2016 International Perforating Symposium (IPS) IPS-16-39

Plastic Collapse Behaviors of Perforating Guns with Scallops

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Outline

I. Introduction to Perforating Gun and Conveyance Systems

II. Ultimate Collapse Strength for Recessed Tubulars

III. Finite Element Analysis (FEA) and Test Validation

IV. Conclusions and Future Work

I. Introduction to Perforating Gun and Conveyance Systems

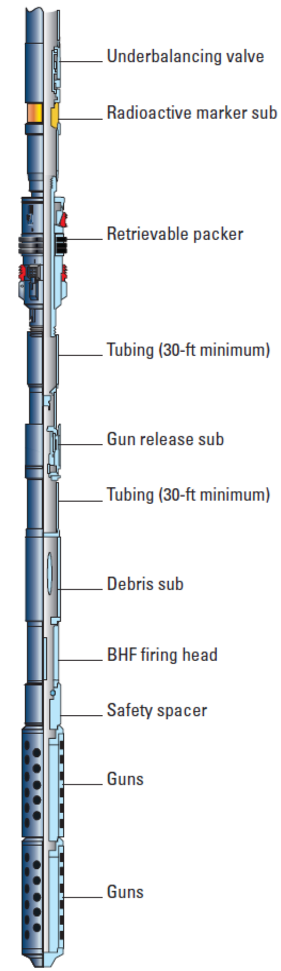
Perforating Gun and Conveyance Systems

Wireline

Tubing-Conveyed Perforating (TCP): Completions and Drillstem testing

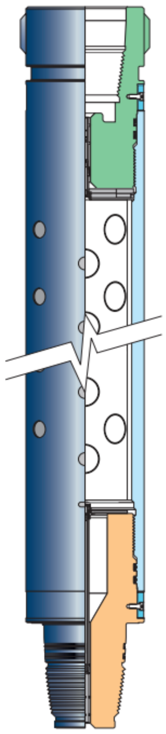
Slickline

Coiled Tubing

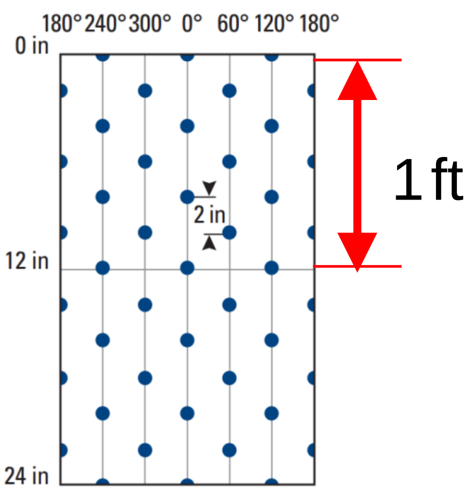


Open-string TCP system

Density and Phasing



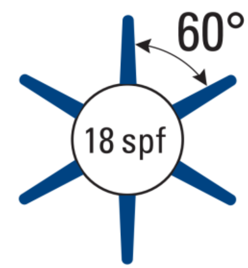
Density



18 spf, 120°/60° Phasing

Number of shots per foot (spf)

Phasing



360°/ 6 =60° phasing

Distance (in degrees) between charges

II. Ultimate Collapse Strength for Recessed Tubulars

Review: Collapse Strength of a Slick Pipe

- **Lamé Thick Wall Yield Collapse Formula** (Yield at Pipe ID)

Open Ends $$P_{Lc} = \sigma_y \frac{D_o^2 - D_i^2}{2D_o^2}$$

Closed Ends $$P_{Lc} = \sigma_y \frac{D_o^2 - D_i^2}{\sqrt{3}D_o^2}$$

$$D_o = D$$
$$t = \frac{1}{2}(D_o - D_i)$$
$$k = D/t$$

$$P_{Lc} = 2\sigma_y \cdot \frac{(k-1)}{k^2}$$
$$P_{Lc} = 2.31 \cdot \sigma_y \cdot \frac{(k-1)}{k^2}$$

- **API Bulletin 5C3**

Yield Collapse	Plastic Collapse	Transition Collapse	Elastic Collapse
$P_{Ys} = 2\sigma_y \cdot \frac{(k-1)}{k^2}$	$P_P = \sigma_y \left[\frac{A}{k} - B\right] - C$	$P_T = \sigma_y \left[\frac{F}{k} - G\right]$	$P_{TE} = \frac{2E}{1-\nu^2} \cdot \frac{1}{k(k-1)^2}$

- **Tamano Ultimate Collapse Equation** (SPE 48331)

