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Razvoj šolskega avtobusa z vidika zagotavljanja pasivne varnosti Development of School Bus from the Passive Protection Point of View

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Z ustreznimi programskimi orodji in raziskavami različnih numeričnih modelov smo izdelali zanesljiv numerični model ogrodja vozila, primerenega za analizo oziroma simuliranje testa varnosti potnikov pri prevračanju z metodo končnih elementov. Rezultate analize, preverjene z modelnimi preizkusmi, smo uporabili pri konstrukciji ogrodja. Celotni proces razvoja, podprt z računalniško podprtoto tehnologijo in preizkušanji, je občutno znižal stroške razvoja, predvsem pa v veliki meri vplival na skrajšanje časa razvoja primerne konstrukcije.

Proces je potekal v več fazah. V prvi fazi smo razvili numerični model, s katerim smo dovolj dobro simulirali razmere, ki se pojavljajo pri dejanskem testu varnosti potnikov pri prevračanju. Numerični model smo potrdili z modelnim preizkusom. Tako numerični kakor eksperimentalni rezultati so pokazali neprimerno nosilnost konstrukcije. Specifične projektantske zahteve, utemeljene predvsem s povsem novo kakovostjo potniškega prostora v primerjavi s šolskimi avtobusi v ZDA, so pomenile občutne omejitve pri sprememjanju osnovne konstrukcijske zamisli. Poseben problem so bili razpoložljivi materiali. Navedenim težavam navkljub nam je uspelo s primernimi konstrukcijskimi rešitvami, ki so bile potrjene z numeričnimi postopki in modelnimi preizkusmi, zagotoviti primerno vozilo, ki je zelo uspešno prestalo test varnosti potnikov pri prevračanju, izveden v ZDA.

By using adequate software tools and carrying out research on diverse numerical models, a reliable numerical model of a bus framework, suitable for Finite Element Method analysis and/or simulation of the rollover test, was built. The analysis results achieved, subsequently confirmed with real test models, were used for framework design. By applying computer-aided technology and conducting tests, development costs were considerably reduced and the time required for developing an adequate design shortened.

The process was carried out in several stages. In the first, we developed a numerical model for simulating conditions occurring during the actual rollover test. The said model was confirmed with a real test model. All results, numerical and experimental, showed an unsatisfactory carrying capacity of the framework. Performance specifications primarily based on a completely new quality of passenger compartment, if compared to the existing school fleet in the United States, substantially limited modifications of the basic design version. Available materials created another problem. By applying appropriate design solutions confirmed with numerical procedures and a test model, however, we managed despite all the difficulties to provide an adequate vehicle that successfully stood the rollover test conducted in the United States.

0. UVOD

Ameriško tržišče, znano po izredno strogih zahtevah glede kakovosti izdelkov, je na področju zagotavljanja pasivne varnosti potnikov gotovo eno najzahtevnejših svetovnih tržišč. Trditev še posebej velja za avtobuse, namenjene prevozu šolarjev. V prispevku prikazujemo razvoj konstrukcije avtobusa TAM 232 A121 predvsem z vidika zahtev standarda FMVSS 571.220, ki obravnava preizkušanje vozila na varnost pri prevračanju. Da bi lahko zagotovili primernost konstrukcije, smo uporabili sodobne numerične postopke, podkrepljene z modelnimi eksperimenti. V članku je pokazano, kako uporaba sodobnih računalniških postopkov v fazi konstruiranja vozila, MCAE (Mechanical Computer Aided Engineering), vpliva na hitrejši in bolj premišljen razvoj končnega izdelka.

0. INTRODUCTION

The American market, extremely demanding as far as product quality is concerned, sets very high standards of passenger passive protection. It is especially true for buses designed for the transport of school children. This paper shows the development TAM 232 A121 bus design, especially from the point of view of the FMVSS 571.220 Standard dealing with vehicle rollover protection. With a view to ensuring an adequate design, modern numerical procedures supported with model experiments were applied. The paper shows how intensive application of modern computer procedures, such as MCAE (Mechanical - Computer Aided Engineering) means that vehicle engineering development of a final product is faster and more economical.

Standard FMVSS 571.220 opisuje potek preizkusa pasivne varnosti avtobusa za prevoz šolarjev v primeru prevrnutve vozila, ki ga mora opraviti vsak izdelovalec tovrstnih vozil, preden se lahko pojavi na ameriškem tržišču. Gre za razmeroma preprost preizkus, pri katerem se preverja predvsem ustreznost konstrukcije.

Preizkus po standardu FMVSS 571.220 (v nadaljevanju: test varnosti potnikov pri prevračanju) se izvaja po naslednjem postopku:

- Vozilo je postavljeno na togo vodoravno podlago in je podprtoto tako, da se navpična obremenitev strehe prenaša na podlago prek okvira ali šasije.

- Na streho vozila je položena toga plošča, prek katere deluje v navpični smeri enkmerno porazdeljena sila. Sila lahko narašča tako hitro, da navpično gibanje toge plošče ni hitrejše od 12,7 mm/s. Preizkus je končan, ko doseže sila vrednost 1,5-kratne teže neobremenjenega (praznega) vozila.

- Dimenzijske toge plošče so določene glede na velikost vozila. Prav tako je natančno določena lega toge plošče, ki mora ležati na strehi simetrično in se mora strehe dotikati vsaj v dveh točkah.

Preizkus bo vozilo uspešno prestalo, če sta hkrati izpolnjena dva pogoja:

- Navpični pomik poljubne točke na togi plošči ne sme pri največji obremenitvi preseči 130,2 mm.

- Med obremenjevanjem, po dokončni obremenitvi in tudi po razbremenitvi mora biti omogočeno odpiranje in zapiranje vseh zasilnih izhodov v skladu s predpisom FMVSS 571.217 (normalno odpiranje in zapiranje oken in vrat nepoškodovanega vozila). Izjema je zasilni izhod na strehi, ki ga med preizkusom ni mogoče preverjati.

