Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division 05

VAPOR SUPPRESSION TANK OF ITER NUCLEAR FUSION REACTOR: STRESS AND STRAIN STATE OF THE STEEL ANCHORS IMBEDDED IN THE CONCRETE FOUNDATION DUE TO A HYDROGEN DETONATION

Alessio Pesetti[1], Marco Olcese[2] and Donato Aquaro[3]

[1] Assistant Professor, University of Pisa- Italy (alessio.pesetti@unipi.it)
[2] Senior Advisor, Iter Organization, St Paul Lez Durance Cedex - France
[3]Full Professor, University of Pisa

ABSTRACT

This paper illustrates dynamic analyses of the support system of Vapor Suppression Tanks (VST's) under loads caused by a hydrogen detonation event. The VST are components of a safety system of the nuclear fusion reactor ITER (International Thermonuclear Experimental Reactor), for the managing of a Loss of Coolant Accident (LOCA) in the Vacuum Vessel (VV). During a LOCA, non-condensable gases, containing H_2, could accumulate in the volume of the suppression tanks. Several hydrogen ignitors are located in the Vapor Suppression Tank (VST) in order to trig the hydrogen combustion. Therefore, hydrogen deflagration and detonation have an extremely low probability to occur. This event is considered '*beyond the design basis loading*' and the correspondent limits are defined in terms of collapse load and accumulated plastic strain.

The paper illustrates several scenarios of hydrogen detonation and the numerical analyses for calculating the pressure histories on the VST components. The lower flange of the VTS, the concrete plinth and the metallic anchors are analysed under the pressure impulses due to hydrogen detonations. A model correspondent to a sector of 45° of the VTS support system has been implemented by means of 3D elements using the FEM computer code MSC-MARC. The stress and strain state have been determined by means an elastic –plastic dynamic transient analysis. The accumulated plastic strain at the final instant of the transient verify the limit established by the Code Case 2564-4 of ASME Section VII – div-3.

INTRODUCTION

The nuclear fusion reactor ITER (International Thermonuclear Experimental Reactor) foresees a Pressure Suppression System (PSS) in order to manage a Loss of Coolant Accident (LOCA) or other over pressurization accidents in the Vacuum Vessel (VV), which has a pressure limit fixed at 150 kPa (abs). This system (VVPSS) has a key safety function because a large internal pressure in the VV could lead to a breach of the primary confinement barrier. The pressure suppression is ensured by discharging the steam, produced by the LOCA, in 4 tanks, 100 m3 of volume partially filled by water, where it condenses. (Figure 1).

The steam condensation occurs at sub-atmospheric pressure conditions. During a LOCA in the Vacuum Vessel, hydrogen can be produced by different processes (oxidation of the beryllium armor, water thermolysis, etc.) and it can be entrained with the steam in the suppression tanks. Hydrogen deflagration and above all hydrogen detonation have an extremely low probability to occur, because several hydrogen ignitors are located in the Vapor Suppression Tank (VST). Nevertheless, considering the hydrogen

detonation as '*beyond design basis loading'*, it has been numerically analyzed for determining the safety margin of the suppression tanks in the case of the occurrence of this event of extremely low probability.
Particular attention has been paid on the behaviour of the lower flange of the VST, of the concrete plinth and of the metallic anchors loaded by the pressure impulses due to hydrogen detonations. In fact, these components are loaded by the resultants (vertical and horizontal) of the pressure histories, originated by the detonation, applied to the VST walls.

