1 Numerical and theoretical analysis of burst pressures for casings 2 with eccentric wear

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7 **Abstract:** With the development of multilateral and extended-reach wells, trajectories
8 of wellbores are becoming more complicated, and operating conditions are extending
9 to higher temperatures and higher pressures. For safe down-hole operations, accurate
10 predictions of casing burst strength are crucial. Based on the elastic–plastic theory for
11 large deformations, we propose a three-dimensional finite element model (FEM) for
12 predicting the burst pressure of a pipe having geometric eccentricity. Using the cross-
13 sectional shape, we divide eccentric casings into two types: crescent-shaped and
14 eccentric cylinder; then, we verify the accuracy and reliability of FEM results by
15 comparing them to a series of full-scale experimental data. To estimate burst pressure,
16 we derive a modified theoretical equation for eccentric pipes. Finally, we discuss how
17 burst pressure is affected by wear radius and pipe eccentricity. Our results show that
18 eccentricity has important effects on burst strength, whereas effects of wear radius are
19 small. Our modified theoretical equation provides results that are consistent with
20 experimental data published by others; moreover, the equation is more accurate and
21 extends over a wider range of applications than previous equations. The FEM
22 approach and the modified theoretical equation presented in this study are appropriate
23 for predicting the burst pressures of pipes employed in the oil and gas industries.

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24 **Keywords:** eccentric casing; burst strength; wear; thickness-to-diameter ratio; finite
25 element method

26 **1. Introduction**

27 In the oil and gas industry, casings are widely used as protective conduits during
28 all phases of drilling operations and production. As the requirement for deep wells and
29 wider applications of multilateral and extended-reach wells continue to increase,
30 trajectories of wellbores are becoming more complicated and operating conditions are
31 becoming harsher. Consequently, problems due to casing wear are becoming more
32 prominent. For example, the integrity of casings is threatened in wellbores at high
33 temperatures and high pressures. Therefore, in integrity analyses, accurate predictions
34 of burst strength are crucial; burst strength is the minimum internal pressure that can
35 cause burst failure of a steel casing.

36 The two modes of casing burst failures are ductile instability and brittle fracture,
37 and a simple criterion for distinguishing between them has been proposed by Tallin et
38 al. [1]. Because of improved manufacturing processes and strengthened materials, a
39 ductile burst failure is more likely than a brittle fracture. Brittle fractures rarely occur
40 in practice; however, they can be induced when the environment is filled with active
41 gases such as H₂S. Early work on the burst strength of casings under internal pressure
42 can be traced back to Hill [2]. In recent years, Klever [3] developed an analytical

43 model based on the von Mises yield criterion and contributed a predictive equation for
44 the burst strength of regular casings. The model was further modified by the Tresca
45 yield criterion by Stewart et al. [4]. Chen et al. [5-6] proposed an analytical method
46 for burst pressure of eccentric worn casing. However, it is difficult to accurately
47 predict the casing burst pressure caused by geometric imperfections (eccentricity and
48 ovality) [7], which may lower the actual casing burst pressure. Furthermore, a casing
49 burst under excessive internal pressure is an elastic-plastic large-deformation problem
50 and a local three-dimensional process. These complex nonlinear phenomena are
51 difficult to simulate accurately. For this study, a three-dimensional elastic-plastic
52 finite element model was used to simulate these processes, and preburst states were
53 clearly observed. A modified theoretical equation and experimental data were used to
54 explore burst strengths of different casings, with and without eccentricities, and to
55 study the effects of wear radius and eccentricity.

56 **2. Geometrical imperfections**

57 In this study, geometrical imperfections mainly refer to eccentricity. During
58 manufacturing, casings occasionally acquire an initial eccentricity [7]. During
59 operations, the continuous reciprocating or rotational movement of the drill pipe can
60 cause casings to wear in the radial and axial directions [8]. Furthermore, dogleg and
61 horizontal wells can increase wear on casings. Based on cross-sectional shapes, most

casings can be divided into two categories: those with uniform-wear cross sections and those with eccentric-wear cross sections. This study focuses on the latter. There are two common models for eccentric-wear casings: the *crescent-shaped* model (**Fig. 1(a)**), which is formed by drill pipes wearing on one side of the casing, and the *eccentric cylinder* model (**Fig. 1(b)**), which is primarily formed by irregular wear on the casing inner wall.

