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Analiza trdnosti nizkopodnega avtobusa za mestni promet

Strength Analysis of Low-Floor City Bus

CSABA MOLNÁR

Pri snovanju in konstruiranju nizkopodnega avtobusa za potrebe mestnega prometa se srečujemo s posebnimi razmerami in problemi, ki jih lahko na kratko opišemo takole:
- majhna oddaljenost podvozja od cestišča,
- poudarjena povečana nosilnost zgornjega dela nadgradnje - strehe,
- posebnost vgradnje sklopov prenosa moči (pogonski motor, gredi ipd.).

Pri načrtovanju nove nadgradnje nizkopodnega avtobusa je torej treba preveriti napetostno stanje konstrukcije, uporabiti dovolj zanesljivih robnih pogojev, ki jih zagotavlja eksperimentalno delo v laboratoriju, ne nazadnje pa je treba prototip vozila izdatno preveriti tudi v praksi.

V članku so prikazani rezultati izračunov napetosti z uporabo MKE in rezultati analize statičnih obremenitev nadgradnje avtobusa v laboratorijskih razmerah. Podrobno so opisani pogoji preizkušanja, vrednotenje rezultatov, nazorno je prikazana primerjava med izračunanimi in izmerjenimi rezultati. Namen pričujočega članka je predvsem prikaz metode, ki je uporabljiva za primerjavo podatkov posameznih avtobusov različnih izvedb, različnih družin. Članek je uporaben tudi za tehnično predstavitev nove družine sodobnih mestnih avtobusov.

(Ključne besede: avtobusi mestni, avtobusi nizkopodni, analize napetosti, metoda končnih elementov)

Concerning design of low-floor city bus framework some special problems have to be faced:
- underframe having small structural height,
- roof structure with increased load-bearing capability,
- installation of main units (engine, axles).

In order to be able to form the adequate framework for a low-floor city bus some strength calculations, static and fatigue laboratory tests, furthermore on-road tests are needed during the design process.

Present paper deals with the finite element strength calculations and static tests carried out in the course of development process. The test conditions, evaluation of available results, comparison of computed and measured values will be discussed in detail. Our main aim was to develop a method, which can be used for comparing the single bus types or type versions, and in this way to promote the development process of a new bus structure.

(Keywords: city buses, low-floor buses, strength analysis, finite element method)

0 UVOD

Pri snovanju okvira novega nizkopodnega avtobusa za mestni promet so se pojavili posebni problemi trdnosti. Da bi poiskali pravilno rešitev nosilne konstrukcije, smo opravili nekatere trdnostne preračune in statične meritve.

Namen teh "laboratorijskih" del je bil na eni strani podpirati konstrukcijski postopek, na drugi pa izdelati enotna načela, ki bodo uporabna v prihodnje pri podobnih nalogah, kakot tudi za primerjavo različnih izvedb v našem podjetju.

Zaradi omenjenih enotnih načel preračunov in meritev, bomo obe razvojni stopnji opisali v tem prispevku, glede na modele okvirov, obremenilne parametre in ocenjevalne postopke dobljenih izsledkov.

0 INTRODUCTION

Establishing the framework of the new low-floor city bus some special strength próblems have arisen. To find the correct solution of the load-bearing structure some strength calculations and static measurements have been carried out.

The aim of these "laboratory" works was to promote the design process on one hand and to work out uniform principles on the other hand, which can be used in the future for similar tasks and comparing the different type versions in our company.

Because the uniform principles mentioned above relate to both calculations and measurements, therefore these two development stages will be discussed below with regard to framework models, loading parameters and assessment methods of results obtained.

Sl. 1. *IK 411 nizkopodni avtobus za mestni promet*
Fig. 1. *IK 411 low-floor city bus*

1 GRADNJA RAČUNSKIH IN MERILNIH MODELOV

Obravnavamo osnovne vidike:
- oblikovanje konstrukcije,
- podpiranje konstrukcij,
- obremenilne primere.

V vsakem primeru so poimenovana osnovna načela ter obravnavane posebnosti računskega modela in preskusnega okvira.

