VIRTUAL TESTING FOR CNG/LNG STRUCTURAL SYSTEMS IN BUSES: SENSITIVITY OF BOLT CONNECTION UNDER SAFETY REQUIREMENTS

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1. ABSTRACT

Virtual testing has become an important tool in automotive safety development, particularly for commercial vehicles utilizing compressed Natural Gas (CNG) and/or liquefied natural gas (LNG) storage systems. This modern approach combines sophisticated computer simulations with analytical calculations, enabling design optimization while ensuring regulatory compliance.

During a collision event, bolted connections become critically important as the vehicle experiences a deceleration pulse, causing all inertial energy from the tank storage mass to be transfer to the roof through the bolt connections. This dynamic loading scenario underscores the importance of a correct connection design, defined torque specifications and precise installation to prevent both over-tightening damage and operational loosening.

This virtual test exercise follows the regulation UN R110.06 requirements applied to CNG/LNG storage systems in commercial vehicles and explains a safety-focused methodology for this type of component integration in the vehicle.

2. INTRODUCTION

The application of virtual testing tools gives the possibility to manufacturers to simulate the same boundary conditions represented in physical test scenarios and gives options to different applications which can solve the difficulties that sometimes the physical tests cannot solve. This alternative method is technically and cost-efficient because it reduces the need for prototypes, it keeps all information of structural behaviour, so the possible countermeasures applied will be more effective, and finally shortens time to market.

The current framework regulation is providing the basis from which the different safety regulations can be prepared to include virtual test methods in the approval process [1].

Technological advancements in Computer-Aided Engineering (CAE) in recent years have significantly contributed to the development of safer and higher-performing vehicles, while also enhancing flexibility for the representation of several types of scenarios. Furthermore, regulatory advancements and the adaptation of technical services as inspection entities to these new technologies have led to increasing popularity and utilization of virtual testing methodologies in the homologation process as well.

However, CAE and homologation engineers face significant communication challenges due to their different technical languages and approaches to data interpretation. While CAE professionals use complex mathematical terminology and generate probabilistic results, homologation specialists operate with regulatory frameworks and require binary pass/fail decisions. To overcome this divergence, it is essential to establish a structured communicative framework based on three elements: nomenclatural standardization, development of simulation methodologies previously validated by homologation criteria, and creation of consensual evaluation metrics that efficiently translate the results into objective determinations of regulatory compliance, thus promoting a technical integration that meets the needs of both specialties.

But with these new technologies, facilities and benefits offered, the use of virtual testing methodologies in the homologation process is becoming increasingly popular.

3. REGULATION BASE

The regulation UN R110.06 establishes the uniform provisions concerning the approval of vehicles regarding the installation of specific components of an approved type for the use of compressed natural gas (CNG) and/or liquefied natural gas (LNG) in their propulsion system. The design and approval should be according to the working pressure and operating temperatures.

The storage system should be installed such that it has the best possible protection against damage, such as damage due to moving vehicle components, collision, grit or due to the loading or unloading of the vehicle or the shifting of those loads.

The fuel tank completely full shall be mounted and fixed so that an acceleration pulse can be absorbed without damage occurring. The acceleration values to be applied, according to the vehicle category, are shown in Table 1. [2]

Vehicle Category	Acceleration Parallel to the Direction of Travel	Acceleration Perpendicular to the Direction of Travel
M1 / N1	20g	8g
M2 / N2	10g	5g
M3 / N3	6.6g	5g

Table 1 – Acceleration values according to vehicle category [2]

A calculation method can be used instead of practical testing if its equivalence can be demonstrated by the applicant for approval to the satisfaction of the Technical Service.

This type of fuel storage considers tanks and structural racks attached to the body frame of the vehicle can be found along with several regulations that use similar test procedures but with different evaluation criteria. Apart from UN R110.06, there are other regulations which have similar test conditions to validate the structural strength. These homologous regulations are the R134.02 concerning the approval of the safety-related performance of hydrogen-fueled vehicles (HFCV), and the Annex 9C of R100.04 concerning the validation of mechanical shock of electric batteries.

The evaluation for the UN R110.06 is basically to check that the plastic strain values obtained are lower than the maximum elongation limit of the material. The methodology applied in this study considers a maximum of 50% of the maximum elongation of the material. This condition will ensure the safety of the storage system under a conservative approach.

