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Development of a continuous motorcycle protection barrier system using computer simulation and full-scale crash testing

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ABSTRACT

Road restraint systems are designed to minimize the undesirable effects of roadside accidents and improve safety of road users. These systems are utilized at either side or median section of roads to contain and redirect errant vehicles. Although restraint systems are mainly designed against car, truck and bus impacts there is an increasing pressure by the motorcycle industry to incorporate motorcycle protection systems into these systems.

In this paper development details of a new and versatile motorcycle barrier, CMPS, coupled with an existing vehicle barrier is presented. CMPS is intended to safely contain and redirect motorcyclists during a collision event. First, crash performance of CMPS design is evaluated by means of a three dimensional computer simulation program LS-DYNA. Then full-scale crash tests are used to verify the acceptability of CMPS design. Crash tests were performed at CSI proving ground facility using a motorcycle dummy in accordance with prEN 1317-8 specification. Full-scale crash test results show that CMPS is able to successfully contain and redirect dummy with minimal injury risk on the dummy. Damage on the barrier is also minimal proving the robustness of the CMPS design. Based on the test findings and further review by the authorities the implementation of CMPS was recommended at highway system.

1. Introduction

Motorcyclists are among the vulnerable road users (SWOV Institute for Road Safety Research, 2012). It is obvious that powered two wheels or PTWs are less stable and less visible than cars on the road and lack occupant compartment protection for riders. Thus, motorcycle accidents, though not necessarily more frequent than other types of accidents, are more likely to result in serious injury or death of the motorcyclists (Nordqvist et al., 2015; European Commission, 2015; Lenné et al., 2015).

Motorcycle safety is an important topic all over the globe. There are about 33 million PTWs in Europe where Greece, Italy, France, UK, Spain and Germany have the highest motorcycle fatality rates in the EU. According to the CARE database, there were 32.951 people killed on EU-15 roads, 3.998 of those are riders and passengers of PTWs (Garcia et al., 2009). Porter (Porter, 2011) mentioned that in the European Union the risk of motorcyclist fatality is 20 times that of a car passenger. On the other hand, the US statistical data suggest that per mile travelled in 2006, there were 35 times more deaths from motorcycle accidents than from car accidents (IIHS, 2013). In 2006, motorcycles accounted for approximately 1% of traffic on UK roads, but accounted for 19% of fatal and serious casualties indicating that they are over-represented in the national casualty statistics (Williams et al., 2008). According to a recent study the most common motorcycle crash type is when automobile maneuvers into the path of an oncoming motorcycle at an intersection (McCarthy et al., 2007).

Even though the number of motorcyclist killed on roads has decreased in the EU between 2010 and 2013, the number of fatalities still represent a fairly large percentage. One of the prime reasons for motorcyclist fatalities during roadside accidents are the presence of non-motorcycle friendly steel guardrail barrier systems with posts. Research by FEMA (FEMA, 2015) showed that unprotected guardrail posts are the leading cause for most serious injuries and high rate of fatalities for motorcyclists.

Abbreviations: ATD, anthropomorphic test device, Hybrid III 50th percentile male ATD; CEN, European Standardization Committee; CMPS, continuous motorcycle protection system; DMPS, discontinuous motorcycle potection system; EN, European Norm; EU, European Union; FEMA, The Federation of European Motorcyclists' Associations; MAIDS, Motorcycle Accident In Depth Study; MPS, motorcycle protection System; PTW, powered two-wheelers; SMC, The Swedish Motorcyclists Association; TC, Technical Committee; prEN, European pre-Norm; Wd, working width; SL, severity level; RRS, road restraint system

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Although the alarming situation of the motorcyclist safety in Europe the use of Motorcycle Protection Systems, or MPS, are still non-mandatory. Motorcycle Protection System is any device installed on a barrier or in its immediate surroundings, the purpose of which is to reduce the severity of a PTW rider impact against the barrier. Nevertheless, there is a detailed testing and evaluation specification, prEN 1317–Part 8 that exists in the Europe (CEN/TC226/WG1, 2011). This specification was developed on the basis of Spanish norm UNE 135900 for "Performance evaluation and acceptance criteria of motorcyclist protection systems in safety barriers". MPS manufacturers in Europe use this specification for the development of state-of-the-art motorcycle friendly designs.

In this paper an existing steel road restraint system was upgraded with a MPS to improve its safety performance. The crash test performance and acceptability of the new MPS design was fully evaluated using finite element analysis and full-scale crash testing. Results of the study show that MPS contains and redirects impacting dummy with minimal risk of injury. The rest of the paper explains the testing and evaluation details of MPS design.

2. European standard prEN 1317-8 on motorcyclist protection

The prEN 1317-8: "Motorcycle road restraint systems which reduce the impact severity of motorcyclist collisions with safety barriers" test specification separates MPDs in two classes: The first type is CMPS, which are MPS placed continuously along a barrier with the purpose of retaining and redirecting an impacting rider, usually preventing direct impact with aggressive elements of the barrier such as posts, anchorages or module connections. It also prevents a sliding rider from passing between the posts of a barrier and coming into contact with any potential hazard that may be behind the barrier. The second type is DMPS, which are MPS placed locally around a potentially aggressive element of a barrier, such as a post, anchorage or module connection, with the purpose of reducing the severity of a direct impact of the rider against it. This type of system is not intended to contain fallen PTW riders due to the discontinuous protection along the length of the barrier (CEN/TC226/WG1, 2011). The design evaluated in this paper is a continuous MPS or CMPS.

2.1. Full scale crash testing details of MPS in prEN 1317-8

According to prEN 1317-8, for a full-scale impact test the minimal length of the test item has to be sufficient to demonstrate the full performance of the MPS and must be installed according to the installation manual provided by the manufacturer, test person or organization. The installation manual also specifies the height above the ground of the lower edge or the elements designed to retrain the PTW rider.

Full-scale tests consist of launching an ATD against the test item in accordance with a determined approach path and test condition. As shown in Fig. 1, for each TM the ATD is launched lying face-up in a "supine decubitus" position, e.g., face up in a horizontal position and completely stretched out on its back, with its upper limbs parallel and adjacent to its trunk, with the palms of its hands oriented towards its trunk, sliding with its back and legs stably in contact with the ground (CEN/TC226/WG1, 2011). The ATD, equipped with an integral type, production motorcycle helmet weighing 1.3 kg with polycarbonate shell, is dressed in one-piece motorcycle suit, leather gloves, and leather boots. The surfaces of the helmet and the test item in the impact area have to be clean, dry and free of any item or substance that may affect the contact between both surfaces.

Table 1 lists test details and performance classes specified in prEN 1317-8 for the testing and evaluation of a MPS (CEN/TC226/WG1, 2011). As shown in this table, tests are run at either 60 or 70 kph. Table 2 illustrates the tests specified for CMPS in prEN 1317-8 based on classes C60 and C70. TM shown in these tables abbreviate Test of Motorcycle. The numbers 1, 2 or 3 come after TM describe the launch configurations for the dummy to the barrier (CEN/TC226/WG1, 2011). Fig. 2 illustrates directions 1, 2 and 3 representing post centered, post offset and mid span, respectively. For the post-centered impact test, designated as TM1, the approach path of the ATD is defined by a line, parallel to the ground, passing through the center of the post section and forming a 30° angle with respect to the centerline of the undeformed test item. This test is required to measure the effectiveness of CMPS in protecting dummy.

For the mid-span impact test, designated as TM3, the approach path of the ATD is also defined by a line, parallel to the ground, passing through the two consecutive posts of the barrier. This test is launched to test the robustness of the test item where it is most flexible and to evaluate the potential for the trapping of limbs in the area where this is most likely to occur. The dynamic deformation of the test item during the test with the ATD is characterized by the working width, Wd. As shown in Fig. 3, if a hand of the ATD protrudes past the rearmost part of the system during the test then the position of this ATD part is taken into account in the determination of the Wd. Protrusion of any other ATD part is constituted as a failure of the test.

