Effect of side stiffening plates on the stiffness of the bus structure

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Abstract. Bus developers focus on creating new bus structures that are safe for the passengers and friendly to the environment. By developing new bus structures with high stiffness and low weight, both requirements can be met. Lowering the weight of the structure can be achieved by several methods, the most common being by using lightweight materials (i.e. aluminum alloy) or by reducing the number of parts of different components of the structure. This paper studies the effect of side stiffening plate on the stiffness of the bus structure. By knowing how the stiffening plate affects the stiffness of the structure, it can be optimized, either by choosing lighter materials, or by reducing the size or the thickness of the plates. The lower stiffening plate slightly influences the stiffness of the structure, and can thus be made of aluminum, while the upper stiffening plate has a greater influence on the stiffness.

1. Introduction
Bus manufacturers focus on the development of new vehicles that provide a high level of safety for passengers, while being profitable for carriers. It is thus desired to obtain light weight bus bodies with high stiffness [1]. The weight of the vehicle directly influences the fuel consumption of the vehicle (thus the cost of operation) and the capacity of the vehicle (number of passengers transported).

The stiffness of the structure influences both the behavior of the vehicle when traveling on the road (i.e. maneuverability, stability) and passenger comfort (fewer vibrations transmitted to the passenger compartment) [1].

Lowering the bus weight is important, considering that the mass of new vehicles increased by about 1.1% per year in the last four decades [2]. This mass increase is due to intensive use of auxiliary systems that improve the quality of life for the passenger (i.e. air-conditioning units, speakers) or additional fuel tanks [3].

Developing a bus structure that meets current requirements, especially mass-related, can be achieved by using multi-material designs (using different materials, i.e. aluminum alloys or high strength steels) [2] [4], or by reducing the number of parts in the whole-body structure [5]. In both cases, a good optimization can be achieved by knowing how the different components of the bus structure affect the stiffness of the whole structure [4].

The bus body can be divided in three parts: the chassis, the bus structure (structural body), interior and exterior parts [3]. The chassis is the frame that supports the main subassemblies (i.e. engine, transmission), as well as the structure that provides the basis for the assembly of axles. The structural body is the passenger compartment and it is divided into six components: the left frame, the right frame, the bottom frame (or the floor frame), the upper frame (or the roof frame), the front and the rear frames. Interior and exterior parts include side panels and stiffening plates, roof sheet, doors etc., with the role of protecting passengers while traveling.
This paper studies the influence of side stiffening plates on the stiffness of the bus structure (figure 1). These stiffening plates are located in the passenger compartment at the junction of the side frames with the roof or floor frames. The assembling of the stiffening plates is made by riveting [1] or spot welding [3]. The dimensions and shapes of the reinforcement plates depend on the type of the bus.

![Figure 1. Stiffening plates – location within the vehicle.](image1)

2. FEM analysis on the influence of the stiffening plates on the stiffness of the bus structure

To observe how the stiffening plates affects the stiffness of the bus structure, the torsional stiffness and the bending stiffness are compared in four cases [1]:

- **C1** – structure without reinforcement plates,
- **C2** – structure having only upper reinforcement plates,
- **C3** – structure having only lower reinforcement plates,
- **C4** – fully reinforced structure.

The influence of two stiffening plates is studied (figure 2): the upper stiffening plate (situated above the side windows) and the lower stiffening plates (situated under the side windows).

![Figure 2. Stiffening plates.](image2)

A simplified model of an urban bus is used to determine the rigidity. The reference model has a length of 12m, a width of 2.55m and a height of 3.4m.
In order to assess the rational use of the material, two coefficients are used, the light construction coefficient \( c_u \) and the body skeleton density \( K \) [3] [5] [6].

\[
c_u = \frac{k_t A}{m_s} \quad (1)
\]

in which \( k_t \) is the torsional stiffness of the structure, \( A \) is the area of horizontal projection of the structure studied and \( m_s \) is the mass of the structure.

\[
K = \frac{m_s}{L_0} \quad [kg/m] \quad (2)
\]

where \( L_0 \) is the body length. The body skeleton density, \( K \), lies in the range of 110 ÷ 170 kg/m [5].

2.1. Torsional stiffness

The following formula is used to assess the torsional rigidity of the bus structure [6]:

\[
k_t = \frac{F - L}{\arctan\left(\frac{d}{F}\right)} \quad [Nm/grad] \quad (3)
\]

in which \( F \) is the force applied to the body, determining the bending torque \( M_t \); \( L \) is the distance between the points where the force \( F \) is applied; \( d \) is the displacement of the points where \( F \) is applied. The torsional stiffness of a bus body lies in the range of \( 1,8 ÷ 4,0 \cdot 10^4 \) Nm/grad [5] [6].

To determine the torsional rigidity, the structure is constrained on the rear suspension supports and two point forces are applied on the front suspension supports (figure 3). The point force has the value of \( 10000N \).

![Figure 3. Boundary conditions for determining the torsional stiffness.](image)

Table 1 shows the results for the four simulations and the values obtained for torsional stiffness, lightweight coefficient and skeletal body density. Figure 4 shows the deformed structure for the four described situations, using the same color scheme and deformation factor.

