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THEORETICAL AND EXPERIMENTAL ANALYSIS OF A CNG CYLINDER RACK CONNECTION TO A BUS ROOF

S. MILOJEVIC* and R. PESIC

Faculty of Mechanical Engineering, Department for Motor Vehicles and Motors,
University of Kragujevac, Kragujevac 340000, Serbia

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ABSTRACT−From our perspective, a global technology development should be focused on resolving the issues of environmental impact and conservation of available natural energy resources. New technological solutions and alternative fuels, such as Compressed Natural Gas (CNG), have increasingly more application for modern engines and vehicles. If we take into account the situation in city transport, where primarily vehicles with diesel engines are used, a strategic proposal is to begin by retrofitting these into bi-fuel or dedicated Natural Gas Vehicles (NGVs). This paper analyzes the retrofit of a diesel bus into dedicated NGV. To confirm the safety of the vehicle in city transport, we addressed the problem of mounting a gas rack with CNG cylinders on the roof of a retrofitted city bus, according to UN ECE Regulation No. 110. This assembly is the most critical part of the retrofitted bus because of the concentration of stress due to increased mass and the application of a specific installation for supply of CNG from the cylinders to the engine. These regulations must be met in all parts of the vehicle, but we only focused on those areas affected by the retrofit to NGV.

KEY WORDS : Natural gas vehicle, Finite element method analysis, UN ECE Regulation No. 110

1. INTRODUCTION

The global energy and environmental situations have intensified the use of alternative and environmentally clean fuels (Cho and He, 2008). This is true for city buses, taxis, delivery vehicles and personal cars (Stocchetti and Volpato, 2011).

As a contribution to the global strategy to address these issues, this paper analyzed the retrofit of a low-floor city bus powered by a diesel engine into a dedicated NGV using an original CNG engine. The bus roof has been additionally loaded with CNG cylinders and with new equipment and specific parts for the CNG fuel line. The main goal of this research, from the design to the retrofit and use of the bus, was to provide theoretical and experimental verification of the joint assembly used to connect the gas cylinder rack to the body grids of the bus roof (Milojevic and Pesic, 2011; Ale *et al*., 2008).

The position of the gas cylinder rack on the bus roof and joint assembly solution was evaluated using Finite Element Method analysis (FEM below) (Kojic *et al*., 1994).

By making experimental measurements on the bus, we determined the deformation and tension at critical points in the roof structure. In this way, we compared the results and verified the calculating model.

The new prototype of low-floor CNG-powered bus was homologated and used in city transport.

**Corresponding author*. e-mail: tiv@kg.ac.rs

2. CNG TANK INSTALLATION

The retrofit of the diesel bus into a dedicated NGV begins with the joining of the CNG cylinders with the original rack (Figure 1) to the bus roof. We selected a CNG storage system that includes type 3 cylinders composed of an aluminum 6061 liner reinforced by carbon fiber in epoxy resin (brand Dynecell®), with a favorable ratio between weight and volume (0.3 kg/L to 0.4 kg/L) (Rasche, 2009).

The position of the new center of gravity is calculated, taking into account the added weight of the CNG cylinders with the rack on the bus roof. During the retrofit, we have considered the existing regulations regarding the dimensions and gross vehicle weight. Specifically, we took into account the requirements relating to the correct joining of the main parts of the CNG fuel line and gas cylinders, all legislated by regulation ECE R 110 (Milojevic *et al*., 2009; Ebrahim *et al*., 2005).

To avoid damage to the existing roof, as in the first proposition, we did not attach the CNG cylinders rack to the chassis by bolts. This assembly also includes bushings, such as spacer sleeves, which were inserted to minimize deformation of the box-shaped profiles.

