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Design and Structural Analysis of Mounded LPG Bullet

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Abstract— **This paper deals with the finite element analysis of a mounded bullet designed based on American Society of Mechanical Engineer's Boiler and Pressure Vessel Code Section VIII, Division 2 for the storage of liquefied petroleum gas. ANSYS Parametric Design Language is used to carry out the structural analysis of mounded bullet. Shell elements are used to model the pressure vessel and surface elements are employed to accommodate the effect of subsoil stiffness. The analysis results are compared with the design requirements.**

Keywords - ASME BPVC, Finite Element Analysis, Mounded, Pressure vessel.

I. INTRODUCTION

Nowadays the storage of dangerous gases becomes a challenging problem. Use of mounded bullets is one of the feasible solutions to the problem. The design aspects of mounded storage vessels are more complicated than conventional above ground spheres or bullets.

Mounded bullets are horizontal pressure vessels which are intended for the pressurized storage of liquefied petroleum gas (LPG) under ambient temperature. In mounded storage facility, a mound of earth or suitable inert material is provided to cover the bullet, which is kept above ground, completely except for nozzles, manhole covers. Mounded bullets are considered to be a safer option for LPG storage than conventional methods, such as Horton spheres, buried storage etc., because situations leading to a possible Boiling Liquid Expanding Vapour Explosion (BLEVE) are eliminated. The mound protects the vessel from engulfment of fire, radiation from a fire in close proximity and acts of sabotage terrorism and vandalism. Mounded storage is also used in situations where minimization of visual impact is important. The mounds reduce the visual impact of storage site. As they have a sand cover around it, they can take impact of external projectiles or flying object. The dished ends of the bullets are the weakest points of material construction susceptible to catastrophic failures. Hence they are to be directed away from process or occupied areas.

Mounded bullet installation is more space efficient than spheres. This is because of the smaller vessel-to-vessel spacing and due to the smaller safety distance requirement between the mounded storage vessels and items such as control rooms, buildings, roads etc. Mounded bullets offer the possibility of partial or total off-site construction. Mounded bullets are installed on sand bed foundations which allow the load to be transferred uniformly to the underlying sand. This requires no heavy foundation work and offers an uncomplicated, low cost installation. The preferred type of foundation for a mounded storage vessel is a continuous sand bed, supporting the vessel over its entire length. The use of the sand foundations allows the vessels to be installed early in the project and also allows vessel loadings to be predicted more accurately for vessel design. Usually the foundation will be constructed with a slope of at least 1:200 to facilitate draining of the vessel and the sand beneath the vessel must have adequate elevation not less than 0.76 m to facilitate drainage. Normally mound is provided with either earth, sand or non-combustible materials like perlite, vermiculate, etc. for at least 700 mm thickness. As there are possibilities for foundation settlement, the surrounding of bottom nozzle should be filled with such material that can absorb settlement. Provisions are provided for monitoring the settlement of vessel in mounded storage facility. Bullets must be coated with special corrosion inhibiting layers such as epoxy layers and cathodic protection is critical to prevent corrosion.

Heckman[9] suggests that finite element analysis is a powerful tool when employed properly. The analysis carried out for exploring the applicable methods of finite element analysis in pressure vessel design. Xue et al. [12] estimate the burst pressure and failure location of a cylindrical shell intersection by use of finite element analysis. 20 node structural solid elements are employed to perform static and nonlinear finite element analysis using ANSYS. Arc- length method is used for the analysis. Numerically predicted solutions are verified using the experimental results. The finite element method can be employed to predict the burst pressure and failure location of cylindrical shell intersections with sufficient accuracy. The results show that the failure of the pressure vessel shell intersection occurs off longitudinal axis of the vessel. Deng and Chen [7] investigate the carrying capacity of pressure vessels under hydrostatic pressure based on elastic - plastic theory. Large deformation analysis of pressure vessels is important in the context of safety and effective use of material. There are no well recognized theoretical analysis methods available for the large deformation of pressure vessels. Finite element analysis can be used for it. The equations of pressure and strain of thin walled cylindrical and spherical vessel under internal pressure are used to understand the large deformation characteristics of pressure vessel. Plastic instability criterion for thin walled pressure vessel under internal pressure is employed for investigating the carrying capacity of pressure vessels. Instability pressures of thin walled vessels under internal pressure can be obtained from pressure- strain curves drawn based on the expressions of pressure and strain of thin walled pressure vessels. The method described is more efficient than finite element method and can be easily employed in engineering applications.