1.1 Oblikovanje konstrukcije

Tako pri preračunskih kakor pri preskusnih modelih smo uporabili naslednja načela:

- upoštevati je treba tiste konstrukcijske elemente, ki so pomembni z vidika splošne obremenljivosti;
- upoštevati je treba samo nosilne pločevine, medtem ko prekrivne pločevine lahko zanemarimo;
- uporabi sorazmerno kratkih nosilcev se v računskem modelu izognemo, saj tehnična teorija nosilcev v teh primerih ne daje ustreznih rezultatov.

Na podlagi omenjenih podmen nastaja samo ena bistvena razlika med obema modeloma: niti računski model in tudi ne osnovni preskusni model ne vsebujeta okenskih stekel, ki pa jih lahko vgradimo na različnih merilnih stopnjah, tako da je omogočena raziskava vpliva okenskih stekel. Slika 2 podaja testni okvir nizkopodnega avtobusa mestnega prometa.

1 BUILDING UP THE MODELS FOR COMPUTATIONS AND MEASUREMENTS

Three tundamental viewpoints will be discussed:
- structural formation,
- support of structures,
- load cases.

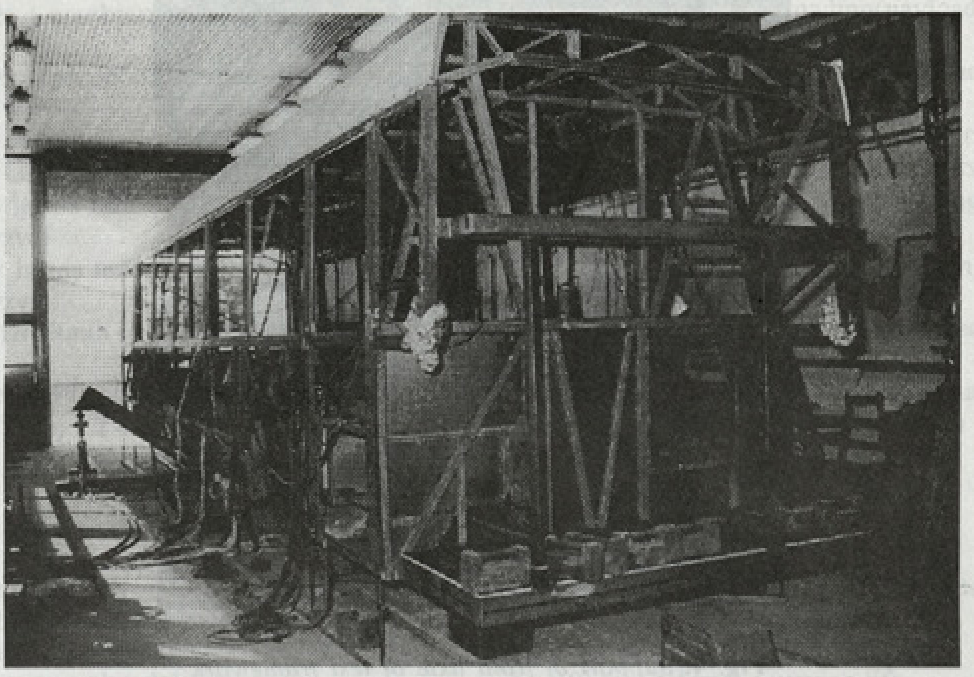
In each case the general principles have been worded and then the special features for both computation model and test framework model will be mentioned.

1.1 Structural formation

The following principles were applied to both computation and test models:

- those structural elements should be taken into consideration , which are deemed to be important from the viewpoint of the general load-bearing capability;
- only the load-bearing plating should be taken into account, thus the effect of covering plates, casing is neglected;
- application of relative short beams in the calculation model should be avoided, because the technical beam theory does not give adequate results for these cases.

On the basis of assumptions mentioned above only one major difference can be observed with regard to the two models: although neither the computation model, nor the basic test model contains the window glasses, they can be installed for the different stages of the measurements; in this way the examination of the effect of window glasses can be made possible. Figure 2 shows the test framework of the low-floor city bus.



