

Raziskave nosilnega okvira vozila Šinkovec MM

Investigation of the Šinkovec MM Vehicle Tube Frame

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Vsa vozila, ki so namenjena uporabi na javnih prometnih površinah, potrebujejo homologacijski dokument vozila. Iz tega razloga je treba pridobiti ustrezna potrdila o trdnostni in/ali funkcijski ustreznosti vseh pomembnih elementov vozila, kar velja tudi za primer izdelave unikatnega prototipnega vozila. V primeru vozila Šinkovec MM spada med najpomembnejše elemente prav gotovo nosilni okvir, saj daje trdnostno oporo vsem drugim elementom vozila. Trdnostni preračun nosilnega okvira je bil izveden na podlagi mejnih obremenitvenih stanj, ki so bila pri računalniško podprtem trdnostnem preračunu vnešena na model MKE nosilnega okvira prek masnih vztrajnostnih sil, ki se pojavijo zaradi delovanja polja pospeška na mase posameznih komponent vozila. Izveden trdnostni preračun obsega preverjanje napetostnega stanja pri statičnih in dinamičnih obremenitvah nosilnega okvira.

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(Ključne besede: konstrukcije nosilne, dinamika vozil, izračuni trdnostni, metode končnih elementov)

For all vehicles on the public highway it is necessary to obtain a motor vehicle approval document. For a unique prototype vehicle it is also required to have the necessary certificates for the strength and/or functional suitability of all the vital vehicle components. One of the most vital components of the Šinkovec MM vehicle is the vehicle's tube frame which offers high-strength support for the other elements of the vehicle. Strength calculations on the vehicle's tube frame have been made on the basis of extreme loads which were, in a computer supported strength calculation, applied on a FEM model of the vehicle's tube frame in the form of mass inertia forces occurring as a result of the action of the acceleration field on the masses of particular components of the vehicle. The strength calculation includes the verification of the stress state as a result of static and dynamic loads on the vehicle's tube frame.

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(Keywords: vehicle tube frame, vehicle dynamics, strength calculations, finite element methods)

0 UVOD

Trdnostni preračun nosilnega okvira Šinkovec MM je bil narejen na podlagi obremenitvenih stanj, ki so posledica kolesnih obremenitev v mejnih režimih obratovanja vozila. Mejne kolesne obremenitve so bile določene na temelju izkustvenih dejavnikov ([1] in [3]) ter na podlagi rezultatov, dobljenih z računalniškim simuliranjem togega modela vozila [2].

Trdnostni preračun je bil narejen z metodo končnih elementov in podaja poteke napetostnega stanja pri trenutnih sunkovitih obremenitvah ter poteke napetostnega stanja, ki pomenijo povprečne obremenitve nosilnega okvira med njegovo dobo trajanja na podlagi spremenljivih obremenitev ([4] do [6]).

0 INTRODUCTION

Strength calculations on the vehicle tube frame of the Šinkovec MM vehicle have been made on the basis of wheel loads that occur under extreme driving conditions. Extreme wheel loads were defined on the basis of empirical factors ([1] and [3]) and result from a computer simulation of a rigid model of the vehicle [2].

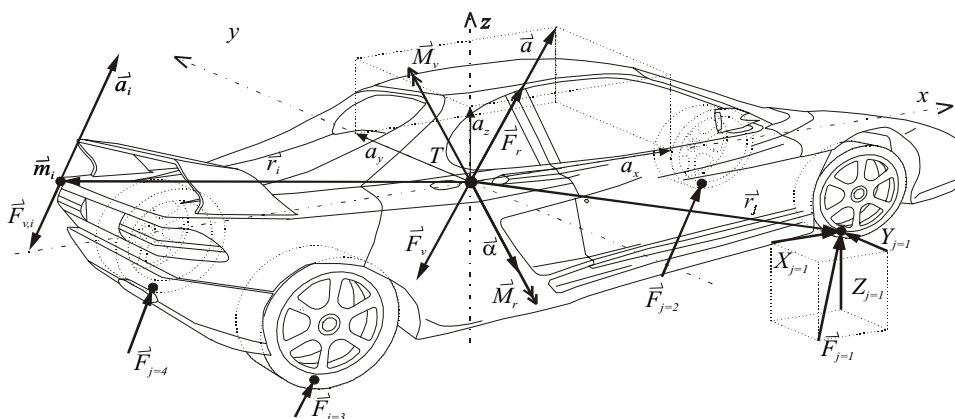
The strength calculation was made using the finite element method that enables the calculation of stress distribution in elements of the body structure that is a consequence of momentary jerky loads, and stress distribution that is a consequence of dynamic loads ([4] to [6]).

