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Evaluating Structural Failure in Subsea Equipment: A Comparative Study of API 17G's 2% Strain Criterion and Strain Energy Methods

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Abstract. One of the most commonly used criterion to determine the structural failure of subsea equipment is found in API standard 17G, according to which the collapse takes place if, for any individual component or part, the average equivalent plastic strain in the through section path reaches 2% in the deformed configuration. This is known as "the 2 % strain method". In the present work we investigate alternative methodologies to determine the structural failure of an equipment using approaches based on strain energy. We conduct a series of numerical simulations of structures with prior damaged geometries and determine their structural capacity based on the 2% strain method of API 17G. Those results are used as input for posterior analyses in which the strain energy around the damage is measured (numerically) so we can correlate the ultimate load and the energy absorbed in the vicinity of the damaged area. The results are used for successfully predicting the failure load of different geometries with different damaged areas and a critical discussion is carried out concerning the conservativeness of the API 17G criterion.

Keywords: Strain Energy, Structural Failure, API 17G, Finite Element Method, Subsea Equipment.

1 Introduction

The structural integrity of subsea equipment is critical for the safety and reliability of offshore oil and gas operations. Critical subsea components, such as the riser systems used for well completion and workover operations, are subjected to severe environmental and operational loads. Consequently, their design must anticipate potential failures that could originate from pre-existing geometric damages or defects.

The standard ISO 13628-7, adopted by the American Petroleum Institute as API RP 17G 2nd Edition [1], provides requirements and recommendations for the design and analysis of such systems. A widely used failure criterion within this standard stipulates that structural collapse occurs when the average equivalent plastic strain (PEEQ) across a through-thickness section reaches 2%. While this strain-based method is a well-established benchmark, the standard itself has been evolving from a Recommended Practice into a more comprehensive Specification [2], reflecting ongoing efforts to enhance safety and incorporate current industry practices.

The design philosophy of ISO 13628-7 is centered on a failure mode-based approach, emphasizing the importance of ensuring ductile material behavior to prevent catastrophic brittle fractures [3]. In this context, methods based on strain energy offer a compelling alternative, as they provide a more direct physical measure of the work done to deform and damage a material. Energy dissipation is intrinsically linked to the development of plasticity and ductile failure.

This paper investigates an alternative methodology for assessing structural failure based on strain energy density. The objective is to correlate the well-established 2% PEEQ criterion with energy metrics calculated within characteristic volumes around a defect. A series of non-linear finite element analyses (FEA) are

performed on a generic pipe model with two distinct simulated defect geometries, subjected to both tensile and compressive loads. By analyzing the energy state of the structure at the precise moment of failure defined by API 17G, this work aims to explore the potential of an energy-based criterion as a robust, physically grounded, and possibly more universal indicator of structural collapse, regardless of defect shape.

2 Methodology

To achieve the proposed objectives, a numerical investigation is conducted using the commercial finite element software Abaqus [4]. The methodology involves the development of a detailed FE model, the setup of non-linear analyses, and a structured post-processing workflow to extract and normalize the required data.

2.1 Finite Element Model

A three-dimensional model of a generic cylindrical pipe was developed. To investigate the influence of damage geometry on the energetic response, two types of defects were modeled on the pipe's external surface: a smooth, semi-elliptical flaw, hereafter referred to as the circular defect, and a flaw with sharper geometric features, referred to as the wedge defect. These configurations, shown in Figure 1, were chosen to evaluate the influence of the stress concentrator's severity, with the wedge defect representing a more critical scenario. The material is defined with an elastic-plastic constitutive law representative of high-strength steels used in subsea applications. The model is meshed using three-dimensional, eight-node hexahedral elements, with a refined mesh density in the region around the defect to accurately capture the high stress and strain gradients expected in this area.

2.2 Analysis Setup

Two distinct load cases are simulated to assess the structural response under different loading modes: uniaxial tension and uniaxial compression. The boundary conditions are defined as follows: one end of the pipe is fully fixed, while a concentrated axial force is applied to a reference point coupled to the nodes of the other end. The analyses are performed using a static, general procedure with non-linear geometry effects enabled. The magnitude of the applied load is chosen to be sufficiently large to drive the structure well into the plastic regime, ensuring that the 2% equivalent plastic strain failure criterion of API 17G is reached during the analysis. To ensure a high resolution of the results and generate smooth response curves, the automatic incrementation scheme is controlled by setting the maximum increment size to 0.01. The initial increment is set to 0.001, with a minimum allowed increment of 1E-05 to aid convergence in highly non-linear regions.

