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HYDROGEN DETONATION IN A VAPOR SUPPRESSION TANK OF THE NUCLEAR FUSION REACTOR ITER: DETERMINATION OF PRESSURE IMPULSES AND VESSEL STRESS AND STRAIN STATE

Alessio Pesetti[1], Marco Olcese[2], 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

The nuclear fusion reactor ITER (International Thermonuclear Experimental Reactor) foresees a Pressure Suppression System (PSS) for managing a Loss of Coolant Accident (LOCA) or other over pressurization accidents in the Vacuum Vessel (VV). This PSS is made of 4 tanks 100 m3 of volume partially filled by water with a cover gas maintained at sub atmospheric pressure (about 10 kPa absolute). Differently by the applications in the nuclear fission reactors, the steam condensation occurs in ITER at sub-atmospheric pressure conditions.

During LOCA, hydrogen can be produced by different processes (interaction of the water steam with the Beryllium first wall, radiolysis or thermolysis) and it can be entrained in the suppression tanks with the steam. In the cover gas several hydrogen ignitors are located in order to trig the hydrogen combustion when an appropriate mixture of oxygen-hydrogen occurs. Hydrogen detonation was analysed in order to determine the stress and strain state if these accidents occurred in the cover gas.

The pressure transients on the different parts of the VSTs has been determined by means MSC-Dytran FEM computer code. On the basis of which structural analyses of two VST tanks have been carried out by means of the FEM code MSC.Marc© (2016). 1D and 2D axisymmetric models, 3D shell model and 3D solid were analysed, considering two scenarios of hydrogen detonation (axial symmetric and non-symmetric wave propagation). The VST material has been modelled as elastic plastic – work hardening rate sensitive material. Allowable values of plastic strains are derived by the ASME VIII-div.3-Code Case 2564-4. The performed analyses have verified that the plastic collapse load, that is the 'load that causes overall structural instability' is not reached under the transient loads simulating a hydrogen detonation in the lower and upper tanks.

INTRODUCTION

In the ITER fusion plant, the interaction of hot plasma with the blanket first wall made of beryllium entails a high amount of Be dust (tens of kg) released into the vacuum vessel (VV). Such a hot material, in case of postulated loss of coolant accident from the in-vessel water cooling systems, could produce hydrogen by reaction with water. In addition, hydrogen amount could increase due to water radiolysis and thermolysis. In this accidental scenario, in case of air ingress into the VV a flammable hydrogen-air mixture could be reached and compromise the VV structural integrity, with consequent loss of radioactive material containment.

The risk of hydrogen combustion does not involve the only VV. Indeed, in presence of VV pressurizing accident (LOCA and LOVA), the fluids in the VV are discharged into the ITER VV Pressure Suppression System (VVPSS), for maintaining the VV pressure below the allowed limit of 0.15 MPa. In this condition, hydrogen could be accumulated in the cover gas of the four tanks composing the VVPSS

(100 m^3 each, called Vapor Suppression Tanks, VST, partially filled with water and working at sub-atmospheric conditions) and eventually undergo hydrogen deflagration or detonation. In the upper part of VST ignitors are implemented for anticipating hydrogen combustion and limiting the energy released.
In this research activity a dynamic analysis [1] was performed, by means of a FEM code MSC.Marc© [2], in order to verify the resistance of the Vapor Suppression Tanks (VSTs) under the loads caused by hydrogen detonation events. A three-dimensional model was required to have a complete representation of the VSTs performance including also shear (or bending) effects

The pressure time histories on the VST walls have been determined [3] analysing two scenarios of hydrogen detonation: 1) an axisymmetric wave propagation (velocity of wave propagation parallel to the symmetry axis of VST); and 2) a non-symmetric wave propagation (velocity of wave propagation at 45° to the VST symmetry axis).

Modal analyses were carried out in order to determine the main natural frequencies of the VST, simulating the assembly of two-tanks. The constitutive equation of all the components simulates a behaviour elastic-perfectly plastic. Conservatively, the factors which can increase the material resistance, as the rate sensitivity of the yielding stress and the work hardening, have not been taken into consideration. Allowable values of plastic strains are derived by the Code Case 2564-4 [4] concerning pressure vessels impulsively loaded.

