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Numerical study on the dynamic response of a massive liquefied natural gas outer tank under impact loading

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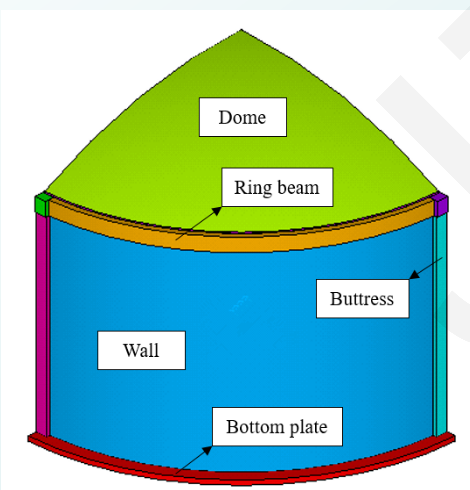
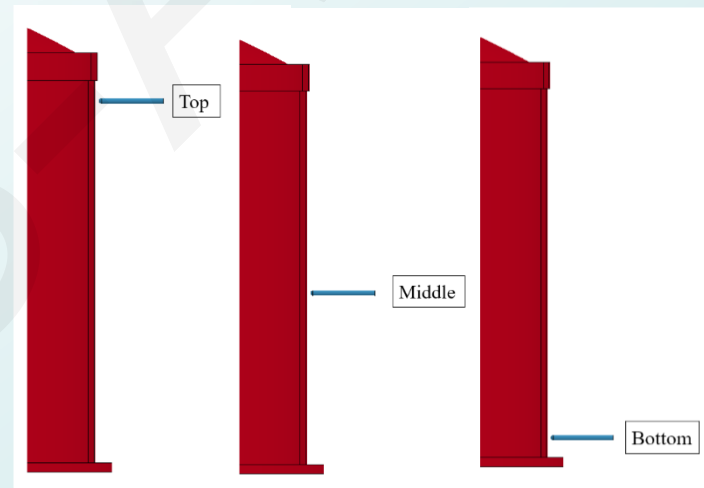
Finite element model

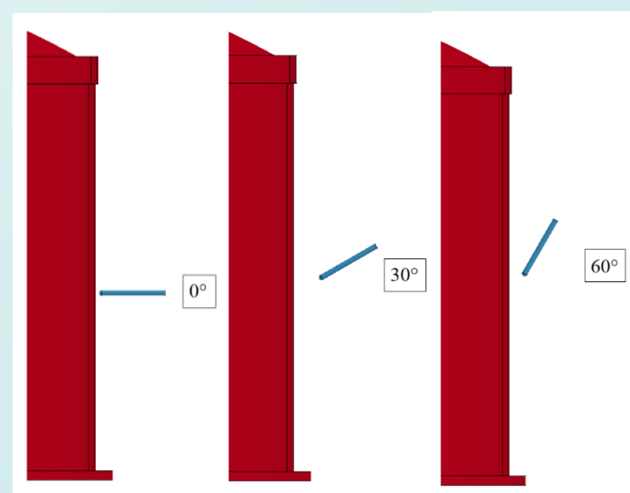
LNG tank



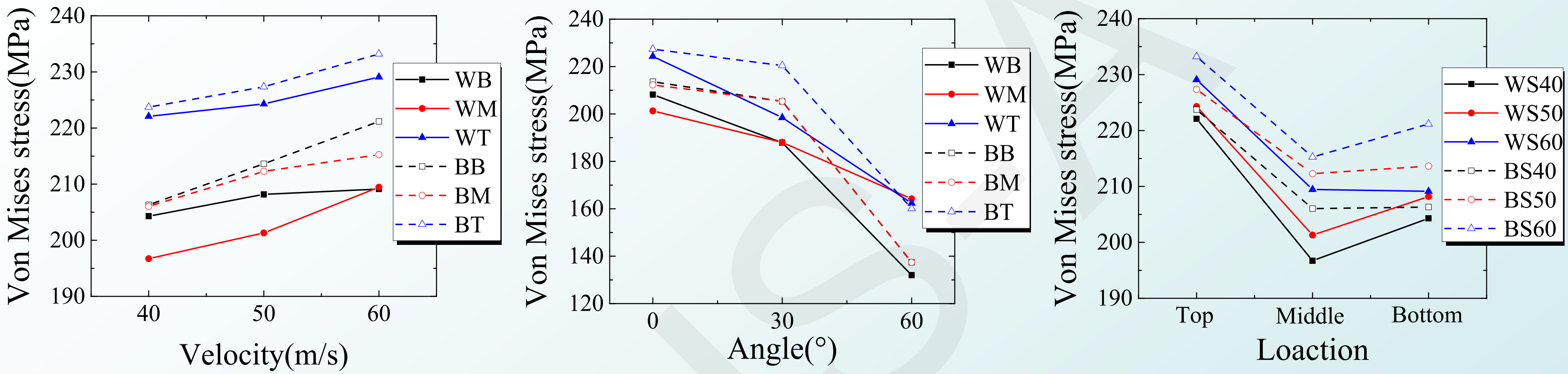
Working condition

- Location: wall — top, middle and bottom; buttress — top, middle and bottom
- Velocity: 40, 50 and 60 m/s
- Angle: 0°, 30° and 60°





Dynamic Response Analysis



Stress-velocity, angle and location curve

Displacement and stress sweep range under different impact velocity and angle (unit: m)

