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Research paper

On analysis of double-impact test of 1500-kg vehicle into w-beam guardrail system

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Abstract: Every day on roads many scenarios of accidents may occur. One of the measures to minimize their consequences is road safety barriers. Finite Element analyses are being increasingly used to support the physical testing of these devices. The paper addresses the issue of a secondary impact into the previously damaged w-beam guardrail system. This situation belongs to one of the most dangerous which can happen on roads and may cause serious hazards, especially if the vehicle goes through the barrier. To evaluate the crashworthiness of the road barrier, the computational model of the crash test was developed and validated against the full-scale crash test. Then two simulations of TB32 crash tests were conducted on both damaged and undamaged road barriers to assess the influence of damage on the effectiveness of the safety system during vehicular impact. The study has revealed that the partially damaged system preserved some of its original functionality.

Keywords: crash test, TB32, w-beam guardrail, numerical simulations, double-impact, crashworthiness

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1. Introduction

Road safety barrier, being one of the elements of road safety devices, as every engineering structure must fulfill the tasks it was designed to. Specifically, these are human safety and preventing damage to property. On the other hand, it is economically desirable that the barrier should not generate high building costs and maintenance costs. In the variety of road safety devices, these are safety barriers that are the most popular. Their main purpose is to constrain and redirect the vehicle and assure that the adverse loads acting on the passengers due to the crash are kept at an appropriate safe level [1-4]. Contemporary numerical simulation tools based on finite element method (FEM) make it possible to assess the influence of various factors on the overall performance of the given road safety barrier [5]. It is done at a relatively lower cost in comparison with field tests. The potential and possibilities offered by FEM are well-described in the literature [6-9]. It seems that the most popular FEM platform is Ls-Dyna (Livermore Software Technology Corporation, Livermore, CA, USA) [10-12]. It should be stressed however that responsible use of FEM in numerical simulations always requires appropriate knowledge and experience and the obtained results must be checked thoroughly.

A typical crash test involves a single collision of the vehicle with the safety barrier. Yet, in reality, other scenarios are possible [13-16]. One of them is the secondary collision with the partially damaged barrier, though still preserving some of its original functionality. Such a situation may occur during a car accident involving larger number of cars that collide with the barrier one after another. It can be observed that with small damages to the barrier, when the accident perpetrator was not found as his/her car was able to continue the ride, the damaged part is not replaced at once. Therefore, there exists a risk that another car may collide with the damaged barrier. Paper [17] presents the analysis of the double impact of a heavy vehicle into a concrete barrier. The barrier was tested in one TB11 and two successive TB81 crash tests. The second TB81 test was conducted for the previously impacted barrier. The study proved that the damaged barrier is capable to contain and redirect the second vehicle, that impacts the barrier.

The aim of the paper is the assessment of safety of the damaged barrier hit again by a vehicle. The study is based on numerical simulations in Ls-Dyna with a numerical model that was validated [18,19] against a field test. The following tests are analyzed:

- modified TB32 test (named Case no. 0),
- TB32 test with the undamaged barrier (Case no. 1),
- TB32 test with the initially damaged barrier (Case no. 2).

Considering Case no. 0, numerical simulation was conducted and the numerical model was validated against the full-scale crash test. The parameters of the test correspond to the TB32 crash test where the angle of impact was reduced from 20 degrees to 7 degrees (1500 kg, 110 km/h, 7°). In the remainder of the paper this test will be also referred to as the "modified TB32 test". The change in the impact angle was motivated by the need to obtain small damage to the barrier. Impacts at such an angle are frequently found on roads, see Fig. 1.

The parameters of the test of Case no.1, in which the vehicle hit the undamaged barrier, correspond to the TB32 crash test, i.e. 1500 kg, 110 km/h, 20°. This test enables the evaluation of the system under the impact conditions of the EN1317 standard crash test.

Case no. 2 refers to a test with an initially damaged barrier. The initial damage emerged as a result of vehicle impact at the angle of 7 degrees by conducting the modified TB32 test for Case no. 0. The parameters of the second impact into the damaged system, Case no. 2, correspond to the TB32 test.