4. SIMULATION AND ANALYSIS OF USE CASE

A Finite Element Model (FEM) consisting of the rear portion of a city bus structure along with three LNG tanks assembled on top of it was built and simulated for this study. Each tank has a total mass of 326 kg, and it is pressurized at 16 bar (1.6 MPa). As per regulation UN R110.06, for M3 / N3 vehicle category, a static equivalent acceleration of 5g in lateral direction and 6.6g in longitudinal direction were applied independently to the model and the results of Von Mises stresses and plastic strains were extracted and the shear forces for the elements representing the actual bolts as well. All the structure was held totally clamped on its free edges.

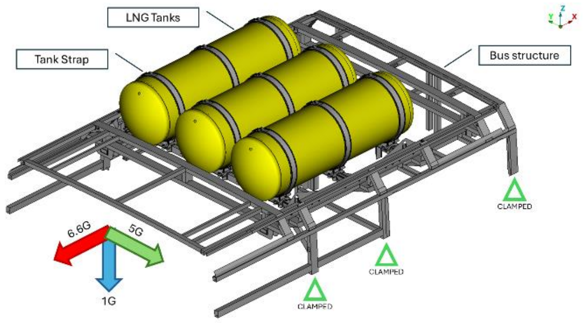

Figure 1 – Finite Element Model (FEM)

The metallic materials of the structure were modeled as having elastoplastic non-linear behavior, where their actual true stress-strain curves were considered in the simulation model except for the bolts, where isotropic linear steel was assigned to them. For the tank strap rubber, Neo-Hookean hyper-elastic model was defined based on the mechanical properties of the EPDM elastomer, namely Young's elastic modulus and Poisson's rate.

Mechanical Property	Unit	Tank Strap (Stainless Steel - EN 1.4404)	Tank Strap Rubber (EPDM)
Young´s Modulus	MPa	193000.	10.
Poisson's Ratio	-	0.28	0.499
Yield Strength	MPa	247.	-
Ultimate Strength	MPa	588.	20.
Total Elongation	%	58.	410.

Table 2 – Mechanical properties of tank strap materials

The sheet parts were modeled with first order (linear) shell elements while in the parts with complex or non-constant geometry, such as strap rubber, linear solid elements were used. On the other hand, the bolted connections were modeled with linear 1D (beam) elements and rigid constraints to represent both head and nut. All the parts in contact (or potentially) such as the tank straps to the LNG cylinders were not allowed to intersect each other. This was accomplished through a penalty stiffness contact formulation. Also, a coefficient of friction of 0.6 between the strap rubber and the tank cylinder was considered based on the results obtained in [3].

Finally, the simulation model was submitted to the IDIADA's HPC in Spain to be calculated. For the run, it was requested 4 CPU cores and 24 MB of RAM memory per core. The commercial software ABAQUS version 2020 was used as the solver. The pre- and post-processors used for building the model and visualizing the results were ANSA and META, in version 24, respectively.

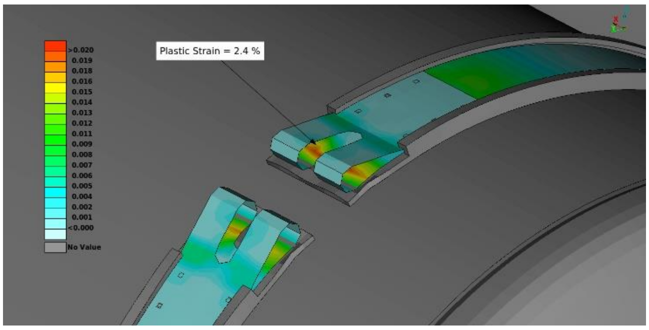

Figure 2 – Plastic strains on tank strap

The results for plastic (permanent) strains are shown in Figure 2. There was a localized plasticity of 2.4 % in the tank straps due to the bolt preloading. Nevertheless, the value is acceptable since it is lower than 50 % of the maximum elongation of the material (29 %) and probably does not avoid the replacement of the tanks for maintaining reasons. In the bus frame the maximum plastic strain is negligible for both lateral and longitudinal loads.