Preizkus se izvede s popolnoma opremljenim vozilom, ki mora biti z vidika konstrukcije popolnoma enako serijski izvedbi, če gre za prototip.

V nalogi je bilo treba izpolniti naslednje zahode:

- definirati numerični model, ki bo kolikor mogoče dobro predstavljal fizikalne razmere pri testu varnosti potnikov pri prevračanju,
- preveriti ustreznost sedanje konstrukcije,
- predlagati nove konstrukcijske rešitve,
- preveriti (dokazati) ustreznost predlagane rešitve.

Pri tem smo se zavedali, da imamo z numerično analizo možnost simulirati le razmere v linearinem območju, test varnosti potnikov pri prevračanju pa se odvija prek meje sorazmernosti.

Standard FMVSS 571.220 – School bus rollover protection describes the course of testing procedures of school bus rollover passive protection which must be conducted by any manufacturer of such vehicles before they can appear on the American market. This relatively simple test has to be done in order to establish performance compliance requirements for school bus design rollover protection.

The test procedures according to the FMVSS 571.220 Standard (hereinafter referred to as the rollover test) are conducted as set forth below:

- Place the vehicle on a rigid horizontal surface so that the vehicle is entirely supported by means of the vehicle frame, and the vertical load on the roof is transferred via vehicle frame and chassis;

- Position the force application plate on the roof and apply an evenly-distributed vertical force in a downward direction to the force application plate at any rate not more than 0.5 inches per second (12.7 mm/s) until the force of 1.5 times the unloaded vehicle weight has been applied.

- The flat, rigid, plate is measured with respect to the vehicle dimensions. Accurately defined is also the position of the plate which must be placed on the roof symmetrically and contact the roof at not less than two points.

It is deemed that the vehicle has successfully stood the test if the following two conditions are simultaneously met:

- The maximum vertical roof displacement at any point on the force application plate should not exceed 5 1/8 inches (130.2 mm).

- During loading, and upon completion of loading and unloading, each emergency exit of the vehicle must be capable of opening and closing in accordance with the FMVSS 571.220 Standard (normal opening and closing of windows and doors of the undamaged vehicle) except the emergency exit located on the roof, which is not required to be capable of being opened during the application of the force.

The test must be conducted on a completely equipped vehicle. Should it be a prototype it has to be identical, as far as design is concerned, with the series production version.

For the analysis to be efficiently done, the below mentioned tasks have to be performed:

- defining a numerical model capable of satisfactorily presenting physical conditions during the rollover test,

- checking the adequacy of the existing design,

- proposing new design solutions, and

- proving the adequacy of the proposed solution.

We were aware that the numerical analysis conditions could be analyzed and simulated in the linear range only, whereas the rollover test runs beyond the limit of proportionality.

1. REŠEVANJE PROBLEMA

Dejavnosti, potrebne za doseg postavljenih ciljev, smo opravili v petih fazah, prikazanih v preglednici 1.

Preglednica 1: Aktivnosti za zagotavljanje ustreznosti konstrukcije po standardu FMVSS 571.220
Table 1: Activities for ensuring engineering compliance in accordance with the FMVSS Standard

Faza Stage	Opis aktivnosti Description of activities	Pričakovani rezultati Anticipated results
1	izdelava prvega numeričnega modela elaboration of the first numerical model	<ul style="list-style-type: none"> * model obremenitve load model * določitev kritičnih mest definition of critical points * ocena nosilnosti evaluation of carrying capacity
2	eksperimentalno simuliranje testa varnosti potnikov pri prevrtačju na preprostem modelu experimental simulation of rollover test on simple model	<ul style="list-style-type: none"> * overitev numeričnega modela in njegovih rezultatov verification of numerical model and results obtained
3	analiza različnih konstrukcijskih izvedb analysis of diverse design versions	<ul style="list-style-type: none"> * ožji izbor ustreznih izvedb narrow selection of adequate versions
4	razširitev numeričnega modela: expansion of numerical model: <ul style="list-style-type: none"> * pločevina na strehi sheet metal on roof * več sekcij more sections 	<ul style="list-style-type: none"> * analitična overitev preprostega modela analytical verification of simple model * natančnejši model za optimalen izbor ustreerne izvedbe * more accurate model for optimum selection of adequate version
5	eksperimentalno simuliranje testa na izbranih izvedbah experimental simulation of rollover test on selected versions <ul style="list-style-type: none"> * preprosti modeli simple models * razširjeni modeli expanded models * popolni modeli complete models 	<ul style="list-style-type: none"> * overitev razširjenega numeričnega modela verification of expanded numerical model * potrditev izbrane izvedbe confirmation of selected version * popolno simuliranje testa na delu vozila complete rollover test simulation on a part of the vehicle * USTREZNA konstrukcija ADEQUATE design

Kombinacijo analitičnega in eksperimentalnega dela smo ocenili kot edino primerno pot, ki nas lahko pripelje do rešitve. Poleg omenjene omejitve z možnostjo izvajanja analiz le v linearinem območju, je bilo opazno delno pomanjkanje izkušenj, saj smo se s takim problemom srečali prvič. Slednje velja predvsem za ocenjevanje vplivnosti posameznih dejavnikov in seveda za odločanje, kaj bomo in česa ne bomo upoštevali.

2. NUMERIČNI MODEL

Analize smo izvajali z metodo končnih elementov (MKE). Uporabili smo računalniški program SUPERTAB iz CAD/CAM/CAE programskega paketa I-DEAS [6], [7].

Analiza MKE terja zelo zahtevno pripravo podatkov. V glavnem so to popolnoma natančni geometrijski podatki o konstrukciji vozila, obremenitvi in podprtju (robni pogoji).