Summarizing, Case no. 0 makes it possible to obtain initial insignificant damage to the system. Cases no. 1 and 2 enable the assessment and comparison of the performance of the damaged and undamaged barrier system during the TB32 test, including the evaluation of the safety of the vehicle occupants.

Fig. 1. View of damaged road barrier as a result of vehicle impact, impact angle was approx. 8 degrees (source: GDDKiA)

The paper uses keyword names in accordance with the LS-DYNA documentation [10-12]. The names and abbreviations of the test indices are given in accordance with EN 1317 [20,21].

2. Full-scale crash test validation

2.1. Numerical model

2.1.1. Safety Barrier

The object of the analysis is the w-beam safety barrier system. The main components of this safety system include the w-beam guardrail, the posts, and the spacers. The numerical model has been developed based on documentation from the full-scale crash test. The total length of the system is 72.8 m (60.0 m straight and two terminals, each 6.4 m long). The height of the system is 0.71 m and the width is 0.35 m. The post spacing equals 2.0 m. The length of the post is 1.6 m and it is embedded 0.98 m in the soil. The main steel parts of the barrier are modeled using fully integrated shell elements of approx. 10-15 mm size with an elastoplastic constitutive law assigned. The material properties were obtained from tensile tests conducted on the samples cut from the barrier. The soil is modelled as individual cylinders for each post (a similar solution can be found in e.g. [8,14]). The model of safety barrier consists of 449 700 nodes and 419 157 finite elements. The numerical model is depicted in Fig. 2 and Fig. 3.

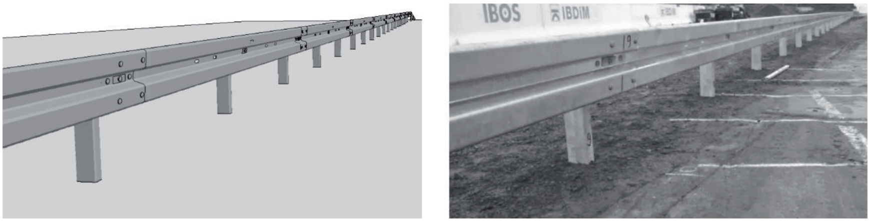


Fig. 2. Comparison between actual safety barrier and its numerical model

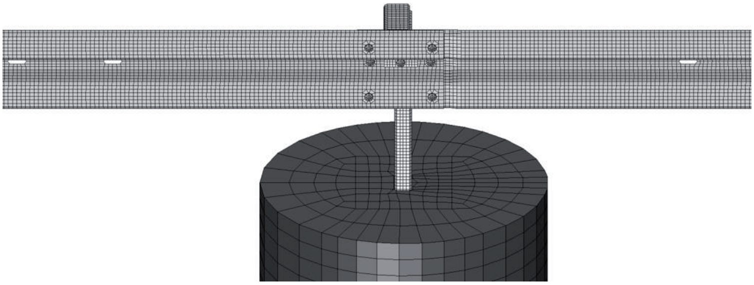


Fig. 3. FEM discretization details of guardrail, post and soil

2.1.2. Vehicle

In the numerical simulations as well as in the full-scale crash test, the BMW e34 520 model was used. The numerical model consists of 29 172 nodes and 28 011 finite elements. The most important vehicle's parameters are summarized in table 1. The general comparison between the actual vehicle and corresponding numerical model is depicted in Fig. 4.

Table 1. Comparison of the numerical model and the full-scale vehicle

	Numerical model	Actual vehicle	EN 1317	Condition
Mass	1521.9 kg	1530.2 kg	1500 ± 75 kg	Fulfilled
Length	4.713 m	4.700 m	n/a	n/a
Width	1.768 m	1.760 m	n/a	n/a
Center of mass location	CG$_X$: 1236 mm CG$_Y$: 1 mm CG$_Z$: 524 mm	CG$_X$: 1323 ± 8 mm CG$_Y$: 7 ± 5 mm CG$_Z$: 553 ± 8 mm	CG$_X$: 1.240 ± 124 mm CG$_Y$: ± 80 mm CG$_Z$: 530 ± 53 mm	Fulfilled
Number of axles	2	2	n/a	n/a
Wheelbase	2.76 m	2.77 m	n/a	n/a
Wheel track (front/rear)	1.49/1.49 m	1.43/1.47 m	1.500 ± 0.225 m	Fulfilled
Wheel radius	0.295 m	0.29/0.30 m	n/a	n/a