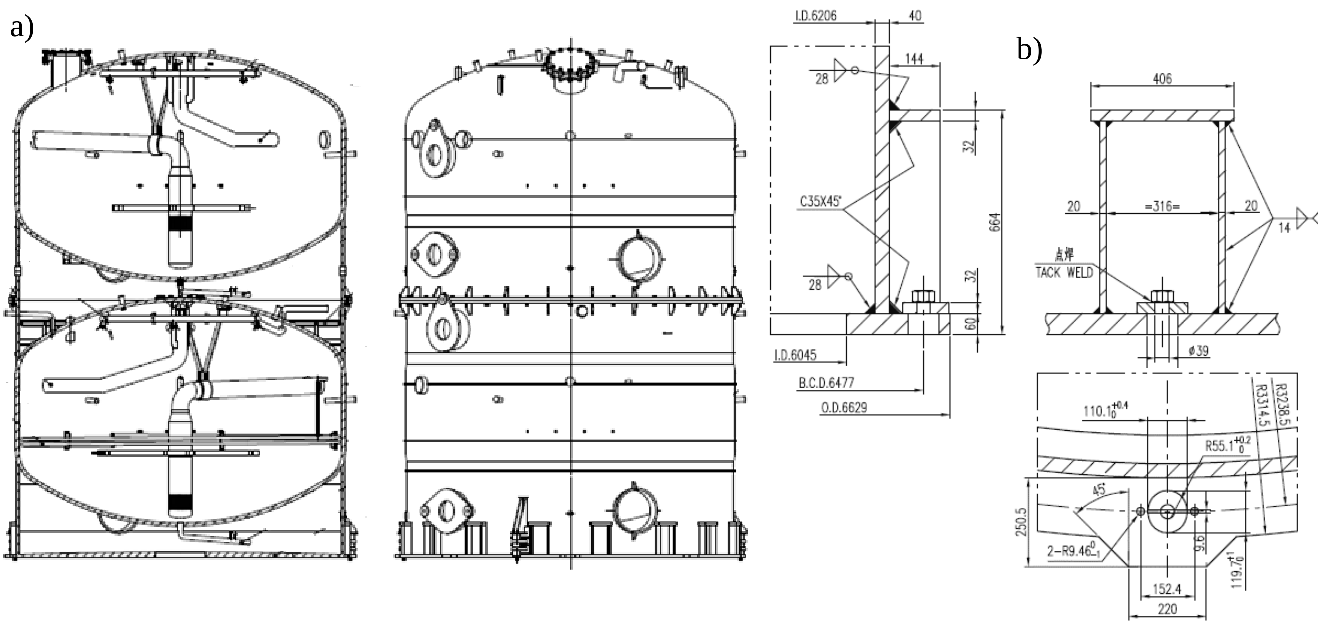


Figure 1. Vapor suppression system (a);Details of the anchors, ribs and welding between skirt and flange (b).

The determination of these pressure histories have been the object of preliminary analyses. Simulations of a shock tube have been performed by means the MSC-DYTRAN (2017) code for verifying the influence of the different parameters on the pressure peaks and on the impulse value due to the hydrogen detonation. The reference pressure pulse has been established considering the simulation results of Baumann et Alii (2001). They studied the detonation in 12 m long pipe, considering an initial pressure of 0.965 bar, temperature of 285 K and a stoichiometric concentrations 30% hydrogen and 70% air.
Moreover, the comparison has been done considering the impulse correspondent to the reference pressure history, determined by the following relation:

$$I = \int (P - Po)dt \qquad (1)$$

being *Po* and *P* the initial and instantaneous pressure, respectively.

Numerical simulations have been performed for assessing if Baumann results could be applied at shock tubes having different lengths (Aquaro 2016). Shock tubes having length of 2.5m, 5 m and 7.5 m have been analysed. The results in terms of impulse versus time agree very well with the reference values obtained considering the correspondent reverberation time. Sensitivity analyses have been performed with the aim to assess a model for determine the pressure loadings on the VST walls due to a hydrogen detonation. The results of sensitivity analyses showed that a great effect on the first pressure peak and on the impulse value is due to :

- propagation velocity of the combusted gases
- total energy of the combusted gases

From the point of view of the effects on the tanks (filled by water), it is more important the final value of impulse than the pressure peak. This result has been demonstrated by means of experimental tests of detonation of explosives in spherical vessel (Nickell et Alii (2003)).

The results of sensitivity analyses pointed out that a diagram of impulse versus time equal to that achievable in a 2.5 m experimental shock tube (where hydrogen detonation occurs) is obtained considering the expansion of a volume of combusted gases with the following initial conditions for both the air and the combusted gases:
a) combusted gas: - propagation velocity = 2700-2800 m/s; - specific internal energy = 2.022e+06 kJ/kg; - density = 1.9361 kg/m^3
b) air:- specific internal energy = 307545 kJ/kg; - density= 0.8129 kg/m^3
c) ratios between volumes, masses and energies of the two materials: -Gas Volume / Air Volume = 0.13; Gas Mass / Air Mass = 0.31; -Gas Energy / Air Energy= 2.05.

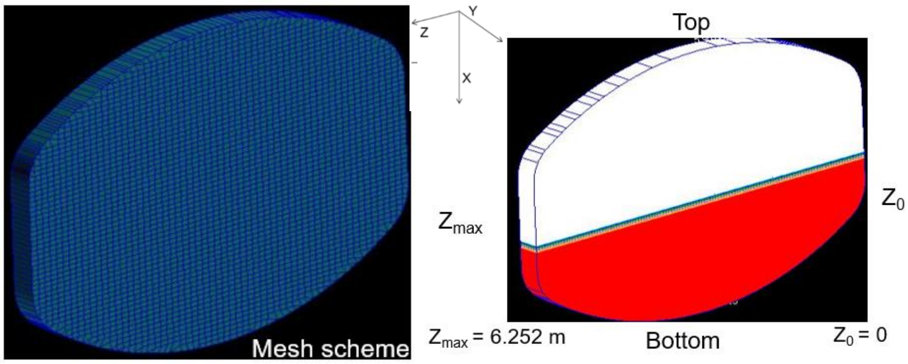


Figure 2. Numerical model of VST for determining the pressure loading due a hydrogen detonation. The red coloured volume is the part filled by water

These results have been applied to a three dimensional domain (Aquaro 2017), related to a VVPSS tank, in order to determine the most severe scenario of hydrogen detonation.

PRESSURE LOADING AND IMPULSE PRODUCED BY HYDROGEN DETONATION IN A VST

The hydrogen detonation was simulated as an expansion of a sphere of combusted gases having a defined direction of velocity vector. The gas sphere has been located in different positions inside the tank volume on the water surface. Several different directions of velocity vector were considered. The pressure transients and the relative impulses on the tank walls were elaborated for calculating the overall force on the tank.

The VST are partially filled with water. 60 m^3 in one tank and 40 m^3 in the three remaining tanks are the volumes (void spaces) on the water surface, normally filled by vapour and air at sub atmospheric pressure. In the hydrogen detonation scenario, this space is filled also by the products of hydrogen deflagration (called combusted gases) that could produce detonation. The VST is made of an upper and lower torospherical heads welded at cylindrical shell. The void space has a maximum width of 6.25 m and 2.5 m of maximum height.