As a benchmark for structural failure, the criterion from API 17G is adopted. A nodal set representing a through-thickness path is created at the center of the defect. The average PEEQ across these nodes was monitored throughout the simulation. For the purpose of this study, the "failure instant" was identified in post-processing as the analysis time at which the average PEEQ reached the 2% threshold.

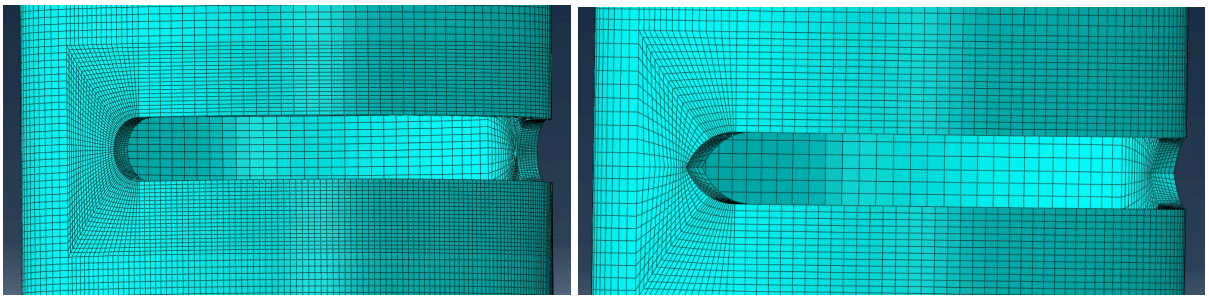
2.3 Data Extraction and Processing

To investigate the energy-based criterion, a series of concentric, cylindrical element sets were defined around each defect, with radii ranging from 40 mm to 300 mm in 10 mm increments. For each of these sets, the total elastic strain energy (ALLSE), plastic dissipation energy (ALLPD), and total element volume (VOL) were recorded as history outputs. Additionally, the concentrated force (CF2) at the reference point was recorded.

Following the simulations, a series of Python scripts were used to automate the extraction and processing of the results. The total energy values (ALLSE and ALLPD) for each radial set were normalized by dividing them by the corresponding total volume of the set, yielding the elastic and plastic energy densities (in J/mm³).

3 Results and Discussion

This section presents the results of the numerical simulations, beginning with a description of the defect geometries shown in Fig. 1. Subsequently, the evolution of the normalized energy densities as a function of the applied force is presented, followed by a comparative analysis of the energy state at the moment of failure, which is determined by the 2% PEEQ criterion.



(a) Circular defect (b) Wedge defect

Figure 1. Configuration of the defects modeled, showing (a) the circular defect (b) the wedge defect

Figure 2 and Figure 3 illustrate the evolution of the normalized plastic dissipation (ALLPD) and strain energy (ALLSE) densities for the circular defect under compression and tension, respectively. A similar analysis for the wedge defect is presented in Fig. 4 (compression) and Fig. 5 (tension). These plots show the complete energetic response of the system throughout the loading history, with the intersection point marking the failure instant according to the API 17G criterion.

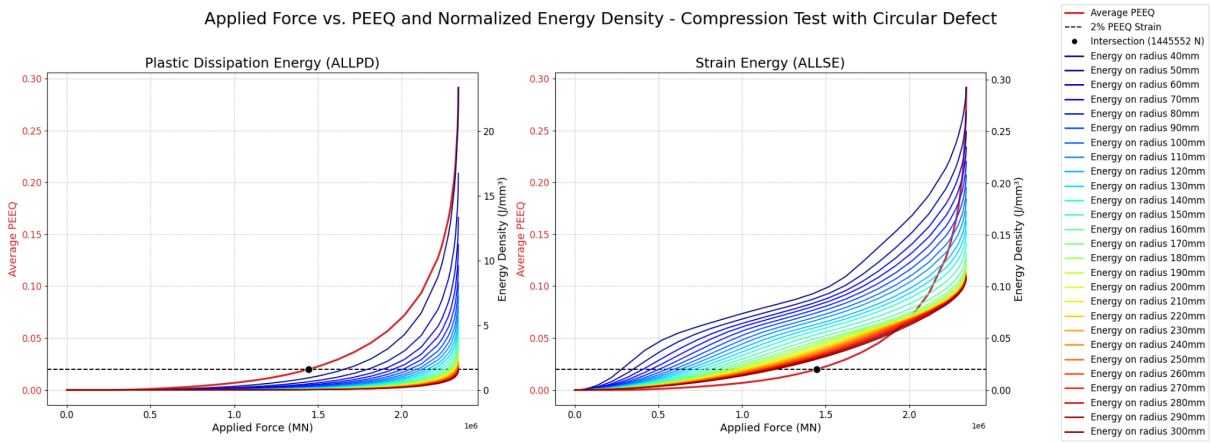


Figure 2. Evolution of normalized plastic dissipation (ALLPD) and strain energy (ALLSE) densities as a function of the applied force for the compression test with a circular defect

