Bi-directionally Coupled Multi-Physics Analysis on Fuel Tank

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***Abstract**: A motorcycle fuel tank is regarded as important safety-related part containing flammable fluids. It may lead to life threatening situation if the fluid leaks. Thus apart from general dynamic simulation, the fuel tank should be subjected to lateral impact test. The physics of fluid-structure impact are complex, and modeling of such events requires proper understanding of both fluid dynamics and structural mechanics. The fluid-structure interaction was achieved through arbitrary Lagrangian-Eulerian (ALE) approach in Abaqus. Since the deformations of the structure are large, the velocity and pressure fields of the fluid will change as a result, thus the problem acts as bi-directionally coupled multi-physics analysis: where the structural deformations affect the flow and pressure and vice versa. As per SAE J1241, 450J of energy was transferred to fuel tank using a pendulum which represents human knee joint. A good correlation was achieved between the deformation of fuel tank in testing and simulation. The focus was to verify whether the fuel tank ruptures under the impact or due to contact with surrounding frame parts.*

***Keywords**: Fuel tank, Impact, Fluid-structure interaction, arbitrary Lagrangian-Eulerian, Coupled Eulerian-Lagrangian.*

1. Introduction

1.1 Fuel tank

A motorcycle fuel tank has multi-functions. Apart from providing ergonomic contact surfaces for the rider and contributing to riding comfort and handling of motorcycle, fuel tank is a safety-related part containing flammable fluids. Fuel tanks are generally evaluated by tilt test for leakage and pave or durability test for checking dynamic stability.

Motorcycle fuel tank contains lot of components attached to it. The HC collector, fuel over flow drain tube, fuel cock, fuel level indicator and fuel cap. Each part has its own unique function and equally plays critical role in performance of vehicle, pollution control and safety of rider. Unlike four wheelers, in motorcycle, fuel tank is exposed outside. Thus makes the part life-threatening and has to be modeled using non-corrosive and fuel storable materials, considering the external factors like environment effects, road excitation, impact loads.

Fuel tank is mounted to frame using rubber grommets. These grommets, acts as dampers to isolate the part from frame thereby, reducing the input excitation. The fuel tank should not rupture due to the impact or interference of any sharp corner of surrounding stays. A small crack can lead to fuel leakage. Figure 1 shows the exploded view of fuel tank assembly. In India where accidents are common, the fuel tank should be tested for lateral impact also to ensure the there is no fuel leakage and life-threatening situation.