The analysed domain is a three dimensional slice, obtained by a vertical section of the tank, 0.36 m of thickness. It simulates the void space and the water (Figure 2). The conditions, determined in the shock tube, were applied at the 3D domain, considering symmetric and non-symmetric wave propagations.
The expansion of a sphere of combusted gases has been analysed with the computer code MSC-DTRAN (2017). The gas has been simulated by the following state equation:

$$p = (\gamma - 1)\rho e \tag{2}$$

Where p is the pressure, ρ the density, γ the specific heat ratio and e the specific internal energy. The sound speed is calculated by the formula:

$$ss = \sqrt{\gamma[(\gamma - 1)e]} = \sqrt{\frac{\gamma p}{\rho}} \tag{3}$$

Considering the results obtained from the shock tube analyses, a sphere of combusted gases, r=0.88 m of diameter, has been considered inside the tank.
The combusted gases have been determined considering the following data:
-abiabatic isocore complete combustion pressure P_{AICC}=7.828E+05 Pa;-Chapman Jouget pressure of combusted gases P_{CJ}=2 P_{AICC} =15.656+05Pa;-γ=Cp/Cv=1.4; -speed of sound, ss=1064 m/s
Propagation velocity: v= 2700 m/s.
The specific internal energy is: sie =2.0216e+06J/g (Eq. 3); the density of the combusted gases is:1.9361 kg/m3 (Eq. 2), using the Chapman Jouget pressure (P_{CJ}).
The air has the following initial conditions:- Pressure 1.0 E+05 Pa; γ =Cp/Cv=1.4; Speed of sound ss=415m/s
The initial specific internal energy (eq. 3): sie =307544 J/Kg; density(eq. 2) = 0.8129 kg/m^3

The performed analyses have been the following:

- axial symmetric analysis: sphere center on the symmetry axis, X, (center coordinates: X=0.88 m, Y=0; Z=3.126 m); propagation velocity directed along x
- asymmetric analysis: sphere center on the symmetry axis, X, (center coordinates: X=0.88 m, Y=0; Z=3.126 m); propagation velocity directed at 45° respect the x axis
- asymmetric analysis: sphere center at X=1.5 m, Y=0, Z=0.9 m; propagation velocity directed in X direction
- asymmetric analysis: sphere center at X=1.5 m, Y=0, Z=0.9 m; propagation velocity directed in Z direction.

The first analysis considers an axial symmetric expansion of the combusted gases sphere. Pressure transients, obtained on the top, bottom and lateral sides, and the correspondent impulses are compared with the reference one (Figure 3). The final value of the impulse on the water surface is in very good agreement with the reference value. This result assesses the reliability of the model in determining the pressure loading on the VST walls.

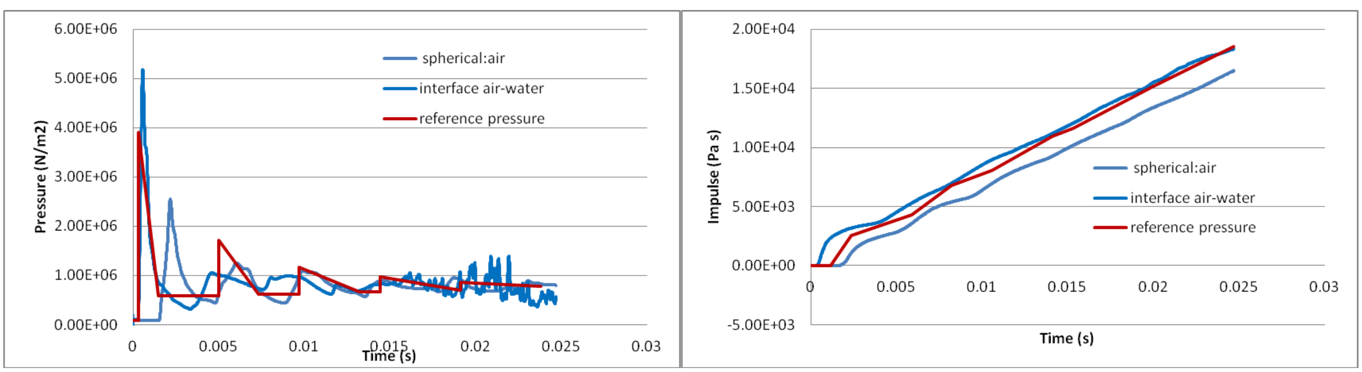


Figure 3. Comparison of the pressure transients (a) and impulse (b) at the top spherical zone (air) and at interface air water (X=2.5 m) with the reference diagrams

The difference between the resultants of the pressure applied on the top and bottom sides determines a net force in vertical direction (being the wave propagation symmetric, the pressure is equal on the lateral sides). Figure 4 shows the expansion of combusted gases in the tank. In all the analyses, the pressure and the impulse diagrams on the different sides have been determined and compared with the reference ones. Moreover, vertical and horizontal resultant forces on the supports have been calculated extrapolating the results from the slice model to the actual shape of tanks (Table 1).
The most severe conditions for the supports of the tank are:

- Symmetric case (maximum vertical force Fx)
- Asymmetric case- propagation at 45° (maximum horizontal force Fz).

These most severe scenarios are assumed occurred not simultaneously in the lower tank and in the upper tank. The loads on the skirt and lower flange have been determined simulating numerically these scenarios in the actual tanks (Aquaro et Alii, 2007).