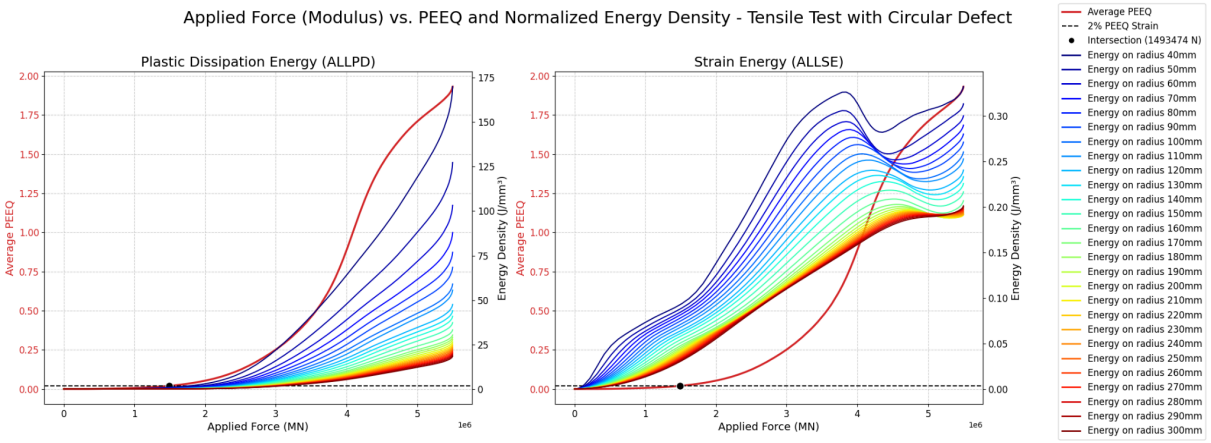


Figure 3. Evolution of normalized plastic dissipation (ALLPD) and strain energy (ALLSE) densities as a function of the applied force for the tensile test with a circular defect.

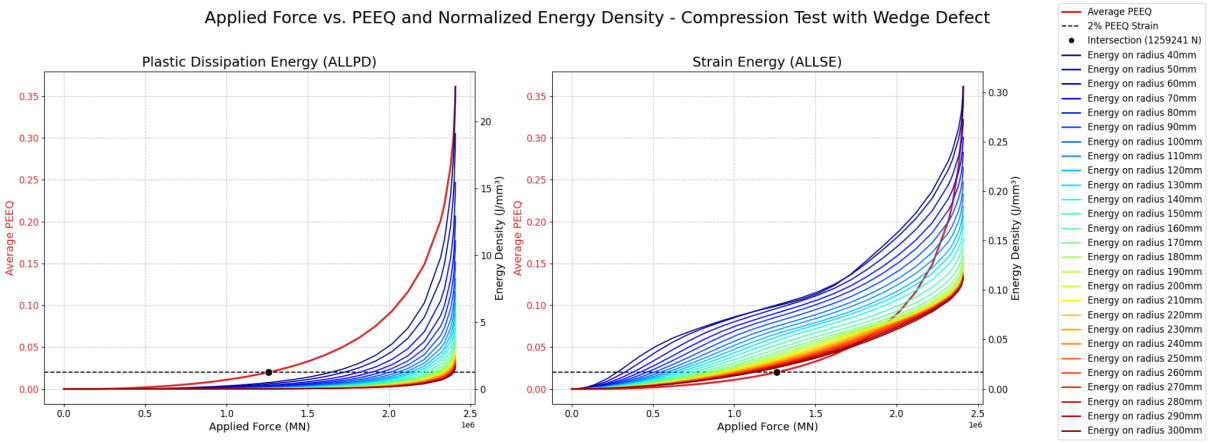


Figure 4. Evolution of normalized plastic dissipation (ALLPD) and strain energy (ALLSE) densities as a function of the applied force for the compression test with a wedge defect

