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Development of a Design Method for Casing and Tubing Strings under Complex Alternating Loads

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Abstract: With the escalating intricacy of downhole operational scenarios, encompassing frequent well cycling, acidification, multi-stage fracturing, steam injection, and intensive extraction, the efficacy of traditional casing-string-design methods rooted in strength considerations is progressively unveiling its limitations. Henceforth, it becomes imperative to establish string-design method standards that embrace the entirety of a well's lifecycle, encompassing the phases of drilling, completion, fracturing, and production operations. Beginning with an analysis of the advantages and limitations of traditional casing-string-design methods, this paper introduces the features of strain and sealing design methods developed for the full lifecycle of the string. The strain design method, a departure from conventional design philosophies, enables the design concept of the controllable deformation of the pipe string. The sealing design method currently stands as the sole standard method for the design of tubing strings. Simultaneously, this paper proposes the establishment of a time dimension-based lifecycle pipe string-design method standard. This approach considers the trend of pipe strength degradation, effectively addressing the safety concerns related to pipe string design in production and operation.

Keywords: oil and gas well; tubing; casing; pipe string design

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1. Introduction

Due to low international oil prices and the contradiction between supply and demand of oil and gas resources, The Ministry of Land and Resources of China has put forward the strategic policy of reducing cost and increasing efficiency for the oil and gas fields [1]. In view of the problems of harsh storage conditions, difficult exploitation, complex and variable load environment, and high casing loss rate in oil and gas wells, such as low-permeability wells, deep wells or ultra-deep wells, offshore wells, and unconventional wells [2], higher requirements are put forward for the design and evaluation methods of casing string, such as the cyclic dynamic-load environment caused by frequent switching, acidizing, multi-stage fracturing, steam half and puff, strong injection, and production [3,4]. At the same time, because the casing selection does not highlight the difference in working conditions, the series of failures and hidden risks will further affect the safe production and operation of oil and gas, especially in high-speed (100 million m^3/day) gas-storage injection-production wells [5].

Prior to the advent of the 21st century, the design standards for tubing strings in oil and gas wells were predominantly centered on the strength design of casing strings. Emphasis was given to static strength calculations and verifications during drilling operations [6–8]. Conversely, the design of tubing strings often resorted to numerical calculations, devoid of any standardized design method [9]. However, with the onset of the 21st century, a shift was noted in the research community towards recognizing the significance of a comprehensive design approach encompassing the entire lifecycle of the pipe string. This paradigm shift instigated the development of design methodologies that integrated casing load and safety assessments throughout drilling and production operations [10,11]. Researchers began to establish design standards for pipe strings grounded in strain design and sealing integrity [12,13], specifically underscoring the importance of tubing string design. This progressive evolution in design methodology aimed to confront the dynamic challenges and operational complexities encountered during the entire lifecycle of the tubing string, encompassing drilling, production, and subsequent operations.

Through the integration of strain-based design principles and meticulous sealing considerations, the revised design standards meticulously safeguard the structural soundness and operational dependability of tubing strings. This all-encompassing strategy empowers engineers to comprehensively factor in variables encompassing load fluctuations, temperature oscillations, pressure differentials, and the distinctive attributes of production fluids. This integrative approach significantly heightens the comprehensive efficacy and safety of oil and gas wells. The progression in tubing-string-design methodologies marks a notable stride towards the attainment of optimal operational efficiency, concurrently mitigating the vulnerability to failures across the entire lifecycle of oil and gas wells.

This paper focuses on the characteristics and applicability of various casing-string-design methods and discusses the gradual establishment of a single-strength design method of pipe strings using a strength-strain or strength-seal lifecycle design method. In view of the complex and changeable working conditions in wells, the casing strength, sealing, deformation, and other factors are comprehensively considered, and the design method of the full lifecycle string considering the time dimension is further proposed.

2. Traditional Casing-String-Design Method

The traditional design method for casing strings primarily focuses on strength-based checks, ensuring that the load applied to the casing string remains within its strength limits and within the elastic range. Various approaches have been employed in traditional casing string design, including the safety factor method, boundary load method, maximum load method, American AMOCO casing design method, German BEB casing design method, former Soviet casing design method, and domestic casing-string strength design method [14]. These methods establish criteria for the casing's load-bearing capacity by considering factors such as material properties, well conditions, and operational requirements.

