Development of a Flex-PLI LS-DYNA Model

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Summary:
A biofidelic flexible pedestrian legform impactor (Flex-PLI) has been developed by Japan Automobile Manufacturers Association, Inc. (JAMA) and Japan Automobile Research Institute (JARI).

The Flex-PLI has good biofidelity as well as several knee ligament elongation measurement capabilities, three femur and four tibia bending moment measurement capabilities. For these reasons Flex-PLI is likely to be used for future pedestrian Global Technical Regulation.

This paper introduces a finite element model of the Flex-PLI type GT for LS-DYNA and compares a full vehicle Flex-GT impact simulation with test. A very accurate vehicle model is needed to predict Flex-PLI injuries. In this paper, a detailed and correlated vehicle model was used.

The Type GT is the 5th version of Flex-PLI and has almost the same structure and performance as final design type GTR.

The Flex-PLI type GT LS-DYNA model was carefully created to ensure every important detail was included. Geometries, masses and material properties of all parts were reproduced from drawings and inspection of the real components. Connectivity and component interaction within the model was determined by thorough experiments. Accurate prediction of injury indices and kinematic behaviour was achieved by correlation to static and dynamic calibration tests. A fine mesh was used but reasonable calculation cost assured by imposing an analysis time step of 0.9 micro seconds.

Keywords:
Pedestrian injury protection, flexible pedestrian legform impactor, Flex-GT LS-DYNA model, full vehicle pedestrian impact simulation

1. Introduction

The increase of traffic accidents between pedestrians and vehicles is recognized as an ongoing serious problem. In particular, pedestrian AIS 2-6 injuries occurred to the legs in 32.6% of cases world wide [1]. In the EU, protection of pedestrian lower legs has already been regulated in EEC2003/102 and assessed by EuroNCAP. These use a rigid-bone type lower leg impactor produced by TRL.

JAMA and JARI have developed a biofidelic **Flex**ible **P**edestrian **L**egform **I**mpactor (Flex-PLI) with improved biofidelity as well as more appropriate injury measurement capabilities. The 1st version of Flex-PLI was created in 2002 [2] and then various technical evaluations have been carried out by the Flex-TEG (Flexible Pedestrian legform Impactor Technical Evaluation Group) from 2005, conducted under GRSP/INF-PS-GR of the United Nations. JAMA and JARI have continued to improve and upgrade Flex-PLI, and in 2007 the 5th version, called Type GT (Flex-GT) was produced [3]. The Flex-GT has been verified globally to have excellent test repeatability and be sufficiently practical for use as a certification test tool [4][5].

From 2008 to 2009 the Flex-GT was upgraded to the 6th version, Type GTR (Flex-GTR) [6]. Flex-GTR is expected to have the same performance as Type GT and is planned to be the final design. It is likely to be used for the future pedestrian Global Technical Regulation.

At the request of Mitsubishi Motors Corporation the development of a Flex-GT LS-DYNA model was started with JSOL Corporation, and in April 2008 version 1.0 completed. In a second phase continuing to 2009, the Flex-GT model was upgraded to version 2.0 and further validated in real-vehicle impact scenarios. It has proven to be a highly accurate yet numerically stable model.

2. Flex-GT LS-DYNA Model Development

2.1. Model General Description

Figure 1 shows the whole view of Flex-GT LS-DYNA model version 2.0. The Flex-GT comprises an internal skeleton structure covered with a flesh material made up of layered neoprene and rubber sheets.