$$P_T = \frac{1}{2}(P_E + P_Y) - \sqrt{\frac{1}{4}(P_E - P_Y)^2 + P_E P_Y H}$$

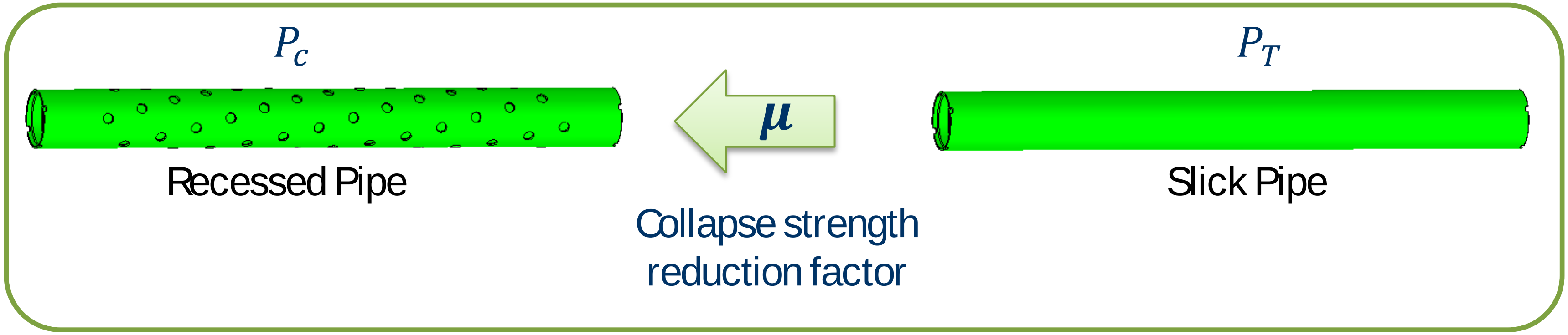
$$\begin{cases} P_E = 1.08 \times \frac{2E}{1-\nu^2} \cdot \frac{1}{k(k-1)^2} \\ P_Y = 2\sigma_y \cdot \frac{k-1}{k^2}\left[1 + \frac{1.5}{k-1}\right] \\ H = 0.071 \cdot u(\%) + 0.0022 \cdot e(\%) - 0.18 \cdot \frac{\sigma_r}{\sigma_y} \end{cases}$$

Ultimate Collapse Strength of Scalloped Gun Carriers

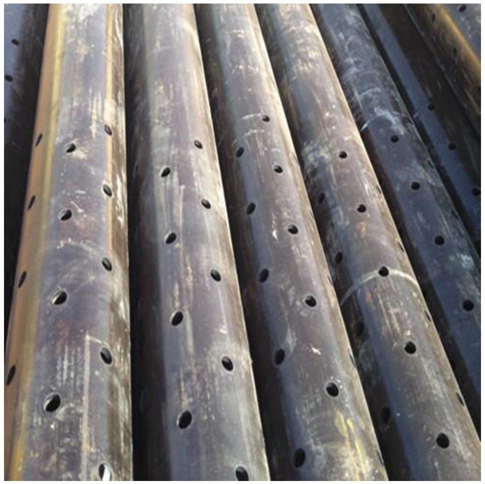
Definition

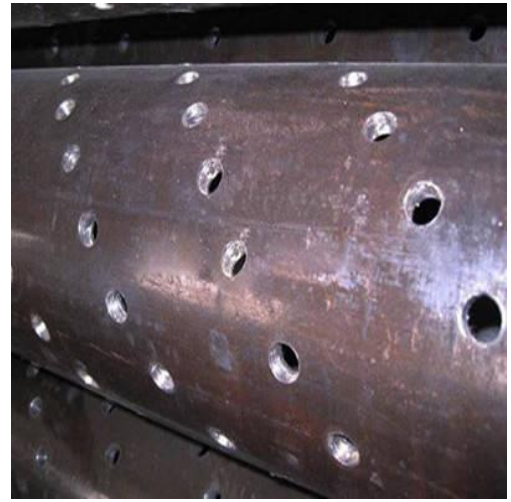
$$P_c = \mu \cdot P_T$$

μ – Collapse strength reduction factor due to scallops
P_T – Tamano ultimate collapse strength equation

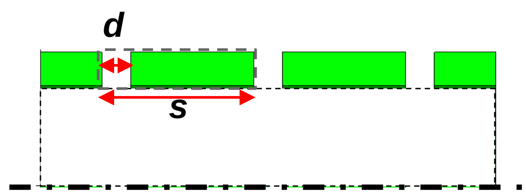


Reference: Collapse Strength of Perforated Casing

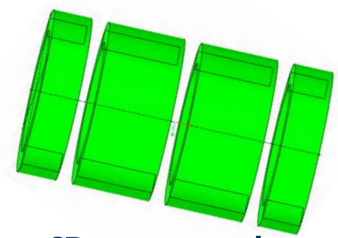




$$\mu_0 = 1 - \frac{d}{S}$$



Cross-section view

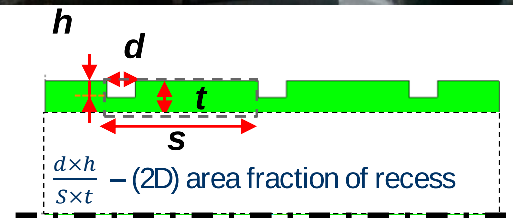


3D representation

d/S – (1D) spacing fraction of recess

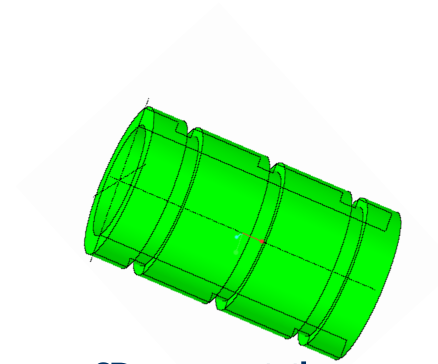
Reference: SPE 51188

μ for Scalloped Gun Carriers

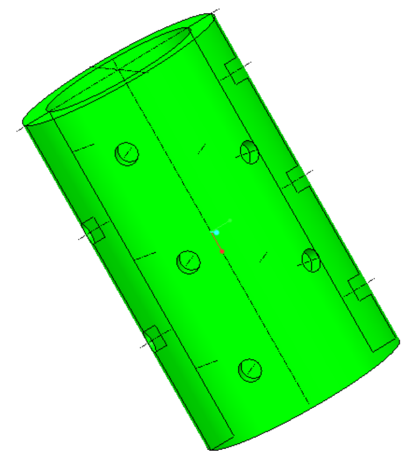


$\frac{d \times h}{S \times t}$ – (2D) area fraction of recess

Cross-section view



3D representation



1. $\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$
2. $\mu_2 = 1 - f_r$
3. $\mu_3 = 1 - \alpha f_r$