Sl. 2. *Testni okvir nizkopodnega avtobusa mestnega prometa*
Fig. 2. *Test framework of low-floor city bus*

1.2 Podpiranje konstrukcije

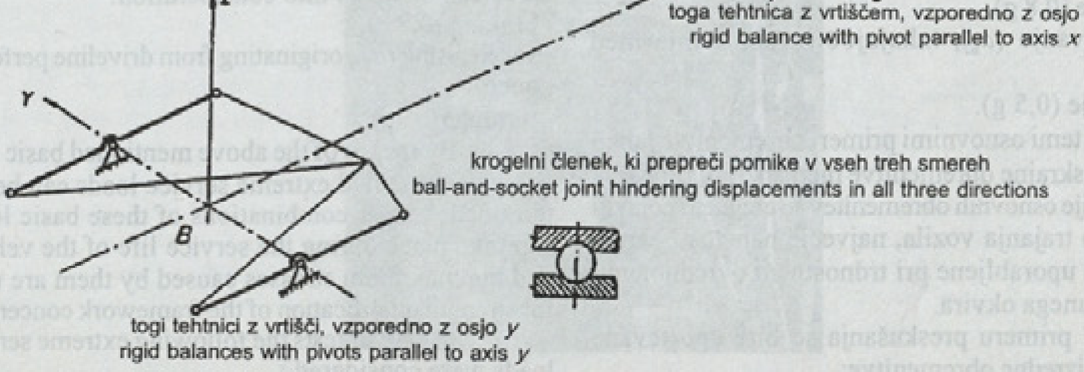
Podporje nosilne konstrukcije je bilo izvedeno tako, da čimbolje ustreza rešitvi, ki je bila uporabljena pri preračunih. Glavno načelo je bilo, da se izognemo pomikom togega telesa konstrukcije, ker v teh primerih ne pride niti do deformacij niti do napetosti.

Po izračunanih rezultatih smo oblikovali podpiranje konstrukcije za statične meritve (sl.3). Podprtje v obliki tehtnice deluje na obe premi z nivojskimi izravnalnimi ventili.

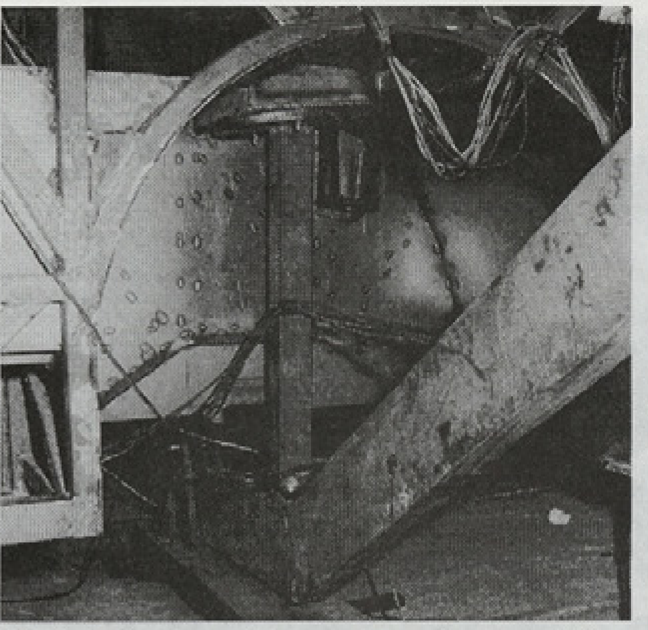
1.2 Support of structure

Support of the load-carrying structure was created so, that it should correspond to the solution used in calculations as much as possible. The main principle was to avoid the rigid body like displacements of the structure, because neither deformation, nor stress can result from those.

On the basis of the computed results we have designed the support of the structure for the static measurements (Fig.3). A balance type support was applied at both axles due to the air suspension levelling valves.