In the crescent-shaped model (**Fig. 1(a)** $R_1 < R$ and $\delta \neq 0$), the eccentricity ratio η can be defined as the ratio of the wall thickness at the point of maximum wear to the original wall thickness,

$$\eta = \frac{R_1 + \delta - R}{t}, \quad (1)$$

where R_1 is the radius of eccentric wear, δ is the distance between the casing centre O and O_1 , R is the radius of the inner wall and t is the original wall thickness of the casing.

In the eccentric cylinder model (**Fig. 1(b)** $R_1 > R$ and $\delta \neq 0$), the eccentricity ratio η can be defined by

$$\eta = \frac{t_{\max} - t_{\min}}{t_{\max} + t_{\min}}, \quad (2)$$

where $t_{\max}$ is the maximum wall thickness and $t_{\min}$ is the minimum wall thickness.

Equation (2) can be simplified to

$$\eta = \frac{\delta}{t}, \quad (3)$$

81 Where $\delta = R_1 - R = (t_{\max} - t_{\min})/2$ denotes the distance between the centre of the
 82 casing O and the centre of the worn casing O_1 , and $t = (t_{\max} + t_{\min})/2$.

83 When $R_1 > R$ and $\delta = 0$, the casing has uniform wear and the wall thickness of
 84 the casing remains the uniform after wearing. Clearly, when the minimum residual
 85 wall thickness is constant, as the wear radius increases, the cross-sectional shape of
 86 the casing sequentially progresses from the crescent-shaped model, to the eccentric
 87 cylinder model and then to the uniform-wear model.

88
 89 **Fig. 1** Models for eccentric wear on casings. (a) Crescent-shaped model and (b)
 90 eccentric cylinder model.

91 **3. Finite element analysis**

92 **3.1 Finite element modelling**

93 An eccentric-wear casing bursts under internal pressure in a three-dimensional
 94 elastic-plastic process with a large deformation failure. Concentration of stress first
 95 appears in the thinnest area of the eccentric casing. Then, yield occurs on the inner
 96 wall and gradually extends to the outer wall. Finally, a yield surface spreads over the
 97 entire wall and a burst occurs. The ABAQUS software (6.10) is capable of simulating
 98 these nonlinear processes. Therefore, ABAQUS [9] was used to perform finite

99 element analysis to investigate the ultimate burst strength of a finite, three-
100 dimensional walled casing that contained geometrical imperfections. It was assumed
101 that the deformed casing was imperfect under internal pressure and that the cross
102 section remained eccentric. **Fig. 2** shows a typical finite element model with
103 geometric imperfections. Ovality has no significant effect [7], and therefore, its
104 influence was not considered in this study. The cross section and imperfections are the
105 same along the length of the casing (seen in **Fig. 2**).

106
107 **Fig. 2** Finite element model for a casing that has geometric imperfections.

108 **3.2 Assumptions and algorithm**

109 Because of the large deformation, a casing burst is a local three-dimensional
110 process in which the material undergoes elastic and plastic stages. Therefore, in
111 modelling the process, three-dimensional materials and geometric nonlinearities need
112 to be considered. To protect casings, many intermediate casings are solidified by
113 cement, although some are used without a surrounding cement ring. The model built
114 in this study was for a casing without the surrounding cement. In practice, casings are

115 not regular tubes and do not have uniform wall thicknesses; geometric imperfections
116 are mainly elliptical or eccentric. Because ellipticity can be automatically corrected by
117 internal pressure and ovality has no significant effect [7], the influence of elliptical
118 imperfections is ignored in this study. This study mainly focused on the effects of
119 eccentric imperfections on the burst pressure of casings.

120 The three-dimensional finite element model was based on the following
121 assumptions:

- 122 1) The casing was isotropically elastoplastic and the C3D20R element (20 nodes
123 second-order reduced solid elements) was selected for calculations.
- 124 2) The casing had no surrounding cement ring and was subjected to a uniform
125 internal pressure. External pressure, axial force, bending moment and torque
126 load impact were ignored.
- 127 3) Eccentric wear and abrasion flaws along the longitudinal direction of the
128 casing were included, but other defects in the casing were ignored.
- 129 4) The influence of residual stress was ignored.
- 130 5) The temperature effect was not considered.

