Design of pedestrian friendly vehicle frontal protection system using computer modelling and simulation

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Abstract

Globally, Vehicle Frontal Protection Systems (VFPS) need to satisfy pedestrian safety crash test requirements. In Australia, the existing designs of VFPS do not consider pedestrian safety due to an absence of pertinent regulatory requirements. This paper develops a design and validation framework for a new pedestrian-friendly concept of VFPS, which is in demand to meet global lower legform pedestrian safety requirements. The design and crash test simulations are carried out in Finite Element Analysis (FEA) program LS-DYNA. A physical crash test under the Euro NCAP Transport Research Laboratory (TRL) lower legform test condition is conducted to confirm the new VFPS design. It has been found the computer simulation results based on the new VFPS design agree with the results obtained by the experiment, satisfying Euro NCAP performance requirements. A Flexible Pedestrian Legform Impactor (Flex-PLI) model is further evaluated on the validated design, which also produces satisfactory predictions for future pedestrian safety testings.

Keyword: Finite Element Analysis, Vehicle Frontal Protection System, Pedestrian safety, Pedestrian protection, Lower legform, TRL legform, Flex-PLI legform

Introduction and background

Vehicle Frontal Protection Systems (VFPS), also known as bull bars and nudge bars in Australia, are the frontal devices fitted to the vehicle for vehicle and occupant protection in the event of a frontal collision, such as a kangaroo strike. While prevalent in the market, mainstream metal VFPSs have been questioned for their perceived aggressiveness towards pedestrians during collisions [1]. Government attempted to propose pertinent regulations to address pedestrian friendly design in VFPS [2][3], however the implementation was not successful because of the backlash from the manufacturers [4][5]. Therefore, the pedestrian safety issue of VFPSs remains unresolved to future society.

This paper is an industry response towards this future trend by researching and developing a new generation of VFPS product. The author commenced the preliminary design work utilising numerical modelling. Finite Element Analysis (FEA), for its characteristic of time-efficiency and cost-saving, was chosen to be the ideal tool to evaluate the new design. In literatures, vehicle pedestrian safety design has been studied using FEA in the past decades, but there is limited FEA R&D work undertaken on VFPS products after Europe and United Nations introduced regulations to mandate a high level of pedestrian friendliness, which caused the European VFPS market to plummet and never recover. Among these works, Ptak et.al investigated several geometry parameters of VFPS on their influences on the TRL legform injury using LS-DYNA [7][8][10][15]. Brooks undertook his research about the material and structural requirements for a VFPS to meet 2005/55/EC criteria [9]**.** Pohlak [6] conducted the parameter study on VFPS bracket designs to investigate the impacts on pedestrian safety performance. There are separate design variable studies in these papers however neither new structure was implemented for VFPS nor real-world product developments were researched or published.

This paper employs the advanced capability of FEA in reconstructing explicit crash simulation using LS-DYNA, abiding by the latest protocol of Euro NCAP using lower legform practice to evaluate the design. As the current version of TRL legform will be replaced by Flex-PLI in Australia post 2018, TRL is used as a validation tool together with designed experiment tests in the lab to confirm the modelling, and generation 2.0 Flex-PLI legform performance is subsequently predicted on the validated model. The research demonstrates the validity of the FEA modelling in helping engineers design the product and the excellent performance of the VFPS design herein included.

Method and tools

In engineering design, computer simulations have been widely adopted across all Original Equipment Manufacturers (OEMs). In pedestrian-vehicle crash simulation where subsystems impactor or pedestrian dummy biomedical injury performance is assessed, FEA has the advantage of accurately predicting the local deformations which can accurately reflect the injury patterns of pedestrian victims. Figure 1 shows the lower legform test, where the lower legform is fired in the direction of the stagnant VFPS-mounted vehicle at an impact speed of 11.1 m/s. The injury parameters on legforms are extracted and used for the product rating.