Fig. 4. Comparison between the full-scale BMW vehicle and corresponding numerical model

2.2. Validation

The results of numerical simulation of Case no. 0 are compared with the results of the crash test which was conducted on the 21th of October 2016 by the Road and Bridge Research Institute (IBDiM, www.ibdim.edu.pl) in the Research Institute for Protective Systems (IBOS, www.ibos.com.pl) in Inowrocław, Poland. It was a modified TB32 crash test (110 km/h, 1500 kg), and the modification regarded the impact angle which was altered from 20° to 7°. The simulation was conducted using LS-DYNA software (MPP double-precision R10.1) on four 12-cores Intel® Xeon® Processors E5 v3 @ 2.3 GHz (i.e. total of 96 threads). The time of the calculation was approx. 6 hours.

In the crash test and in the simulation, the car struck the barrier at a distance of 21 cm after the post no. 11. The measured impact speed equaled 114 km/h, and the impact angle was 7.06°. The safety barrier contained the vehicle. After approx. 0.15 s after the impact, the vehicle started to be redirected and continued its movement. The vehicle-barrier contact lasted approx. 0.35 s. The most important crash test indices are listed in table 2. A visual representation of the vehicle trajectories in the full-scale crash test as well as in the numerical simulation is displayed in Fig. 5. The comparison of the ASI course and its assessment based on MPC and ANOVA metrics is depicted in Fig. 6. All criteria are met. Because of the small impact angle, the damage of the barrier was not significant. The screws connecting the guardrails were not broken. Fig. 7 presents the lateral displacements of front and rear points on the length of the barrier obtained from numerical simulation and its comparison to the measured ones after the experimental test. The requirement of the exit box was met. It should be noted that the values of the indices are small and, as expected, the impact into the considered barrier at 7 degrees and 110 km/h did not result in serious damage to the vehicle or vehicle occupants.

Table 2. Comparison of the numerical and the full-scale crash test results

	Simulation	Crash test
ASI	0.5	0.6
THIV, km/h	19	19
Working Width, m	0.5	0.7
Dynamic deflection, m	0.3	0.4
Length of contact, m	6.3	7.9