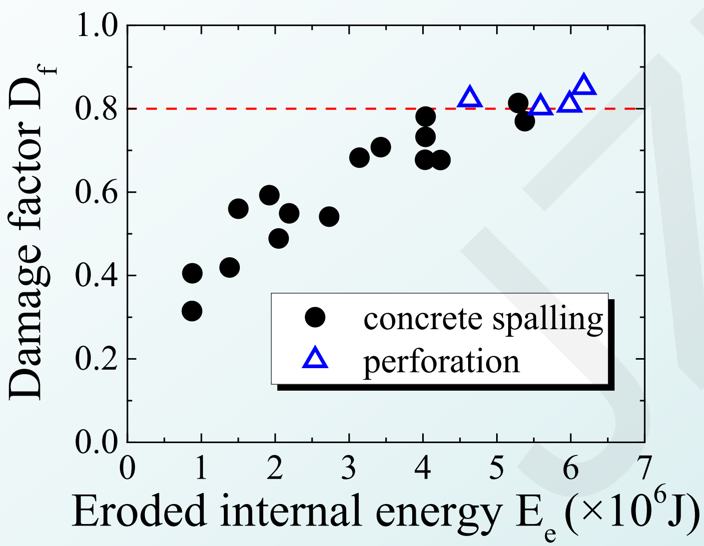
Impact cases		MD	SR	MD	SR	MD	SR	MD	SR	MD	SR	MD	SR
		Impact location											
		WB		WM		WT		BB		BM		BT	
Velocity (m/s)	40	0.054	0.367	0.054	0.393	0.052	0.361	0.046	0.400	0.050	0.424	0.047	0.392
	50	0.066	0.500	0.066	0.583	0.065	0.500	0.058	0.566	0.062	0.566	0.059	0.533
	60	0.080	0.640	0.080	0.640	0.078	0.640	0.069	0.603	0.073	0.640	0.070	0.603
Angle (°)	0	0.066	0.500	0.066	0.583	0.065	0.500	0.058	0.566	0.062	0.566	0.059	0.533
	30	0.041	0.424	0.041	0.500	0.042	0.424	0.043	0.500	0.041	0.495	0.038	0.500
	60	0.016	0.283	0.016	0.361	0.016	0.283	0.018	0.300	0.013	0.241	0.017	0.241

Note: MD means maximum displacement of the nodal and SR means stress sweep range.

Classification of impact damage

The detail of damage classification under Tomahawk cruise missile

Damage types	Velocity for dome（m/s）	Velocity for wall（m/s）	Failure characteristics
local distortion	0-75	0-66	Element distortion, no failure
concrete spalling	75-127	66-147	Element fails, the failure range is spreading with the velocity is increasing
penetration	127-	147-	The missile penetrates



Damage factor distribution

The parameter is defined as the damage factor (D_f). The equation for calculating the damage factor is:

$$D_f = \frac{E_e}{E_t}$$

When $D_f = 0$, there is no eroded internal energy. In this situation, the damage type will be local distortion. When $0 < D_f \leq 0.8$, the damage type will be concrete spalling. When $D_f > 0.8$, the damage type will be perforation.

Empirical formulas

Empirical formulas

Formulas	Scabbing thickness	Perforation thickness
DOE-Standard	$t_s = 1.84\left(\frac{U}{V}\right)^{0.13}\frac{(MV^2)^{0.4}}{D^{0.2}(f_c')^{0.4}}$	$t_p = \left(\frac{U}{V}\right)^{0.25}\left(\frac{MV^2}{Df_c'}\right)^{0.5}$
CEA-EDF	-	$t_p = 0.82(f_c')^{-\frac{3}{8}}\rho^{-\frac{1}{8}}\left(\frac{M}{D}\right)^{\frac{1}{2}}V^{\frac{3}{4}}$
Bechtel	$t_s = \frac{38.62}{\sqrt{f_c'}}\left(\frac{M^{0.4}V^{0.5}}{D^{0.2}}\right)$	-
CRIEPI	$t_s = 1.75\left(\frac{V_0}{V}\right)^{0.13}\frac{(MV^2)^{0.4}}{D^{0.2}(f_c')^{0.4}}$	$t_p = 0.90\left(\frac{V_0}{V}\right)^{0.25}\left(\frac{MV^2}{Df_c'}\right)^{0.5}$

Comparisons of empirical and numerical results

Impact cases	Perforation velocity (m/s)	Numerical results t_{pn} (m)	Empirical results t_{pe} (m)		
			DOE-Standard	CEA-EDF	CRIEPI
TC for dome	127	0.500	0.983	0.946	0.885
TC for wall	147	0.667	1.097	1.056	0.988
KD for dome	111	0.500	0.867	0.834	0.780

- For checking the LNG outer tank under impact loading and simulating the minimum thickness of the outer tank, four empirical formulas are given in the DOE-Standard
- t_{pe} is larger than t_{pn} no matter which formula is used. It means that using empirical formulas to calculate the perforation thickness is safer than numerical results.
- It is also noted that the DOE-Standard formula is the safest.

Conclusion

- **The most unfavorable impact location is the top part of the wall, followed by the bottom part of the wall, especially the connection between the wall and the ring beam and the connection between the wall and the bottom plate.**
- **Numerical simulation results showed that the LNG outer tank had three damage types, i.e., local distortion, concrete spalling and perforation. The critical velocities to distinguish these three damage types were also defined.**
- **For the general situation, a method to predict which damage type will happen is to use the damage factor (D_f). When $D_f = 0$, the damage type will be local distortion. When $0 < D_f \leq 0.8$, the damage type will be concrete spalling. When $D_f > 0.8$, the damage type will be perforation.**
- **By using empirical formulas, the tank could accept the impact suggested by the British standard and the flange cited from the reference. Comparing numerical results with empirical results revealed that empirical results are conservative under the same projectile perforation velocity. From the three formulas, DOE-Standard formula provided the most conservative prediction.**