In 2012, Stefanovic and Noman [11] describe a methodology for the design and analysis of buried LPG storage bullets supported on multiple saddles. The method applies to underground bullets supported on five saddles. The loads induced by weight of the mound, pressure due to mound and the loads due to longitudinal and thermal expansion and soil resistance to this expansion are addressed. A method for the calculation of reactions on saddles and bending moments at spans and supports are provided. The fundamental equations for various loads are taken from EEMUA publication 190. A simplified method for assessing the effect of differential settlement of pressure vessel between saddles is proposed. Yogesh and Lakshmi [13] present the results of finite element analysis of a mounded bullet designed according to ASME codes. Analysis has been carried out for internal pressure, mound load, seismic loads and uneven settlement. SHELL63 elements are used for the analysis. Analytical calculations are done using existing formulas. Plots showing the deformations of the bullet under various load cases are shown.

II. DESIGN OF PRESSURE VESSEL

American Society of Mechanical Engineer's (ASME) Boiler and Pressure Vessel Code (BPVC) Section VIII, Division 2 has been employed for the design of bullet. The parameters considered for the design are shown in Table I.

TABLE I. DESIGN SPECIFICATIONS

Design Pressure	1.8148 MPa
Design Temperature	-45 ^{0}C to +55 ^{0}C
Working Pressure	1.2749 MPa
Operating Temperature	40 ^{0}C
Capacity	2700 m^3
Length	93.00 m
Diameter	6.40 m
Density of LPG	467 kg/m^3
Viscosity at 40^{0}C	0.0860 cP
Design code	ASME Section VIII Division 2
Wind design code	IS-875
Seismic design code	IS-1893 RSM

Pressure vessels are usually constructed by the assemblage of different components such as shells, heads, nozzles and stiffener rings.

- Shells

Shells are the primary components that store liquids. Cylindrical shells are widely employed as they are having maximum section modulus and minimum induced stress for a given diameter. Pressure vessel shells are welded together to form a structure that has a common rotational axis. Spherical and conical shells are also in use.

- Heads

A variety of heads are used for closing the ends of pressure vessel shells. These include hemispherical, elliptical, torispherical, conical and flat shaped heads. Curved configurations are stronger and allow the heads to be lighter, thinner and less expensive than flat heads. Heads are usually categorized by their shapes. Ellipsoidal, hemispherical, torispherical, conical, tori-conical and flat are the common types of heads.

- Nozzle

Nozzles are necessary components of pressure vessel for the process industries. Nozzle is a component that is welded to the shell or heads of a pressure vessel for connecting the vessel to inlet and outlet pipes to convey working fluid in and out of the vessel. In order to minimize stress concentrations, preferred shape of nozzles are circular. Usually the nozzle ends are flanged to allow for the connections and to permit easy disassembly for maintenance or access.

- Stiffener Rings

Stiffener rings are used all around the periphery of the vessel to increase the moment of inertia at local positions, thus increasing the resistance or strength and reducing the thickness requirements. The material used for stiffener rings is of comparatively low cost and it allows economically favorable manufacturing of pressure vessels.

The material used for the construction of different parts of the bullet along with their tensile strength and yield stress values are listed in Table II.

TABLE II. MATERIAL SPECIFICATION

Description	**Material**	**Type of Steel**	**Tensile Stress MPa**	**Yield Stress MPa**
Shells	SA-516 60	Carbon Steel	413.70	220.64
Dished Ends	SA-516 60	Carbon Steel	413.70	220.64
Rings	SA-516 60	Carbon Steel	413.70	220.64
Nozzles	SA-350 LF2	Carbon Steel	482.65	248.22

III. FINITE ELEMENT ANALYSIS OF MOUNDED BULLET

A. Description of Finite Elements

SHELL181 is suitable for analyzing thin shell structures such as pressure vessels. It is a 4-node element with six degrees of freedom per node; three translations in X, Y and Z directions and three rotations about X, Y and Z axes. It is well suited for linear, large rotation and large strain non-linear applications. A degenerate triangular element option is also available. The element geometry and node locations are shown in Fig. 1.

