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FLUID-STRUCTURE INTERACTION IN A TANK VEHICLE TRANSPORTING LIQUID FUEL

ABSTRACT: Sloshing in tank vehicles transporting liquid fuels is influencing the vehicle stability during braking and cornering manoeuvres, increasing the rollover risk. The requirements for the design and the construction of metallic tanks intended for the carriage of liquid fuels are described in EN13094. According to this standard, finite element analysis of the tank simulating dynamic driving conditions, operating conditions and test pressure conditions is required for the assessment of the structural integrity of the tank as well as its mounting on the heavy vehicle. In this paper, a two-way fluid-structure interaction finite element model of a box-shaped tank during the braking conditions described in EN13094 is built in Ansys Workbench. A computational fluid dynamics simulation with the volume of fluid (VOF) method is coupled to a transient structural simulation in order to model the movement of the fluid in the tank and monitor its effect on the structural dynamic response of the tank construction. Two different filling ratios have been simulated (80% and 20% of its maximum carrying capacity) and the stress distribution on the tank shell as well as the forces developed on mounting of the tank on the vehicle are investigated providing a useful insight for the construction of the tank vehicle.

KEYWORDS: tank vehicle, sloshing, fluid-structure interaction, EN13094, structural integrity

INTERAKCIJA FLUIDA I KONSTRUKCIJE CISTERNE ZA TRANSPORT TEČNOG GORIVA

REZIME: "Pljuskanje" u cisternama koje prevoze tečna goriva utiče na stabilnost vozila tokom kočenja i manevara u krivinama, povećavajući rizik od prevrtanja. Zahtevi prema projektovanju i konstrukciji metalnih rezervoara namenjenih za prevoz tečnih goriva opisani su u standardu EN13094. Prema ovom standardu, analiza rezervoara metodom konačnih elemenata koja simulira dinamičke uslove vožnje, uslove rada i uslove pritiska pri ispitivanju potrebna je za procenu strukturnog integriteta rezervoara, kao i njegovog postavljanja na teško vozilo. U ovom radu,

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izgrađen je u Ansys Workbench-u dvosmerni model konačnih elemenata interakcije fluida i strukture rezervoara u obliku kutije tokom uslova kočenja opisanih u EN13094. Računarska simulacija dinamike fluida metodom zapremine fluida (VOF) povezana je sa prolaznom strukturnom simulacijom kako bi se modeliralo kretanje fluida u rezervoaru i pratio njegov uticaj na strukturni dinamički odziv konstrukcije rezervoara. Simulirana su dva različita odnosa punjenja (80% i 20% njegove maksimalne nosivosti) i ispitana je raspodela napona na omotaču rezervoara, kao i sile koje se razvijaju pri montaži rezervoara na vozilo, što pruža koristan uvid za konstrukciju cisterne.

KLJUČNE REČI: cisterna, „pljuskanje“ tečnosti, interakcija fluida i konstrukcije, EN13094, strukturni integritet

INTRODUCTION

Liquid fuels are critical energy carriers used in the industrial and commercial activities as well as in transport. Their supply chain includes long-distance transportation by marine tankers, pipelines, and rail tank wagons, followed by shorter-distance distribution using road tank vehicles. Maritime transport mainly supports international and intercontinental flows of crude oil and refined products, whereas pipelines provide continuous transfer between production, storage, and refining facilities. Tank vehicles constitute a primary means of supplying fuel stations, industrial plants and local distribution networks. Liquid fuels, in the Agreement concerning the International Carriage of Dangerous Goods by Road (ADR 2025) are classified as Class 3 – flammable liquids. Consequently, their transportation is subjected to strict technical and operational safety requirements. One of the operational safety requirements in ADR (2025) regarding tanks that are not subdivided in compartments by partitions or surge plates with a capacity not exceeding 7500 l, specifies a filling ratio of either no more than 20% or no less than 80% of the tank capacity.

Furthermore, the design and construction requirements for metallic gravity-discharge tanks intended for the carriage of dangerous goods by road and rail is described in detail in EN 13094:2020+A1:2022. This Standard includes design and construction requirements related to the tank shell, openings, closures, pipework, mountings and structural equipment and describes the functional and test loads applied on the tank by the transported material. For the structural verification of the tank shell, its attachments and the structural equipment, the Standard specifies that the tank shall withstand, separately, an acceleration of 2 g in the direction of travel, simulating braking conditions, an acceleration of 1 g acting at right angles to the direction of travel simulating cornering manoeuvre, an acceleration of 1 g acting downwards and 2 g acting upwards, all of them applied to the maximum design mass.