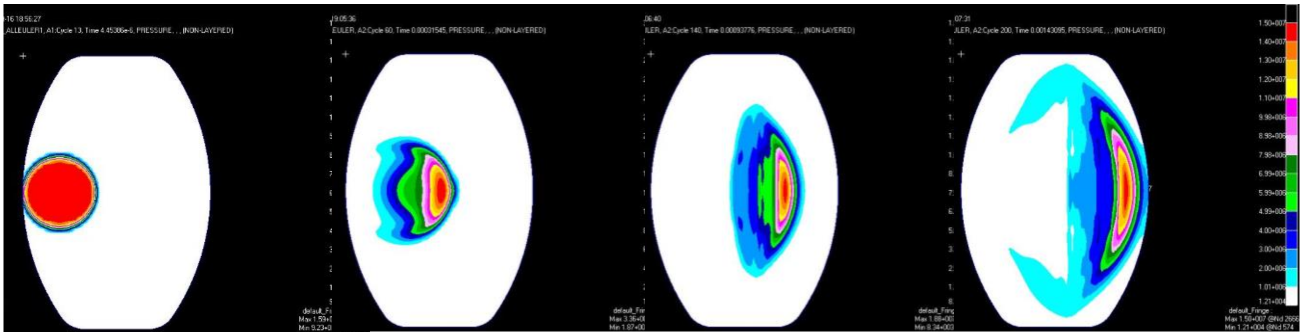


Figure 4. Hydrogen detonation simulation considering an axial symmetric expansion

NUMERICAL ANALYSES OF THE JOINT BETWEEN TANK LOWER FLANGE AND FOUNDATION PLINTH

Four loading conditions have been determined for the joint lower flange-concrete plinth:
-Axial symmetric detonations in upper or lower tank**:** the reaction forces have vertical (positive upwards) and radial components and are uniformly distributed (Figure 5). The load on the plinth has opposite direction of the reactions.
-Asymmetric detonation in upper or lower tank**:** the reaction forces are not uniform. Their distribution has been analysed in each of the quadrants of the lower flange, as illustrated in Figure 6, where the reference system respect which the quadrants are defined and the vectorial representation of the tangential reaction are illustrated.

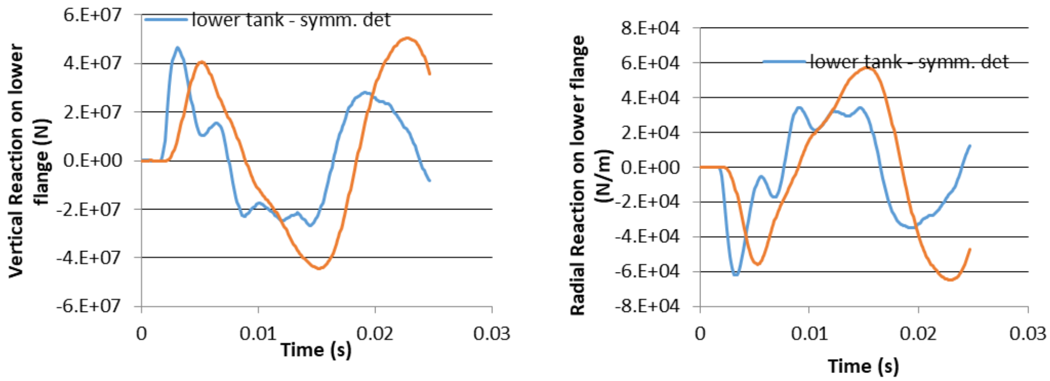
Table 1- Comparison between the forces on the supports for the examined cases of Hydrogen detonation

Numerical analysis	**Fx (N)**	**Fz (N)**
Axial Symmetric case- propagation in X direction	4.38e+8	
asymmetric case- propagation at 45°	2.74 e+8	1.76 e+8
asymmetric case- propagation in X direction	1.63 e+8	-1.5 e+8
asymmetric case- propagation in Z direction	4 e+7	1.31 e+8

The resultant of the horizontal reaction in each quadrant has tangential direction. The tangential components are equal in the first and third quadrants (as well as in second and fourth quadrant). The sign is considered positive if this component gives a positive moment around the vertical axis (Figure 6). The resultants of vertical reaction are equal (sign and module) in the 1^{st} and 2^{nd} quadrants as well as in the 3^{rd} and 4^{th} quadrants (Figure 7).

The numerical analyses simulate the joint between the lower flange of the VST and the concrete plinth. Considering the layout of the anchors and of the foundation plates, a sector of 45° of the tank skirt-flange and of the concrete plinth has been modelled. Figures 8 show the circumferential distribution of anchors, foundation plates and the localization of steel reinforced bars in the concrete plinth.
The VST support is made of:
- 8 steel plates (1500mmx900mmx60mm), located with their center at 45° each other.
- 16 anchors (two for each plate at angular distance of 21°), located on a circumference 3.125m of radius.