DYNAMIC ANALYSIS OF HYDROGEN DETONATION IN THE VST

The 100 m^3 Vapour Suppression Tanks of ITER VVPSS are shown on the left of Figure 1, they are partially filled with water. The lower tank has 40 m^3 of water (Small Loca Tank, SLT) and the upper tank has 60 m^3 of water (Large Loca Tank, LLT). The VST is made of an upper and lower torospherical heads welded at cylindrical shell. The void space has a maximum diameter of 6.25 m and 2.5 m of maximum height.

For evaluating hydrogen detonation in the VST, the expansion of a combusted gas was simulated in a slab geometrical model (on the right of Figure 1) by MSC-DYTRAN code [5]. The initial conditions of the expanding gas are: propagation velocity = 2700-2800 m/s; specific internal energy = 2.022e+06 kJ/kg; density = 1.9361 kg/m^3. The air data are: specific internal energy = 307545 kJ/kg; density= 0.8129 kg/m^3. The ratios between volumes, masses and energies of the two materials are gas volume / air volume = 0.13; gas mass / air mass = 0.31; gas energy / air energy= 2.05.

The domain analysed with MSC-Dytran code is a vertical central slice of VST (0.36 m thick), as shown on the right of Figure 1. Considering the results obtained from a previous analysis of a shock tube [6], a sphere of combusted gases, r=0.88 m of diameter, has been considered inside the tank.

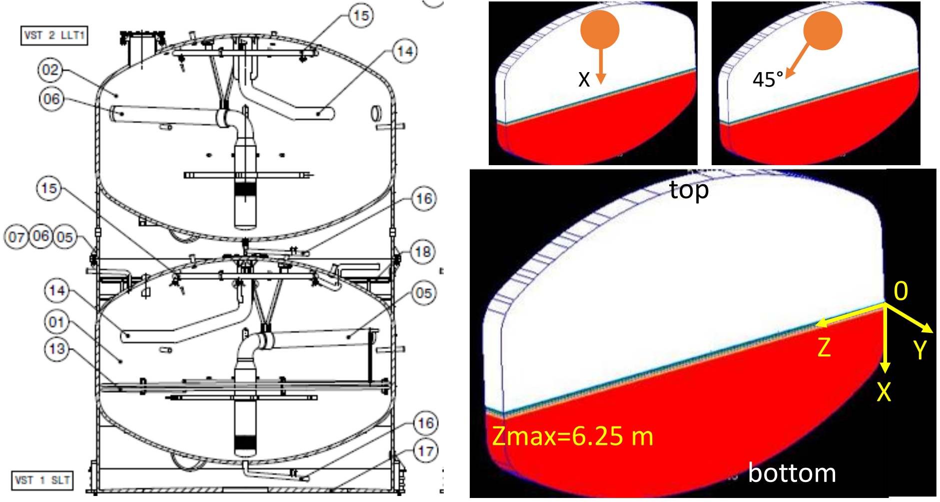

Figure 1. Vertical section of two VST tanks(left), MSC-Dytran calculation domain, cover gas (white) and water (red)(right)

The two investigated scenarios of hydrogen detonation are:

- axisymmetric analysis (see Figure 2): cylindrical cloud of combusted gas positioned at the centre, on the symmetry axis "X" (X= 0.88 m, Y= 0 m and Z= 3.126 m), expanding in "X" direction;
- non-symmetric analysis (see Figure 3): cylindrical cloud of combusted gas positioned as at the previous point (X= 0.88 m, Y= 0 m and Z= 3.126 m), expanding at 45° between "X" and "Z" direction.

In Figure 2 and Figure 3 the expansion of combusted gas is shown, for different time instants, for axisymmetric and non-axisymmetric detonation. In all the analyses, the pressure and the impulse diagrams on the different sides have been determined and compared with the reference ones of the shock tube. Moreover, vertical and horizontal resultant forces on the supports have been calculated extrapolating the results from the slice model to the actual shape of VSTs.
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).