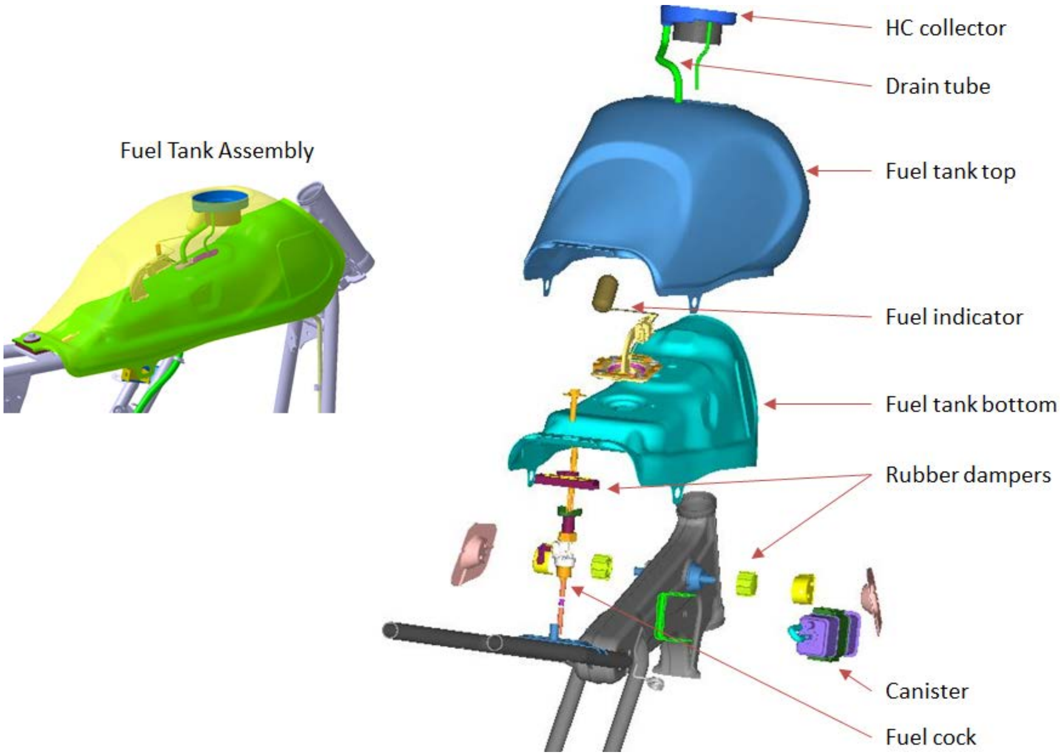

Figure 1. Exploded view of fuel tank assembly

1.2 Testing standard

SAE J1241 is a guideline for all types of fuel tanks traditionally located between the front cowl and saddle. It includes a lateral impact test with increased impact energy. The fuel tank is filled up to certain percentage of the rated capacity with liquid fuel substitute. The impact is performed with 450Nm energy induction at the knee point by a hemispherical test body. Steel tanks are tested at room temperature. Figure 2 shows the determination of impact location as given in SAE J1241.

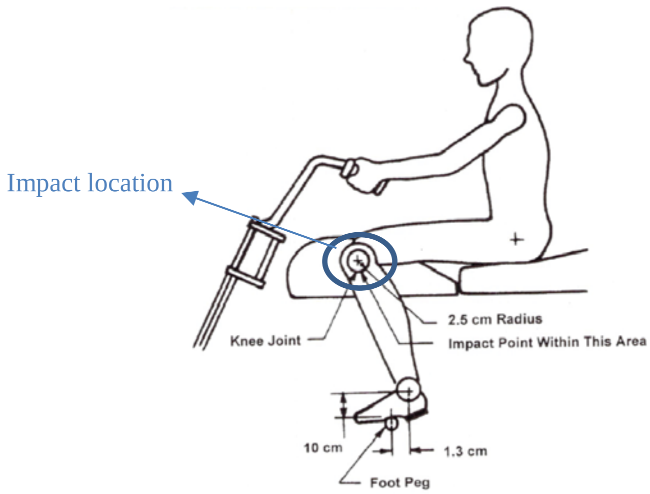

Figure 2. Impact location for lateral impact test

1.3 Analytical procedure

A failure in physical testing, leads to design and die change. Thus simulating the condition virtually plays a key role in the lead time, quality and cost. A high-velocity collision (an impact) does not provide sufficient time for deformations and vibrations to occur. Thus, the struck material behaves as if it were more brittle than it would otherwise be, and the majority of the applied force goes into fracturing the material. The presence of fuel makes the problem further complex. This leads to interaction of two major fields in Continuum mechanics, namely solid mechanics and fluid mechanics which are based on the basic principles of mass-, momentum- and energy conservation. Continuum mechanics is the analysis of the kinematic and mechanical behavior of materials modeled on the assumption that the mass is continuous instead of discrete particles and voids. It is convenient to use the Lagrangian formulation in solid mechanics since the material follows the deformation and constitutive laws often are in terms of total deformation. The Eulerian formulation is used in fluid mechanics where constitutive laws are deformation rate dependent and independent of the total deformation. Abaqus uses Coupled Eulerian-Lagrangian approach which is based on general concept of arbitrary Lagrangian-Eulerian (ALE) method to understand the coupling between fluid and solid mechanics, the Fluid Structure Interaction (FSI).

2. Simulation

2.1 Analysis setup

Fuel tank, the Lagrangian mesh was modeled in using a preprocessing tool as shown in figure 3. Few surrounding components were also meshed to study its effect on fuel tank as the impact test leads to large deformation. Non-linear material properties were provided for fuel tank, frame sheet metals and tubes. The fuel tank is supported or bolted to frame with the help of rubber dampers. The rubbers were modeled with mooney-rivlin material properties.