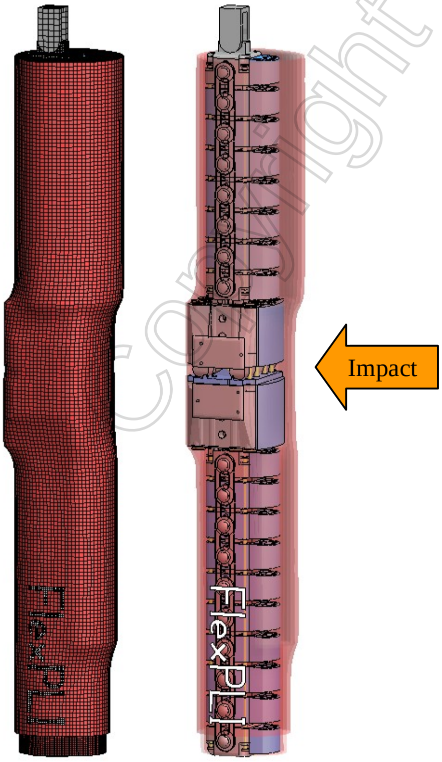

Figure 1: Flex-GT model whole view

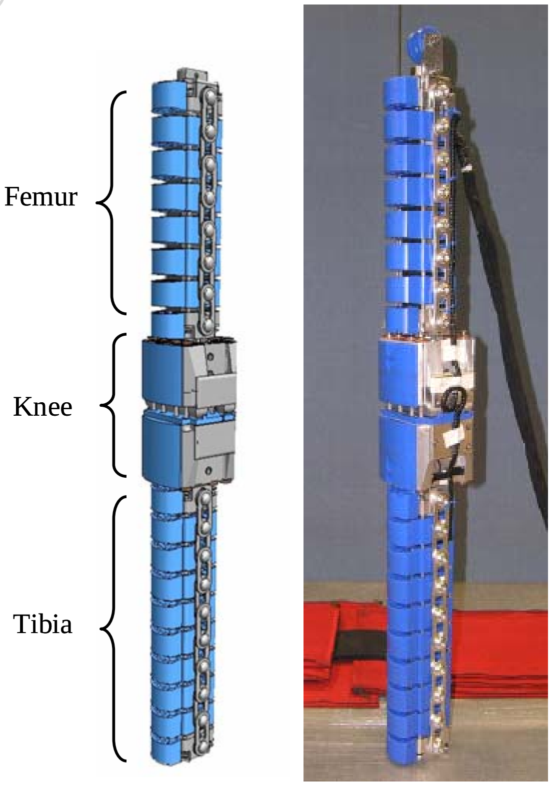

Figure 2: Flex-GT internal structure:
LS-DYNA model and a physical impactor

The mesh size and distribution in the model was developed to achieve sufficient accuracy at minimal calculation cost. The minimum mesh size of deformable parts was limited by imposing a 0.9micro second time step. Total elements amount to around 540,000 but deformable elements only to 220,000.

The geometry of the model was created not only from 2D drawings but also from long and detailed inspection of a physical impactor. The real device was completely disassembled to measure accurately the size and weight of all components. The Flex-GT model is thus set up carefully to have the exact same mass distribution as the physical impactor.

Figure 2 shows the internal structure of Flex-GT. On the left is the LS-DYNA model, on the right is the physical impactor [7]. The internal structure is composed of three portions: femur, knee and tibia. Bone cores form the fundamental structure inside the femur and tibia, and provide the flexibility and stiffness in those areas. The knee joint is made up of two blocks connected by steel cables and springs which replicate ligaments in the real human knee.

The Flex-GT model version 2.0 was developed using LS-DYNA Version 971 R3.2.1 (Revision 47756) and has been confirmed to give the same result using Version 971 R2 (Revision 7600.1224) [8].

2.2. Model Detailed Description

2.2.1. *Bone Core Model*

Figure 3 shows the femur and tibia bone cores attached to the center knee section. The real bone cores are made of strong glass fiber reinforced plastic (FRP) and an appropriate material was used to model this. Spring elements with weak stiffnesses model the strain gauges, and in line with the Flex-GT specification, three were attached to each side of the femur bone and four to each side of the tibia.

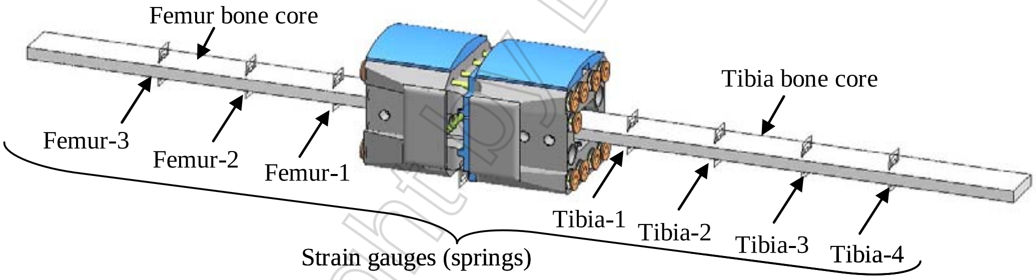

Figure 3: Bone cores and strain gauges

2.2.2. *Femur and Tibia Models*

Figure 4 shows sections though the femur and tibia. The bone core lies down the middle of square section exterior housings which are chained together by links down their flanks. The exterior housings were modelled using a deformable material and the aluminium core binders and connection bolts by a rigid material.

Connection plates tie the exterior housing structures together and link together around connection bolts. Accurate connectivity of the links was determined from detailed observation of the physical impactor. The stopper cables which limit the maximum bend of the bone cores were modelled explicitly to behave in the same way as the physical impactor.

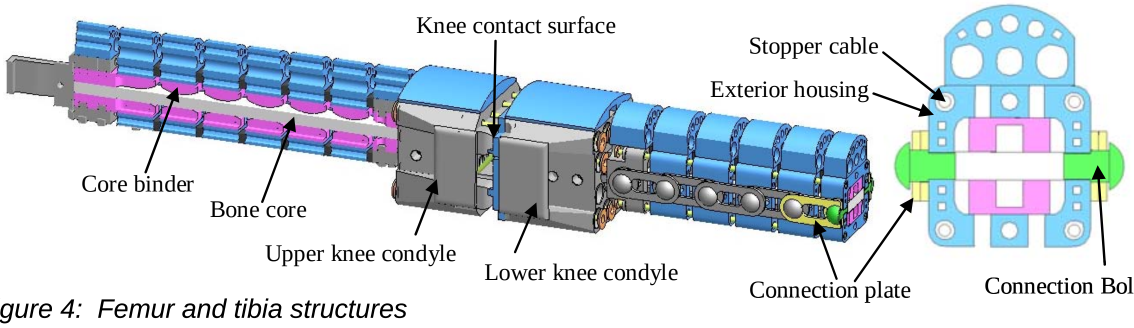

Figure 4: Femur and tibia structures

2.2.3. Knee Model

Figure 5 shows the model of the knee. The upper and lower condyles were modelled using a rigid material and the impact faces and the knee contact surface using deformable elements.