We initially used classic engineering methods to select the best position to attach the gas cylinders rack onto the bus roof and joint assembly solution, which was then

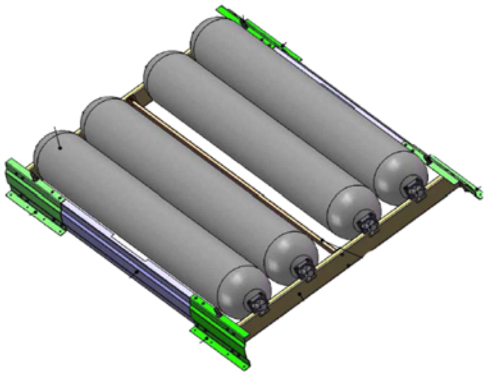

Figure 1. CNG cylinders rack DYNETEK V294.

confirmed by FEM.

By applying classic engineering methods on the first proposed joint assembly, we calculated tensile stress values very close to the material yield strength for this assembly. From this, we conclude that the proposed joint assembly with unadjusted bolts does not provide the required security.

Afterward, we examined the joining of the CNG cylinders with the original rack on the bus roof using "U" profiles. The "U" profiles are welded to the roof construction of the bus chassis (Figure 2). The results of the preliminary classic engineering methods confirmed the second proposed solution as applicable.

The joint assembly with welded profiles also requires the partial destruction of the bus roof constructions, but this is minimal and limited to the positions where the "U" profiles are welded.

The overall dimensions of the reconstructed bus with jointed CNG cylinders-type DYNETEK V294 are presented in Figure 3. Also presented in Figure 3 is the new center of gravity, CG, calculated for the unloaded bus. The measured unloaded bus weight with full cylinders and a driver is m=12100 kg.

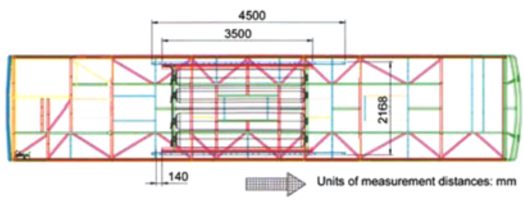

Figure 2. CNG cylinder rack position on the bus roof.

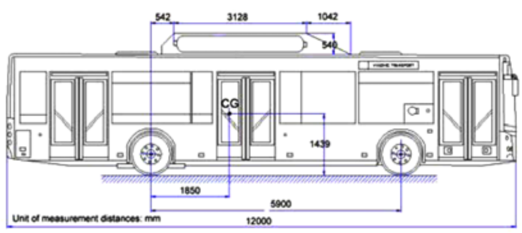

Figure 3. Main dimensions of CNG bus.

The CG of the CNG powered bus chassis was displaced 15 mm ahead and 90 mm in the vertical direction, compared with a diesel-powered bus chassis. This displacement was reduced in the corresponding changes, with regard to the loads on the front (steering) and rear (driving) axles. The front axle of the unloaded CNG bus is more loaded by approximately 7% and the rear by 5% in static conditions. However, in the case of a fully loaded CNG bus, the rear axle is less and the front axle is more loaded by approximately 1%. Calculations were made for a gross vehicle weight of m=18000 kg for both bus versions. The changes in loads on the axles do not produce serious changes in the distribution of braking forces and do not give rise to increased tire tread wear. This analysis will be the topic of other studies.

The CNG bus satisfied the requirements for braking and rollover, according to regulations ECE R 13 and ECE R 66, which were validated using the obtained homologations (Milojevic *et al.*, 2011; Liang and Le, 2010).

The same chassis type is used in both diesel and CNG bus versions. This chassis type was homologated according to all ECE regulations, in a low-floor city bus, trolleybus (with trolley pole base with similar weight added on the roof) and NGV (ECE R 110).

3. MODEL OF SUPPORTING STRUCTURE

The principal requirement for NGVs of the M3 and N3 categories is the strength at destruction of the joint assembly between the CNG cylinders and the chassis during a deceleration of 6.6·g in the longitudinal direction and 5·g in the transverse direction (UN ECE No. 110. 2008; ISO/DIS 11439, 2000).