1. PROBLEM SOLUTION

In order to achieve the objectives set, the activities were carried out in five stages, as shown in the table 1.

Faza Stage	Opis aktivnosti Description of activities	Pričakovani rezultati Anticipated results
1	izdelava prvega numeričnega modela elaboration of the first numerical model	<ul style="list-style-type: none"> * model obremenitve load model * določitev kritičnih mest definition of critical points * ocena nosilnosti evaluation of carrying capacity
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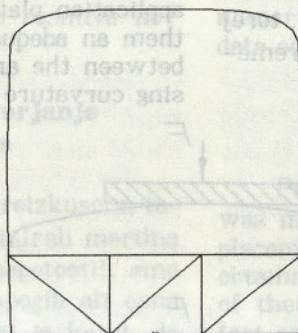
According to our estimation, a combination of analytical and experimental work was the only adequate way to a satisfactory solution. However, beside the above mentioned limitation of making an analysis within the linear range only, we also lacked experience, since we were meeting such a problem for the first time. It is especially true for the assessment of individual factor influences, as well as making a decision as to what to take into consideration.

2. NUMERICAL MODEL

The Finite Element Method (FEM), SUPER-TAB computer programme of the I-DEAS package [6], [7] was applied in the analysis.

The application of the FEM analysis requires a complex preparation of data, accurate geometric data on vehicle design, loads and restraints (boundary conditions).

Ogrodje vozila smo opisali z izoparametričnimi linijskimi končnimi elementi z linearimi oblikovnimi funkcijami in s po šestimi prostostnimi stopnjami na vozlišče (3 pomiki in 3 zasuki). Preden smo se lotili modeliranja vsega vozila, smo vse analize izvajali na »izrezu ogrodja«. Ogrodje vozila lahko razdelimo na 17 dokaj podobnih delov. Predpostavili smo, da je z vidika prevračanja v prvih fazah mogoče analizirati le en del ogrodja, sestavljen iz prečnega prereza vozila (podvozje, stebra in lok na strehi), prikazanega na sliki 1.



Sl. 1. Model MKE dela ogrodja (ena sekcija)
Fig. 1. FEM model of frame part (one section)

Posebno pozornost smo posvetili pripravi podatkov o lastnostih prerezov uporabljenih profilov. Nekaj teh podatkov lahko najdemo v standardih, ni pa podatkov o vzvojnem vztrajnostnem in odporностnem momentu ter o strižnih oblikovnih koeficientih. Za nesimetrične profile je treba nujno poznati tudi lego strižnega središča. Vse potrebne podatke smo izračunali z lastnim programom PREREZ, ki sloni na MKE in izračuna več podatkov, kakor jih je takrat zmogel podobni modul v SUPERTAB-u. Preverili smo tudi vpliv tolerance izdelave profilov (debeline sten, zaokrožitveni polmer itn.) na lastnosti prereza. Vpliv je zanemarljiv, zato smo pri vseh profilih upoštevali imenske mere. Tako smo dobili »knjižnico« lastnosti prerezov, ki jo lahko po potrebi dopolnjujemo in popravljamo. To nam je vzelo veliko časa, vendar je omogočilo mnogo lažje in hitrejše delo v kasnejših fazah.

2.1 Numerični model obremenitve

V naslednjem koraku smo se lotili izdelave numeričnega modela obremenitve strehe prek toge plošče. Cilj te naloge je bil določiti in preveriti tak numerični model, ki bo zagotavljal dovolj verjeten opis razmer pri testu varnosti potnikov pri prevračanju, hkrati pa bo omogočal dovolj hiter preračun celotne konstrukcije vozila.

Prva predpostavka je bila, da imamo poleg materialne nelinearnosti, ki se pojavi zaradi prekoračitve meje proporcionalnosti, tudi oblikovno nelinearnost. Predpostavljali smo namreč, da se bo

We described the vehicle frame with isoparametric line finite elements with linear shape functions and six degrees of freedom per node (3 displacements and 3 rotations). Before starting to model a complete vehicle, all analyses were conducted on a »frame cutout«, in which the frame can be divided into 17 rather similar parts. We assumed that, from the rollover test point of view, only one part of the frame, consisting of a transverse vehicle cross section (chassis, columns and roof arc), shown on figure 1, could be analyzed.

2.2 Experimental checking of the numerical model

Analizo MKE smo izvedli pred preizkusom, da smo na podlagi rezultatov delovalnosti potnikov in napetosti, zanj pomerili tudi vrerek za preverjanje. Preizkus je potrdil izredno dobro ujemanje obremenitve potnika s rezultatom, ki je predstavljal drugi vpliv na vozilo. Analizo smo izvedli tako, da smo na vozilo naložili obremenitev, katero je ujemala s rezultatom preizkusa. Vpliv na vozilo je bil zanesljiv, zato smo ga uporabili za preverjanje numeričnega modela. Po tem, ko smo izvedli eksperiment, so rezultati podatkov, ki smo jih dobili, ujemali s rezultati, ki so jih dobili na preizku. To je potrdilo, da je numerični model dovolj natančen.

A special attention was paid to the preparation of data concerning the cross section properties of the profiles used. Some of these data may be found in the relevant standards, except those regarding torsion inertia and section modulus moment as well as shear area ratios. For unsymmetrical profiles, we needed also the position of the shear centre. All necessary data were calculated by applying our own program based on the FEM model, capable of computing more data than the then existing similar module to that in SUPERTAB. The influence of profile building tolerances (wall thickness, rounding radii, etc.) on cross section properties had also to be checked. Since the influence could be neglected, nominal dimensions for all profiles were taken into consideration. In this way we got the »base properties« (structural element library) of cross sections which can, if so required, be revised and completed at any time. Though it took a lot of time, it enabled easier and faster work in the stages to follow.

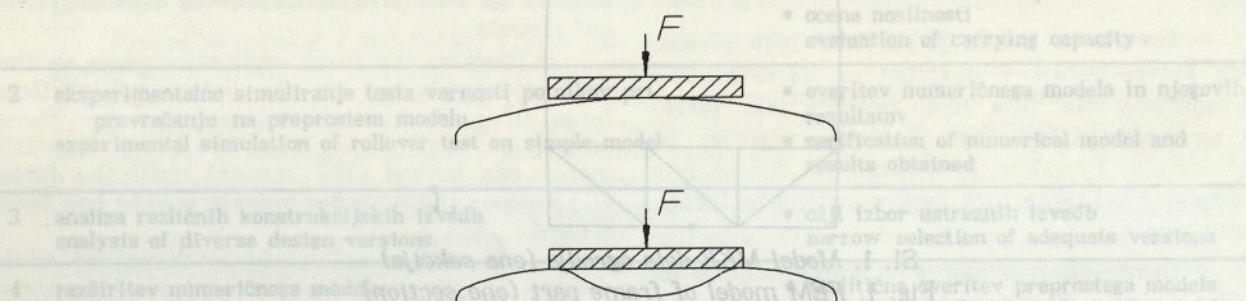
2.1 Numerical model of load

The next stage deals with building a numerical model of the roof load by applying the force on the force application plate. It was necessary to determine and check such a numerical model as would allow a sufficiently credible description of rollover test conditions, and at the same time enable fast computing of the complete vehicle structure.

The first assumption was that in addition to material non-linearity occurring due to exceeding the limit of proportionality, geometrical non-linearity would also occur. We assumed that the load

izbočena streha pod vplivom obremenitve močno deformirala, kar bo povzročilo spremembo togosti strehe (sl. 2). Za doseganje dovolj natančnega rezultata smo ta vpliv upoštevali, kar se je kasneje pri meritvah izkazalo kot zelo pomembna in pravilna odločitev. Togo ploščo smo modelirali s togim končnim elementom. Med streho in togo ploščo smo postavili kontaktne končne elemente, ki smo jih definirali tako, da so lahko prenašali le tlačne obremenitve (stik med togo ploščo in streho), nateznih pa ne (ločevanje toge plošče in strehe). Poleg tega jih lahko predpišemo ustrezni ohlap, torej oddaljenost med lokom in togo ploščo pred obremenitvijo, ki nastane zaradi ukrivljenosti loka.

would strongly deform the convex roof, the result of which would be modified roof rigidity (fig. 2). To obtain a sufficiently accurate result, we had to take this influence into consideration, and the measures subsequently verified our decision. The rigid plate was modeled with a rigid (non-deformable) finite element. Contact finite elements defined so as to be able to transfer only pressure load (contact between the roof and the rigid force application plate) and not tensile strength (separation of rigid force application plate from the roof) were placed between the roof and the force application plate. In addition, we could prescribe them an adequate »gap separation«, i.e. distance between the arc and the plate prior to load causing curvature of the former.

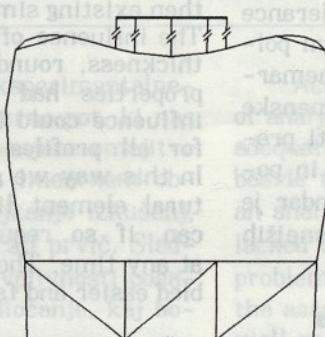


Sl. 2. Pričakovana deformacija strehe

Fig. 2. Anticipated roof deflection

Obremenitev smo simulirali s pomiki toge plošče v navpični smeri. Predpisali smo, da se pomik plošče v navpični smeri povečuje za 5 mm in smo pri vsakem takem koraku izračunali pomike, napetosti in sile v modelu. Izračun je pokazal, da toga plošča vedno nalega le v dveh točkah, saj že najmanjša obremenitev povzroči povesvrha loka (sl. 3).

The load was simulated by movements of the force application plate in a vertical direction. The plate was moved downwards by 5 mm stages and displacements, stresses and forces in the model were calculated each time. The calculation showed that the rigid plate was always in contact with the roof at not less than two points as even the minimum load caused the arc central part deflection (fig. 3).



Sl. 3. Deformacija modela MKE ene sekcije

Fig. 3. FEM model (one section) deformation

Tak numerični model obremenitve je praktično popln opis fizikalnih razmer, ki se pojavijo pri testu varnosti potnikov pri prevračanju, vendar je za praktično iskanje ustreznih rešitev, za katere je potrebno zelo veliko preračunov, neprimeren. Uporaba togih in kontaktnih končnih elementov namreč zelo podaljša računski čas in potrebe po zmožljivostih zunanjega pomnilnika.

Such a numerical load model practically presented a complete description of physical conditions occurring during the rollover test but was found completely unsuitable for searching adequate solutions which required a large number of calculations. Application of rigid and contact finite elements thus required a lot of time for calculations and larger capacities of the external memory.

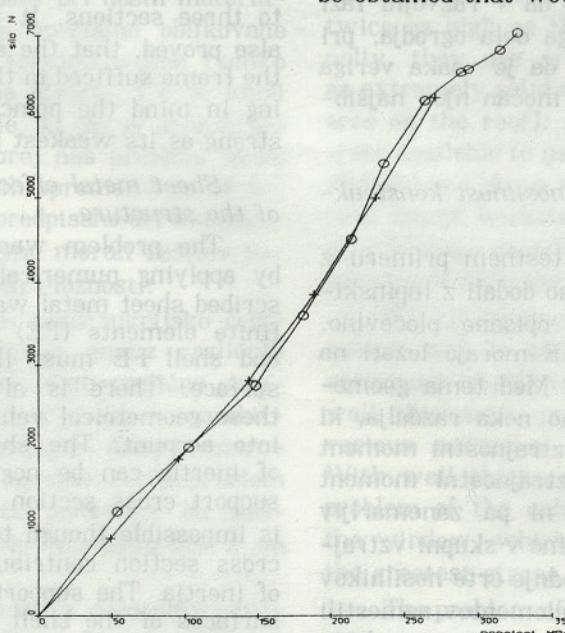
Iz prikazanih spoznanj smo skleiali, da bi lahko podali oceno nosilnosti zaradi obremenitve loka s točkovno obremenitvijo. Tak izračun je najpreprostejši in najhitrejši. Kot tak je primeren za analizo celotnega vozila.

Preden smo se lotili same analize loka, smo izbrali meritve oziroma preizkus, s katerim smo simulirali test prevračanja na enem samem loku. Rezultate preizkusa moramo primerjati z izračunom, da lahko preverimo ustreznost numeričnega modela, hkrati pa dobimo podatke o resnični nosilnosti loka.

2.2 Eksperimentalno preverjanje numeričnega modela

Analizo MKE smo izvedli pred preizkusom, tako da smo na podlagi rezultatov definirali merilna mesta pomikov in napetosti. Pri napetostih smo želeli preveriti tudi vzrok zanje (upogib ali osna sila). Preizkus je potrdil izračun, ki je kazal, da upogibne obremenitve popolnoma prevladujejo. Napetosti zaradi drugih vplivov so bile zanemarljive.

Preizkus smo izvedli tako, da smo »stiskali« izrez ogrodja, pri tem pa merili pomike in deformacije konstrukcije in silo, potrebno za izvano stanje. Sam preizkus smo izvajali podobno, kakor smo predpisovali robne pogoje pri numerični analizi, to je tako, da smo podatke odbirali za vsakih 5 mm pomika »toge plošče«. Meritev in analiza sta pokazali, da največji pomiki toge plošče zagotovo ne bodo preseženi, če nam bo le uspelo izdelati konstrukcijo, ki se zaradi obremenitve ne bo preprosto sesedla.



Sl. 4. Ujemanje meritve (O) in izračuna (X)
Fig. 4. Measurement (O) and calculation (X) compliance

Considering all the above facts, we concluded that an assessment of the carrying capacity resulting from the arc load over the force application plate could be made on the basis of the point load simulation. Such a calculation, being the simplest and the fastest, is therefore appropriate for the analysis of the complete vehicle.

Before starting with the arc analysis, we anticipated measurement and/or testing which we used for rollover test simulation on a single arc. Results obtained had to be compared to the calculation so as to check the adequacy of the numerical model and, at the same time, obtain data on the actual carrying capacity of the arc.

2.2 Experimental checking of the numerical model

Prior to the experiment, the FEM analysis was made by defining measuring points for displacements and stresses on the basis of results obtained. For the latter, we checked the cause of their occurrence (bending or axis load). The test conducted confirmed the calculation showing that bending loads entirely predominated. Stresses due to other influences were negligible.

We conducted the experiment by »pressing« the frame cutout, thereby measuring displacements and specific deformation of the structure and the force required for the provoked state. The test itself was conducted in a similar way as when prescribing the boundary conditions of numerical analysis, i.e. collecting data for each 5 mm displacement of the force application plate. Both measurements and analysis showed that maximum displacements of the force application plate would not be exceeded if a structure could be obtained that would not collapse under load.

Primerjava meritve in izračuna je pokazala presenetljivo dobro ujemanje (sl. 4). S tem smo potrdili numerični model ogrodja avtobusa in dobili zadosten dokaz, da lahko ustrezeno rešitev lščemo z numeričnim modelom. Po preizkusu in analizi izreza je znašala nosilnost izreza okoli 7 kN, zagotoviti pa je bilo treba vsaj 10 kN. Analiza in preizkus sta pokazala, da obstajajo na konstrukciji tri kritična mesta, na katera smo se osredotočili pri iskanju ustreznih konstrukcijskih rešitev.

2.3 Vpliv pločevine

Dobljene rezultate smo predstavili projektantom in strokovnjakom iz ZDA. Glede na dokajšnjo novost zasnove vozila je prevladalo mnenje, da posebnih konstrukcijskih sprememb, ki bi vplivale na kakovost potniškega prostora, ni mogoče upoštevati. Napovedana kakovost potniškega prostora je bila ena od najmočnejših zagotovil za poslovni uspeh na ameriškem tržišču.

Pojavila so se naslednja vprašanja:

- Kakšen je učinek analize ene same sekcije na verodostojnost opisa razmer v celotnem vozilu?
- Kakšen je vpliv pločevine na nosilnost konstrukcije?
- Kako pritrdiriti pločevino?
- Kakšna je ustrezena konstrukcija?

Analizirati eno ali več sekcij?

Dokler smo analizirali prvo različico, je gotovo zadoščala ena sekcija. Sprememba te različice, vezane na tržne zahteve, je narekovala razširitev numeričnega modela na tri sekcije. Napovedali smo, in kasneje tudi dokazali, da v razvojni fazi zadošča analiza samo majhnega dela ogrodja, pri tem pa smo se držali načela, da je vsaka veriga močna samo toliko, kolikor je močan njen najšibkejši člen.

Kako vpliva pločevina na nosilnost konstrukcije?

Vprašanje smo rešili na testnem primeru z numerično analizo. Ogrodju smo dodali z lupinski-mi končnimi elementi (KE) opisano pločevino. Tako nosilci kakor lupinski KE morajo ležati na osrednji črti oziroma ploskvi. Med temi geometrijskima vrednostmi je vedno neka razdalja, ki jo moramo upoštevati. Sam vztrajnostni moment prereza lupine je glede na vztrajnostni moment prereza nosilca zanemarljiv, ni pa zanemarljiv prispevek površine prereza lupine v skupni vztrajnostni moment. Tako smo osrednje črte nosilnikov in osrednje ploskve lupinskih elementov namestili na različna mesta v prostoru, ustrezena vozlišča pa povezali z dodatnimi enačbami (povezave prostostnih stopenj).

