roof section with CNG tanks, see Figure 1. The beam-type finite elements are commonly utilized in the literature for modeling large tubular structures, similar to the upper structures of buses and coaches [7-9]. In this paper, general beam finite elements are used, with a total of 487 elements and 287 nodes.

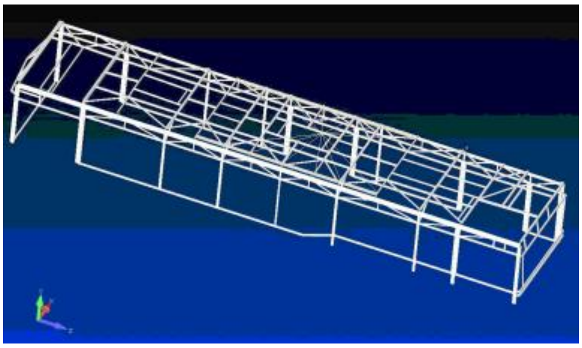

Fig. 1. Supporting roof structure for CNG tanks.

The beam finite elements of the chassis were divided into 22 groups. The chassis structure of the bus consists of four groups of box profiles with the following dimensions: 40×100 mm, 40×120 mm and 40×135 mm. The finite element computer code PAK (abbreviation for „Program for Structural Analysis" in Serbian) [6] was used for the analysis.

The bus roof structure loading conditions were defined following the Table 1, considering the CNG tanks weight and equipment that are installed on the bus roof (m = 733 kg or G = 720 daN).

Based on Table 1, the maximum values of the inertial forces in both directions can be calculated by applying equations (1) and (2):

$$F_a = 6.6 \cdot m \cdot g = 4750 \text{ daN}, \quad (1)$$

$$F_b = 5 \cdot m \cdot g = 3600 \text{ daN}. \quad (2)$$

Where are:

F_a - the intensity of the inertial forces in the driving direction and

F_b - the intensity of the inertial forces in the horizontal plane perpendicular to the driving direction.

The loading model, represented as a system of rigid bodies, was defined by a concentrated resultant force acting at the imaginary center of the CNG tank assembly located on the bus roof at the height of h = 200 mm.

2.2 Stresses in the bus structure for the first loading case (longitudinal direction)

The bus structure model for the first loading case, in accordance with equations (3) and (4), is shown in Figure 2.

$$Z=(-F_a) = (-4750) \text{ daN}, \quad (3)$$

$$Y = (-G) = (-720) \text{ daN}. \quad (4)$$

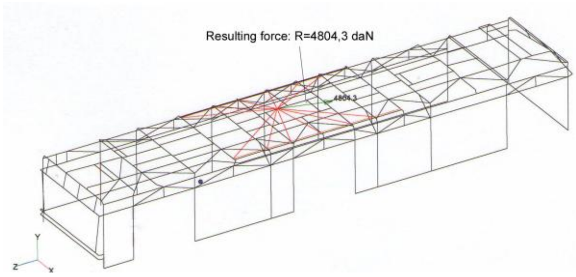

Fig. 2. Bus structure model (first loading case).

The deformed shape of the bus structure model for the first loading case is shown in Figure 3.

Fig. 3. Bus model in the deformed state (first loading case).

Figure 4 shows the stress distribution in the bus structure for the first loading case. The maximum stress $\sigma_{max} = 19.95 \text{ daN/mm}^2$ occurs in the box-section profiles of the structure.

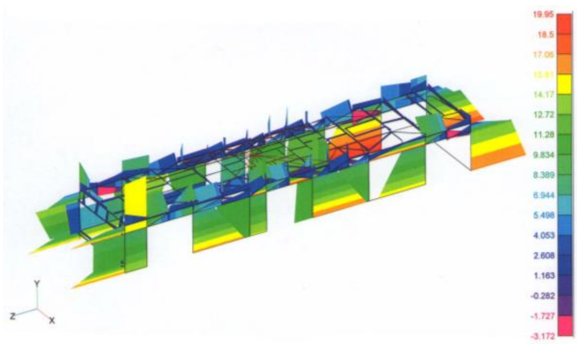

Fig. 4. Stresses distribution within the model (first loading case).

The maximum deflection of the structure obtained for the adopted loading case is Δu_{max}=5.95 mm.

2.3 Stresses in the bus structure for the second loading case (normal to the driving direction)

The bus structure model for the second loading case, in accordance with equations (5) and (6), is shown in Figure 5.

$$X=(-F_b) = (-3600)\ \text{daN}, \quad (5)$$

$$Y = (-G) = (-720)\ \text{daN}. \quad (6)$$

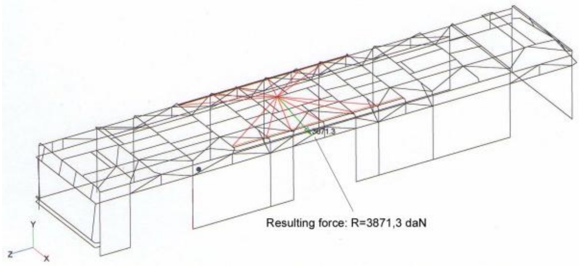

Fig. 5. Bus structure model (second loading case).

Figure 6 depicts the deformed shape of the bus structure under the second loading case.

