CAAP Quarterly Report

12/30/2025

Project Name: Risk-informed and uncertainty-aware strain capacity prediction model development and verification for vintage pipelines

Contract Number: 693JK32550003CAAP

Prime University: University of Dayton

Prepared By: Hui Wang, Ph.D., hwang12@udayton.edu, 937-229-2039

Hao Wang, Ph.D., hw261@soe.rutgers.edu, 848-445-2874

Lei Wang, Ph.D., wang4li@ucmail.uc.edu, 513-556-7649

Homero Castaneda, Ph.D. hcastaneda@tamu.edu, 979-458-9844

Yong-Yi Wang, Ph.D. ywang@cres-americas.com, 614-376-0765

Reporting Period: [10/01/2025 – 12/30/2025]

Project Activities for Reporting Period:

Items Completed During this Quarterly Period

Per the contract, Task 1 is associated with the first quarterly report. The following activities have been completed

Item #	*Task #*	*Activity/Deliverable/Title*
1	1	1st Quarterly Report (the 8-page main text)
2	1	Comprehensive literature review report (the Appendix)

Items in Progress During this Quarterly Period

During this performance period, we have briefly started the preparation work for *Task #2 Identify critical factors* and *Task #3 lab testing experiments* based on the literature review outcomes from Task 1 and these items are still on-going at the very early stage hence is not presented in this report and will be covered in the following quarterly report.

Item #	*Task #*	*Activity/Deliverable/Title*
1	2	Define candidate factors from literature
2	3	Start to design testing matrix

Overall Summary

During the first quarter of the project period, the research team focused on project initiation, coordination, kick-off, and foundational technical activities consistent with the approved Statement of Work in the original proposal. Primary efforts during this reporting period concentrated on establishing the technical baseline for the project through a comprehensive literature review, confirming project scope and deliverables, and initiating coordination among project partners and stakeholders. These activities were designed to ensure that subsequent modeling, data integration, and experimental tasks are built upon a rigorous and well-documented understanding of current practices, limitations, and research gaps relevant to pipeline safety and risk assessment. More detailed task-based summaries are listed below.

Task #1 Objective:

During the first quarterly reporting period, the project team focused on Task #1: Literature Review, as defined in the approved technical proposal. The primary objective of Task #1 is to establish a rigorous technical and regulatory foundation for the development of a risk-informed and uncertainty-aware strain capacity prediction and verification framework for vintage pipelines.

This task aims to systematically assess existing knowledge related to strain-based design and assessment, displacement-controlled failure mechanisms, material behavior of vintage pipelines, geotechnical loading conditions, and uncertainty treatment in current analytical and probabilistic models. Particular emphasis is placed on *identifying limitations* in current industry practice and research approaches that *motivate the need for improved strain capacity prediction models that explicitly incorporate uncertainty and risk considerations*.

The outcomes of Task #1 are intended to directly inform subsequent project tasks, including existing data identification and availability assessment for Task 3, factor identification for Task 2, model development, and experimental and analytical verification activities in the following tasks.

Scope of Work

The scope of work for Task #1 encompassed a comprehensive and structured review of relevant federal regulations, industry standards, technical reports, and peer-reviewed research articles related to strain capacity and integrity assessment of pipelines subjected to geohazard- and displacement-induced loading.

The review covered the following topical areas:

- Regulatory frameworks and guidance related to pipeline integrity, strain-based assessment, and geohazard management;
- Industry practices for strain demand and strain capacity evaluation, including treatment of vintage pipeline materials;
- Experimental and analytical methods for characterizing pipeline deformation, fracture, and failure under displacement-controlled loading;
- Existing probabilistic and reliability-based modeling approaches for strain capacity prediction;
- Treatment of epistemic and aleatoric uncertainty in material properties, loading conditions, and model assumptions;
- Gaps in existing verification and validation methodologies for strain capacity models.