The standard ECE R 110 legislates the proofing of these requirements using calculations rather than experimental testing.

The goal of the following calculations is to confirm whether the joint assembly of the CNG cylinders rack on the bus roof is damaged by inertial loads imposed by the CNG cylinders.

The model of the bus construction is comprised of beam-type elements; the model has 287 nodes and 487 elements. For modeling, we used the corresponding data for the dimensions and materials of the elements integrated in the bus construction. For analysis, we used the FEM software PAK, which was developed by faculty of the Mechanical Engineering department at the University of Kragujevac (Kojic *et al.*, 1994).

The model includes the supporting structures of the bus to a level below the windows (Figure 4). According to the geometrical characteristics of the chassis elements, these are classified into 22 groups of beam elements.

In certain parts of the bus construction, the basic

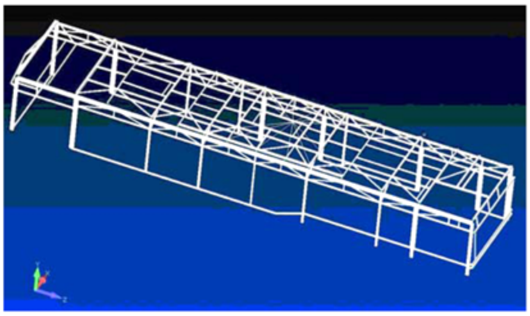

Figure 4. Model of the supporting bus structure.

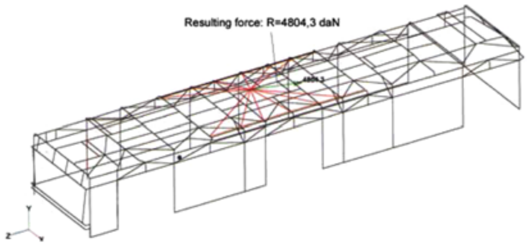

Figure 5. Load on the model for the first case.

Figure 6. Deformed view of the model for first case.

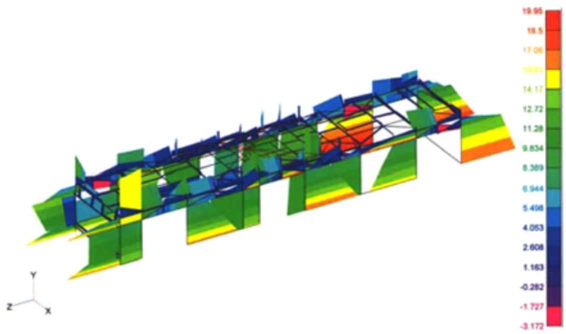

Figure 7. Tension distribution in the model.

elements are packed on top of one another such that they form four groups of complex profiles (40 mm wide, with heights of 135 mm, 120 mm and 100 mm).

The model also includes elements made with a rectangular cross-section and specifically designed supports in the cross-section from the roof to either side of the bus construction.

The weight of the rack with the cylinders filled is m=733 kg. According to the requirements legislated by the standard, we calculated the maximal values of the inertial forces (UN ECE No. 110, 2008):

$$F_a = 6.6 \cdot m \cdot g = 47458 \text{ N } 4750 \text{ daN} \quad (1)$$

$$F_b = 5 \cdot m \cdot g = 35954 \text{ N } 3600 \text{ daN} \quad (2)$$

Here, F_a defines the intensity of the inertial forces in the direction of the vehicle drive, equation (1), while F_b defines a value in the horizontal plane normal to the direction of drive (2) for the first and second load case.

The loading model was introduced as a concentrated resultant force in an imaginary center of the gas cylinder rack assembly at a height of h=200 mm from the level where the longitudinal "U" profiles are jointed. The defined load was introduced to the model construction of the bus through a system of rigid bodies (Rasche, 2009; UN ECE No. 110, 2008).