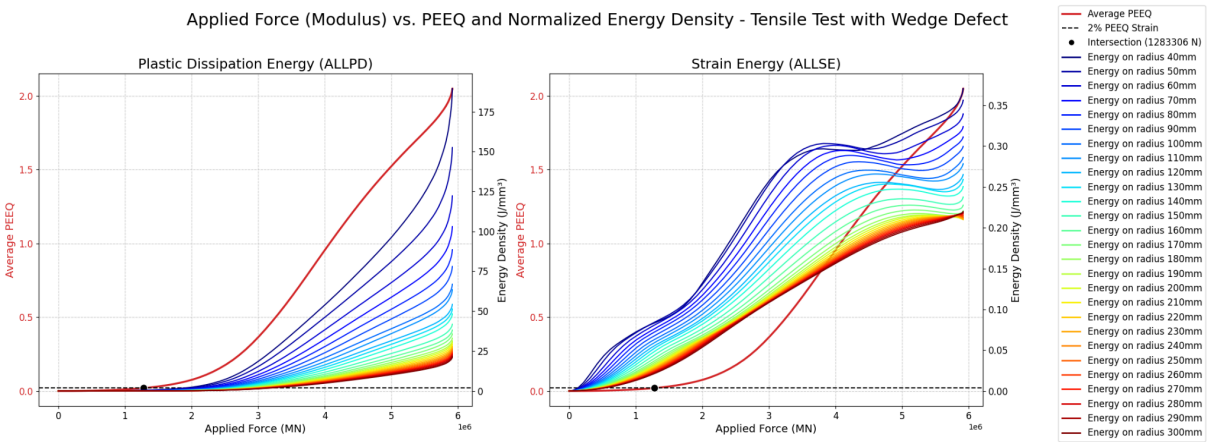


Figure 5. Evolution of normalized plastic dissipation (ALLPD) and strain energy (ALLSE) densities as a function of the applied force for the tensile test with a wedge defect

The primary results of this study are synthesized in Fig. 6 and Fig. 7, which plot the calculated energy densities as a function of the set radius at the precise moment of failure for the circular and wedge defects, respectively. These plots allow for a direct comparison between the tension and compression load cases for each defect geometry.

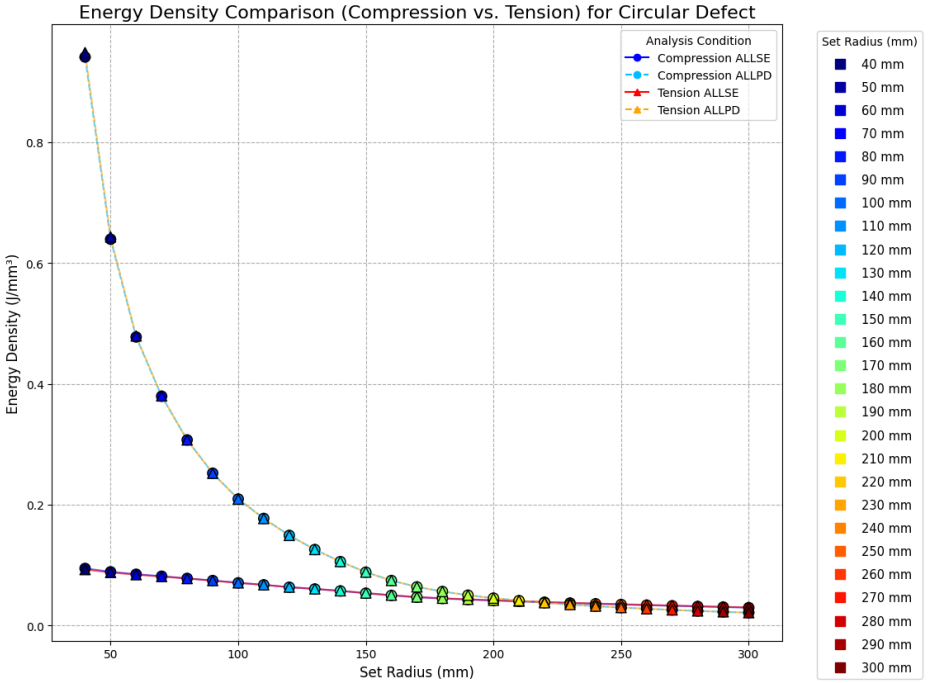


Figure 6. Comparative plot of energy density as a function of the set radius for both tension and compression cases, extracted at the 2% PEEQ failure instant, for the circular defect

