OPTIMIZATION OF DEVICE ALLOWING VARIATION OF ADHESION FORCE FOR ROAD VEHICLE TESTING AT SAFE SPEED

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Abstract. In this paper the authors discuss optimizing the key point of the subframe. The objective of the paper is to optimize the current design of the Alternative SkidCar frame. It is an auxiliary device, which attaches to the chassis of the car and allows controlled variation of the adhesion force transmitted between the wheels and the ground. The current form of the frame is assembled only from the point of view of functionality. The frame is obviously designed to make production as simple as possible. At the same time, it is oversized in terms of material. Optimization consists of finding a key construction node, which is the weakest point of the frame structure, while minimizing the weight, using the finite element method. Subsequently, we used the finite element method simulation for another material and we evaluated the current form of mechanical stress in this node, achieving a minimized weight. A new software study of the proposed design was subsequently performed. Based on the conclusions of the paper, the weight of the Alternative SkidCar frame was significantly reduced while respecting the required load capacity. Because the frame of the Alternative SkidCar is attached to the car as an accessory, it is desirable that it influences the vehicle's behaviour minimally. The change was made by reducing the thickness of the material profile and changing the material used. Just reducing the weight of the frame – it is this change that has a significant positive effect on the behaviour of the car, complemented by the Alternative SkidCar system.

Keywords: road vehicle, car weight, mechanical stress, radial reactions.

Introduction

The safety of road vehicles in motion is mainly due to their stability. If the driving situation of the car requires transmission of a force greater than the adhesion force, the balance of forces is disturbed and the car skids. The resulting behaviour of the car in a skid is determined by its design, the tyres used and the position of the car's centre of gravity and other factors. Car testing is primarily for longitudinal and transverse stability and rollover threshold. Ideally, cars are tested under real conditions, but it is not always possible. For example, before the actual production of cars. Their testing under artificial conditions is often used in the area of car development. In addition to real conditions, the driving stability [1] of a car can also be tested under conditions of artificial induction of reduced adhesion force [2; 3]. This can be achieved by reducing the radial response transmitted by the car wheels on the road, or by reducing the coefficient of adhesion. In the first case, a commercially available SkidCar device [4; 5] is used to reduce the radial response of car wheels, in the second case it is possible to use sliding surfaces or sliding tyres, for example, with the designation Easy Drift Ring [5; 6]. The SkidCar system is an additional frame with wheel units which is retrofitted to the car. Depending on the lifting of the supporting wheels, the car is raised and thus the radial reaction transmitted by the car wheels is reduced. Since it is an additional device, it is desirable that this device affects the parameters as little as possible, ideally not at all [6-8].

The paper deals with the optimization of the cross-bar material of the existing frame of the experimental system of Alternative SkidCar. Using simulations in the MSC Adams software [9-11], we determined the limit load on the supporting wheels of the frame corresponding to the static state as well as to the change of direction. The least favourable load found was used as the input load for strength analysis. The analysis was performed by the finite element method in SolidWorks [12-14]. Based on geometrically and materially nonlinear strength analysis, we determined the course of stress of the frame cross bar at critical points with the highest stress concentration. Subsequently, according to the obtained results, we designed a new material of the frame cross bar. We chose the material for maximum weight reduction without further modification of the design.

The result of the paper is the material optimization of the current form of the frame in order to minimize the weight while maintaining sufficient strength. The paper evaluates the design of the frame arm of the Alternative SkidCar system. Loading the frame supporting wheels of the Alternative SkidCar in MSC Adams software simulation creates the load force of the frame. The evaluation is made through mechanical stress and limit states. The strength analysis was evaluated from the point of view of mechanical stress and limit states.

Materials and methods

The authors' department specializes in verifying the stability of road vehicles. An experimental car is available for this purpose. As an accessory for simulating adhesion conditions, the car can be supplemented with an auxiliary frame with supporting wheel units. It is similar to a commercially available device called SkidCar [7]. Since the cross bars extend over the width of the car, i.e. over the car plan view, they have a great influence on the change of the moment of inertia of the car as a whole when using the additional ASC frame [6], therefore, it is necessary to optimize their design. As this is an additional device that is fitted to the car, it is desirable that its weight be kept to a minimum. It creates a great assumption that the behaviour of the car will be minimally affected. The current form of the frame was designed so that its construction was as simple as possible in production and the weight was not considered in the actual design. Thus, it is clear that the entire Alternative SkidCar (ASC) system [6-8] is oversized in terms of strength and, above all, material. Design proposals for optimizing the frame have already taken place. Now the problem of choosing a suitable material is solved in order to minimize the weight while maintaining the required strength. The current form of the experimental car with Alternative SkidCar is shown in Fig. 1. The main part is a steel frame that is attached to the car. The frame consists of a pair of cross bars and a pair of longitudinal bars forming a three-dimensional structure. Supporting wheel units are attached to the sides of the frame. By changing the position of these wheels, the radial response transmitted by the car wheels is reduced and the amount of adhesion force is changed.