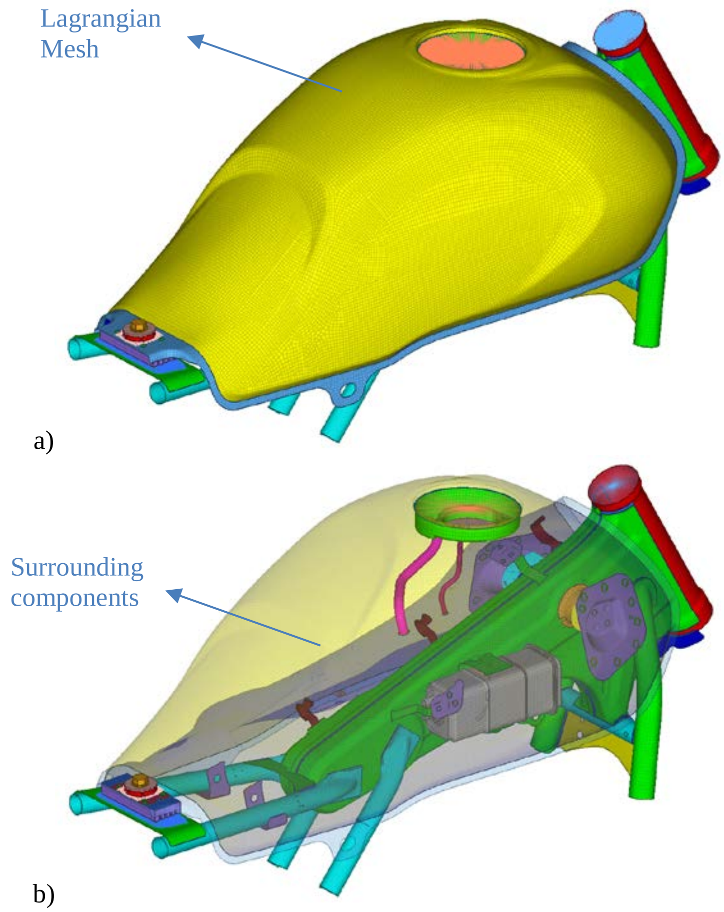

Figure 3. Mesh of fuel tank and surrounding parts

During the impact, the damping and force transfer of fluid plays an important role. Thus modeling of fluid inside the fuel tank and achieving contact is critical. The fluid was modeled in Abaqus/CAE as Eulerian elements. It is essential to model the fluid inside the fuel tank alone. Abaqus/CAE ensures that using volume of fluid (VOF) method. Eulerian elements were modeled as shown in figure 4 representing the level of fluid and assembled along with Lagrangian mesh of fuel tank (without free edges).

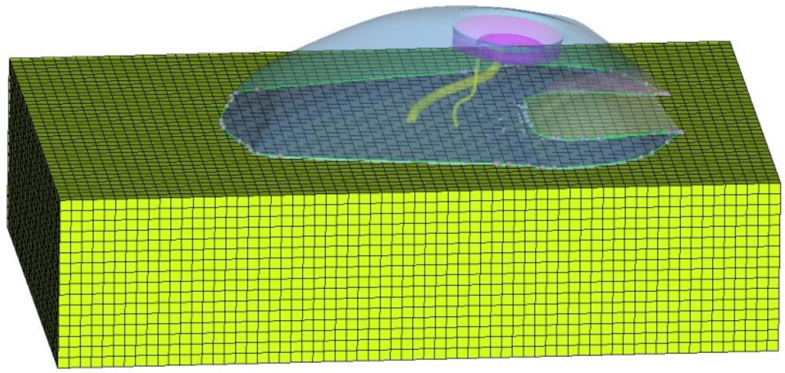

Figure 4. Eulerian mesh to model fluid inside fuel tank

The Eulerian capability can be coupled with traditional Lagrangian capabilities to model interactions between highly deformable materials and relatively stiff bodies, such as in fluid-structure interactions. The principle of calculation is based on the volume of fluid method (VOF). This method is the key to determine the location of the free surface of the fluid and figure 5 shows the same. The volume fraction tool creates a scalar discrete field by performing a Boolean comparison where, the fuel tank intersects the fluid instance. When the volume fraction of the fluid in an element is between zero and one the element is partially filled and thus the surface of the fluid must be in that element. The surface of the fluid is then approximated with the information for the element and the surrounding elements. This is calculated for each time increment in the analysis.