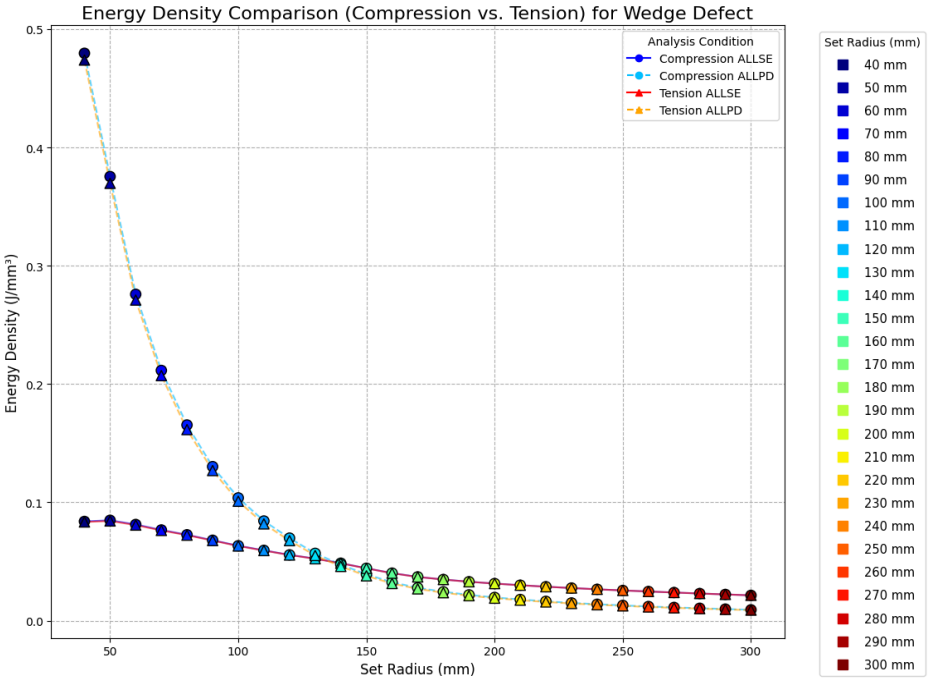


Figure 7. Comparative plot of energy density as a function of the set radius for both tension and compression cases, extracted at the 2% PEEQ failure instant, for the wedge defect

From these final plots, three major conclusions can be drawn. First, a strong localization effect is evident for both defect types. The energy density is extremely high for small radii and decays rapidly as the measurement radius increases, eventually approaching an asymptotic value. This behavior quantifies the extent of the plastic zone, demonstrating that the energy associated with the failure event is concentrated in a small volume immediately surrounding the defect.

Second, the results show a remarkable symmetry between the tension and compression cases for both the circular and wedge defects. For any given radius, the calculated energy densities for both ALLSE and ALLPD are nearly identical, regardless of the loading direction. This suggests that the energy state of the characteristic volume at the point of failure is independent of the loading mode.

Third, a comparison between Fig. 6 and Fig. 7 reveals that the defect geometry has a minimal influence on the energy density signature at failure. Although the absolute load capacity may differ, the normalized energy profiles as a function of the radius are strikingly similar for both the smooth circular defect and the sharper wedge defect. This finding reinforces the robustness of the energy-based approach, suggesting that the energy density within a characteristic volume could be a universal failure parameter, less sensitive to the specific geometry of the damage than traditional stress or strain metrics.

To directly quantify the influence of the defect's severity, the total energy density (ALLSE + ALLPD) of the wedge defect was divided by that of the circular defect for each corresponding case. The results are presented in Fig. 8. The plot shows the dimensionless ratio of total energy density as a function of the set radius. Both tension and compression curves converge to a stable ratio of approximately 0.6 for larger radii. This suggests that the sharper stress concentration of the wedge defect localizes the plastic deformation more intensely, leading to the failure criterion being met with about 40% less average energy density in the surrounding volume. This ratio provides a quantitative measure of the defect's severity, although further studies with varying geometries and materials would be necessary to validate it as a more general parameter.

