



Article A Collapse Strength Model for a 7" Crescent-Worn Casing Connection Considering Sealing Integrity

Xing Zhou¹, Qinfeng Di¹, Xiaoliang Wang², Dakun Luo¹, Feng Chen^{3,*} and Wenchang Wang^{1,*}

- ¹ School of Mechanics and Engineering Science, Shanghai University, Shanghai 200444, China
- ² CNPC Tarim Oilfield Company, Korla 841000, China
- ³ School of Mechatronics Engineering and Automation, Shanghai University, Shanghai 200444, China
- * Correspondence: chenfeng536@shu.edu.cn (F.C.); vincentw@shu.edu.cn (W.W.); Tel.: +86-5633-3256 (F.C.)

Abstract: Collapse failure under external pressure is one of the common failure forms of casing. Much research has been performed on the casing body, but few on the threaded connection, in view of the general belief that the threaded connection has a thicker wall and larger collapse strength than the casing body. However, under external pressure, the sealing capacity of a worn casing connection will decrease due to deformation of the sealing structure, so the influence of sealing ability should be considered to determine the collapse strength of casing. In this paper, we established a three-dimensional finite element model of a 7" crescent-worn casing connection and calculated the collapse strength of the connection under different wear depths. Meanwhile, the stress distribution characteristics on the sealing surface were obtained and the influence of wear on the sealing performance of the casing connection under external pressure was analyzed. The results showed that when the wear rate exceeds a certain value, the collapse strength of the connection based on sealing integrity was lower than that of the casing body. Based on these, a collapse strength model for a 7" crescent-worn casing connection considering sealing integrity was developed and a safety evaluation method of the collapse strength of the worn casing string was proposed.

Keywords: collapse strength; casing connection; crescent wear; sealing integrity; finite element method

MSC: 74S05

1. Introduction

In recent years, the cessation of production and the abandonment of oil and gas wells due to wellbore integrity damage frequently occurs, and the problem of wellbore integrity has attracted more attention [1–5]. The wellbore system involves tubing, casing, wellhead, packer, and more. Among them, the casing string is an important downhole tool to protect the borehole, reinforce the wellbore, isolate the oil, gas, and water layers, and seal various complex formation; it is also the key barrier of wellbore integrity. Therefore, its failure will pose a serious threat to production safety. Unfortunately, such failures do exist and are more likely to take place when casing wear takes place, which is caused by the friction between the down-hole tubular string and wellbore wall in complex structure wells [6].

Collapse is one of the common failure modes of the casing string under the action of external pressure. There are a lot of researchers working on the mechanism of casing collapse. Both analytical [7–12] and finite element methods [13–16] have been employed to carry out various studies on casing collapse, leading to the development of a relatively rigorous theoretical system and mature technical methods. However, most of these works focus on the casing body, treating the casing as a uniform round pipe. In fact, the casing string is not only composed of the casing body, but also threaded connections, which connect thousands of meters of casing together and could be the main failure location of the casing string. According to field statistics, 64% of casing failure accidents take place at threaded connections and some wells even reach 86% [17]. In addition, the failed



Citation: Zhou, X.; Di, Q.; Wang, X.; Luo, D.; Chen, F.; Wang, W. A Collapse Strength Model for a 7" Crescent-Worn Casing Connection Considering Sealing Integrity. *Mathematics* 2023, 11, 489. https:// doi.org/10.3390/math11020489

Academic Editors: Lihua Wang, Benny Y. C. Hon and Sheng-Wei Chi

Received: 1 December 2022 Revised: 6 January 2023 Accepted: 14 January 2023 Published: 16 January 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). connections found on the field have serious wear phenomenon [18], but little attention has been paid to the strength of casing connections. One of the reasons is that the threaded connection has a larger wall thickness compared to the casing body, giving people an impression that the collapse strength of the connection is greater than that of the casing body. The other reason is that the structure of the connection is too complex to analyze. The engaged surface of the pin and box is a three-dimensional spiral surface, which involves strong nonlinearities, making it difficult to carry out the relevant research in depth. In addition, it should be noted that compared to the casing body, the threaded connection has a sealing problem. Chen et al. [19] established a three-dimensional finite element model of the casing connection and studied the distribution characteristics of contact stress on the joint sealing surface under complex loads. Xu [4] studied the contact pressure on the sealing surface by an analytical method. The current research on connection sealing are mostly about the contact stress on the sealing surface, but the criterion of seal failure caused by the change of contact stress is not given; the wear phenomenon and how to measure the mechanical properties of the connection under the condition of considering the integrity of the seal are not unified. Under the action of external load, the worn casing connection will have a larger structural deformation and this affects the sealing performance; it is thus necessary to consider the sealing performance when determining the collapse strength. However, this problem has not been received enough attention so far. In this paper, the finite element method was used to calculate the collapse strength of a worn 7" casing connection. Based on the accuracy verification of the model and simulation algorithm, a three-dimensional finite element model of the worn casing connection was proposed to evaluate the collapse strength and the mechanical characteristics of the sealing surface of crescent-worn casing connections. Then, the influence of wear on the sealing integrity was discussed; the collapse strength considering the sealing integrity of the worn casing connection was also assessed using a sealing criterion. Finally, the partition evaluation diagram of collapse strength of the 7" worn casing connection was obtained considering the sealing integrity when wear rates of the casing body and the connection are different.