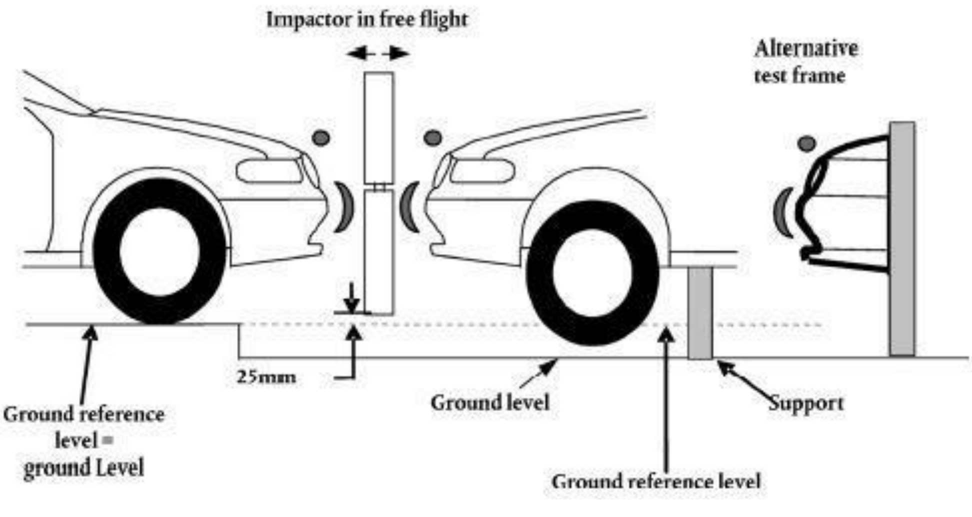


Figure 1 Lower legform to VFPS test (1)

This research involves the application of test legform tool models in LS-DYNA: TRL legform and Flex-PLI legform. TRL legform accords with the impactor in EC regulations and the Euro NCAP pre-2018 protocol [11]. As shown in Figure 2 the measuring parameters on TRL legform are: accelerator node unidirectional acceleration, knee bending angel of femur and tibia, and the shear displacement of the knee.

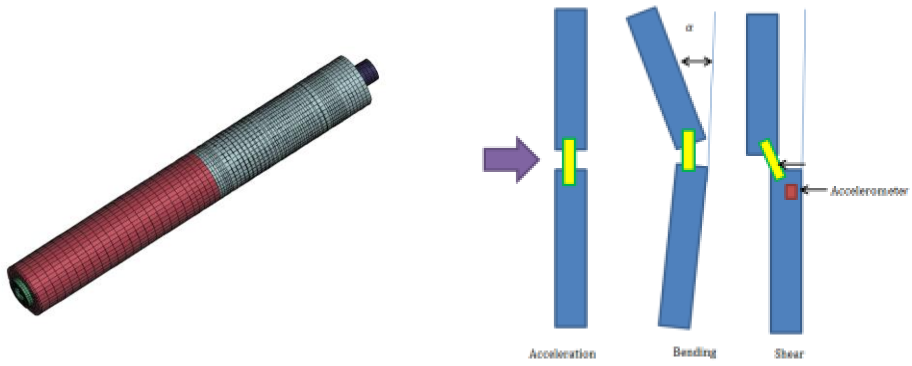


Figure 2 Left: TRL legform structure; Right: injury

Flex-PLI legform is a complex bio-fidelic legform, containing seven location bending moments and complex knee ligament injuries, used for Euro NCAP post 2018 in Australia (Figure 3) [12]. As for the injury, four tibia bending moments and four major knee ligaments: Medial collateral ligament (MCL), Anterior cruciate ligament (ACL), Posterior cruciate ligament (PCL) and Lateral collateral ligament (LCL) are designed for vehicle ratings. The FEA model is acquired through Humanetics, which is fully validated and verified for the use [14].

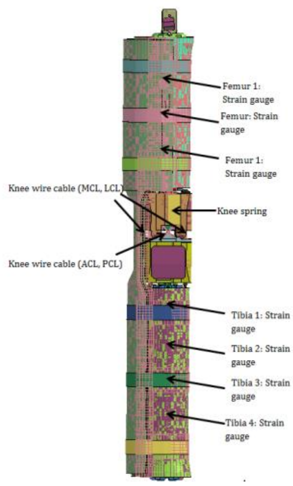


Figure 3 Left: Flex-PLI FEA model

VFPS Design Model

The VFPS model designed in this paper is a parametrically optimised nudge bar, based on the existing industry product retrofitted with a sandwich structure, consisting of a plastic cover, foam filling and metal back plate bonded with glues (Figure 4). Geometry, material, pan positioning, thicknesses are carefully chosen through an extensive parametric study conducted by the authors. The product model is designed to be tested without mounting to the vehicle, being held together by two rigid side constraints angle steels, creating worse scenario constraints for crash development.