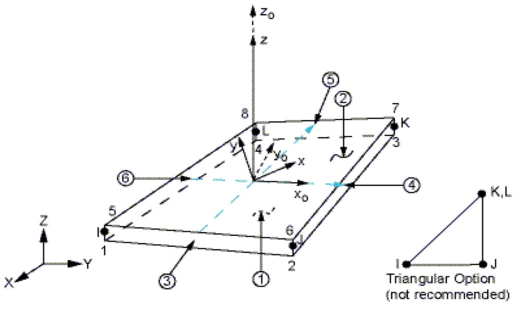

Fig. 1. Structural Geometry of SHELL181 element

SURF154 has been used for various load and surface effect applications. It is overlaid onto an area. The element is applicable to 3-D structural analyses. Various loads and surface effects may exist simultaneously. The element is defined by four to eight nodes. Each node has three degrees of freedom; namely UX, UY and UZ. The structural geometry of the element is shown in Fig. 2.

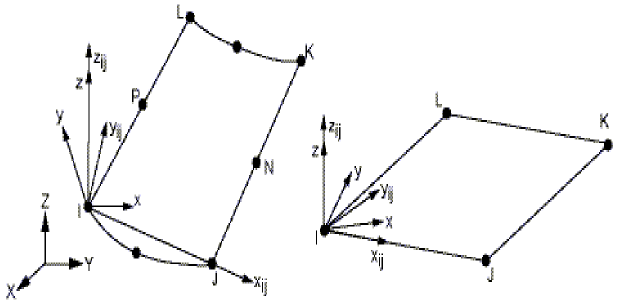

Fig. 2. Structural Geometry of SURF154 element

B. Finite Element Model

Finite element analysis has been carried out for LPG storage mounded bullet which has been modeled as Quarter symmetry. The model was meshed with SHELL181 and SURF154 elements. The analysis is carried out in the bullet without assuming the openings. By considering that assumption quarter model is enough for the analysis as it yields better results and consumes less time. Corroded thickness is considered for service conditions and un-corroded thickness for hydro test condition. The finite element quarter model of bullet is shown in Fig. 3.

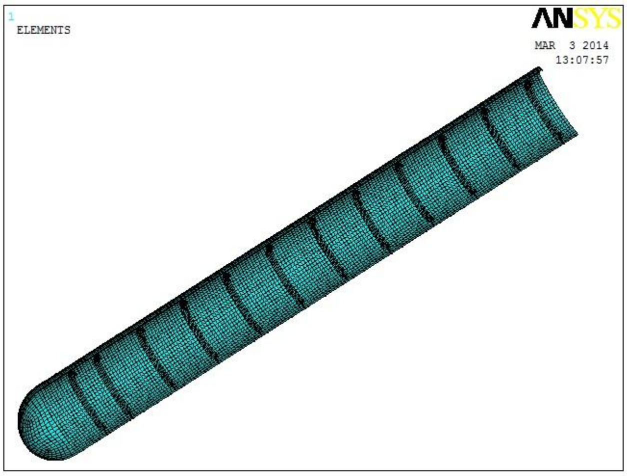

Fig. 3. Finite element model of mounded bullet

Internal stiffening rings are provided in the bullet to reduce the thickness requirement of the shell. Stiffening rings also increase the collapsing strength of pressure vessels. Stiffeners have been modeled with web, flange and gussets. The web and flange of stiffening rings are having same thickness of 48 mm. The width of flange is 450 mm and length of web is 580 mm. Meshed model of stiffener ring with shell is shown in Fig. 4.