3.1. Tension in the Body Elements

Linear structural model analysis of the city bus constructions was performed for both cases of the load. The resulting force consists of the inertial force and the weight of the CNG cylinders and rack, at approxiamtely G=720 daN.

3.1.1. First case of loads

Load on the model for this case of tension stresses is shown in Figure 5.

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

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

The maximal distortion of the construction determined by calculation for this load case is u_{max}=5.95 mm. Figure 6 shows the model in a deformed position.

Figure 7 shows the distribution of the equivalent tensions in the model for the first case of loads. The maximal tension occurs in the box-like profile complexes with a value of σ_{max}=19.95 daN/mm^2.

3.1.2. Second case of loads

The load on the model for this case of tension stresses is shown in Figure 8.

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

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

The maximal distortion of the construction determined by the calculations for this load case is u_{max}=24.19 mm. Figures 9 (a) and 9 (b) show the model in a deformed position.

Figure 10 shows the distribution of the equivalent

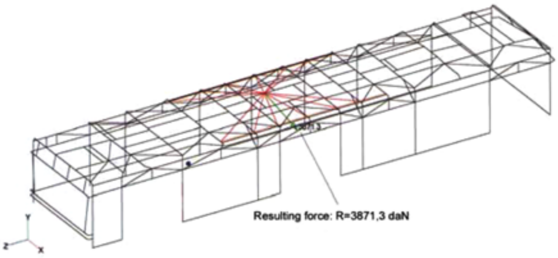

Figure 8. Load of the model for the second case.

tensions in the model for the second case of loads. The maximal tension occurs in the box-like profile complexes with dimensions of 40 mm x 40 mm and has a value of σ_{max}=26.99 daN/mm^2.

For the bus construction, a tensile strength of materials of σ_m=41.2 daN/mm^2 was adopted. The value for the "U" profiles on the roof is σ_m=36 daN/mm^2.

The values for safety coefficients SC (defined as the relationship between tensile strength and calculated tensions), were calculated, according to FEM PAK results, in the following chassis elements:

- The supporting bus structure: SC=1.53,
- The longitudinal "U" profiles: SC=3.60, and
- The M12 bolts connecting the CNG cylinder rack to the "U" profiles (exposed to pressure and elongation): SC=1.68.

For defining the static strength in the bus construction, it

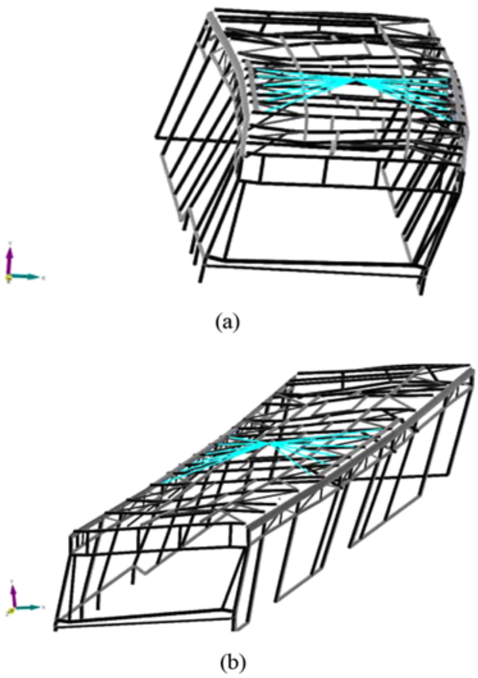

Figure 9. (a) Deformed view of the model for second case (b) Deformed view of the model for second case

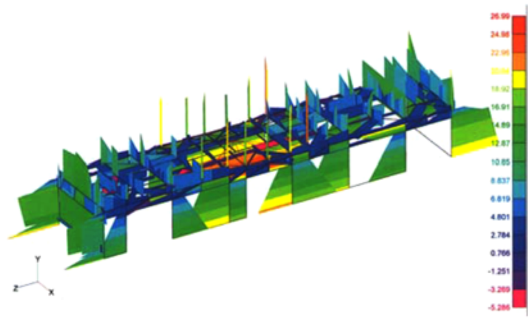

Figure 10. Tension distribution in the model.

was accepted that the limiting value of the safety coefficient was SC=1.5. This value was adopted based on references defined in the corresponding standard (Liang and Le, 2010).