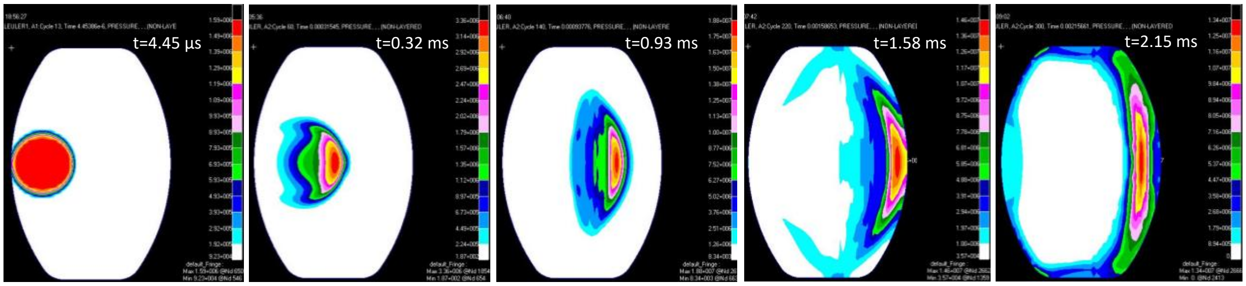

Figure 2. MSC-Dytran simulation of pressure profiles during combusted gas expansion (axisymmetric)

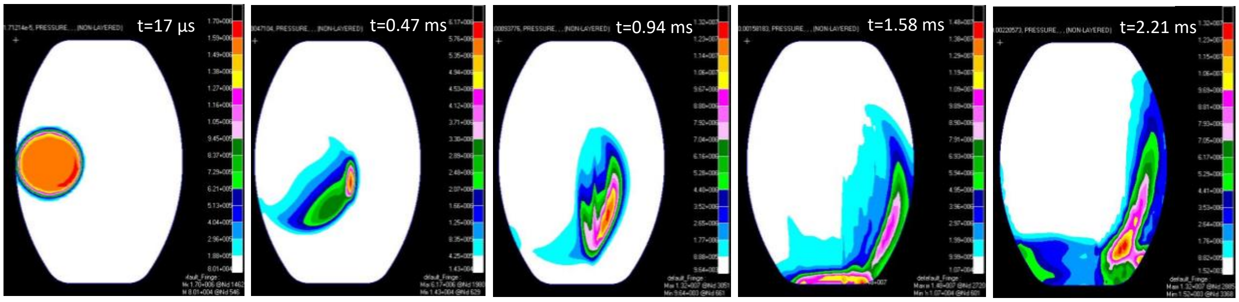

Figure 3. MSC-Dytran simulation of pressure profiles during combusted gas expansion (axisymmetric)

TRANSIENT ANALYSIS

The simulation of the tank behaviour under the pressure transients due to an internal hydrogen detonation is performed by a multi-step calculation. In what follows, the effects on VST of different hydrogen detonations, as determined by the numerical analyses by means of a FEM code, are presented and discussed.

The VSTs are made of A304 steel, material properties of which, at the foreseen operation temperature, have been determined according to the ASME sect. III rules. The constitutive equation of all the components simulates a behaviour elastic-perfectly plastic. Conservatively, the factors which can increase the material resistance, as the rate sensitivity of the yielding stress and the work hardening, have not been taken into consideration.

The parameters of the elastic perfectly plastic constitutive equation are the following: σy = 175 MPa; ν = 0.3 and Ec = 200000MPa, where, σy is the yielding stress; ν is the Poisson Modulus; and E is the Young modulus.

Numerical simulations of the hydrogen detonations in VST have been performed considering the following scenarios:

- axial symmetric detonation separately in the lower and upper tank
- non axial symmetric detonation separately in the lower and upper tank

Both axial and non-axial symmetric detonation have been analysed with a 3D shell element model.

Results from the simulation of hydrogen detonation are given in terms of forces and pressure versus time. The load on the different parts of tank depends on the wave propagation. Therefore, at any instant of time, it is different in each point of tank. In order to facilitate the control of the correctness of input data and to decrease the input complexity, spatial average values of loads have been used. At any instant of time, average loads have been calculated for the different geometric part of the tank. In particular, the tank has been subdivided in two parts: zone in contact with the air (combusted gases) and zone in contact with the water. For each zone, the following geometric parts have been considered. Zone in contact with the air: a) upper spherical zone; b) upper toroidal zone; and c) upper cylindrical zone. Zone in contact with the water: d) lower cylindrical zone; e) lower toroidal zone; and f) lower spherical zone.