There are 2 Domes, manhole and liquid inlet / outlet nozzles in the bullet. The design of Dome and Man-way is identical on both sides of the mounded LPG bullet, except Nozzles on dead end of Domes are different. Study of nozzles show that the nozzles on the Dome-2 have larger size correspondingly higher loads. Hence, model of Dome-2 and manhole along with shell (Fig. 5) has been evaluated.

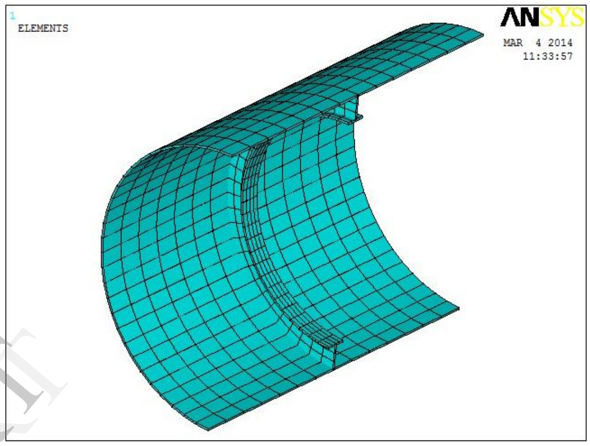

Fig. 4. Finite element model of stiffener ring with shell

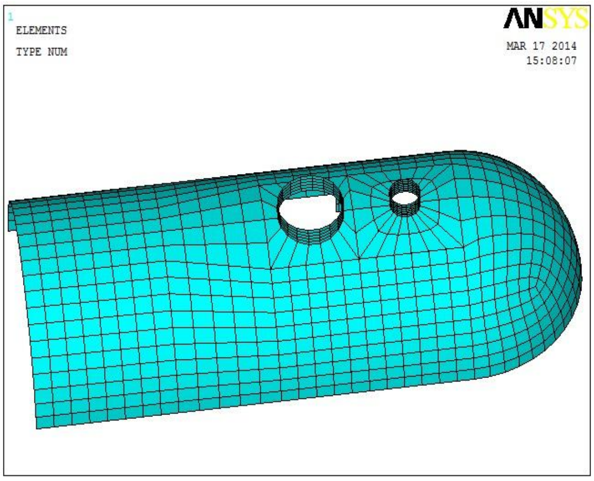

Fig. 5. Finite element model of nozzles on bullet

C. Boundary Conditions

Symmetrical boundary conditions are applied in quarter symmetry model of bullet and nozzle. As per Engineering Equipment & Material Users' Association (EEMUA) 190: 2005 standard, the mounded bullet is supported on a sand foundation with sand bed at an angle of 120^0. As per the standard it has been considered two support cases for the bullet (Fig. 6).

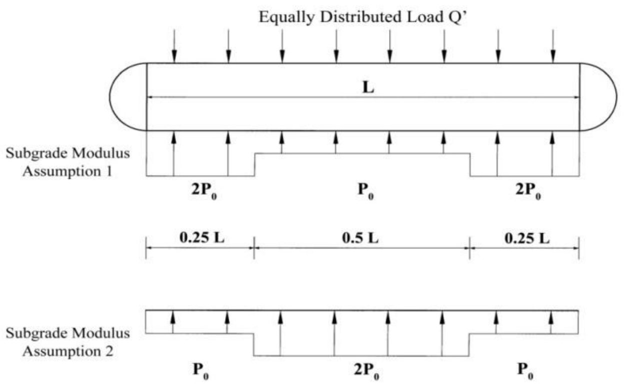

Fig. 6. Support Load Distribution

As per good engineering practice the maximum theoretical differential settlement is limited to 1:2500. Based on the long-term settlement of the bullet subgrade modulus has been derived. The effect of foundation on the bullet is incorporated as Elastic Foundation Stiffness (EFS) along the length of bullet on bottom 120^0 support angle.

- Middle Soft [EEMUA Subgrade Modulus Assumption 1] will be P_0 in the middle of bullet (0.5L) and $2P_0$ at ends of bullet (0.25L).
- Middle Hard [EEMUA Subgrade Modulus Assumption 2] will be $2P_0$ in the middle of bullet (0.5L) and P_0 at the ends of the bullet (0.25L).