Based on the results of the FEM PAK calculations and the determined SC values, we have concluded that the proposed solution of joint assembly with welded "U" profiles meets the standard requirements.

4. EXPERIMENTAL MEASUREMENTS

To verify the model, we have undertaken experimental research during use of the CNG bus. In these experiments, we measured the deformation at critical points of the roof structure.

The measurements on the bus were taken during intense braking from a constant speed to a full stop. The decelerations obtained during the experiment were significantly less than the demanded deceleration. Therefore, the experimental loads on the bus roof in real conditions are much lower than the loads demanded by regulation UN ECE No. 110.

4.1. Measurement of Tension

Measuring equipment:

√ Strain gauges (HBM Type 10/120LY41),
√ Accelerometers (Type 8309),
√ Amplifier (TRANSAMERICA PSC-8015-1),
√ Charge Amplifier (BRUEL&KJAER Type 2635), and
√ Laptop Computer.

The measurements were taken by strain gauges (HBM Type 10/120LY41), (Figure 11), which are attached by glue X60 (HBM) on the places previously specified as critical with regard to the calculated maximal tension. We determined four measuring points (horizontal and vertical carriers) near the middle and rear doors, where the section crossing from the roof to both sides of the bus construction is located.

To measure the accelerations/decelerations of the vehicle in three directions, we used type 8309 accelerometers fixed

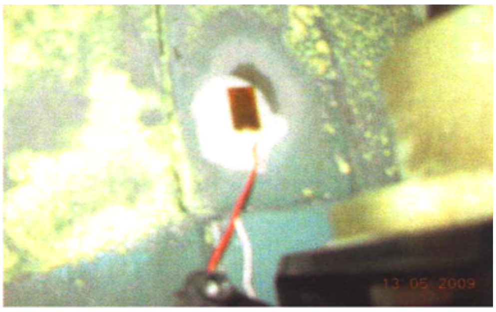

Figure 11. Strain gauge glued on the carrier.

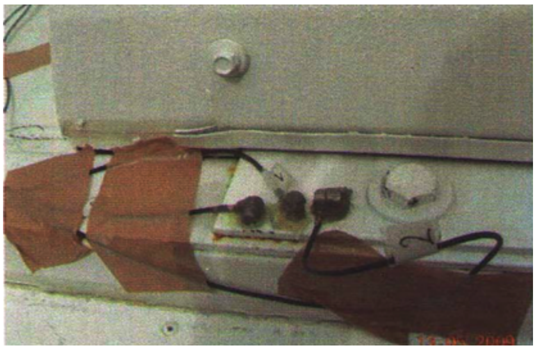

Figure 12. Type 8309 accelerometers fixed on carrier.

Figure 13. Measuring equipment – instrumentation.

on the bus roof along the longitudinal "U" profile, which is part of the assembly with the CNG cylinder rack (Figure 12).

To receive and amplify the signals we used a DC amplifier (TRANSAMERICA PSC-8015-1) and a charge amplifier (BRUEL & KJAER type 2635), (Figure 13). The signals were processed with a special program and were recorded in a database on a laptop.

The mounting positions of the strain gauges – the measuring points MPs, are indicated in Figure 14:

4 – $\varepsilon = \Delta l / l$, distortion on the place of the vertical carrier near the middle doors MP4,
5 – Distortion on the place of the horizontal carrier near the middle doors MP5,
6 – Distortion on the place of the horizontal carrier near the rear doors MP6, and
7 – Distortion on the place of the vertical carrier near the rear doors MP7.