Four kinds of ligament cables: ACL (Anterior Cruciate Ligament), MCL (Medial Collateral Ligament), PCL (Posterior Cruciate Ligament) and LCL (Lateral Collateral Ligament), were created using very detailed and complicated modelling techniques. Weak spring elements were modelled as potentiometers to measure knee ligament elongations at ACL, MCL and PCL locations.

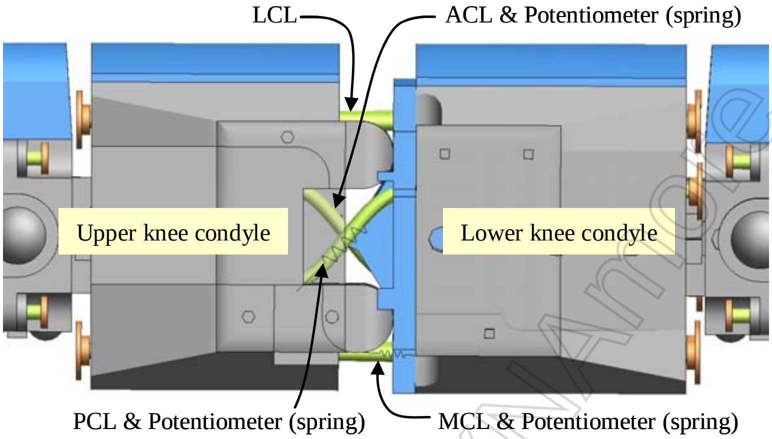

Figure 5: Knee ligament structure and potentiometers

2.2.4. Flesh

Figure 6 and 7 show the layered structure of neoprene and rubber sheets that form the flesh in the same way as the physical impactor.

The neoprene was modelled using *MAT_SIMPLIFIED_RUBBER and the rubber using *MAT_OGDEN_RUBBER. Their material properties were developed from accurate static and dynamic tests of production sheets.

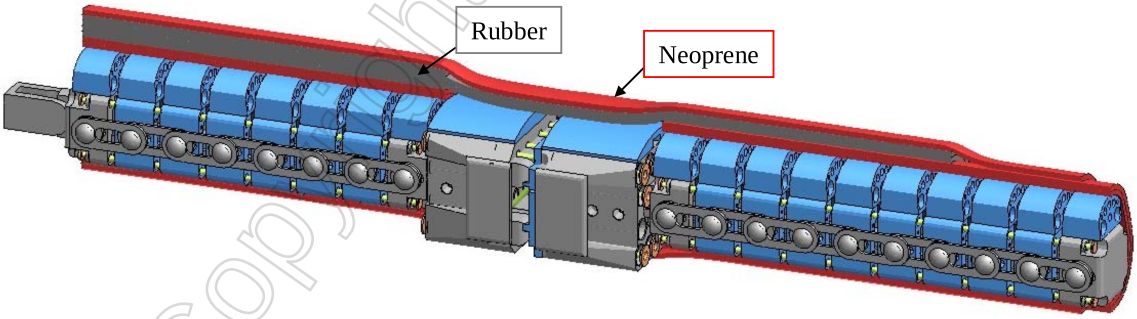

Figure 6: Layered sheets of flesh construction

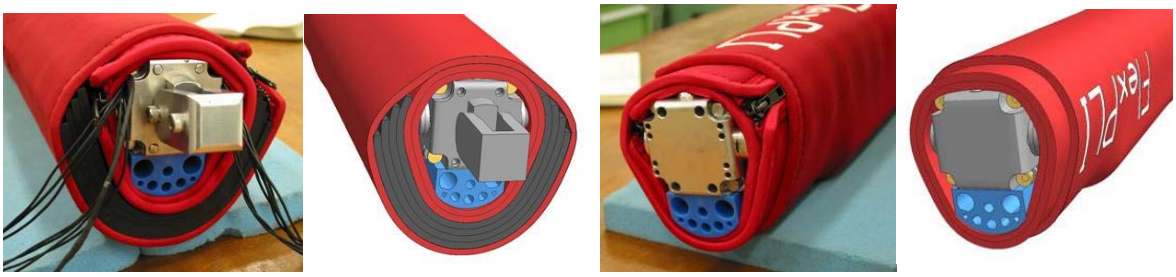

Figure7: Flesh construction of a physical impactor and LS-DYNA model (Top and Bottom)

2.3. Model Calibrations

2.3.1. *Bone Core Static Calibration*

Simulations of 3-point bending static calibration tests for the femur and tibia bone cores [9] were performed using the quasi-static method and material properties of the core were adjusted to achieve the correct calibration stiffness (see Figure 8).

