New Structure Concept of the Bus Construction with the Addition Carbon Fiber Layers and Filling Foams

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Abstract: The construction of buses is a complex and complicated field with different requirements. The mass of the body frame is a very important property. The lower mass can lead to higher occupancy, but it usually means lower stiffness of the construction. Lower mass (while maintaining rigidity) can be achieved by optimizing the geometry or using new advanced materials. In this paper the new structure concept of the bus construction with the addition carbon fibre layers and filling foams, used as local reinforcement of the whole structure, is described. The main goal is the investigation of the feasibility of these hybrid joints in the bus construction (hybrid beams and structural nodes).

Keywords: bus construction; composite; foam; explicit; crash.

1 Introduction

The most significant load on the bus skeleton falls into the area of fatigue and crash. The raw materials' cost in the steel design is cheaper than in the composite one, but the number of hours employed to manufacture the steel design is much higher than in the composite one [1]. This paper is mainly focused on the crash field (especially roll-over Ro.66). Here the composite materials and manufacturing technologies reduce the weight of the bus and the tram vehicle [2]. The effort to lighten the construction of the bus (with same or better stiffness) has two levels. First, it is necessary to create a numerical model (based on available material data) as the first support for experimental work. Second, it is necessary to validate the numerical model using data from those experimental measurements. It is a good idea to validate individual materials separately and subsequently validate more complex units (such as a combination of a steel beam with glued composite strip and foam). The main work is connected with a simple beam model, but the general results will be applied in the bus construction. The commercial solver Pam-Crash is used for simulations.

2 The theory of explicit numerical simulation

The beginnings of the development of explicit solvers date back to the 1960s. At that time, such development took place mainly at universities. The HEMP program, whose code was freely accessible, was the very beginning of today's software packages. Explicit time integration is suitable for simulating processes which involve large strains and changes in shape. It offers better representation of the nonlinear behavior of materials, and failures. Explicit solvers are generally better suited for problems with complex contact. The essence of an explicit code is Newton's second law of motion. It is an equation of motion in the matrix Eq. 1. This equation is defined for the given time. In order to maintain equilibrium between dynamic forces, the relationships below must be met [4].

$$\{a_t\} = [M]^{-1}\left(\{F_t^{ext}\} - \{F_t^{\mathrm{int}}\}\right) \tag{1}$$

Here, $\{a_t\}$ denotes the acceleration vector (at time instant t), $[M]$ is the mass matrix, F_{text} stands for the vector of external forces acting on the body, and F_{tint} is the vector of internal forces.

Once the internal forces have been defined and some fundamental elements have been added, an equation for the numerical solution can be obtained in the following Eq. 2. The element $\{F_{houg}\}$ was added to prevent the hourglassing effect, and $\{F_{cnt}\}$ is a vector of contact forces. Furthermore, $\{\sigma_n\}$ is an internal stress matrix, and $[B]$ is a strain matrix.

$$\left\{\mathrm{F}_{\mathrm{t}}^{\mathrm{int}}\right\} = \sum\left(\int\limits_{\Omega} [B]^{T} \{\sigma_n\}\, d\Omega + \left\{F^{houg}\right\}\right) + \left\{F^{cnt}\right\} \tag{2}$$

Solvers that use the explicit code are conditionally stable. This means that they are only stable under certain conditions, referring mainly to the time step size. This, in turn, is related to the propagation of stress waves through the material (see the following Eq. 3). Here, c is the velocity of the wave propagating through the material, l is the characteristic size of an element, E is the modulus of elasticity, and ρ the density of the material.

$$t_{comp} \leq t_{krit} = \frac{l}{c} = l\sqrt{\frac{\rho}{E}} \tag{3}$$

A great advantage of the explicit method is usage of elements with a single integration point. A downside is the reduced stability of computation. If an element deforms symmetrically, no corresponding change in internal energy takes place. Eventually, the computation leads to an imbalance between the kinetic and the internal energy of the system. This numerical error is known as hourglassing. The total energy must be controlled in dynamic calculations. The recognized critical threshold is an increase in the hourglassing energy above 5 % of the total energy of the system. In extreme cases with a significant hourglassing effect, the simulation run may even crash. Various methods are available to control hourglassing.