1 OBREMITVENO STANJE NOSILNEGA OKVIRA

Pri določitvi obremenitvenega stanja nosilnega okvirja je vozilo predstavljeno kot sistem, ki je sestavljen iz cevne nosilnega okvira, na katerem so pritrjene mase posameznih komponent vozila. Ta nosilni okvir je prek podvozja ter koles povezan z okolico, vse skupaj pa je postavljeno v polje pospeška $\vec{a}(x, y, z, t)$, ki je v splošnem funkcija lege in časa. Pri določanju polja pospeška je upoštevano, da je polje posledica sil, ki se pojavijo kot kolesne obremenitve ((1) do (3)), ter da se vozilo obnaša kot togo telo (sl. 1).

1 CONDITION OF LOADS OF THE BODY STRUCTURE

To define the load conditions the vehicle was represented as a tube frame construction. Such a design offers high-strength support to the masses of other components of the vehicle. The frame is connected to the driving surface through suspension elements and wheels. The whole system was loaded with an acceleration field $\vec{a}(x, y, z, t)$ which is generally a function of space and time. The acceleration field was determined with the assumption that the acceleration field is a result of forces in wheel-driving surface contact ((1) to (3)) and that the vehicle behaves as a rigid body (Fig. 1).



Sl. 1. Kinetične razmere na vozilu
Fig. 1. Kinetics conditions of vehicle

$$\sum_{j=1}^4 \vec{F}_j - \sum_{i=1}^{n_k} m_i \vec{a}_i = \vec{F}_r - \vec{F}_v = \vec{0} \quad (1),$$

$$\sum_{j=1}^4 \vec{r}_j \times \vec{F}_j - \sum_{i=1}^{n_k} \vec{r}_i \times m_i \vec{a}_i = \vec{M}_r - \vec{M}_v = \vec{0} \quad (2),$$

$$\vec{a} = \frac{1}{m} \sum_{j=1}^4 \vec{F}_j \left(a_x = \frac{1}{m} \sum_{j=1}^4 X_j; a_y = \frac{1}{m} \sum_{j=1}^4 Y_j; a_z = \frac{1}{m} \sum_{j=1}^4 Z_j \right) \quad (3).$$

2 MODEL NOSILNEGA OKVIRA NA OSNOVI MKE

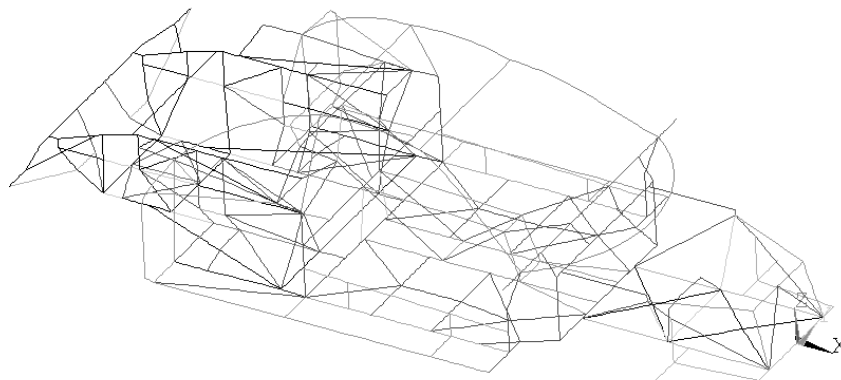
Model nosilnega okvira na osnovi MKE je bil zgrajen tako, da omogoča vnos vseh potrebnih obremenitvenih stanj prek polja pospeška.

Sam model je zelo zapleten. Gradnja je potekala tako, da je bil najprej zgrajen linijski model cevne konstrukcije nosilnega okvira sl.2. Temu modelu po MKE so bili nato dodani vsi členi, ki so potrebni za vnos obremenitvenih stanj. Tako je bilo dograjeno podvozje, ki je namenjeno pravilnemu prenosu nastalih reakcijskih sil iz točk nakotaljenja na nosilni okvir ter samo podprtje točk nakotaljenja prek elastičnih podpornih palic, te rabijo za pravilno porazdelitev vzdolžnih in prečnih sojemnih sil. Za vzpostavitev obremenitvenega stanja prek polja pospeška so namenjene poleg same mase nosilnega okvira še dodane masne točke, ki predstavljajo maso posameznih komponent vozila. Celoten model po MKE je prikazan na sliki 3.

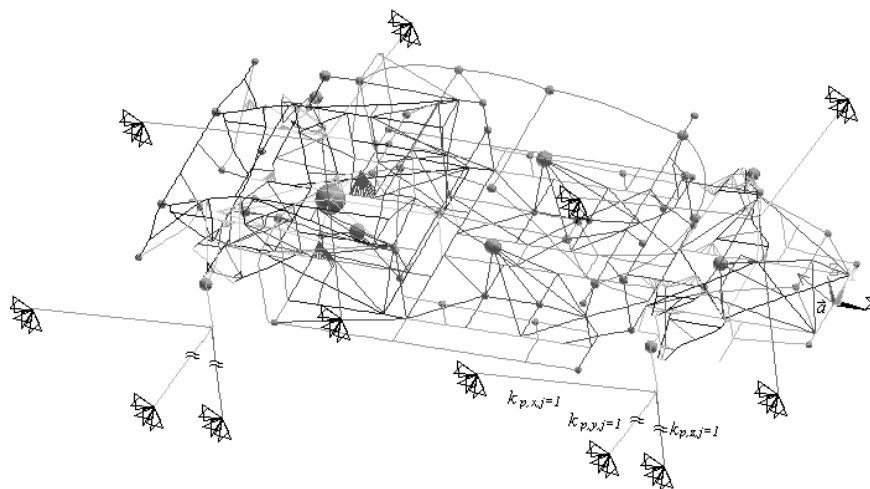
2 FEM MODEL OF VEHICLE TUBE FRAME

The FEM model of the vehicle's tube frame is built in such a way that it enables the application of loads through an acceleration field.