The dynamic behaviour of liquid cargo in partially filled tanks is an important factor affecting road transport safety. This phenomenon, commonly referred to as sloshing, describes the oscillatory motion of the liquid free surface when the tank is subjected to external excitation, such as acceleration, braking, cornering, lane-change manoeuvres. Abramson (1966) provided one of the fundamental contributions to the study of liquid dynamics in moving containers and established a theoretical and experimental basis for subsequent sloshing research. Liquid motion causes time-dependent changes in the pressure distribution acting on the tank walls, generating dynamic forces and moments and, in some cases, local impact loads at wave-impingement regions. In road tank vehicles, these effects may influence the structural loading of the tank shell, internal baffles and support connections, while also affecting vehicle dynamic stability, braking performance and rollover risk. Li et al. (2013) investigated the driving stability of tank vehicles using an equivalent pendulum-based representation of liquid sloshing, while Talebitooti et al. (2015) examined the influence of sloshing on the rollover-threshold acceleration of tank vehicles. The severity of sloshing is primarily governed by the filling ratio of the tank, the tank geometry, the presence and arrangement of baffles or surge-control devices, the properties of the transported liquid and the characteristics of the imposed motion. Particularly adverse conditions may occur when the excitation frequency approaches the natural frequencies of the liquid, resulting in amplified free-surface motion and hydrodynamic loads.

In the literature, sloshing has been investigated through experimental, theoretical and numerical approaches. Experimental studies are commonly conducted using scaled or full-scale tanks subjected to representative acceleration, braking, cornering or lane-change manoeuvres, while the liquid and structural responses are monitored through pressure sensors, free-surface measurements, accelerometers and force and moment measuring systems. Such experiments are essential because sloshing is highly nonlinear and transient and they also provide the data required for numerical model validation. Xie et al. (2024) combined experimental, theoretical and numerical approaches to investigate sloshing behaviour, while Firoozkoobi et al. (2010) examined experimentally and numerically the effect of swash bulkheads on sloshing mitigation. Early theoretical approaches were primarily based on potential-flow theory, usually assuming inviscid and incompressible flow. These methods are mainly employed to estimate free-surface natural frequencies and to describe small-amplitude oscillations in relatively simple tank geometries. Within this framework, Nakayama and Washizu (1981) applied the Boundary Element Method to two-dimensional nonlinear sloshing problems. Although potential-flow and Boundary Element approaches involve relatively low computational cost, they are limited in their ability to represent viscous effects, turbulence, wave breaking, and local impact pressures.

Equivalent mechanical models have also been developed for vehicle-dynamics applications, in which liquid motion is represented by lumped masses, springs, dampers, or equivalent pendula. Such models are suitable for multi-degree-of-freedom vehicle models and stability-control analyses because they substantially reduce computational cost. Shrimali and Jangid (2011) employed simplified mechanical representations to investigate the response of liquid-containing structures under dynamic excitation, whereas Li et al. (2013) proposed an equivalent pendulum formulation for the study of tank-truck stability. More recently, Qi et al. (2023) combined a multi-degree-of-freedom pendulum model with a free-surface fluctuation sensor to support real-time observation of liquid sloshing. However, equivalent mechanical models cannot accurately reproduce local wall-pressure distributions, impact loads, or the three-dimensional flow field developing around baffles and internal structural members.

The development of Computational Fluid Dynamics (CFD) has enabled a more detailed investigation of sloshing through the solution of the Navier–Stokes equations and the tracking of the air–liquid interface using multiphase-flow models. In particular, the Volume of Fluid (VOF) method is widely applied because it can capture the free surface, large wave deformation, liquid impact on tank walls, and interaction with internal baffles. Gómez-Goñi et al. (2013) performed a two-phase VOF analysis of sloshing in a rectangular container, while Ambade and Kale (2013) employed a CFD–VOF approach to investigate sloshing in a tank under acceleration and deceleration conditions. Ranganathan et al. (2008) also developed and validated a CFD–VOF model to assess different transverse-baffle configurations in a road tanker under braking, showing that baffle geometry, orifice location, and filling level strongly affect sloshing forces and pitch moments. Beyond the hydrodynamic response, Fluid–Structure Interaction (FSI) becomes important when thin-walled tanks, baffles, and support regions are considered. Arora and Vasudevan (2017) investigated sloshing-induced loads on a fuel tank structure and demonstrated the importance of coupled fluid and structural modelling. Arora et al. (2018) subsequently presented a partitioned FSI methodology for analysing sloshing-induced loads on a fuel tank structure.

In the present study, the sloshing in a road tank vehicle transporting liquid fuels is numerically investigated and the results are compared to the results of a static structural analysis. In more detail abrupt braking of a tank designed following the requirements of EN13094 (2022) is simulated. The followed approach combines a three-dimensional transient CFD simulation based on the Volume of Fluid (VOF) method, used to capture the air–liquid interface and calculate time-dependent hydrodynamic loads with a nonlinear transient finite-element structural analysis. A two-way Fluid–Structure Interaction (FSI) approach is implemented to account for the mutual interaction between liquid-induced pressure and the deformation of the tank structure. The structural response of the tank parts and the stress developed on the bolted connections of the tank to the vehicle is evaluated in terms of stress, displacement and reaction forces. The results are presented along with those obtained from a static structural analysis conducted using the EN 13094:2020+A1:2022 design loads. Moreover, two filling ratios, 20% and 80% of the maximum design mass, are examined using the FSI approach, corresponding to the limiting filling conditions specified in ADR (2025) for tank vehicles.