The numerical model (Figure 9) is made of 17832 elements and 19761 nodes. The simulated concrete plinth corresponds approximately at a 45° sector even if it has a prismatic shape being the reinforced steel bars assembled in a Cartesian reference system.



a) b)

Figure 5. Vertical reaction resultant (a) and radial reaction (b) on the lower flange caused by a symmetric detonation in the lower and upper tank

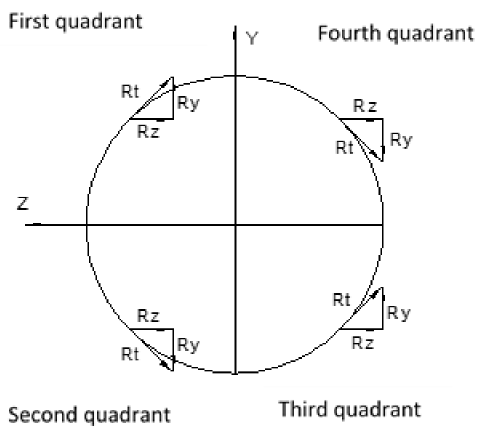


Figure 6. Vectorial sum of the horizontal reactions caused by an asymmetric detonation

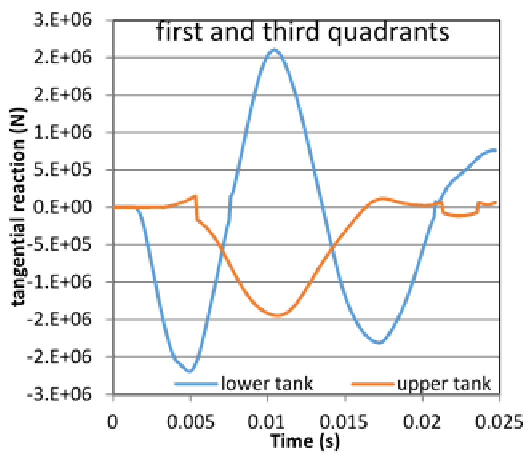


Figure 7. tangential reaction on lower flange caused by an asymmetric detonation in the lower and upper tank

Flange, skirt, anchor washers, foundation plate and plinth have been simulated by means three dimensional elements (element n.7 of MSC-MARC code) while the ribs by means three dimensional shell elements (element n.75 of MSC-MARC code). The steel reinforced bars and the anchors are embedded inside the concrete plinth. The FEM code MSC –Marc simulates the reinforced bars by means layers embedded in dummy elements (element n.146 of MSC-MARC code) which have the same nodes and connectivity of the concrete elements (Figure 9). The anchors, simulated by means three nodes truss elements (element n.64 of MSC-MARC code), are inserted in the concrete elements and have the same strains of the concrete. The '*insert*' function of MSC-MARC has been used for constraining the anchors to the concrete material. The upper part of the anchors is out of the plinth and it is screwed to the nut after freely passing through the foundation plate, the flange and washer

Constitutive Equations

The behaviour of the materials has been simulated considering all the contributes to the resistance. In particular the following constitutive equations have been considered for the different materials:

- *stainless steel* (skirt, flange, foundation plate, shear connector: yielding stress σ_y=175 MPa; Young Modulus E=200000 MPa); *carbon steel* (reinforced bars: σ_y=500 MPa; Young Modulus E=200000 MPa): Elastic-perfectly plastic with the yielding stress sensitive to the strain rate.

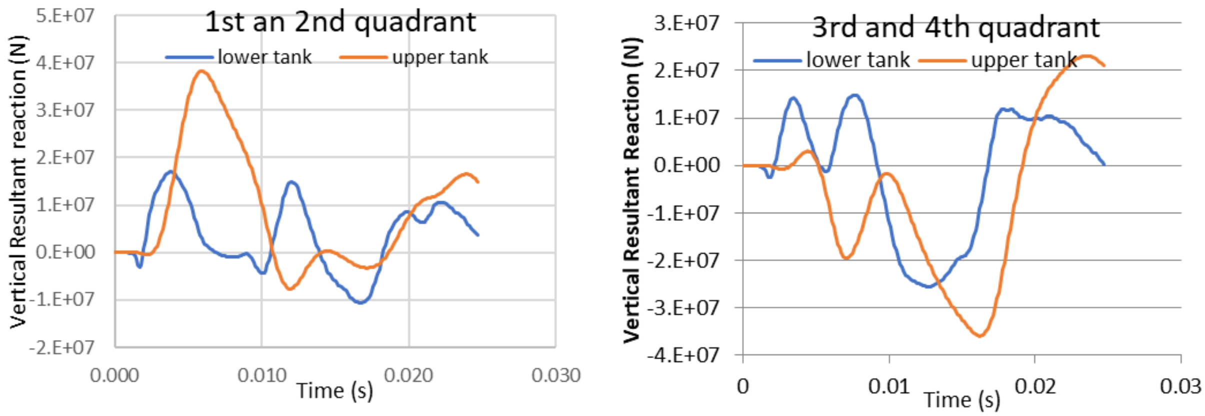


Figure 8. Vertical reaction resultant on the lower flange caused by an asymmetric detonation in the lower and upper tank (a) 1st -2nd quadrant; b) 3rd -4th quadrant)