The FEM model is very complex. At first the FEM model of the vehicle's tube frame was made of line finite elements - Fig. 2. Then this FEM model was completed with all the elements needed to apply the loads. Suspension elements were made that serve as links for the transmission of wheel forces to the vehicle's tube frame. Nodes that are in contact with the driving surface were flexibly restrained to enable the proper distribution of longitudinal and transverse wheel forces. Mass points, which substitute for the masses of certain vehicle components, were added for the purpose of load state re-establishment through the acceleration field - Fig. 3.



Sl. 2. Model nosilnega okvira po MKE
Fig. 2. FEM model of body structure



Sl. 3. Celoten model po MKE
Fig. 3. Complete FEM model

3 REZULTATI TRDNOSTNEGA PRERAČUNA

Nosilni okvir vozila Šinkovec MM je linijska cevna konstrukcija, zato je tudi model po MKE zgrajen iz končnih elementov, ki popisujejo lastnosti linijskih nosilcev. Takšni modeli MKE v programskem paketu ANSYS ne omogočajo prikaza poteka primerjalnih napetosti, zato so rezultati podani z največjo absolutno napetostjo, ki se pojavi v prečnem prerezu nosilca, (4) sl.4.

Vsi trdnostni preračuni so izvedeni z upoštevanjem linearnih (elastičnih) lastnosti materiala; v primerih, ko je takšen preračun pokazal prekoračitev meje tečenja materiala, pa je bil preračun ponovljen z upoštevanjem plastičnih lastnosti materiala.

Trdnostni preračun je bil izveden na osnovi 23 različnih režimov obratovanja vozila, prikazani pa so samo najbolj zanimivi primeri.

$$\sigma_{maks} = maks \left(\left| \sigma_{u,y,T} + \sigma_{u,z,T} + \sigma_n \right|, \left| \sigma_{u,y,N} + \sigma_{u,z,N} + \sigma_n \right| \right) \quad (4).$$

Dobljeni rezultati so grafično predstavljeni v obliki slik nosilnega okvira, na katerem so prikazani poteki dobljenih veličin.

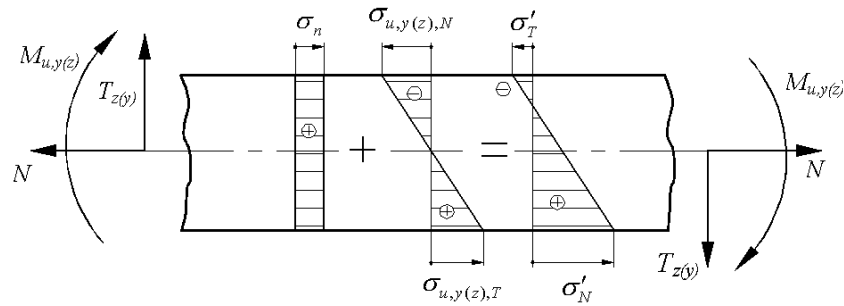
3 RESULTS OF STRENGTH CALCULATION

The tube frame of the Šinkovec MM vehicle is composed of tubes, so the FEM model is composed of beam elements with adequate cross sections. Such FEM models can not display von Mises stresses distribution. Therefore the results are displayed through maximum absolute stresses on the transverse section of the beam (4) - Fig. 4.

Strength calculation was, in all cases, made by consideration of linear material characteristics. In some cases the stress exceeded the yield strength of the material. For these load cases, the calculation was repeated with plastic material characteristics taken into consideration.

The strength calculation was made on the basis of 23 different load states but here only the most critical and most interesting cases will be presented.

Calculated results are presented graphically with a picture of the vehicle frame with the stress distributions on a grey scale.