The remainder of this paper is organised as follows. Section 2 presents the description of the computational model including the CFD, structural and FSI-coupling methodology. Section 3 presents the numerical results, including the free-surface motion, hydrodynamic pressure, stress, displacement and response of the connection between the tank and the vehicle. Section 4 discusses the results obtained for each approach. Finally, Section 5 summarises the main conclusions.

ROAD TANK VEHICLE COMPUTATIONAL MODELLING

In this section the geometrical and the numerical modelling of the road tank vehicle is presented with emphasis to the CFD and the structural computational modelling.

Geometrical models

Two geometrical models have been implemented, one for the CFD and one for the Structural simulation. The tank geometry was developed in SolidWorks CAD software based on a design compliant with the requirements of EN 13094 (2022). As illustrated in **Figure 1**, the tank has a box-shaped cross-section with rounded corners and is divided into six compartments by internal baffles. The tank shell cross-section has a width of 2348 mm, a height of 1608 mm, and a corner radius of 584 mm. The tank has an overall length of 6910 mm and a total volume of 22124 l. The structural model includes the shell, the covers, baffles, the six manholes, the four supports and the eight support plates. The support plates connect the tank to the vehicle chassis through bolted connection. Through the bolted connection forces and moments arising from the tank weight and the sloshing-induced hydrodynamic loads are transferred to the vehicle chassis.

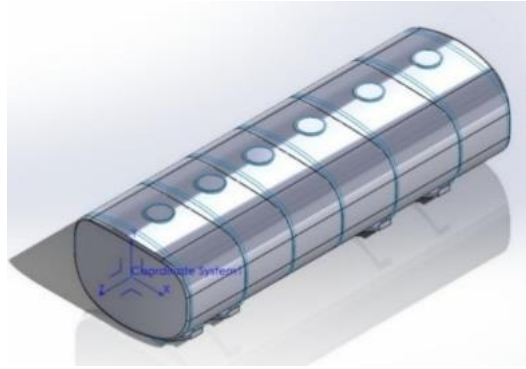


Figure 1 Three-dimensional geometrical model of the tank

The fluid domain was derived from the internal volume of the tank and it was designed in SolidWorks, as well, as the inverse volume of the solid tank model. This approach ensured geometrical consistency between the CFD and structural model of the tank. **Figure 2** illustrates the computational fluid domain corresponding to one compartment of the tank.

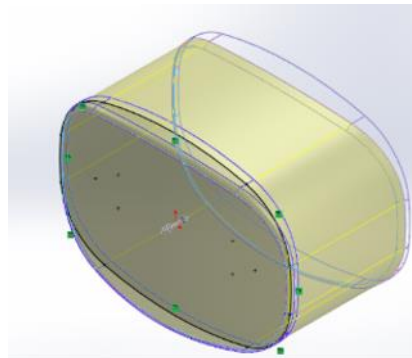


Figure 2 CAD model of the fluid domain of one tank compartment

Computational modelling

The movement of the liquid and the structural response of the tank structure are both modelled with CFD and Mechanical systems in ANSYS Workbench and they are coupled using the FSI tool.

Structural model

Within this framework, the tank geometry was imported into ANSYS Workbench as a thickness-free surface model. The thickness of each individual component was assigned using shell sections. Particularly, a thickness of 6 mm was assigned to the shell, covers, baffles and manholes, 8 mm were assigned to the supports and 20 mm were assigned to the support plates. The tank was manufactured with aluminium alloy EN AW-5186 (O/H111) with the mechanical properties provided in Table 1.

Table 1 Mechanical properties of EN AW-5186 (EN 14286, 2008)

Mechanical property	Unit	Value
Density	kg/m ³	2660
Elastic modulus	MPa	70300
Poisson's ratio		0.30
Tensile strength	MPa	125

All connections between the individual structural components of the tank were defined as bonded representing the welded joints of the structure. Consequently, no relative sliding or separation was allowed between the connected surfaces, ensuring load transfer between the shell, covers, baffles, supports and support plates.

The boundary conditions applied to the structural model are shown in **Figure 3**. The eight support plates were assigned fixed support boundary conditions to represent the connection between the tank and the vehicle chassis. The self-weight of the structure was taken into account by applying standard earth gravity. In addition, the internal tank surfaces in contact with the liquid were defined as a System Coupling Region to enable data exchange with the fluid model.