For the axial symmetric detonation, the pressure is uniform in the previous defined zones, while in the non-axial symmetric detonation, two spatial average loads for each geometric zone have been determined subdividing them in two parts with reference to the vertical coordinate plane XY:

- zone having coordinate $z<0$;
- zone having coordinate $z>0$.

This subdivision is consistent with the direction of the wave propagation in the considered scenario and the loads, function of the time, have been obtained from the preliminary numerical analyses of the hydrogen detonation. Each carried out analysis lasts 25ms that corresponds to the duration of the detonation effects.

STRUCTURAL ANALYSYS

Symmetric Detonation in the lower tank

Figure 4 illustrates the distribution of the equivalent Von Mises stresses in a vertical cross section of VST for different instants of time. The stresses refer to the external surface (top layer). Being elastic perfectly plastic the constitutive behaviour of the material, the maximum stress is equal to the yielding stress (175 MPa). Figure 4 shows that a great part of the lower tank reaches the yielding stress in the first instants of the transient. Subsequently the most solicited zones are the lower toroidal zone (connected to the skirt) and the lower spherical zone, both in contact with the water. This is demonstrated by Figure 5 and Figure 6 that show the distribution of equivalent plastic strains at different instants of time correspondent to the external surface (top layer), average surface (middle layer) and internal surface (bottom layer). During the transient, the maximum values of plastic strains are localized in these two zones.

The maximum plastic strains are obtained in the node of lower spherical zone which is equal to 1,05% on the external surface. Only in this point, the average equivalent plastic strain is greater than 0.2% (maximum value: 0.67%; final value:0.29%). The other two limits, foreseen by the code case 2564-4, are verified anywhere.

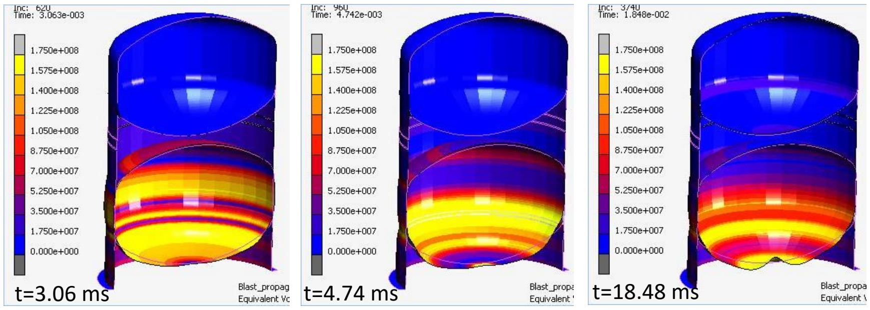

Figure 4. Equivalent Von Mises stresses for axisymmetric detonation in lower tank

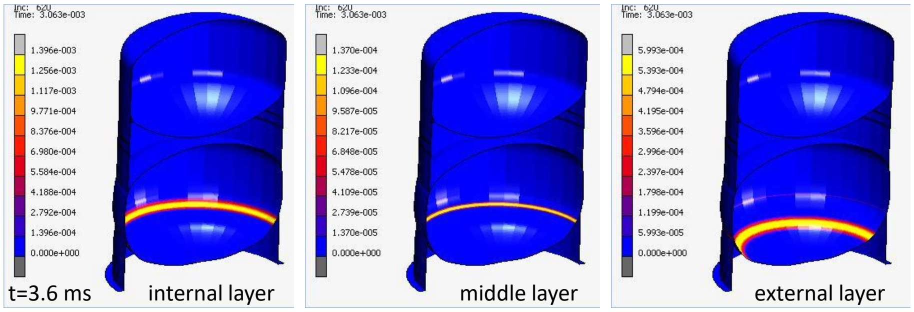

Figure 5. Equivalent plastic strain for axisymmetric detonation in the lower tank (at 3.6 ms)