3 Numerical model

For calculations in the field of passive safety, the project use the FEM solver Pam-Crash from the VPS (Virtual Performance Solution) software package. This solver allows to calculate the events of structural dynamics through an explicit integration scheme and is suitable for problems with significant nonlinearities (geometric, material, contact). To compile the calculation, it is necessary to create a FEM mesh with the necessary entities (welded joints, glued joints, contacts,…) and above all it is necessary to create relevant material models. Innovative design requires the usage of models that can be divided into categories:

- Standard steel materials;
- Composite materials;
- Foam;
- Glue.

Because some materials and their uses are relatively unique, this task requires a considerable amount of experimentation, and conventional material testing (like tensile test only) cannot be used. Three-point and four-point bending tests seem to be relatively suitable (quite similar approach to literature [3]), as they can be performed on samples corresponding to the real construction of the bus and their deformation mode is close to the deformation in the rollover type of test. Material models are compiled gradually. Steel parts of the structure can be defined on the basis of routine tensile tests. The beam test, from which the bus structure is formed (and which most influences the behavior of the rollover test), can be considered a suitable validation of the FEM material model (see Fig. 1). If the deformation characteristics match, the material model of the steel can be considered sufficient. The measure of the numerical reliability of the FEM model is the energy balance, where the total energy change must be less than 10 %.

4 Possible approaches for glue joint idealization

4.1 Link with basic material and additional rupture model

The most widely used link (in Pam-Crash) is based on penalty algorithm (with node to segment coupling). Nonlinear contact force can be computed by Eq. 4 where A and B are stiffness parameters and is the distance. The more significant disadvantage of this approach is, than external rapture criterion is the same for all-possible modes of rupture (even same in shear and normal direction).

$$FNL = A \cdot \delta + B \cdot \delta^3 \tag{4}$$

4.2 Link with advanced material model

The more sophisticated solution is to use the material model with failure criterion calculated for two modes of rupture. It is useful to have different criterion for glue joint than for shear and normal direction. The modulus in normal direction E_0 and modulus in shear direction G_0 depend on the energy absorbed in the connection after the rupture starts progress (see Eq. 5).

$$\begin{pmatrix} \sigma_n \\ \sigma_t \end{pmatrix} = \begin{pmatrix} E_0 & 0 \\ 0 & G_0 \end{pmatrix} \begin{pmatrix} \varepsilon_n \\ \varepsilon_t \end{pmatrix} \tag{5}$$

4.3 Cohesive element and link with advanced material model

This approach is the most accurate one. The model is based on a “traction-separation” law with rate dependent trilinear elastic plastic cohesive zone “mixed” mode. It is using the Benzeggagh and Kename criteria or the power criteria for cohesive elements. The theory is described in literature [5, 6]. In the numerical model, the cohesive element does not influence the time step (in Eq. 3). This is a very important feature of a thin layer of glue (typically elements with characteristic length smaller than 0.1 mm).

5 First results of numerical simulations

The very first results of numerical simulations (based on adhesive rupture model) are finished. If the deformation characteristics is in coincidence with experiment, the material model can be considered sufficient. The measure of the numerical reliability of the FEM model is the energy balance, where the total energy change must be less than 10 %.