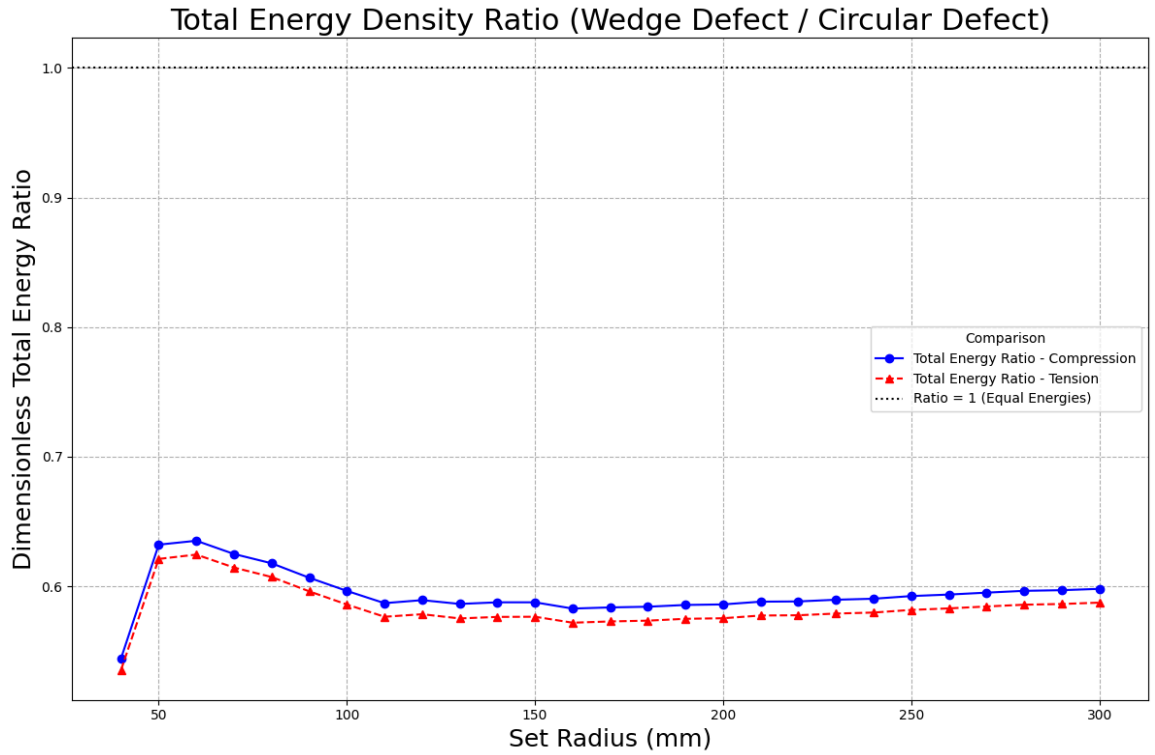


Figure 8. Ratio of total energy density (Wedge Defect / Circular Defect) as a function of the set radius for tension and compression cases

4 Conclusions

This numerical study investigated the viability of an energy-based methodology for structural failure assessment as an alternative to the 2% average PEEQ criterion found in API 17G [1]. By analyzing the energy density in concentric regions around two different simulated defect geometries (circular and wedge), several key conclusions were drawn. The energy state of the structure at the point of failure exhibits a strong localization effect, allowing for the quantification of the plastic zone size. Furthermore, a notable symmetry was observed in the energy density profiles between tensile and compressive loading cases for both defect types, suggesting that the energy required to bring a characteristic volume to a state of failure is independent of the loading mode. Most importantly, the energy density profiles were found to be remarkably similar for both the circular and wedge defects, allowing for the establishment of a consistent energy ratio that quantifies the influence of the defect's geometric severity. These findings support the potential of an energy-density-based criterion as a robust, physically grounded, and mode-independent indicator of structural failure, warranting further investigation as a supplement or alternative to existing standards.

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References

[1] API RP 17G, Recommended Practice for Completion/Workover Risers, Second Edition, American Petroleum Institute, Washington, D.C., 2006 (Identical to ISO 13628-7:2005).
[2] Stawaisz, R., Muff, D. A., and Skeels, B., "API 17G Specification for Subsea Well Intervention Equipment", Offshore Technology Conference, OTC-25402-MS, Houston, Texas, USA, May 2014.
[3] Kirkemo, F., "Structural Design of Metallic Components in ISO 13628-7", Proceedings of the ASME 2014 Pressure Vessels & Piping Conference, PVP2014-28712, Anaheim, California, USA, July 2014.
[4] Dassault Systèmes Simulia Corp., Abaqus Analysis User's Manual, Providence, RI, USA, 2024.