### Table 1. Results for the torsional stiffness.

| Case | Structure Mass [kg] | Strain [MPa] | Displacement [mm] | Torsional Stiffness [Nm/grad] | Lightweight Coefficient [-] | Skeletal Body Density [kg/m] |
|------|----------------------|--------------|-------------------|-----------------------------|-----------------------------|-----------------------------|
| C1   | 2581,8               | 199,33       | 11,805            | 19020,5                     | 225,15                      | 215,15                      |
| C2   | 2749,9               | 149,12       | 5,8661            | 38274,9                     | 425,37                      | 229,15                      |
| C3   | 2856,6               | 163,96       | 10,434            | 21519,38                    | 230,2282                    | 238,05                      |
| C4   | 3024,7               | 146,83       | 5,6146            | 39989,35                    | 404,05                      | 252,05                      |
Figure 4. Comparison of total displacement in the four considered situations for the torsional stiffness, using a deformation factor of 10.

2.2. Bending stiffness
Bending stiffness, $k_b$, for the structure is assessed using the formula [6]:

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

(4)

where $F$ is the force that deforms the structure and $\delta$ is the displacement in the point where the force $F$ is applied. As in the case of the torsional stiffness, the maximum stress that occurs during simulation in the structure should not exceed the maximum permissible tension, with regard to the used material [7].

Figure 5. Boundary conditions for determining the bending stiffness.
Figure 5 shows the boundary conditions for determining the bending stiffness, four constrains (the mounting points for the suspensions) and two concentrated forces, having the value of 10000N. The simulations results for bending stiffness are shown in table 2 and in Figure 6.

**Table 2. Results for the bending stiffness.**

| Case | Strain [MPa] | Displacement [mm] | Bending Stiffness [Nm/grad] | Lightweight Coefficient [-] |
|------|--------------|-------------------|----------------------------|----------------------------|
| C1   | 62,943       | -2,2472           | 4449,98                    | 52,6761                    |
| C2   | 48,831       | -1,447            | 6910,85                    | 76,8055                    |
| C3   | 64,525       | -1,6712           | 5,983,724                  | 67,2525                    |
| C4   | 49,201       | -0,4585           | 8441,668                   | 89,3541                    |

**Figure 6.** Comparison of total displacement in the four considered situations for the bending stiffness, using a deformation factor of 30.
3. Conclusions
The way the stiffening plates affects the performance of the bus (the stiffness of the structure, its mass) depends on their location, the two stiffening plates having different effects on the stiffness of the bus structure. By knowing the influence of the two panels on the performance of the bus structure, some measures can be taken to improve the performances of the bus (i.e. adopting different materials, modifying the thickness of the panels, their dimensions).

From the experimental data (table 1 and table 3), there is a small influence on the torsional stiffness of the lower panel. The large dimensions of this panel lead to a \(10.64\%\) increase in the structure’s mass, while the rigidity of the structure changes slightly (by \(13\%\)).

**Table 3.** Effects of stiffening plates on the torsional stiffness.

| Case | Structure mass [kg] | Strain [MPa] | Torsional Stiffness [Nm/grad] | Lightweight Coefficient [-] |
|------|---------------------|--------------|-------------------------------|---------------------------|
| C1   | 2581.8              | 0%           | 199.33                        | 19020.5                   |
| C2   | 2749.9              | 6.51%        | 149.12                        | 38274.9                   |
| C3   | 2856.6              | 10.64%       | 163.96                        | 21519.38                  |
| C4   | 3024.7              | 17.15%       | 146.83                        | 39989.35                  |

By comparison, the influence of the upper stiffening plate is higher, the torsional stiffness of the structure rising by about \(101.23\%\). Using only the upper reinforcement plate, the highest value for lightweight coefficient is obtained, due to the small mass of the upper panel and the reduced influence that the lower panel has on the stiffness of the structure.

The small influence that the lower panel has on the stiffness is due to the fact that a greater part of the load is distributed through the side frame. Because the upper part of the side frame is less reinforced, the upper panel improves the stiffness of the structure by transferring the load, especially across the door openings.

There is a greater influence of the lower stiffening plate in the case of bending stiffness, resulting in a \(34.47\%\) increase in stiffness. Thus, in the case of bending stiffness, the highest lightweight coefficient is obtained when using both reinforcement panels.

**Table 4.** Effects of stiffening plates on the bending stiffness.

| Case | Structure Mass [kg] | Strain [MPa] | Bending Stiffness [Nm/grad] | Lightweight Coefficient [-] |
|------|---------------------|--------------|-----------------------------|---------------------------|
| C1   | 2581.8              | 0%           | 62.94                       | 4449.98                   |
| C2   | 2749.9              | 6.51%        | 48.831                      | 6910.85                   |
| C3   | 2856.6              | 10.64%       | 64.525                      | 5983.72                   |
| C4   | 3024.7              | 17.15%       | 49.21                       | 8441.66                   |

As stated before, the two panels have different influences on the stiffness of the structure. The lower panel has a small effect on the total stiffness of the structure, in both cases (torsional and bending). This stiffening plate helps to distribute load but it is not important for this task since a greater part of the load is distributed through the side frame pillars. Thus, to reduce the mass of the bus body, this panel can be made from different materials (i.e. aluminum) or may have smaller dimensions (thickness).

The upper stiffening panel helps distribute a greater load, especially across the door openings. Therefore, its influence on stiffness is greater. In this case, optimizing the structure can be achieved by using thinner panels made of high strength steels.
4. References

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