2.2. Full scale crash test evaluation criteria in prEN 1317-8

On basis of full scale crash tests of MPS the following three performance indicators are reported:

1. Speed class, which is determined by the impact speed of the tests performed;
2. Severity level, which is determined by the level of the biomechanical indices from data obtained from the ATD instrumentation during the test;
3. Working width (Wd), which is the distance between the foremost part of the un-deformed system and the maximum dynamic lateral position of any part of the system.

The severity levels of an MPS are determined by the maximum values of the biomechanical indices measured from the head and neck regions of the dummy during a full scale crash test. Table 3 provides severity level thresholds for the evaluation (CEN/TC226/WG1, 2011).

Severity levels, SL, defined as Level I or Level II in prEN 1317-8, are determined based on full scale crash test results as indicated in Table 3. Values Fx, Fz_{ten} and Fz_{comp} are taken from Figs. 4–6 and finally severity level is determined by the level of the biomechanical indices from data obtained from the ATD instrumentation. Either SL is achieved only when the values of all biomechanical indices in the table are equal or less than the corresponding maximum limits. The SL that will apply to a MPS, for a given speed class, is the highest of the SL obtained from the impact tests performed.

Following the test, the ATD is not allowed to remain trapped in the test item and is deemed to be trapped when in contact with the test item in such a way as to require further deformation or displacement of the test item, or dismantling of the ATD, in order to remove the ATD from the test item. No limb nor the head or neck of the ATD is allowed to become totally detached from the ATD following the impact with the test item, no lacerations to the ATD flesh resulting from the test. If the Wd of the test item exceeds the working width of the barrier tested according to EN 1317-2, then the working width of the complete tested item is equal to the Wd of the MPS test. In addition, any barrier incorporating a MPS design must also meet to the requirements of EN 1317-2 for the appropriate containment level.

3. Details of CMPS design developed

The CMPS design used in this study was developed by the Pass + Co engineers. Since MPS design are not separate systems CMPS design studied herein was incorporated onto an existing vehicle restraint

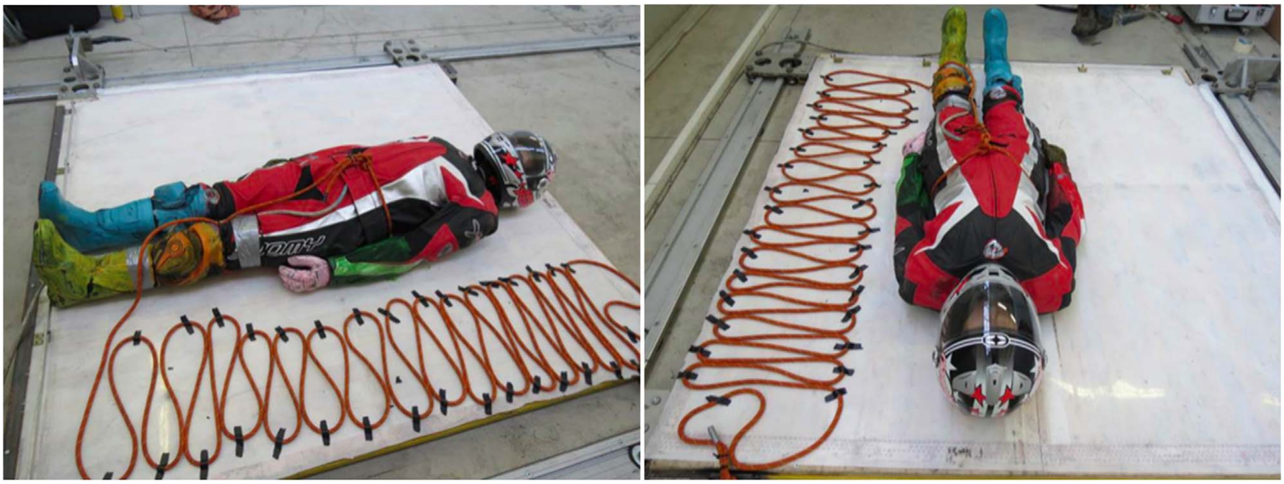


Fig. 1. Supine decubitus position of ATD before full scale crash testing.

Table 1
MPS test details in prEN 1317-8.

Test	MPS type	Launch configuration	Speed (km/h)
TM 1.60	CMPS and DMPS	Post-Centered	60
TM 2.60	DMPS	Post offset	60
TM 3.60	CMPS	Mid-span	60
TM 1.70	CMPS and DMPS	Post-Centered	70
TM 2.70	DMPS	Post offset	70
TM 3.70	CMPS	Mid-span	70

Table 2
Tests specified for CMPS in prEN 1317-8.

Class	Tests required	
C60	TM 1.60	TM 3.60
C70	TM 1.70	TM 3.70

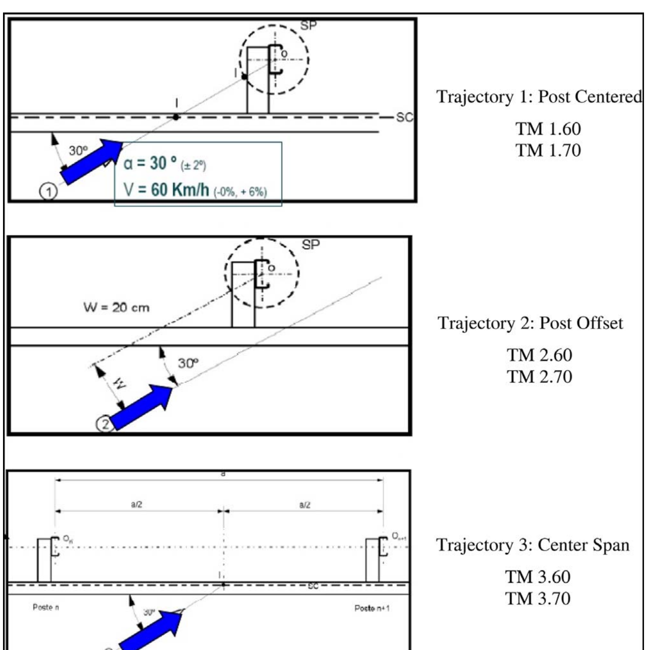


Fig. 2. ATD launch configurations in prEN 1317-8.

system shown in Fig. 7. As shown in this figure, the post spacing of the existing system was 2.0 m and systems was consisted of a C120 post and 2.5 mm B-type rail with a top height of 730 mm. Basically, CMPS design incorporated an extra continuous 1.5 mm thick lower rail below the existing rail and a 5 mm thick connector plate between upper and lower rails. Even though developing the CMPS design seems a fairly straightforward task, several other details were also considered to make sure that the design is as forgiving as possible for motorcyclist impacts. For example, the lower rail to post connection, location and thickness of rail connector were altered and geometries of the CMPS parts were varied until the expected performance levels were reached.

The first design improvement was, as shown in Fig. 8, the enlargement of slot holes which facilitated smoother barrier response and improved the flexibility of the system. The second design consideration was the position of spacers. As shown in Fig. 9, three different rail hanger positions were evaluated and it was decided that utilization of spacers at mid-span locations provided most favorably in terms of injury risk for the ATD. Finally, in order to attenuate the shock, reduce the impact forces on motorcyclists the lower beam was rotated counter clockwise and raised from ground level as illustrated in Fig. 10. Top height of the CMPS system was 730 mm from ground level and Table 4 illustrates the name, dimensions, material properties and characteristics of materials used in Pass + Co CMPS design.