131 The algorithm uses a modified Riks method to adjust the quantity and direction
132 of the load while calculating displacements to reach a static balance in the unstable
133 stage of the structure. During the simulation, the internal pressure changes direction as
134 the casing deforms, although it remains perpendicular to the casing wall. The internal
135 pressure is gradually increased from zero to the burst pressure. The finite element

136 program automatically increases the internal pressure during the casing burst
137 simulation.

138 **3.3 Material response**

139 Material response is crucial to accurately predict the casing burst strength;
140 however, such a response is not always available. Therefore, generalized material
141 behaviour is necessary to study the effects of geometric factors on casing burst
142 strength. Casing burst is a large elastic and plastic deformation under internal pressure,
143 and the size of the casing changes significantly after bursting. Therefore, in this study,
144 stress-strain relations should be described using true stress and true strain rather than
145 engineering stress and engineering strain, which usually apply under the assumption
146 of small deformations and without considering any effects of changes in size. The true
147 stress-strain relationship can be expressed as [7]

$$148 \quad \sigma = K \varepsilon^n, \quad K = \left(\frac{e}{n} \right)^n \sigma_{\text{uts}}, \quad (4)$$

149 where σ is the true stress, ε is the true strain, e is a constant of nature, σ_{uts} is the
150 ultimate strength and n is the material hardening parameter, which is determined by
151 the uniaxial tensile test, $n = \ln(1 + \varepsilon_{\text{uts}})$ with ε_{uts} being the ultimate strain. In this
152 study, these true stress-strain relations were adopted in the finite element simulation
153 of the behaviour of a real casing material.

154 **4. Theoretical analysis of casing burst**

155 Since the finite element analysis is complex, it may be difficult for some
156 researchers to employ it. Alternatives to this analysis are development of analytical

157 solutions or a proper empirical equation. Under excessive internal pressure, ductile
 158 burst of a casing occurs when a yield of the entire casing cross section precedes casing
 159 failure. A ductile burst failure requires a limit state model based on the fully plastic
 160 section of a casing. As the casing load dominated by the internal pressure increases,
 161 yield of the casing body starts at the inner fibres [8]. The plastic zone continues to
 162 spread until the outer fibres of the casing yield. Experiments by Gulati [9] show that,
 163 under excessive internal pressure, the ultimate burst capacity of a casing is
 164 approximately 2%–3% larger than the yield strength of the outer fibre of the casing.
 165 Huang [7] used the yield strength of the outer fibre to represent the ultimate limit state
 166 of a casing burst. In this study, the ultimate internal fibre is used to represent the
 167 ultimate limit state of a casing burst; this assumption corresponds more closely to
 168 what happens experimentally.

169 Klever [3] and Stewart [10] proposed an equation for the burst strength of regular
 170 and worn casings; their equation is considered to be the most accurate predictive
 171 equation,

$$172 \quad P_b = \frac{2\sigma_{uts}t}{D-t} \left[\left(\frac{1}{2} \right)^{1+n} + \left(\frac{1}{\sqrt{3}} \right)^{1+n} \right], \quad (5)$$

173 where D is the nominal outside diameter, t is the nominal wall thickness and n is the
 174 material hardening parameter, which is usually considered as the strain ε_{uts}
 175 corresponding to the ultimate tensile strength σ_{uts} .

176 The ultimate tensile strength of the internal fibre can be used to represent the
 177 ultimate limit state of a casing burst. We proposed a predictive equation for eccentric
 178 casing burst strength based on the elastic-plastic theory and the Tresca criterion [6],

$$P_b = \frac{f_0 + f_1\xi + f_2\xi^2}{c_0 + c_1\xi + c_2\xi^2} \sigma_{\text{uts}}, \quad (6)$$

where $f_0 = 2\lambda - 6\lambda^2 + 8\lambda^3 - 4\lambda^4$

$$f_1 = -2\lambda + 8\lambda^2 - 12\lambda^3 + 8\lambda^4$$

$$f_2 = -2\lambda^2 + 4\lambda^3 - 4\lambda^4$$

$$c_0 = 1 - 4\lambda + 8\lambda^2 - 8\lambda^3 + 4\lambda^4$$

$$c_1 = -4\lambda^2 + 12\lambda^3 - 8\lambda^4$$

$$c_2 = -4\lambda^3 + 4\lambda^4$$

$\xi = 2\delta / t = 2\eta$, δ is the distance between the centres of the inner and outer

circles and $\lambda = t / D$.