SURF154 elements are employed for incorporating the long-term subgrade modulus of the subsoil in ANSYS. It has been modeled as EFS which is equal to Subgrade Modulus per unit area of vessel.

D. *Loads on Mounded Bullet*

The analysis of mounded bullet is carried out by considering different loads mentioned in EEMUA Publication 190:2005. The loads are applied in finite element analysis as uniformly distributed forces and point loads at nodes. Dead weight of the bullet, internal design pressure, weight of the maximum volume of liquid allocated to one stiffener, the pressure exerted by the mound on top of the cylinder and domed ends, axial loads due to changes in vessel length which are caused by variations in pressure and temperature, pressure exerted by the foundation and earthquake loads are considered in the analysis.

E. *Load Combinations*

There are three load combinations considered in the analysis for two support conditions, middle soft case and middle hard case, as mentioned in clause A.4.2.10 of EEMUA 190: 2005.

- Service (Filled with LPG in corroded condition)

  Internal Design Pressure + Liquid Head + Design Temperature + Weight of Mound

- Hydro test (Filled with water and in un-corroded (new) condition)

  Hydro test pressure + Liquid Head + Weight of mound

- Service (Filled with LPG in corroded condition)

  Internal Design Pressure + Liquid Head + Design Temperature + Weight of mound + Seismic loads

F. *Permissible Limits of Stresses*

The results of the finite element analysis have to be compared with the limiting stress values suggested by ASME Section VIII Division 2 to determine whether the component is suitable for the intended design conditions. The equivalent stress is computed at various locations in the component and compared to an allowable value of equivalent stress specified by the standard. The computed equivalent stresses for a component subjected to loads shall not exceed the specified allowable values. The maximum distortion energy yield criterion shall be used to establish the equivalent stress. The equivalent stress is equal to the von Mises equivalent stress.

$$S_E = \sigma_E = [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 / 2]^{0.5}$$
(1)

Permissible limits of stresses as per ASME Section VIII Division 2 for service conditions;

$$P_M \leq 1.5\ S_D$$
(2)

$$C_Z \leq F_{HA} \text{ and } S_Z \leq T_Z$$
(3)

For Hydro test conditions;

$$P_M \leq 0.95\ S_Y$$
(4)

For Seismic load cases;

$$P_M \leq S_{DE}$$
(5)

Where,

C_Z = Circumferential Compressive stress

F_{HA} = Allowable circumferential compressive stress

P_M = Global membrane stress

S_D = Allowable design stress

S_{DE} = Allowable design stress (Earthquake Load)

S_Y =Yield stress

S_Z = Longitudinal compressive stress

T_Z = Allowable tensile stress

Allowable design stress for earthquake load is increased by a design factor of 1.2 than normal allowable design stress as per the standard.

G. *Results and Discussion*

Finite element analysis has been carried out on LPG storage mounded bullet by incorporating all the possible loads proposed by EEMUA. The service load combination considered in analysis simulates the behavior of mounded bullet at operating condition (Fig. 7). The analysis results show that maximum equivalent stress is located in the joining region of hemispherical head with cylindrical shell for middle soft support condition (Fig. 7).

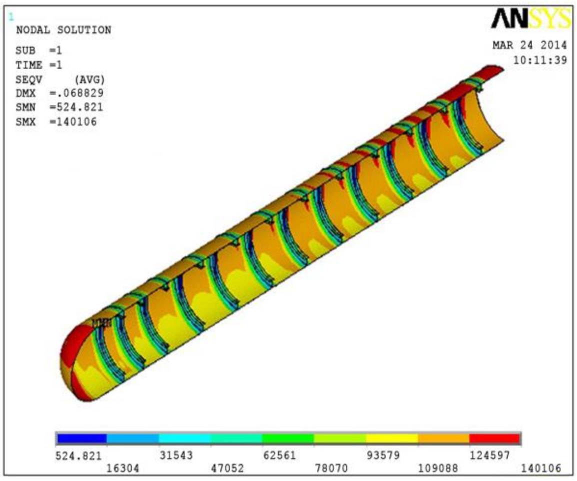

Fig. 7. von Mises stress contour - Service (Middle soft)

The hydro test load case helps to evaluate the maximum ability of the bullet against the applied hydrostatic pressure at test temperature. Fig. 8 shows the hydro test load case for middle soft support condition and Fig. 9 shows that of middle hard condition. Out of these three test cases, the highest value of equivalent stress results in hydro test. For middle hard condition highest equivalent stress is located in the middle of the bullet.