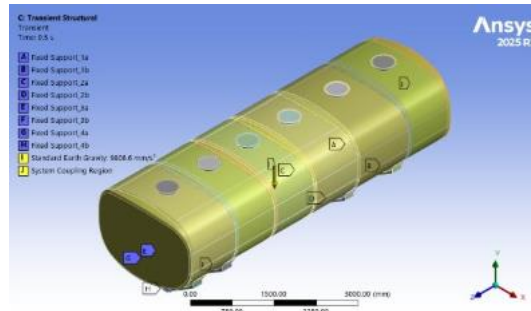


Figure 3 Boundary conditions of the structural model in ANSYS Transient Structural

The surface geometry of the tank was discretized using SHELL181 finite elements, which are suitable for the modelling of thin-walled metallic structures. Meshing was performed in the ANSYS Meshing environment using a characteristic element size of approximately 73 mm. The final structural mesh comprised 37742 FE and 39371 nodes. The mean aspect ratio was 1.11, while the mean element quality was 0.99, indicating a high-quality mesh.

The transient structural analysis was performed using a constant time step of 0.0001 s. This time step was selected to match that of the Fluent simulation and ensure temporal consistency during the two-way FSI coupling.

CFD model

The liquid fuel, in the CFD model was considered to have the properties of water and its flow was considered transient, incompressible and two-phase, consisting of water and air. The free-surface motion was simulated using the Volume of Fluid (VOF) multiphase model, which enables tracking of the water-air interface and representation of the large liquid motions. An inviscid flow assumption was adopted to provide a computationally efficient representation of the global sloshing response and the resulting transient wall-pressure distribution. The fluid domain was meshed in ANSYS Meshing using the CFD/Fluent meshing option and a characteristic element size of 150 mm. The final mesh comprised 605896 cells and 136985 nodes. The resulting computational mesh is presented in Figure 4.

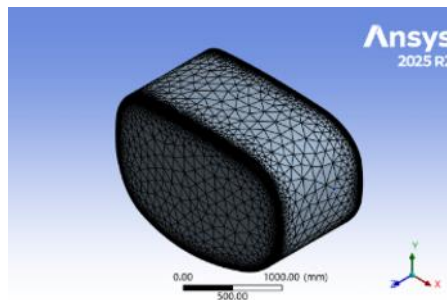


Figure 4 Computational mesh of the fluid model

The simulations were performed using the pressure-based solver in ANSYS Fluent. Pressure-velocity coupling was achieved using the PISO algorithm. The Body Force Weighted scheme was employed for pressure discretization, the Second Order Upwind scheme for the momentum equations and the Compressive scheme for volume-fraction discretization. Time integration was performed using the First Order Implicit scheme. To account for changes in the computational domain during the solution, the dynamic mesh model was activated in ANSYS Fluent. Mesh motion was handled using smoothing with implicit update, without remeshing. In the two-way fluid-structure interaction analyses, the tank wall surfaces participated in the coupling with the structural model through ANSYS System Coupling.

The flow field was initialized at rest, with zero initial velocity throughout the domain. The initial distribution of the liquid phase was imposed using cell registers and patching to represent tank filling levels of 80% and 20%. The simulations were performed with a constant time step of 0.0001 s and a maximum of 20 inner iterations per time step. For the braking simulation, standard gravitational acceleration was applied in the vertical direction, while a longitudinal acceleration of 2g was imposed for the first 0.05 s of the analysis to be in accordance with the braking dynamic load specified in EN 13094 (2022). The duration of the imposed acceleration was defined in the present numerical model to initiate the liquid motion and reproduce the subsequent transient sloshing response. After 0.05 s, the longitudinal acceleration was set to zero, allowing the subsequent sloshing response of the liquid inside the tank to develop. The total simulation time was 0.50 s.

RESULTS

The presented results focus on the displacement along the longitudinal axis, the equivalent Von Mises stress, the time evolution of the water-probe level at the tank centre and the corresponding evolution of the fluid field. For each filling ratio, representative result snapshots and time histories of the corresponding quantities are presented. In the plots, the original time-history signal is shown together with its FFT-filtered counterpart, while the maximum value of the filtered signal is also indicated. Furthermore, the results of the static structural analysis provisioned in EN13094 (2022) simulating braking are presented.

Filling ratio of 80%

The time history of the Von Mises stress for the 80% filling ratio is presented in Figure 6. The plot shows the original signal, the filtered signal and the maximum value of the filtered response. The maximum filtered von Mises stress is equal to 60.70 MPa and occurs at $t=0.105s$.

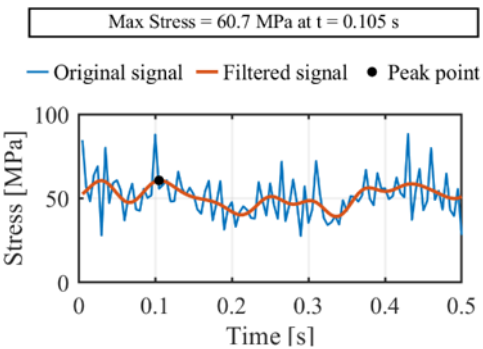


Figure 6 Time history of Von Mises stress during longitudinal braking, 80% filling level

The distribution of the equivalent Von Mises stress at the time of its maximum value ($t=0.105s$) is shown in Figure 5 for the (a) tank and the (b) component with the maximum value.