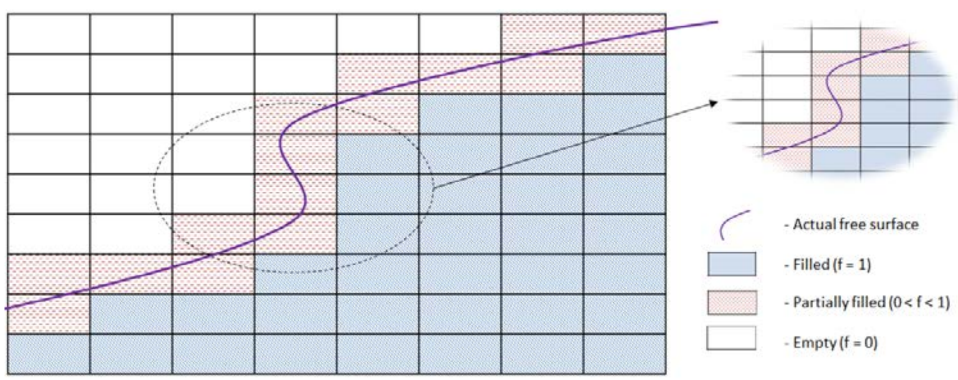

Figure 5. Volume of fluid method (VOF), f is volume fraction

Other mesh components were then introduced and equivalence of node was done to generate connectivity. The Eulerian mesh was dragged upwards also such that the whole fuel tank was inside the fluid domain. Hemisphere was modeled with respect to SAE standards to transfer 450J of energy at knee contact zone.

Contact pair was given at critical locations like rubber and frame regions. General contact was introduced to develop contact between fluid-structure, and structural parts during deformation. The Eulerian-Lagrangian contact formulation is based on an enhanced immersed boundary method. In this method the fuel tank structure occupies void regions inside the fluid mesh. The contact algorithm automatically computes and tracks the interface between the fuel tank structure and the fluid materials. Eulerian-Lagrangian contact constraints are enforced using a penalty method, where the default penalty stiffness parameter is automatically maximized subject to stability limits. Adaptive mesh refinement technique was introduced for Eulerian mesh to ensure better force transfer and contact generation of fluid elements closer to Lagrangian mesh. Figure 6 shows the complete finite element model for analysis.

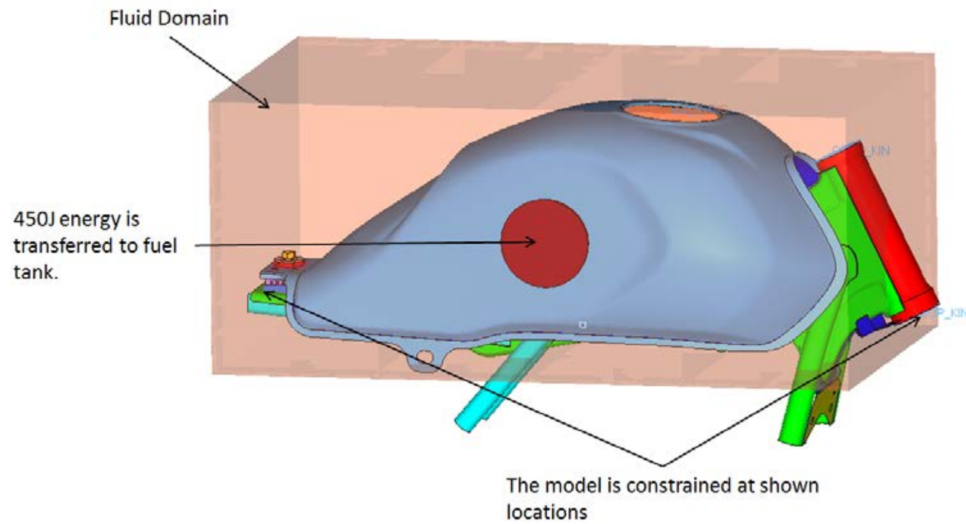

Figure 6. Finite element model for analysis

Simulation that includes this type of analysis is referred to as coupled Eulerian-Lagrangian (CEL) analysis. The general calculation procedure is shown in figure 7. First a Lagrangian approach is used for fuel tank and surrounding components as the mesh deforms, after which the material flow between the connecting elements is calculated. The mesh is then restored and the volume fraction is updated. Table 1 show the element type used and total number of elements in the model.