2. The Calculation Formula of Collapse Strength for Worn Casing and Verification of Finite Element Model

2.1. The Calculation Formula of Collapse Strength for Worn Casing

According to the theory of elasticity, the collapse strength formula of the eccentricworn casing body can be derived as [20]:

$$P_{s} = -\frac{Y_{p}(a^{2} + b^{2})\left[\left(a^{2} + b^{2} - c^{2}\right)^{2} - 4a^{2}b^{2}\right]}{2b^{2}\left[\left(b^{2} - c^{2}\right)^{2} - a^{2}(a - 2c)^{2}\right]}$$
(1)

where Y_P is the yield strength of casing, MPa; $b = \frac{D_c}{2}$, D_c is the outer diameter of casing, mm; and $a = b - \frac{t_{\text{max}} + t_{\text{min}}}{2}$, $c = \frac{t_{\text{max}} - t_{\text{min}}}{2}$ with t_{max} and t_{min} denoting, respectively, the maximum and minimum wall thickness of casing, mm.

The collapse strength formula of the crescent-worn casing body can be expressed as [20]:

$$P_{yw} = P_s \left(\frac{d}{D_i + \delta}\right)^{\binom{\delta}{i}} \tag{2}$$

where P_{yw} is the collapse strength of crescent-worn casing, MPa; *d* is the diameter of drill pipe causing casing wear, mm; D_i is the inner diameter of casing, mm; δ is the wear depth, mm; and *t* is the thickness of wall, mm.

2.2. Finite Element Calculation of Collapse Strength for Crescent-Worn Casing

Figure 1a shows a three-dimensional model of 7" (ϕ 177.8 mm × 12.65 mm) crescentworn casing body. The simulation results will be compared with Formula (2) in Section 2.1 so as to verify the reliability of the finite element model. In Figure 1b, R1 represents the radius of drill pipe causing casing wear, which is taken as 44.5 mm in this paper. The model has a total of 107,870 nodes and 80,100 elements. The element type is C3D8I, and the mesh is evenly distributed. The crescent internal wear of 0~4 mm was considered; the influence of wear depth on stress characteristics of casing under external pressure was calculated by ABAQUS 6.14. The density, elastic modulus, and Poisson's ratio of the casing material are 7850 kg/m³, 210 GPa and 0.29, respectively.



Figure 1. Three-dimensional finite element model of casing body.

The results of the finite element method and the analytical solution calculated by Formula (2) were compared in Table 1. The results show that the minimum relative error is only 1.14% (occurring at 1 mm worn), the maximum relative error is 5.39% (occurring at 2 mm worn), and the average of relative error is 3.86%. The relative error is the absolute value of the error between Formula (2) and the finite element simulation results under the same wear condition. The above results show that the finite element results are in good agreement with the results by Formula (2), which verifies the accuracy of the finite element model.

Table 1. Comparison of results by Formula (2) and finite element method for casing body.

0	1	2	3	4
97.13	85.23	73.33	61.54	50.00
99.78	86.20	69.38	58.29	47.61
2.72%	1.14%	5.39%	5.29%	4.77%
	0 97.13 99.78 2.72%	0 1 97.13 85.23 99.78 86.20 2.72% 1.14%	0 1 2 97.13 85.23 73.33 99.78 86.20 69.38 2.72% 1.14% 5.39%	0 1 2 3 97.13 85.23 73.33 61.54 99.78 86.20 69.38 58.29 2.72% 1.14% 5.39% 5.29%

3. Calculation of Collapse Strength of Crescent-Worn Casing Connection

Figure 2 depicts a three-dimensional finite element model of casing connection with P110 steel grade. The specific geometric parameters of casing connection are given in Table 2.