Sl. 4. Porazdelitev napetosti v nosilcu
Fig. 4. Stress distribution in the beam

Namen trdnostnega preračuna je ugotoviti potek napetosti v konstrukciji, ki jih nato primerjamo z dovoljenimi napetostmi. Za zagotovitev ustrezne trdnosti morajo biti dobljene napetosti v konstrukciji vedno manjše od dovoljenih napetosti materiala:

The purpose of the strength calculation was to find the stress distributions in the structure. The maximum stresses in the structure should be lower than the allowed ones:

$$\sigma_{maks} \leq \sigma_{dop, st / d, osn} \quad (5)$$

Nosilni okvir je zgrajen iz konstrukcijskega jekla Fe 361 B, ki ima naslednje lastnosti [7]:

The vehicle's tube frame is made of low alloyed carbon steel Fe361 B, whose characteristics are [7]:

$$R_m = 360 \text{ MPa}; \sigma_o = 240 \text{ Mpa} \quad (6)$$

3.1 Mirovanje vozila

3.1 Steady state of vehicle

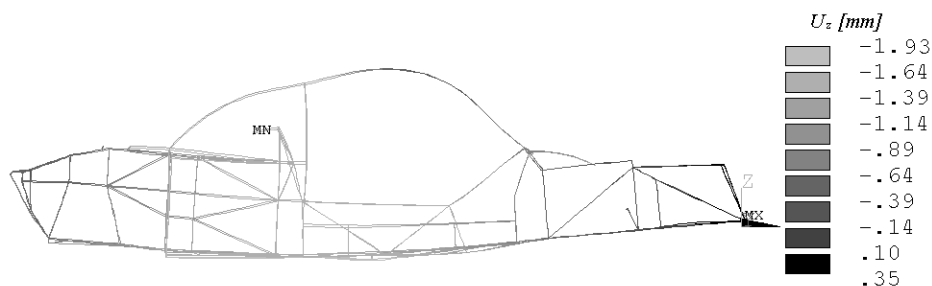
Tu so prikazani rezultati dveh mejnih obremenitvenih primerov, ki se pojavijo pri mirovanju vozila. Rezultati prikazujejo poleg napetostnega stanja tudi upogibno in vzvojno togost nosilnega okvira.

This section presents results of the two extreme load cases, which occur during steady state conditions of the vehicle. Results show stress distribution as well as bending and twist strength.

Preglednica 1. Vhodni podatki za preračun napetosti mirujočega vozila
Table 1. Data for stress calculation for steady state conditions of vehicle

Primer Case	a_x m/s ²	a_y m/s ²	a_z m/s ²	$k_{p,x,1(2)}$ N/mm	$k_{p,x,3(4)}$ N/mm	$k_{p,y,1(2,4)}$ N/mm	$k_{p,y,3}$ N/mm	$k_{p,z,1(4)}$ N/mm	$k_{p,z,2(3)}$ N/mm
P31-1	0	0	9.81	0	∞	0	∞	∞	∞
P31-2	0	0	9.81	0	∞	0	∞	∞	10

P31-1 vodoravna in ravna podlaga; horizontal and even surface;
P31-2 vodoravna in valovita podlaga; horizontal and rough surface;



Sl. 6. Deformacije nosilnega okvira v smeri koordinate z za primer P31-1
Fig. 6. Deformation of vehicle tube frame in z direction - case P31-1

3.2 Mejni navidezno statični režimi vožnje

Pod navidezno statične režime vožnje spadajo vsi režimi vožnje, pri katerih se vozilo sicer giblje, vendar je vpliv tega gibanja na nosilno konstrukcijo časovno nespremenljiv, kar pomeni, da je vozilo v nespremenljivem polju pospeška (zaviranje/pospeševanje in hkratna vožnja z različnimi hitrostmi v ovinek).

Trdnostni preračun je bil izveden za več obremenitvenih stanj, ki so bila določena s simuliranjem na togem modelu vozila [2], prikazani pa so samo rezultati za primer pospeševanja in zaviranja, pri katerih dobimo največje največje napetosti.

3.3 Dinamični režimi vožnje

Ti režimi vožnje obravnavajo razmere, pri katerih se pojavijo velike sunkovite obremenitve zaradi naleta vozila na oviro na cesti, ki so v bistvu kratkotrajni sunki na kolesa, zaradi česar se njihov vpliv na nosilni okvir z oddaljevanjem od točke nakotaljenja hitro zmanjšuje. Prikazani rezultati so dobljeni pri obremenitvenem stanju določenem na osnovi izkustvenih faktorjev [1].

Pri preračunu primera P33-1 je bila upoštevana plastifikacija materiala.

3.4 Spremenljive obremenitve nosilnega okvira

Ta obremenitvena stanja so dobljena iz izkustvenih dejavnikov, ki so določeni na podlagi analize realnih kolesnih obremenitev cestnih osebnih vozil [1]. Z izkustvenimi dejavniki sta tako določeni dve obremenitveni stanji, ki podajata spodnjo (PIF1) in zgornjo (PIF2) obremenitev nosilnega okvira, kar omogoča prikaz in vrednotenje dinamike napetostnega stanja. Za boljše predstavitev rezultatov je dinamika napetostnega stanja najbolj obremenjenih

3.2 Extreme quasi-static regimes of driving

Under quasi-static driving conditions belong all those load cases where the acceleration field is held constant (speeding up or braking and simultaneous driving through a curve with different speeds).