The literature review was conducted collaboratively across project partners, with each institution contributing domain-specific expertise. More detailed, Rutgers University (RU) team focused on critical factors influencing strain capacity; Texas A&M University (TAMU) team led the review of strain capacity testing approaches, particularly those applicable to vintage steels and girth welds;

University of Dayton (UD) team assessed key deficiencies and implementation barriers in current SBDA methodologies regarding uncertainty quantification; University of Cincinnati (UC) team conducted review on gaps in risk metrics for displacement-controlled pipeline failure.

Summary of Literature Review Work Performed

During this reporting period, the project team completed an extensive literature review synthesizing current state-of-practice and state-of-the-art knowledge relevant to strain capacity prediction for vintage pipelines. The review identified key trends and limitations in existing approaches.

The literature indicates that current strain capacity models often rely on simplified assumptions regarding material behavior, loading paths, and boundary conditions, which may not adequately represent the complex deformation mechanisms experienced by vintage pipelines subjected to geohazard-induced displacement. Many existing methods are deterministic in nature and do not explicitly account for uncertainty in material properties, defect characteristics, soil-pipe interaction, or loading demand.

Recent research advances demonstrate the potential of probabilistic and reliability-based frameworks to improve strain capacity assessment; however, their adoption in practice remains limited. Gaps were identified in the integration of experimental data, limited full-scale testing results, and field observations into model calibration and verification processes. Additionally, there is a lack of standardized approaches for quantifying and propagating uncertainty through strain capacity prediction models in a risk-informed manner.

These findings underscore the need for the proposed project's focus on developing and verifying strain capacity prediction models that are explicitly uncertainty-aware and suitable for application to vintage pipelines. Detailed summaries of reviewed regulations, standards, analytical methods, experimental studies, and identified research gaps are provided in Appendix A: Comprehensive Literature Review.

Project Financial Activities Incurred during the Reporting Period:

A cost breakdown list of the expenses during this quarter in each of the categories according to the budget proposal is provided below:
Sponsor Number: 21-000370
Prime Contract Number: 693JK32550003CAAP
Contract Value: $1,000,000.00
Funded Value: $1,000,000.00
Cost-share amount: $261,432

	Current Period Actual	Year To Date Actual	Contract To Date Actual
Salaries & Wages FTFac-Non-Tenure	$2,030.49	$2,030.49	$2,030.49
Benefit-Faculty/Staff	$478.99	$478.99	$478.99
Total Labor Cost	$2,509.48	$2,509.48	$2,509.48
Total Indirect Cost	$1,264.78	$1,264.78	$1,264.78
Total Expense	$3,774.26	$3,774.26	$3,774.26
Cost-share	$0	$0	$0

The full-time labor hour cost is for the senior personnel Dr. Yusheng Jiang. The UD team has recruited a PhD student Joseph Yoon Young Lee, whose graduate assistant contract will start from Jan 15th. The PI's research time will be charged during the academic semester 2026 Spring using the cost-share account.

We have been working on subcontracting processes with TAMU, UC, and RU. Currently, we have set up the subcontract with RU and TAMU and sent the document to UC for signing. It is expected to have the paperwork finished in the early January and the subcontractors will start to charge the project accordingly.

Project Activities with Cost Share Partners:

Overview

During the first quarterly reporting period, the University of Dayton (UD), as the prime institution, conducted project coordination activities with its cost-share university partners, Rutgers University (RU), University of Cincinnati (UC), and Texas A&M University (TAMU), to support effective initiation of the project and execution of Task #1 (Literature Review). These coordination efforts were consistent with the project management plan outlined in the approved technical proposal and were documented through a series of project meetings.

The primary objectives of these coordination activities were to confirm partner roles and responsibilities, align the scope and focus of Task #1 across institutions, and ensure consistency between the literature review effort and the project's overarching goal of developing a risk-informed and uncertainty-aware strain capacity prediction and verification framework for vintage pipelines. Coordination meetings also served to establish communication protocols, review task sequencing, and discuss how Task #1 outcomes would inform subsequent tasks, including data identification, model development, and verification activities.