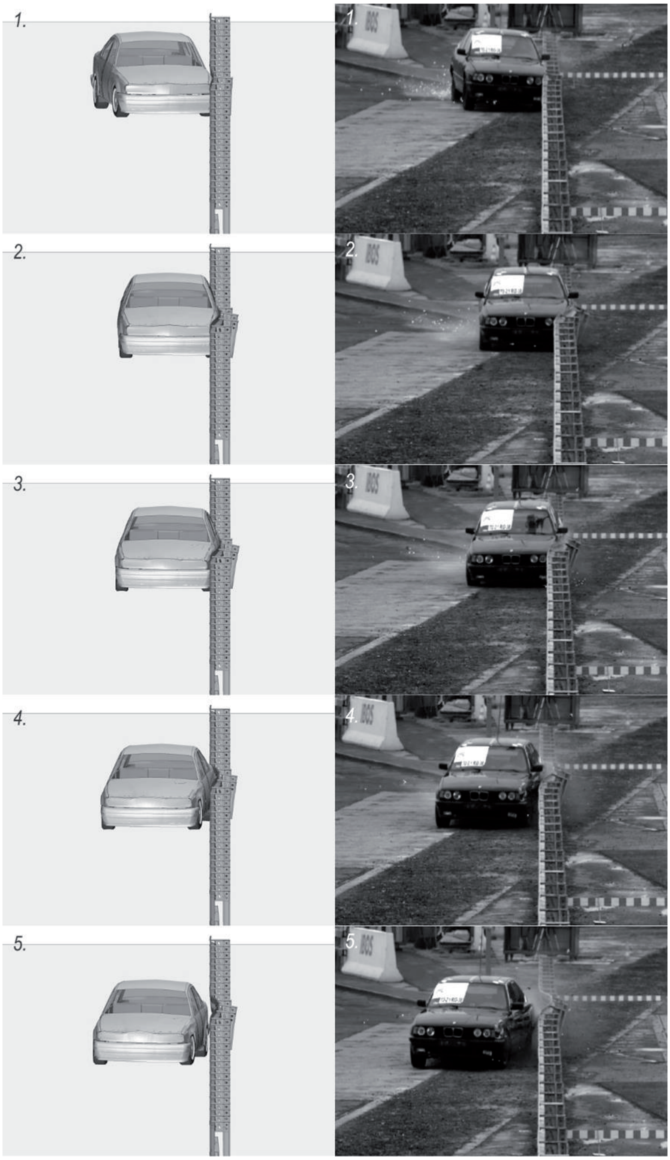
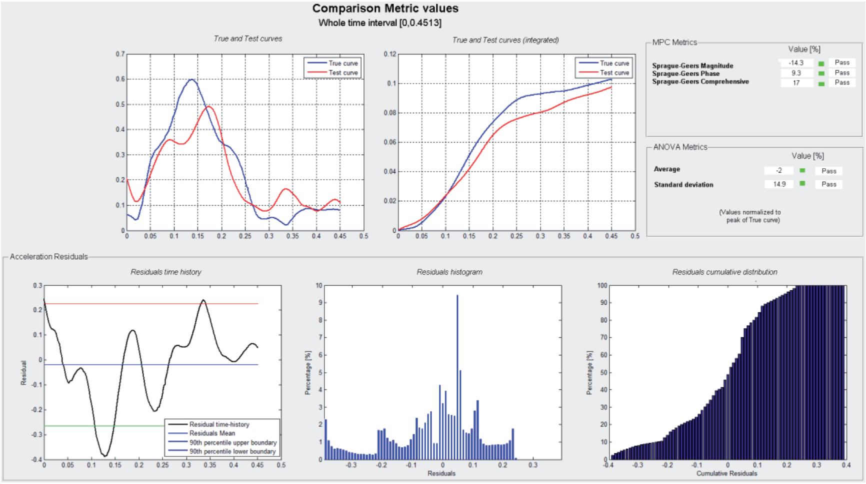


Fig. 5. Comparison of trajectories in simulation and full-scale crash test



MPC Metrics

	Value [%]		
Sprague-Geers Magnitude	-14.3	🟩	Pass
Sprague-Geers Phase	9.3	🟩	Pass
Sprague-Geers Comprehensive	17	🟩	Pass

ANOVA Metrics

	Value [%]		
Average	-2	🟩	Pass
Standard deviation	14.9	🟩	Pass

(Values normalized to peak of True curve)

Fig. 6. Comparison of ASI curves using RSVVP code: blue — full-scale crash test; red — simulation