Figure 2. Three-dimensional finite element model of casing connection.

Parameter	Value/Type		
Thread profile	Buttress		
Pitch	5.08 mm		
Thread taper	1:16		
-	The ball to the cone		
Sealing structure	Cone taper of 1:16		
	Radius of the ball 18 mm		
Outer diameter of the connection	194.5 mm		
Outer diameter of casing body	177.8 mm		
Inner diameter of casing body	152.5 mm		

Table 2. Geometric parameters of casing connection.

An eight-node hexahedron element was selected to calculate the deformation of above model. The total number of nodes and elements are 604,572 and 495,530, respectively. The mesh was refined in the stress-concentrated parts such as thread teeth and sealing surface. Material properties are the same as those in Section 2.2. The crescent wear was established on the inner wall of the casing connection, and the wear depth was also 0~4 mm.

To be clear, in this study, the calculation of the casing connection is based on the following assumptions:

- (1) The basic physical quantities of the box and pin are continuously distributed, such as stress, strain, and displacement;
- (2) The material of the pin and box of the casing connection adopts the assumption of uniformity and isotropy;
- (3) Under the action of external force, the casing connection deformation is elastic deformation before the yield load, and plastic deformation after the yield load, without considering the viscosity, creep, and other effects.

The load was applied by establishing the coupling form of distributing nodes on the end surface of the pin; the constraint was imposed by establishing the coupling form of the kinematical node at the end surface of the box, as shown in Figure 3. Load cases are shown in Table 3.



Figure 3. Boundary conditions.

Table 3. Load cases.

Load Cases	Magnitude		
Step 1: Make-up	9.49 kN⋅m		
Step 2: External pressure	200 MPa		

For the convenience of the following description, the section diagram of the connection is given below and the key parts are marked in red boxes, as shown in the Figure 4. In the figure, zone I represents the engagement area of thread teeth, and zone II represents the sealing surface. The red and white symbols in the zone I and zone II are the locations of the two critical nodes A1 and A2 in the analysis below, and their function and selection will be explained below.



Figure 4. The section diagram of connection.

In order to reveal the influence of wear depth on the collapse strength of the casing connection, the von Mises stress curve at a node where the stress is relatively concentrated on the engagement area of thread teeth (corresponding to the red symbol of zone I in Figure 4) was plotted with the change of external pressure during the increase of wear depth, as shown in Figure 5. For simplicity, it is referred to as node A1 below.



Figure 5. Curve of stress variation with load at node A1.

The external pressure corresponding to the stress reaching the yield strength is getting smaller with increased wear depth, as shown by the blue dotted line in Figure 5. It is widely known that if a small load increment causes a large increment of the maximum von Mises stress in the finite element calculation, it indicates that the casing connection has lost the ability to resist a further increase of external pressure and the corresponding von Mises stress can be regarded as the collapse strength of the casing connection. The collapse strength of the crescent-worn casing connection is 125.9 MPa, 103.8 MPa, 88.8 MPa, 74.1 MPa, and 63.5 MPa, corresponding to the wear depth of 0mm, 1mm, 2mm, 3mm, and 4mm, respectively. In other words, when crescent wear takes place, the collapse strength of the connection decreases with the increased wear depth. It can be found that under the same wear condition, the collapse strength of the casing connection is slightly greater than that of the casing body shown in Table 1. This is because the connection after engagement is greater than the casing body.

However, wear reduces the collapse strength of the casing connection. When the wear depth reaches 4 mm, the collapse strength of the crescent-worn connection decreases by 49.6% compared with that of the unworn connection. That is to say, when the wear rate reaches about 30%, the collapse strength of the connection is reduced by nearly half. In this case, the casing connection is more likely to collapse, which greatly increases the risk of wellbore integrity damage.

Through curve fitting, the relationship between wear rate and the collapse strength of the crescent-worn casing connection can be obtained:

$$P_{\rm cj} = -196.6\zeta^3 + 362\zeta^2 - 291\zeta + 125.6 \tag{3}$$

where ζ is the wear rate, defined as the ratio of wear depth δ to original wall thickness *t*; and *P*_{*c*j} is the collapse strength of the connection with crescent-worn, MPa.

Figure 6 shows the collapse strength of the worn connection considering the sealing integrity calculated based on the finite element solution and fitting curve drawn by the formula (3).