Activities

[Project internal discussion Dec 18, 2025 09:30 AM EST]

Attendees: Hui Wang, Yusheng Jiang, Banglin Liu, Homero Castaneda, Ulises Martin, Yong-Yi Wang, Hao Wang, Joseph Yoon Young Lee, Lei Wang.

Summary: The meeting focused on discussing the scope and deliverables of this CAAP project, with particular emphasis on addressing questions raised during the kickoff meeting about longitudinal stress (girth weld failures) and circumferential stress (seam weld failures). The team, including representatives from Texas A&M, Rutgers, and Cincinnati universities, along with CRES researchers, discussed how to define the project's scope and testing matrix. They agreed to use the first quarterly report as a communication vehicle to clarify research scope expectations with PHMSA, particularly regarding the investigation of seam weld failures, which is not mentioned in the original proposal. The team also discussed experimental testing requirements, with TAMU Postdoc Dr. Ulises tasked to review past research and identify suitable test samples, while considering the limited budget of 12-15 samples for new testing. The team established a new bi-weekly meeting schedule for Fridays from 12-1pm, with separate meetings planned for different team components.

[Project internal kick-off meeting Nov 21, 2025 12:00 PM EST]

Attendees: Hui Wang, Yusheng Jiang, Gary Choquette, Sreelakshmi Sreeharan, Shujun Yu, Lei Wang, Banglin Liu, Hao Wang, Homero Castaneda.

Summary: The team discussed plans for an upcoming public kickoff meeting with PHMSA and outlined the structure of monthly and quarterly project updates, including the use of various collaborative tools and systems. We have reviewed a three-year project involving experiments, risk assessment, and model development, with detailed discussions on numerical simulations, model validation, and data-driven approaches. The team addressed project timelines, subcontract processes, and resource sharing, emphasizing the importance of collaboration with universities and industry partners. PRCI provided important input regarding industry perspectives on strain-based assessment of vintage pipelines, current challenges in strain capacity modeling, and expectations for model applicability and verification, which helped reinforce the practical relevance of the proposed research and informed planning for future industry engagement. Also, a plan for forming a TAP is discussed.

Accomplishments

Through coordinated efforts among UD, RU, UC, and TAMU during this reporting period, the project team successfully aligned and executed the literature review activities associated with Task #1. Each cost-share partner contributed domain-specific expertise consistent with the approved proposal. UD team focused on reviewing literature related to uncertainty quantification, probabilistic modeling, and risk-informed assessment approaches relevant to strain capacity prediction. UC team concentrated on geotechnical loading mechanisms, soil–pipe interaction, and displacement-controlled strain demand considerations for pipelines subjected to ground movement. TAMU team emphasized material behavior, corrosion effects, and integrity considerations for vintage pipeline steels under large strain conditions. RU team focused on the major factors affecting the strain capacity of vintage pipelines.

The UD team also led the integration and synthesis of partner contributions, ensuring consistency in terminology, scope, and technical focus across the compiled literature review. Coordination communications facilitated cross-institutional discussion of key findings, identified knowledge gaps, and clarified how reviewed methodologies and data sources would be leveraged in later project tasks. These discussions also helped refine expectations for experimental, analytical, and probabilistic components planned for subsequent phases of the project.

In addition to technical alignment, the coordination activities established a clear framework for ongoing collaboration, including regular communication, documentation practices, and planning for future data sharing and model integration. As a result, the project completed Task #1 on schedule, with a comprehensive literature review delivered as the Q1 technical appendix and a well-defined pathway established for transitioning into Task #2 activities in the next reporting period.

Team management (Personnel summary)

As mentoring is a key component of this CAAP program, in this quarter, we have recruited the following mentees into our team:

UD team has recruited two Postdocs: Sreelakshimi Sreeharan, Yusheng Jiang, and one PhD student: Joseph Yoon Young Lee, expected graduation May 2029.