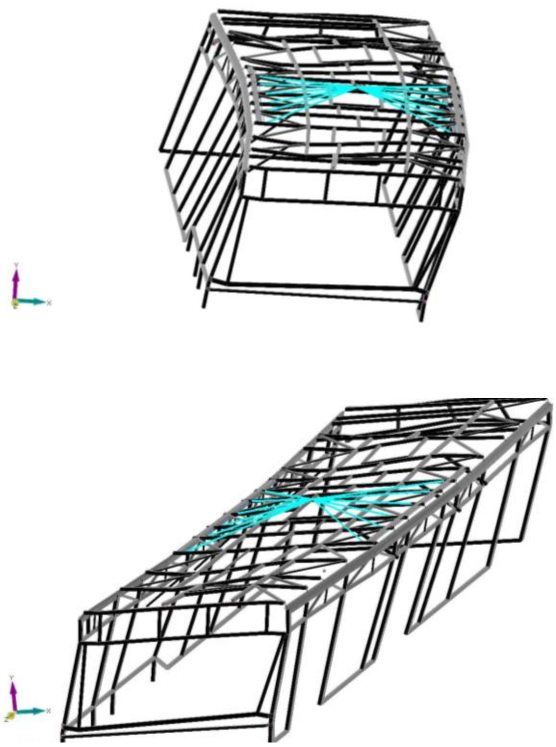

Fig. 6. Bus model in the deformed state (second loading case).

Figure 7 shows the stress distribution in the bus structure for the second loading case. The maximum stress $\sigma_{max} = 26.99\ \text{daN/mm}^2$ occurs in the box-section profiles of the structure with cross-section dimensions (40 × 40) mm.

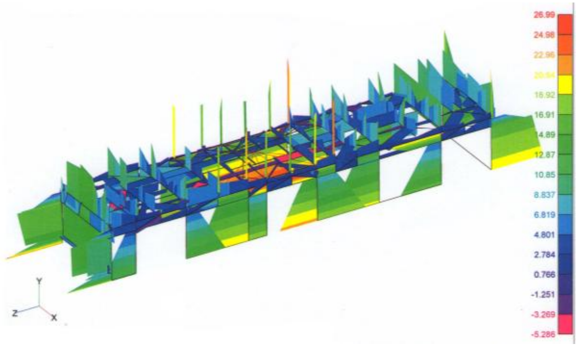

Fig. 7. Stresses distribution within the model (second loading case).

The maximum deflection of the structure obtained for the adopted second loading case is Δu_{max}=24.19 mm.

For the bus structure, the material tensile strength of $\sigma_m = 41.2\ \text{daN/mm}^2$ was adopted. For "U" profiles through which the battery with four CNG tanks is bolted to the bus roof structure, as shown within Figure 8, the tensile strength value of $\sigma_m = 36\ \text{daN/mm}^2$was adopted.

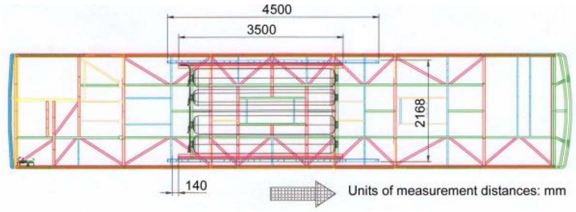

Fig. 8. Position of the CNG tanks with U-profile supports on the bus roof.

The values of the safety coefficients (SC), defined as the ratio between the tensile strength and the calculated stresses, were determined, based on FEM results for the following elements of the bus chassis:

- ✓ Roof base structure: SC = 1.53;
- ✓ U-profiles for connecting the CNG tanks to the bus roof: SC = 3.60;
- ✓ M12 bolts for the detachable connection of the CNG tank battery to the bus roof structure (the bolts are subjected to both tensile and compressive stresses): SC = 1.68.

In order to maintain the structural strength of the bus construction, the limiting value of SC = 1.5 was adopted. This value was selected based on available data from the relevant scientific literature.

Based on the FEM calculation results and the obtained SC values, it can generally be concluded that the proposed solution for connecting the CNG tank battery to the bus roof structure, using welded

U-profiles and bolts, meets the requirements of the UN ECE 110R standard.

In general, the goal of the proposed solution for installing CNG tanks was not only to ensure traffic safety but also to achieve better accessibility to the tanks during inspections and maintenance throughout the bus operation [1].

In this way, the connection with bolts through the U-profile also enables easier disassembly during inspection or replacement of devices and equipment, since in such cases it is necessary to dismantle the tanks and empty the natural gas.

The reliability of the structure, as well as the time between maintenance intervals of CNG buses in operation, can be determined on the basis of research data by applying appropriate distribution functions [10, 11].

3. Conclusions

The transition to buses powered by natural gas and fuel cells represents a significant step toward cleaner and more sustainable public transport. However, the integration of heavy roof-mounted components, such as pressurized storage tanks and fuel cell systems, introduces additional demands on vehicle structure and safety. The roof must not only bear increased static loads but also maintain its integrity under dynamic conditions, particularly during rollover scenarios.

The analysis of conditions affecting roof strength highlights the need for careful structural design and adherence to safety standards. By addressing these challenges, manufacturers can ensure that alternative fuel buses are both environmentally friendly and safe for passengers.

Future research should focus on advanced materials, innovative design methods, and simulations to optimize structural performance while reducing vehicle weight. Such efforts are key to advancing sustainable bus technologies without compromising safety or reliability.

The paper presents a technical solution for the installation of CNG tanks on the bus roof, in accordance with the requirements of relevant regulations and standards. The proposed solution has been implemented in practice and facilitates the maintenance of CNG tanks with their complete equipment during the operational service of buses in traffic.

By applying the proposed solution, in addition to traffic safety, contributions are also made to occupational safety as well as to the reduction of maintenance costs during the operational service of buses.

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