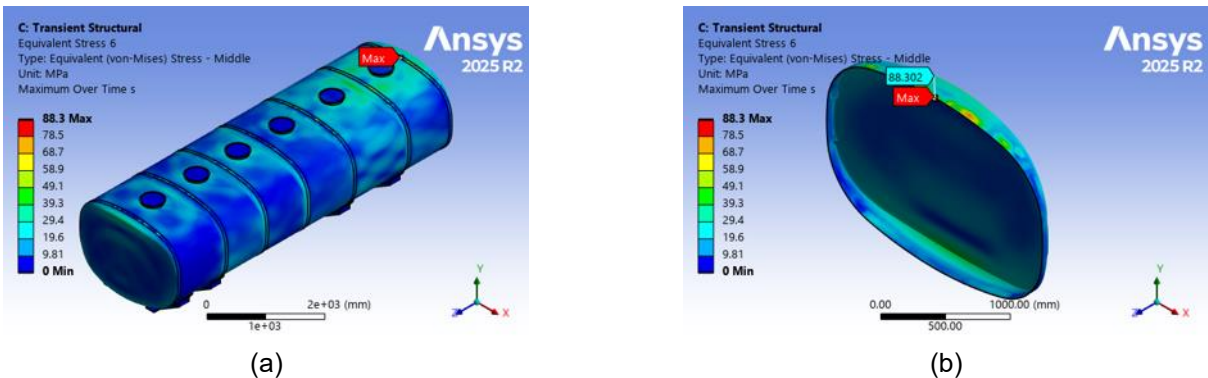


Figure 5 Equivalent Von Mises stress distribution in the tank at the time of maximum stress during longitudinal braking (80% filling ratio)

The time history of the directional deformation is presented in Figure 6 (a) and the distribution of the longitudinal deformation in the braking direction, on the tank baffles at the instant of its maximum value is presented in Figure 6 (b). The maximum filtered longitudinal displacement is 6.07 mm, occurring at $t=0.025s$.

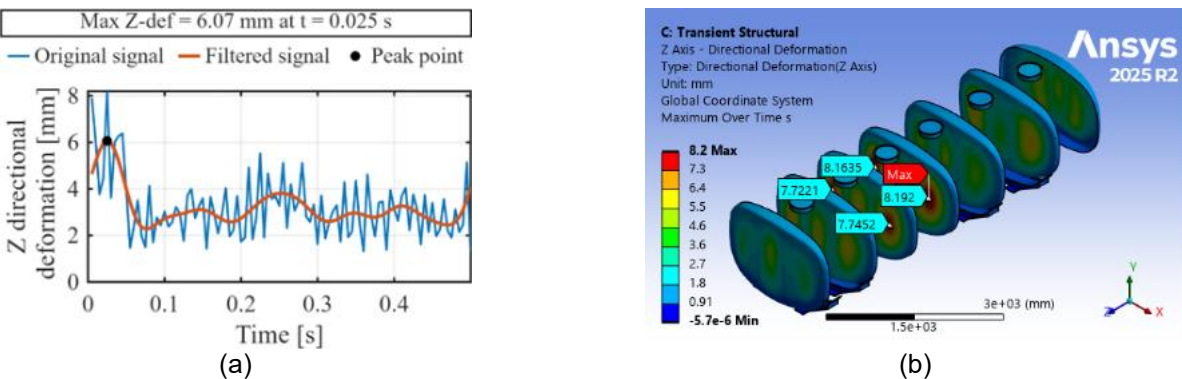


Figure 6 Longitudinal directional deformation along the z-axis during longitudinal braking, 80% filling level: (a) ANSYS contour result; (b) time history of the z-directional deformation

The time history of the water-probe variable at the centre of the tank is presented in Figure 7(a). A snapshot of the fluid volume-fraction field at the time corresponding to the selected free-surface configuration is shown in Figure 7(b).

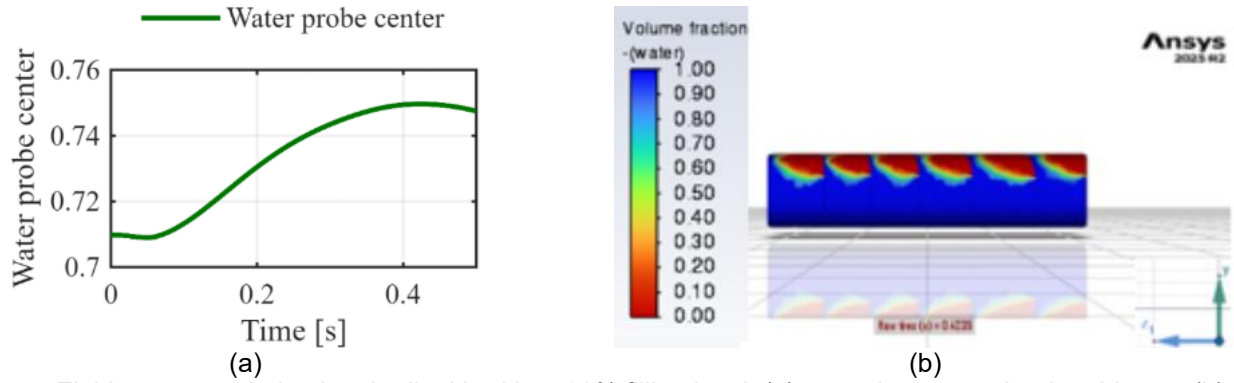


Figure 7 Fluid response during longitudinal braking, 80% filling level: (a) central water-probe time history; (b) volume-fraction distribution at the selected time instant