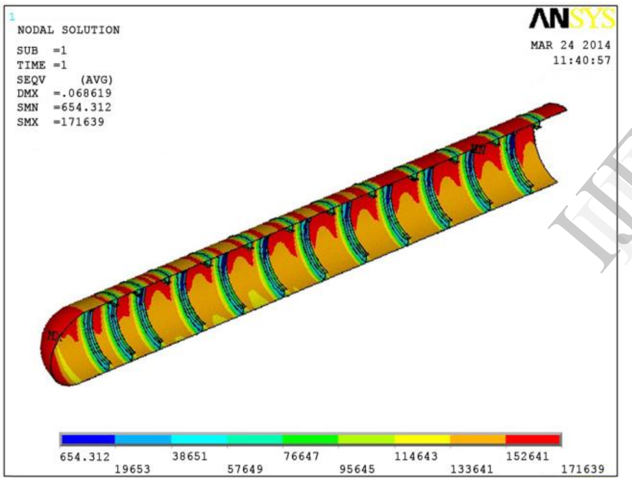

Fig. 8. von Mises stress contour - Hydro test (Middle soft)

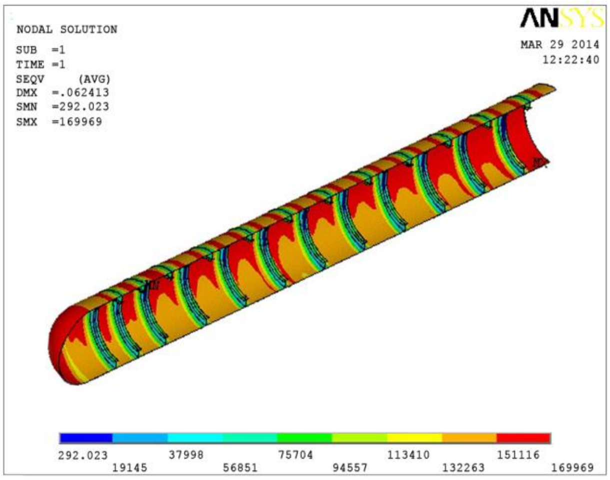

Fig. 9. von Mises stress contour - Hydro test (Middle hard)

Similar to hydro test case, service under seismic load also plays a vital role in the design of mounded bullet. Under middle soft condition dished ends are prone to failure as their exist very high load and the centre portion of the shell is the critical location for middle hard support case (Fig. 10).

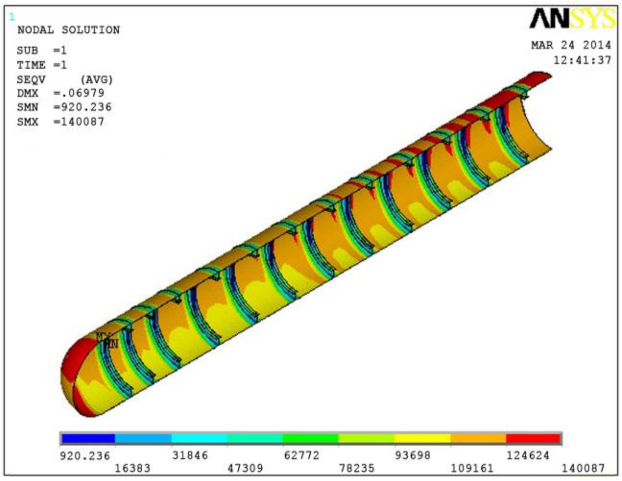

Fig. 10. von Mises stress contour - Service with Seismic load (Middle soft)

The von Mises equivalent stresses and allowable limits for service condition, hydro test condition and service under seismic load cases are compared in Table III.