Figure 6. The finite element calculation results and fitting curve.

4. Influence of Wear Depth on Sealing Performance of Connection

Formula (3) is the collapse strength model only considering strength characteristics. However, a very important fact should be recognized, which is that casing connection is not a real thick-wall casing body due to the engagement of the pin and box. Not only its strength but also its sealing performance should be paid attention to under the external pressure. When the casing connection deforms greatly under external load, sealing failure may occur and the integrity of the casing string may be problematic. Therefore, it is more practical to study the casing collapse strength considering the sealing integrity.

Similarly, for the convenience of subsequent analysis and explanation, the diagrams of the critical path are given below, as shown in the Figure 7. Figure 7a shows the complete connection and the circumferential path on the sealing surface (corresponding to zone II in Figure 4). It should be noted that the circumferential path is a ring of sealing ring composed of the node where the maximum contact stress is located along the axial direction on the sealing surface. Figure 7b shows only the sealing ring of the sealing surface in the connection.



(a) Location of circumferential pathFigure 7. Critical path.



(b) Circumferential path and axial path

4.1. Axial Distribution Characteristics of Stress on Sealing Surface

The casing connection studied in this paper adopts a sphere-cone sealing structure, as shown in Figure 8. The sealing is realized by a radial interference fit of the sealing surface and the sealing performance is mainly reflected in the distribution of contact stress on the sealing surface.



Figure 8. Sealing structure of the casing connection.

A higher contact stress and a larger contact width are the two important features of an excellent sealing performance in the elastic range. The stress on the sealing surface has greatly exceeded the elastic limit. Meanwhile, there is plastic deformation which is helpful to the sealing performance in a certain range. Therefore, it is difficult to accurately describe the micro channel on the sealing surface, which increases the difficulty of evaluating the sealing performance of the sealing surface. In view of both elastic and plastic deformation, fluid leakage will appear in the direction of small leakage resistance, so the fluid leakage resistance is also affected by the contact stress and contact width of the sealing surface. The contact pressure along the axial path on the wear side of the sealing surface was selected (as shown in Figure 7) to analyze the variation of stress characteristics with different wear depths. The simulation results of the model showed that the width of the sealing surface of the connection corresponding to different wear depths are the same (3.75 mm); thus, only the contact stress on the sealing surface is discussed below.

The node with the maximum contact stress on the sealing surface was taken from the axial path (the intersection of the green-color circumferential path and the black-color axial path is shown in Figure 7b); for simplicity, it is referred to as node A2. Node A2 is the node of maximum stress on the axial path and the critical node for sealing the connection; its location is in the marked white symbol of zone II in Figure 4. It can be said that the value of contact stress at A2 node determines the sealing quality of the connection, as shown in Figure 9. The change of contact stress at this point with external pressure was observed under different wear depths, as shown in Figure 10.



Figure 9. Axial distribution characteristics of stress on sealing surface.



Figure 10. Change of contact stress on node A2 with external pressure and partially enlarged diagram.

As can be seen from Figure 10, with the increase of external pressure, the contact stress on the sealing surface of the casing connection increases gently at first (in the elastic stage), then increases sharply (in the plastic stage), finally dropping rapidly to zero, at which time-step a structural plastic failure has occurred (as shown in Figure 11). The partially enlarged diagram in Figure 10 shows that the contact stress on the sealing surface of the pretightening connection decreases with the increased wear depth when the external pressure is zero. With the gradual increase of external pressure, the connections with different wear depths reach the yield strength successively. The calculation results show that a greater wear depth corresponds to a smaller external pressure when the contact stress reaches the yield strength—that is, the sealing integrity of the connection decreases.



Figure 11. Structural plastic failure occurred in casing connection.

In order to illustrate the influence of wear on the sealing performance of the connection, the collapse strength of each model calculated in Section 3 was taken as the dividing line of elastic–plastic, and the average contact stress on the sealing surface of the crescent-worn connection at the elastic stage was obtained, as shown in Table 4.

It can be found that the average contact stress on the sealing surface of the crescentworn casing connection decreases gradually with increased wear depth. When the wear depth reaches 4 mm, the average contact stress on the sealing surface is reduced by 16.5%, which reduces the sealing performance of the connection to a certain degree.

Table 4. Average contact stress of node A2 at elastic stage.