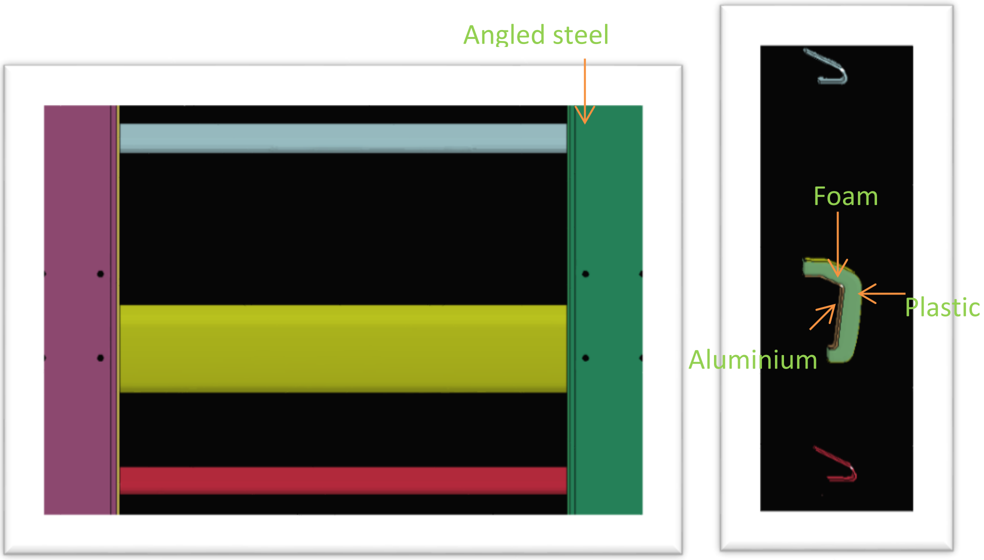


Figure 4 Left: VFPS frontal view; Right: VFPS cross section view

Part elements

The CAD CATIA model is processed and discretised in ANSYS for preparation of FEA simulation. Element-wise, Belyschoko Lin-Tsay ELFORM=2 one-integration shell elements are used across most of the parts except foam layers. Foam layer is modelled with ELFORM=2 fully integrated S/R solid elements to eliminate hourglass zero mode. To combat negative volume stability issue, besides using hex meshes instead of tet meshes, a method of coating the foam elements with a stiffer null shell closely around the surfaces was applied in the model. One tenth of the foam density was assigned to the null material *MAT_NULL so that the weight of the shell could be neglected in computation. *SECTION_SHELL was activated for a thin thickness and larger Young's modulus input to maintain desirable stability while the over-penetrations into the adjacent parts were avoided. Contact definitions are then therefore placed on the null shell.

Mesh-wise, uniformly-sized meshes are generated to produce a smooth transition between elements which leads to a more stable solution. Quadrilateral meshes (Quad) are preferred over triangular element (Tria) for shell elements. Hexahedral meshes for foam are chosen over tetrahedral. The mesh sizes in Table 1.

Table 1 Mesh sizes

Part name	Mesh size
Upper rail	5mm
Central rail	5mm
Lower rail	5mm
Foam	5mm
Plastic cover	5mm
Upright	7mm
Angled steel	7mm

Contact

As the sandwich structure is bonded together using glue, TIED_CONTACT_SURFACES_TO_SURFACES_OFFSET with SOFT=2 pinball segment-based contact is activated to tie the structure together with a modelled distance which also combats geometry irregularities. TIED_CONTACT_NODES_TO_SURFACE_OFFSET is used for foam shell bonding to the upright bracket. A CONTACT_INTERIOR is defined for foam part to resist overcompression by generating internal forces inside the foam. AUTOMATIC_SURFACE_TO_SURFACE two-sides search is used for legform to outer surfaces of the bar with SOFT=2 definition.