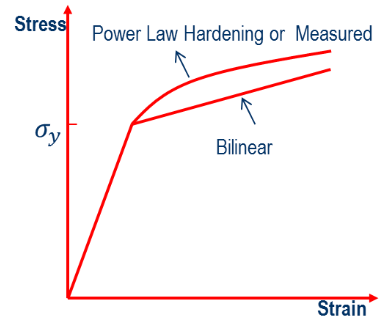
f_r – (3D) volume fraction of recess
α – fitting factor

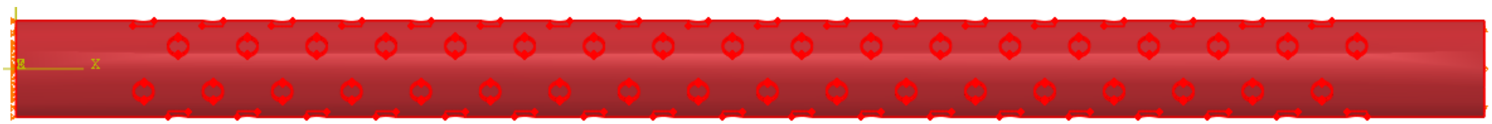
III. FEA and Test Validation

Modeling Approach

Description

- Nonlinear post-buckling analysis using Riks method based on arc length scheme in ABAQUS
- Material model: isotropic hardening plasticity with bilinear, power law or measured stress-strain curve
- Boundary conditions: external pressure prescribed on the exterior surface with end connection supported

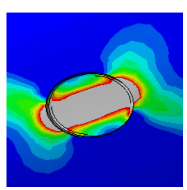




Collapse Criteria

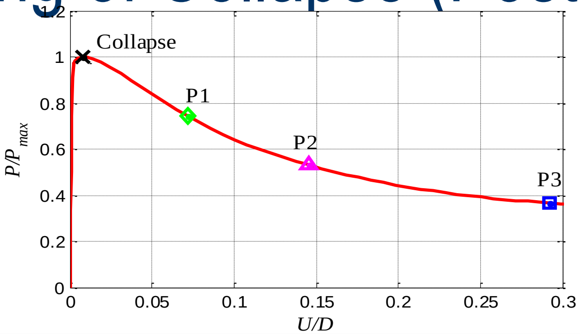
- When the collapse pressure is reached, the structure will deform dramatically and lose pressure-bearing capacity.

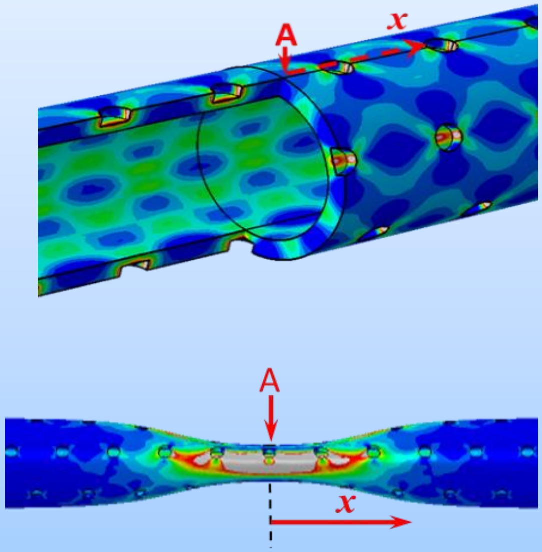
Local Yielding

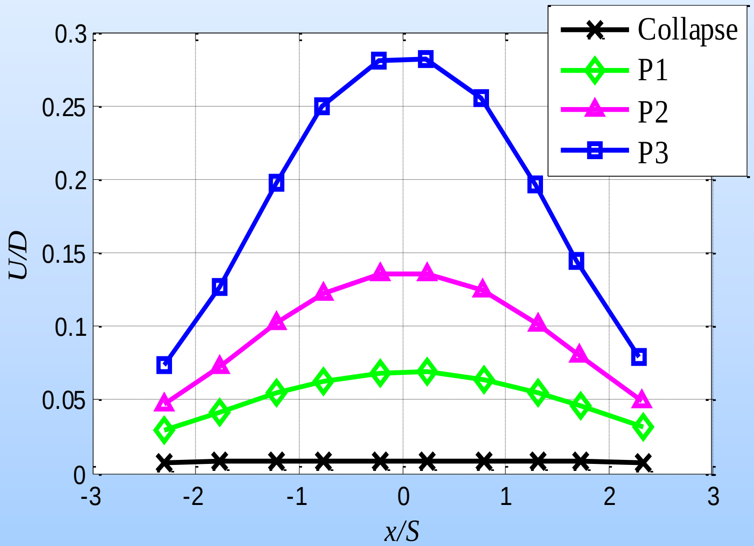


Physical Understanding of Collapse (Post-buckling)