Expanding upon these conventional design techniques, notable progress has been achieved through the evolution of probabilistic reliability design and strength margin design methods. The probabilistic reliability design method integrates statistical analysis and probabilistic modeling to evaluate the casing string's reliability amid unpredictable load conditions and operational uncertainties. This methodology accommodates the variations in loads and material attributes, furnishing a far-reaching comprehension of the casing's performance and dependability. Similarly, the strength margin design method focuses on ensuring an adequate margin of safety between the maximum load applied to the casing string and its ultimate strength. By considering the potential uncertainties and deviations in loadings and material properties, this method allows for a more robust design that provides a sufficient safety margin, reducing the risk of failure. The evolution and implementation of these sophisticated design methodologies within casing string design substantially augment the safety, dependability, and longevity of oil and gas wells. Through the integration of probabilistic factors and strength margins, engineers are empowered to finely tune the design to endure a diverse spectrum of operational situations, thereby alleviating potential vulnerabilities stemming from load fluctuations, downhole pressures, temperature oscillations, and other operational variables.

2.1. Safety Factor Method

To ensure a safe and cost-effective design, the casing string must be designed with a specified safety factor that ensures the casing's strength exceeds the applied external loads.

Given that the axial load increases from the bottom to the top of the well and the extrusion pressure increases from the top to the bottom, the casing string is typically composed of multiple sections with varying strengths. Each section is constructed using different steel grades and wall thicknesses, allowing for a balance between safety and economy. The design of each casing section considers the specific loads it will experience and aims to achieve a minimum safety factor that matches the specified safety factor. This means that the casing sections are designed to provide sufficient strength to handle the expected loads while meeting the safety requirements. By utilizing sections with different strengths, the casing string can effectively manage the varying load conditions throughout the wellbore. The stronger sections are positioned where the loads are higher, ensuring the casing can withstand the axial load and extrusion pressure at those depths. Conversely, sections with lower loads can be constructed using materials with lower strength, optimizing the cost-effectiveness of the design.

2.2. Boundary Load Method

The design method for internal pressure and collapse resistance in this approach follows the same principles as the equal safety factor method. The allowable strength for these design considerations is calculated based on the tensile strength of the casing and the specified safety factor. For the tensile design, the boundary load determined by the tensile strength and safety factor of the casing in the first section is used to select the subsequent casing sections. By doing so, the boundary load between each casing section is consistent, ensuring a smooth transition. However, the safety factor may vary between sections to achieve an optimal design. This design approach aims to avoid selecting casings with excessive residual strength, which would result in unnecessary weight and higher costs. By carefully selecting casing sections based on the specified boundary load and appropriate safety factors, the total weight of the casing string can be reduced while maintaining the required strength and safety. This approach ensures a more reasonable and economical design outcome, considering both structural requirements and cost optimization.

2.3. Maximum Load Method

The design of the casing string takes into account the actual operating conditions and applies a suitable safety factor to ensure its structural integrity. One significant feature of this design approach is the careful consideration given to the calculation of external loads. The calculation of external loads varies depending on the classification of the casing, such as technical casing, reservoir casing, and surface casing. Each type of casing has specific external-load calculation methods tailored to its particular application. By utilizing these specific calculation methods, the design can accurately reflect the actual external load conditions experienced by the casing string. By considering the unique characteristics and operational requirements of each type of casing, the design ensures that the external loads are comprehensively accounted for. This approach provides a more accurate representation of the actual external load conditions in the design process, enhancing the reliability and safety of the casing string.

2.4. Former AMOCO Casing Design Method in the United States

The former AMOCO company in the United States introduced two distinctive casing design methods: the graphical method and the analytical method. These methods exhibit unique features in terms of load analysis and design approaches. Both the anti-extrusion and internal pressure aspects consider the influence of tensile stress. In the load analysis, the casing design takes into account the resistance against extrusion forces as well as the effects of internal pressure. Additionally, the design accounts for the shoulder force when calculating the external load. The graphical method provides a visual representation of the load analysis and design process. It involves plotting load profiles and comparing them with the casing strength limits to determine the suitability of the design. On the other hand, the analytical method utilizes mathematical equations and formulas to analyze and calculate the loads acting on the casing. It provides a more detailed and precise approach to design, incorporating various factors such as tensile stress, extrusion resistance, internal pressure, and shoulder force. These casing design methods proposed by AMOCO offer comprehensive considerations of various load factors, ensuring the integrity and safety of the casing under different operating conditions.