Sl. 3. *Podprtje preskusnega okvira*
Fig. 3. *Support of test framework*



Sl. 4. *Podprtje prednje preme preskusnega okvira*
Fig. 4. *Support of front axle of test framework*

Taka vrsta podpiranja preprečuje pomike zadnje preme v vseh treh smereh, omogoča pa pomik R = 20 mm prednje preme v ravnini xy. Na tak način se lahko izognemo neželenim obremenitvam v podpornih točkah. Izvedena oblika pri prednji premi je vidna na sliki 4.

1.3 Primeri obremenitve

Uporabljeni so bili trije osnovni primeri obremenitve obeh modelov:
- prazna (neobremenjena) teža,
- imenska obremenitev,
- vzvoj (izvedena z dvojico sil na tehtnici).

Prva dva primera obremenitve sta določljiva iz podatkov o masi avtobusa, vzvoj pa ustreza dvigu "h" koles prednje preme, ki ima lahko dve vrednosti:
- h = 100 mm pri imenskem vzvoju,
- h = 200 mm pri ekstremnem vzvoju.

Pri izračunih so lahko upoštevani trije osnovni primeri obremenjevanja:
- zaviranje (0,8 g),
- pospeševanje (a_{gy}, izhajajoč iz obnašanja med vožnjo),
- obračanje (0,5 g).

S temi osnovnimi primeri obremenitve lahko določimo skrajne obremenitve med vožnjo. Linearne kombinacije osnovnih obremenitev se utegnejo pojaviti med dobo trajanja vozila, največje napetosti zaradi njih pa so uporabljene pri trdnostnem ovrednotenju obravnavanega okvira.

V primeru preskušanja so bile upoštevane naslednje izredne obremenitve:
1. lastna teža + ekstremni vzvoj
2. lastna teža - ekstremni vzvoj

This kind of support prevents displacements in all the three directions at the rear axle, however it makes a displacement of R = 20 mm possible in plane xy at the front axle. In this way it is possible to avoid the undesirable loads at the supporting points. The realized layout for the front axle can be seen in Figure 4.

1.3 Load cases

Three basic load cases were applied to both models:
- empty (unladen) weight,
- nominal payload,
- torsion (realized by a couple through the balance).

The first two load cases can be determined from the mass data of the bus and the torsion corresponds to a wheel lifting of "h" at the front axle, which can have two different values:
- h = 100 mm for nominal torsion,
- h = 200 mm for extreme torsion.

In case of calculations three more basic load cases can be taken into consideration:
- braking (0.8 g),
- accelerating (a_{gy}, originating from driveline performance),
- turning (0.5 g).

By means of the above mentioned basic load cases the so called extreme service loads can be determined. Linear combinations of these basic loads can take place during the service life of the vehicle and the maximum stresses caused by them are used for strength qualification of the framework concerned.

In case of tests the following extreme service loads were considered :
1. empty weight + extreme torsion
2. empty weight - extreme torsion

3. lastna teža + preobremenitev (tovor) + ekstremni vzvoj
4. lastna teža + preobremenitev (tovor) - ekstremni vzvoj
5. $(1 + \beta) \times$ lastna teža + imenski vzvoj
6. $(1 + \beta) \times$ lastna teža - imenski vzvoj
7. $(1 + \beta) \times$ lastna teža + preobremenitev (tovor) + imenski vzvoj
8. $(1 + \beta) \times$ lastna teža + preobremenitev (tovor) - imenski vzvoj.

Pri izračunih so bili uporabljeni še naslednji podatki:

- preobremenitev (tovor) = 1,25 × imenski tovor
- ekstremni vzvoj = 2 × imenski vzvoj

3. empty weight + overloading(payload) + extreme torsion
4. empty weight + overloading(payload) - extreme torsion
5. $(1 + \beta) \times$ empty weight + nominal torsion
6. $(1 + \beta) \times$ empty weight - nominal torsion
7. $(1 + \beta) \times$ empty weight + overloading(payload) + nominal torsion
8. $(1 + \beta) \times$ empty weight + overloading(payload) - nominal torsion.