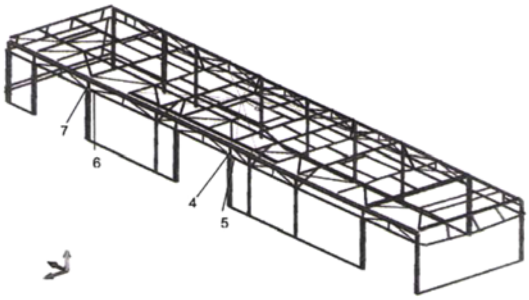

Figure 14. Positions of strain gauges during the experiments.

The experimental measurements were recorded during acceleration and braking deceleration from the speeds of V=70, 60, 50 and 40 km/h to a full stop. Thus, we achieved different decelerations. The CNG bus was equipped with standard ABS and disc brake mechanisms on both axles of the ZF type. The power unit is an original CNG engine with maximal power of 210 kW, coupled to a six-speed automatic gearbox (Milojevic *et al*., 2009).

The following diagrams present the values of distortions at the characteristic MPs that were measured during vehicle decelerations.

Table 1 presents the values obtained by measuring the distortions at the four MPs of the bus structure for different measured negative acceleration (deceleration), in the direction of the bus drive.

Decelerations obtained during the experiment were significantly less than the deceleration demanded by the ECE regulation ($6.6 \cdot g$), Table 1. A comparison between the experimental and the calculated results was performed for one value of the deceleration (only $0.65 \cdot g$ in the shaded column). Thus, we conducted new calculations for new

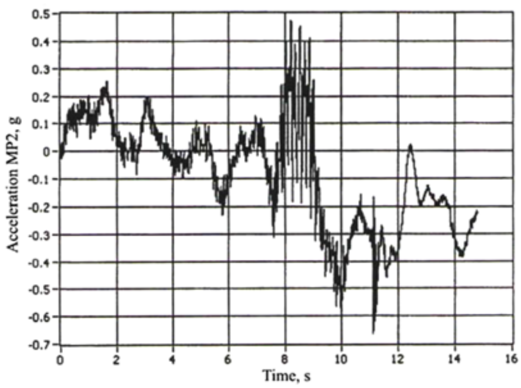

Figure 15. Accelerations in the direction of drive.

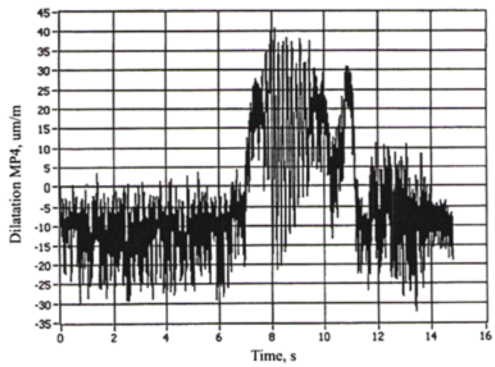

Figure 16. Measured distortions at MP4.

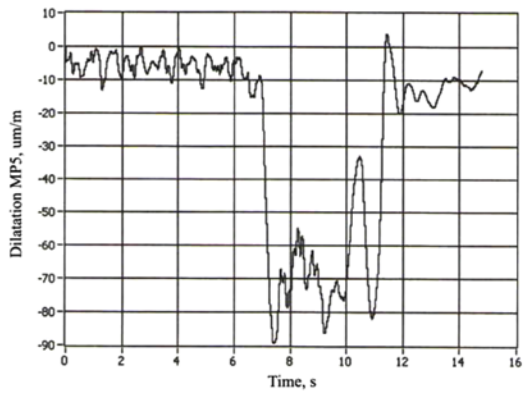

Figure 17. Measured distortions at MP5.