Filling ratio of 20%

In the case of a filling ratio equal to 20% the time-history of the Von Mises stress during braking is presented in Figure 8(a). The maximum value of the filtered Von Mises stress is 8.25 MPa and it occurs at $t=0.045$ s. The distribution of the equivalent von Mises stress in the tank baffles is presented in Figure 8(b) at the same instant.

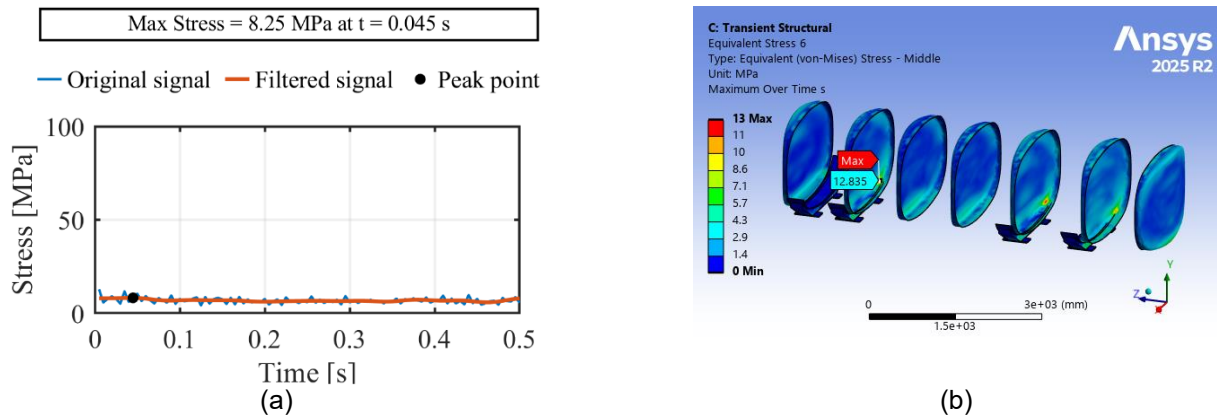


Figure 8 Equivalent von Mises stress results for longitudinal braking at a 20% filling level (a) time history of the maximum equivalent von Mises stress, including the original and FFT-filtered signals, (b) equivalent von Mises stress distribution in the tank baffles at the instant of maximum stress

The distribution of the longitudinal displacement (Z-axis) on the tank baffles, on the braking direction along with the time history of the maximum value of longitudinal displacement is presented in Figure 9. In more detail, Figure 9 (a) includes the original signal, the filtered signal, and the point corresponding to the maximum value of the filtered signal. The maximum filtered longitudinal displacement is 0.39 mm, occurring at $t=0.025$ s.

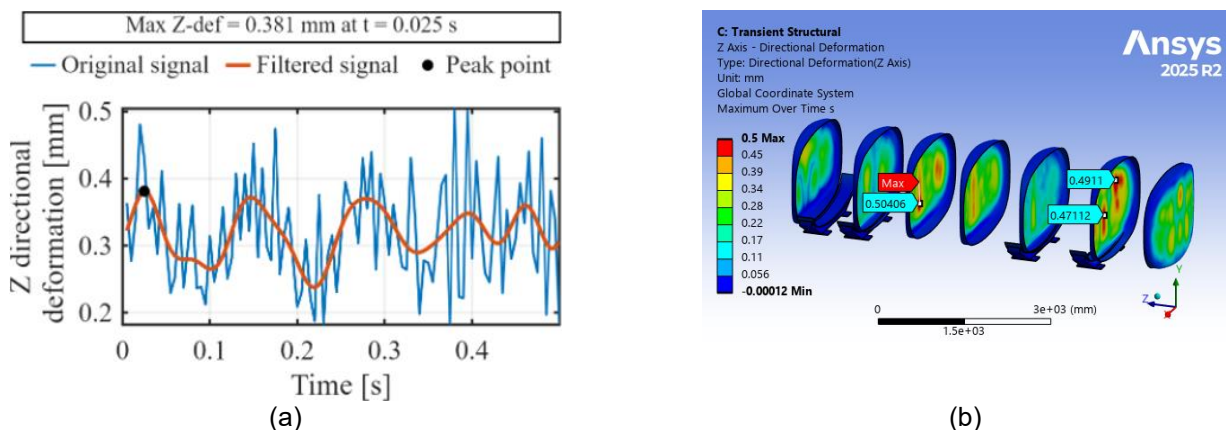


Figure 9 Longitudinal displacement during braking, 20% filling: (a) baffle displacement distribution; (b) maximum displacement time history

For the 20% filling ratio, the time history of the water-probe variable at the tank center is presented in Figure 10 (a). The corresponding snapshot of the liquid volume-fraction field is shown in Figure 10 (b), at the time instant corresponding to the maximum water-probe value.