Strength calculations were made for several load cases, which were defined with a simulation on the rigid model of the vehicle [2]. Here we present results for load cases which result in maximum stresses in the structure.

3.3 Dynamic driving regimes

Dynamic driving regimes are made up of large and jerky loads caused by driving over an uneven point on the road. The effects of these loads are very transitory, their influence drops with distance from the point of contact of the wheel with the driving surface. The presented results are calculated on the basis of loads that were defined with empirical factors [1].

Plastic material properties were considered in the calculation of case P33-1

3.4 Variable loads of vehicle tube frame

The dynamic loads of vehicle's tube frame were defined with the help of empirical factors. These factors are calculated through the analysis of real loads on the wheels [1]. Two load cases were defined. Load case P34-1 represents the lowest variable load and load case P34-2 represents the highest variable load on the vehicle's tube frame. Results of these load cases represent dynamic stress distributions of the vehicle's tube frame. With the aim of

Preglednica 2. Vhodni podatki za napetostni preračun pri izjemnih navidezno statičnih režimih vožnje
Table 2. Data for stress calculation at the extreme quasi-static regimes of driving

Primer Case	a_x m/s ²	a_y m/s ²	a_z m/s ²	$k_{p,x,1}$ N/mm	$k_{p,x,2}$ N/mm	$k_{p,x,3}$ N/mm	$k_{p,x,4}$ N/mm	$k_{p,y,1}$ N/mm	$k_{p,y,2}$ N/mm	$k_{p,y,3}$ N/mm	$k_{p,y,4}$ N/mm	k_p N/mm
P32-1	-6,73	6,79	11,47	143,8	82,1	133,5	60,6	143,8	82,1	133,5	60,6	105
P32-2	6,12	3,53	9,81	0,4	0,4	159,9	111,9	92,6	55,6	159,9	111,9	105

P32-1 - primer zaviranja/case of braking; $R = 200\text{m}$; $v = 153\text{ km/h}$; $\mu_H = 0,587$; $\mu_S = 0,592$

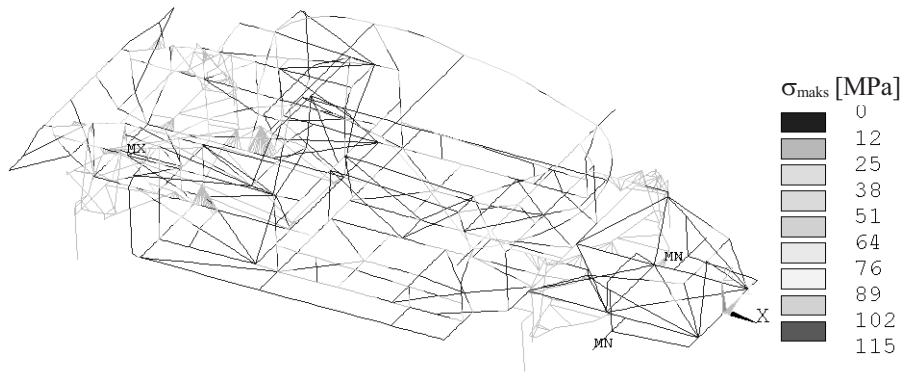
P32-1 - primer pospeševanja/case of speeding up; $R = 200\text{m}$; $v = 93\text{ km/h}$; $\mu_H = 0,961$; $\mu_S = 0,36$

Preglednica 3. Vhodni podatki za napetostni preračun pri dinamičnih režimih vožnje
Table 3. Data for stress calculation at dynamic regimes of driving

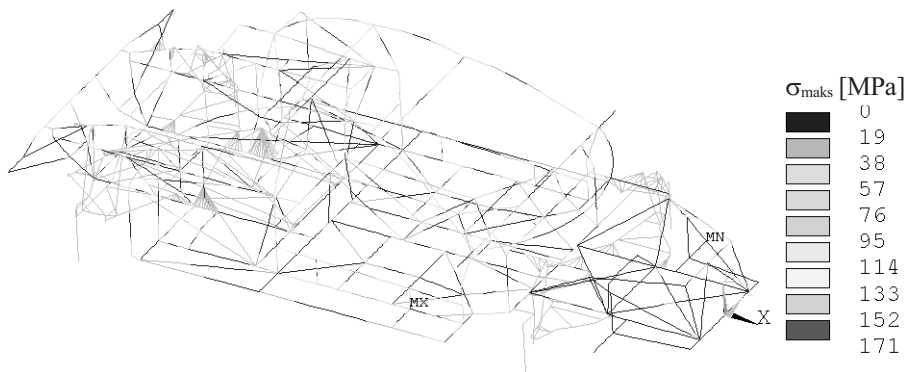
Primer Case	a_x m/s ²	a_y m/s ²	a_z m/s ²	$k_{p,x,1}$ N/mm	$k_{p,x,2}$ N/mm	$k_{p,x,3}$ N/mm	$k_{p,x,4}$ N/mm	$k_{p,y,1}$ N/mm	$k_{p,y,2}$ N/mm	$k_{p,y,3}$ N/mm	$k_{p,y,4}$ N/mm	k_p N/mm
P33-1	1,70	$\pm 1,40$	28,0	0,4	0,4	137,7	130,7	76,5	75,2	137,7	130,7	105
P33-2	3,67	$\pm 3,70$	18,1	0,4	0,4	153,0	146,0	61,1	59,9	153,0	146,0	105