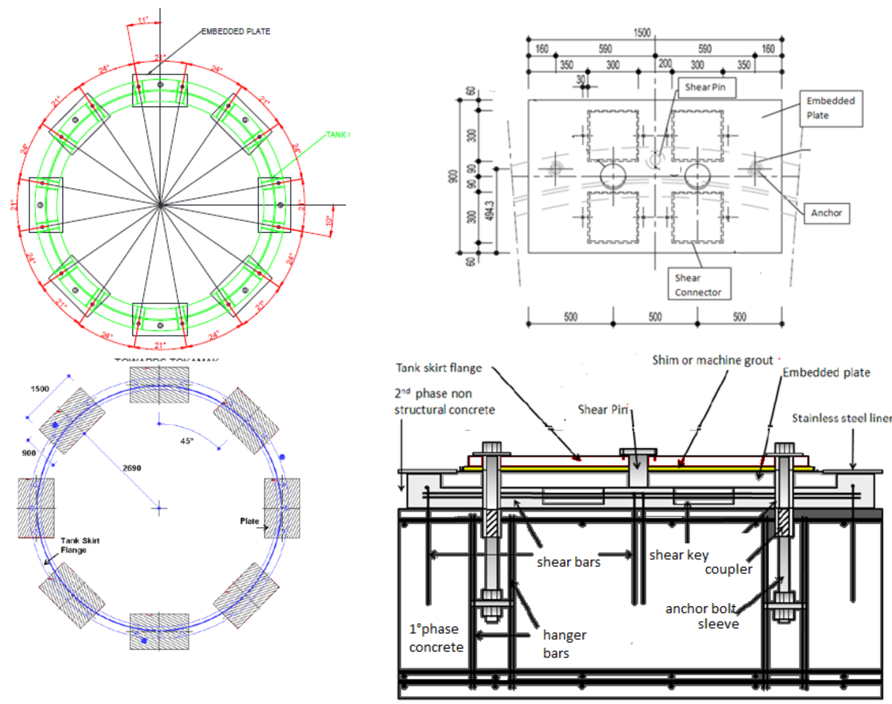


Figure 9. Circumferential distribution of the anchors, of the foundation plates and localization of the steel reinforced bars in the concrete plinth

For the anchor material (carbon steel Grade 12.9: σ_y=1100 MPa; ultimate tensile stress σ_u=1220 MPa; ultimate tensile strain ε_u=8%), a work hardening has also been considered as a linear increases of the plastic stress between the yielding stress and the ultimate tensile stress. The linear variation has been determined considering the following two conditions: for $\varepsilon_p=0$ $\sigma=\sigma_y$; for $\varepsilon_p=\varepsilon_u$ $\sigma=\sigma_u$
being ε_p the plastic strain.

-*Concrete*: Elastic- perfectly plastic in compression and elastic in traction. The failure of concrete in compression occurs when the plastic strain reaches a value called crushing strain (ε_{cru}). In traction the limit

is the cracking stress (σ_{cr}). After reaching this cracking stress, the concrete cracks and the stress goes down with a linear law defined by a softening modulus (E_{sf}).
The parameters of the constitutive equation are the following: σ_y = 40 MPa; σ_{cr} = 2.5 MPa; ε_{cru} = 0.0035; ν = 0.2; E_c = 35000MPa; E_{sf} = 3500 MPa; τ = 0.3
where ν is the Poisson Modulus; τ is the shear retention factor (the capability to transfer shear through a crack closure when the stress becomes compressive).

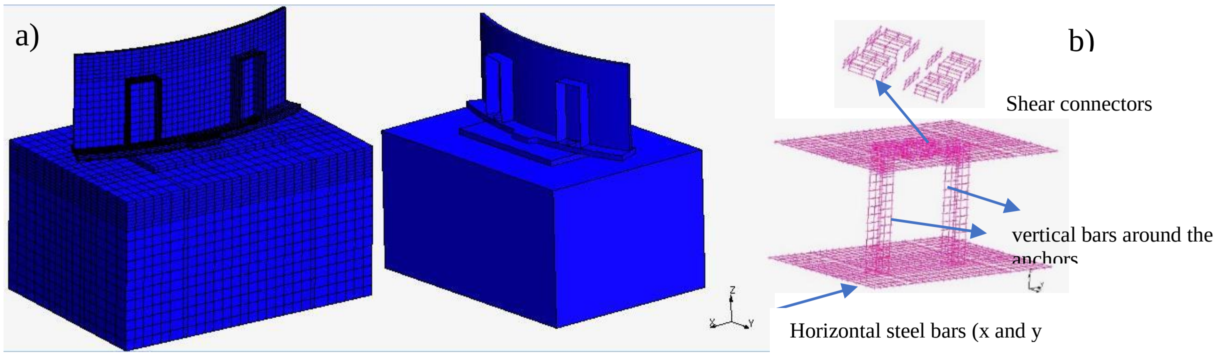


Figure 10. Numerical model of a sector of 45° of the joint between tank lower flange and foundation (a); layers which simulate the reinforced bars (b)

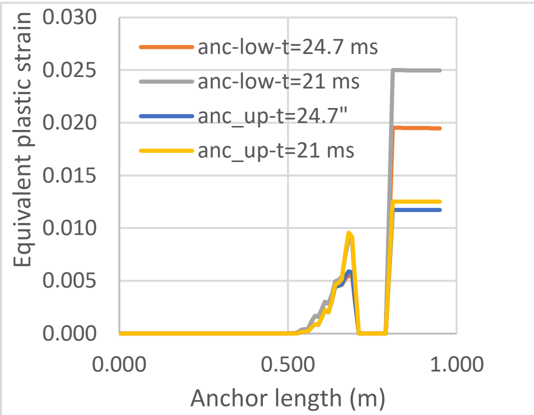
The plastic behavior follows the von Mises yield criterion. The rate sensitivity for carbon steel and stainless steel is governed by the Cowper-Symonds strain rate rule, which has the following form:

$$\sigma_{yd} = \sigma_y \left[1 + (\dot{\varepsilon}/D)^{1/p} \right] \tag{4}$$

being, σ_{yd} the dynamic yielding stress; σ_y the static yielding stress; $\dot{\varepsilon}$ the strain rate; D and p material constants. For stainless steel D=100 s^{-1} , p=10; for carbon steel D=40 s^{-1} , p=6.