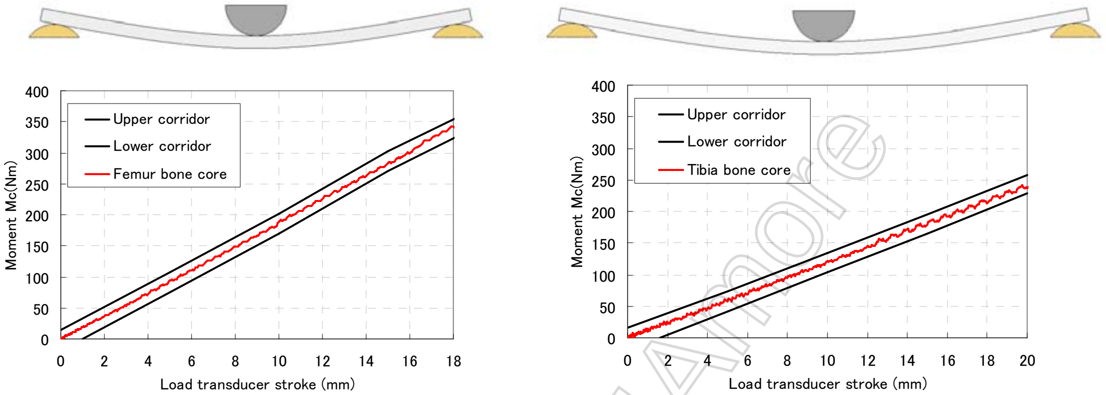

Figure 8: Femur and tibia bone cores calibration results

2.3.2. *Femur and Tibia Static Calibration*

Figure 9 shows the results of the 3-point bending quasi-static calibration analysis for the femur and tibia model assemblies [9]. The models were adjusted to satisfy calibration stiffness requirements.

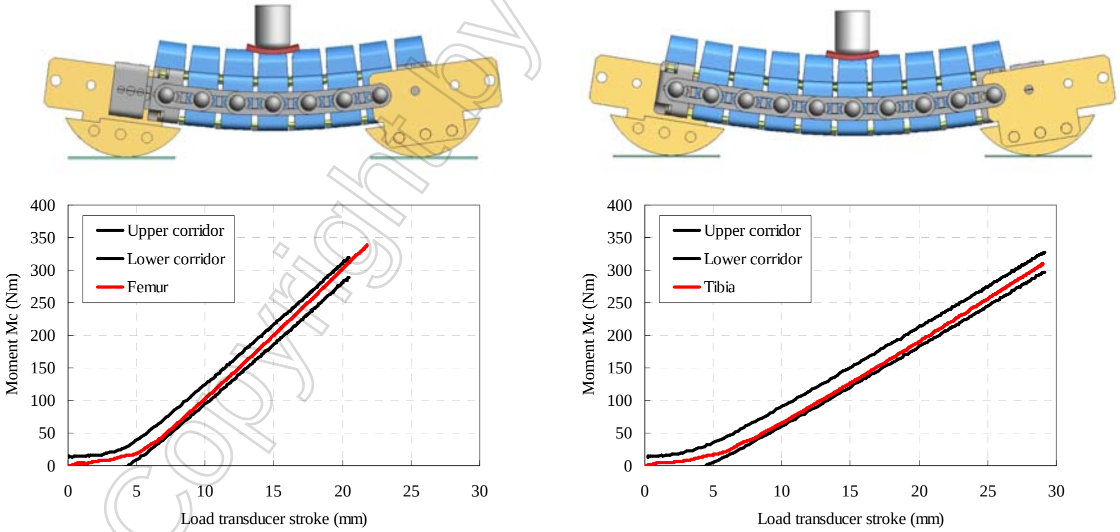

Figure 9: Femur and tibia static calibration results

2.3.3. *Knee Static Calibration*

Figure 10 shows the result of the 3-point bending quasi-static calibration analysis for the knee model [9]. The model was adjusted to satisfy calibration stiffness requirements.