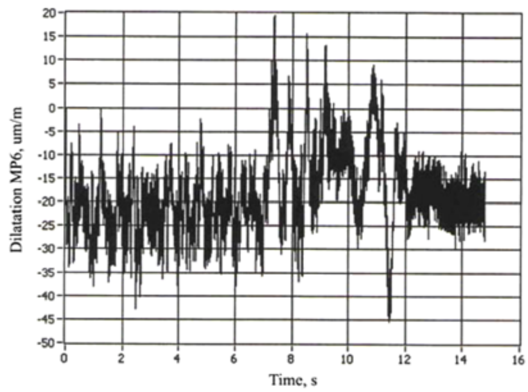

Figure 18. Measured distortions at MP6.

forces, which are defined by a deceleration of $0.65 \cdot g$ and the weight of the CNG cylinders with the rack:

$$Z=F_a=0.65 \cdot m \cdot g=4674 \text{ N } 470 \text{ daN} \quad (7)$$

$$Y=-G=-720 \text{ daN} \quad (8)$$

The normal tension stresses obtained experimentally are calculated according to Hooke's law:

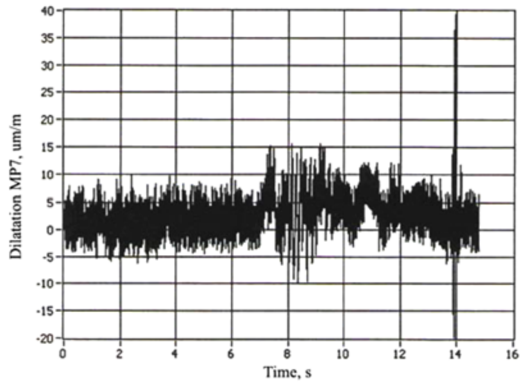

Figure 19. Measured distortions at MP7.

Table 1. Values of measured distortions.

Decele-ration		0.5.g	0.55.g	0.65.g	0.9.g
MP4	ε (μm/m)	28	31	35	44
MP5		85	88	90	93
MP6		39	42	45	51
MP7		14	14	15	17

$$(\sigma_{eks}=\varepsilon \cdot E) \quad (9)$$

where

E=21000 daN/mm^2 - elastic modulus for steel.

In Table 2, the values of the tensions obtained by the calculated σ_{calc} and by the experimental σ_{eks} are simultaneously presented as well as the percentage difference of calculated values compared with the experimental values.

Causes of the differences between the calculated values and their corresponding experimental results include the following:

√ Measurement error and

√ Positioning errors (mounting positions of the strain gauges do not precisely match those of the calculated sections).

The general view is that the experimental and calculated results showed good agreement, with errors less than 10%. It has already been noted that the comparisons were

Table 2. Calculated and experimental values.

	σ_{calc} (daN/mm^2)	σ_{eks} (daN/mm^2)	Δ (%)
MP4	0.78	0.74	5.4
MP5	1.94	1.89	2.6
MP6	0.88	0.95	7.4
MP7	0.29	0.32	9.3

performed at relatively low loads.

5. CONCLUSIONS

Application of CNG as an alternative fuel is an effective and realistic method to resolve the current problems of environmental protections and preservation of oil reserves.

By application of Type 3 CNG cylinders comprised of lightweight materials and retrofitted to the supporting bus roof structure according to UN ECE Regulation No. 110, the aspects of a vehicle's safety in traffic was maintained at a high level. In addition, the remainder of the CNG fuel line equipment is in accordance with UN ECE Regulation No. 110.

The joint assembly of CNG cylinders with the original rack on the bus roof was realized using "U" profiles, which were welded onto the roof construction of the bus chassis.

Based on the results of the FEM PAK calculations and received SC values, we have concluded that the proposed solution of joint assembly with welded "U" profiles meets the standard requirements.

Decelerations obtained during the experiment were significantly less than the deceleration that was demanded by the ECE regulation. However, the obtained data were very useful for comparison between the experimental and calculated results.

The experimental results and the calculation results showed good agreement with errors less than 10%.

The presented methods and the results of the experimental and theoretical research can be useful for constructors in practice.

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