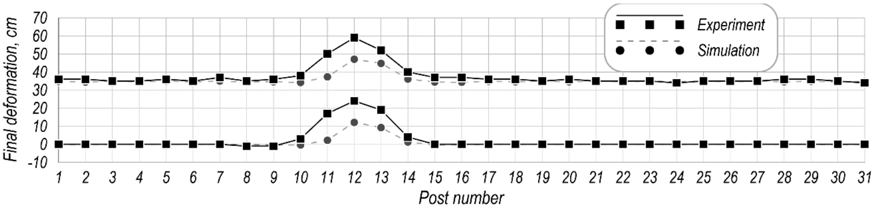


Fig. 7. Comparison of lateral displacement of the barrier

3. Analyses of the second impact

This section presents the analysis of the second impact into the damaged road barrier. For comparative purposes, the simulation of the TB32 vehicular impact test on the barrier intact was also conducted. The vehicle crash into the undamaged barrier is be referred to as Case no. 1 and the impact into the initially damaged barrier as Case no. 2. The general trajectory for the simulations is presented in Fig. 8. The impact speed for both cases equaled 112 km/h and the impact angle was 20°. The impact point was 56 cm behind the post no. 11. Then, in both cases, the vehicle started moving closely to the guardrail for about 0.5 s. While the vehicle's body was sliding on the guardrail, the left, front wheel of the vehicle hit the consecutive posts (no. 12, 13, 14), breaking the connections with the corresponding spacers. In both cases, the barrier properly contained and redirected the vehicle. Case no. 1 resulted in the working width equal to 1.1 m, the dynamic deflection of 0.9 m, and the length of the contact equal to 8.1 m. Similar results were obtained for the Case no. 2., the only difference was for the length of the contact, and it equals 8.2 m. Concerning the occupant severity indices the ASI equals 0.8 for Case no. 1, and ASI equals 0.9 for Case no. 2. On the other hand, THIV for Case no. 1 and no. 2 equals 28.4 km/h and 22.8 km/h, respectively. Those results are summarized in Table 3. The differences in the results are small due to the fact that the initial damage of the barrier in Case no. 2 were not significant - compare snapshots no. 1 at the top of Fig. 8. The details of the final deformations for the barrier from the two different views are depicted in Fig. 9 and Fig. 10. The comparison of the effective plastic strain surface plots is also presented in Fig. 11. The values are presented in the greyscale, where the darker colour represents the higher effective plastic strain value with the maximum value of 0.1.

Table 3. Results of analyses

TB32 crash test simulation	Undamaged barrier	Damaged barrier
ASI	0.8	0.9
THIV, km/h	28.4	22.8
Working Width, m	1.1	1.1
Dynamic deflection, m	0.9	0.9
Length of contact, m	8.1	8.2

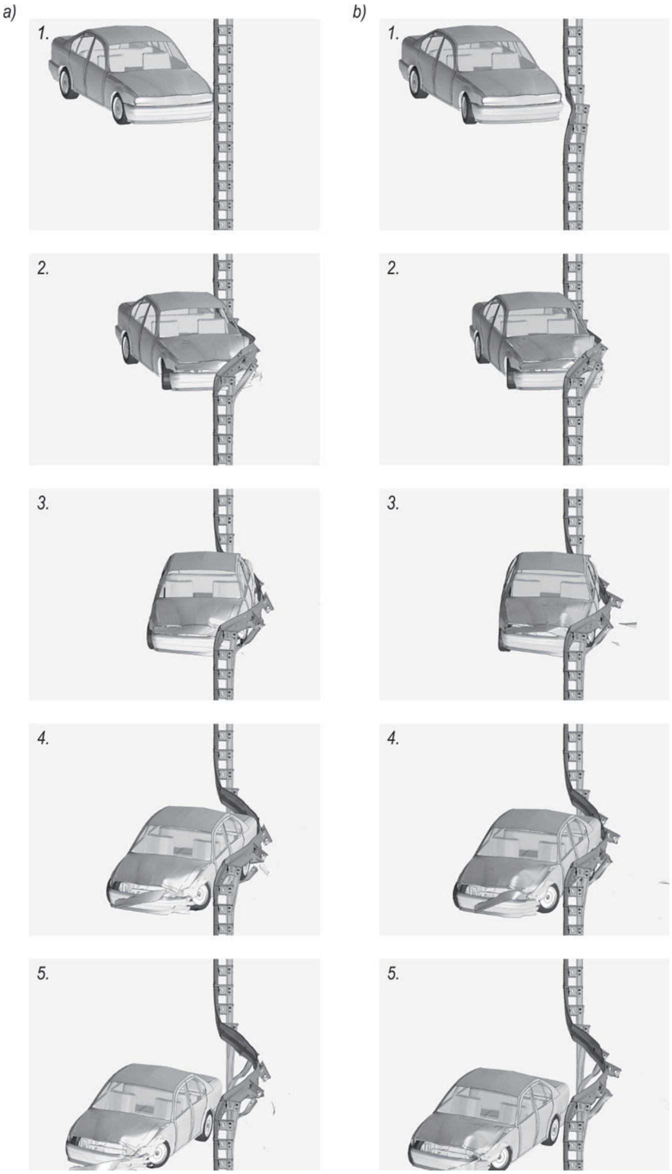


Fig. 8. Comparison of the trajectories for the TB32 crash test in the a) intact barrier b) damaged barrier