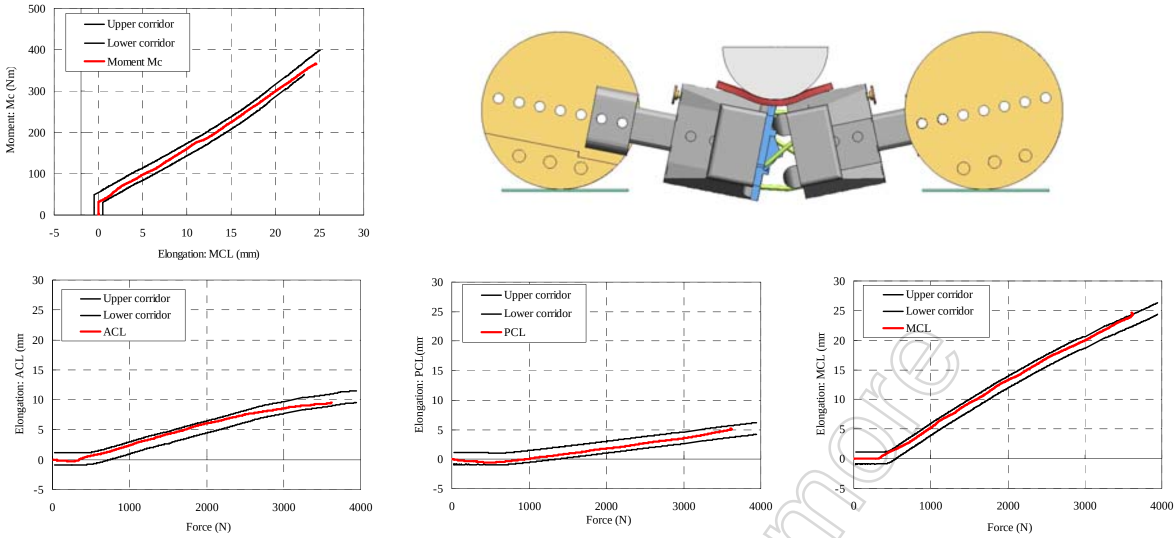

Figure 10: Knee static calibration result

2.3.4. Assembly Dynamic Calibration

The whole internal structure of the Flex-GT was assembled from the calibrated femur, tibia and knee models and a model of the test jig created according to the dynamic calibration test specification. As shown in Figure 11, the top of the femur is connected to the jig via a pin joint and the leg is released to freely swing down from a position 15 degrees above horizontal.

Calibration requirements are defined by a corridor for peak value of knee MCL, PCL and ACL elongations, three femur bending moments and four tibia bending moments [9]. The graphs in Figure 11 show that the Flex-GT model not only satisfies all calibration requirements but also predicts the rise and fall of output over time with great accuracy.

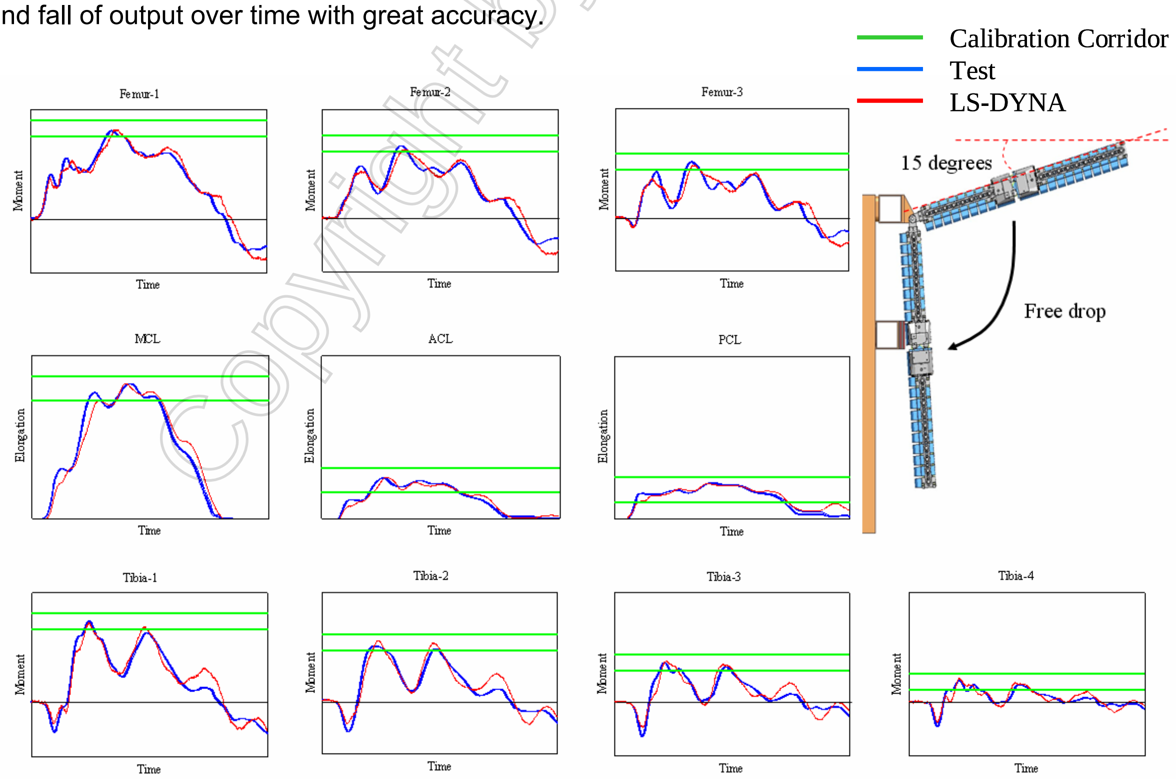

Figure 11: Dynamic calibration result: comparison of LS-DYNA and test

3. Flex-GT Simplified Car Rig Impact

A series of simplified car rig impacts were performed to validate the accuracy of the Flex-GT model. Figure 12 and 13 show one case of impact conditions and injury graphs of test and the LS-DYNA results. The peak values and graphical trends are well correlated.