Numerical Analyses

Considering the reaction forces reported in Figures 5, 7 and 8, it is evident that the most severe loading condition is determined by tensile component of vertical force. The implemented model permits to determine the stress and strain state of the entire structure in the case of axial symmetric detonation. While in the case of asymmetric detonations different analyses have to be done in order to analyse the behaviour of the entire structure, because the implemented model permits to determine the behaviour of only one quadrant of the structure at time.
The asymmetric detonation in upper tank scenarios and the loads on the 3rd (or 4th) quadrant subjected to the maximum tensile reaction is the most severe condition.
The anchors have to transmit the tensile force to the concrete foundation and are the most critical components. The first part of the anchors (thread M36 cl. 8.8) is embedded in the concrete and is jointed to a second part by means a coupler. This second part (with the coupler) is partially embedded in non-structural concrete and passes through the thicknesses of the foundation plate and of the flange.
Zero circumferential displacements are applied to the skirt and to the flange as boundary conditions. The dead load (0.357 MN) and the vertical component of force (Figure 8-b) are applied to the upper surface of the skirt while the tangential component (Figure 7) is applied to the internal surface of the flange. The diameter of the upper part of the anchor has been increased at the value of M50 and the material is carbon steel Gr.12.9. Figure 11 illustrates the equivalent plastic strain and the equivalent Von Mises stress along the anchors length (M50 Gr12.9) at two instants of time (when the maximum value is reached and at the end of transient).
The maximum equivalent plastic strain is 2.5% and the correspondent equivalent Von Mises stress is 2000 MPa. This value corresponds to a strain rate equal to 7.6 s^{-1} in according to the Cowper Symonds rule (eq.4).



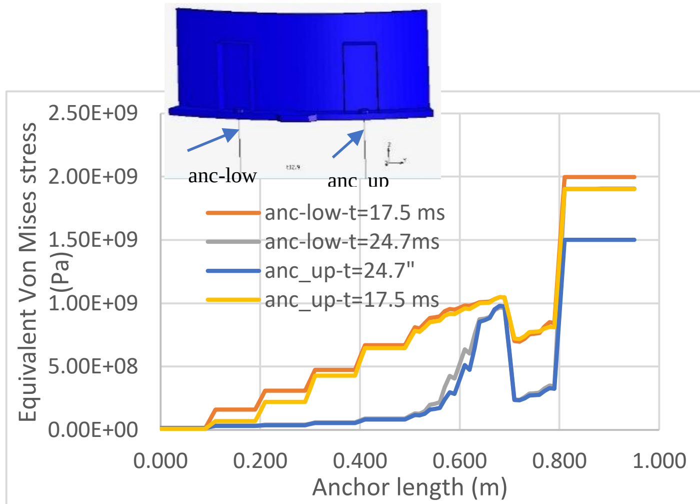


Figure 11. Equivalent plastic strain and the equivalent Von Mises stress along the anchors length

Figure 12 illustrates the distribution of equivalent Von Mises stresses and equivalent plastic strains at different instant of time for the skirt, lower flange and foundation plate. The maximum plastic strain is equal to 17.2% and is obtained in the zones in contact with the anchors. At the end of the transient the plastic strain is about 5%. Figure 13-a) illustrates the equivalent plastic strain of concrete at the end of the transient. The maximum plastic strain is near the anchors and is equal to 6.7e-4 (the crushing strain is 3.5e-3). Figure 13-b) shows the cracking strains in the instant of time in which the maximum tensile force is applied. The zone grey coloured is the part in which the concrete has reached the cracking stress and the tensile resistance goes to zero with a linear law defined by the softening modulus. The cracked zone has a residual resistance to support shear stress when, reversing the loads, the stresses become compressive and the crack closure occurs. This residual resistance is defined by the shear retention factor. The plastic strain is zero in all the reinforced bars.

DISCUSSION OF RESULTS AND CONCLUSIONS

Being the hydrogen detonation a severe accident, yielding of tank walls and accumulation of plastic strains can be admitted. From a mechanical point of view the design limit is the collapse load of the tanks and their supports. The numerical analysis has to verify that the plastic collapse load, that is the '*load that causes overall structural instability* is not reached. '*This point is indicated by the inability to achieve an equilibrium solution for a small increase in load (i.e, the solution will not converge)* (from ASME VIII div. 3 – KD-231.1).

Allowable values of plastic strains are derived by the Code Case 2564-4 concerning pressure vessels impulsively loaded.