UC team has recruited one PhD student Roshan Prajapati, expected graduation is May 2028.

RU team has recruited one PhD student Shujun Yu, expected graduation is Oct. 2029.

TAMU team has recruited Postdoc: Dr. Ulises Martin, and one PhD. Student: Abdul Mannan expected graduation is Dec 2028.

Project Activities with External Partners:

Overview

During the first quarterly reporting period, the project team engaged with external partners to support effective project initiation and alignment with industry needs. External engagement during this period primarily involved coordination with Pipeline Research Council International (PRCI), PRCI member companies (the project's Technical Advisory Panel (TAP)), ROSEN, and also PHMSA technical task inspectors. These interactions were conducted and structured to ensure that the project's objectives, technical scope, and planned deliverables remain aligned with current industry challenges and PHMSA safety priorities related to strain capacity assessment of vintage pipelines.

The primary external engagement activity during this reporting period was the public kick-off meeting. This meeting established a common understanding of project goals, clarified expectations for industry participation, and set the foundation for ongoing collaboration throughout the project duration.

Activities

[Public Kick-off Meeting Dec 10, 2025 01:00 PM]

<u>*Attendees*</u>: Hui Wang, Angie Mallahan, Yusheng Jiang, Homero Castaneda, Hao Wang, Jeffery Gilliam, Nusnin Akter, Sreelakshmi Sreeharan, Jones Stephen, Ulises Martin, Shujun Yu, Yong-Yi Wang, Gary Choquette, David Bastidas, Lei Wang, and all TAP members.

<u>*Summary*</u>: The team organized and conducted a public kick-off meeting with participation from PHMSA representatives, PRCI representatives, TAP members from PRCI member companies, ROSEN, and other invited stakeholders. The public kick-off meeting provided an overview of the project's motivation, technical approach, management structure, and anticipated outcomes. External partners from industry were invited to provide input on industry needs, practical constraints, and expectations for model usability and verification, particularly with respect to strain-based assessment of vintage pipelines.

PRCI facilitated communication with its member companies and provided guidance on effective TAP engagement. ROSEN participated in discussions related to industry practices, inspection data considerations, and potential future coordination related to model validation and applicability. Meeting discussions also addressed plans for future engagement, including periodic technical updates, review meetings, and opportunities for industry feedback as the project progresses.

Accomplishments

The project team successfully established an initial framework for industry and stakeholder collaboration. The kick-off meetings clarified the roles of PRCI, TAP members, and ROSEN in supporting the project, particularly in providing industry perspective, technical feedback, and guidance on practical relevance and implementation considerations.

Input from PRCI and TAP members reinforced the importance of developing strain capacity prediction models that are transparent, uncertainty-aware, and applicable to real-world vintage pipeline conditions. Feedback from ROSEN and other TAP members helped inform expectations regarding data availability, inspection practices, and verification needs, which will be considered in subsequent project tasks.

These early engagement activities ensured alignment between the research team and external partners and established a clear pathway for continued collaboration throughout the project. The outcomes of the internal and public kick-off meetings position the project to effectively incorporate industry input into future data identification, model development, and verification activities while maintaining alignment with PHMSA CAAP objectives.

Potential Project Risks:

During the project kick-off meetings, the research team reviewed and reiterated the potential project risks identified in the approved technical proposal, with particular emphasis on risks associated with pipeline sample acquisition and testing. These risks are inherent to experimental and data-driven research involving vintage pipeline materials and are being actively monitored to ensure timely mitigation and minimal impact on project schedule and technical objectives.

A primary risk discussed during the meetings relates to the availability and timely acquisition of representative vintage pipeline samples required for experimental testing and model verification. To address this risk, the team emphasized early coordination with PRCI and proactive planning to ensure that testing can proceed using available and representative materials.