Table 1. FEA model

Parts	Element type	No. of elements
Rubber	C3D8R	2730
Solid body	C3D4	3627
Shell surface	S3	5478
Shell surface	S4	173180
Fluid	EC3D8R	76183

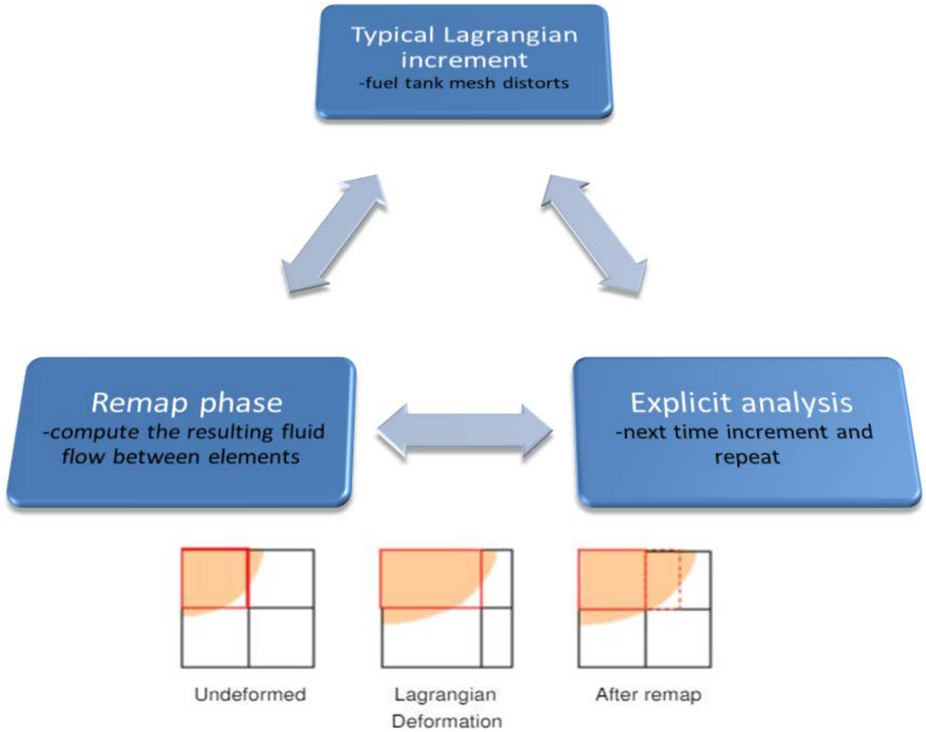

Figure 7. Lagrange-plus-remap algorithm

2.2 Numerical calculation

The Coupled Eulerian-Lagrangian Formulation requires the use of an explicit analysis procedure. The finite element discretization for a dynamic case can be written in the form,

$$M\ddot{u} = P - I$$

where, M is the Mass matrix, ü is the accelerations, P is the external forces and I is the internal forces.

An effective method for modeling fluid in Abaqus/Explicit is to use a simple Newtonian viscous shear model and a linear U_s-U_p form of the Mie-Gruneisen equation of state for the bulk response. The bulk modulus functions as a penalty parameter for the incompressible constraint. The shear viscosity also acts as a penalty parameter to suppress shear modes that could tangle the mesh.

Abaqus/Explicit solves the continuity, motion and energy equations, reduced by the constitutive law and the equation of state in an explicit manner.

The equation of state is assumed for the pressure, p, as a function of the current density, ρ, and the internal energy per unit mass, E_m. Mie-Gruneisen equation of state is linear in energy. Assuming negligible shear stress and lack of heat source, the most common form of equation is

$$p - p_H = \Gamma\rho(E_m - E_H)$$

where, p_H and E_H are the Hugoniot pressure and specific energy (per unit mass) and are functions of density only, and Γ is the Gruneisen ratio defined as

$$\Gamma = \Gamma_0 \frac{\rho_0}{\rho}$$

where, Γ_0 is a material constant and ρ_0 is the reference density.

The Hugoniot energy, E_H is related to the Hugoniot pressure by

$$E_H = \frac{p_H \eta}{2\rho_0}$$

where, $\eta = 1 - \rho_0/\rho$ is the nominal volumetric compressive strain. Elimination of Γ and E_H from the above equations yields,

$$p = p_H \left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m$$

The equation of state and the energy equation represent coupled equations for pressure and internal energy. Abaqus/Explicit solves these equations simultaneously at each material point.