Fig.1. **Alternative SkidCar on the car**

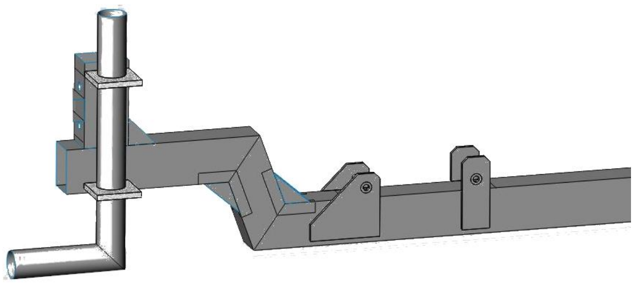

Fig. 2. **Half of the ASC cross bar**

Determination of load force

The input load of the ASC cross bar depends on the weight, driving mode and degree of lightening of the car. We determined the input load of the wheel units when the car was stationary by weighing with a step change of the radial reaction. The load due to the centrifugal force that arises in the centre of gravity of the system during turning was determined using a simulation in MSC Adams. Model bodies have a defined own weight, rigidity, moments of inertia and other characteristics. The tyres have a defined flexibility and damping, which were determined according to [2] on a dynamic adhesor. Parts with relative motion have defined internal friction. The car body was replaced by a material point located in the centre of gravity of the car. The body is connected to the SC frame by a fixed coupling and tied to the car's axles via a suspension. The wheel units with deformable tyres are on the rotary couplings at the ends of both ASC cross bars. The wheel units rotate around their vertical axis with defined internal friction. These pins allow vertical movement of the wheel units. In this way we are able to achieve a change in radial reactions on the car wheels. We defined the resulting value of the load force as the product of the maximum value of Z_{SCFL} (Table 1) and the factor of safety 1.8.

Table 1

Resulting values of load forces from wheel units

k	Z_{SCFL}, N	Z_{SCFR} , N	Z_{SCRL}, N	Z_{SCRR} , N
0.0	0	0	0	0
0.2	834	831	456	453
0.4	1677	1658	956	937
0.6	2516	2498	1430	1413
0.8	3439	3422	1872	1855
1.0	4227	4143	2338	2315

Note: Z_{SCFR} – radial force of the front right wheel unit, N;
Z_{SCFL} – radial reaction of the front left wheel unit, N;
Z_{SCRR} – radial reaction of the rear right wheel unit, N;
Z_{SCRL} – radial reaction of the rear left wheel unit, N;
k – wheel unit lifting coefficient.

Original and new state

S235JR unalloyed killed structural steel is used as the original material for production of the cross bar. Welding technology is used to connect the frame elements together. To determine the course of stresses in the design, we created a cross bar network in SolidWorks. Subsequently, we identified critical areas of the design, where we refined the network in order to achieve more accurate results. We optimized the size of the elements of standard and refined areas for the best possible ratio between the accuracy of the results and the speed of the calculation. The bilinear von Mises model was used to determine the mechanical stress for the state of maximum load force. We performed the simulation for the limit state of stability, where we determined the point with the maximum stress. Subsequently, we plotted the load characteristic for this node (Fig. 3). At the point where these two tangents intersect, we subtract the value of the *Load Factor* for the stability limit state L_{Fst} = 3.94.