The project team highlighted the importance of leveraging industry and research resources, including archived test data and existing sample inventories, while maintaining flexibility in test planning and model development. In this context, the team is working closely with PRCI to develop a clear understanding of samples needed from literature study and the available samples within PRCI’s inventory and their suitability for the project’s experimental and analytical needs. This ongoing effort is intended to reduce uncertainty related to sample procurement and to support informed decision-making regarding test matrix design.

Additional future possible risks items discussed include the potential for unexpected test behavior, computational demands associated with advanced numerical and probabilistic modeling, and limitations in available geotechnical or loading data needed for integrated strain demand and risk assessment. The team emphasized that these risks will be addressed through adaptive modeling strategies, iterative testing and analysis, and close coordination among project partners.

Throughout the project, risk monitoring and mitigation will be conducted with regular input from the project’s TAP and PHMSA. Feedback from these stakeholders will be used to reassess risk priorities, refine mitigation strategies, and ensure alignment with PHMSA CAAP objectives. At this stage, no risks have been identified that threaten the overall feasibility of the project, and the team is actively implementing management practices to address potential challenges as the project progresses.

Future Project Work:

The project is progressing according to the approved schedule. Following completion of Task #1 (Literature Review), the research team is currently transitioning into Task #2 and initiate preparatory activities for Task #3. Planned work over the next 30, 60, and 90 days is summarized below.

Next 30 Days: The research team have already initiated Task 2 by starting to define candidate critical factors influencing strain capacity in vintage pipelines, drawing directly from the completed literature review, relevant codes and standards, and prior PRCI and CRES studies. Initial coordination with PRCI, CRES, and TAP members will support expert input on factor relevance, measurability, and applicability to vintage pipeline conditions. In parallel, the team will refine detailed sample requirements and continue engagement with PRCI to assess the availability of vintage pipeline materials from existing inventories.

Next 60 Days: The team will evaluate the significance and interdependencies of identified critical factors using engineering judgment, expert feedback, and preliminary sensitivity analysis informed by semi-empirical SBDA frameworks. Development of the initial *Critical Factor Matrix* will begin, with prioritization of factors to guide experimental design in Task 3. Continued coordination with TAMU will ensure alignment between factor identification and early laboratory planning, while regular engagement with PHMSA and TAP members will support oversight and alignment with project objectives.

Next 90 Days: Task 2 activities will advance toward refinement of the *Critical Factor Matrix*, incorporating feedback from expert discussions and early planning insights from Task 3. The team will document identified data needs, gaps, and practical constraints relevant to vintage pipelines, and prepare for iterative feedback between Task 2 and Task 3 as laboratory testing begins. Ongoing coordination meetings and experiments coordination reporting to PHMSA will ensure that factor prioritization, sample planning, and experimental objectives remain aligned across the research team, industry partners, and PHMSA.

Potential Impacts to Pipeline Safety:

We are preparing a draft conference paper to be submitted to the ASCE UESI Pipelines 2025 Conference, and a technical review article to be submitted to the Journal of Pipeline Science and Engineering based on the outcomes from the literature review.

Appendix A: Comprehensive Literature Review

A.1. Objective

The objective of this appendix is to critically review and synthesize existing experimental evidence, analytical methods, and assessment practices relevant to strain-based design and assessment (SBDA) of vintage pipelines. Drawing on contributions from four university teams and previous seminal work done by Center for Reliable Energy Systems (CRES), this review examines factors governing strain capacity of vintage materials and welds, laboratory and full-scale testing approaches, treatment of uncertainty in strain demand and capacity estimation, and the adequacy of current risk metrics used in SBDA applications. By consolidating these perspectives, the appendix aims to clarify current capabilities and limitations of SBDA practice specifically for vintage pipelines and to identify technical gaps that constrain its consistent and reliable implementation. This work will set up the foundation of the following technical tasks.