5. ANALYSIS OF BOLTED CONNECTIONS

For the assessment of the structural integrity of the bolted connections, the analytical treatment presented in the standard VDI 2230 [4] was applied. First, it was identified the critical zone based on the bolt size and the forces acting on them due to the external applied acceleration. The bracket that connects the LNG tank straps to the rack structure has four bolts, each side being the outer two of metric M14 and the inner two of metric M10. Those bolts have standard thread (pitch P = 1.5 mm) and a class of resistance 10.9 being responsible to clamp together two steel plates of 5 mm thickness each. For that reason, this was considered the critical region to be assessed and the safety factors against joint separation and slipping for all M10 bolts were calculated. All the calculation steps were automated in a tool developed by IDIADA Automotive Technology.

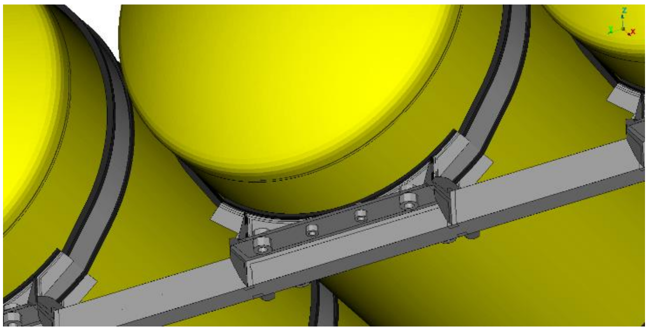

Figure 3 – Critical region for bolt assessment

Considering that the assembly was designed for yielding and an angle-controlled tightening tool was used to tight the bolts, the scatter factor α_A – a measure of the level of variation of the preload applied – will be one, in other words, the minimum assembly preload $F_{M\,min}$ will be equal to the maximum assembly preload $F_{M\,max}$. The coefficient of friction between both threads μ_G and the head/nut against plates μ_T is 0.16. According to the VDI 2230 [4], the clamp load F_{KQerf} to allow a transversal load (pure shear, no moment) without causing the slippage of the joint is:

$$F_{KQerf} = \frac{F_{Q\,max}}{q_F \cdot \mu_{T\,min}} \quad (1)$$

Where $F_{Q\,max}$ is the transversal load acting on the bolt and q_F is the number of interfaces in grip, in this case, one. Assuming that no preload losses occur due to embedding nor by thermal effects and defining the load factor f as the ratio of additional bolt load F_{SA} by the axial working load component F_A, the minimum residual clamp load $F_{KR\,min}$ is calculated as:

$$F_{KR\,min} = \frac{F_{Mzul}}{\alpha_A} - (1 - \phi) F_{A\,max} > F_{KQerf} \quad (2)$$

Considering the utilization factor υ = 0.9, which means that the bolt can be loaded until 0.9 $R_{p0,2min}$, the maximum permitted assembly preload F_{Mzul} for the bolt under study is calculated according to the equation below:

$$F_{Mzul} = A_0 \frac{\nu\, R_{p0,2min}}{\sqrt{1+3\left[\frac{3d_2}{2d_0}\left(\frac{P}{\pi d_2}+1{,}155\mu_{G\,min}\right)\right]^2}} \quad (3)$$

The tightening torque required for torque-controlled tightening can be taken from Table A2 in the annex of VDI 2230 [4] (only if υ = 0.9). The tightening torque M_A may be calculated as follows:

$$M_A = F_{Mzul}\left[0.16P + 0.58 d_2 \mu_{G\,min} + \frac{D_{Km}}{2}\mu_{K\,min}\right] \quad (4)$$

The values of assembly preload and tightening torque as a function of the coefficient of friction for M10 metric can be seen in Figure 4.