Wear depth/mm	0	1	2	3	4
Average contact stress/MPa	593.81	562.04	542.93	520.98	495.67

4.2. Circumferential Distribution Characteristics of Stress on Sealing Surface

In order to observe the circumferential distribution of contact stress along the sealing surface of the worn connection in the process of increasing external pressure, the circumferential contact stress along the ring (corresponding to the green-color ring in Figure 7a) on the sealing surface was extracted and expressed in Figure 12.



Figure 12. Contact stress distribution on the circumferential path under different wear depths.

It can be found that the stress characteristics along the circumferential path show irregular fluctuations corresponding to each wear depth, which is mainly due to the nonlinear contact characteristics caused by the helix angle of the threaded teeth. With the increase of wear depth, the circumferential contact stress on the sealing surface is gradually decreased, and the contact stress along the circumferential becomes more uneven, which will have an adverse effect on the sealing performance.

As shown in Table 5, the maximum contact stress, minimum contact stress, and average contact stress on the circumferential path decrease gradually with increased wear depth, and when the wear depth reaches 4 mm, they decrease by 16.2%, 54.9%, and 18.6%, respectively, compared with the unworn connection.

The calculation results show that the maximum contact stress and average contact stress decrease slightly whereas the minimum contact stress decreases greatly. The minimum contact stress on the unworn connection is 845.0 MPa, slightly greater than the yield strength of the material. When the wear depth is 1 mm, the minimum contact stress has decreased to 674.8 MPa, which is lower than the yield strength of the material. With the increase of the wear depth, the minimum contact stress further decreases. When the wear depth is 4 mm, the minimum contact stress decreases by more than half compared with the unworn connection, which is much lower than the yield strength of the material.

Although the maximum contact stress and the average contact stress are both greater than the yield strength under different wear depths, it seems that the connection has reliable sealing performance. Since the contact stress along the circumferential path taken in this paper is the maximum value along the axial path on the whole sealing surface, the minimum contact stress on the circumferential path in Table 5 is also the maximum contact stress on the axial path where the point is located. Therefore, the minimum contact stress is too much lower than the yield strength of the material, indicating that there may be a leakage channel along the axial path at this position, resulting in connection seal failure. By observing the node of the minimum contact stress on the circumferential path, it was found that the minimum contact stress occurred on the side where the wear occurred under different wear depths, which also proves that the wear has a strong destructive effect on the sealing integrity of the connection.

Table 5. Contact stress on circumferential path.

Wear/mm	0	1	2	3	4
Maximum contact stress/MPa	1068.6	1010.1	976.5	937.9	896.0
Minimum contact stress/MPa	845.0	674.8	560.8	452.4	381.5
Average contact stress/MPa	926.8	865.9	825.5	785.0	754.5

4.3. Collapse Strength of Worn Casing Connection Considering Sealing Performance

According to the analysis in Section 4.2, the occurrence of wear reduces the contact stress on the sealing surface of the casing connection and increases the uneven distribution along the circumferential direction, which obviously has an adverse effect on the sealing performance of the connection. Although the worn connection has not been collapsed and sealing failure may have occurred, the obtained collapse strength will be divorced from reality and will have no practical value only considering the collapse strength of the connection without paying attention to the reduction of its sealing performance. Therefore, a calculation model of the collapse strength of the casing connection considering sealing integrity should be proposed.

Based on the theory of sealing contact energy [21], the flow resistance preventing gas from passing through metal to the metal sealing structure can be characterized by some integral value of contact stress on effective contact width.

When gas seal index W_a > critical gas seal index W_{ac} , there is no Leakage;

When gas seal index W_a < critical gas seal index W_{ac} , leakage takes place.

Murtagian's experimental results show that the gas seal index of the metal sealing structure with a sphere-cone can be expressed as [22]:

$$W_a = \int_0^L P^n e(l) \mathrm{d}l \tag{4}$$

 $P_{\rm e}$ is the contact stress along the axial path of the wear side of the sealing surface corresponding to the moment of collapse failure occurs, MPa; *l* is the contact width of the sealing surface, mm; and *n* is set to 1.2 when sealing compound is used—otherwise, it is set to 1.4.

The critical gas seal index obtained through the experiment test can be expressed as [22]:

$$W_{ac} = 1.84 \times \left(\frac{P_{gas}}{P_{atm}}\right)^{1.177} \tag{5}$$

 P_{gas} is gas pressure that needs to be sealed, MPa; and P_{atm} is atmospheric pressure, MPa.

Equations (4) and (5) can be used to obtain the maximum gas pressure in the casing with reliable sealing, which is equivalent to the collapse strength corresponding to seal failure under the action of external pressure.