P33-1 - vožnja prek ovire s prednjimi in zadnjimi kolesi; driving over an uneven point with front and rear wheels

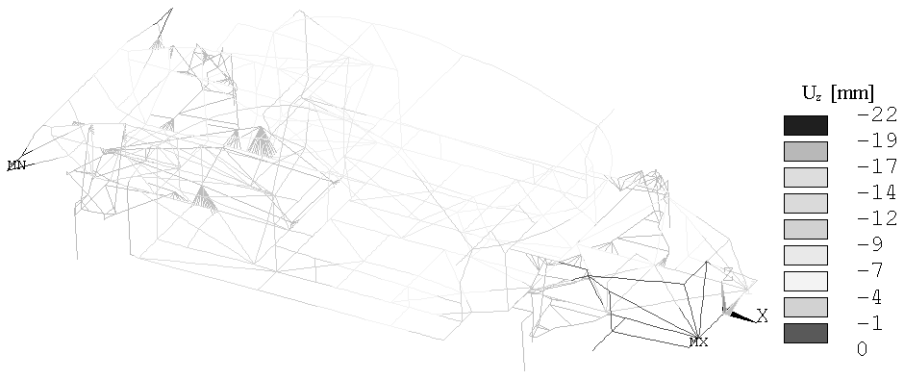
P33-2 - vožnja po jamasti cesti; driving on the rough road



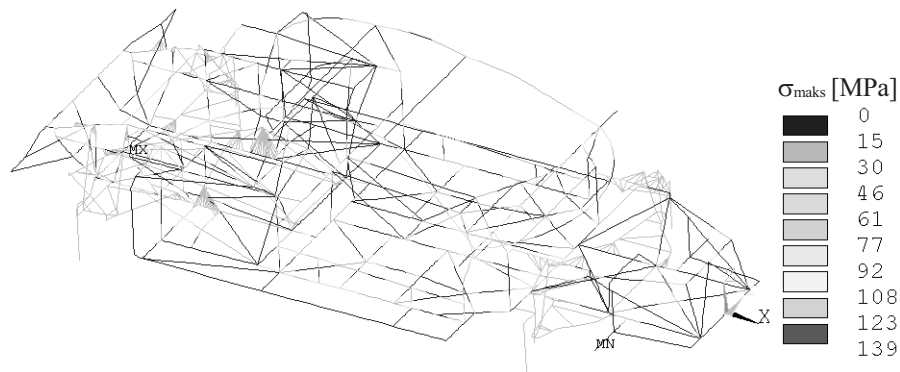
Sl. 5. Potek največjih napetosti v nosilnem okviru za primer P31-1
Fig. 5. Maximum stress distribution in elements of vehicle's tube frame - case P31-1



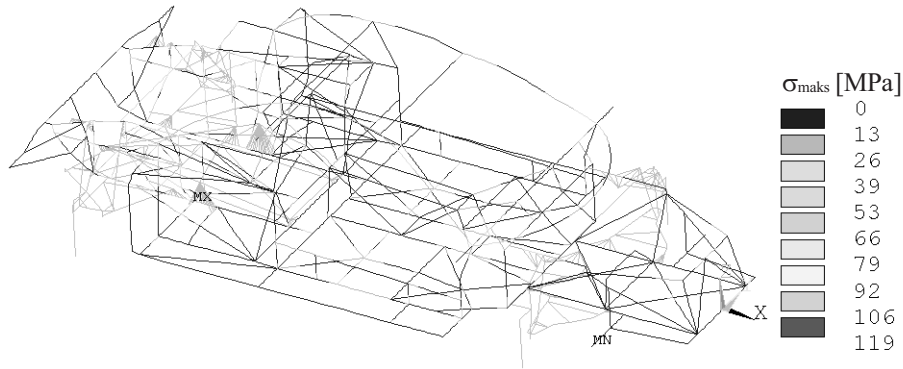
Sl. 7. Potek največjih napetosti v nosilnem okviru za primer P31-2
Fig. 7. Maximum stress distribution in elements of vehicle's tube frame - case P31-2