2.5. German BEB Casing Design Method

The German BEB Company introduced a comprehensive set of casing design methods that offer detailed calculation approaches for external loads based on different casing types. One notable feature of these methods is the consideration of various factors when calculating the external load. For instance, when determining the collapse strength of a technical casing due to leakage, the BEB method takes into account buoyancy, calculates the neutral point, and performs a double-extraction stress calculation. The collapse calculation considers the formation pore-pressure value based on the specific gravity of the mud during casing installation. When calculating the resistance to internal pressure, the BEB method specifies that 40% of the kick volume serves as the basis for internal pressure assessment. Additionally, a formation pore-pressure gradient of 0.115 bar/m is selected. Following the composite verification of anti-collapse and internal pressure resistance, an initial casing string structure is chosen. Tension checks are conducted to ensure the integrity of the design. Finally, the casing string structure is determined, and the maximum test pressure at the wellhead is calculated while waiting for solidification. The BEB casing design methods provide a comprehensive and systematic approach to address the specific requirements of different casing types. By considering various factors and employing detailed calculation methods, these design methods ensure the safety and reliability of the casing under various operating conditions.

2.6. Casing Design Method in the Former Soviet Union

The casing design method previously employed in the Soviet Union presents equations for establishing the internal and external pressures across distinct segments of the casing string across diverse temporal intervals and various downhole operational circumstances. Notably, the calculation of the external pressure within the cementing section factors in the unloading effect attributed to the cement sheath. Nevertheless, it is important to highlight that this method does not incorporate the decrease in tensile strength against collapse under biaxial stress conditions. Instead, it specifies that when the tensile stress of the pipe body reaches 50% of the yield strength, the safety factor against collapse should be increased by 10%. The buoyancy of the drilling fluid is not considered when calculating the axial tension. When designing the technical casing, there are two methods available: considering wear and not considering wear. The casing design methodology previously utilized in the Soviet Union furnishes directives and formulas for the precise determination of the internal and external pressures at various junctures along the casing string. Notably, it accounts for significant elements including the unloading impact of the cement sheath. Nevertheless, this method has its constraints, specifically the oversight of diminishing tensile strength under biaxial stress conditions and the disregard of buoyancy effects in axial tension computations. These considerations hold paramount importance in safeguarding the integrity and dependability of casing design across diverse downhole scenarios.

2.7. Domestic Casing-String Strength Design Method

In the 1980s, a group of experienced petroleum experts in China embarked on the development of domestic casing-string strength design standards. Drawing upon advanced practices from abroad, they formulated the "SY/T 5322-1988 Recommended Method for Casing String Strength Design" in 1988 [15]. Building upon this initial work, they further refined and updated the design standards in 2002 with the publication of the "SY/T 5322-2000 Design method of casing string strength" [16]. Subsequently, in 2008, the "SY/T 5724-2008 Design for casing string structure and strength" was introduced [8]. This revised standard incorporated modifications to the casing-string load calculation and strength calculation methods and was developed in conjunction with other relevant standards. It has since been widely adopted and utilized in the industry. The "SY/T 5724-2008" standard [8] provides a comprehensive framework for casing design procedures, offering guidelines for selecting basic parameters and design conditions. Over time, the design method has undergone continuous improvement. Nevertheless, there remain ongoing debates among domestic experts concerning the two-way stress calculation, strength calculation, and design methods outlined in the latest standard. These disagreements highlight the complexity and challenges associated with casing design and the ongoing quest for further refinement and consensus within the industry.

2.8. Probabilistic Reliability Design Method

Using the stress–strength interference theory, it is assumed that the expected load and rated value of the design are functions of two random variables C and L (where C is the load capacity of the casing and L is the estimated value of the maximum load during drilling). The design goal is to ensure that C is greater than L ($C > L$). The size of the probability $P(C > L)$ is the probability of design success PS.