In the absence of any eccentricity, Eq. (6) simplifies to

$$P_b = \frac{f_0}{c_0} \sigma_{\text{uts}}. \quad (7)$$

On comparing with the Klever equation, Eq. (6) reduces to the following

equation:

$$P_b = \frac{f_0 + f_1\xi + f_2\xi^2}{c_0 + c_1\xi + c_2\xi^2} \sigma_{\text{uts}} \left[\left(\frac{1}{2} \right)^{1+n} + \left(\frac{1}{\sqrt{3}} \right)^{1+n} \right], \quad (8)$$

and without any eccentricity, Eq. (8) simplifies to

$$P_b = \frac{f_0}{c_0} \sigma_{\text{uts}} \left[\left(\frac{1}{2} \right)^{1+n} + \left(\frac{1}{\sqrt{3}} \right)^{1+n} \right], \quad (9)$$

195 Compared with the equation in literature [6], Eq. (8) and (9) contain the material
196 hardening parameter n . Eq. (8) and (9) can more comprehensively depict the progress
197 of casing burst.

198 The American Petroleum Institute (API) bulletin 5C3 provided a formula for
199 calculation of internal yield pressure of pipe [11], which was used for prediction of
200 burst pressure of regular casing and expressed as [7]

$$201 \quad p_b = 0.875 \left(\frac{2\sigma_y t}{D} \right), \quad (10)$$

202 where σ_y is yield strength of pipeline material.

203 In the following validation of the finite element analysis, these predictive
204 equations were evaluated by using full-scale burst experimental data.

205 **5. Validation using casing burst data**

206 **5.1 Finite element method**

207 Scholars have made a multitude of researches of Oil Country Tubular Goods
208 (OCTG) in testing of tubular goods [12-14]. **Table 1** shows geometric and material
209 parameters for 32 test data taken from the literature [4, 15-16]. Each test specimen
210 was selected to reach a length-to-diameter ratio of at least eight. In **Table 1**, we can
211 see that the FEM and theoretical method are more close to the experimental date.
212 Whereas, comparing the experimental date, Eq. (10) results in a large error. This is
213 because Eq. (10) was derived from an ideal plastic thin-walled pipe model, the
214 hardening effect was not considered after material yield. In fact, the internal yield
215 pressure for pipe in API [11] does not mean the internal burst pressure. For the FEM

and theoretical model proposed in this paper, we carefully consider the elastic-plastic properties and hardening effect of the material. Therefore, the calculated results from the FEM and theoretical method have a good agreement with those from the existing experiments.

Fig. 3(a) compares burst strengths from the experiments and from the FEM predictions; the latter have a mean predictive error of 2.49%. **Fig. 3(b)** compares burst strengths from the modified theoretical Eq. (9) and the FEM predictions; the latter have a mean predictive error of 2.24%. These results imply that the finite element analysis used in this study satisfactorily predicts the ultimate burst strength of a casing.

Fig. 3 Tests of the finite element method (FEM) used in this study. (a) Comparison of the FEM to experimental data. (b) Comparison of the FEM to theoretical predictions.

5.2 Theoretical analysis

To evaluate the accuracy of the prediction of the ultimate burst strength of a casing, predictions from different design equations were compared with the full-scale burst experimental data, as shown in **Fig. 4**. In particular, the mean error of the modified theoretical equation (8) or (9) was 0.26%, whereas it was 0.60% for the Klever equation. The modified equation (8) or (9) provides more accurate predictions than does the Klever equation, which has heretofore been considered to be the most

236 accurate predictive equation [17]. In addition to higher accuracy, the modified
 237 theoretical equation (8) has a wider range of applications: it can be used to predict
 238 burst pressures for regular and eccentric casings.

239 (a) Klever Equation (b) Modified Theoretical Equation
 240
 241 **Fig. 4** Comparisons of predicted and experimental burst strengths. (a) Predictions
 242 from the Klever equation. (b) Predictions from the modified theoretical equation (8).