Material

For an accurate FEA design model, real-world materials are researched through laboratory testings to extract the most accurate information for the design. MAT_PIECEWISE_LINEAR_PLASTICITY (24) is used for steel and plastic of the sandwich, which is characterised by multi-linear strain-stress behaviour, and isotropic hardening. The necessary inputs of this material are density, Young's modulus, Poisson ratio, yield strength, failure strain and stress-strain curve in plastic region. The material tensile testings are designed to record the stress-strain behaviour of aluminium alloy and plastic cover (Figure 5a and b). Eight tests for alloy samples and ten tests for Acrylonitrile butadiene styrene (ABS) plastic samples are repeated to ensure average stress and strain behaviours are recorded. Among various foam models that can be used for FEA, MAT_FU_CHANG_FOAM (83) is chosen to simulate the polyurethane foam supplied for the sandwich because of this model's simplicity, efficiency, accuracy, and the inclusion of strain-rate effect for foam modelling. Four compression tests with four different velocities (50mm/min, 500mm/min, 1500mm/min and 3000mm/min) are designed to monitor its compression behaviour and its unloading characteristics (Figure 5 c).

Figure 5 Left: Aluminium alloy tensile test; Middle: ABS plastic tensile test; Right: foam compression test

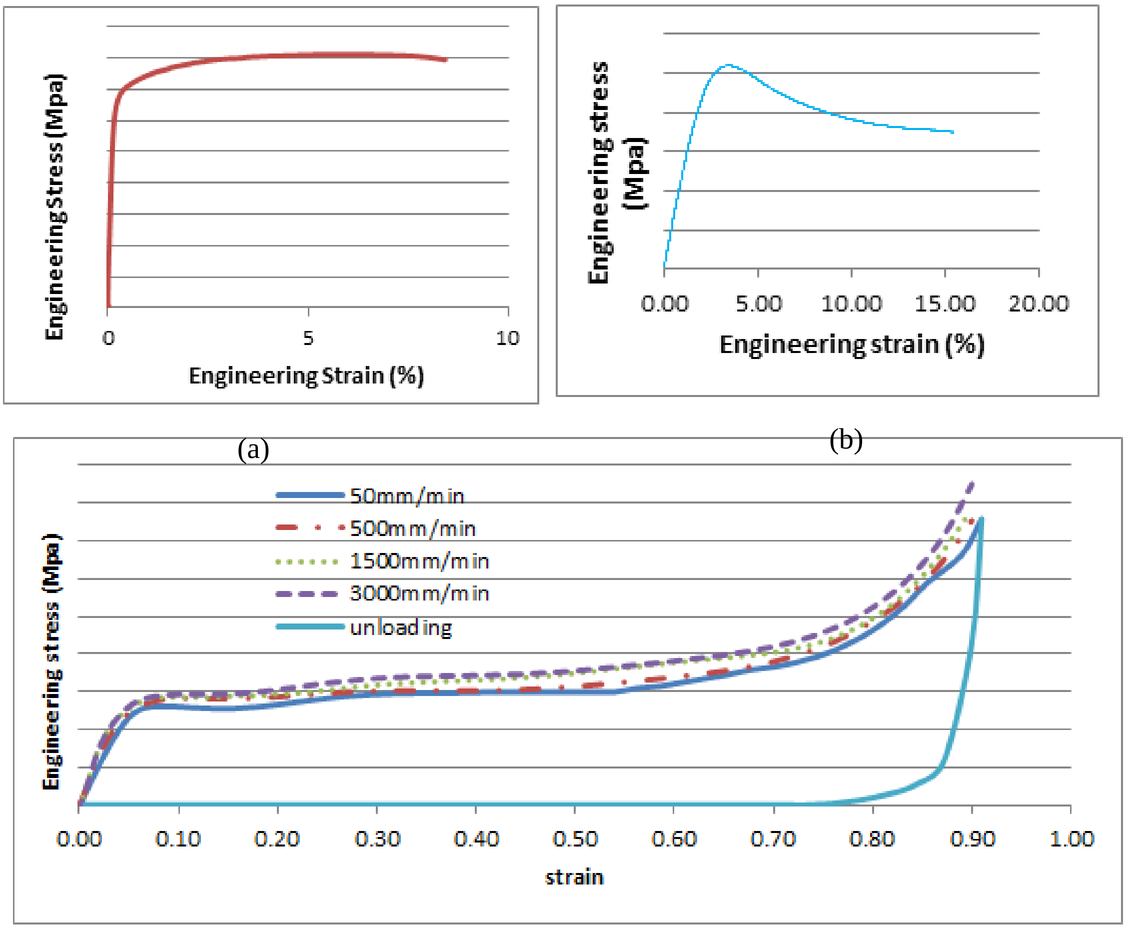
Stress-strain curves required as input for aluminium alloy and ABS plastic are expressed as true uniaxial stress and true plastic strain which are equivalent to Von Mises stress and effective plastic strain in the uniaxial case. The experimental data from the tensile test are engineering stress and strain, which are converted to true stress and strain and effective plastic strain through the formula:

$$\text{True strain} = \ln(1 + \text{engineering strain}) \tag{1}$$

$$\text{True stress} = (\text{engineering stress}) * \exp(\text{true strain}) = (\text{engineering stress}) * (1 + \text{engineering strain}) \tag{2}$$

$$\text{Effective plastic strain} = \text{total true strain} - \frac{\text{True stress}}{\text{Young's Modulus}} \tag{3}$$

It is recommended that curves utilise minimal number of points constituting a smooth curve. A number of approximately 50 points are selected for the input curve. ABS plastic effective S-S curve is straightened up horizontally from the yield point in plastic region as MAT24 cannot handle the plastic softening [16]. MAT_FU_CHANG_FOAM allows the use of engineering stress-strain curve to define the model. The averaged engineering stress-strain curves of aluminium alloy, ABS plastics, and foams are as Figure 6.



(a) (b)

(c)

Figure 6 Engineering Stress-strain curves. (a) Al alloy; (b) ABS plastic. (c) Polyurethane foam

As the unloading behaviour of the foam cannot simply be represented by inputting unloading curve, the alternative method of specifying HU (the hysteretic unloading factor) and SHAPE factors is used for this model as the following formula:

$$\sigma_{\varepsilon,unloading} = (1 - d)\sigma_{\varepsilon,loading} \tag{4}$$

$$d = (1 - \mathrm{HU})(1 - (\frac{W_{current}}{W_{max}})^{SHAPE}) \quad (5)$$

where W is the value of the absorbed hyperelastic energy per unit deformed volume [11].

Result

The virtual FEA model of the new VFPS is prepared in LS-PREPOST firstly with the TRL legform. The legform moves towards the VFPS centreline with initial velocity of 11.1m/s. Bolt holes on angle steel that are used to fix the bar to the chassis rail are locked up with Single Point Constraint nodes. Contact between legform neoprene outer skin and the PART_SET of upper rail, lower rail and plastic cover are defined by AUTOMATIC_SURFACE_TO_SURFACE. The relative height is designed to be Euro NCAP condition when the VFPS is mounted on the vehicle. In post-processing, the animations frames are recorded for the first 25ms where impact happens.

In the meantime, the VFPS is prototyped to undertake the physical crash test in the laboratory. As Figure 7, VFPS prototype is mounted on the mock chassis rail simulating the mounting on the vehicle, and a TRL legform is held by a hydraulic pusher designed with ballistic compensation to make sure the legform hits the designed first contact spot after free flight distance. The Euro NCAP standard high-speed camera captures all the happenings during the test. The data acquisition system is wired to the legform to record the critical injury parameters for the test.

Figure 7 Experimental crash test TRL legform

Comparing motion results obtained by FEA (Figure 8 (a)) and the experiment (Figure 8 (b), a similar motion trajectory can be captured in motion pictures within the quick crash window of 25ms, as shown in Figure 8.