2.9. Strength Margin Design Method

The casing strength margin design must be studied using a combination of safety factor design methods for casing loads (such as the maximum load method) and probabilistic reliability design methods. That is, in the design of the casing string, the safety factor method is still used to determine the casing load, and the probability statistical method is used to study the distribution law of the casing strength performance to clarify the existence of a strength margin in the casing. Then, the strength margin is used to reduce the safety factor in the design of the casing string. Then, reliability analysis is conducted on the casing string to ensure that the casing string remains reliable after reducing the safety factor, meets the use requirements, and ensures that the drilling cost is reduced.

3. Full-Lifecycle String-Design Method

The traditional casing-string-design methods described above have their own strengths and limitations, and their application should be carefully evaluated and optimized based on the specific operational conditions of the oilfield. However, it is worth noting that these methods often prioritize drilling conditions over production conditions. In order to address this imbalance, further research and development efforts have been focused on full-lifecycle string-design techniques that take into account the changes in temperature and pressure during production. For instance, strain-based casing-string-design methods have been developed specifically for thermal recovery wells. These methodologies encompass the thermal expansion and contraction of the casing string in response to temperature fluctuations, thereby ensuring the enduring structural integrity of the wellbore throughout its operational duration. Furthermore, a comprehensive exploration of sealing design techniques has been undertaken for gas-storage injection and production strings. These approaches entail the development of proficient seals to avert gas leakage and uphold operational safety and efficiency. Through the assimilation of factors tied to production and an encompassing perspective of the casing string's entire lifecycle, these advanced strategies strive to elevate the dependability and efficacy of casing designs across diverse operational contexts.

3.1. Design Method of Casing String for Thermal Recovery Wells Based on Strain

The casing-string-design method for heavy oil thermal recovery wells includes casing-string strength design and strain design [17]. That is, when performing casing-string strain design for thermal recovery wells, the casing-string strength design should be performed first, and then the casing-string strain design should be performed. The purpose of the strength design is to make the casing string meet the requirements of the drilling and completion process of heavy oil thermal recovery wells, and the purpose of the strain design is to make the casing string meet the requirements of the production process of heavy oil thermal recovery. Therefore, the strain design of the casing string in heavy oil thermal recovery wells follows two design criteria: strength design criteria and strain design criteria.

The strength design criteria for the casing string are shown in Equation (1):

$$\sigma = \begin{Bmatrix} p_{be} \\ p_{ce} \\ T_e \end{Bmatrix} \leq [\sigma] = \begin{Bmatrix} \frac{p_{bo}}{S_i} \\ \frac{p_{co}}{S_c} \\ \frac{T_o}{S_t} \end{Bmatrix} \tag{1}$$

In the formula, σ is the working stress of the casing string, which is obtained by calculating the effective internal pressure p_{be}, effective external pressure p_{ce}, and effective axial force T_e (including bending stress) borne by the casing string according to SY/T 5724 standard [8]; and the internal pressure resistance p_{bo}, collapse resistance p_{co}, and tensile strength of the casing string T_o are divided by the internal pressure safety coefficient S_i, collapse resistance safety coefficient S_c, and tensile safety coefficient S_t specified in SY/T 5724 standard [8].

The design criteria for casing-string strain are shown in Equation (2):

$$\varepsilon_\Sigma \leq [\varepsilon] = \frac{\delta}{S_s} \text{ or } S_{sc} = \frac{\delta}{\varepsilon_\Sigma} \geq S_s \tag{2}$$

In the formula, ε_Σ is the working strain of the casing string, %; $[\varepsilon]$ is the allowable strain of the casing string, %;δ is the uniform elongation of the casing material, %; S_s is the strain safety factor. This design method has formed the Chinese petroleum and natural gas industry standard "SY/T6952.1-2014 Thermal Recovery Well Casing String Based on Strain Design: Part 1 Design Method" [12].