A.2. Background and Introduction

A significant portion of pipeline infrastructure in North America consists of vintage pipelines constructed prior to the implementation of modern design standards, material specifications, and quality control practices. Therefore, it is obvious that these pipelines will exhibit considerable variability in material properties, undocumented construction details, and aging-related degradation mechanisms such as corrosion defects and girth weld imperfections. Similarly, many of these pipeline networks are located in geohazard-prone regions where ground movement caused by natural hazards like floods, landslides, frost heave and seismic activity imposes large displacement-controlled loading. Under such conditions, pipelines may undergo substantial plastic deformation, rendering traditional stress-based integrity assessment approaches inadequate. Approximately USD $391 million in property damage was reported in the United States between 2002 and 2021, underscoring the significant threat to buried pipelines (Schell et al., 2024).

SBDA is an engineering approach in which strain (deformation), rather than stress (load), is used as the primary parameter for evaluating the structural integrity and safety of pipelines. Prior to the adoption of SBDA, pipeline integrity evaluations relied primarily on stress-based design limits, pressure-based fitness-for-service methods, and deterministic pipeline-soil interaction (PSI) analyses. These approaches assessed safety using allowable stress, burst pressure, or empirical ground movement limits, implicitly assuming elastic behavior and neglecting plastic strain effects. Although advanced numerical and fracture-mechanics tools were occasionally applied, they lacked integration into systematic integrity frameworks and did not account for uncertainty in strain capacity assessment. Consequently, conservative assumptions or non-uniform criteria were often adopted when addressing ground movement hazards, leading either to overly conservative mitigation measures or insufficient protection against strain-driven failure. The inability of these methods to reliably evaluate displacement-controlled loading, girth-weld behavior, and combined damage mechanisms ultimately motivated the wider application of SBDA.

Pipeline service has become an integral part of urban development. Aging pipeline infrastructure, particularly vintage pipelines constructed prior to modern design and quality standards, faces increasing integrity challenges due to material degradation, undocumented construction practices, and exposure to displacement-controlled loading from geohazards. So, SBDA has emerged as an important alternative to traditional stress-based methods for pipelines subjected to displacement-controlled loading, such as that induced by geohazards, ground movement, or differential settlement. Unlike stress-based design, which evaluates integrity based on allowable stress limits, SBDA evaluates pipeline performance by comparing imposed strain demand with the strain capacity of the pipe and its welds (Wang et al., 2014). While significant progress has been made in modeling strain capacity and strain demand, the manner in which SBDA outputs are translated into meaningful risk metrics remains inconsistent, particularly for vintage pipeline systems subject to considerable amounts of uncertainties.

In most SBDA applications, integrity decisions are based on deterministic comparisons between estimated strain demand and allowable or critical strain limits. These comparisons implicitly represent risk but do not formally define or quantify it in a manner consistent with modern risk-based integrity management frameworks. This limitation is particularly consequential for vintage pipelines, where material properties, weld quality, and historical operating conditions are often poorly documented (Jia et al., 2020; Wang et al., 2020). It is observed that a comprehensive risk assessment framework for vintage pipe SBDA is missing. The recent development of SBDA with a focus on vintage pipelines is explained below.

A.2.1. SBDA Framework development

One of the foundational contributions to SBDA was provided by Wang et al., (2014), who proposed an overall framework integrating strain demand estimation with tensile and compressive strain capacity. The framework emphasized that strain demand and strain capacity are interdependent and influenced by common factors such as internal pressure, geometry, material behavior, and modeling assumptions. The authors also highlighted inconsistencies in industry practice, including differences in strain definitions, gauge lengths, and numerical modeling approaches, underscoring the need for a unified SBDA methodology. We have summarized the more details about the SBDA framework in section A.6 of this document.