243 6. Results and discussions

244 6.1 Burst process analysis

245 In the simulation, the entire burst process can be clearly observed. A key state is
 246 the preburst state of casing (in **Fig. 5**). Since the worn casing is eccentric, the wall
 247 thickness is not uniform. Therefore, under an excessive internal pressure, each
 248 direction of the casing cross section causes a different deformation. Clearly,
 249 deformations are larger in thin areas than in thick areas. The cross section does not
 250 vary along the length of the casing, and thus, one side of the casing can produce a
 251 larger deformation than the other side. Furthermore, in this study, nonuniformities in
 252 the meshing lead to nonuniformities in regions during the finite element calculation,
 253 and the node sequences are different. For these reasons, uplifts, such as those in **Fig. 5**,
 254 appear stochastically. In this study, accumulation of errors leads to stress

255 concentrations at two points; therefore, two uplifts appear, as at points a and b in **Fig.**
256 **5**. In fact, nonuniformities of elements in size and distribution during the calculation
257 approximately simulate nonuniformities in the material during manufacturing.

258

259 **Fig. 5** State of casing after burst with uplifts appearing at points a and b.

260 **6.2 Effects of wear radius**

261 When the wear radius R_1 gradually increases from zero, the cross section of the
262 casing changes from crescent-shaped to eccentric cylinder (in **Fig. 1**). Consider the
263 sample casing No. 1 in Table 2 (TP140) as an example. Assuming that the minimum
264 wall thickness of the eccentric casing was unchanged (half of the initial wall
265 thickness), the finite element result for the burst pressure was as shown in **Fig. 6**. The
266 vertical line is the dividing line between the two models and divides **Fig. 6** into two
267 zones. Zone I corresponds to the crescent-shaped model, and zone II corresponds to
268 the eccentric cylinder model. The figure shows that, when the minimum wall
269 thickness is constant, the casing burst pressure is almost independent of the wear
270 radius. This suggests that, for estimating the burst pressure, both the crescent-shaped
271 and eccentric cylinder models can be used with confidence.

272

Table 2. Geometric and material parameters for two different casings.

No.	Casing type	D (mm)	t (mm)	σ_y (MPa)	σ_{uts} (MPa)	n
1	TP140	273.05	13.84	965	1034	0.09
2	WSP110T	244.48	11.99	851	933	0.09

Fig. 6 Effects of wear radius on burst pressure.

Fig. 7 Effects of eccentricity on burst pressure.

6.3 Effects of eccentricity ratio

Crescent-shaped eccentric wearing (**Fig. 1(a)**) is one of the main forms of eccentric wear on casings. Actual measurements noted that 50% of recycled casings are crescent-eccentric worn [18]. The eccentricity ratio denotes the ratio of the maximum worn depth to the original wall thickness of the casing. This ratio provides the residual wall thickness of a worn casing. Consider a WSP110T casing as an example for which geometric and material parameters are shown as sample No. 2 in Table 2. When the eccentric-worn radius is constant (60 mm), the relationship between the eccentricity ratio and the casing burst pressure is as shown in **Fig. 7**. An eccentricity ratio of zero corresponds to a regular casing, and the other values for the ratio correspond to eccentric casings. The figure shows that the numerical method, the

theoretical method and the experimental data [19] are consistent: as the eccentricity ratio increases, the burst pressure decreases nearly linearly.

6.4 Safe and burst areas

Consider sample No. 1 in Table 1 as an example casing. Using the modified theoretical equation (8), we obtain a safe area and a burst area, as shown in **Fig. 8**. When the eccentricity and internal pressure locate a point in the green area in **Fig. 8**, the calculated results show that the casing is safe. However, when they locate a point in the red area, the casing will burst. In practical applications, the internal pressure should be below the boundary between the safe and burst areas. The safe area is conservative because pipelines are usually wrapped in cement and surrounded by geological formations. That is, cement and geological formations can reinforce the casing and reduce the possibility of a burst.

Fig. 8 Safe and burst areas calculated from (8) for sample casing No. 1 in Table 1.