4. Finite element study of CMPS model

4.1. Model development

To accurately predict the crash test behavior of the CMPS design an identical finite element model of the system was developed using LS-DYNA software (LSTC, 2014). Similar studies in the past investigated the adequacy of different motorcycle protection systems using finite element simulations (Mantaras and Luque, 2015). The CMPS model developed consisted of 32528 nodes and 30105 shell elements. There were no solid elements in the model. The shell elements of the rail that are expected to undergo direct vehicle contact and experience severe deformations are modeled with full integration formulation to accurately represent the complex interactions and behavior. All other sections were modeled with default belytschko-tsay formulation for computational efficiency.

Since rail material sustains impact loads and possible crushing, large plastic deformations are likely to occur in the rail. To account for these, a piecewise linear plastic material definition was used to model both rails. Since most of the crushing and energy absorption is expected to take place at rail, a relatively coarse mesh was selected for the posts and rail connectors for computation efficiency. As shown in Table 5, a

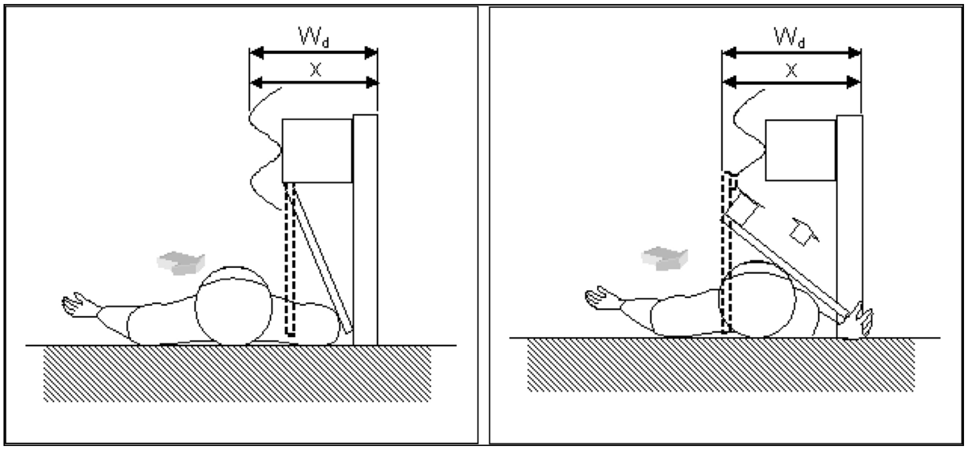


Fig. 3. Working width determination and acceptable performance of CMPS in prEN 1317-8.

piecewise linear material definition was used to represent the material properties of CMPS model developed.

In an actual CMPS installation, connections between the members, such as post to rail were established using bolts and nuts. To accurately represent the behavior of these connections during impact loading CONSTRAINED_SPOTWELD option in LS-DYNA was used. By definition, this option keeps members connected until a certain force criteria is met. Then the connection fails and members allow moving freely. To determine the required force level that fails a bolt, a detailed post-to-rail connection model was constructed using LS-DYNA. The behavior of connection was examined under different loading conditions. A reasonable failure criterion obtained from the component simulation was used in the post-to-rail connection model.

To simulate the physical behavior of posts mounted on soil, an approximate method was utilized. Even though the closest approximation to represent soil was through the use of solid elements with shear failure, this model was not implemented due to immense computational time required. Instead, soil was modeled as an array of uni-directional nonlinear springs extending from the face of the post to the ground along the depth of the post. This model was used in many previous projects and all reported success with the model (Atahan, 2002). In this model, the stiffness of the non-linear springs is increased with depth, and the spring stiffness is defined by the load curves at a specific depth.

It is a fact that splice connections generate weaker cross-sections due to the reduced effective rail area at the bolt holes, and these connections are prime locations for stress concentrations. As reported in many full-scale crash tests, failure initiates at a splice connection resulting complete rupture of rail. Special attention was paid to develop an accurate splice model for the CMPS model. After experimenting several options, including an explicit bolted connection, it was decided that the use of an equivalent bolt opening area on the rail could represent the behavior of bolted connection. Previous simulations show that this model proved to be a fairly accurate and immensely cost-effective in capturing the potential failure behavior at splice connections (Atahan and Ross, 2004).

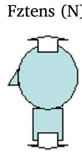
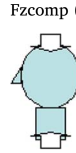
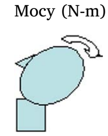
Finite element model of the ATD used in the study is a Hybrid III 50th percentile male dummy in conformance with U.S. Department of transportation Code of Federal Regulations Title 49, Part 572, Subpart E. This model is available in LS-DYNA's dummy library. As shown in Fig. 11, dummy was positioned face up position on the ground and a helmet model was developed for the head protection. Through the simulation, it was possible to identify performance issues inherent to the system design and continuous modifications were incorporated into the model for improved response behavior.

4.2. Finite element analysis results

4.2.1. TM 1.60 case

The dummy was aligned in front of the CMPS design to perform the TM 1.60 simulation. Dummy impacted the CMPS with a velocity of 60 kph and at 30°. Sequential pictures showing the dummy-CMPS interaction is presented in Fig. 12. As shown in this figure, the dummy impacted the lower rail with its helmet at post centered configuration. Shortly after the initial contact, the CMPS began to deform allowing the dummy to be redirected. 0.07 s after the initial impact, the dummy was sliding parallel to the CMPS. As shown in Fig. 13, after 0.1 s, the dummy exited the CMPS in an acceptable angle and the damage to CMPS was minimal. In addition to qualitative results, quantitative results were also obtained from the simulation. The resulting HIC is reported in Table 6. As it was only a development model, the forces and

Table 3
Severity level details in prEN 1317-8 for the head and neck injury.

Severity Level	Maximum acceptable levels						
	Head	Neck					
	HIC36	Fx (N)	Fztens (N)	Fzcomp (N)	Mocx (N-m)	Mocy (N-m)	Mocy flex (N-m)
							
I	650	Fig. 3	Fig. 4	Fig. 5	134	42	190
II	1000	Fig. 3	Fig. 4	Fig. 5	134	57	190

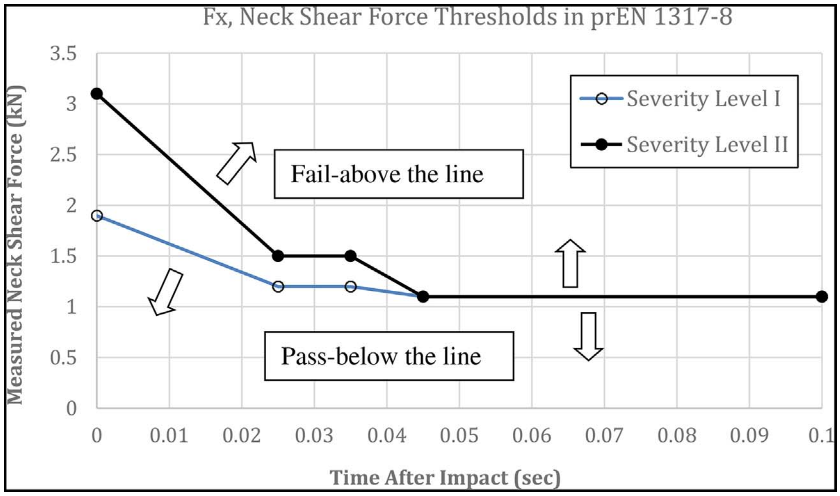


Fig. 4. Anterior – posterior neck shear force thresholds, Fx, for Levels I and II.