Abm. / Size	Fest.-Klasse / Strength grade	Montagevorspannkräfte / Assembly preload $F_{M\,Tab}$ in kN für / for μ_G =							Anziehdrehmomente / Tightening torque M_A in N·m für / for $\mu_K = \mu_G$ =						
		0,08	0,10	0,12	0,14	0,16	0,20	0,24	0,08	0,10	0,12	0,14	0,16	0,20	0,24
M10	8.8	31,0	30,3	29,6	28,8	27,9	26,3	24,7	36	43	48	54	59	68	75
	10.9	45,6	44,5	43,4	42,2	41,0	38,6	36,2	53	63	71	79	87	100	110
	12.9	53,3	52,1	50,8	49,4	48,0	45,2	42,4	62	73	83	93	101	116	129

Figure 4 – VDI 2230: Assembly preload F_{MTab} and tightening torque M_A for M10 bolts [4]

The safety factor against slipping can be expressed as:

$$S_G = \frac{F_{KR\,min}}{F_{KQerf}} > 1.0 \quad (5)$$

In a similar manner, the safety factor against the shearing of the bolts will be:

$$S_A = \frac{\tau_b A_\tau}{F_{Q\,max}} \geq 1.1 \quad (6)$$

To understand the influence of the tightening torque and assembly preload on safety of the bolted connections a sensitivity study was conducted based on the most loaded bolt found in the critical region and the results were compiled in Table 2. It can be observed that for low values of tightening torque the safety factors became less than unity, indicating a high probability of failure. On the other hand, it's worth to mention that high torque values could deform permanently the bolt and potentially also other parts of the joint, which also need to be avoided.

Tightening Torque	Assembly Preload	Safety Factor (Slipping)	Safety Factor (Shearing)
Nm	kN	-	-
87	38.74	4.23	10.23
50	22.27	2.40	5.88
25	11.13	1.16	2.94
10	4.45	0.42	1.05

Table 3 – Sensitivity study of bolted connections

6. RESULTS AND CONCLUSIONS

To obtain results from simulation that agree well with physical tests it is very important to control all the variables involved such as, but no restrict to it, the correct application of boundary conditions and loads, the use of actual and reliable material data (mechanical properties, stress-strain curves, etc.) or even the choice of the most appropriated finite element according to each part being modeled. Specifically, for the assessment of the bolted connections, the actual (measured) values of coefficient of friction between the parts in contact and the torque applied to the bolts by the tightening tool are the variables that most affect the quality of the results.

7. MODEL QUALITY CONTROL

The control of the model uses the next quality check control for the input file, pre-processing, and for the output file, post-processing.

The pre-processing requirements check the next points:

- Element criteria selected for different components.
- Mesh quality control.
- Setting for intersections and penetrations between parts.
- Contact and frictions.
- Connection settings used for assembly parts.
- Setting of masses and positions.
- Appropriate material models.
- Control settings, on local and global level.
- Setting to define the output messages.

The post- processing requirements check the next points:

- Plausibility of contact interactions (i.e. visual animation check, trajectories of stablished landmarks, etc.).

In addition, definitions such as unit systems, element formulations and controls, mesh size, material formulations and contact definitions should be compatible in the context of consistency over various small adjustments, like the modification of mesh size, the time step or the use of different CPU's configuration for computing the calculation.

8. MODEL TRACEABILITY

Implementing robust data security of the model files used is crucial to address concerns about unauthorized modifications or access to the simulation model. This involves controlling access, secure storage, backup systems, and monitoring for any unauthorized changes. By safeguarding the integrity and security of the simulation model data, the risk of manipulation or tampering is minimized, providing reassurance of technical services.

The generation of unique serial numbers to each approved simulation model enhances traceability and control. The input and output model control uses cryptographic algorithms such hash functions or digital signatures that ensures the integrity and authenticity. Then, the technical services will be able to use a verification tool to verify that the models were not manipulated compared to other simulation runs.

9. REFERENCES

[1] Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009.

[2] Regulation No 110 of the Economic Commission for Europe of the United Nations (UN/ECE) Uniform provisions concerning the approval of vehicles with regards to strength of buses.

[3] Karger-Kocsis, Jozsef & Mousa, Ahmad & Major, Zoltan & Békési, Nándor. (2008). Dry friction and sliding wear of EPDM rubbers against steel as a function of carbon black content. Wear. 264. 359-367. 10.1016/j.wear.2007.03.021.

[4] VDI 2230 Systematische Berechnunghochbeanspruchter Schraubenverbindungen. Zylindrische Einschraubenverbindungen / Systematic calculation of highly stressed bolted joints. Joints with one cylindrical bolt. Blatt 1 / Part 1. November 2015.

10. ABOUT THE AUTHORS

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