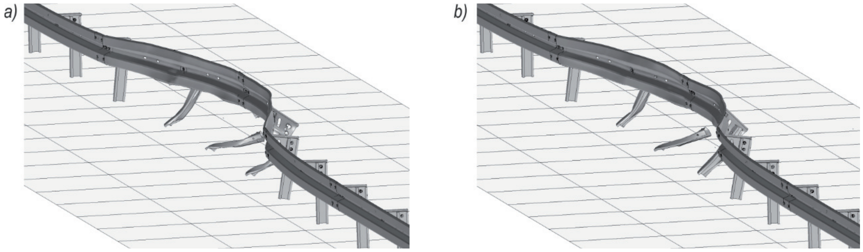


Fig. 9. Front view of the final deformation of the steel barrier after the TB32 crash test in the a) intact barrier, b) damaged barrier

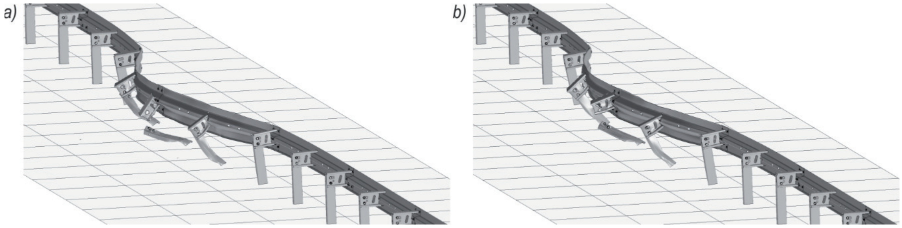


Fig. 10. Rear view of the final deformation of the steel barrier after the TB32 crash test in the a) intact barrier, b) damaged barrier

Fig. 11. Effective plastic strain contour plots after the TB32 crash test in the a) intact barrier, b) damaged barrier

4. Conclusions

The article presents the analysis of the double-impact of the vehicle into the steel road barrier. The second vehicular impact into a previously damaged barrier system can be a serious hazard. For the purpose of the analysis, the numerical model of a 1500-kg vehicle impact into the road barrier at the speed of 110 km/h and the angle of 7 degrees was developed and validated against the results from the full-scale crash test. Then, this computational model was used to conduct and evaluate the vehicle impact at the angle of 20 degrees (i.e. TB32 crash test). These TB32 tests were carried out for the damaged as well as the undamaged barrier system. Studies have shown that the considered system, which was previously struck, preserve part of its original functionality, however, the barrier deformation and the severity for the vehicle crew during the second impact is slightly higher than in the case of the impact into the undamaged system. Therefore, any damaged w-beam barrier system should be repaired or replaced immediately.

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Analiza podwójnego uderzenia pojazdem o masie 1500 kg w barierę o prowadnicy typu W

Słowa kluczowe*: test zderzeniowy, TB32, prowadnica typu W, symulacje numeryczne, podwójne uderzenie, analiza wypadków*

Streszczenie:

Systemy ograniczające drogę stosuje się, aby redukować potencjalnie negatywne skutki zjazdu pojazdów z toru jezdni. Przede wszystkim chodzi o zminimalizowanie występowania obrażeń bądź ich intensywności dla uczestników ruchu, w tym dla kierujących pojazdami, pasażerów oraz pieszych. Jednym z typów wypadków są zderzenia pojazdów z barierami drogowymi pod względnie małym kącie uderzenia. Charakteryzują się tym, że bariera pozostaje w niewielkim stopniu zdeformowana, a kierowca często może kontynuować jazdę i odjeżdża z miejsca zdarzenia. Może zdarzyć się tak, że tego typu uszkodzenia przez długi czas pozostają niezgłoszone do służb utrzymujących drogi. Może to powodować, że taki odcinek bariery drogowej może zostać wtórnie uderzony. W związku z powyższym postanowiono przyjrzeć się temu zjawisku przy pomocy narzędzia w postaci symulacji numerycznych MES.