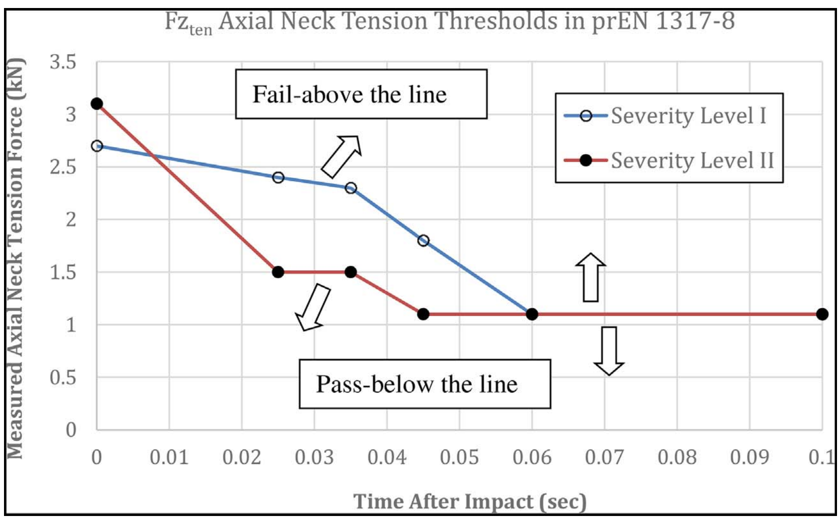


Fig. 5. Axial neck tension, Fz_{ten} thresholds for Levels I and II.

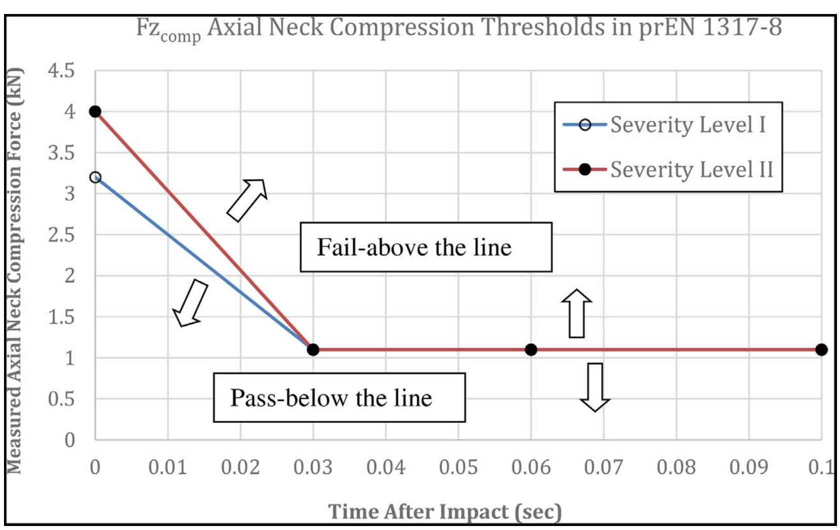


Fig. 6. Axial neck compression, Fz_{comp} thresholds for Levels I and II.

moments were not taken into account.

4.2.2. TM 3.60 case

TM 3.60 case simulation was also performed according to prEN 1317-8 on CMPS. For this simulation dummy was positioned as shown in Fig. 11. Sequential pictures obtained from TM 3.60 simulation is shown in Fig. 14. For this test, the dummy takes more time to be redirected by the barrier since it goes deeper into the barrier, creating a

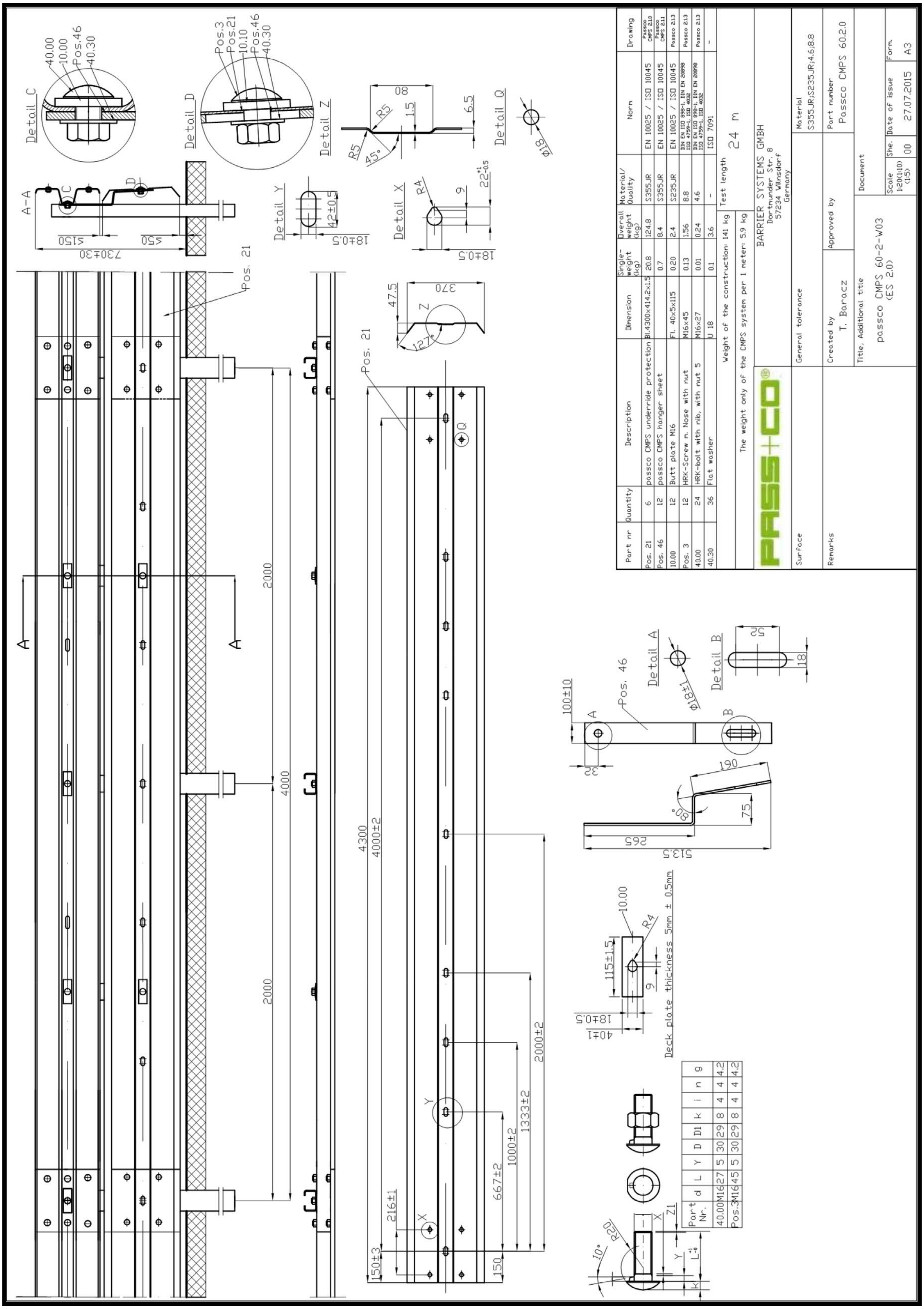


Fig. 7. Details of CMPS design.

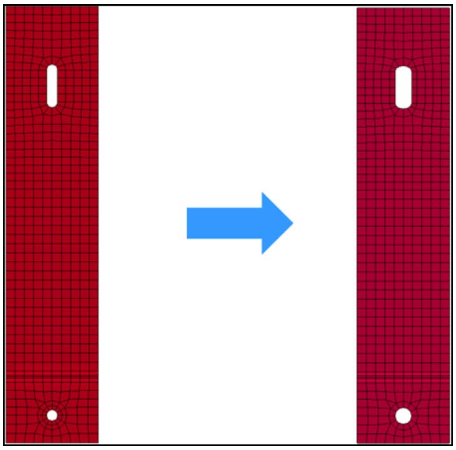


Fig. 8. Modification to connections.