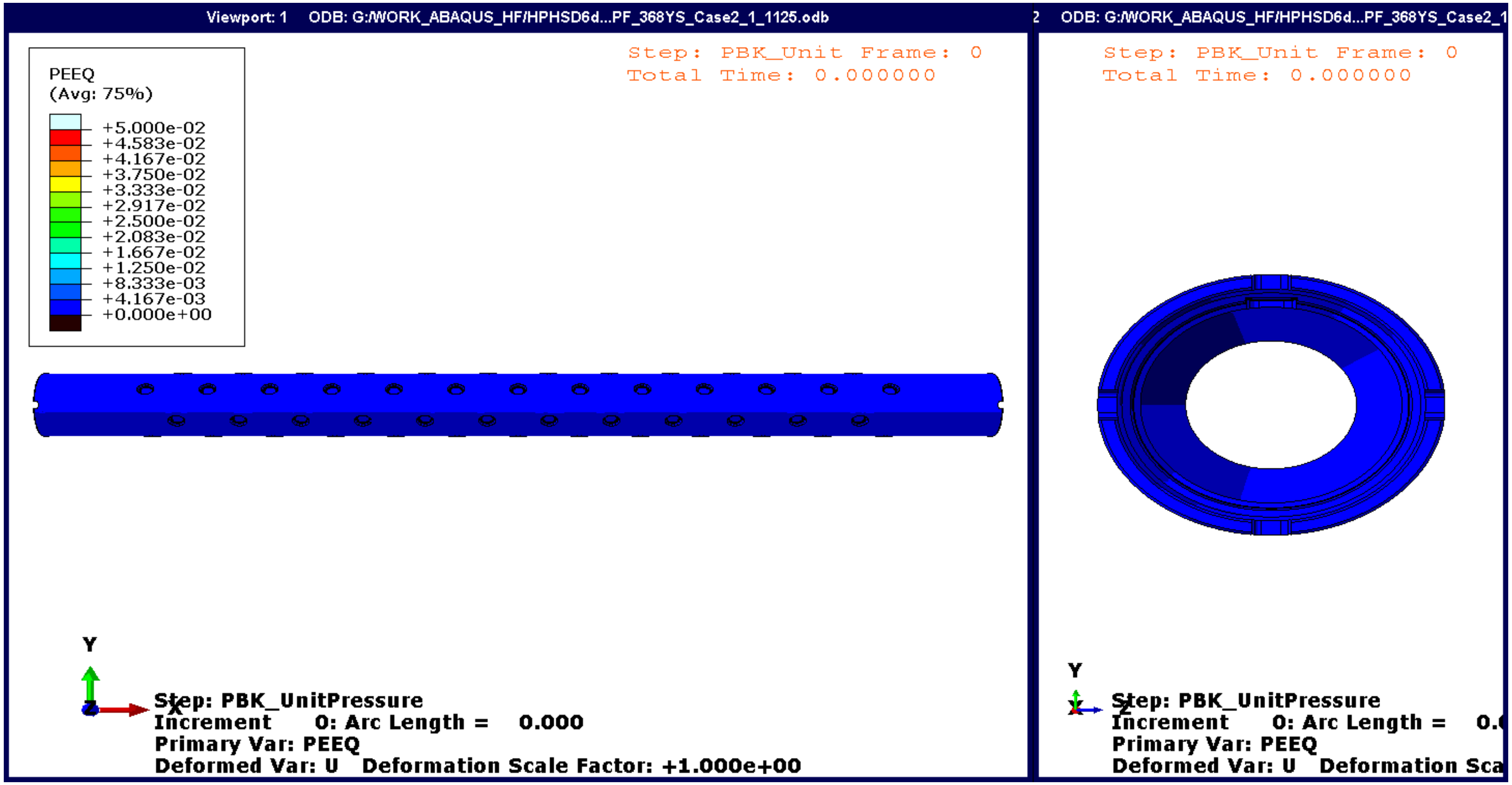
Collapse pressure definition







Example: Collapse Animation of 15SPF 5 FT



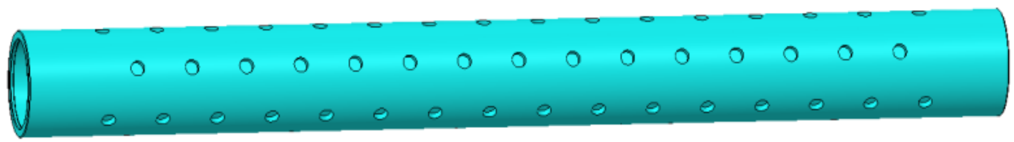
Deformation Scale Factor = 1

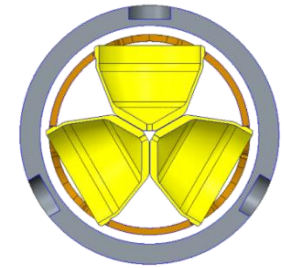
Test Validation of FEA

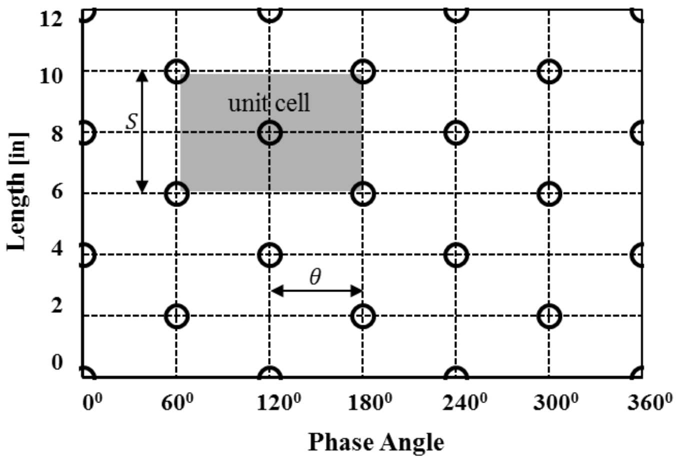
Description	Test Temp [Deg F]	D/t	Tested Collapse Pressure [psi]	FEA $P_{collapse}$ [psi]	Difference with Tests [%]
Test 1	368	9.4	32,250	30,660	**-4.9%**
Test 2	318	10.7	22,500	22,831	**+1.5%**
Test 3	250	10.7	24,263	23,651	**-2.5%**
Test 4	250	14.0	18,329	18,633	**+1.7%**
Test 5	400	11.6	22,745	23,311	**+2.4%**