TABLE III. LIMITS OF VON MISES STRESSES (SERVICE)

Support Condition	Locations	FEM (kN/m^2)	Allowable Design Stress, S_D (kN/m^2)	Allowable Stress, 1.5S_D (kN/m^2)
Middle Soft	Full	140106	146855	220282
	Shell	137855	146855	220282
	D'end	140106	146855	220282
Middle Hard	Full	140627	146855	220282
	Shell	140627	146855	220282
	D'end	140166	146855	220282

TABLE IV. LIMITS OF VON MISES STRESSES (HYDRO TEST)

Support Condition	Locations	FEM (kN/m2)	Yield Stress, SY (kN/m2)	Design Allowable Stress, 0.95*SY (kN/m2)
Middle Soft	Full	171639	220630	209599
	Shell	170042	220630	209599
	D'end	171639	220630	209599
Middle Hard	Full	169969	220630	209599
	Shell	169969	220630	209599
	D'end	169275	220630	209599

TABLE V. LIMITS OF VON MISES STRESSES (SERVICE EARTHQUAKE)

Support Condition	**Locations**	**FEM (kN/m^2)**	**Allowable Design Stress (Earthquake Load), S_{DE} (kN/m^2)**	**Allowable Stress, $1.5S_{DE}$ (kN/m^2)**
Middle Soft	Full	140087	176226	264338
	Shell	138095	176266	264338
	D'end	140087	176226	264338
Middle Hard	Full	141133	176226	264338
	Shell	141133	176266	264338
	D'end	140166	176226	264338

Analysis results show that the von Mises equivalent stress is higher in hydro test load combination under middle soft support condition. Hydro test load case is the critical load combination for a mounded bullet. For all load combinations the circumferential compressive stresses and longitudinal tensile stresses falls under the allowable limits specified by ASME BPVC Section VII Division 2.

The analysis results for the Dome 2 and Manhole shows that the maximum stress results in the nozzle to shell junction. The maximum von Mises equivalent stress due to internal pressure including normal liquid level on Dome 2 and manhole of LPG mounded bullet are within those allowable stresses as per ASME Section VIII, Division Part 5 - Design by analysis requirements. The equivalent von Mises stress contour for the Dome 2 and Manhole is shown in Fig. 11 and the finite element results with permissible stress limits are compared in Table VI.

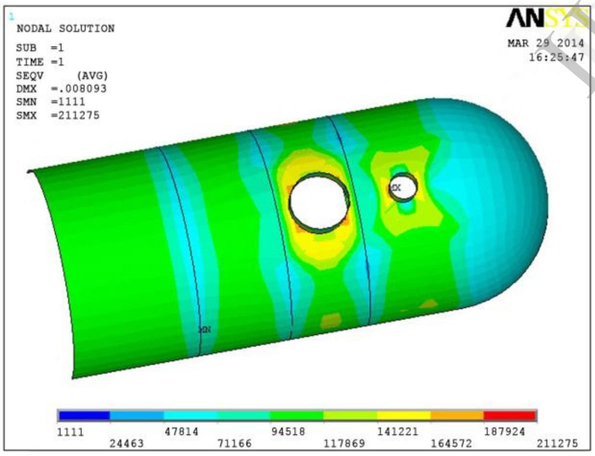

Fig. 11. von Mises stress contour of nozzles

TABLE VI. LIMITS OF VON MISES STRESS FOR NOZZLES

TABLE VII.

Load Condition	**FEM (kN/m^2)**	**Allowable Design Stress, S_D (kN/m^2)**	**Allowable Stress,$1.5S_D$ (kN/m^2)**
Design internal pressure including normal liquid level	214341	146855	220282

IV. CONCLUSION

For the mounded bullet design, ASME BPVC Section VIII, Division 2, design by analysis method is valid even with considering all load combinations. The middle soft foundation mode condition is more critical than middle hard mode. So construction of mound from middle to ends of the bullet is safer and preferred. Hydro test is the critical load case among service and earthquake load combinations.

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