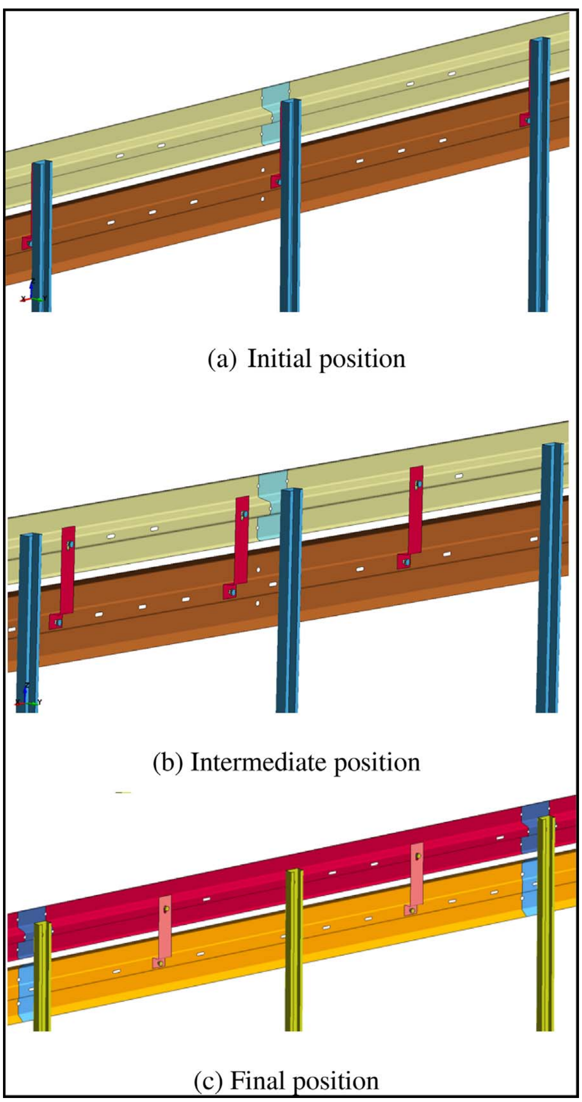


Fig. 9. Hanger positions evaluated in CMPS design. (a) Initial position, (b) intermediate position and (c) final position.

bigger pocket. The dummy slides parallel to the barrier after 0.1 s and exits the barrier after 0.15 s. The resulting HIC is reported in Table 7. Deformation of the barrier is shown in Fig. 15.

Simulation results obtained from TM 1.60 and TM 3.60 predicted that the CMPS design developed would perform successfully.

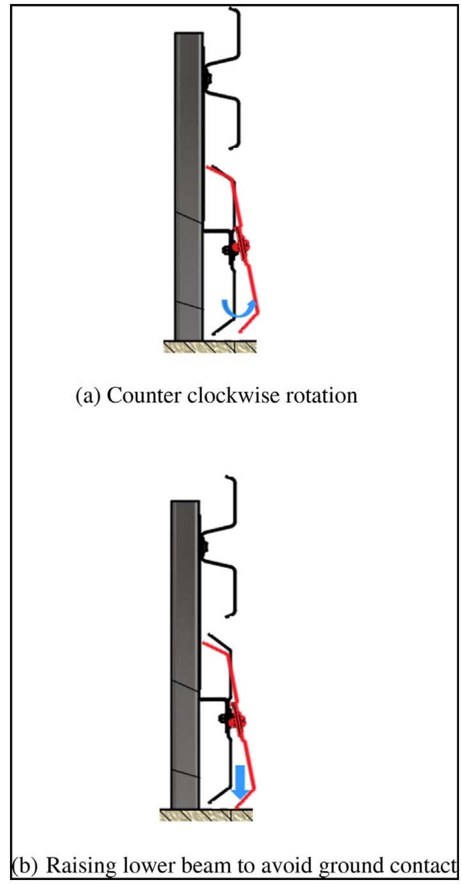


Fig. 10. Modifications to lower beam of CMPS design. (a) counter clockwise rotation and (b) raising from ground.

Table 4
Details of materials used in CMPS design.

Part Name	Dimensions	Material Properties	Characteristics
Post	C120 × 60 × 25 × 4	S355JR	Standard C post
Upper Rail	4300 × 310 × 2.5	S355JR	Standard B-rail
Lower Rail	4300 × 414.2 × 1.5	S355JR	Motorcyclist rail
Rail hanger	513.5 × 10 × 5	S235JR	Rail-to-Rail Connector
Rail support plate	115 × 40 × 5	S235JR	Bolted connection part
Bolts	M16 and M10	8.8 and 4.6	Standard parts

Table 5
Steel properties used in LS-DYNA model.

Property	S355 JR Material Properties	S235 JR Material Properties
Material Type	Piecewise linear plastic material with failure (Type 24)	Piecewise linear plastic material with failure (Type 24)
Density	7.85E–09 t/mm^3	7.85E–09 t/mm^3
Modulus of Elasticity	200,000 MPa	200,000 MPa
Poisson's Ratio	0.3	0.3
Yield Stress	337 MPa	274 MPa
Failure Plastic Strain	0.27	0.22

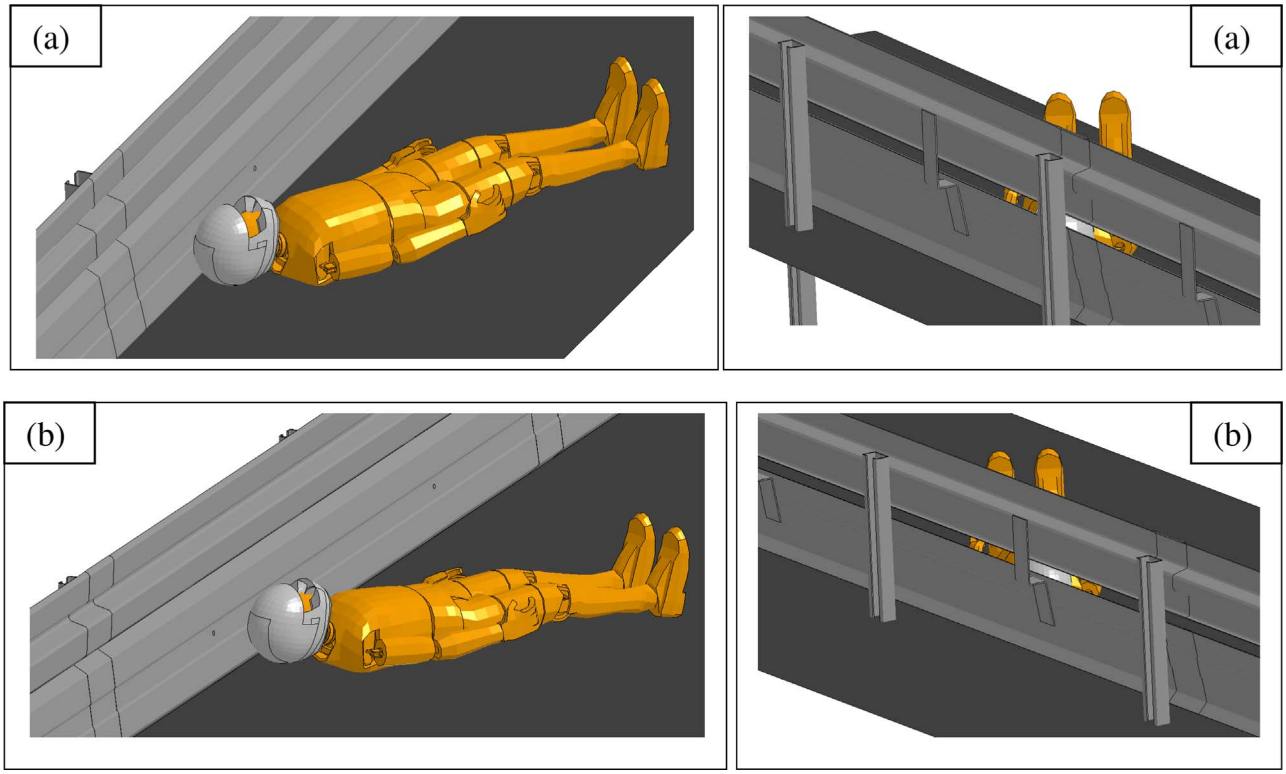


Fig. 11. Isometric view of CMPS design before LS-DYNA simulation (a) TM 1.60 and (b) TM 3.60 cases.