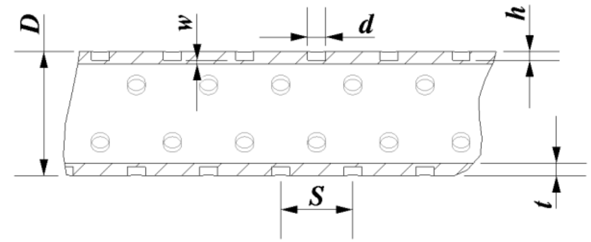
Note:
- Detailed geometric, product name and material parameters are confidential.
- Stress/strain data utilized in the FEA analyses is full measured data from a test

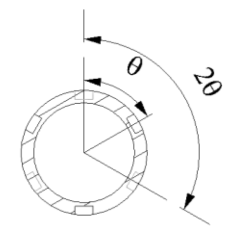
Case Study: μ_2 Expression











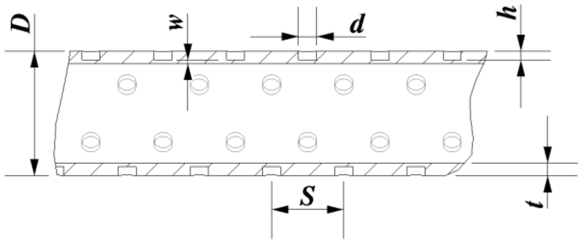
$$f_r = V_s / V_u$$

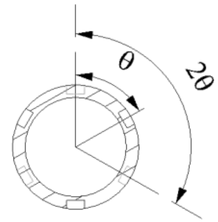
$$V_u = S \times \frac{\pi}{180} \theta D \times t$$

$$V_s = 2 \times \frac{1}{4} \pi d^2 h$$

$$\mu_2 = 1 - f_r = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

Case Study: Parametric Study of 7-in OD, 5-ft Length Carrier





Angular Phasing, θ

D [in]	t [in]	θ [deg]	S [in]	h [in]	d [in]
7	0.7	25.7 36 45 60 90	4.0	0.5	1.0

Wall Thickness, *t*

D [in]	t [in]	θ [deg]	S [in]	w [in]	d [in]
7	0.5 0.7 1.0	60	4.0	0.2	1.0

Scallop Depth, *h*

D [in]	t [in]	θ [deg]	S [in]	h [in]	d [in]
7	0.7	60	4.0	0.3 0.4 0.5 0.6	1.0

Longitudinal Spacing, *S*

D [in]	t [in]	θ [deg]	S [in]	h [in]	d [in]
7	0.7	60	4.0 6.0 8.0 12.0 16.0	0.5	1.0

Definition of "true" μ

$$\mu_{\text{FEA}} = P^{\text{FEA}}_{\text{scallop}} / P^{\text{FEA}}_{\text{pipe}}$$

Dimension of slick pipes

D [in]	t [in]
7	0.5 0.7 1.0

Scallop Diameter, *d*

D [in]	t [in]	θ [deg]	S [in]	h [in]	d [in]
7	0.7	60	4.0	0.5	0.7 1.0 1.3

Sensitivity Study of Collapse Strength Reduction Factor

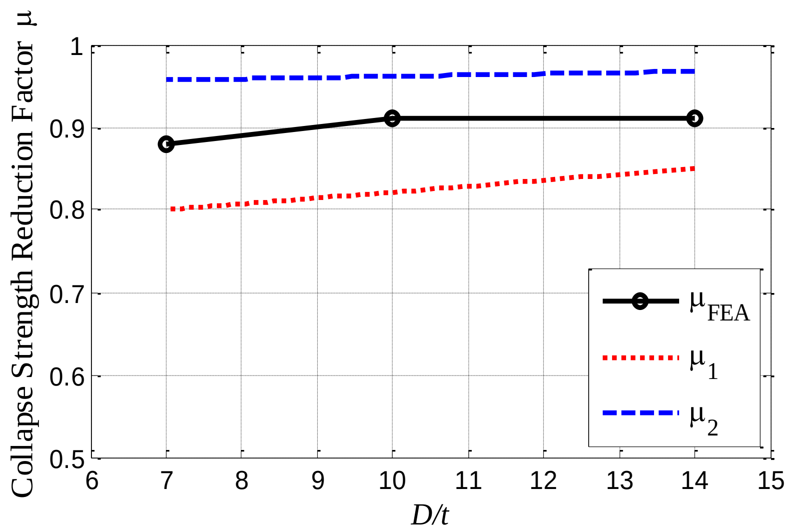
$$\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$$