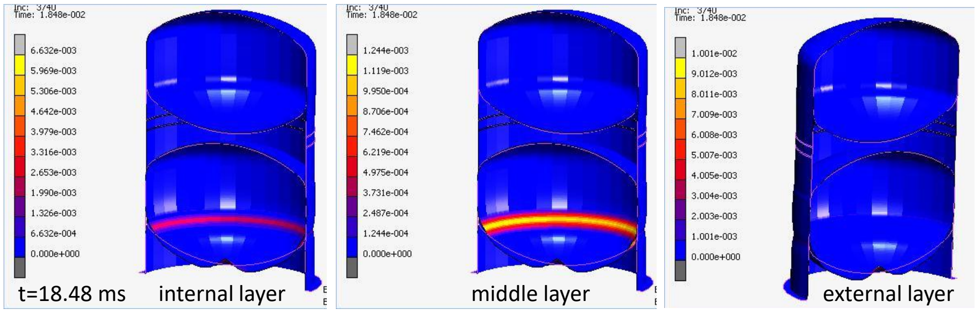

Figure 6. Equivalent plastic strain for axisymmetric detonation in the lower tank (at 18.48 ms)

Symmetric Detonation in the upper tank

Figure 7 shows that a great part of the upper tank reaches the yielding stress in the first instants of the transient. Subsequently the most solicited zones are the lower toroidal zone (connected to the skirt) and the lower spherical zone, both in contact with the water. This is confirmed by Figure 8 and Figure 9 that show the distribution of equivalent plastic strains at different instants of time correspondent to the external surface, average surface and internal surface. During the transient, the maximum values of plastic strains are localized in the lower toroidal zone and the lower spherical zone.

The maximum plastic strain is obtained in the node of lower spherical zone where is equal to 1.49% on the external surface. Only in this point, the average equivalent plastic strain is greater than 0.2% (maximum value: 0.75%; final value:0.63%).

The other two limits, foreseen by the code case 2564-4, are verified anywhere (in any points the plastic strain is lower than 1.49%).

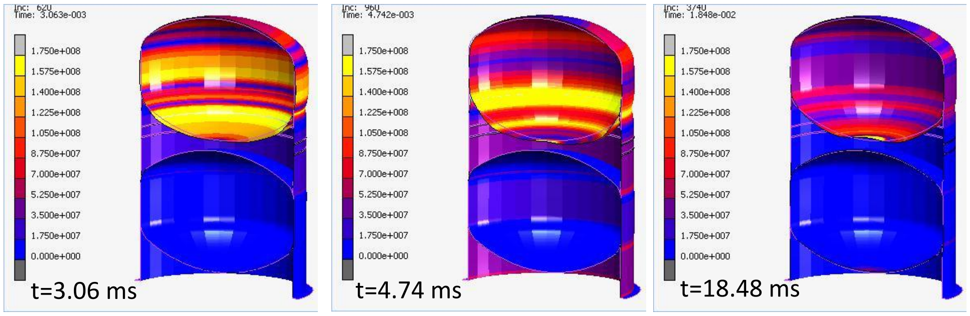

Figure 7. Equivalent Von Mises stresses for axisymmetric detonation in the upper tank

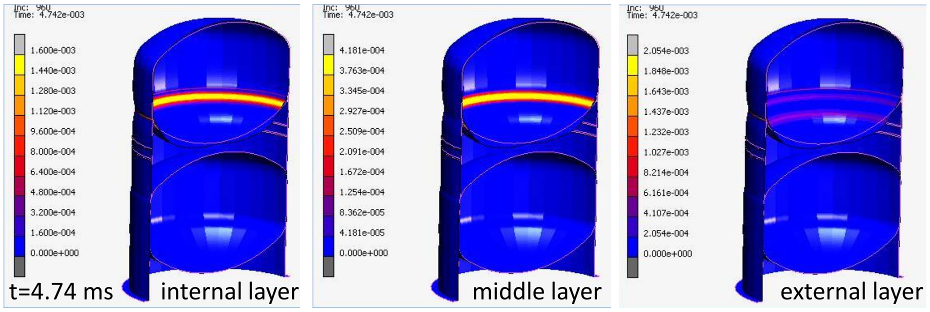

Figure 8. Equivalent plastic strain for axisymmetric detonation in the upper tank (at 4.74 ms)