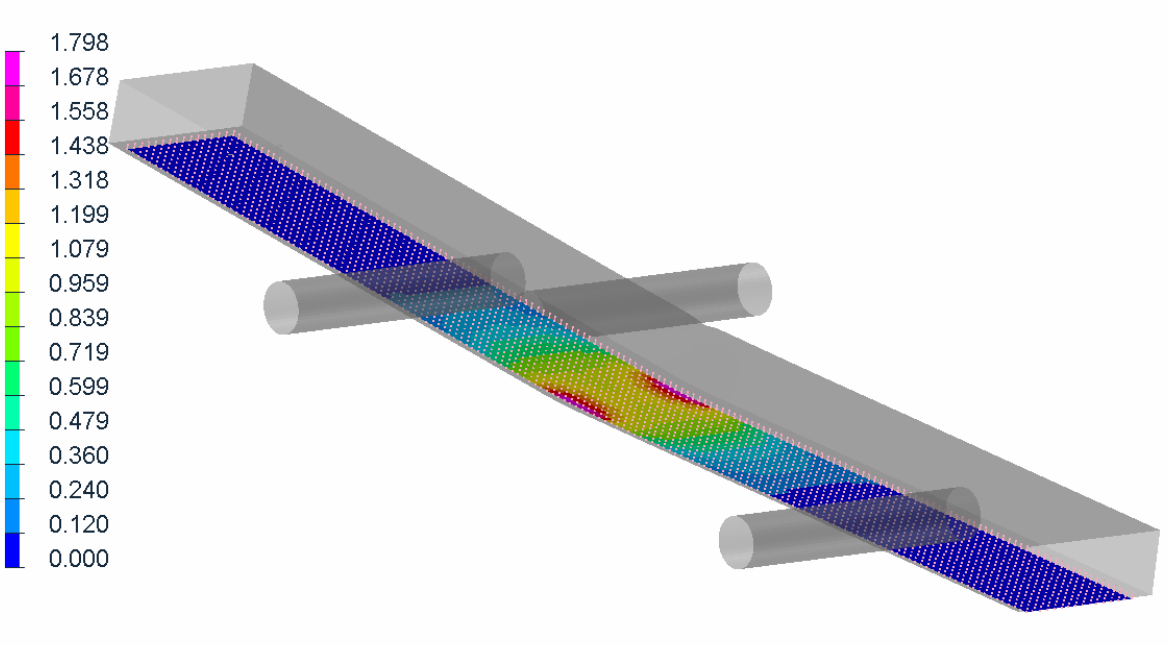

Fig. 1: The calculation of three-point bending of a component reinforced with CFRP tape (VM stress [GPa]).

6 Conclusion

The paper shows some very first results and approaches for numerical simulations of a hybrid beam structure. The partially validated model of a steel hollow profile with glued composite strip and filled with foam gives some observations. The good cooperation of the composite and the steel has better results for composites

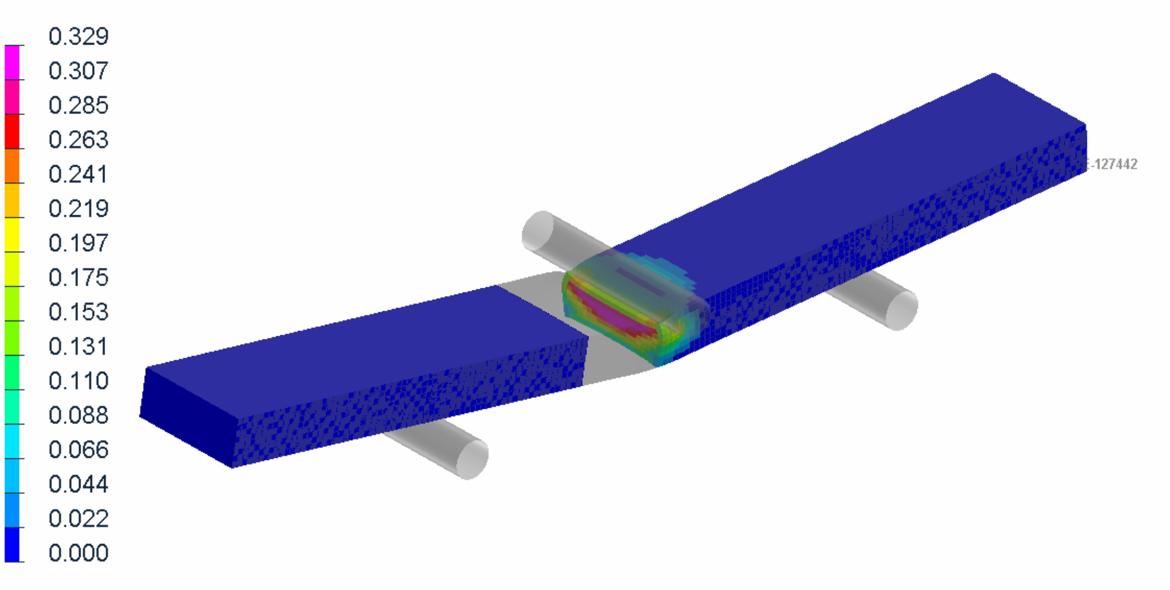

Fig. 2: The calculation of a three-point inside view of the foam equivalent plastic strain [-].

with young modulus close to young modulus of steel. The glue connection will be probably the key point of the good working part of construction. The three-point bending test with its simulation can help to validate the material models, but the numerical simulation and the full-scale experiment of the bus segment is recommended. This type of experiment will be performed in the near future.

Acknowledgement

This work has been supported by the project TH71020003 “Composite reinforcement in a light stainless steel bus structure” provided by the Ministry of Industry and Trade of Czech Republic.

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