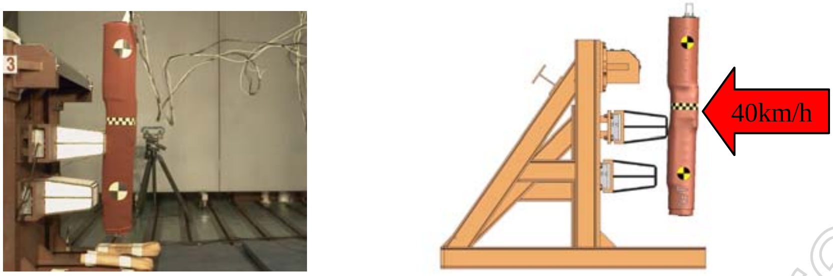

Figure12: A simplified car rig impact case

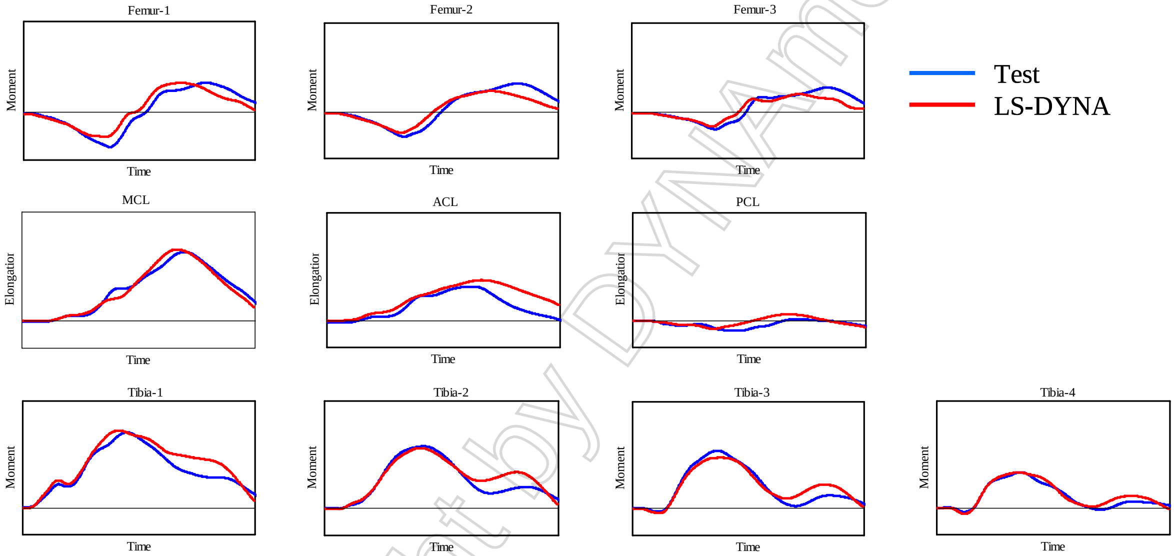

Figure13: Comparison of the test and the LS-DYNA results

4. Flex-GT Full Vehicle Impact

A series of full vehicle impact tests were performed to validate the LS-DYNA model injury prediction performance. Two types of vehicles, SUV (Sport Utility Vehicle) and sedan were impacted at various front end locations by the Flex-GT impactor. This paper presents the kinematic behaviour of one impact case and compares the LS-DYNA results to test.

Figure 14 shows a SUV type vehicle and corresponding LS-DYNA model. Impact occurs to the left of center at around 40km/h.

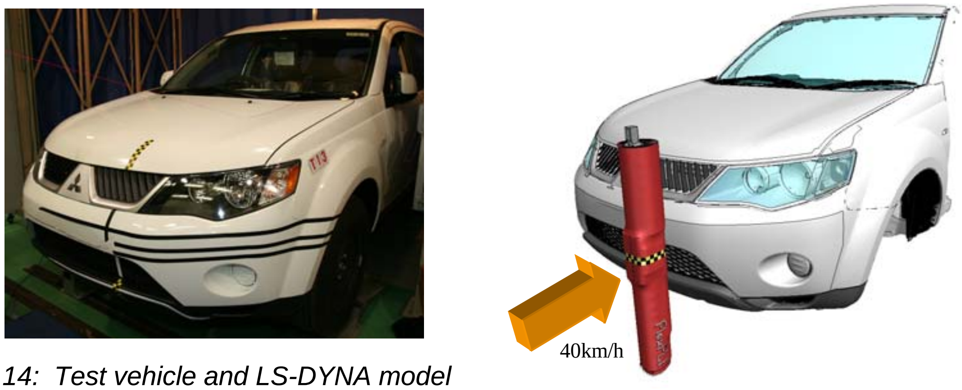

Figure 14: Test vehicle and LS-DYNA model

Four accelerometers (femur upper, knee upper, knee lower and tibia lower) were added to the internal structure of the Flex-GT to investigate its kinematic behaviour (see Figure 15).

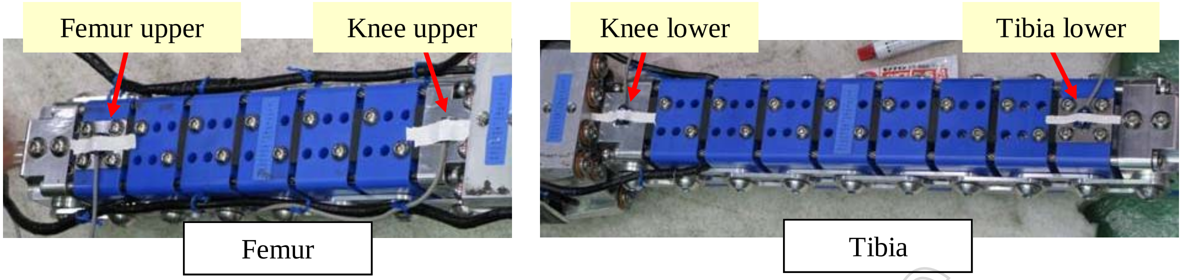

Figure 15: Accelerometers added to Flex-GT

A very detailed and accurate model of the vehicle front end structure was required to predict the same results as test. The Flex-GT model was first validated to high accuracy levels in the simplified car rig impact studies, so initial discrepancies in preliminary vehicle impact simulations could be attributed to the vehicle model or impact set up.