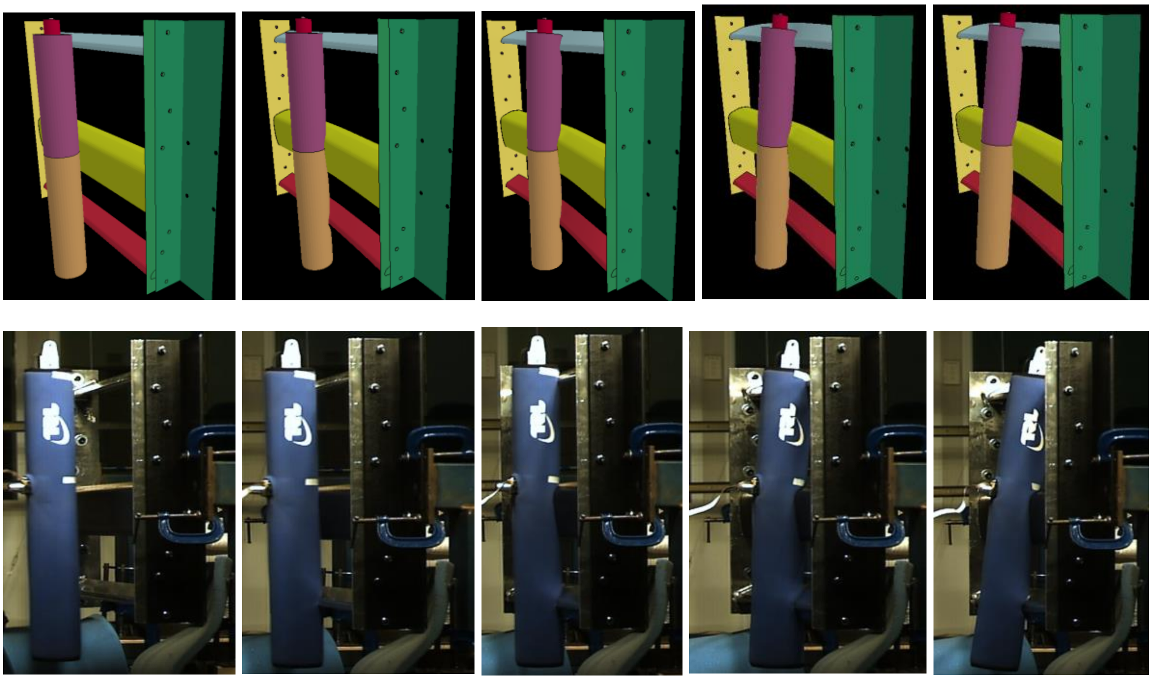


Figure 8 (a) FEA and (b) test crash frames

Figure 9 presents the comparisons of the three subtle legform injury parameters (tibia acceleration, knee shear displacement and knee bending angle) changed with time after sifting with a SAE filter of 180Hz as specified by Euro NCAP. The FEA and test curves illustrate very good agreements. This correlation has demonstrated an excellent capability of the FEA model developed in predicting the lower legform injury, in a crash scenario.