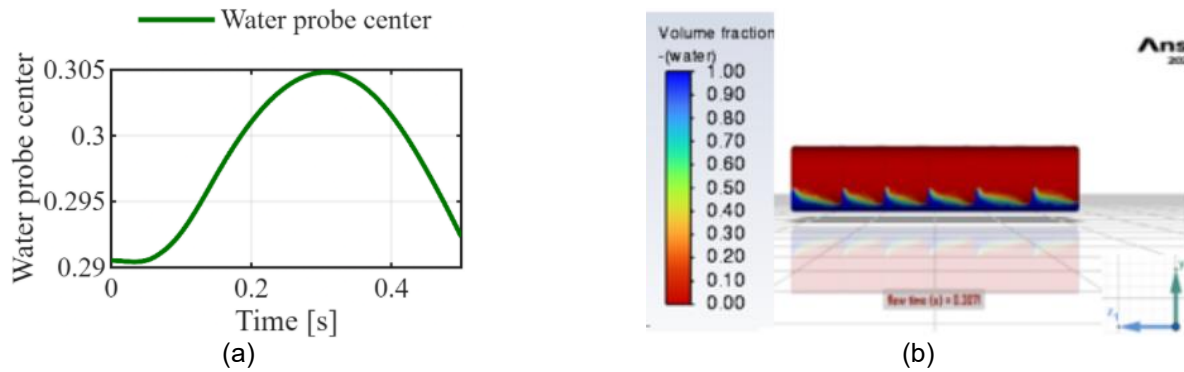


Figure 10 Fluid response during longitudinal braking at a 20% filling level: (a) time evolution of the water-probe variable at the tank centre (b) liquid volume-fraction field at the instant of maximum water-probe value

Static structural analysis

In the case of the static structural analysis, a reference simulation was performed for a fully filled tank subjected to the longitudinal braking design load. In addition to gravity and a longitudinal acceleration of 2 g, a breather-valve pressure of 0.012 MPa and compartment-dependent pressures acting on the internal bulkheads were considered. The latter pressures represent the longitudinal inertial effect of the fully filled liquid cargo.

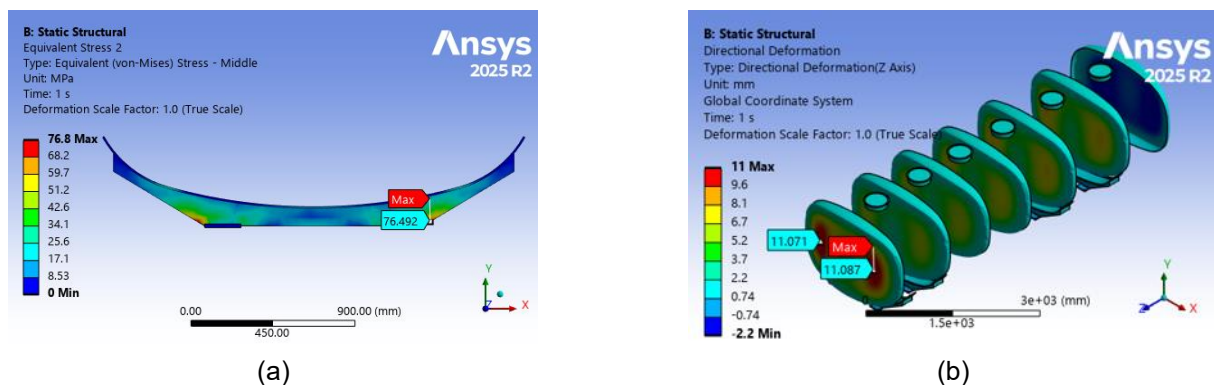


Figure 11 Static structural response under longitudinal braking for the fully filled tank: (a) equivalent von Mises stress; (b) longitudinal displacement

The equivalent von Mises stress distribution obtained from the static analysis is shown in Figure 11 (a), while the longitudinal displacement along the z-axis, i.e., in the braking direction, is presented in Figure 11(b). The maximum equivalent von Mises stress was 76.8 MPa and occurred in the region of the first tank support. The maximum longitudinal displacement was approximately 11 mm and was observed at the first baffle.

Support plates

The locations of the support plates considered in the analysis are shown in Figure 12. For the 80% filling ratio, the maximum equivalent von Mises stress is equal to 374.1 MPa and it appears on the plate F3b. In contrast, for the 20% filling ratio, the plate with the maximum Von Mises stress shifts to F2a and the maximum value is limited to 58.8 MPa.