Subsequently full scale crash tests proved the accuracy of the simulations and verified the crashworthiness of the design.

5. Full-scale crash testing of CMPS

After achieving satisfactory results from the finite element simulations of the CMPS design, TM 1.60 mid-span and TM 3.60 on-post the full-scale crash tests were performed at CSI S.P.A. proving ground facility in Italy. The materials were manufactured and installation in soil was completed according to installation manual of the CMPS. Following sections provide the details of crash tests required for C60 performance level verification.

5.1. Crash test TM 1.60

The first crash test, 0044/ME/HRB/14, performed on the CMPS design was TM 1.60 (CSI, 2014). A picture of the installation just before the test is shown in Fig. 16. The dummy wearing a helmet, motorcycle suit leather gloves and leather boots was aligned such that its center would coincide with post 3. The total length of the installation was 24 m. Dummy was placed face up on a sled, rotated 30 ° with respect to the barrier and accelerated to 60 kph velocity as recommended by TM 1.60.

Dummy impacted the CMPS at 0.0 s and shortly after the impact lower rail began to deform. At 0.042 s after the initial impact dummy was begun to redirect by the barrier and at 0.115 s after the initial impact dummy became parallel with the CMPS. Sequential pictures showing the dummy-CMPS interaction is presented in Fig. 12. As shown in this figure, the CMPS was able to kept ADT away from any sharp ends of the barrier by preventing it from sliding under the barrier. Finally, at 0.26 s into the crash test the ADT was safely redirected away from the barrier with 100 mm lower beam deformation. Damage to the barrier is shown in Fig. 13. In addition to qualitative results quantitative results were also obtained from the crash test to reach a conclusive decision about the acceptability of TM 1.60. As shown in Table 6, other than the Neck Moment in y direction Moc_y, all injury parameters were at the lowest severity level of I according to prEN 1317-8.

5.2. Crash test TM 3.60

Damaged section of the CMPS was repaired and 24 m long barrier reconstructed for the second crash test, 0039/ME/HRB/15 (CSI, 2015). Successful completion of this test is essential to verify adequacy of CMPS developed for C60 performance level. Similar to TM 1.60 test, the dummy accelerated to 60 kph velocity as recommended by TM 3.60 and initial contact took place at mid span between posts 6 and 7. Due to the flexibility of the rail at mid span the head section of the dummy advanced into the lower rail until 0.08 s. Beyond this time the dummy was begun to redirect by the barrier and at 0.124 s after the initial impact dummy became parallel with the CMPS. Sequential pictures showing the dummy-CMPS interaction is presented in Fig. 14. As shown in this figure, the CMPS allowed the ATD to softly collide with the barrier and was able to kept ADT away from any sharp ends of the barrier. Finally, at 0.35 s into the simulation ADT exited the barrier with a maximum 140 mm lower beam deformation. Damage to the CMPS is shown in Fig. 15. As shown in Table 7, all injury parameters, such as HIC and neck moments were found to be within severity level I limits according to prEN 1317-8. Only the compression Fz positive criteria parameter was in Level II. No parts of the ATD were sliding under the CMPS, the ATD did not show any movements that could had lead to fractures or damages. Both crash tests, passed with 60 kph, in Severity Level 2 with a dummy working width of 0.30 m.

6. Limitations of the study

The study presented herein is limited with the details in Technical Specification prEN1317-8, such as 30° impact angle, 60/70 kph impact speed and 80 kg of ATD weight. The results of actual motorcyclist to MPS accidents may vary if these parameters were to be changed. In addition, it is believed that the material selection as well as geometrical details of the CMPS design has tremendous impact on the performance of the system. Designs made out of fiberglass, plastic or wood or

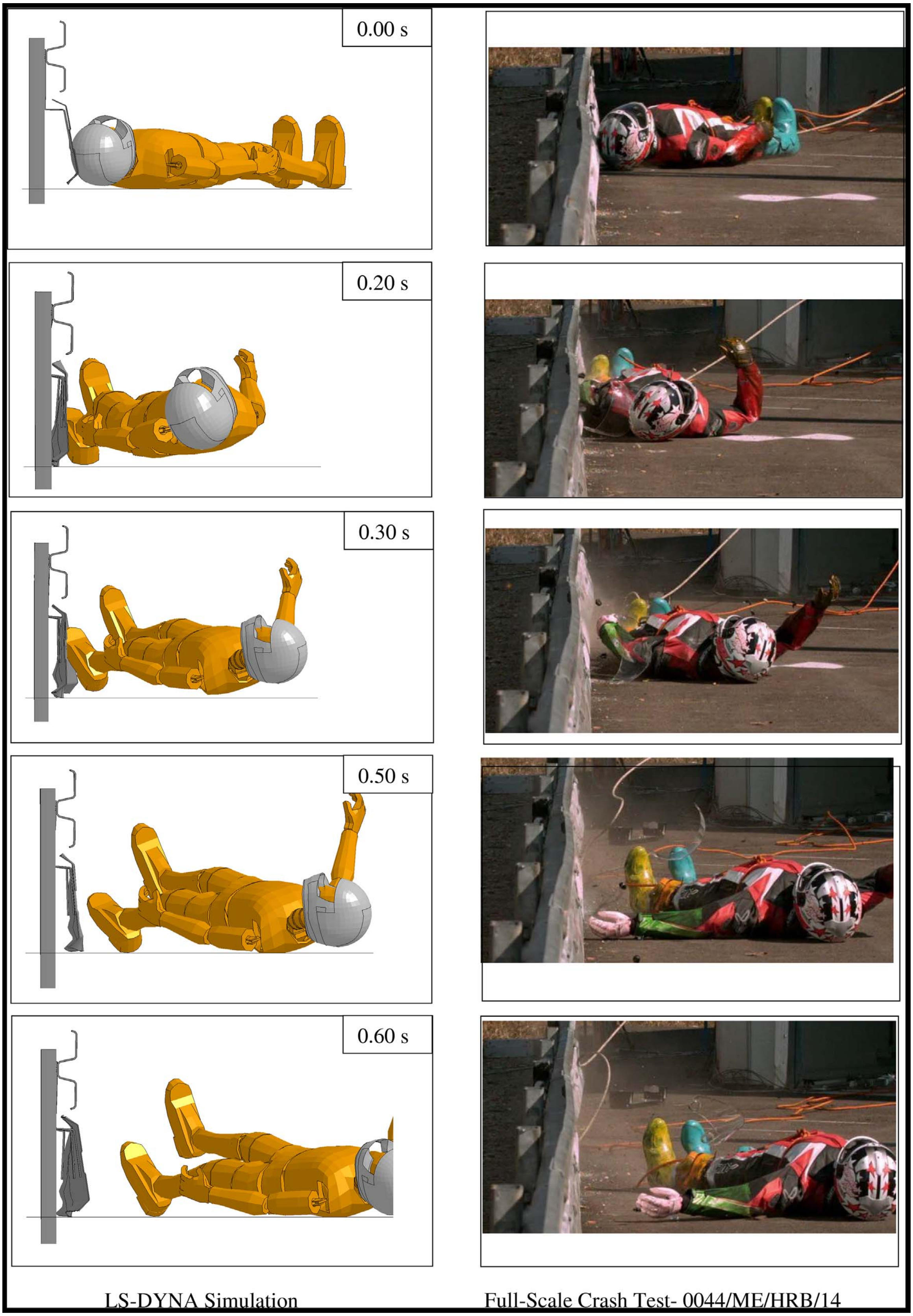


Fig. 12. Sequential pictures comparison for TM 1.60 case.