Aiming at the steam huff and puff thermal recovery conditions in the FC and HD blocks of the western oilfield, a Φ177.8 mm × 8.05 mm TG80H special thread casing was selected. The maximum vertical depth of the eight test wells was 600 m, with a steam injection temperature of 280 °C, a steam injection pressure of 7 MPa, and two rounds per year, and each round had a steam soaking time of 15 days, with a design life of six years. The known parameters of TG80H casing include a mass density of 7.85 g/cm^3, a linear expansion coefficient of 1.21 × 10^{-5} 1/°C, and a uniform elongation of 8%. The yield strength of TG80H casing at 280 °C is 469 MPa, the elastic modulus is 1.61 × 105 MPa, the plastic modulus is 4.00 × 103 MPa, the Poisson's ratio is 0.3, and the creep rate is 5.79 × 10^{-8} %/s. According to the SY/T6952.1 standard and Formula (2), the cumulative strain of the casing was finally calculated to be 3.74%, and the strain safety factor = 8%/3.74% = 2.14 > 1.80; thus, the use of Φ177.8 × 8.05 mm TG80H steel-grade casing for the production casing column can better meet the production conditions requirements. Currently, the production performance of these 8 wells remains favorable, having completed a minimum of 12 cycles of steam injection and up to a maximum of 20 cycles. Following four production cycles, well logging confirmed the absence of casing-column deformation and leakage, thereby addressing the issue of casing damage observed after two cycles of steam injection in this block. This resolution has significantly extended the safe production cycle, contributing to enhanced operational longevity.

3.2. Sealing Design Method for Injection-Production Strings of Gas Storage

When undertaking the design of gas-storage injection and production pipe strings, it is crucial to factor in the repercussions of oscillating loads stemming from varying parameters such as temperature, pressure, and flow rate. This consideration becomes especially significant for pipe strings subjected to alternating tensile and compressive loads. The design procedure should encompass not only structural strength but also the assurance of sealing integrity. This means not only addressing the structural strength design of the pipe string but also ensuring its sealing efficacy. As such, the design process for gas-storage injection and production pipe strings requires a holistic approach, integrating perspectives on both structural strength and sealing integrity. Beyond simply adhering to strength design criteria, the design of these pipe strings should also meet specific sealing design criteria. The strength design criteria include various stages of load and strength analysis, ranging from the tubing's placement, setting the packer, and executing annular pressure tests, to the operations of injection and production. In contrast, the sealing design criteria are primarily concerned with evaluating the string's load-bearing capacity during the oscillating processes of injection and production. These sealing design criteria for injection and production strings can be mathematically expressed using Equations (3) and (4).

$$\frac{F_{et\max}}{T_{to}} \times 100\% \leq \frac{\delta_t}{S_{tt}} \tag{3}$$

$$\frac{F_{ec\max}}{T_{to}} \times 100\% \leq \frac{\delta_c}{S_{tc}} \tag{4}$$

In the formula, F_{etmax} is the maximum axial tensile load of the injection production string, N; F_{ecmax} is the maximum axial compressive load of the injection production string, N; T_{to} is the rated tensile strength of the injection production string, N; δ_t is the tensile efficiency of the injection production string joint under airtight sealing, %; δ_c is the compression efficiency under airtight sealing of the injection production string joint,%; S_{tt} is the tensile safety coefficient of the joint under the gas seal of the injection production string; S_{tc} is the safety factor against compression of the joint under the gas seal of the injection production string.

This design method has formed the Chinese petroleum and natural gas industry standard [13].

Based on the gas-storage reservoir well conditions, as detailed in Table 1, the calculated maximum tensile load and the maximum compressive load endured by the completion casing column under cyclic alternating operational conditions are determined in accordance (Table 2). These calculated loads notably fall well below the rated tensile strength of the casing column, thereby signifying the safety of the casing column's tensile strength design. By further comparing with the rated tensile strength, the requisite joint tensile efficiency and compression efficiency for the completion casing column under operational conditions can be ascertained (Table 2).

Table 1. Operation parameters of the injection-production tubing string in gas storage wells.

Gas Storage Well	Specifications	Tubing Depth m	Geothermal Gradient °C/100 m	Operating Pressure MPa	Daily Gas Injection $\times 10^4$ m^3/d	Daily Gas Production $\times 10^4$ m^3/d
1	Φ114.3 × 6.88 mm P110	2900	2.5	27~32	100	150
2	Φ114.3 × 6.88 mm L80	4735	2.5	29~49	60	80

Table 2. Tensile and compressive efficiency of the injection-production tubing string connection.