A common fit to the Hugoniot data is given by

$$p_H = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}$$

where, c_0 and s define the linear relationship between the shock velocity, U_s, and the particle velocity, U_p, as follows:

$$U_s = c_0 + sU_p$$

With the above assumptions the linear U_s-U_p Hugoniot form is written as

$$p = \frac{\rho_0 c_0^2 \eta}{(1 - s\eta)^2}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m$$

where, $\rho_0 c_0^2$ is equivalent to the elastic bulk modulus at small nominal strains. In Abaqus/Explicit CEL methodology the value of Γ_0 and s are zero.

To obtain a stable solution the critical time increment is calculated automatically by Abaqus/Explicit but by manipulating its controlling factors the total analysis time may be reduced. The time increment in Abaqus/Explicit can be estimated by the equation

$$\Delta t = \min\left(\frac{L}{C_d}\right)$$

where, L is the characteristic element length, which approximately is the smallest element edge, and Cd is the dilatational wave speed of the material. This estimation does not take into account the effects of damping or contact conditions.

3. Results

The setup was built by testing team and performance of a fuel tank design was studied for the lateral impact test with fluid substitute. Figure 8 shows the large deformation which the fuel tank undergoes. The fuel tank did not rupture under 450Nm impact load.

Figure 8. Deformation in physical testing

The same was simulated virtually. Post processing tool was used to visualize the results for Lagrangian and Eulerian domains. The displacement contour, shown in figure 9 was similar to that of deformed part in testing. The importance of fluid modeling and hyper elastic material modeling was visible from the simulation results, without which the deformed shape was totally different.

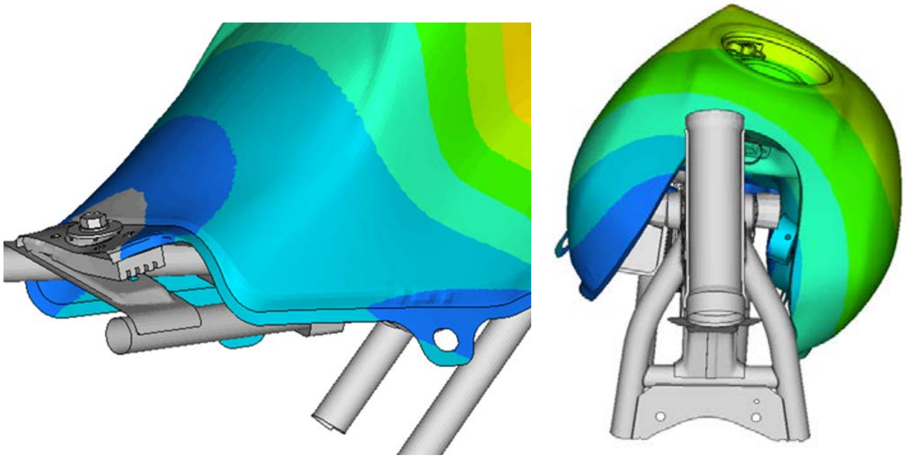

Figure 9. Displacement Contour

The stress plot of fuel tank due to lateral impact is shown in figure 10. The red contour region had maximum stress, however since the stress was less than ultimate tensile strength of fuel tank material, the design shall not rupture due to the lateral impact. The stresses due to contact of fuel tank with surrounding components were also less.