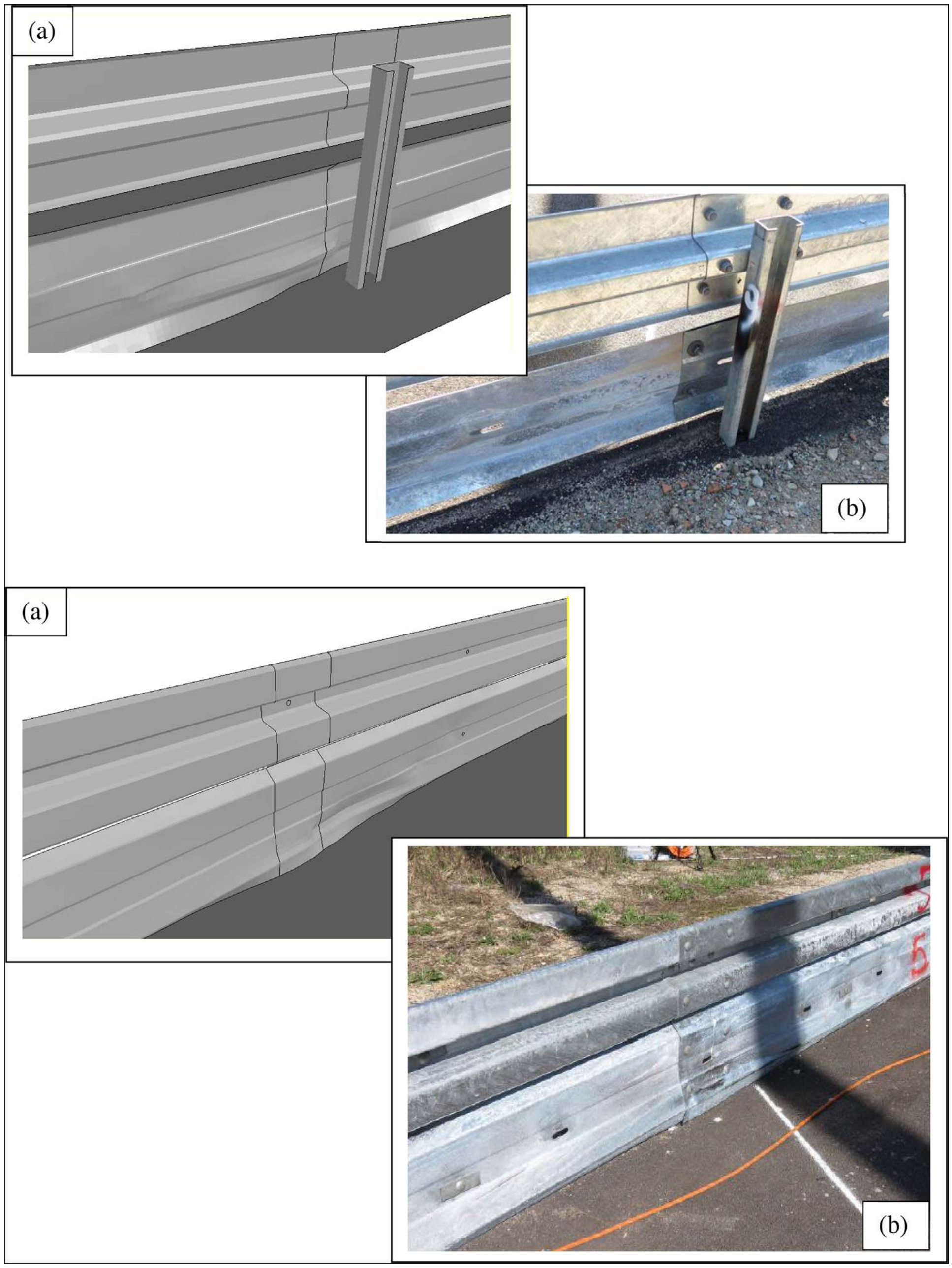


Fig. 13. Deformation of CMPS after TM 1.60 test (a) finite element simulation and (b) full-scale crash test.

Table 6
Injury Criteria Results Comparison for TM 1.60 Case.

Parameter	LS-DYNA Simulation	0044/ME/HRB/14	Severity level
HIC_{36}	254	316	I
Fx (N)	1441	1500	I
Fz_{tens} (N)	1826	1800	I
Fz_{comp} (N)	3547	3800	I
Moc_x (N-m)	77	85	I
Moc_y (N-m)	48	51	II
Moc_{yflex} (N-m)	44	57	I

existence of spacers, connectors could possibly alter the crash outcome. It is also clear that the post spacing in guardrail designs play an important role since larger post spacing makes designs more flexible against impact loads. If the CMPS developed is attached to an existing guardrail design with post spacing other than 2.0 m or with a post-to-rail spacer, the performance of the CMPS may vary, e.g. the ATD could slide under the system, or parts of the ATD may pass under the CMPS or even be stuck in the system. Proper and audited installation is the key to the performance of the system and must be constructed according the installation manual.

Another limitation of the CMPS developed could be the installation of CMPS in a curved section of the road. The technical specifications prEN1317-8 does not incorporate performance requirements of CMPS installed with a radius. Since most MPS designs are utilized at curved sections of the road running further simulation studies is recommended to better understand the impact characteristics of CMPS with radius.

It is important to note that test dummy used in the study is a standard Hybrid III 50th percentile male ATD in conformance with U.S. Department of Transportation Code of Federal Regulations Title 49, Part 572, Subpart E (Code of Federal Regulations, 2017). It is a fact that biofidelity of a dummy is an important aspect for MPS research. Currently there is an ISO 13232 motorcycle antropometric test dummy