Gas Storage Well	Specifications	Thread Type	Rated Tensile Strength kN	Maximum Tensile Load kN	Maximum Compressive Load kN	Tensile Efficiency		Compression Efficiency	
						Operating Conditions	Rated	Operating Conditions	Rated
1	Φ114.3 × 6.88 mm P110	T	1760	1140	985	64%	100%	56%	80%
2	Φ114.3 × 6.88 mm L80	G	1280	880	732	69%	100%	57%	40%

Using Equations (3) and (4) to analyze the data in Table 2 again, the safety factor of the gas-tight threaded joints used in Gas Storage Well 1 is above 1.40, with a high safety margin. The safety factor for the tensile strength of the gas-tight threaded joint used in Gas

Storage Well 2 is 1.45, which is higher than the specified safety factor, but the safety factor for compression is 0.70, far lower than the specified value. That is, the gas-tight threaded joint used in Gas Storage Well 2 is not suitable for this operating condition. However, in the actual operation process, the annulus pressure of Gas Storage Well 2 appeared quickly, while Gas Storage Well 1 operated safely.

(a) Compression efficiency refers to the proportion of the critical compression load at which the tubing thread connection experiences leakage, arising from the concurrent influence of internal pressure and the compression load. This occurs within the range of 95% of the VME (Verified Maximum External) load envelope line and the compression yield load of the tubing.

(b) Tensile efficiency denotes the ratio of the critical tensile load at which the tubing thread connection manifests leakage, resulting from the simultaneous effects of internal pressure and the tensile load. This phenomenon transpires within the spectrum encompassed by 95% of the VME (Verified Maximum External) load envelope line and the tensile yield load of the tubing.

Therefore, the selected gas-tight threaded joint must meet the requirements of Equations (3) and (4) at the same time to ensure the sealing integrity of the casing column.

4. Design Method of Pipe String Based on Time Dimension

Under complex operational scenarios such as multi-stage fracturing in unconventional oil and gas wells, multi-cycle injection and production in gas reservoirs, deep natural oil and gas acid fracturing, and frequent well opening and closing, the wellbore undergoes significant cyclic variations in pressure and temperature.

In a gas storage facility located in the western region, the injection-extraction tubular column used was of Φ114.3 × 6.88 mm specification and made of P110-grade tubing. During the injection-extraction operations, the tubular column experienced maximum tensile loads equivalent to 80% of its yield strength and maximum compressive loads amounting to 60% of its yield strength. In order to analyze the impact of operational fluctuations on the tubular column, a cyclic load test was designed using the MTS testing machine. The test was conducted with a loading rate of 5 MPa/s. The tensile stress during each cycle fluctuated between 75% and 85% of the yield strength with a sustained duration of 4 h. Similarly, the compression stress during each cycle varied between 55% and 65% of the yield strength and was also maintained for 4 h. Considering the alternating tensile and compressive stresses in this experiment, based on the calculation and analysis of material mechanics stability, a standard specimen with $L_0 = 5d_0$ was selected. This can ensure that no instability failure occurs during the application of compressive loads under alternating tensile and compressive conditions. Specimen fabrication and a photograph are shown in Figure 1, and the loading process within one load cycle is illustrated in Figure 2.

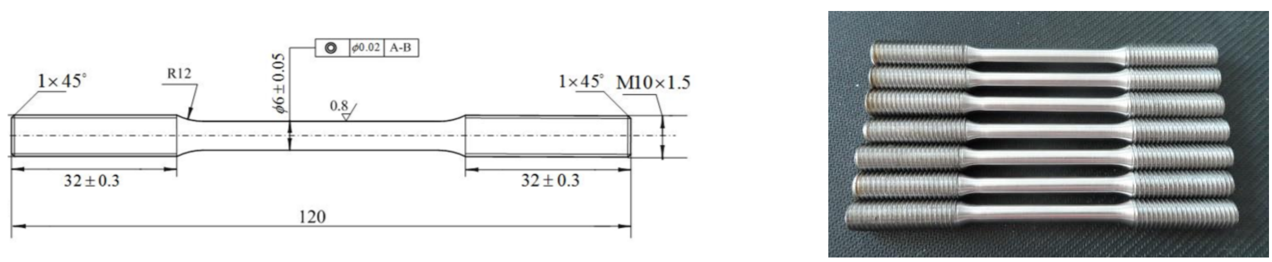

Figure 1. Specimen fabrication and photograph.