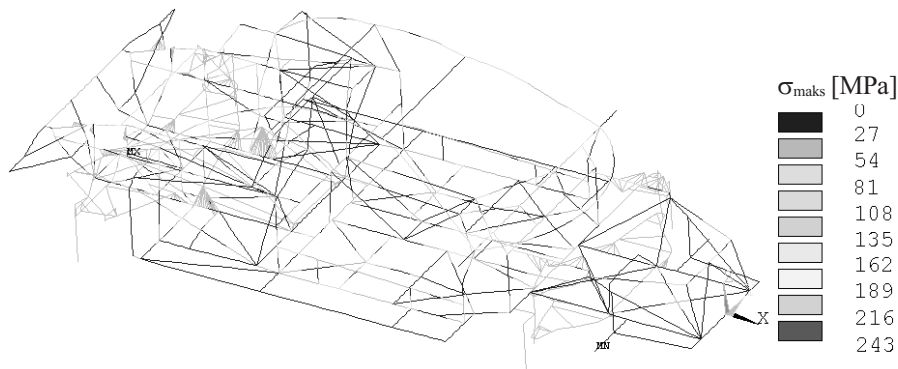
Sl. 8. Deformacije nosilnega okvira v smeri koordinate z (P31-2)
Fig. 8. Deformation of vehicle's tube frame in z direction - case P31-2



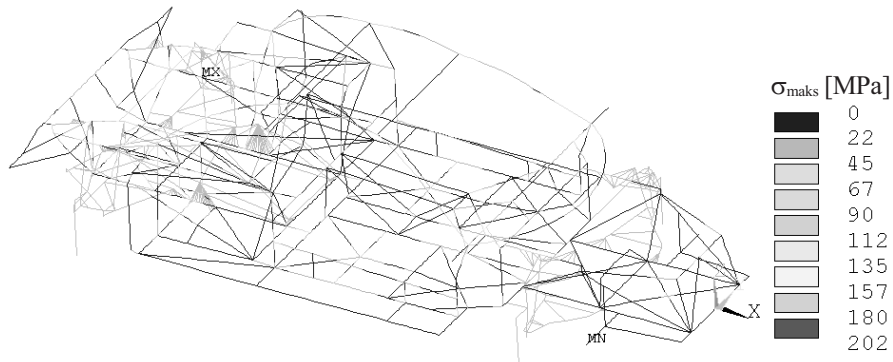
Sl. 9. Potek največjih napetosti v nosilnem okviru za primer P32-1
Fig. 9. Maximum stress distribution in elements of vehicle's tube frame - case P32-1



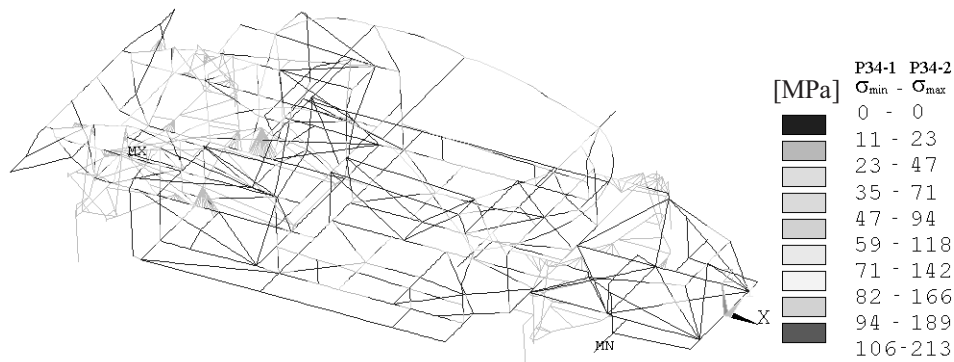
Sl. 10. Potek največjih napetosti v nosilnem okviru za primer P32-2
 Fig. 10. Maximum stress distribution in elements of vehicle's tube frame - case P32-2



Sl. 11. Potek največjih napetosti v nosilnem okviru za primer P33-1
 Fig. 11. Maximum stress distribution in elements of vehicle's tube frame - case P33-1



Sl. 12. Potek največjih napetosti v nosilnem okviru za primer P33-2
 Fig. 12. Maximum stress distribution in elements of vehicle's tube frame - case P33-2



Sl. 13. Potek največjih napetosti v nosilnem okviru za primer P34-1 in P34-2
 Fig. 13. Maximum stress distribution in elements of vehicle's tube frame - cases P34-1 and P34-2

cevi zraven slik s poteki napetosti prikazana še v Smithovem diagramu (sl.15).

V našem primeru trdnostni preračun podaja potek imenskih napetosti, pri čemer je predpostavljeno, da je napetost v primeru tlaka, natega in striga enakomerno porazdeljena po prerezu, v primeru upogiba pa linearno. V resnici je stanje večinoma povsem drugačno. V primeru, da so na površini opazne zarezne (hrapavost površine, utori, zarezne zaradi varjenja), prihaja v njihovi bližini do velikega lokalnega povečanja napetosti (zarezni učinek); kar pa se dogaja zaradi zarez, nastalih pri varjenju tudi v primeru obravnavanega nosilnega okvira.