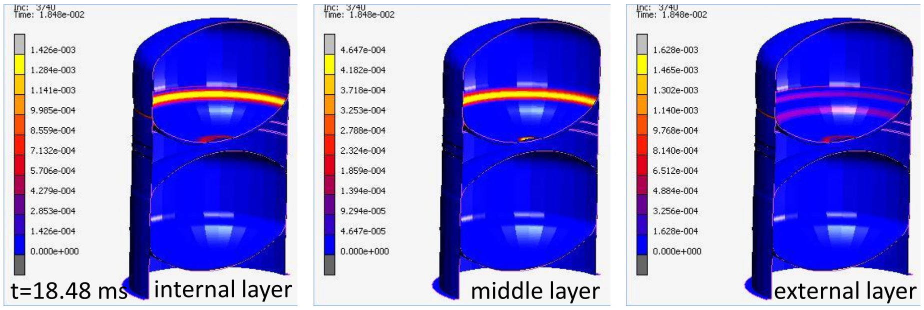

Figure 9. Equivalent plastic strain for axisymmetric detonation in the upper tank (at 18.48 ms)

Non-symmetric Detonation in the lower tank

Figure 10 shows that the first peak of pressure determines stresses equal to the yielding stress in the cylindrical part of tank correspondent to the coordinates z>0. In fact, this zone is the first hit. Subsequently, the most solicited zones are the lower toroidal zone (connected to the skirt) and the lower spherical zone, both in contact with the water. It is confirmed by Figure 11 and Figure 12 that show the distribution of equivalent plastic strains at different instants of time correspondent to the external surface, average surface and internal surface. During the transient, the maximum values of plastic strains are localized in these three zones.

The maximum plastic strains are obtained in the node of lower spherical zone which is equal to 0.497% on the external surface. The points where the average equivalent plastic strain is greater than 0.2% are:

- Central node lower spherical zone (maximum value: 0.25%; final value:0.05%)
- skirt-toroidal zones interface (maximum value: 0.22%; final value:0.22%)
- node of upper cylindrical zone (maximum value: 0.204%; final value:0.204%)

The other two limits, foreseen by the code case 2564-4, are verified anywhere.

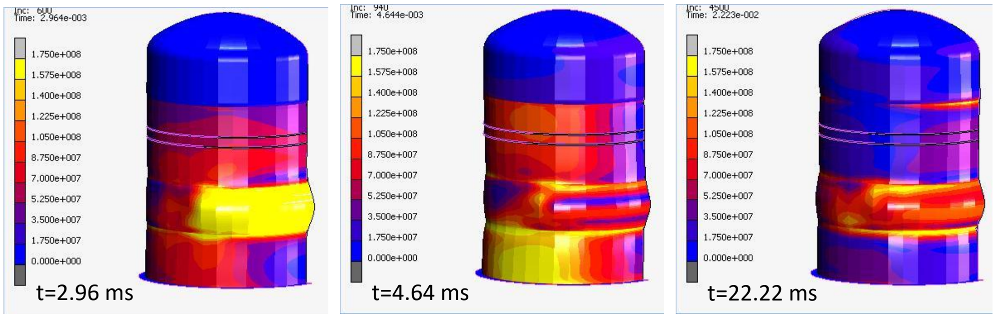

Figure 10. Equivalent Von Mises stresses for non-axisymmetric detonation in the lower tank

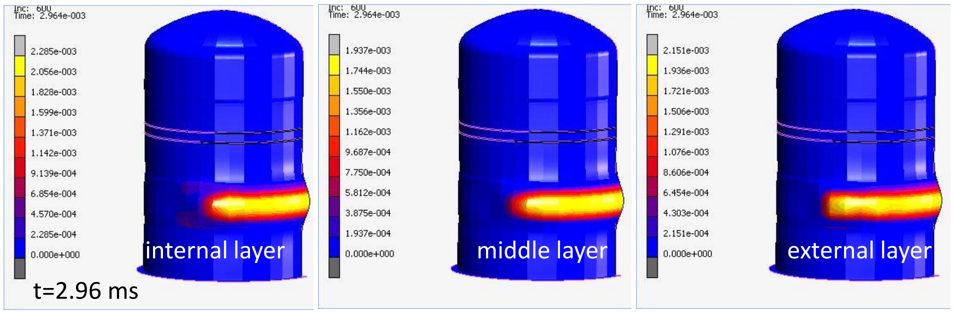

Figure 11. Equivalent plastic strain for non-axisymmetric detonation in the lower tank (at 2.96 ms)