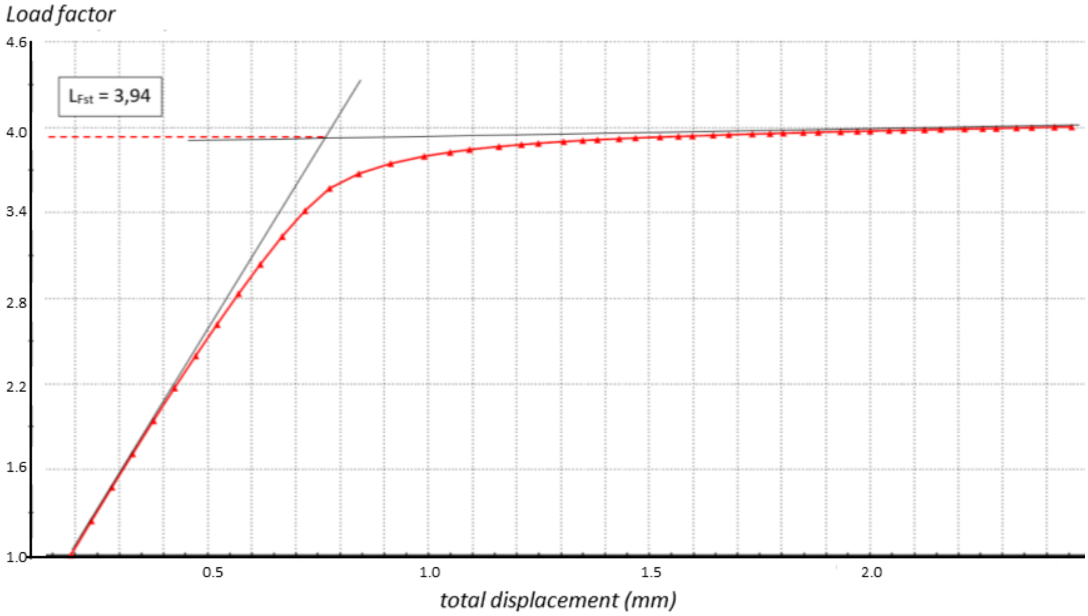

Fig. 3. **Load characteristics for the original material S235JR**

The initial state of load of key points of the structure at the load given from operation is evident in Fig. 4. Geometric boundary conditions include a symmetry condition, because the frame is symmetrical about its longitudinal median plane. In this way, the normal movements of the profiles relative to this plane are disabled and the rotation of the profiles in this plane is disabled. A fixed fixture that characterizes the full tightening of the bolts was applied to the split lines on the frame brackets. From the outside of the frame mount, the area separated by the split line simulates the M10 bolt washer and from the inside covers the split line entire surface of the mount above the cross bar profile, that is the area that seats on the profile welded to the car frame. Another frame fixture was to disable the vertical movements (y-axis) that were applied to the contact surface (upper cross bar profile area between the mounts), where the profile welded to the car frame seats on the cross bar of the Alternative SkidCar frame.

Curved tubes simulating the caster of wheeled units have been used for the application of strength boundary conditions. Vertical force (radial reaction) and horizontal force (rolling resistance) are applied at the end of these curved tubes (at the point of the SC stub axle).

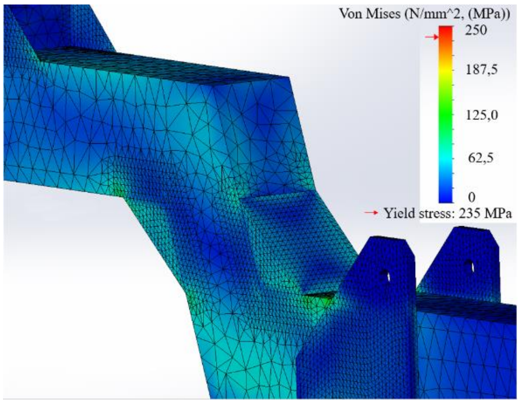

Fig. 4. **Initial load state of the cross bar**

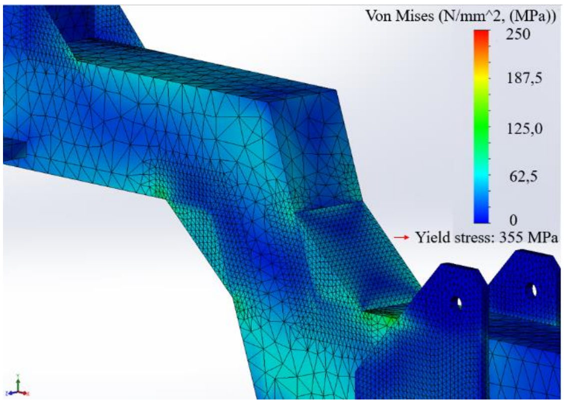

Fig. 5. **Load state of the cross bar from S355J0**

As part of the optimization of the Alternative SkidCar system frame, we performed a load simulation using S355J0 structural steel in order to reduce weight. We used this material because of the declared higher yield strength and manufacturer's warranty to meet the specified catalogue parameters than the original material. In terms of the structural elements joining design, the welding process has been maintained as it was done on the original frame version.

The procedure for assembling the load characteristic is identical to the procedure for the original material. The stress display in the critical area of the frame for L_{Fst} = 1, i.e. for the entered load value, is shown in Fig. 5. After forming tangents to the elastic and plastic part of the load characteristics of the point with maximum mechanical stress (Fig. 6) and subtracting the value of the degree of load at the point of their intersection, the value of L_{Fst} = 5.76 is obtained.