These alterations lead to the degradation of oil casing materials' strength, subsequently diminishing the service strength of the string. For instance, tests conducted after 30 weeks of injection and production operation in a gas storage unit confirmed a 9.2% decrease in the yield strength of the injection and production string (Figure 3). This led to a 9.20% reduction in tensile strength, a 9.30% decrease in internal pressure strength, and a 5.46% reduction in the collapse strength of the injection and production string (Figure 4). Furthermore, the casing material strength of a tight oil well demonstrated signs of weakening during multi-stage fracturing. After 30 fracturing operations, the tensile strength, internal pressure resistance, and crush resistance of the 139.7 mm × 7.72 mm P110 fracturing casing string decreased by 5.0%, 5.0%, and 2.43%, respectively (Figure 5).

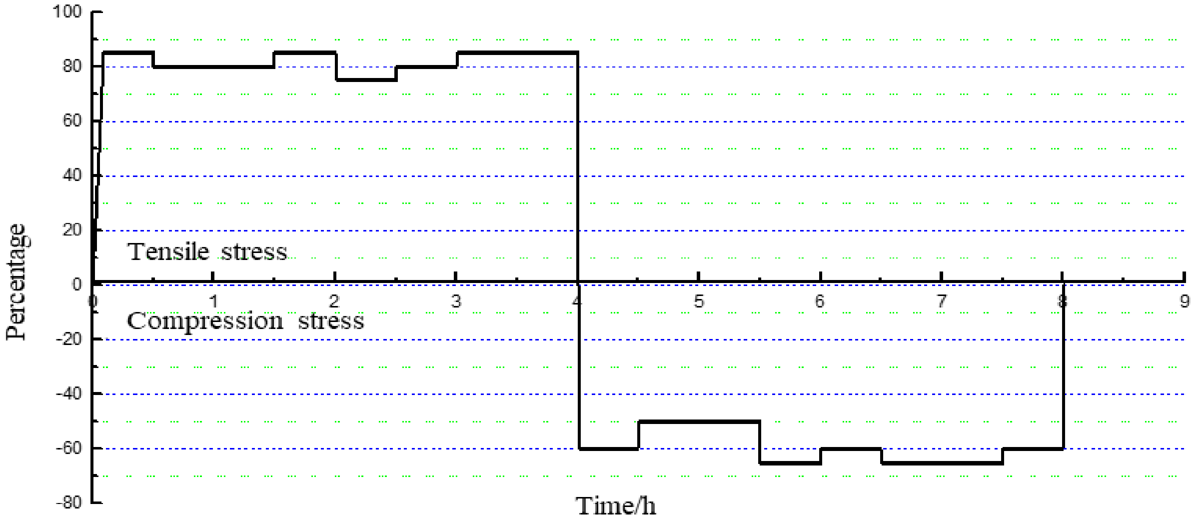

Figure 2. The path of load application.

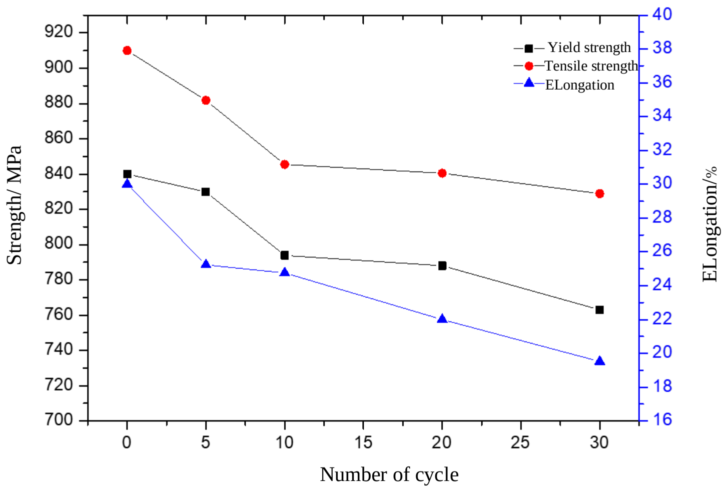

Figure 3. Material properties of tubing after alternating tension and compression cycles.

The previously discussed full-lifecycle string-design method does account for load factors throughout drilling, completion, pressure testing, and production stages. However, it falls short of sufficiently acknowledging the potential impact of temporal strength alterations. Furthermore, it does not encompass a comprehensive method for evaluating casing strength under conditions where both load and temperature fluctuate. Consequently, this design method overlooks the potential decrease in casing strength margin during operation, which could inadvertently elevate production safety risks. Hence, it is of paramount importance to undertake further research and development to address these limitations. An augmented design method for pipe strings, which incorporates a time-based dimension and evaluates strength fluctuations under diverse loads and temperatures throughout the casing's operational lifespan, should be established. This inclusive approach will amplify the accuracy and dependability of casing design, thereby assuring an ample strength margin that can endure the uncertainties associated with varying downhole conditions.