The following data are still needed for computations:

- overloading (payload) = 1.25 × nominal payload
- extreme torsion = 2 × nominal torsion

$$\beta = \sqrt{\frac{V_N}{V_O}} \lg \frac{t_u}{t_o} = \sqrt{\frac{63}{80}} \lg 5 = 0,62 \qquad (1),$$

kjer so:
V_N - dovoljena hitrost vožnje,
V_o = 80 km/h, primerjalna hitrost,
t_u - načrtovana doba trajanja,
t_o - 10^5 km, primerjalna doba trajanja.

Pri uporabi postopka končnih elementov lahko izvedemo tudi druge kombinacije obremenitev ob upoštevanju načinov zaviranja, pospeševanja in prevračanja. Ker te obratovalne obremenitve ne morejo biti ustvarjene v laboratorijskih razmerah, so bile prej omenjene kombinacije obremenitev uporabljene za primerjavo izračunanih in izmerjenih rezultatov.

V računalniškem modelu so obremenitve delovale na konstrukcijo kot koncentrirane sile z uporabo t.i. obremenilnih piramid. Togostne lastnosti teh dodatnih naprav so bile izbrane tako, da praktično ne spremene izvirnih pogojev togosti.

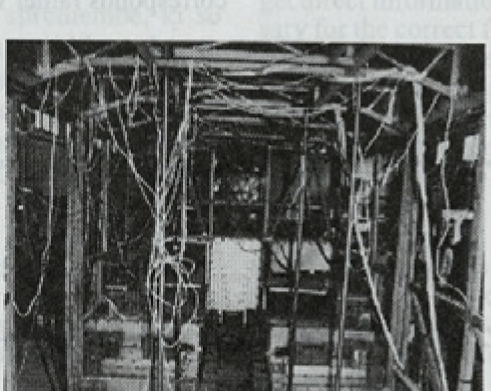
Pri statičnih meritvah smo uporabili uteži 25 kg za ponazoritev osnovnih obremenitvenih primerov v skladu z bremeni, uporabljenimi v preračunih. Kot ponazoritev prikazuje slika 5 porazdelitev mas v primeru lastne teže.

where:
V_N - velocity permissible by the driveline,
V_o = 80 km/h, reference velocity,
t_u - planned service life,
t_o - 10^5 km, reference service life.

In case of finite element analysis some other load combinations can be created considering operation modes of braking, accelerating and turning. Because these service loads can not be realized under laboratory conditions thus the abovementioned load combinations were used for comparing computed and measured results.

Concerning the computational model the loads were acting on the structure as concentrated forces by means of so called loading pyramids. The stiffness features of these supplemental structures were chosen so that they should not change the original stiffness conditions from practical point of view.

In case of static measurements we have used weights of 25 kg for realizing the basic load cases in correspondance with those used in calculations. As an illustration Figure 5 shows the mass distribution in case of empty weight.



Sl. 5. *Porazdelitev mas pri lastni (nenaloženi) teži*
Fig. 5. *Mass distribution for empty (unladen) weight*

2 OCENITEV DOBLJENIH REZULTATOV

Največja med napetostmi zaradi osmih izrednih delovnih obremenitev je rabila za oceno ustreznega okvira. T.i. količnik učinkovitosti gradiva je bil uveden pri vrednotenju konstrukcije avtobusa:

2 ASSESSMENT OF RESULTS OBTAINED

The maximum stress from among the stresses caused by the eight extreme service loads was used for qualification of the relevant framework. The so called material efficiency coefficient was introduced for checking the bus structure:

$$\omega_{ex} = \frac{n_{ex,o}}{n_{act}} = \frac{R_{eH} \cdot n_{ex,o}}{\sigma_{red}} \quad (2),$$

kjer so:
$n_{ex,o}$ - predpisani varnostni količnik,
R_{eH} - napetost tečenja,
σ_{red} - največja relativna ekstremna napetost, izračunana iz izmerjene deformacije.

V odvisnosti od vrednost količnika ω lahko dele konstrukcije avtobusa zvrstimo v naslednje skupine:

- $\omega \leq 1$ del ustreza in vrednost ω podaja stopnjo izkoriščenosti gradiva,
- $1 < \omega \leq n_{ex,o}$ ekstremna napetost ne preseže točke tečenja, toda predpisana raven varnosti ni zagotovljena,
- $\omega > n_{ex,o}$ ekstremna napetost presega točko tečenja, zato pride do lokalnih trajnih deformacij; potrebne so nekatere konstrukcijske spremembe.