7. Conclusions

Finite element analyses were performed to investigate casing bursts of finite, three-dimensional, thick-walled casings subjected to excessive internal pressure. The accuracy and reliability of the proposed methodology were validated through careful comparisons with a series of test data from full-scale casing bursts. Comparisons were also conducted to evaluate published predictive equations for casing bursts. A

309 modified theoretical equation was noted to provide predictions that are more accurate
310 than those of the Klever equation, which has heretofore been considered to give the
311 most accurate predictions. In addition, the theoretical and modified theoretical
312 equations can be applied to a wider range of situations than the Klever equation. In
313 our analyses, we studied how casing burst strength is affected by major factors. Our
314 results show that eccentricity had an important effect on burst strength, whereas the
315 effects of wear radius were small. In practice, both the crescent-shaped and eccentric
316 cylinder models can be confidently used to estimate the burst pressure of casings.
317 Temperature effect should be considered at the bottom of ultra-deep wells in future.

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380 **Table 1.** Validation of Eq. (9), Eq.(10) and FEM for casing burst.

No.	D (mm)	t (mm)	σ_y (MPa)	σ_{uts} (MPa)	n	Experiment (MPa)	Eq.(10) (MPa)	Eq.(9) (MPa)	FEM
1	507.93	14.30	508.8	571.0	0.090	34.50	25.03	33.69	34.56
2	544.05	13.50	623.9	624.0	0.010	33.84	27.09	33.98	35.87
3	762.40	20.00	531.5	608.0	0.110	30.63	24.40	32.96	33.60
4	762.40	20.00	555.0	580.0	0.090	31.95	25.48	31.83	33.80
5	609.60	15.90	534.3	653.0	0.110	34.79	24.39	35.19	34.96
6	609.60	15.90	440.5	585.0	0.140	31.76	20.11	30.95	29.95
7	609.60	15.90	511.5	600.0	0.110	31.72	23.35	32.33	32.59
8	609.60	15.90	501.2	581.0	0.130	30.20	22.88	30.93	31.46
9	912.00	19.00	517.1	559.0	0.090	24.85	18.85	24.23	25.41
10	912.00	19.00	457.8	546.0	0.100	23.11	16.69	23.53	23.58
11	912.00	19.00	508.8	604.0	0.100	25.80	18.55	26.02	26.11
12	912.00	19.00	426.7	578.0	0.130	23.17	15.56	24.45	23.64
13	591.80	18.20	636.0	645.0	0.040	41.76	34.23	42.98	46.11
14	591.20	18.90	563.0	589.0	0.090	37.68	31.50	39.61	42.09
15	591.20	18.90	607.0	630.0	0.120	40.79	33.96	41.59	45.26
16	893.70	22.50	526.0	608.0	0.110	27.93	23.17	31.60	32.05
17	162.20	9.80	602.0	776.0	0.180	86.60	63.65	95.85	93.70
18	397.60	13.50	364.0	523.0	0.190	36.50	21.63	35.19	33.10
19	390.80	12.80	807.0	869.0	0.080	59.60	46.26	60.29	63.02
20	179.40	8.94	468.8	737.7	0.115	77.70	40.88	77.45	74.69
21	90.35	6.50	696.3	751.4	0.077	119.27	87.66	118.98	125.01
22	198.20	14.60	903.1	992.7	0.065	173.80	116.42	162.39	168.33
23	179.50	13.30	834.2	903.1	0.061	152.29	108.17	149.02	155.54
24	180.30	10.40	613.6	723.8	0.093	92.17	61.94	89.81	90.66
25	179.10	10.30	848.0	916.9	0.070	118.51	85.34	115.04	119.94
26	247.10	9.86	641.1	717.0	0.102	61.08	44.76	60.20	62.04
27	252.40	13.50	606.7	703.2	0.102	81.56	56.86	80.15	81.35
28	89.00	14.40	606.7	730.8	0.115	294.65	171.79	273.00	285.24
29	67.30	3.91	689.4	834.2	0.065	113.34	70.09	106.12	107.38
30	179.60	12.01	779.0	896.2	0.068	136.09	91.16	132.03	134.63
31	198.90	14.70	903.1	992.7	0.065	171.66	116.80	162.96	168.93
32	180.60	14.90	903.1	992.7	0.065	178.55	130.39	183.31	190.41

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