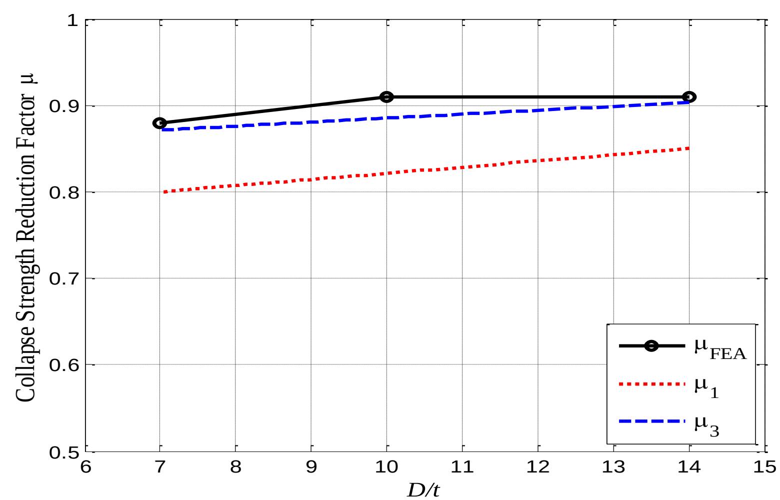
$$\mu_2 = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_3 = 1 - 3 \cdot 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_{\mathrm{FEA}} = P_{\mathrm{scallop}}^{\mathrm{FEA}} / P_{\mathrm{pipe}}^{\mathrm{FEA}}$$

[1] D/t vs. μ





Collapse strength reduction factor μ is linearly proportional to D/t ratio.

Sensitivity Study of Collapse Strength Reduction Factor

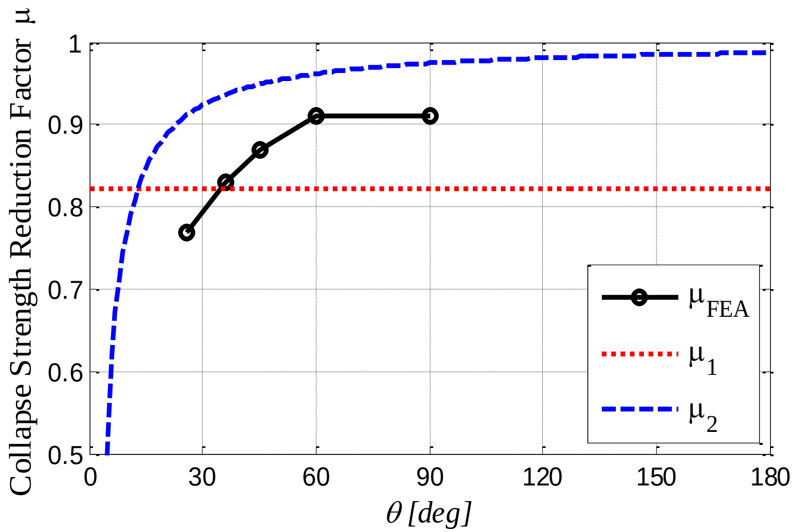
$$\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$$

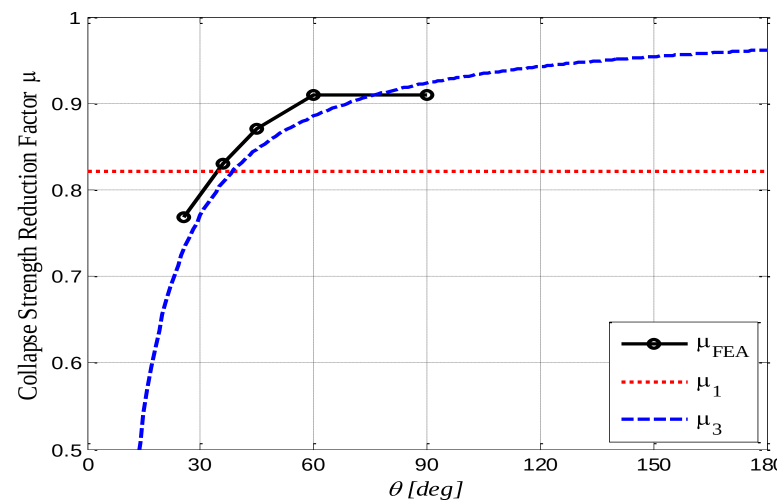
$$\mu_2 = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_3 = 1 - 3 \cdot 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_{\text{FEA}} = P_{\text{scallop}}^{\text{FEA}} / P_{\text{pipe}}^{\text{FEA}}$$

[2] θ vs. μ





Collapse strength reduction factor μ is inversely proportional to θ.

Sensitivity Study of Collapse Strength Reduction Factor

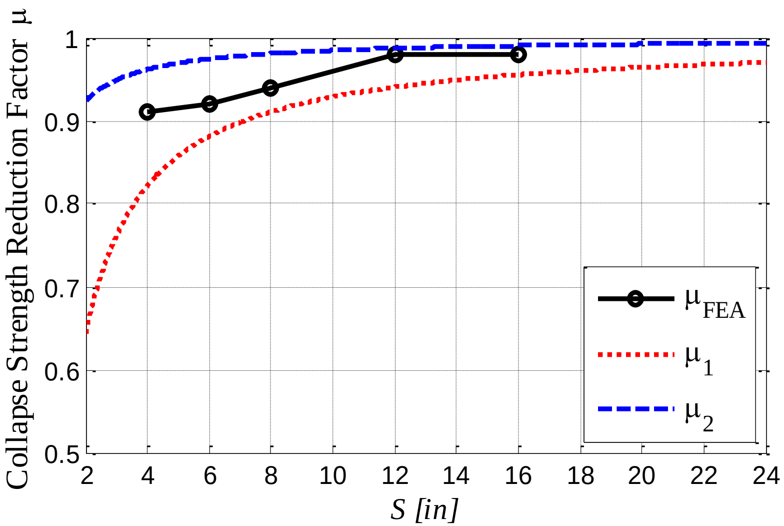
$$\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$$