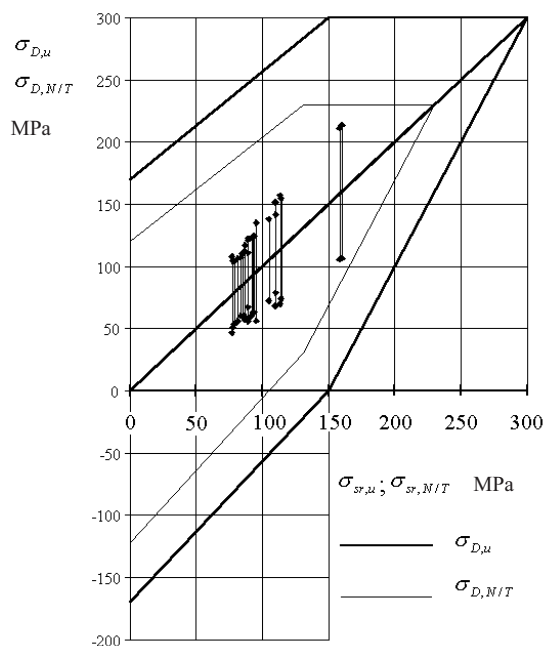
improving presentation of the results, the dynamic stress of the most critical elements are presented in a Smith diagram in Fig. 15 beside the picture of the stress distribution.

The results of strength calculations present in our case, only nominal stress. This means that compression, tensile and shear stresses are approximately constantly distributed and the distribution of bending stress is approximately linear through the transverse section of beam, which is not true for real cases. Initial cracks always exist on the surface, which results in local stress concentrations. In our case there exist a lot of small cracks because of the welding process.

Preglednica 4. Vhodni podatki za napetostni preračun pri spremenljivih obremenitvah

Table 4. Data for stress calculation at variable conditions of driving

Primer Case	a_x m/s ²	a_y m/s ²	a_z m/s ²	$k_{p,x,1}$ N/mm	$k_{p,x,2}$ N/mm	$k_{p,x,3}$ N/mm	$k_{p,x,4}$ N/mm	$k_{p,y,1}$ N/mm	$k_{p,y,2}$ N/mm	$k_{p,y,3}$ N/mm	$k_{p,y,4}$ N/mm	k_p N/mm
P34-1	1,73	±1,40	9,81	0,4	0,4	132,8	110,3	96,5	80,4	132,8	110,3	105
P43-2	1,73	±1,40	18,1	0,4	0,4	153,0	146,0	61,1	59,9	153,0	146,0	105



Sl. 15. Diagram dinamične trdnosti z vrisanimi dinamičnimi napetostmi najbolj obremenjenih cevi

Fig. 15. Diagram of dynamic strength with dynamic stress values in critical spots of the structure

5 SKLEP

Trdnostni preračun nosilnega okvira je bil izveden z metodo končnih elementov. Za preračun je bil zgrajen model vozila po MKE, ki je z linijskimi elementi popisal lastnosti nosilnega okvira. Vnos obremenitvenega stanja je bil izveden prek polja pospeškov, zato je na modelu prek masnih točk modelirana tudi masa posameznih komponent vozila. Vpetje modela po MKE na okolico je izvedeno prek

5 CONCLUSION

Strength calculation of the vehicle's tube frame was made with the finite element method. For the purpose of calculation a FEM model of the vehicle was made. It was built of beam elements with proper cross sections and inertia moments. To this FEM model, mass points were added which substitute for the masses of vehicle components, suspension elements and flexible restraints which simulate

modeliranega podvozja vozila. Polje pospeškov je bilo določeno na podlagi mejnih kolesnih obremenitev za različne režime vožnje. Takšen model omogoča popis dejanskih razmer med vožnjo.

Uporabljen model po MKE pri preračunu ne upošteva zarezni učinkov zvarov ter vplivov oblike cevni spojev, zato dobljeni rezultati prikazujejo potek imenskih napetosti, kar je treba pri vrednotenju rezultatov upoštevati.

Iz dobljenih rezultatov je razvidno, da je nosilna konstrukcija v temelju dovolj trdna, toda na nekaterih ceveh prihaja v določenih režimih obratovanja do preobremenitve. Vzrok velikih napetosti v kritičnih ceveh je v neugodni postavitvi teh cevi, zaradi česar morajo prenašati velike upogibne obremenitve. Iz teh ugotovitev izhaja, da bi bilo za odpravo teh kritičnih mest treba narediti na nosilnem okviru manjše popravke.

a contact of the wheels with the driving surface. This was required to establish loads through the acceleration field. The acceleration field was determined from the extreme loads on the wheels for different driving conditions. The load state, defined in this manner, was very close to reality.

The applied FEM model did not consider the stress concentration that occurs due to welding processes and the shape of the tube joints. So calculated results present only a nominal stress distribution which has to be considered when evaluating the results.

It is evident from the results that the load carrying capacity of the vehicle's tube structure is generally adequate but in some load cases results in stresses that are too large. The reason for this overloading in critical tubes are the large bending stresses because of the disadvantageous positioning of these tubes. From these statements it follows that the existing vehicle frame should be modified in critical areas.

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Prejeto: 15.10.1999
Received:

Sprejeto: 3.12.1999
Accepted: