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Simulacija naleta tovornega vozila ob cestno varnostno ograjo

Simulating the Impact of a Truck on a Road-Safety Barrier

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Cestno varnost lahko izboljšamo s postavitvijo cestnih varnostnih ograj, ki preprečujejo udeležencem cestnega prometa vstop v nevarna območja. Za dvig stopnje varnosti morajo biti cestne varnostne ograje oblikovane tako, da pri naletu vozila le-to preusmerijo nazaj na cestišče. Med preusmerjanjem vozila morajo s svojo deformacijo absorbirati čim večjo količino kinetične energije, da se zmanjšajo pojemki potnikov v vozilu. V prispevku je predstavljena računalniška simulacija naleta tovornega vozila ob cestno varnostno ograjo. Izvedene so bile parametrične računalniške analize za oceno primernosti različnih dodatnih elementov varnostne ograje. Za izvajanje eksplicitnih dinamičnih analiz je bil uporabljen program LS-DYNA. Računalniške simulacije dokazujejo, da je nosilnost analizirane ograje dovolj velika, da tovornjak zadrži in preusmeri nazaj na cestišče. Hkrati pa se pokaže tudi ustrezno visoka stopnja akumulacije kinetične energije vozila v obliki deformacije cestne varnostne ograje, kar zmanjša pojemke vozila in se kaže v povečani stopnji varnosti za potnike v vozilu.

(Ključne besede: varnost na cestah, ograje varnostne, analize trkov, simuliranje dinamično, LS-DYNA)

Road safety can be improved by applying appropriate road-safety barriers that prevent road-traffic participants from entering dangerous areas. In terms of preventing vehicles from veering off the road, a road-safety barrier should redirect the impacting vehicle back onto the road. In the process of doing so it should absorb as much of the vehicle's kinetic energy as possible through its deformation, so reducing the deceleration of the vehicle's occupants. This paper considers a computer simulation of a truck's impact on a steel road-safety barrier. Parametric computer simulations were used to evaluate the different additional safety elements of the road-safety barrier. The dynamic finite-element explicit code LS-DYNA was used for this purpose. The computer simulations prove that the analyzed road-safety barrier design is strong enough to retain and redirect the truck back onto the roadway. Appropriately, the high absorption of the impacting vehicle's kinetic energy through the safety-barrier deformation is observed at the same time, which indicates a reduction in a vehicle's deceleration, and with that, a higher safety level for the vehicle's occupants.

(Keywords: road safety, road safety barrier, impact simulations, dynamic simulations, LS-DYNA)

0 UVOD

Visoka stopnja varnosti je zelo pomembna v sodobnem cestnem prometu. Na eni strani avtomobilska industrija razvija nove pasivne in aktivne varnostne sisteme za povečanje varnosti potnikov v cestnem prometu, na drugi strani pa se varnost cest povečuje z uporabo učinkovitejših cestnih varnostnih elementov.

Zagotovitev dovolj visoke stopnje varnosti v cestnem prometu je primarnega pomena. Eden od

0 INTRODUCTION

A high level of safety is a very important aspect in modern road traffic. On the one hand, the car industry is developing new, passive and active vehicle-safety systems to increase the safety of road-vehicle occupants, and on the other hand, the roads are being made safer with the installation of more effective road-safety elements.

Ensuring appropriate safety levels in road traffic is of primary importance. One way to improve načinov izboljšanja varnosti je postavitev varnostnih ograj. Namen cestnih varnostnih ograj je preprečiti zdrs vozila s ceste, torej preprečiti izlet vozila s cestišča ali prehod vozila na nasprotnosmerno vozišče. S tem se preprečijo oziroma popolnoma odpravijo možnosti poškodbe potnikov v vozilu ter oseb in objektov ob vozišču.

Novo postavljene cestne varnostne ograje v Sloveniji morajo izpolnjevati zahteve novega slovenskega pravilnika o postavitvi cestnih varnostnih ograj in standarda SIST EN 1317 [1]. Vsaka na novo postavljena ograja mora imeti uspešno opravljen preizkus naleta za stopnjo zadrževanja, za katero je namenjena. Zaradi visokih cen preizkušanj varnostnih ograj je smiselno njihovo konstrukcijo poprej preveriti z izvajanjem računalniških simulacij.

Tako so bile, z namenom, da bi izbrali najustreznejše konstrukcijske rešitve varnostne ograje, izvedene računalniške analize naleta tovornjaka ob ograjo. Za izvajanje teh simulacij je bil uporabljen programski paket LS-DYNA ([2] in [3]).

1 KONSTRUKCIJSKE ZAHTEVE ZA CESTNE VARNOSTNE OGRAJE

Cestne varnostne ograje morajo bili postavljene le na odsekih, kjer je možnost za hujše poškodbe pri naletu vozila manjša, kakor v primeru, če ograje ne bi bilo. Na javnih cestah v Sloveniji se lahko postavljajo le varnostne ograje, ki so atestirane po standardu SIST EN 1317.

Najpogosteje uporabljena vrsta cestnih varnostnih ograj v Sloveniji so jeklene varnostne ograje (sl. 1). Postavljene so predvsem na avtocestah, glavnih in regionalnih cestah. Na redkeje prevoznih cestah se uporabljajo le na nevarnih območjih, kjer je povečana verjetnost zdrsa vozila s cestišča.

Glavni konstrukcijski elementi enostranske jeklene varnostne ograje so (sl. 1):

- ščitnik – vzdolžni element ograje; s svojo deformacijo zmanjša moč udarca, hkrati pa mora biti dovolj tog, da se med trkom ne poruši;
- steber – nosilo distančnika in/ali ščitnika, ki zagotavlja lego ščitnika na določeni oddaljenosti in višini od vozišča oziroma nad njim;
- distančnik – zagotavlja določeno lego ščitnika glede na steber ograje;
- zaključni element – del varnostne ograje, ki je na njenem začetku oziroma koncu in je namenjen zmanjšanju posledic naleta vozila na ograjo.

road safety is to install road-safety barriers. The purpose of such systems is to restrain a vehicle from entering dangerous areas, i.e., to prevent it from veering off the road or on to the other side of the road. This effectively reduces or completely alleviates damage to vehicle occupants and other road-traffic participants and objects.

Newly installed road-restraint systems in Slovenia have to fulfill the new Slovenian regulation requirements for road-restraint systems and the SIST EN 1317 standard [1]. Every newly installed restraint system has to be certificated for the containment level it is designed for by a full-scale crash test. Since these tests are very expensive, it is advisable to preliminary check the adherence of safety-barrier design to the set regulations by means of a computer simulation.

This paper reports on a computer simulation of a truck impact into a road-safety barrier with the aim of determining the most effective safety-barrier design. The software system LS-DYNA ([2] and [3]) was used for this purpose.

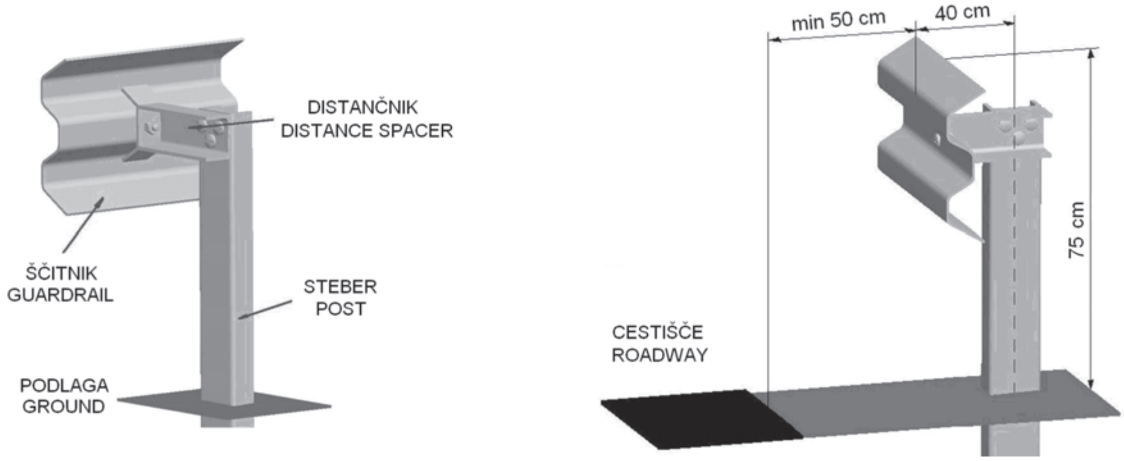
1 DESIGN REQUIREMENTS FOR ROAD-SAFETY BARRIERS

Road-safety barriers only need to be installed on road sections where the possibility of severe injuries during vehicle impact is reduced by the installation of such barriers. Only certified road-safety barriers according to SIST EN 1317 may be installed on public roads in Slovenia.

The most frequently used type of road-safety barriers in Slovenia are steel road-safety barriers (Fig. 1). They are installed mainly on highways, main and regional roads. On roads with less traffic they are only used in dangerous areas with a high probability of the vehicle veering off the road.

The main design elements of a single-sided steel road-safety barrier are (Fig. 1):

- the guardrail – a longitudinally placed element, the deformation of which reduces the severity of an impact, but it should also be strong enough not to rupture during an impact;
- the post – carries the distance spacer and/or the guardrail and it ensures the guardrail position at a certain distance from and above the road;
- the distance spacer – ensures a certain position of the guardrail in relation to the post,
- the end element – a part of the safety barrier placed at its beginning and end, which reduces the consequences of a direct vehicle impact.



Sl. 1. *Konstrukcijski elementi in glavne mere jeklene cestne varnostne ograje*
Fig. 1. *Main elements and regulated dimensions of a steel road-safety barrier*

Pravila za postavitev cestnih varnostnih ograj v okviru tehnične specifikacije za javne ceste v Sloveniji še niso popolnoma določena, saj jih še zmeraj usklajujejo različne agencije [4].

2 ZAHTEVE STANDARDA SIST EN 1317

Glede na standard SIST EN 1317 ocenjujemo ustreznost varnostne ograje z ozirom na tri glavne kriterije [5]:

- raven zadrževanja vozila – pomeni raven zadrževanja za različne vrste vozil;
- moč udarca – se določa s tremi parametri: z merilom velikosti pospeškov (MVP - ASI), s pojemkom glave po udarcu (PGU - PHD) in s teoretično hitrostjo glave pri udarcu (THGU - THIV);
- deformacija ograje.

Najpomembnejši parameter ASI je brezrazsežna veličina, ki se uporablja kot splošno merilo za določanje posledic naleta vozila na potnike v vozilu. ASI je določen kot:

The technical regulations for the installation of road-safety barriers on Slovenian public roads are not yet fully operational, as they are still in the process of final approval by various agencies [4].

2 SIST EN 1317 REQUIREMENTS

The suitability of a safety barrier is, according to the SIST EN 1317 standard, determined by three main criteria [5]:

- the containment level – represents the level of containment for different types of vehicles;
- the impact severity – defined by three parameters: the acceleration severity index (ASI), – the post-impact head deceleration (PHD) and the theoretical head-impact velocity (THIV),
- the deformation of the barrier.

The most important ASI parameter is a dimensionless variable, which is used as an overall measure of vehicle-impact consequences for the vehicle occupants. The ASI is determined as:

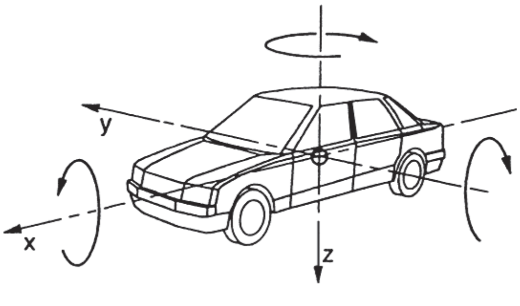
$$ASI = \max\left[ASI\left(t\right)\right] = \max\left[\sqrt{\left(\frac{\bar{a}_x}{\hat{a}_x}\right)^2+\left(\frac{\bar{a}_y}{\hat{a}_y}\right)^2+\left(\frac{\bar{a}_z}{\hat{a}_z}\right)^2}\right] \le 1{,}0\ \left(1{,}4\right) \qquad (1),$$

kjer $\bar{a}_x, \bar{a}_y$ in $\bar{a}_z$ pomenijo povprečne vrednosti pospeškov masnega središča vozila v njegovem lokalnem koordinatnem sistemu v tekočem časovnem koraku $\Delta t = 50$ ms (sl. 2). $\hat{a}_x, \hat{a}_y$ in $\hat{a}_z$ pomenijo mejne vrednosti pospeškov za posamezne koordinatne osi ter znašajo $\hat{a}_x = 12 \cdot g$, $\hat{a}_y = 9 \cdot g$ in $\hat{a}_z = 10 \cdot g$, kjer je $g = 9{,}81$ m/s^2.

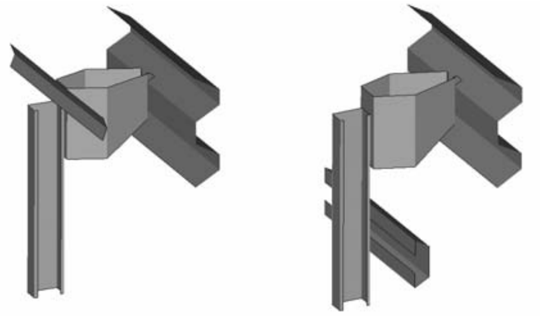
Parameter moči udarca MVP mora biti merjen in izračunan samo za teste z vozili majhnih mas

where $\bar{a}_x, \bar{a}_y$ and $\bar{a}_z$ represent the average values of the acceleration of the vehicle's center of gravity in a local coordinate system of the vehicle in a running-time interval of $\Delta t = 50$ ms (Fig. 2). $\hat{a}_x, \hat{a}_y$ and $\hat{a}_z$ stand for the acceptable acceleration limits for individual coordinate directions and are equal to $\hat{a}_x = 12 \cdot g$, $\hat{a}_y = 9 \cdot g$ and $\hat{a}_z = 10 \cdot g$, where $g = 9.81$ m/s^2.

The impact severity parameter ASI needs to be measured and determined only for tests with low



Sl. 2. *Lokalni koordinatni sistem vozila*
Fig. 2. *Local coordinate system of the vehicle*



Sl. 3. *Konstrukcija ograje s pasnico (levo) in trapeznim vodilom (desno)*
Fig. 3. *Design of a barrier with tension belt (left) and wheel guidance (right)*

(osebna vozila), na katera med testom delujejo večji pojemki. Kljub temu je bil v tem prispevku parameter MVP uporabljen tudi za analizo razmer med naletom tovornjaka. Ta parameter pomeni dobro mero za normiran dejanski pospešek, saj se izračuna iz filtriranih koordinatnih pospeškov in je normiran z njihovimi mejnimi vrednostmi. Tako je bil tukaj uporabljen za prikaz vpliva različnih konstrukcijskih rešitev cestne varnostne ograje na skupno obnašanje vozila.

3 KONSTRUKCIJSKA IZVEDBA VARNOSTNE OGRAJE

S simulacijami je bilo preizkušenih več konstrukcijskih rešitev cestne varnostne ograje za raven zadrževanja H1. Po standardu SIST EN 1317 mora takšna ograja uspešno prestati nalet osebnega vozila (test TB11) in tovornjaka (test TB42). Osebno vozilo ima maso $m = 900$ kg, začetno hitrost $v = 100$ km/h in trči v cestno varnostno ograjo pod kotom $\alpha = 20°$ glede na postavitev ščitnika ograje. Tovornjak ima maso $m = 10.000$ kg in trči v varnostno ograjo z začetno hitrostjo $v = 70$ km/h pod vpadnim kotom $\alpha = 15°$. Test TB11 je namenjen določitvi parametrov moči udarca, medtem ko je test TB42 namenjen določitvi nosilnosti cestne varnostne ograje. Oba testa sta enako pomembna za končno odločitev o izbiri konstrukcijske rešitve cestne varnostne ograje.

Osnova za konstrukcijo nove cestne varnostne ograje je bila atestirana ograja za raven zadrževanja N2. Njeni glavni sestavni deli so v celoti izdelani iz konstrukcijskega jekla S 235. Ščitnik je narejen iz 3 mm debele pločevine in v dolžino meri 4.200 mm, kjer je 200 mm namenjenih spoju med sosednjimi ščitniki. Distančnik ima obliko šestkotnika [6], s tem ima največjo zmožnost absorpcije energije trka in predvidljivo deformacijo, narejen pa je iz 4 mm

weight vehicles (personal vehicles), which sustain significant deceleration during impact. However, in this paper the ASI parameter is also used to assess a truck's impact conditions. Since it is calculated from filtered coordinate acceleration data and normalized by their limiting values, it represents a good measure of the normalized effective acceleration. Thus, it was used here to illustrate the influence of different road-safety barrier designs on overall vehicle behavior.

3 ROAD-SAFETY BARRIER DESIGN

Simulations were used to test different designs of road-safety barrier for the containment level H1. According to the SIST EN 1317 standard such safety barrier has to successfully sustain the impact of a personal vehicle (TB11 test) and a truck (TB42 test). A personal vehicle has a mass of $m = 900$ kg, an initial velocity of $v = 100$ km/h and impacts the barrier at an angle of $\alpha = 20°$ with regard to the guardrail. The truck has a mass of $m = 10{,}000$ kg and impacts the barrier with an initial velocity of $v = 70$ km/h at an impact angle of $\alpha = 15°$. The TB11 test is used to determine the impact-severity parameters and the TB42 test is used to test the load-carrying capability of such a system. Both tests are equally important when making the final choice of road-safety barrier design.

The new H1 road-safety barrier was a design upgrade of an already-certified safety barrier for the containment level N2. The main components of this safety barrier are made of construction steel S 235. The guardrail is made from 3-mm-thick metal sheet and is 4,200 mm long, where the splice length is equal to 200 mm. The distance spacer is shaped in a hexagonal form [6] to provide the highest crash-energy absorption and controllable deformation and pločevine. Steber je izdelan iz profila C izmer 100 × 55 × 4 mm, dolžine 1.900 mm. Ščitniki so medsebojno spojeni z vijačnimi zvezami z vijaki M16, v preostalih vijačnih zvezah pa so uporabljeni vijaki M10. Vsi uporabljeni vijaki so trdnostnega razreda 5.8.

Ta osnova cestne varnostne ograje je bila dodatno ojačana na dva različna načina. Enkrat z dodatno pasnico, ki je privijačena na hrbtni del distančnika, drugič pa s trapeznim vodilom, privijačenim neposredno na sprednji del stebra (sl. 3). Dodaten namen trapeznega vodila je preprečiti neposredni udarec kolesa vozila ob steber ograje ter tako zmanjšati pojemke v vozilu in zmanjšati moč udarca.

Pasnica in trapezno vodilo sta enake dolžine kakor ščitnik ograje in sta privijačena z vijaki M10. Debeline pločevin obeh ojačitev so bile predmet parametričnih numeričnih analiz. Debelina pločevine je obsegala vrednosti 3,0, 5,0 in 7,0 mm pri pasnici in 2,0, 2,5, 2,8 ter 3,0 mm pri trapeznem vodilu.

4 NUMERIČNE ANALIZE

4.1 Numerični model tovornega vozila

Za model tovornega vozila je bil uporabljen prosto dostopen model po MKE vozila Ford Single Unit Truck (poenostavljen) [7]. Dolžina tovornega vozila znaša 8,5 m, višina 3,3 m in širina 2,4 m (sl. 4.). Model po MKE sestavlja približno 22.200 linearnih končnih elementov z reducirano integracijsko shemo [8]. Od tega je okoli 1.000 prostorninskih, 500 linijskih elementov, ostalo pa predstavlja 20.700 lupinskih končnih elementov.

Model po MKE tovornega vozila je bil nekoliko spremenjen, da je ustrezal zahtevam standarda SIST EN 1317. Masa vozila je bila povečana iz 7.320 kg na

is made from 4-mm-thick sheet metal. The posts are C-shaped with dimensions of 100 × 55 × 4 mm and 1,900 mm long. The guardrails are joined together with M16 screws, while all other connections are made with M10 screws. All the screws are of strength class 5.8.

The basic design was additionally reinforced in two different ways. First, with a tension belt that is connected to the back of a distance spacer; and, second, with a wheel-guidance profile connected to the front of the post (Fig. 3). An additional purpose of the wheel guidance is to hinder the direct vehicle-wheel impact into the post, which results in smaller vehicle decelerations and lessens the severity of the impact.

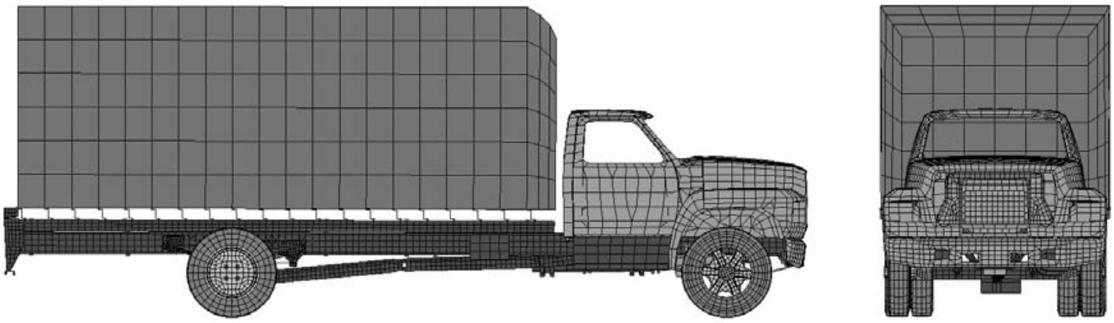
The tension belt and the wheel guidance are of the same length as the guardrail and connected with M10 bolts. The sheet-metal thicknesses of both reinforcements were the subject of a parametrical analyses. Thicknesses of 3.0, 5.0, and 7.0 mm were used for the tension belt and 2.0, 2.5, 2.8, and 3.0 mm for the wheel-guidance profile.

4 COMPUTATIONAL SIMULATIONS

4.1 Computational model of a truck

A publicly accessible FEM model of a Ford Single-Unit Truck (Reduced Model) [7] was used as a basic truck model in the computational simulations. The truck is 8.5-m long, 3.3-m high and 2.4-m broad (Fig. 4). The FEM model is made of approximately 22,200 linear elements with a reduced integration scheme [8]. It consists of 1,000 solid elements, 500 beam elements and the rest is represented by 20,700 shell elements.

The FEM model of the truck was subjected to further changes to fulfill the SIST EN 1317 standard. The vehicle mass was raised from 7,320 kg to 10,000 kg by increasing the material density of all



Sl. 4. *Model po MKE tovornega vozila Ford*
Fig. 4. *The FEM model of a Ford single-unit truck*

10.000 kg, tako da je bila povečana gostota vseh delov tovornjaka. V težišče tovornega vozila je bil dodan merilnik pospeškov kot tog lupinski končni element, ki omogoča zajem pomikov, hitrosti in pospeškov v lokalnem koordinatnem sistemu vozila.

4.2 Numerični model ograje

Podrobneje so bili modelirani ščitnik, steber in distančnik ograje, medtem ko so bile vijačne zveze modelirane poenostavljeno. Glede na rezultate prejšnjih simulacij in hitrost vozila je bila dolžina modelirane ograje omejena na 39 m, od tega 5 m ograje pred naletno točko tovornega vozila in 34 m za njo. Po celotni dolžini ograje je bilo razporejenih 19 stebrov in distančnikov na medsebojni razdalji 2 m.

Glavni sestavni deli cestne varnostne ograje so bili modelirani z lupinskimi elementi. Stebri in distančniki so bili modelirani z lupinskimi Belytschko-Tsayevimi končnimi elementi s tremi integracijskimi točkami po debelini, ščitniki, pasnice in trapezna vodila pa s polnimi integracijskimi lupinskimi elementi s petimi integracijskimi točkami po debelini, da je bil preprečen pojav nične deformacijske energije. Predpisana debelina končnih elementov je ustrezala konstrukcijski izvedbi posamezne ograje, kakor je navedeno v 3. poglavju. Vijačne zveze so bile modelirane z linijskimi Hughes-Liujevimi končnimi elementi. Celoten model ograje je tako sestavljen iz približno 100.000 elementov in 110.000 vozlišč.

Materialne lastnosti pločevin različnih debelin so bile določene s preizkusi. Glede na dobljene rezultate je bil izbran bilinearen izotropen elastoplastični model s kinematičnim utrjevanjem (preglednica 1). Porušitev materiala je bila predpisana z dejansko plastično deformacijo, ki je znašala 0,28.

Pri vijačnih zvezah z vijaki M10 je bil upoštevan trdnostni razred 5.8 z mejo plastičnosti 400 MPa in natezno trdnostjo 500 MPa, pri vijačnih zvezah z vijaki M16 pa so bile uporabljene vrednosti, navedene v preglednici 2. Te vrednosti so bile

the vehicle parts. A rigid shell element was added at the vehicle's center of gravity to act as an accelerometer and to record the displacements, velocities and accelerations in the local coordinate system of the truck.

4.2 Computational model of the safety barrier

The main safety barrier parts, the guardrail, the posts and the distance spacers were modeled in detail, while simplified modeling was used for the bolts. Based on previous simulations and the speed of the impacting vehicle the length of the modeled safety barrier was 39 m: 5 m before and 34 after the impact point. Along the whole length of the road-safety barrier 19 posts and distant spacers were placed 2-m apart.

Shell finite elements were used to model the main parts of the safety barrier. Posts and distance spacers were modeled with Belytschko–Tsay shell finite elements with three integration points through the shell thickness, while the guardrails, the tension belts and the wheel-guidance profiles were modeled using full-integration shell elements with five integration points through the thickness to prevent "hourglassing". The thicknesses of the shell elements were defined according to the construction plans of each design, as described in Section 3. The bolt connections were modeled with linear Hughes–Liu finite elements. The complete safety-barrier model consisted of approximately 100,000 finite elements and 110,000 nodes.

The material properties of the different sheet metal thicknesses were obtained experimentally. Experiment results were used to define an isotropic bilinear elastoplastic material model with kinematic hardening (Table 1). Material failure was prescribed according to the effective plastic deformation, which was set to 0.28.

A yield stress of 400 MPa and a limit stress of 500 MPa were prescribed for the M10 bolt connections of strength class 5.8, while the M16 bolt connections were modeled with the parameters presented in Table 2. The parameters were obtained from a correlation analysis

Preglednica 1. *Materialne lastnosti pločevin varnostne ograje*
Table 1. *Material properties of sheet-metal thicknesses*

d mm	E GPa	ν	σ_y MPa	E_t MPa	σ_u MPa
2,0 2,5 2,8 3,0	190	0,29	285	696	400
4,0 5,0 7,0	200	0,29	330	969	450

Preglednica 2. *Materialni podatki za vijačne zveze z vijaki M16*
Table 2. *Material properties for the M16 bolt connections*

E GPa	ν /	σ_y MPa	E_t MPa	ε_u %
190	0,29	240	0	170

dobljene s primerjavo med preizkusi in numeričnimi simulacijami vijačnih zvez z vijaki M16. Zaradi tega je dopustna dejanska plastična deformacija ε_u tako velika, saj zajema deformacijo celotne vijačne zveze in okoliškega materiala.

4.3 Začetni in robni pogoji

Robni in začetni pogoji za tovorno vozilo so predpisani s standardom SIST EN 1317. Vozilo pri testu TB42 je postavljeno pod kotom 15° glede na cestno varnostno ograjo s predpisano začetno hitrostjo, ki znaša 70 km/h.

Nadaljevanje ščitnika in ojačitev ograje je bila simulirana z vzmetnimi elementi (1 na sl. 5) ustrezne togosti in elastično linearno značilnico. Vpliv zemljine je bil simuliran z vzmetnimi elementi elasto-viskoplastičnih lastnosti spremenljivih po globini, ki je bila določena s predhodnimi parametričnimi simulacijami [9].

V modelu so bili predpisani štirje ločeni stiki: med posameznimi deli ograje, med posameznimi deli tovornega vozila, med desnim bokom tovornega vozila in ograjo ter med kolesi vozila in podlago. V prvih treh stikih je bila vrednost statičnega koeficienta trenja μ_s = 0,2, dinamičnega koeficienta trenja pa μ_d = 0,15. V zadnjem stiku pa je bila za oba koeficienta trenja uporabljena vrednost 0,3.

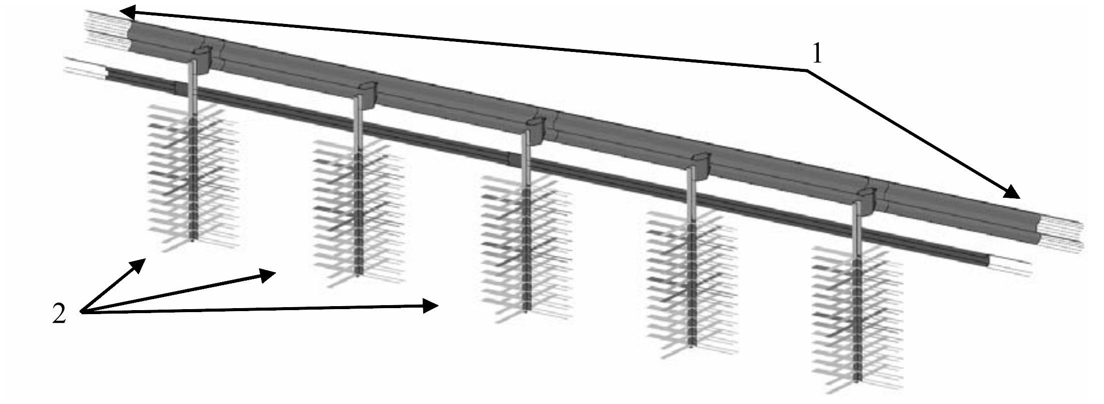
of the experimental measurements and the computational simulation of the M16 bolt connections. This explains the very high ultimate effective plastic deformation, ε_u, which actually accounts for the bolt and surrounding material deformation.

4.3 Initial and boundary conditions

The initial and boundary conditions for the vehicle are prescribed by the SIST EN 1317 standard. The impacting vehicle for the TB42 test is positioned at an angle of 15° to the safety barrier, and the initial velocity is equal to 70 km/h.

Continuation of the guardrail and the barrier reinforcement was modeled with spring elements (No. 1 in Fig. 5) with a linear elastic characteristic and an appropriate stiffness. The soil influence was simulated using spring elements with an elasto-viscoplastic characteristic varying with depth, which was obtained from previous parametric simulations [9].

Four different contact definitions were used in the model: between the safety-barrier parts, the contact between the vehicle parts, the contact between the impacting part of the vehicle and the barrier, and the contact between the wheels of the vehicle and the ground. The static and dynamic frictions in the first three contact definitions were set to μ_s = 0.2 and μ_d = 0.15, respectively. In the fourth contact definition, both friction coefficients were set to 0.3.



Sl. 5. *Robni pogoji za varnostno ograjo s stebri, zabitimi v zemljino*
Fig. 5. *Boundary conditions for a safety barrier with posts rammed into the soil*

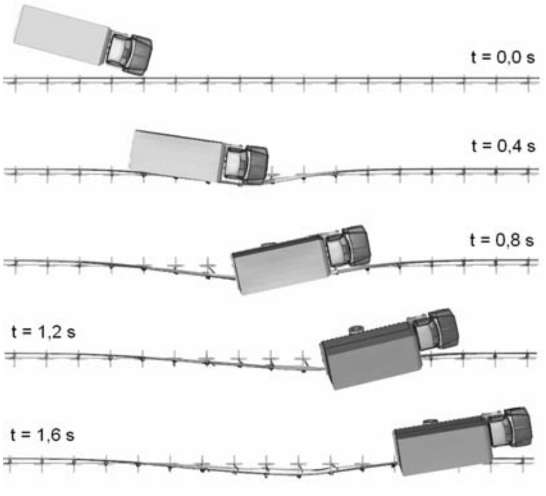
4.4 Parametri računalniške simulacije

Analiza naleta vozila v cestno varnostno ograjo je bila simulirana s programskim paketom LS-Dyna Version MPP 970. Vse predstavljene analize so bile izvajane na sistemu z osmimi procesorji Intel Pentium IV 3,2GH s tehnologijo prepleta pod operacijskim sistemom Linux. Računalniške simulacije so bile izvedene v časovnem koraku t = 1,6 s, takoj po prvem stiku med vozilom in ograjo. Časovni korak analize je bil samodejno izračunan glede na najvišjo prvo resonančno frekvenco celotnega modela in je znašal 1,7 µs. Izvajanje ene same simulacije je na opisanem sistemu trajalo med 100 in 110 urami.

5 ANALIZA NUMERIČNIH REZULTATOV

Razlike med poteki trka parametričnih analiz različnih debelin pasnic in vodila so zanemarljive, zato je potek trka prikazan le za eno simulacijo (sl. 6). Rezultati vseh analiz kažejo, da vse konstrukcijske različice cestne varnostne ograje vozilo uspešno preusmerijo nazaj na vozišče. Največja deformacija varnostne ograje je dosežena v času t = 0,8 s. Vozilo se loči od ograje v času t = 1,5 s.

Pred izračunom časovnega poteka parametra MVP so bili vsi zbrani pospeški filtrirani z uporabo filtra CFC 180 (najmanjša frekvenca zbiranja podatkov znaša 1800 Hz) kakor zahteva standard SIST EN 1317.



Sl. 6. *Potek naleta tovornega vozila ob cestno varnostno ograjo s pasnico*
Fig. 6. *The truck impact into a safety barrier reinforced with a tension belt*

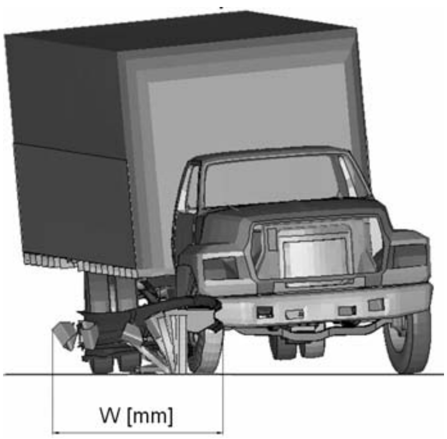
4.4 Computational simulation properties

The computational simulation of a vehicle impact into a road-safety barrier was performed using the dynamic explicit software code LS-DYNA MPP Version 970. All the simulations were done on a PC cluster with eight Pentium-IV 3.2-GHz processors with hyper-threading technology and a Linux operating system. The simulations were done for the time interval of 1.6 s after the first contact between the vehicle and the barrier. The time-step increment was computed with regard to the highest first-resonant frequency of the model, and was equal to 1.7 µs. One simulation run on the reported configuration took from 100 to 110 hours.

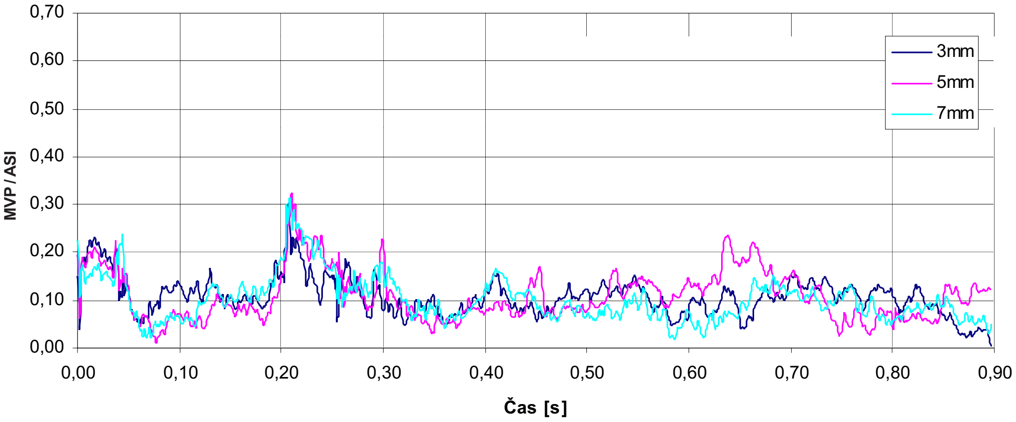
5 ANALYSIS OF THE COMPUTATIONAL RESULTS

Due to the similarity of the vehicle behavior for different sheet-metal thicknesses of the tension belt and the wheel guidance only one vehicle-impact sequence is shown in Fig. 6. The results of all the simulations prove that all safety-barrier designs redirect the impacting vehicle back on to the road. The maximum system deformation is observed at time t = 0.8 s. The vehicle separates from the barrier at time t = 1.5 s.

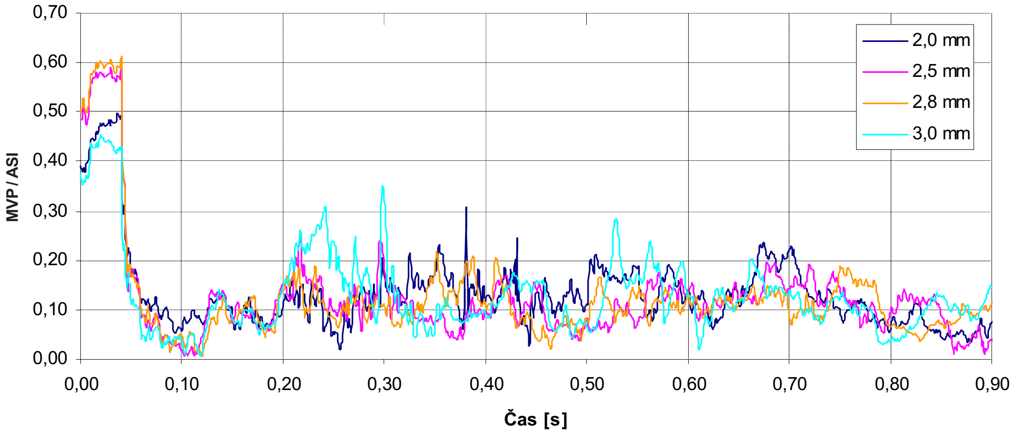
Before calculating the ASI parameter all the measured vehicle-mass acceleration data was filtered using a CFC 180 filter (the minimum measurement frequency equals 1,800 Hz) according to SIST EN 1317.



Sl. 7. *Delovna širina (W)*
Fig. 7. *Working width (W)*



Sl. 8. *Potek parametra MVP pri ograji s pasnico*
Fig. 8. *ASI parameter for the barrier with the tension belt*



Sl. 9. *Potek parametra MVP pri ograji z vodilom*
Fig. 9. *ASI parameter for the barrier with the wheel guidance*

Potek parametra MVP v odvisnosti od časa pri analizah cestne varnostne ograje s pasnico je prikazan na sliki 8, pri ograji z vodilom pa na sliki 9. Največje dosežene vrednosti parametra MVP so podane v preglednici 3. Pri obeh časovnih potekih parametra MVP sta opazna dva izrazitejša vrha. Eden takoj v času t = 0,0 s, ko pride tovorno vozilo prvič v stik z ograjo in drugi v času t = 0,2 s, ko kolo vozila zadene steber varnostne ograje. Primerjava obeh slik pove, da so povprečne in največje vrednosti parametra MVP pri varnostni ograji s trapeznim vodilom večje. Razlog za večjo togost je večja dolžina razvitega profila pri trapeznem vodilu, ki znaša l = 285,0 mm in le 75,4 mm pri pasnici. Togost cestne varnostne ograje z vodilom je dodatno povečana še zaradi neposredne pritrditve trapeznega vodila na stebre, medtem ko je pasnica privijačena na distančnik.

Primerjava poteka parametra MVP med enakimi ojačitvami različnih debelin pokaže manjše

The time dependency of the ASI parameter for the road-safety design with a tension belt is given in Fig. 8, and for a wheel guidance in Fig. 9. The maximum values of the ASI are presented in Table 3. In both time dependencies of the AIS parameter two distinct peaks can be observed. One immediately after the time t = 0.0 s, when the vehicle impacts the barrier, and the second one at t = 0.2 s, when the wheel hits the barrier post. A comparison of both figures reveals that the average and maximum values of the ASI are higher for the barrier with the wheel guidance. The reason is in the greater length of the unfolded profile of the wheel guidance, which equals l = 285.0 mm, and only l = 75.4 mm for the tension belt. The stiffness is additionally increased due to the direct connection of the wheel guidance to the posts, while the tension belt is connected to the distance spacer.

The comparison of the ASI parameter for the same reinforcements of different thicknesses shows razlike. Pri ograji s pasnico so največje dosežene vrednosti parametra MVP pri pločevinah različnih debelin enake, povprečne vrednosti pa pričakovano pokažejo manjše vrednosti pri tanjši pločevini. Pri ograji z vodilom je največja vrednost parametra MVP dosežena pri debelini pločevine d = 2,8 mm, kljub temu pa je pri tej debelini povprečna vrednost parametra MVP najmanjša. Večje povprečne vrednosti imata vodili debeline d = 2,0 mm in d = 3,0 mm, vendar imata manjšo največjo vrednost.

Razlike med vrednostmi delovnih širin (sl. 7) pri različnih debelinah pločevine cestne varnostne ograje ojačane s pasnico, so zanemarljive, medtem ko so razlike pri cestni varnostni ograji s trapeznim vodilom nekoliko večje. Pričakovali bi manjšo deformacijo ograje pri debelejši pločevini vodila, a izmerjeni rezultati kažejo drugače. Natančnejša analiza poteka trka pokaže, da je večji del te razlike posledica različne deformacije distančnikov in premikanja varnostne ograje med trkom. Primerjava vrednosti delovne širine med posameznima konstrukcijskima rešitvama pa pokaže manjše deformacije pri ograji z vodilom. To se sklada z ugotovitvijo o večji togosti te ograje.

6 SKLEP

Za oceno različnih konstrukcij varnostne ograje za raven zadrževanja H1 so bile izvedene računalniške simulacije naleta tovornega vozila v cestno varnostno ograjo na podlagi parametričnih nelinearnih dinamičnih analiz po metodi končnih elementov. Rezultati parametričnih analiz kažejo, da je z vidika moči udarca primernejša cestna varnostna ograja s pasnico. Ker vse konstrukcijske rešitve varnostne ograje s pasnico uspešno zadržijo vozilo na cestišču, je s cenovnega vidika najzanimivejša izbira najtanjše pasnice debeline 3,0 mm.

smaller differences. The maximum values of the ASI for the safety barrier with a tension belt are the same for all thicknesses, while the average values are lower for the thinner sheet metal, as expected. The highest value of ASI for the barrier with the wheel guidance is determined for the sheet-metal thickness d = 2.8 mm, while the average value of ASI is the lowest at the same time. Higher average values are recorded for metal thicknesses d = 2.0 mm and d = 3.0 mm, but with a lower maximum value.

The differences in working-width (Fig. 7) values for different sheet-metal thicknesses are negligible for the barriers reinforced with the tension belt, while they are more pronounced for the barriers reinforced with the wheel guidance. A lower working width is expected for the reinforcements with thicker sheet metal, but the results show otherwise. A more precise analysis of the impact shows that this effect can be attributed to the difference in the distance-spacer deformation and the barrier movement during impact. Comparisons of the working widths between both reinforcements show smaller deformations for the barrier reinforced with a wheel guidance. This is consistent with previous findings.

6 CONCLUSION

Computational simulations based on a parametric, nonlinear, dynamic finite-element analysis of a vehicle impact into a road-safety barrier were employed to evaluate different road-safety barrier designs for the containment level H1. The results of the parametric analyses showed that the barrier design reinforced with a tension belt is the appropriate choice when considering an impact severity. Because all the barrier designs with a tension belt successfully redirect the vehicle back onto the road the thinnest tension belt of thickness 3.0 mm is the best choice in terms of cost.

Preglednica 3. *Rezultati parametričnih simulacij cestnih varnostnih ograj*
Table 3. *Results of parametric simulations of road-safety barriers*

Ojačitev Reinforcement	d mm	maks MVP max ASI	Delovna širina Working width mm	Razred delovne širine Working width class
Pasnica Tension belt	3	17,5	1867	W6
	5	20,0	1820	W6
	7	19,3	1834	W6
Trapezno vodilo Wheel guidance	2,0	18,1	1519	W5
	2,5	18,3	1595	W5
	2,8	21,0	1682	W5
	3,0	13,9	1695	W5

Končna ocena o primernosti cestne varnostne ograje za raven zadrževanja H1, pa terja tudi upoštevanje delovne širine in preizkus cestne varnostne ograje z osebnim vozilom. Rezultati teh testov kažejo precej manjše vrednosti moči udarca pri varnostni ograji s trapeznim vodilom. Pri varnostni ograji s pasnico namreč pride do neposrednega udarca kolesa osebnega vozila v steber varnostne ograje, kar se kaže na večjih pojemkih, ki zaradi tega presežejo s standardom SIST EN 1317 predpisane mejne vrednosti. Tako lahko povzamemo, da je cestna varnostna ograja okrepljena s trapeznim vodilom najprimernejša konstrukcija varnostne ograje, ki izpolnjuje zahteve za raven zadrževanja H1.

Glede na rezultate simulacij je najprimernejša cestna varnostna ograja z vodilom iz pločevine debeline 2,0 mm, saj pomeni najboljšo poravnavo med povprečno in največjo vrednostjo parametra MVP ter ima hkrati tudi najmanjšo delovno širino.

For the final evaluation of the road-safety barrier's suitability for the containment level H1, the working width and the impact of a personal vehicle also had to be taken into account. The results of these computations show lower values of impact severity for the barrier with a wheel-guidance profile. In the case of the barrier with a tension belt the wheel of the personal car impacts directly into the post, and the higher accelerations that result in large impact-severity parameters exceed the limits defined in the SIST EN 1317 standard. It is, therefore, concluded that the safety-barrier design reinforced with the wheel-guidance profile is the most suitable choice to fulfill the H1 containment-level requirements.

According to the simulation results, the safety barrier with the 2.0-mm-thick wheel-guidance profile is the most appropriate design, since it offers the best compromise between average and maximum values of ASI and has the smallest working width.

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