The Code Case foresees limits on the accumulated plastic strain components for the design basis impulsive loading:

- the maximum equivalent plastic strain during the transient averaged through the thickness: 0.2%
- the maximum plastic strain components during the transient linearized through the thickness: 2% (1% at welds)
- the maximum peak equivalent plastic strain during the transient at any point in the vessel : 5% (2.5% at welds)

The results of the performed analyses permit to conclude that the joint lower flange-concrete plinth is able to support the loads caused by a hydrogen detonation in the tank, because the collapse load has not reached in all the analysed transients. The Code Case 2564-4 limits on the accumulated plastic strain components have been verified except in the flange near the contact with the anchors during the examined transient. The final value of the plastic strain verifies the Code Case limits. A decrease of the plastic strain of the flange can be obtained increasing the diameter of the washers.

The concrete, in the zone near to the anchors, has reached the cracking stress and the tensile resistance is decreased to zero with a linear law defined by the softening modulus. The crushed strain has not been reached in any point of the plinth. All the steel reinforced bars remain in elastic regimen.

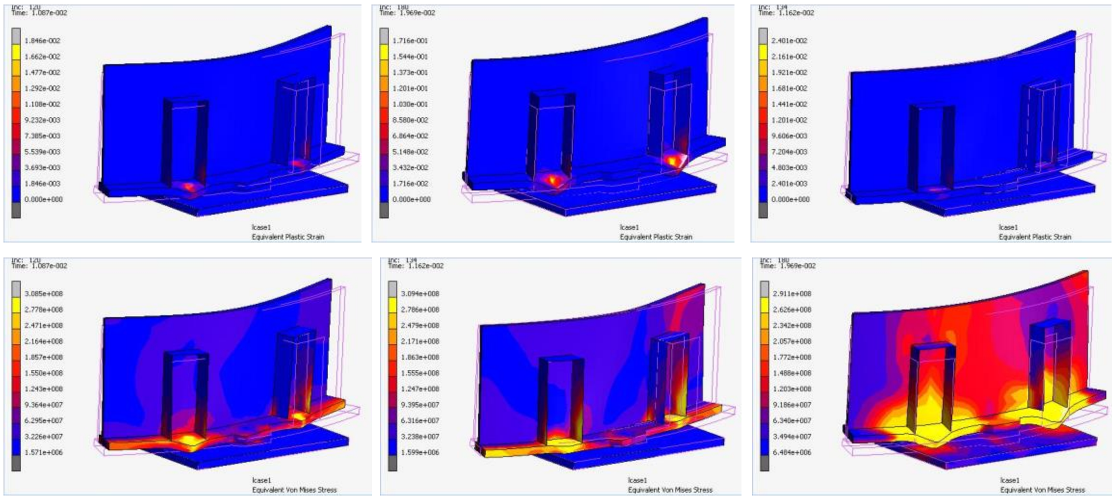


Figure 12 Distribution of equivalent Von Mises stresses and equivalent plastic strains at different instant of time on the skirt, lower flange and foundation plate

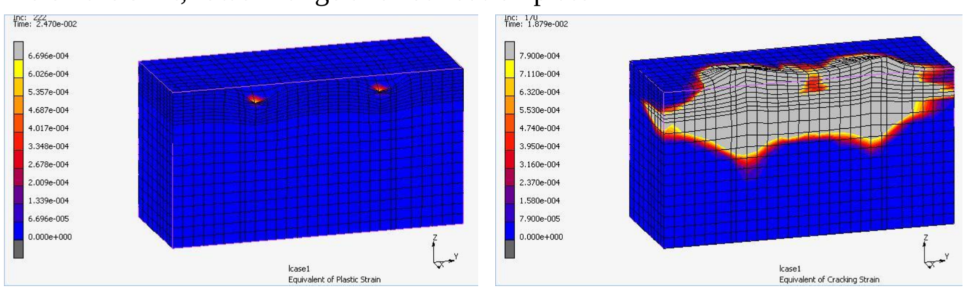


Figure 13 Equivalent plastic strain (a) and cracking strains (b) in the zone of the concrete plinth near the anchors

REFERENCES

Aquaro, D., *Sensitivity analysis of the simulation of hydrogen detonation in a shock tube*- Technical Report D001- rev.1-2016 – Depart. Civil and Industrial Engineering –University of Pisa- Ctr-ITER-DICI

Aquaro, D., *Determination of the pressure transient due to hydrogen detonation in a tank* - Technical Report D002- rev.1-2017 – Depart. Civil and Industrial Engineering –University of Pisa- Ctr-ITER-DICI

Aquaro, D., Lo Frano, R., *Dynamic analysis of Vapor Suppression tanks (VSTs) following an internal hydrogen detonation: structural integrity of VST* Technical Report D003- rev.1-2017 – Depart. Civil and Industrial Engineering –University of Pisa- Ctr-ITER-DICI

ASME BPVC Sect.VIII div. 3 – 2021

Baumann, W., Breitung, W., B. Kaup, R. Redlinger, J.R. Travis, *ITER-FEAT accident analysis on hydrogen detonation using DET3D and GASFLOW*, Report FZKA-6584, Forschungszentrum Karlsruhe, February 2001.

Code case 2564-4 'Impulsively loaded pressure vessels' – 2014 ASME Section VIII – div-3

MSC-DYTRAN – rel. 2017 – MSC Software Corporation- Newport Beach, CA 92660

MSC-MARC – rel. 2016 – MSC Software Corporation- Newport Beach, CA 92660

Nickell, R. E., Duffey T. A., Rodriguez E. A., ASME *Code Ductile Failure Criteria For Impulsively Loaded Pressure Vessels*- 2003 ASME Pressure Vessels and Piping Conference Cleveland, OH USA