Atmospheric pressure is 0.1 MPa. The collapse strength of the worn connection calculated based on this is 104.7 MPa, 81.8 MPa, 64.4 MPa, 56.0 MPa, and 48.0 MPa, respectively, corresponding to the wear depth of 0 mm, 1 mm, 2 mm, 3 mm, and 4 mm, respectively. Considering the sealing integrity, the relationship between the collapse strength and wear depth of the connection is similar to that of the casing body; that is, with the increase of wear depth, the collapse strength decreases gradually, but the corresponding

value decreases slightly. According to the calculated results, the polynomial relationship between wear rate ζ and the collapse strength of the casing connection considering sealing integrity is formulated as follows:

$$P_{\rm cs} = -403.91\zeta^3 + 638.39\zeta^2 - 339.15\zeta + 104.67\tag{6}$$

Figure 13 shows the collapse strength of the worn connection considering the sealing integrity calculated based on the finite element solution and fitting curve. Compared with the results in Section 3, the collapse strength of the connection is greatly reduced after considering the sealing integrity.



Figure 13. Finite element calculation results and fitting curve.

5. Discussion

In engineering practice, the sealing integrity of the threaded connection is evaluated by the leakage rate. Leakage rate refers to the leakage rate of medium fluid per second through the sealed interface under standard test conditions. For metal–metal seals, according to the requirements of the threaded connection test procedure of tubing/casing (ISO 13679), the gas leakage rate during the test is less than $0.9 \text{ cm}^3/15 \text{ min}$, which is an indicator of good sealing [23]. However, in this study, it is not very possible to quantitatively calculate the leakage rate of the casing connection under wear condition or the collapse strength under critical leakage rate. Therefore, the seal integrity in this article refers to that idea that when the casing string (including casing body and threaded connection) is worn at different degrees, the collapse strength considering the sealing integrity is calculated based on the contact energy theory of the metal seal. This evaluation method considering the sealing integrity of connections makes up for the shortcomings of the current research which only pays attention to the collapse strength in the casing string and ignores the sealing failure of connection. As the weak part of the casing string, the threaded connection is the common site of failure due to a seal problem, so the entire casing string can be considered safe when the safety of the threaded connection is guaranteed.

Figure 14 shows the corresponding casing body collapse strength P_{cb} , casing connection collapse strength P_{cj} , and casing connection collapse strength considering sealing integrity P_{cs} . For an unworn connection, the collapse strength is 129.50 MPa, and the collapse strength of the connection considering sealing integrity is 104.74 MPa. For an unworn casing body, its collapse strength is 97.13 MPa, which is lower than connection. At this point, the collapse strength of the connection can be calculated according to the casing body, which is consistent with the current understanding that the collapse strength of the connection is much larger than the casing body.

When the casing body and the connection have the same wear depth, the above conclusion is also established if the sealing integrity is not considered. However, when the wear rate exceeds 5.5% (corresponding to the wear depth of 0.69 mm), the collapse strength of the connection considering sealing integrity is smaller than the casing body. If the wear depth of the connection and the casing body is different, it can also be judged by Figure 14 to determine the minimum collapse strength of the casing string.



Figure 14. Collapse strength of casing body and connection under different wear depths.

For both the casing body and the connection, with the deepening of wear, the collapse strength will decrease in different degrees. Without wear, the finite element calculation result in Section 2.2 was compared with the full-scale collapse test data of a casing body of the same size (ϕ 177.80 mm \times 12.65 mm P110) in [24]: the experimental result was 99.1 MPa, which was very close to the 99.8 MPa calculated by the model in this paper. For the casing connection, we compared it with the experimental data, which is equivalent to two layers of casing body with a larger wall thickness. In the experiment [25], for P110 steel casing, when the diameter-thickness ratio Dc/t is less than 14 (the corresponding diameterto-thickness ratio Dc/t in the model of an equivalent casing is 9.3), the collapse strength is greater than 124.1 MPa (18,000 psi); this is consistent with the 125.9 MPa calculated for the unworn connection in Section 3. However, when considering the sealing integrity of the connection, the collapse strength of the unworn connection is only 104.7 MPa, a decrease of 16.8%, indicating that when considering the sealing integrity, the effective collapse strength of the connection cannot reach the expectation, which is consistent with the current understanding. That is to say, if only considering the connection strength, the connection may have had a seal failure while the structure was intact; if wear is taken into account, the effective collapse strength of the connection is even lower.