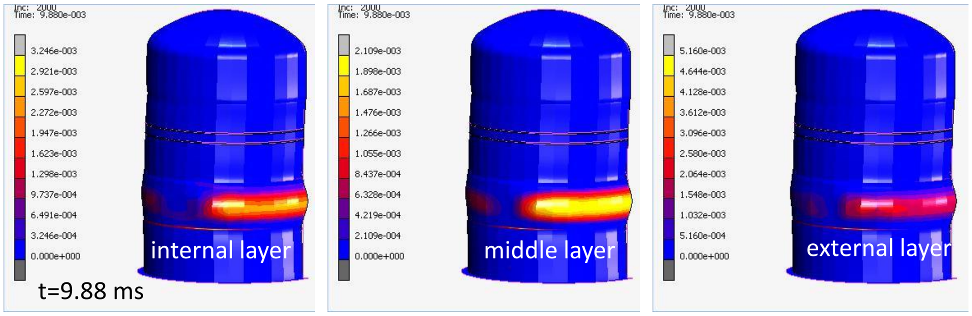

Figure 12. Equivalent plastic strain for non-axisymmetric detonation in the lower tank (at 9.88 ms)

Non-symmetric Detonation in the upper tank

The maximum plastic strain is obtained in the node of lower spherical zone where is equal to 0.80% on the external surface. The average plastic strain is equal to 0.4%. There are not any other points where the average equivalent plastic strain is greater than 0.2%.
The other two limits, foreseen by the code case 2564-4, are verified anywhere.

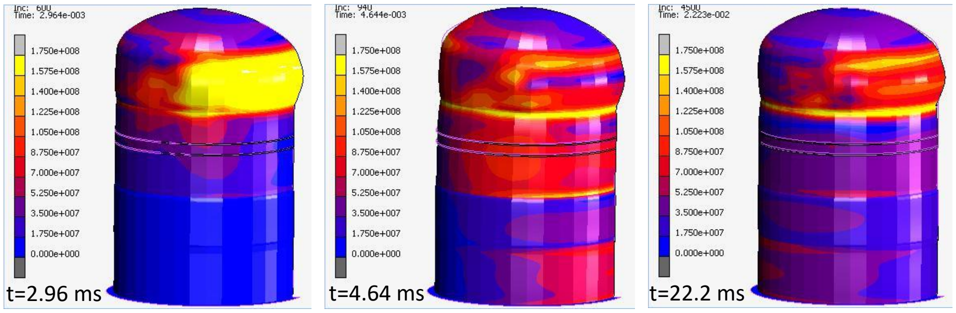

Figure 13. Equivalent Von Mises stresses for non-axisymmetric detonation in the upper tank

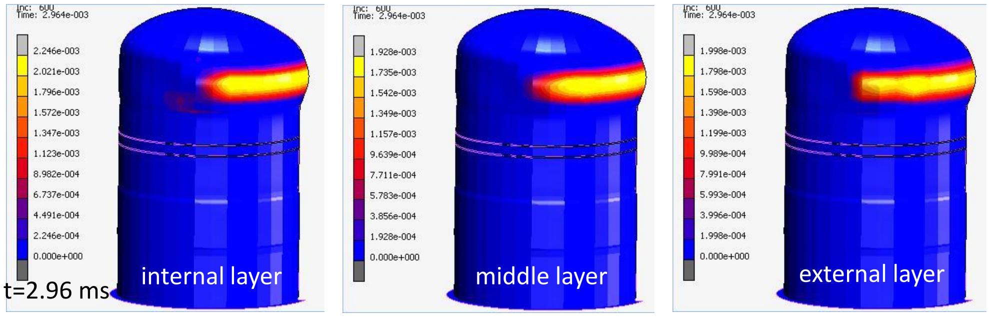

Figure 14. Equivalent plastic strain for non-axisymmetric detonation in the upper tank (at 2.96 ms)