Postopek razvrstitve delov konstrukcije opravi računalniški program, ki poišče največje vrednosti napetosti ter določi ustrezen količnik učinkovitosti gradiva.

where:
$n_{ex,o}$ - prescribed safety factor,
R_{eH} - yield stress,
σ_{red} - maximum reduced extreme stress (calculated and measured).

Depending on the value of ω coefficient the elements of the bus structure can be classified by grouping them as follows:

- $\omega \leq 1$ the element is appropriate and the value of ω gives the degree of using up material,
- $1 < \omega \leq n_{ex,o}$ the extreme stress does not exceed the yield stress yet, but the prescribed safety level is not ensured,
- $\omega > n_{ex,o}$ the extreme stress exceeds the yield stress, thus local permanent deformation must be reckoned with; some structural modifications are necessary.

Procedure of classifying the structural elements is done by a computer program, which chooses the maximum stress value and determines the appropriate material efficiency coefficient.

3 NEKAJ PRIMEROV PRIMERJAVE IZRAČUNANIH IN IZMERJENIH REZULTATOV

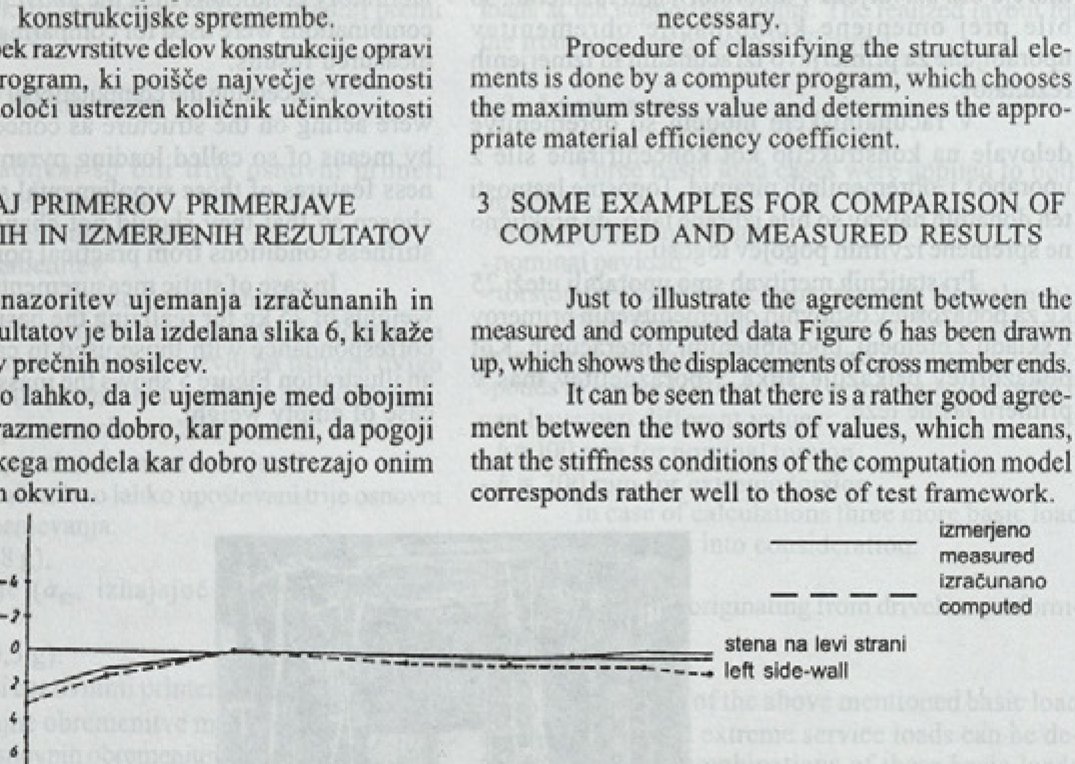
Za ponazoritev ujemanja izračunanih in izmerjenih rezultatov je bila izdelana slika 6, ki kaže pomike koncev prečnih nosilcev.