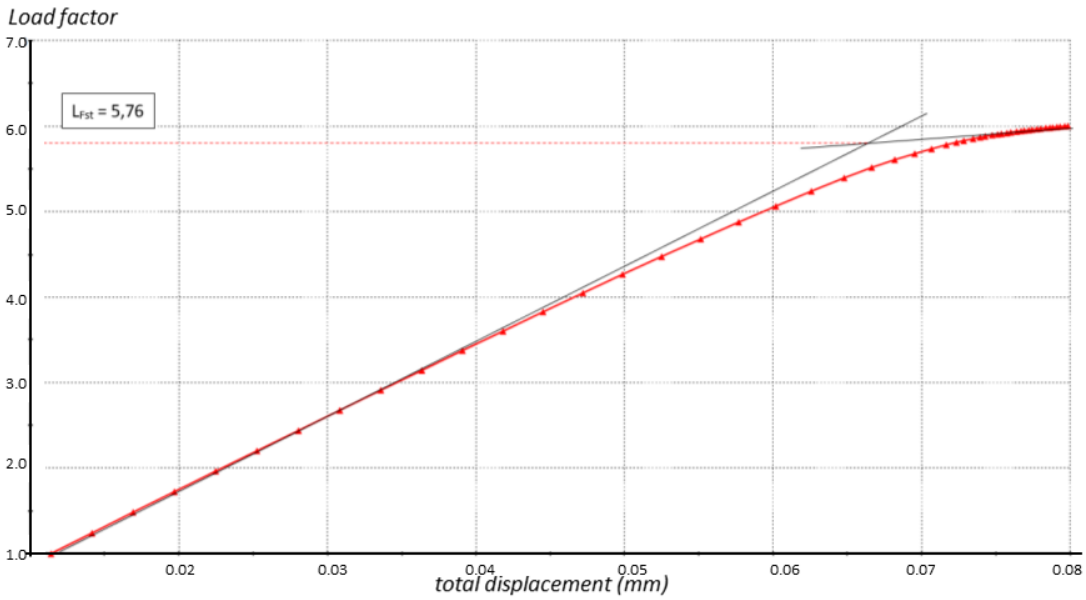

Fig. 6. **Load characteristics for new material S355J0**

We evaluated the strength in terms of limit states and the calculation of the allowable load according to equation (1):

$$L_{FD} = \min\left\{\frac{L_{Fpl}}{n_T};\frac{L_{Fst}}{n_u}\right\}\cdot\varphi, \quad (1)$$

where L_{FD} is the allowable *load factor*, with factor of safety, L_{Fpl} is plasticity *load factor*;
L_{Fst} is stability *load factor*;
n_T is factor of safety for yield strength;
n_u is factor of safety for loss of stability.

The allowable *Load Factor* (1.68) is greater than 1, so this frame concept is satisfactory in terms of strength. The maximum allowable load on SC wheels could increase by 68% to comply with the requirements. The design therefore complies with the plasticity and stability limit states and the maximum allowable stress.

Results and discussion

It is possible to minimize the cross-bar wall thickness for material S355J0, which has a higher strength than the original material S235JR. Table 2 shows the weights and thicknesses of the individual parts of the frame and the entire frame after optimization for S355J0 steel and a comparison of these parameters with the original weight of the frame and its parts and the thicknesses of the individual frame parts before optimization.

Table 2

Comparison of the thickness and weights of the frame parts using the original S235JR steel and the newly designed S355J0 steel

Frame part	Original wall thickness, mm	Wall thickness after optimization, mm	Original weight, kg	Weight after optimization, kg	Difference, %
Cross bars	5	3	32.6	24	26.3
Longitudinal bars	3	3	7.4	5.4	26.6
Whole frame	—	—	80.0	58.9	26.6

Due to the use of a material with a higher yield strength, it is possible to achieve a significantly lower weight after modification of the structure. The optimization of the cross-bar design was made only in the form of a change in the wall thickness of the used profile. With this change, we reduced the weight on the cross bar by 26.3%.

Conclusions

Depending on the correct choice of material, it is possible to achieve a significant reduction in the weight of the structural unit. The original frame was constructed of steel profiles from the material of S235JR alloyed rimmed steel. The proposed S355J0 steel has a higher yield strength. Therefore, it was possible to use a structure with a lower wall thickness during optimization. Based on the material with higher strength, we achieved a reduction in the weight of the cross bar by 26.3%, which is 12 kg per piece while maintaining the prescribed strength. Another way to reduce the weight of the frame is to use a light alloy material, such as aluminium alloy EN AW-6060 T6. Another way to achieve weight reduction is to optimize the frame design. From the above conclusions, it is always necessary to address its design in relation to the material used when designing a structure. Only in this way is it possible to achieve the desired results with minimal effort.

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