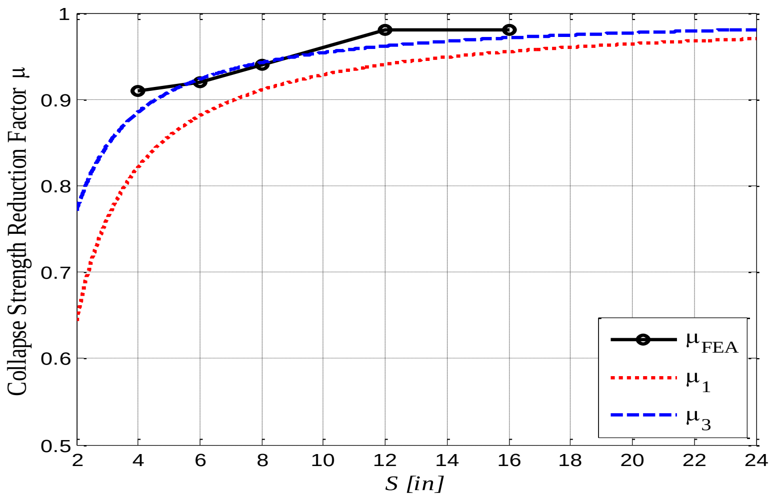
$$\mu_2 = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_3 = 1 - 3 \cdot 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_{\mathrm{FEA}} = P_{\mathrm{scallop}}^{\mathrm{FEA}} / P_{\mathrm{pipe}}^{\mathrm{FEA}}$$

[3] S vs. μ





Collapse strength reduction factor μ is inversely proportional to S.

Sensitivity Study of Collapse Strength Reduction Factor

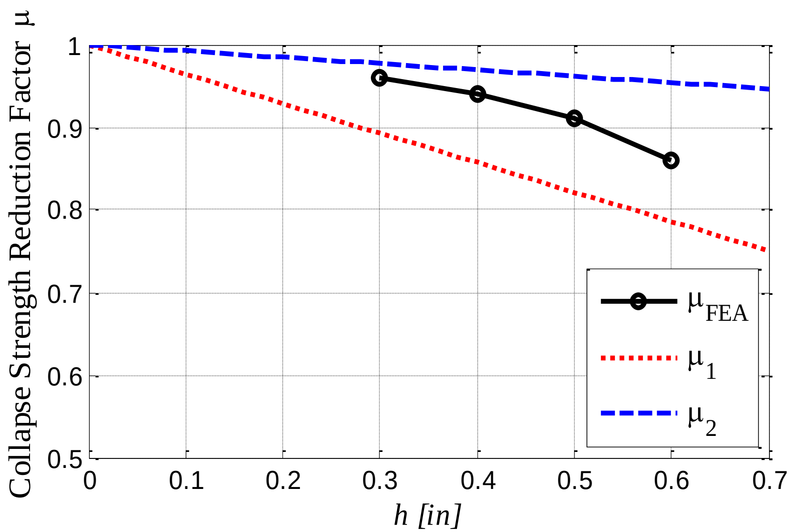
$$\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$$

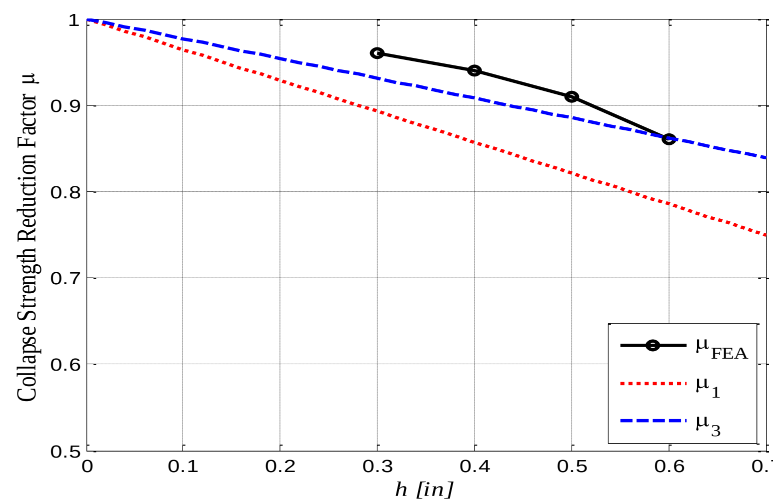
$$\mu_2 = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_3 = 1 - 3 \cdot 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_{\text{FEA}} = P_{\text{scallop}}^{\text{FEA}} / P_{\text{pipe}}^{\text{FEA}}$$

[4] h vs. μ





Collapse strength reduction factor μ is "linearly" proportional to *h*.