When comparing measurements with the calculation, almost identical results were obtained (fig. 4). In this way the numerical bus frame model was confirmed, and a sufficient evidence that an adequate solution can be found by means of the said model was provided. According to the test and cutout analysis results, the carrying capacity of the cutout was about 7 kN, although at least 10 kN should be ensured. There were three critical points on the structure on which we had to focus when searching for adequate design solutions.

2.3 Sheet metal effect

The results obtained were presented to American designers and experts. Considering the rather new vehicle concept, it was deemed that no special design changes affecting the quality of the passenger compartment should be taken into account. Anticipated better quality of the passenger compartment was one of the best guarantee of success on the American market.

The following issues were brought up:

- What is the effect of a single section analysis on credibility of a description of the complete vehicle conditions?
- What is the sheet metal effect on the structure carrying capacity?
- How to fix sheet metal?
- What construction is an adequate structure?

Should one section suffice for the analysis?

As long as only the first version was analyzed, one section was enough. The change of this version conditioned by the requirements of the market led to an expansion of the numerical model to three sections. It was anticipated, and later also proved, that the analysis of a small part of the frame sufficed in the development stage, bearing in mind the principle that each chain is as strong as its weakest member.

Sheet metal effect on the carrying capacity of the structure.

The problem was solved on a test sample by applying numerical analysis. The above described sheet metal was added with shell formed finite elements (FE) to the frame. Both beam and shell FE must lie on the central line or surface. There is always a distance between these geometrical values which should be taken into account. The shell cross section moment of inertia can be neglected with regard to the support cross section moment of inertia, but it is impossible though to neglect the shell surface cross section contribution to the total moment of inertia. The support central lines and central surfaces of the shell elements were thus positioned on different areas in the space, and relevant nodes connected with additional equations (connections of degrees of freedom).

Ugotovili smo, da pločevina nesporno vpliva na nosilnost ogrodja. Vpliv je celo tako močan, da se v določenih delih pojavijo napetosti zaradi osne obremenitve in ne zaradi upogiba. Na dveh kritičnih mestih pločevina ogrodje »razbremenjuje«, na enem pa se obremenitev nosil poveča. Iz analitičnih rezultatov in kasneje tudi preizkusov lahko z dokajšjo zanesljivostjo trdimo, da pločevina poveča nosilnost konstrukcije (glede na test varnosti potnikov pri prevračanju) za okoli 15 odstotkov.

Vpliv pritrditve pločevine

Ugotovili smo, da način pritrditve pločevine bistveno ne vpliva na nosilnost. Analiza kaže, da je bolj neugoden primer, ko je pločevina pritrjena le na vzdolžnih nosilcih, ne pa tudi na prečnih.

3. REŠITEV

Rešitev problema (zagotoviti konstrukcijo, ki bo vzdržala test varnosti potnikov pri prevračanju), smo lahko iskali le v dveh smereh:

- dodajanje različnih elementov na strehi,
- ojačanje nekaterih nosil.

Glede na to, da velikost pomikov toge plošče ni bila vprašljiva, smo predlagali uporabo materialov z višjo mejo trdnosti. S tem bi lahko občutno izboljšali nosilnost ob majhnih posegih v konstrukcijo. Iz propagandnega gradiva konkurenčnega ameriškega izdelovalca smo izvedeli, da pri izdelavi šolskih avtobusov uporabljajo t.i. jeklo z veliko trdnostjo oziroma specialno konstrukcijsko jeklo s trdnostjo 90.000 psi (okoli 630 MPa), kar je skoraj dvakrat višja trdnost kakor pri naših materialih. Poleg tega uporabljajo specialno oblikovane profile, konstrukcija pa je izredno močna (veliko število stebrov in lokov na strehi). Če bi imeli na voljo materiale in profile, ki jih je uporabljalo konkurenčno podjetje, bi torej naš problem lahko rešili brez vsakih oblikovnih sprememb in bi sedanja konstrukcija zdržala predpisano obremenitev. Ker pa to ni bilo mogoče, smo morali rešitev poiskati v okviru razpoložljivih možnosti.

Da bi poiskali primerno konstrukcijsko rešitev, smo izvedli večje število analiz različnih modelov. Pri tem smo spremenjali različne parametre, kakor so: debelina sten profilov, morebitne spremembe profilov in različne dodatke oziroma ojačitve. Z debelino sten smo rešili problem stebra, ki je bil na mestu pritrditve na nadokensko vez eno najbolj obremenjenih mest na ogrodju.

Problem strehe smo rešili z dodatnimi prečkami, ki so bile sicer zamišljene že v osnovni izvedbi in s pollokri. Računsko smo prišli do štirih izvedb, ki smo jih preverili tudi na sedmih modelih

It was established that sheet metal in fact affected the carrying capacity of the frame, the influence even causing axial stresses resulting from axial load and not bending. In two critical areas sheet metal »relieved« the frame, whereas on one area the load of supports was even higher. On the basis of analytical results and subsequent tests, we may almost state that the carrying capacity of the structure is increased (with regard to the rollover test) by about 15%.

from What is the effect of the sheet metal mode of attachment?

It was established that the mode of sheet metal attachment was of no vital importance as far as carrying capacity was concerned. The analysis showed that the attachment of sheet metal was least suitable if executed on both transversal and longitudinal members, and not only on the latter.