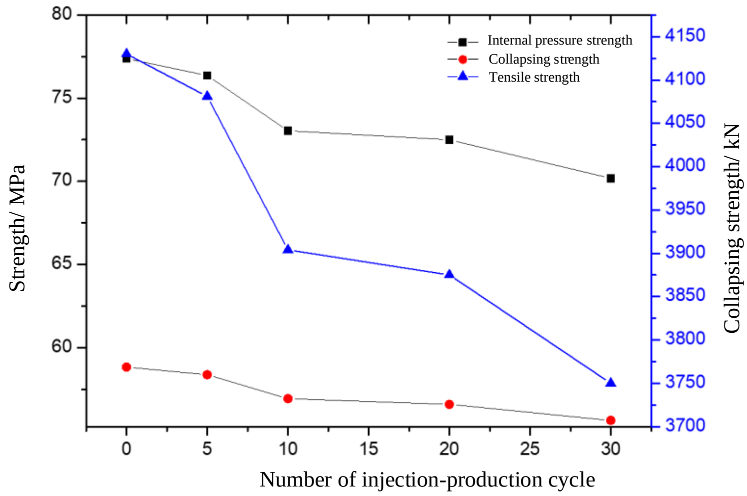

Figure 4. Service performance of tubing in different production periods.

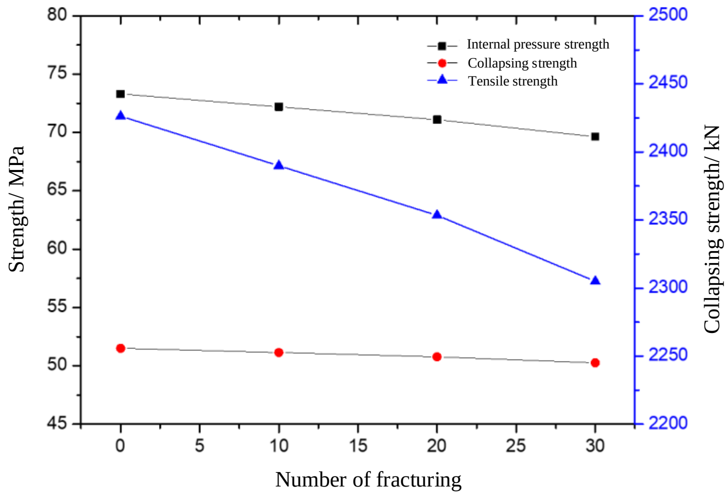

Figure 5. Service performance of Φ139.7 mm × 7.72 mm P110 casing in different fracturing periods.

5. Conclusions

(1) Conventional methodologies for casing string design primarily focus on strength aspects, demanding rigorous assessment and optimization tailored to the unique operational context of the oilfield. However, to ensure holistic casing integrity and optimal performance, an integrated strategy is imperative. This strategy must encompass a spectrum of factors, encompassing but not confined to drilling, completion, and production operation conditions.

(2) Adopting a comprehensive lifecycle string-design methodology presents a more encompassing perspective, considering the casing's operational lifespan in its entirety. This approach extends beyond mere strength considerations, considering the dynamic and evolving downhole conditions spanning drilling, completion, and production phases. Consequently, this integrated approach significantly augments the precision and safety of string design. Furthermore, this holistic approach contributes to the advancement of industry-wide design standards that harmoniously resonate with the contemporary demands and intricacies of the oil and gas sector.

(3) The increasing intricacy of downhole environments, particularly the intensified load cycles experienced by casing strings, inherently results in the degradation of material strength over time. Consequently, it becomes imperative to advance research endeavors aimed at formulating a comprehensive lifecycle string-design methodology and concomitant industry standards that integrate the temporal dimension. Such an approach would

facilitate a more refined assessment of casing performance under diverse loading scenarios across its operational lifespan, thereby ameliorating the vulnerabilities associated with fatigue and material deterioration.

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