Sensitivity Study of Collapse Strength Reduction Factor

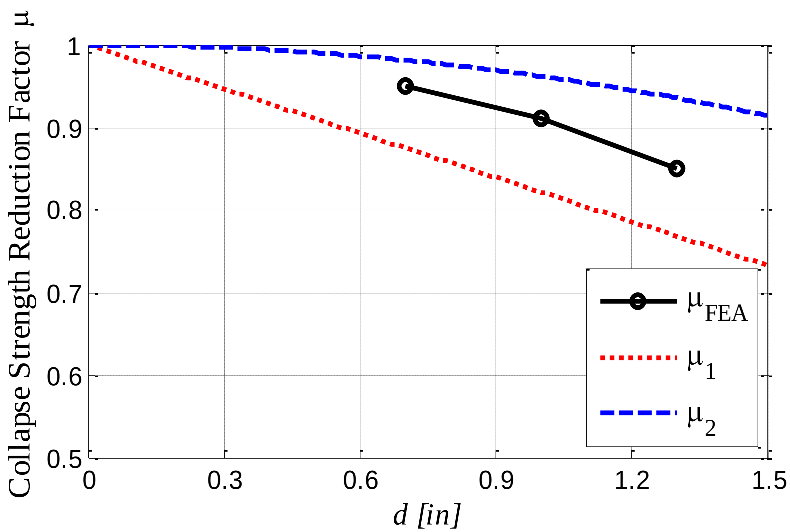
$$\mu_1 = 1 - \frac{d}{S} \cdot \frac{h}{t}$$

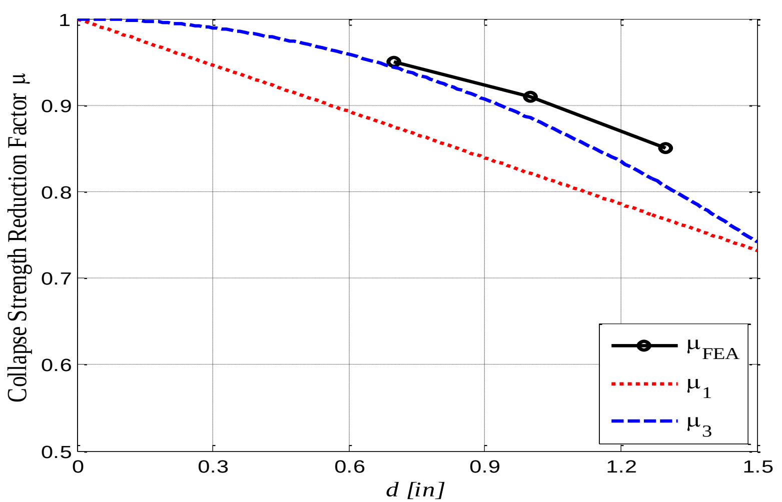
$$\mu_2 = 1 - 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_3 = 1 - 3 \cdot 90 \cdot \frac{d^2}{SD\theta} \cdot \frac{h}{t}$$

$$\mu_{\mathrm{FEA}} = P_{\mathrm{scallop}}^{\mathrm{FEA}} / P_{\mathrm{pipe}}^{\mathrm{FEA}}$$

[5] d vs. μ





Collapse strength reduction factor μ is a quadratic function of *d*.

IV. Conclusions and Future Work

Conclusions and Future Work

- An analytical collapse strength equation based on Tamano formula was proposed for scalloped perforating guns.
- The proposed equation was thoroughly validated with the aid of FEA in a multivariable parametric space – an analysis hardly affordable with the use of physical tests.
- An FEA method used to validate the proposed equation showed strong agreement with the test data giving collapse predictions for scalloped tubulars within 5% of the test results.
- The method applied to scalloped perforating guns can also be used for any tubulars with patterned cutouts or recesses, such as prepacked sand screens, perforated or slotted liners, etc.

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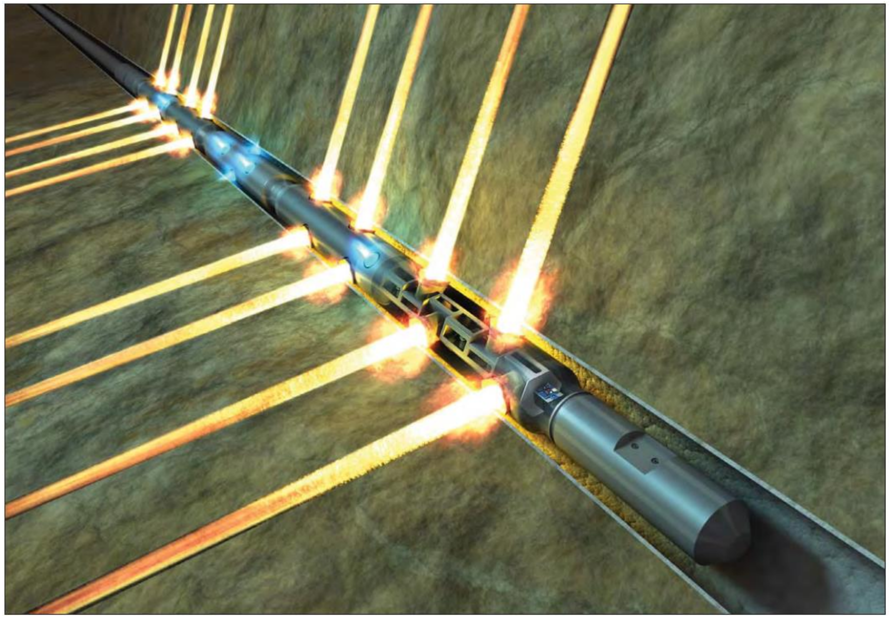
Questions?



Publications

- Zhao, H., Iblings, D., Barykin, A., and Mehdi, M., 2015, Plastic Collapse Behaviors of Tubulars with Recess Patterns, Proceedings of ASME International Mechanical Engineering Congress & Exposition, IMECE2015-50204, Houston, TX.
- Zhao, H., Iblings, D., Barykin, A., and Mehdi, M., 2016, Plastic Collapse Behaviors of Tubulars with Recess Patterns, ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering , Accepted.