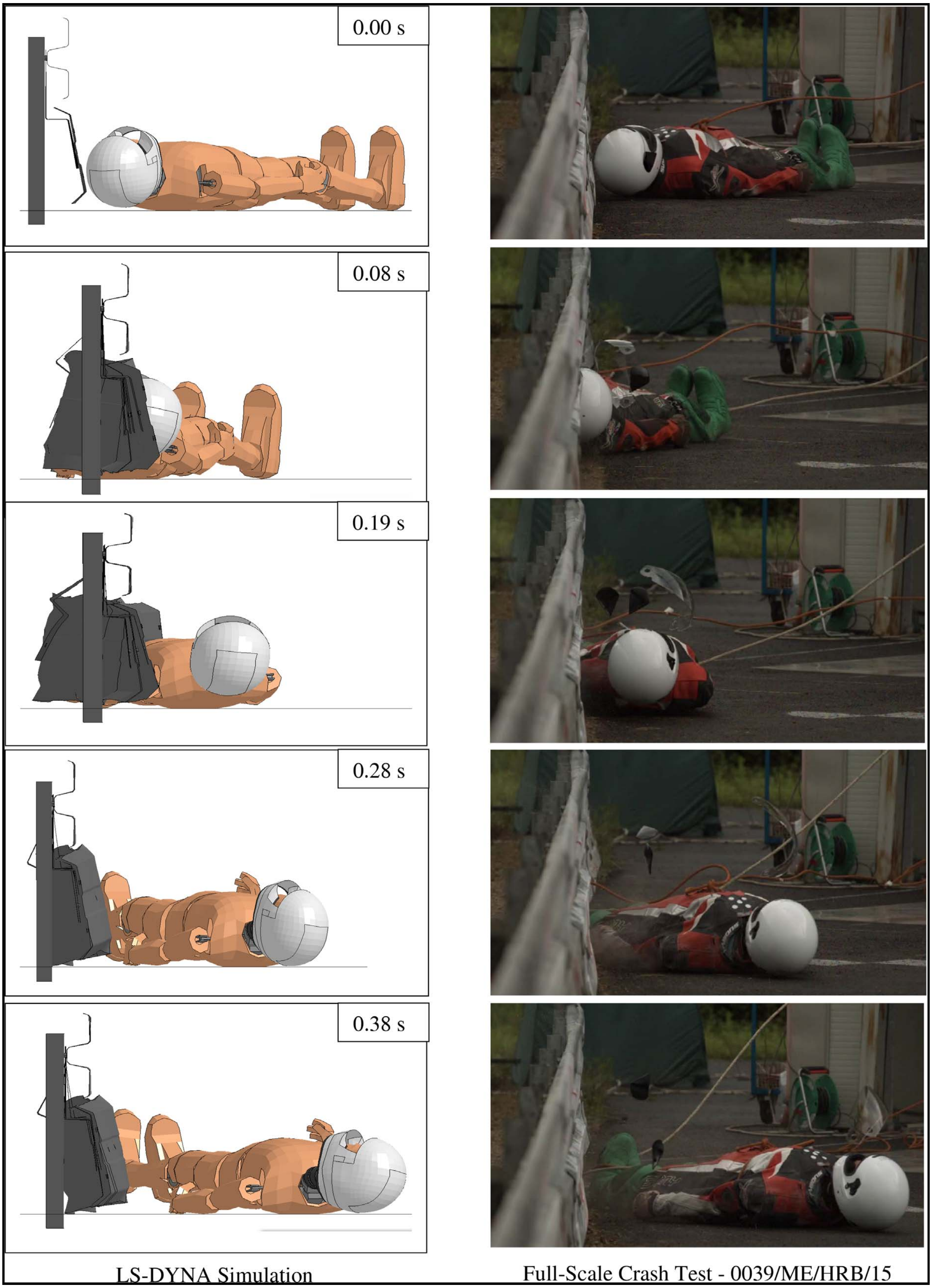


Fig. 14. Sequential pictures comparison for TM 3.60 case.

Table 7
Injury criteria comparison for TM 3.60 Case.

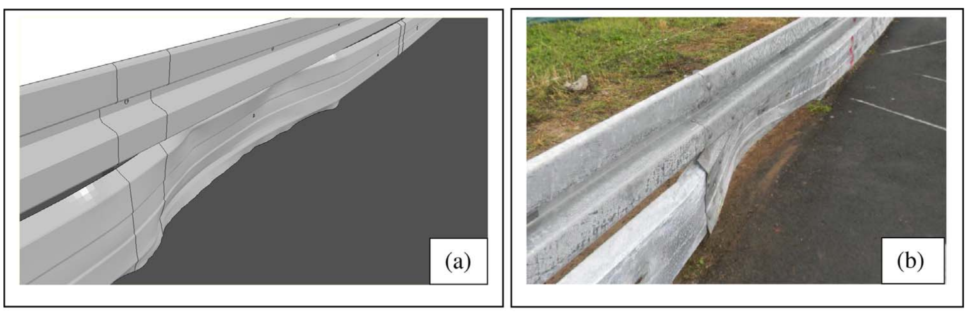
Parameter	LS-DYNA Simulation	0039/ME/HRB/15	Severity Level
HIC_{36}	227	267	I
Fx (N)	388	400	I
Fz_{tens} (N)	1442	1500	I
Fz_{comp} (N)	3547	3800	I
Moc_{x} (N-m)	57	62	I
Moc_{y} (N-m)	16	20	I
Moc_{yflex} (N-m)	18	17	I

with an improved neck in the literature. Therefore utilization of more appropriate dummy models are recommended for further MPS development studies.

Finally, for a quantitative validation of finite element models a program called the Roadside Safety Verification and Validation Program (RSVVP) is frequently used (Ray et al., 2011). This quantitative verification approach is based on the comparison of acceleration and angle rate curves obtained from both simulation and test data according to Sprague and Geers and variance metrics. However, crash test data collected from TM 1.60 and TM 3.60 tests are not sufficient to run the RSVVP. Therefore, in this study mostly visual comparisons were used to achieve a level of confidence in the finite element models used.

7. Summary and recommendations

This paper is intended to provide development and testing details of a versatile and motorcycle friendly CMPS design. A model of the CMPS design was constructed using finite elements. To assess the adequacy of the model against a dummy impact and verify its safety performance a 3D nonlinear finite element analysis program LS-DYNA was utilized. Several design parameters, such as geometrical shape of slot holes, position of rail to rail connectors, lower rail material characteristics were evaluated in detail to make CMPS design as forgiving as possible without compromising its crash performance. Based on the promising results obtained from the LS-DYNA analysis, two full-scale crash tests were performed in accordance with prEN 1317-8 specification to validate its acceptability. Results of the study show that newly



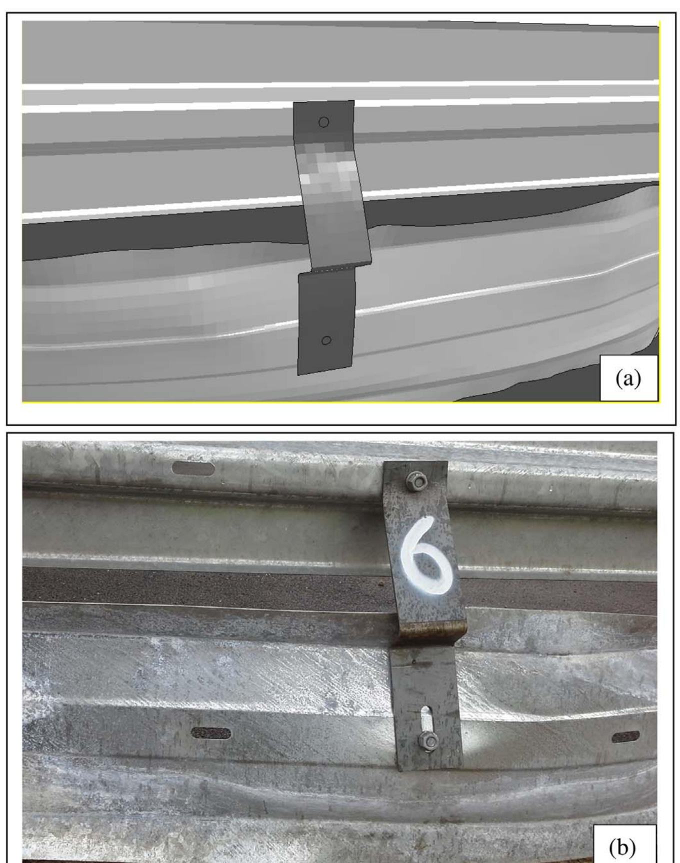


Fig. 15. Deformation of CMPS after TM 1.60 test (a) finite element simulation and (b) full-scale crash test.

Fig. 16. Completed CMPS installation before crash testing.

developed CMPS design is able to satisfy requirements of 60 kph dummy impact, C60, case with minimal risk of injury to motorcyclist. Head Injury Criteria as well as other biomechanical indices measured from the head and neck regions of the dummy in both impacts were within acceptable limits. In both tests the damage on the barrier were also minimal which demonstrates the robustness of the CMPS design and low maintenance costs of the barrier. Final full-scale crash tests with automobiles will be performed on CMPS design to fully certify the system according to EN1317 part 2.

CMPS developed in this study is of importance since it is the first German CMPS fully crash tested and evaluated in accordance with prEN 1317-8 specification. It is essential to note that the system is fully compatible with most existing guardrail systems regardless of the post and rail profile type. Implementation of CMPS will provide the additional safety required to the existing guardrail designs used at black spots for PTW and areas of with high casualties of PTW.

Finally, research explained herein has shown that there is a high potential of further development and optimization of MPS systems for the future. It is recommended that future studies should concentrate on lighter, stronger and more energy absorbing materials as well as on innovative designs.

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