Vidimo lahko, da je ujemanje med obojimi vrednostmi sorazmerno dobro, kar pomeni, da pogoji togosti računskega modela kar dobro ustrezajo onim pri preskusnem okviru.

3 SOME EXAMPLES FOR COMPARISON OF COMPUTED AND MEASURED RESULTS

Just to illustrate the agreement between the measured and computed data Figure 6 has been drawn up, which shows the displacements of cross member ends.

It can be seen that there is a rather good agreement between the two sorts of values, which means, that the stiffness conditions of the computation model corresponds rather well to those of test framework.



Sl. 6. *Primerjava izračunanih in izmerjenih rezultatov pomikov koncev prečnih nosilcev*
Fig. 6. *Comparison of computed and measured results concerning diplacements of cross member ends*

Preglednica 1. *Vzvojna togost okvira*
Table 1.

preskusna stopnja test stage	brez stekel without glazing		s stekli with glazing	
vrsta okvira framework type	izračunano computed	izmerjeno measured	izračunano computed	izmerjeno measured
preskusni avtobus test bus	7,3	4,7	-	6,6
prototip prototype	-	5,4	-	7,3 *

* ocenjena vrednost
estimated value

Prav tako dobra primerjalna ponazoritev izmerjenih in izračunanih rezultatov je vzvojna togost v preglednici 1.

Ugotovimo lahko, da osteklitev poveča vzvojno togost za 40 odstotkov pri izmerjenih rezultatih. Toda izračunana vrednost togosti je bistveno večja od izmerjene (~ 55 %). Ta pojav lahko pojasnimo z vzrokoma:
- model končnih elementov je vedno bolj tog od izvirne konstrukcije, kar izhaja iz samega postopka;
- talne plošče so bile v računskem modelu povezane s spodnjim okvirom, medtem ko v preskusnem modelu ni bilo povezave, kar predvsem vpliva na vzvojno togost.

4 SKLEP

Pri oceni trdnosti okvira avtobusa smo predvsem podali podmene, poenostavitve in načela, ki so lahko pomembni z vidika ponovljivosti izračunov in merilnih postopkov. Ti postopki pomagajo primerjati različne različice avtobusnih konstrukcij.

Sorazmerno zelo lahko je izbrati nekaj preprostih obremenilnih primerov, s katerimi lahko določimo veliko število izrednih obratovalnih obremenitev, ki jih imamo predvsem za pomembne z vidika dobe trajanja vozila.

Kot izsledek naših trdnostnih ocen lahko dobimo neposredne napotke za spremembe, ki so potrebne pri oblikovanju okvira z vidika trdnosti. Poudariti želimo, da so pri oblikovalnem postopku nove konstrukcije avtobusa potrebni trdnostni računski pa tudi merilni rezultati pri pravilnem in natančnem konstrukterskem delu.

Another good illustration for comparison of measured and computed results is the torsional stiffness of the framework (Table 1).

It can be concluded that the glazing increases the torsion stiffness by 40 % in the case of test results. However the computed stiffness value is considerably bigger than the measured one (~ 55 %). This phenomenon can be explained by two facts below:
- a finite element model is always stiffer than the original structure, which comes from the method itself;
- the floor panels were connected to the underframe in the computation model, however there was no connection between them in the test model, which affects the torsional stiffness above all.

4 SUMMARY

Concerning the strength analysis of a bus framework our main aim was to lay down all the assumptions, simplifications and principles which can be important from the viewpoint of reproducibility of calculation and measurement procedures. These procedures help us to be able to compare the different versions of bus structures.

It is rather easy to define some simple load cases, by means of which a great number of extreme service loads can be determined, which are considered primarily important from the viewpoint of service life of vehicle.

As a result of our strength analyses we can get direct information about the modifications necessary for the correct formation of the framework from strength point of view. We would like to emphasize that during the design process of a new bus structure the results of both strength calculations and measurements are needed for the correct and accurate design work.

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