A.2.2. Strain Capacity Characterization

Extensive research has focused on quantifying tensile strain capacity (TSC) and compressive strain capacity (CSC), particularly for pipelines with girth welds, flaws, and material imperfections. Experimental programs using curved wide plate and full-scale bending tests demonstrated that TSC is highly sensitive to weld strength mismatch (the welded material has a different strength (yield or tensile) than the surrounding base metal), flaw geometry, internal pressure, and strain hardening behavior, especially in vintage pipelines with limited documentation (Agbo et al., 2019; Wang et al., 2020). Numerical methods, including elastic-plastic finite element analysis and extended finite element methods (XFEM), have been successfully calibrated against experimental data to simulate ductile fracture and crack propagation in vintage steels such as X52 (Elyasi et al., 2021; Jang et al., 2019). Similarly, CSC has been investigated through experimental and numerical studies focusing on local buckling, wrinkle formation, and ovalization. Refined CSC models have improved representation of geometry imperfections, loading sequence, and internal pressure effects, while revealing significant variability among existing models (Liu et al., 2014; Zhang et al., 2014). Additional studies have examined the influence of corrosion anomalies on both tensile and compressive strain capacity, demonstrating that metal loss can significantly reduce allowable strain limits and must be considered explicitly in SBDA (Zhou et al., 2018). More detailed discussion about the factors influencing strain capacity can be found from section A.4. of this document. More detailed discussion about the strain capacity characterization methods can be found from section A.5. of this document.

A.2.3. Strain Demand Estimation

Strain demand estimation has been addressed through a wide range of PSI, including analytical solutions, soil-spring formulations, and high-fidelity continuum or smoothed particle hydrodynamics (SPH) models. Reviews of PSI modeling approaches have shown that predicted strain demand is highly sensitive to assumptions regarding soil behavior, ground movement geometry, and boundary conditions (Yu et al., 2020). Advanced numerical studies have demonstrated the ability of 3D continuum models to capture complex strain localization and failure modes at slope crossings (Fredj & Dinovitzer, 2014). More recently, field monitoring technologies such as inertial measurement units (IMUs) and satellite-based Interferometry Synthetic Aperture Radar (InSAR) have been integrated into strain demand estimation frameworks. These approaches enable spatially extensive assessment of ground movement and pipeline deformation, particularly in data-limited or remote regions (Liu et al., 2022; Schell et al., 2024). More detailed discussion on strain demand estimation can be found from section A.6 of this document.

A.2.4. Probabilistic and Risk-based SBDA

To address uncertainty inherent in vintage pipelines, recent studies have proposed probabilistic SBDA frameworks. Bayesian network models have been developed to integrate heterogeneous data sources, including strain measurements, metallurgical data, PSI models, and geohazard information, enabling probabilistic estimation of strain demand, strain capacity, and failure probability (Schell et al., 2023a). Reliability-based analyses combining finite element modeling and Monte Carlo simulation have also been applied to slope crossings, supporting risk-informed integrity decisions (Fowler et al., 2022). These efforts represent a shift toward SBDA as a risk-oriented decision-support tool rather than a purely deterministic assessment method. More detailed discussion about probabilistic and risk-based SBDA can be found from section A.6. and A.7. of this document.

A.3. Review Scope

This literature review was conducted through a structured survey of published and unpublished sources relevant to SBDA of vintage pipelines. The reviewed materials include peer-reviewed journal articles, conference proceedings, industry technical reports, government-sponsored research outputs, and applicable standards and recommended practices. These sources were identified through targeted searches of academic databases, industry knowledge repositories, and regulatory documentation platforms, with particular attention to studies addressing girth weld behavior, material heterogeneity, geohazard-induced strain demand, uncertainty treatment, and integrity decision-making.

Rather than cataloging the literature by publication type or chronology, the review is organized according to technical focus areas aligned with the project work plan. Responsibilities were distributed among four collaborative university teams, each examining a distinct aspect of SBDA implementation challenges: critical factors governing strain capacity (RU), experimental and testing-based characterization of vintage steels and girth welds (TAMU), uncertainty representation and propagation within SBDA frameworks under geohazard loading (UD), and the formulation and limitations of risk metrics for vintage pipeline integrity management (UC). This structure enables direct traceability between reviewed literature, identified gaps, and subsequent project tasks. This practice also directly aligns with the approved original proposal. The organizational framework and logical flowchart of this literature review are presented in Figure A.1

Across the reviewed studies, emphasis was placed on how experimental evidence, analytical models, and assessment frameworks are applied in practice, particularly for pipelines with limited documentation, aging-related degradation, and complex loading environments. Where available, the review also considers how regulatory guidance and industry practices interpret or operationalize SBDA results. Detailed findings, thematic syntheses, and identified gaps emerging from each focus area are presented in the sections that follow.