Aktualnie metody numeryczne MES są używane na całym świecie, przez wszystkie czołowe Uniwersytety, firmy z branży motoryzacyjnej oraz bezpieczeństwa ruchu drogowego. Niewątpliwą zaletą jest redukcja kosztów w porównaniu do pełnowymiarowych testów zderzeniowych, przy jednoczesnym zachowaniu wiarygodności wyników. Warunkiem wiarygodności jest kompetentny zespół badaczy lub pracowników, który przeprowadza symulację oraz przyrównanie wyników symulacji do co najmniej jednego rzeczywistego testu zderzeniowego. W tej pracy wybrano właśnie tę drogę, gdzie przygotowany został model numeryczny ok. 73 m stalowej bariery drogowej o prowadnicy typu W. Następnie skorzystano z numerycznego modelu samochodu marki BMW o masie 1500 kg, którym zasymulowano uderzenie w tę barierę z prędkością 110 km/h pod kątem 7°. Wyniki tej symulacji porównano z rzeczywistym testem zderzeniowym przeprowadzonym przez Instytut Badawczy Dróg i Mostów (IBDiM) na poligonie Instytutu Badań Ochronnych Systemów (IBOS) w Inowrocławiu. Walidację symulacji numerycznej przeprowadzono zgodnie z raportem technicznym PD CEN/TR 1603-1:2012. Raport ten dopuszcza pewien subiektywizm podczas walidacji, aby go ograniczyć zdecydowano się dodatkowo porównać rezultat ASI z symulacji i pełnowymiarowego testu przy pomocy wskaźników MPC oraz ANOVA, które służą do zbadania podobieństwa dwóch krzywych. Na podstawie przeprowadzonej walidacji użyte modele uznano za poprawne, przez co można przejść do kolejnego kroku.

Po poprawniej walidacji modelu przeprowadzono symulację numeryczną zderzenia TB32 (110 km/h, 20°) w dwóch wariantach:

- Przypadek 1-szy - zderzenie z barierą nieuszkodzoną,
- Przypadek 2-gi - zderzenie z barierą wstępnie uszkodzoną pojazdem BMW 1500 kg, który uderzył w nią z prędkością 110 km/h pod kątem 7°.

Rezultaty symulacji porównano ze sobą i rezultaty pokazują, że wskaźniki deformacji bariery: szerokość pracująca oraz ugięcie dynamiczne (wg EN 1317), dla obu przypadków wychodzą sobie równe. Jeżeli chodzi o wskaźniki intensywności zderzenia ASI oraz THIV (wg EN 1317) to ASI wychodzi nieznacznie wyższe dla przypadku ze wstępnie uszkodzoną barierą, natomiast dla tego samego przypadku THIV uzyskało wartość niższą. Rezultaty pokazują, że barierę podczas obu przypadków zderzenia można zaklasyfikować do tej samej klasy. Większe różnice przy obu przypadkach można zauważyć dopiero podczas analizy efektywnych plastycznych odkształceń, gdzie dla wstępnie uszkodzonej bariery można zaobserwować większe uplastycznienie w okolicach otworów śrubowych.

W pracy przebadano stalową barierę drogową o prowadnicy typu W. Poprawnie przeprowadzono walidację modelu, a następnie dokonano analizy przypadku zderzenia TB32 w barierę nienaruszoną oraz wstępnie uszkodzoną.

Z przedstawionych rezultatów wynika, że dla testu TB32 bariera utrzymała swoje cechy funkcjonalne, tj. zachowała swoją klasę szerokości pracującej, ugięcia dynamicznego, oraz intensywności zderzenia. Poza tym poprawnie powstrzymała i wyprowadziła pojazd na swój tor. Należy mieć na uwadze, że jest to wyłącznie analiza konkretnego przypadku i w celu wyciągania bardziej ogólnych wniosków należałoby ją odpowiednio rozszerzyć. Kolejnym kierunkiem do badania mogłoby być sprawdzenie jak uszkodzony system mógłby się zachować przy zderzeniu o większej energii kinetycznej, np. uderzenie pojazdem ciężkim.

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