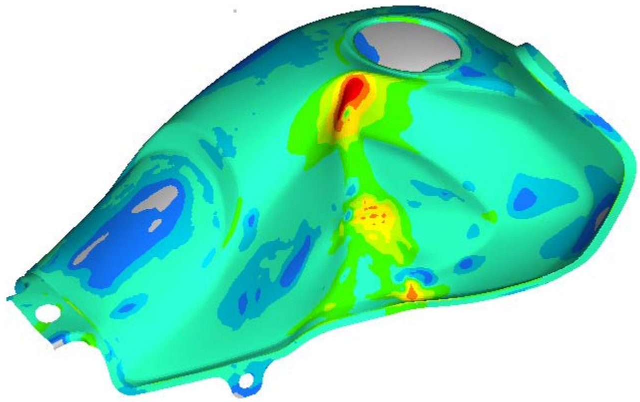

Figure 10. Stress Contour

The results of an Eulerian analysis must be interpreted differently than those from a Lagrangian analysis. Visualization of material instances, that is the fluid, is based on output variable EVF, the Eulerian material volume fraction. It measures the amount of fluid within an element as a relative fraction. Figure 11 depicts the movement of fluid in a cut section view, for different time increment during the impact. The red contour is element with EVF as one, i.e. fully filled with fluid. Grey region is EVF as zero, i.e. is the element contains no fluid. Other colors represent the EVF is between zero and one.

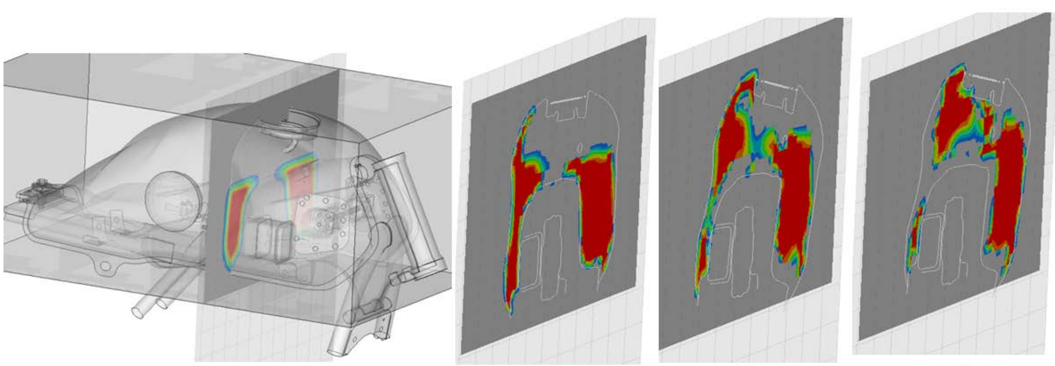

Figure 11. EVF output for a cross section at different time increment

As per SAE standards the test should be conducted with fluid. However, to study the effect of fluid during impact, the assembly was analyzed without fluid. Table 2 shows the difference in results between filled and unfilled fuel tank during impact analysis.

Table 2. Impact analysis – Filled vs Empty fuel tank

Parameter	Filled fuel tank	Empty fuel tank	Inference
Displacement	x	1.12 x	Fluid dampens the system
Plastic work	z	1.03z	

4. Summary/ Conclusion

Fuel tank being the most life-threatening part of motorcycle during impact was subjected to lateral impact test with SAE, J1241, as reference. In order to reduce the time and cost in physical testing the impact test to be simulated virtually was desirable.

Modeling the fluid and achieving the multi-physics interaction was a challenge. The deformations of the fuel tank should be captured along with material movement, whereas fluid has to be modeled in Eulerian approach. Contact between Lagrangian and Eulerian model was also important as the force transfer is bi-directionally coupled.

The coupled Eulerian-Lagrangian, CEL technique in Abaqus/CAE has made it easier to model the effect of fluid structure interaction. Fluid was modeled as Eulerian elements and other parts were modeled as Lagrangian elements. Using volume of fluid method fluid was defined inside fuel tank. General contact was defined to generate contact between the fluid and fuel tank which is based on an enhanced immersed boundary method. Using explicit analysis procedure, the coupling between fluid and solid mechanism was simulated.

The stress obtained on fuel tank due to 450J of lateral impact load was less than the ultimate tensile strength of the material. Thus the part shall not rupture and fuel leakage is prevented during accidents. The outcome from CEL methodology is similar to testing results.

5. References

1. Adrian Constantinescu, Aboulghit El Malki Alaoui, Alain Neme and Philippe Rigo, “Numerical and Experimental Studies of Simple Geometries in Slamming”, University of Liege, Belgium.
2. Henrik Johansson and Jonathan Ollar, “Polymer Flow in Package Sealing Process - A Coupled Eulerian-Lagrangian Numerical Approach”, Master’s Dissertation, Lund, January 2011.
3. SAE, J1241, REV. NOV1999.
4. Abaqus User’s Manual, Version 6.14, Dassault Systemes Simulia Corp., Providence, RI.