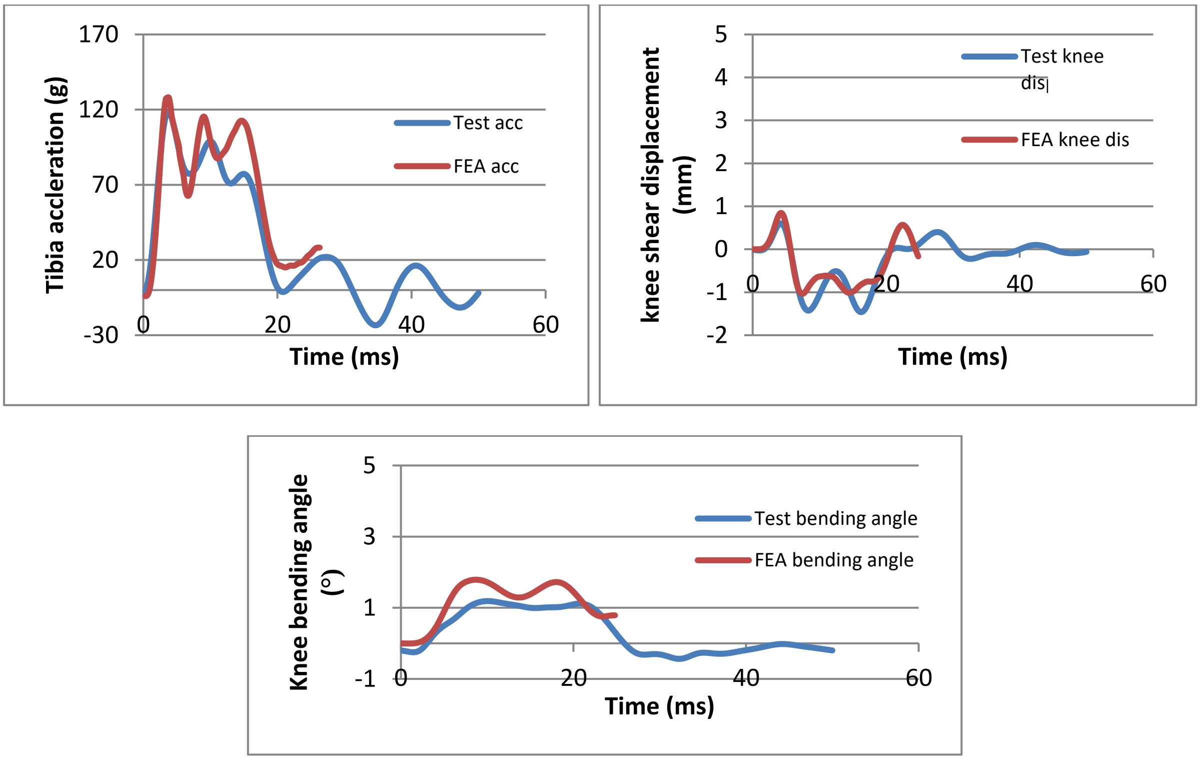


Figure 9 Test and FEA measurement results

Additionally, the leg crash injury severity caused is significantly low. All three injury parameters well exceed the Euro NCAP 5 star full performance criteria (Table 2). It is also worth noting that with this VFPS design the maximum knee displacement and maximum knee bending angle are very low (1.5mm and 1.195°) when the five star margin are much still higher (6mm and 15°). This means the safety design of this model is extremely effective in protecting and cushioning human knees and legs. This performance signifies an exceedingly high industry standard for vehicle product in terms of safety.

Table 2 Test results and Euro NCAP protocol 5.3.1 [12]

Injury parameters	Euro NCAP 5 star full mark	Test	FEA
Maximum tibia acceleration	<150g	118g	128g
Maximum knee shear displacement	<6mm	1.5mm	1.03mm
Maximum knee bending angle	<15°	1.195°	1.78°

Having built the validated VFPS model, it is of many manufacturers' interests to witness how the generation 2.0 Flex-PLI legform performs when crashes the VFPS design, with a design vision of the future. Flex-PLI FEA model is set up with a height of its bottom 50mm lower than the TRL legform in accordance with the Euro NCAP protocol 8.1 [13] (Figure 10). The contact of AUTOMATIC_SURFACE_TO_SURFACE is defined between the Flex-PLI skin null shell and the VFPS contact surfaces. Four lower tibia bending moments are measured and knee ligament injuries (MCL, PCL, ACL and LCL) are reflected from the discrete elements change length.

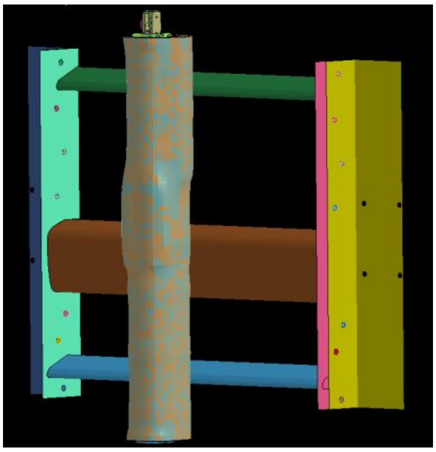
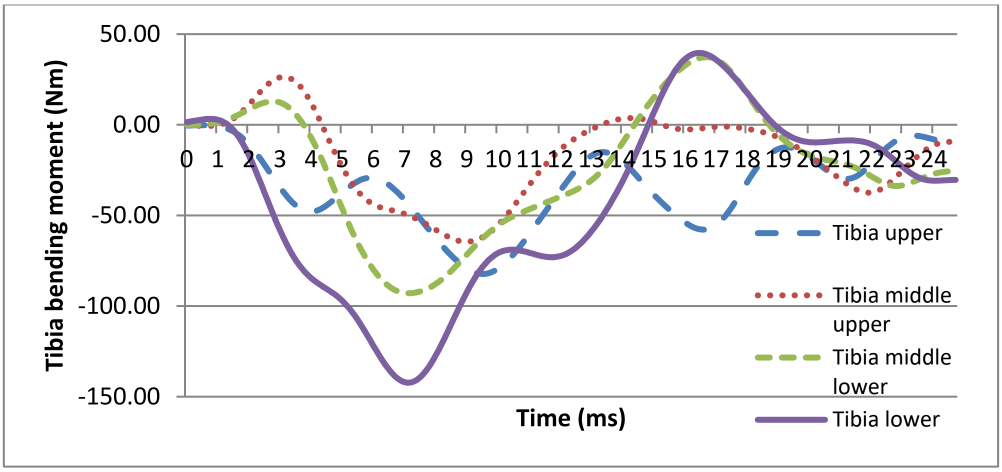


