The influence of the roof frame on the stiffness of a bus structure

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Abstract. In order to respect the more stringent emissions regulations, the weight of the bus must be optimized. The bus structures weight can be lowered by decreasing the thickness of the its components. By doing so, the stiffness of the structure will be affected. A deeper understanding of how different elements influence the stiffness is necessary, for optimizing the bus structure. The aim of this paper is to study the influence of the roof frame on the stiffness of the bus structure. Two cases are studied, one in which the roof frame forms a common body with the side frames, and one in which the roof frame is a standalone component, attached to the side frames via connecting elements and steel plates. The stiffness and the weight of the two bus structures are compared. Using a standalone roof frame gives a better flexibility for optimizing the structure, by choosing a different thickness or material for the frame, increasing the stiffness and reducing the weight.

1. Introduction

Recent emissions control regulations and local laws regarding the emissions of heavy and commercial vehicles have made the bus producers to design and build greener vehicles, regarding its engines (i.e. hybrid vehicles or with internal combustion engines that can ran with natural gases – CNG or LNG) or the material used for building the vehicle itself.

Switching to alternative fuel systems comes with advantages, but also with disadvantages. The advantages are lower emissions (reducing the pollution in heavy populated areas) and quiet operation.

![Figure 1. Energy density comparison of several transportation fuels [1].](image)

One big disadvantage of alternative fuel systems comes from the storage of the energy (electrical energy for hybrid and fully electrical vehicles or gas for gas engines) [1]. In figure 1 are presented...
different types of fuels, and their energy content, relative to gasoline. Both CNG and LNG have an energy density lower than diesel, meaning that for the same autonomy, a CNG vehicle needs to have a bigger fuel tank than a diesel one. This causes a problem regarding the installation of the alternative fuel tanks. To maximise the space available in the passenger compartment, generally the gas tanks are mounted on top of the roof.

The same problem and solution are available for electrical and hybrid vehicles. In this case, the battery pack is installed on the roof of the bus.

Placing heavy equipment up high raises two problems: the centre of gravity of the bus raises, affecting the stability and drivability of the vehicle. Also, the roof frame must be reinforced to withstand the additional load. On a regular diesel bus, there is little or no load on the roof frame - in general, the only equipment mounted on the roof is the climate system. In comparison with a standard diesel bus, the side pillars and roof frame are reinforced for a hybrid or gas bus, in order for the roof to withstand the increased load.

2. Reinforcing the roof frame

Using a hybrid structure, made from different materials, can lead to a lighter, but more rigid structure, resulting in an energy efficient vehicle. The usage of different materials or changing the thickness of the same material depends on the way the structure was designed and how it is built. In the same time, the influence different components have on the stiffness of the bus is of great importance.

There are two major directions regarding the construction of the bus frame. In the first one (figure 2), the roof frame is integrated in the bus structure. The crossmembers of the frame bend down, forming the side pillars. These transversal frames are joined together by long beams, stretching from the front to the back of the vehicle.

In the second method of assembly, the roof frame is attached by the side frames with connecting elements. In this case, the roof’s crossmembers are not connected with the side pillars, they are distinct elements. The connecting elements can be made from the same materials as the side pillars and the roof’s crossmembers, or from different materials. There are some builds that use connecting elements made form cast metal or from sheets of metal, welded together. The most common method of assembling the side pillars or the roof crossmembers to the connecting elements is with screws or rivets, but spot welding is common too [2].

Because the roof is not integrated with the side frames, the second method of construction (figure 3) has the advantage that the roof frame can be built from different materials or have different thickness. Also, different models of roof frames can be used in conjunction with the same side frames, creating a modular system. A reinforced roof frame can be used for hybrid buses, while a diesel bus can use a lightweight roof frame.

3. FEM analysis of the roof frame

Since the roof frame is not integrated, the stiffness of the bus structure is affected. This paper studies these two methods of construction, by simulating a bus body structure and calculating the rigidity of the structure. Two structures are used for this simulation, for each type of structure. To compare how
each version affects the rigidity of the bus, the torsional stiffness and bending stiffness are determined for each version.

3.1. Torsional stiffness
The torsional stiffness is calculated using the following formula [3]:

\[
k_t = \frac{F \cdot L}{\arctan\left(\frac{d}{2L}\right)} \text{ [Nm/deg]}
\]

where \(F\) is the force applied to the structure, \(L\) is the distance between the points where \(F\) is applied; \(d\) is the displacement of the points where \(F\) is applied. The stress that appears in the structure when applying \(F\) should not exceed the maximum permissible tension, in regard to the material used [4].

For a bus, the structure – without side panels or other components installed – has a torsional stiffness of \(1.8 \div 4.0 \cdot 10^4\) Nm/deg [3][4][5].

In both cases, the structure is constrained on the rear suspension supports, while two forces are applied on the front suspension supports (figure 4 and figure 5). The point forces have opposite directions (to generate a torsion torque) and have the value of 10000N.