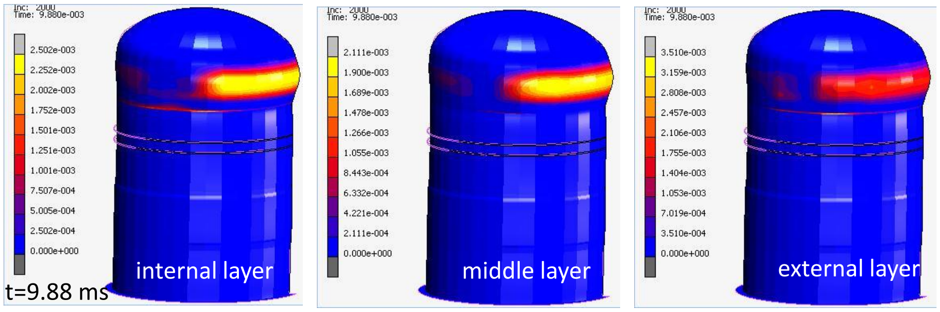

Figure 15. Equivalent plastic strain for non-axisymmetric detonation in the upper tank (at 9.88 ms)

SOLICITATIONS AT THE UPPER FLANGES

The upper and lower tanks are connected by bolted joint. Obviously greater forces through the joint are transmitted in the case of detonation in the upper tank. In the case of axial symmetric detonation, only a vertical force (Nx) is transmitted through the joint. The maximum and minimum values are 2.2E+6 and -2.19E+6 N/m, respectively.

In the non-axial symmetric detonation, the upper bolted joint has to transmit a complex stress state.

Neglecting the bending and twisting moments due to the fact that the skirt is a thin shell, and the bolted joint is far from geometric discontinuity, the forces considered are the vertical force Nx, tangential force Nxt and shear force Qxr. The shear forces, Qrx, are smaller than the other forces.

CONCLUSION

This work illustrates the dynamic analyses performed in order to verify the resistance of the ITER Vapor Suppression Tanks (VST's) under the loads caused by two hydrogen detonation events.

The pressure time histories of an axisymmetric and a non-axisymmetric hydrogen detonation in the VST were evaluated with MSC.Dytran code and constituted the boundary condition for a structural analysis carried out by FEM code MSC.Marc©.

A shell FEM models of two VST tanks assembly was developed. The modal analysis permitted to determine the frequencies of the first bending modes of the lower spherical zone of the tanks (48-68 Hz) and characterize the complex bending modes of the tanks (higher than 68 Hz).

For axisymmetric detonation, the most solicited zones are the lower toroidal zone (connected to the skirt) and the lower spherical zone, both in contact with the water. The maximum plastic strains (detonation in lower tank) are obtained in the node of lower spherical zone where is equal to 1,05% on the external surface. Only in this point, the average equivalent plastic strain is greater than 0.2. In the simulation of the detonation in the upper tank, the maximum plastic strains are obtained in the node of lower spherical zone where is equal to 1,49% on the external surface. Only in this point, the average equivalent plastic strain is greater than 0.2% (maximum value: 0.75%; final value:0.63%).

For non-axisymmetric detonation in lower and upper tank, the most solicited zones (maximum values of plastic strains) are the cylindrical part of tank correspondent to the coordinates z>0, the lower toroidal zone (connected to the skirt) and the lower spherical zone. In the case of detonation in the lower tank, the maximum plastic strains are obtained in the node of lower spherical zone where is equal to 0.497% on the external surface. The average equivalent plastic strain is greater than 0.2% in the central node lower spherical zone, skirt-toroidal zones interface and node of upper-cylindrical zone. The maximum displacement is 11.3 mm at the nodes of upper cylindrical zone. For detonation in the upper tank, the maximum plastic strains are obtained in the node of lower spherical zone where is equal to 0.80% on the external surface. The average plastic strain is equal to 0.4%. There are not any other points where the average equivalent plastic strain is greater than 0.2%. The maximum displacement is 12.06 mm at node of upper cylindrical zone.

The performed analyses have verified that the plastic collapse load, that is the ‘load that causes overall structural instability’ is not reached under the transient loads simulating a hydrogen detonation in the lower and upper tanks. The accumulated plastic strain components limits, foreseen by the Code Case 2564-4, have been verified.

REFERENCES

[1] 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
[2] MSC-MARC – rel. 2016 – MSC Software Corporation- Newport Beach, CA 92660
[3] 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
[4] Code case 2564-4 ‘Impulsively loaded pressure vessels’ – 2014 ASME Section VIII – div-3
[5] MSC-DYTRAN – rel. 2017 – MSC Software Corporation- Newport Beach, CA 92660
[6] 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