The vehicle front end structure, including bumper fascia, foam, grill, headlamps, spoiler, bonnet and radiator parts, had already been well validated in simulations of TRL lower leg impact or other CAE studies, however it was found that further improvements were required to achieve the excellent prediction performance shown below. In particular, realistic material failure and correct unloading stiffness of the vehicle structure was needed to accurately predict Flex-GT injury and kinematics.

Figure 16 shows the impact sequence of the test and LS-DYNA results. The kinematic behaviour of the Flex-GT is predicted very well.

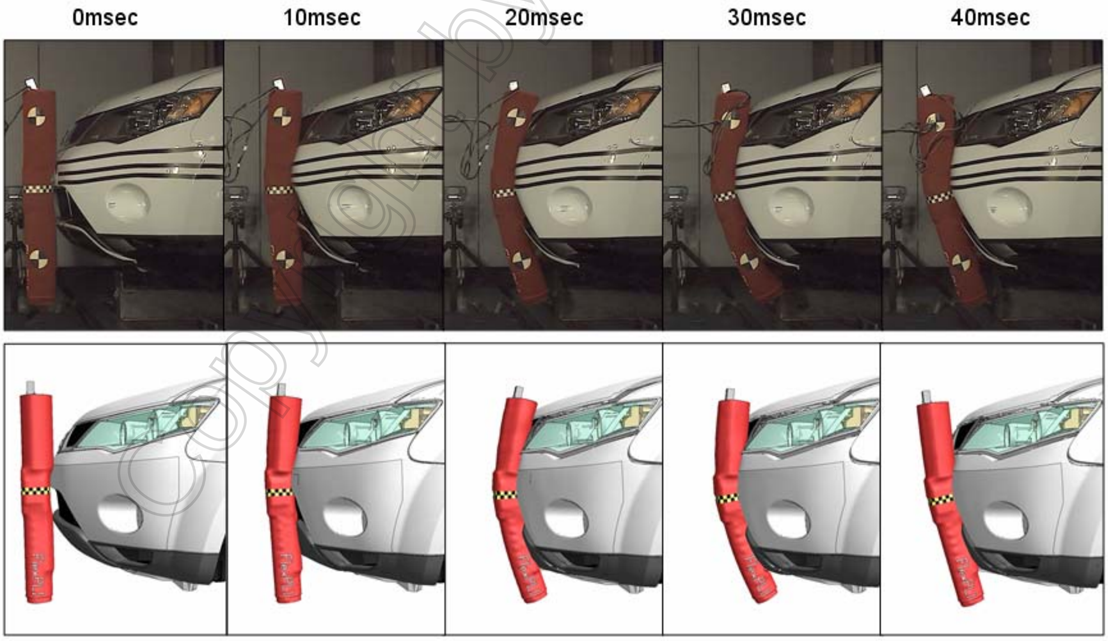

Figure 16: Comparison of vehicle deformation modes between test and LS-DYNA results

Figure 17 shows acceleration and displacement graphs of the test and LS-DYNA results. The peak values and trends over time and stroke are well correlated.