![Figure 4. Boundary conditions for determining torsional stiffness. First type of structure.](image1)

![Figure 5. Boundary conditions for determining torsional stiffness. Second type of structure.](image2)

Table 1 shows the results of the simulation, for both types of structures, while figure 6 presents the deformation of the first type of structure and figure 7 the second type of structure.

| Model     | Mass (kg) | Strain (MPa) | \(d\) (mm) | Total Deformation (mm) | Torsional Stiffness (Nm/deg) | Difference (%) |
|-----------|-----------|--------------|------------|------------------------|-----------------------------|----------------|
| Model 1   | 2707.3    | 187.32       | 9.318      | 15.221                 | 24096.18                    | 0              |
| Model 2   | 2709.6    | 202.91       | 8.5952     | 15.591                 | 26122.62                    | +8.41          |

3.2. Bending stiffness
The bending stiffness is determined using the following formula [3]:

\[
k_b = \frac{F}{\delta} \text{ [N/mm]}
\]

where \(F\) is the force applied to the structure and \(\delta\) is the displacement of the point where \(F\) is applied [4].
Figure 6. Total deformation of Model 1 for determining the torsional stiffness.

Figure 7. Total deformation of Model 2 for determining the torsional stiffness.

For this simulation, the structure is constrained in four points – the mounting points for the suspension. Two $10000\, N$ forces are applied to the structure. The boundary conditions are presented in figure 8 for the first type of structure and in figure 9 for the second type.

The simulation’s results are presented in table 2 and in figure 10 and 11 the deformed structures are presented.

| Table 2. Results for bending simulation. |
|-----------------------------------------|
| Mass (kg) | Strain (MPa) | Displacement (mm) | Bending Stiffness (Nm/mm) | Difference (%) |
|-----------|-------------|-------------------|--------------------------|----------------|
| Model 1   | 2707.3      | 55.216            | 1.377                    | 7259.581        | 0              |
| Model 2   | 2709.6      | 69.678            | 2.0395                   | 7494.089        | +3.23          |

Figure 8. Boundary conditions for determining bending stiffness. First type of structure.

Figure 9. Boundary conditions for determining bending stiffness. Second type of structure.
Figure 10. Total deformation of Model 1 for determining the bending stiffness.

Figure 11. Total deformation of Model 2 for determining the bending stiffness.

4. Conclusions

The difference between the two structures is small, both have approximately the same bending and torsional stiffness, the second version having a small advantage. Because the second version is stiffer, the maximum strain obtained in the simulation is higher, but still lower than the limit of the material. In table 3 the lightweight coefficient is calculated. This coefficient is used to compare different types of structures [3, 5]. This coefficient considers the area projected by the structure on the ground – to compare structures of different sizes; the area is the same for this simulation. Another parameter that this coefficient considers is the mass of the structure, to assess how the material was used.

| Structure Mass (kg) | Strain for the torsional stiffness simulation (MPa) | Strain for the bending stiffness simulation (MPa) | Lightweight Coefficient | Difference of Lightweight Coefficient (%) |
|---------------------|---------------------------------------------------|-------------------------------------------------|-------------------------|------------------------------------------|
| Variant 1 2707.3 | 187.32 0 | 55.216 0 | 272.0133 0 | +27.20133 |
| Variant 2 2709.6 | 201.16 7.38 | 69.235 25.389 | 294.638 294.638 | +8.317 |

The lightweight coefficient is calculated using the following formula [5]:

$$c_w = \frac{k_t A}{m_s}$$

where $k_t$ is the torsional stiffness of the structure, $A$ is the area of the horizontal projection of the structure and $m_s$ is the mass of the structure.

The strain for the first variant is smaller because the deformation energy passes through the structure more easily, given that there is a continuous beam that forms the side pillars and roof cross members.

In the case of the second variant, where the roof frame is connecting with the side frames via individual elements, the strain is higher. The assembly method between the side pillars, roof cross members and connecting elements is very important to the whole structure’s stiffness. The advantages of the second variant remains: the possibility of using different materials for the side frames and roof frame, the possibility of designing attachments elements between the side frame and roof frame to improve one or another characteristic of the structure (bending or torsional stiffness, etc), the modularity of the structure (using different roof frames, depending on the type of, or rather engine – diesel, hybrid or gas).
References
[1] U.S. Energy Information Administration 2013 Few transportation fuels surpass the energy densities of gasoline and diesel TODAY IN ENERGY, February 2013
[2] Korta J 2013 AGH University of Science and Technology
[3] Lan F, Chen J and Lin J 2004 Journal of Automobile Engineering 218 1067-75
[4] Meznar D and Lazovic M 2010 Strojinski vetnik – Journal of Mechanical Engineering 9(56) 544-50
[5] Iosza D. 2016 Motor Vehicles Bodies (Bucharest: Politehnica Press)