3. SOLUTION

We were looking for a solution to the problem of how to ensure a structure which would be able to stand the rollover test – in two directions:

- by adding various elements on the roof,
- by reinforcing some supports.

Considering that the displacement length of the force application plate was not questionable, the application of material with a higher limit of proportionality was proposed. In this way, the carrying capacity would substantially improve by only minor alterations of design. In the USA, school bus manufacturers use ultra high tensile steel or special structural steel with a hardness of 90,000 psi (about 630 MPa), which is twice as high as that of local material. Additionally, they use profiles of special shapes with an extremely solid structure (a lot of columns and arcs on the roof). If such materials and profiles were available to us, our problem would be solved without any shape alterations; the existing structure would withstand the prescribed load. Since this was not possible, we had to find an adequate solution within the existing possibilities.

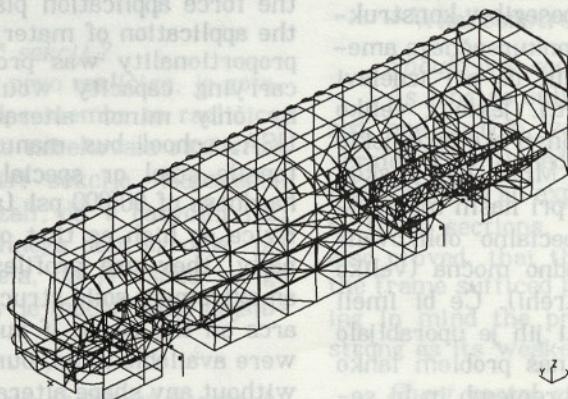
For this purpose many analyses of different models had to be performed. We made wide variations of different parameters such as profile wall thickness, possible profile alterations and various additional elements or reinforcements. With wall thickness, we managed to solve the problem of the column on the fixing spot above the window, which was one of the spots under the greatest stress.

The problem of the roof was solved by adding more cross members than anticipated in the basic version, and semi arcs. Through calculations, we obtained four versions which were later checked

izreza avtobusa. Preizkusili smo modele s pločevino in brez nje. Preizkuse smo izvedli takrat, ko smo na podlagi preračunov že tudi predlagali končno izvedbo (sl. 3). Tudi tokrat smo dobili potrditev računskega rezultata, poleg tega, pa smo v enem primeru lahko tudi preverili možnost odpiranja in zapiranja vrat zasilnega izhoda. Ko smo tako ugotovili, kaj je treba narediti, da zagotovimo ustrezno konstrukcijo, smo se lotili modeliranja celotnega vozila [1], [2], [3].

3.1 Analiza celotnega ogrodja vozila

Pri analizi celotnega modela vozila smo želeli dokončno preveriti trditev, da zadošča analiza ene (ali več) sekcijs vozila. Rezultat analize je pokazal, da so nosila prednje in zadnje stene, še posebej pa stebri pri vratih, močneje obremenjeni od nosil v vmesnih sekcijs, kjer smo dobili praktično enake rezultate kakor pri analizah ene same sekcijs. Na podlagi teh rezultatov smo nato loke in stebre na ustreznih mestih dodatno ojačali (sl. 5). Na podlagi naših predlogov je bila izdelana končna izvedba avtobusa, ki je bila poslana na preizkušanje v MSE v ZDA [4]. S konstrukcijskimi spremembami smo zagotovili enako kakovost potniškega prostora, kakršna je bila določena v projektnih zahtevah.



Sl. 5. Model celotnega avtobusa

Fig. 5. Complete bus model

Preizkus avtobusa TAM 252 A 121 po standardu FMVSS 220, je bil uspešno opravljen 8. in 9. avgusta 1991, na preizkuševališču družbe MSE v San Bernardinu, Kalifornija [4].

4. PRESLIKAVA REZULTATOV

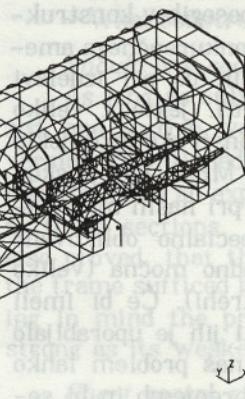
PREIZKUŠENEGA MODELA MKE NA SPREMENJENE MODELE

Zaradi predelave šolskega avtobusa v medkrajevni avtobus je bilo treba ugotoviti, ali bi tudi nekoliko spremenjena konstrukcija avtobusa prestala test varnosti potnikov pri prevračanju. Zaradi

on seven bus cutout models. All models were tested with and without sheet metal. The tests conducted after the final version had been proposed on the basis of calculations once again confirmed the calculation results (fig. 3). In one case we could also check the capability of opening and closing emergency exits. Once we had established what had to be done to ensure an adequate structure, we started modeling the whole vehicle ([1], [2], [3]).

3.1 Analysis of complete vehicle frame

With the analysis of a complete vehicle model, we wanted to confirm that a single analysis of one (or more) vehicle sections (parts) suffices. The analysis showed that the front and rear wall supports, especially columns near doors, are put under greater stress than those in intermediate (sections) parts. The results were practically the same as those of the analysis dealing with one section only. On the basis of these results arcs and columns were additionally reinforced (fig. 5). On our suggestion, the final version of the bus was made and sent to MSE to America for testing [4]. The design alterations gave the same quality of passenger compartment as envisaged in the project requirements.