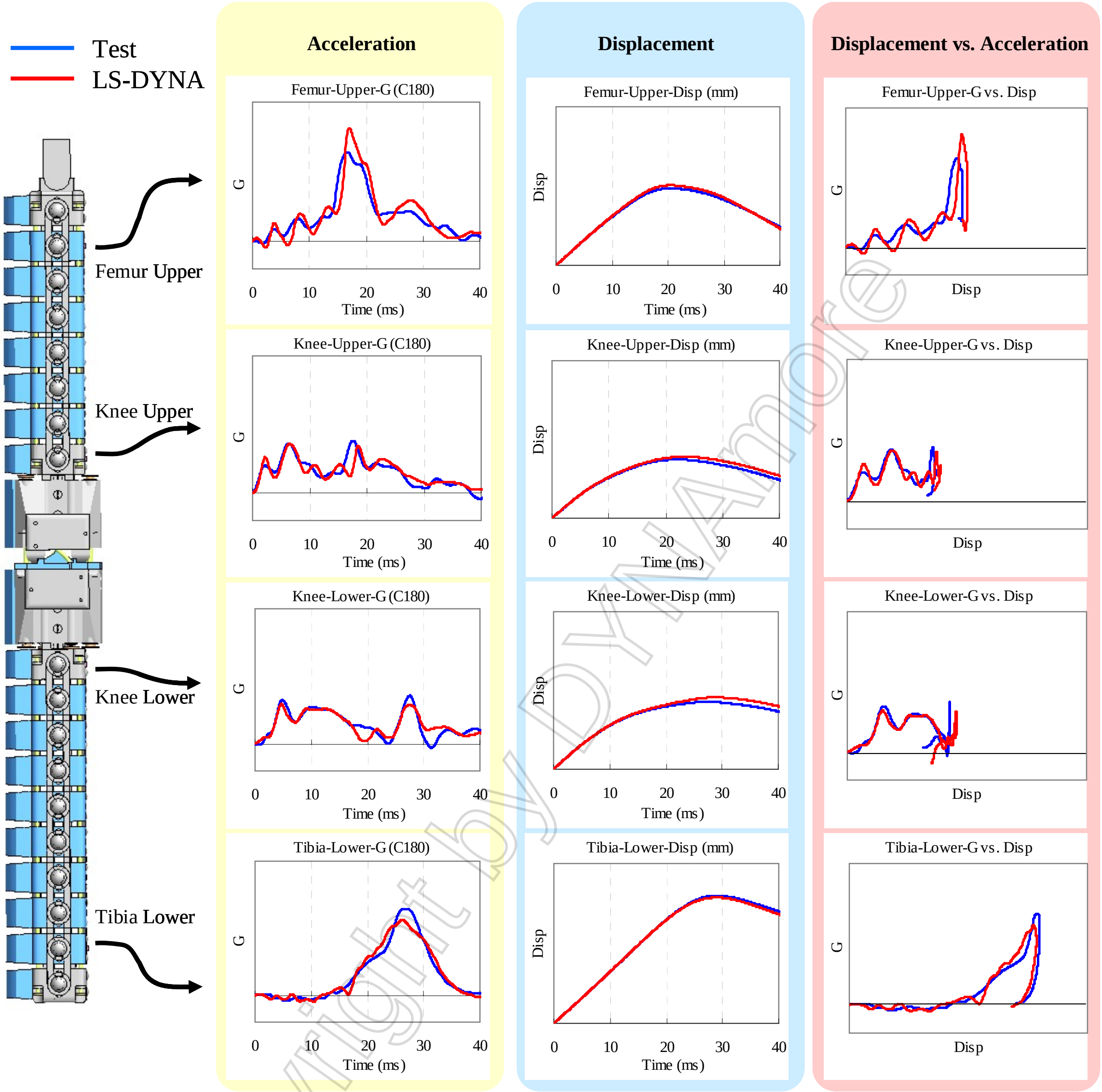

Figure 17: Comparison graphs of accelerations and displacements between test and LS-DYNA results

The knee joint system can flex in complicated kinematic modes: not only in bending but also in shear and torsion. It is designed to behave in the same way as a human knee. In particular, when it hits a curved area of the vehicle, a combined twist, shear and bend mode can often occur (see Figure 18). Accurate realisation of all kinematic modes is vital for correct injury prediction and this has been achieved using detailed modelling techniques and thorough validation stages.

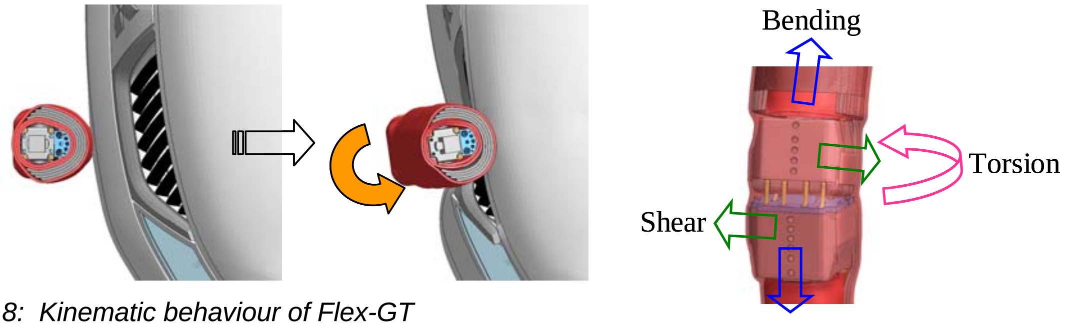

Figure 18: Kinematic behaviour of Flex-GT

5. Flex-GTR Model Development Plan

An effort to upgrade Flex-GT LS-DYNA model into Flex-GTR is currently underway. Part of the upgrade includes changes to the knee ligament system [10], but most of structure and performance of Flex-GTR is reported to be similar to the Flex-GT. The modelling techniques and methods employed in developing Flex-GT model will be directly applied to Flex-GTR, ensuring the same high level of accuracy and realism.

In the near future, the Flex-GTR LS-DYNA model will be available from JSOL Corporation.

6. Conclusions

1) A high accuracy Flex-GT LS-DYNA model has been successfully developed that satisfies all calibration requirements.

2) Excellent correlation of injury and kinematics was achieved in the dynamic calibration test, and accurate predictive performance validated using a series of simplified car rig impacts.

3) Further validation was achieved using a series of impact tests on 2 different vehicles at 40km/h, confirming sufficient high performance and robustness.

7. Acknowledgement

The authors show grateful appreciation to the engineers at JARI for their cooperation and help in understanding the physical Flex-GT impactor and for executing the calibration and vehicle impact tests used in this study. They would also like to thank Richard Taylor of Arup for advice and support.

8. References

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