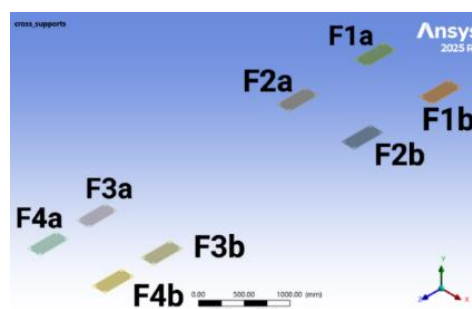


Figure 12 Tank support plates

DISCUSSION

Reviewing the structural response of the tank in the two filling ratios is obvious that both the peak value and the time of the peak value changes. The maximum filtered von Mises stress is 60.7 MPa for the 80% filling ratio, compared with 8.25 MPa for the 20% filling ratio. Therefore, the stress obtained at 80% filling is approximately 7.4 times higher than that at 20% filling ratio. This ratio is greater than the ratio of the filling ratios, which is equal to 4. Consequently, the structural response under braking does not exhibit a linear dependence on the filling ratio. This difference can be attributed to the combined effects of the varying liquid mass, inertial loading, free-surface evolution, and fluid–structure interaction. The time at which the maximum filtered Von Mises stress occurs also differs between the two cases. For the 80% filling ratio, the maximum occurs 0.08 s later compared to the 20% filling level. The shift in peak time indicates that the dynamic evolution of the sloshing phenomenon and the transfer of loads to the tank structure are affected by the filling ratio.

In all approaches maximum value of equivalent Von Mises stress remains below both the material yield strength of 125 MPa and the design stress value of 93.75 MPa, corresponding to $0.75R_e$ (EN13094, 2022). Therefore, the static braking load case does not exceed the adopted design criterion for the tank structure in any approach.

A similar variation is observed in the longitudinal deformation. The maximum filtered directional deformation is 6.07 mm for the 80% filling ratio, whereas it is 0.39 mm for the 20% filling ratio. This comparison reveals that the structural displacement in the braking direction is substantially greater at the higher filling ratio.

In Table 2 the value of the stress developed on the support plates, hence the bolted connection between the tank and the vehicle, is presented for the static structural analysis as well as the two FSI simulations.

Table 2 Maximum bolt stresses at the critical support plate under longitudinal braking

Simulation	Critical plate	Stress (MPa)		
		Axial	Shear	Equivalent
Static structural analysis	F4b	100	190	343
FSI, 80% filling	F3b	238	167	375
FSI, 20% filling	F2a	49	19	59

Table 2 shows that the 80% two-way FSI case produces the highest equivalent von Mises stress in the bolts, equal to 375 MPa at plate F3b. The static fully filled case produces a slightly lower equivalent stress of 343 MPa at plate F4b, but the highest shear stress, equal to 190 MPa. In contrast, the 20% two-way FSI case produces substantially lower axial, shear, and equivalent stresses, with a maximum equivalent stress of 59 MPa at plate F2a.

The comparison of the braking cases at 80% and 20% filling levels confirms that the 80% filling condition is clearly more critical for the bolted support connections while the static structural analysis provide stress values lower than that of the FSI for filling ration of 80%. Furthermore, the most critical support plate is not the same in all three cases. This indicates that both the approach and the filling ratio affect the mechanical response of the structure. The maximum equivalent stress, in the case of the static analysis, on the support plates is 343 MPa, which is slightly lower than the maximum value obtained by the FSI approach with 80% filling ratio.

CONCLUSIONS

In this paper, a tank for road transport of liquid fuels, designed according to EN13094 (2022), is computationally simulated in braking conditions, using two different approaches (two-way FSI and Static structural). Using the two-way FSI approach two filling ratios have been simulated, 80% and 20%. The results of the analyses demonstrated that the filling ratio has a substantial effect on the structural response of the road tank during longitudinal braking.

In more detail, it was shown that the static structural approach revealed the maximum value of Von Mises stress (76.80 MPa) followed by two-way FSI with 80% filling ratio which led to significantly more severe response compared to 20% filling ratio. Therefore, the maximum value of Von Mises stress obtained with FSI was 21% lower in the case of 80% filling ratio and 90% lower in the case of 20% filling ratio. The same observation was made for the axial deformation. Still, no approach led to stress values above design stress.

As far as the equivalent Von Mises stress developed on the support plates the FSI approach considering the filling ratio of 80% led to 10% higher value compared to the static structural approach. Comparing the different filling ratio is observed that a decrease of 4 times in the volume of the carried liquid lead to a reduction of the equivalent Von Mises stress by 83%.

Overall, the two-way FSI approach provided a detailed representation of the coupled liquid and structural response during the investigated braking manoeuvre. The static analysis, based on EN13094 (2022) is the reference approach

for structural verification, while the transient simulations complement it by capturing the evolution of sloshing-induced loads and their effect on the tank structure and its connection to the vehicle.

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