Sl. 5. Model celotnega avtobusa

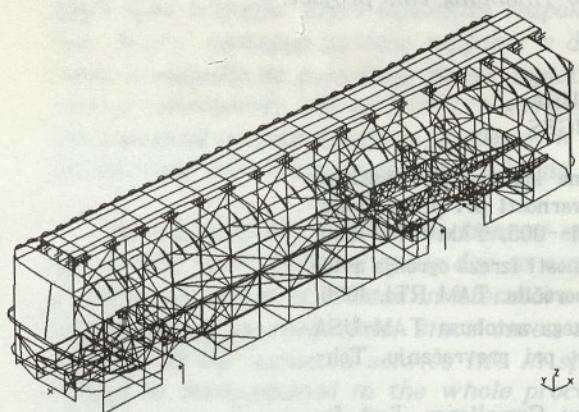
Fig. 5. Complete bus model

Test procedures on the TAM 252 A 121 bus in accordance with FMVSS 220 Standard (»SCHOOL-BUS ROLLOVER PROTECTION«) was conducted and efficiently withstood on 8 and 9 August 1992, on the testing ground of the company MSE in San Bernardin, California [4].

4. APPLICATION OF RESULTS OF TESTED FEM MODEL TO MODIFIED MODELS

In order to adapt the school bus into a transit bus, it was necessary to establish whether the bus structure could stand the rollover test or not with minor modifications. With a view to including the possibility of mounting

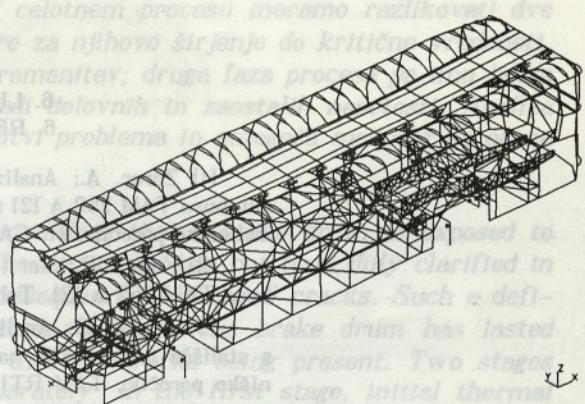
možnosti vgraditve dvigala za invalidske vozičke, je poleg nadgradnje treba nekoliko spremeniti tudi šasijo in razširiti sprednja vhodna vrata. Vse te spremembe smo uporabili na sedanjem numeričnem modelu in tako zgradili še dva dodatna modela MKE, na katerih smo z enakimi robnimi pogoji simulirali test prevračanja (sl. 6 in 7). Rezultati, to so izračunani pomiki in porazdelitve napetosti v obeh modelih, so pokazali, da v modelih ne pride do bistvenih razlik v primerjavi z rezultati osnovnega modela MKE. Ker sta modela po zgradbi skoraj enaka kakor osnovni model, ta pa je bil preizkušen na test prevračanja in ga ugodno prestal, lahko sklepamo, da izvedene spremembe ne vplivajo na osnovno togost vozila in bi tudi ta vozila prestala test [5].



Sl. 6. Modificiran končni model,
obremenjen s ploščo

Fig 6. Modified final model with force applied to
the force application plate

an invalid chair lift, modifications had to be made not only on the body but also on the chassis because of widening the front door. All these modifications were taken into consideration in the existing numerical model, and we built two additional FEM models on which the rollover test was simulated under the same boundary conditions (see figs. 6 and 7). The results - calculated deflections and distributions of stress on both models showed that no major differences occurred on the models if compared to the results obtained from the basic FEM model. Bearing in mind that both models were almost the same as the basic model, which had already successfully withstood the rollover test, we may conclude that the above mentioned modifications do not affect the basic rigidity of the vehicle, and these vehicles would therefore also stand the test.



Sl. 7. Deformacije modificiranega modela

Fig. 7. Deformation of modified model

5. SKLEP

V članku je prikazan sodoben način pri oblikovanju izdelka z uporabo postopkov CAE. Postopek, imenovan MCAE, pri katerem namesto preizkušanja na prototipih, z uporabo CAE, izdelujemo matematične modele, simuliramo obremenitve v preizkuševališču in spreminjamamo prototip – model na podlagi izračunanih vrednosti, omogoča hitrejši in cenejši razvoj končnega izdelka. Na podlagi osnovne konstrukcije avtobusa smo z MKE razvili ustrezni matematični model, na katerem smo simulirali zahtevano obremenitev preizkusa prevračanja in izračunali deformacije in napetosti. V modelu smo enako obremenjeno konstrukcijo spremenjali glede na doseganje želenih rezultatov, kar je bilo na koncu temelj za predlagane spremembe prototipa. Na prototipu je bil kasneje uspešno izveden preizkus prevračanja, kar potrjuje ustreznost našega dela. Po tako potrjenem modelu, so bile kasneje izvedene še druge manjše spremembe konstrukcije avtobusa, njihov vpliv na

5. CONCLUSION

This article deals with a new approach to product shaping with the CAE technique. This procedure – called MCEAE, where instead of prototype testing the application of the CAE method enables building of mathematical models, simulating loads inside the testing room, and modifying a prototype – a model on the basis of calculated values, allows a final product to be developed faster and cheaper. Applying MCAE we developed a mathematical model on basis of the basic bus structure, on which the force required in accordance with the rollover test protection was simulated, and deflections and stresses calculated. On the model we modified the structure to which the force was applied in a similar way in order to achieve anticipated results. This eventually provided the basis for proposed modifications of the prototype. The prototype put to the rollover test successfully withstood the test, which once again confirmed the adequacy of our approach. This model later served as the basis for subsequent modifications

preizkus prevračanja pa je bil dokazan glede na preizkušeni model in ocenjen kot zanemarljiv. Uporaba MCAE se je izkazala za izredno ugodno metodo pri razvoju novih konstrukcij avtobusov, še posebej pa takih, ki bodo morali izpolnjevati vedno strožje predpise glede nosilnosti in varnosti.

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of the bus structure. The effect of these modifications on the rollover test was shown in relation with the tested model, and was estimated as negligible. The application of the MCAE proved extremely efficient in developing new bus structures, especially those that will have to meet ever stricter protection and carrying capacity regulations.

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