In actual working conditions, the wear depth of the casing body and the connection are often different, and the wear condition of the connection is usually more serious. Therefore, it is necessary to discuss the collapse strength of the casing body and the connection when the wear is not synchronous.

Considering the sealing performance of the connection, the difference of the collapse strength of the connection and casing body with wear rate is shown in Figure 15. The meaning of this figure is the relative strength relationship between the collapse strength of the connection and the casing body when their wear rate changes, respectively. As shown in the Figure 15, the grey plane gives a zero datum; above the datum plane is the area where the collapse strength of the casing connection is higher than that of the casing body when the wear rate changes, respectively; below the datum plane is the area where the collapse strength of the casing connection is lower than that of the casing body.

Generally, the wear of the connection is more serious; that is, the wear rate of the connection is greater than that of the casing body. Due to the thicker wall of the connection, only the collapse strength of the casing body is usually considered. However, from the perspective of wellbore integrity, not only the collapse strength under the influence of wear but also the sealing integrity of the casing string should be considered to make the risk assessment of the casing string collapse more practical.





A projection of Figure 15 on the XY plane can be used to obtain the collapse strength of the casing body and connection based on the sealing integrity, as shown in Figure 16. Using ζ_p to represent the wear rate of the casing body and ζ_c to represent the wear rate of the connection, the expression of the red and green areas in Figure 16 can be obtained by polynomial fitting as follows:





The green area in Figure 16 shows that the collapse strength of the connection is higher than that of the body under different wear rates. Based on the above considerations, this area is defined as a "safe area". Since the collapse strength of the connection is greater than that of the body under the corresponding wear rate of the "safety zone", it is only necessary to evaluate the impact of wear on the collapse strength of the casing body according to Formula (2) to protect the whole casing string from collapse and leakage. The red area in Figure 16 shows that the collapse strength of the casing connection is lower than that of the body; this area is defined as a "dangerous area". Under the corresponding wear rate of the "dangerous area", the impact of wear on the collapse strength of the casing string should be evaluated according to Formula (6) based on the connection.

(red area)

(green area)

(7)

6. Conclusions

In this article, we established the finite element model of a 7" crescent-worn casing threaded connection. In addition to studying the effect of wear on the collapse strength traditionally, we also proposed an evaluation method of the worn casing connection with consideration of seal safety. According to the study above, we reached the following conclusions:

- (1) Under external pressure, the contact stress on the sealing surface of the worn casing connection will decrease significantly, increasing the risk of leakage of the connection.
- (2) The collapse strength of the connection without considering sealing integrity is greater than that of the casing body under the same wear condition, which is consistent with the current understanding.
- (3) The collapse strength of the connection may be less than the casing body when considering the sealing integrity. For the 7" casing in this paper, the collapse strength of the connection is smaller than the casing body when the wear rate exceeds 5.5% for gas seal conditions.
- (4) Since the casing body and connection often have different wear depths, an evaluation model of the collapse strength of the worn casing connection considering the sealing integrity was developed, which can determine the wear depth at which the collapse strength of the connection is lower than that of the casing body.

Author Contributions: Conceptualization, Q.D. and F.C.; methodology, X.Z., F.C. and D.L.; software, X.Z. and F.C.; validation, X.W., W.W. and Q.D.; formal analysis, X.Z. and F.C.; investigation, D.L. and X.W.; resources, W.W.; data curation, Q.D.; writing—original draft preparation, X.Z. and F.C.; writing—review and editing, Q.D., F.C. and W.W.; visualization, X.Z. and D.L.; supervision, W.W. and Q.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the National Natural Science Foundation of China (52174003, U1663205, 51804194, 51704191).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this article are available upon reasonable request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