Figure 10 Flex-PLI FEA crash test



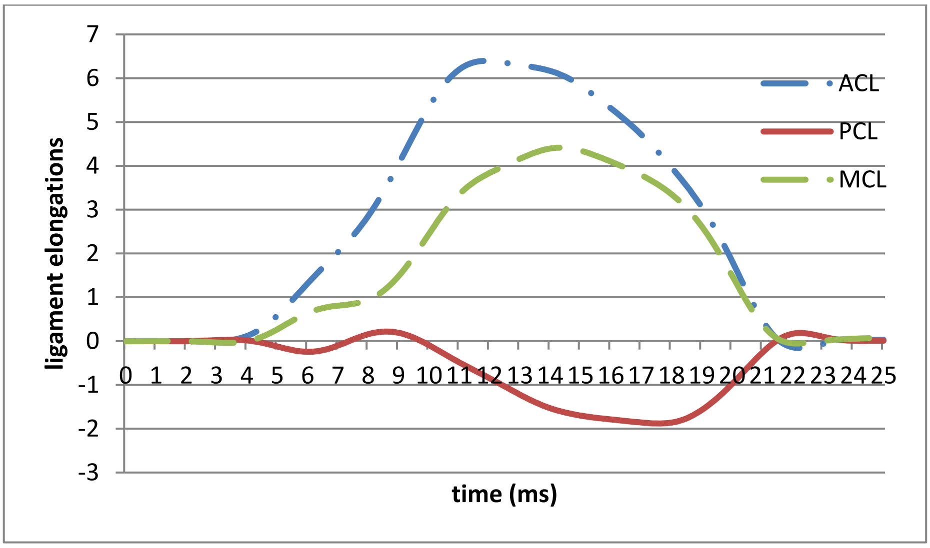


Figure 11 Flex-PLI Test results

As shown in Figure 11, the Flex-PLI crash test also produced a five-star rating for the VFPS as the maximum tibia bending moment 141.97Nm is much lower than the 2018 five star criteria of 200Nm, maximum ACL,PCL elongations 6.39mm are within 10mm, and maximum MCL elongation is 4.41mm as shown in Table 3. This reflects the VFPS also satisfies the top performance criteria of the future Flex-PLI legform.

Table 3 Flex-PLI test results and Euro NCAP protocol 8.1 [13]

Injury parameters	Euro NCAP 5 star full mark	FEA
Maximum Tibia acceleration	<282Nm	141.97Nm
MCL Elongation	<19mm	4.41mm
ACL/PCL Elongation	<10mm	6.39mm

Discussion and conclusions

In this paper, a sandwich structure three-pan VFPS is designed and evaluated using FEA model and experimental testing to meet current and future Euro NCAP pedestrian safety requirements. The correlated results in TRL test indicated that the VFPS FEA model developed is highly reliable in predicting pedestrian safety crash results for design of the new frontal protection system. The following main conclusions can be drawn from this study.

The proposed VFPS design well exceeds the highest performance criteria in terms of the requirements of Euro NCAP protocol 5.3.1 for TRL legform test. The injury readings from both FEA and experimental tests report satisfactory peak legform tibia acceleration, knee shear displacement and knee bending angle.

Using the validated model to evaluate a Flex-PLI legform crash test, the design can also well meet all optimum safety requirements. The maximum tibia bending moment of 141.97Nm, maximum MCL of 4.41mm and maximum ACL/PCL of 6.39 all well satisfy the five star performance level. The results will satisfy the criteria of Euro NCAP protocol 8.1.

The successful design and FEA modelling of the VFPS are well demonstrated through this process. The choice of the design parameters can well address the pedestrian injury during a frontal crash. Further work will be carried out with the assistance of this virtual and physical platform in the optimal product design study using Flex-PLI.

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Figures

(1) European Commission, COMMISSION REGULATION (EC) No 631/2009 of 22 July 2009 laying down detailed rules for the implementation of Annex I to Regulation (EC) No 78/2009 of the European Parliament and of the Council on the type-approval of motor vehicles with regard to the protection of pedestrians and other vulnerable road users, amending Directive 2007/46/EC and repealing Directives 2003/102/EC and 2005/66/EC, 2009. Figure 0-32 Lower legform to VFPS test; p.54; Figure 0-33 Left: Upper legform to bonnet leading test. Right: Upper legform to VFPS leading edge test; p.56