- 1. Smith, L.; Milanovic, D. The total control of well integrity management. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 3–6 November 2008; p. SPE117121.
- Annandale, A.; Conway, R.; Copping, S. A systematic approach to well integrity management. In Proceedings of the SPE Digital Energy Conference & Exhibition, Houston, TX, USA, 7–8 April 2009; p. SPE123201.
- 3. Buchmiller, D.; Rengard, O.; Haug, L.T.; Horte, T.; Grytoyr, G.; Katla, E. Advancements in structural well integrity design and operation. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 30 April–3 May 2012; p. SPE23278.
- 4. Xu, H. Study on Joint Strength and Sealing Theory for Casing and Tubing Premium Connection. Ph.D. Thesis, Southwest Petroleum University, Chengdu, China, 2015.
- 5. Liu, K. Research on Well Integrity of Horizontal Shale Gas Well with Hydraulic Fracturing. Ph.D. Thesis, China University of Petroleum, Beijing, China, 2019.
- 6. Chen, L. Analysis of the Rub-Impact and Its Induced Wear Characteristics of Drill String on Casing. Master's Thesis, Shanghai University, Shanghai, China, 2019.
- 7. Li, H. China Pipe Engineering; Petroleum Industry Press: Beijing, China, 1999.
- 8. Clinedinst, W.O. A Rational Expression for the Critical Collapsing Pressure of Pipe under External Pressure; American Petroleum Institute: Chicago, IL, USA, 1963; pp. 383–391.
- 9. Mimura, H.; Mimaki, T.; Tamano, T. Finite Element Analysis of Collapse Strength of Casing; Nippon Steel Corporation: Tokyo, Japan, 1987.
- 10. Qiu, W.; Zhao, H. Analysis of casing extrusion. Acta Pet. Sin. 1995, 16, 99–107.
- 11. Gong, W. Application of trigonometric series to calculate critical external pressure of circular pipe with uneven wall thickness. *Oil Drill. Prod. Technol.* **1990**, *12*, 1–10.
- 12. Huang, W.; Gao, D. A theoretical study of the critical external pressure for casing collapse. J. Nat. Gas Sci. Eng. 2015, 12, 290–297. [CrossRef]

- 13. Huang, X.; Mihsein, M.; Kibble, K.; Hall, R. Collapse strength analysis of casing design using finite element method. *Int. J. Press. Vessel. Pip.* **2000**, *77*, 359–367. [CrossRef]
- Berger, A.; Fleckenstein, W.W.; Eustes, A.W.; Thonhauser, G. Effect of eccentricity, voids, cement channels, and pore pressure decline on collapse resistance of casing. In Proceedings of the SPE Annual Technical Conference and Exhibition, Houston, TX, USA, 26–29 September 2004.
- 15. Chen, Z.; Zhu, W.; Di, Q. Effects of eccentricity of casing on collapse resistance in non-uniform in-situ stresses. J. Shanghai Univ. (*Nat. Sci. Ed.*) **2012**, *18*, 83–86.
- 16. Jin, C.; Qian, F.; Feng, F. Effect of variable drill pipe sizes on casing wear collapse strength. J. Pet. Sci. Eng. 2020, 12, 195. [CrossRef]
- 17. Cai, X.; Gao, L. Current development situation of the special threaded connection for tubing/casing. *Welded Pipe Tube* **2008**, *4*, 41–44+94.
- Wang, N. Analysis of 3D Mechanical Characteristics of Special Threaded Joints of Worn Tubing. Master's Thesis, Shanghai University, Shanghai, China, 2020.
- Chen, W.; Di, Q.; Zhang, H.; Chen, F.; Wang, W. The sealing mechanism of tubing and casing premium threaded connections under complex loads. J. Pet. Sci. Eng. 2018, 171, 724–730. [CrossRef]
- Liang, E. Test on Wear Rule and Prediction on Wear Degree of Casing in Deep Wells and Extended Reach Wells. Ph.D. Thesis, Yanshan University, Qinhuangdao, China, 2012.
- Xu, H.; Yang, B.; Shi, T.; Zhang, Z. Analysis of influencing hermetic seal performance with a spherical-conical surface and special screw threads. J. Southwest Pet. Univ. (Nat. Sci. Ed.) 2017, 39, 162–166.
- Murtagian, G.R.; Fanelli, V.; Villasante, J.A.; Johnson, D.H.; Ernst, H.A. Sealability of stationary metal-to-metal seal. J. Tribol. 2004, 126, 591–596. [CrossRef]
- 23. ISO 13679; Petroleum and Natural Gas Industries—Procedures for Testing Casing and Tubing Connection. IX-ISO: Geneva, Switzerland, 2019.
- Lou, Q.; Du, W.; Han, X.L.; Li, D.F.; Zhang, G.L. Analysis on the influence factors of casing collapse resistance strength. *Adv. Mater. Res.* 2012, 415–417, 2121–2125. [CrossRef]
- 25. Brechan, B.; Kornberg, E.; Sangesland, S.; Dale, S.I. Well integrity model- klever&tamano collapse. In Proceedings of the SPE/IADC Middle East Drilling Technology Conference and Exhibition, Abu Dhabi, United Arab Emirates, 29–31 January 2018.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.