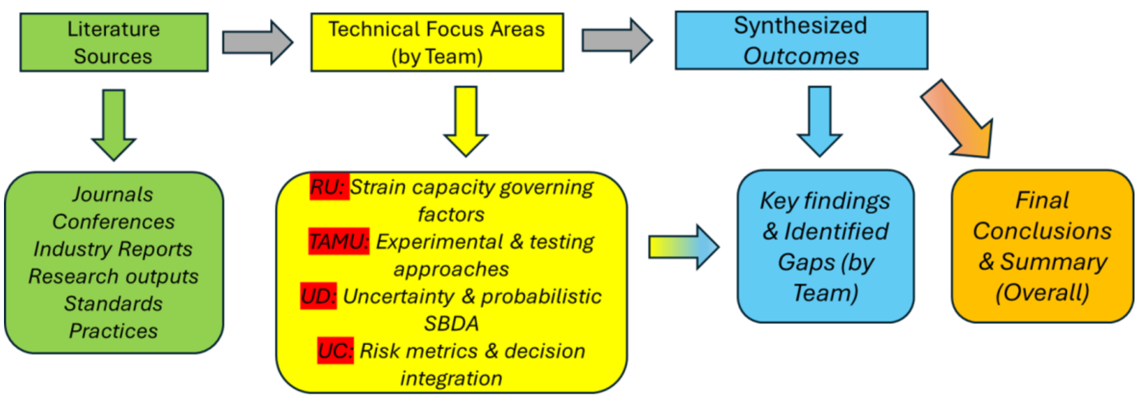

Figure A.1 Organizational framework and logical flow of the literature review.

A.4. Critical Factors Influencing Strain Capacity of Vintage Pipelines

This section reviews the critical material, geometric, loading, and modeling factors that govern the strain capacity of vintage pipelines. Emphasis is placed on weld strength mismatch, geometric discontinuities, internal pressure effects, loading mode, material properties, and defect interactions. Specific discussions are presented as follows.

A.4.1. Influence of Weld Strength Mismatch

Weld strength mismatch is the dominant factor controlling tensile strain capacity. Chen et al. (2022) developed a TSC prediction model for X80 pipelines with improper transitioning and undermatched girth welds. Their parametric analysis demonstrates that undermatched welds exhibit substantially reduced strain capacity compared to matched or overmatched configurations. The effect of weld undermatch dominates over geometric factors such as misalignment when both are present simultaneously. Wang et al. (2022) confirmed this finding through numerical simulation, showing that *strength matching coefficient ($M < 1$) leads to significant TSC reduction*, with the effect being more pronounced for larger initial flaw sizes. Additionally, Hertelé et al. (2013) highlighted that beyond yield strength mismatch, the ultimate tensile strength mismatch and the uniform elongation of the base metal are critical parameters determining the plastic response and failure mode.

The protective effect of weld overmatching diminishes under severe geometric discontinuity. From a design perspective, Wu et al. (2021) proposed that rather than relying on arbitrary overmatch ratios, an optimal strength matching factor should be determined based on reliability methods to satisfy specific target reliability indices. Guo et al. (2025) investigated the influence of weld metal properties on stress triaxiality and strain concentration. Their results indicate that while increasing weld strength can reduce crack-tip constraint, this protective effect is substantially weakened when wall thickness ratio or misalignment exceeds critical thresholds. Furthermore, high yield-to-tensile (Y/T) ratio in weld metal increases strain sensitivity, a condition frequently encountered in vintage weld consumables.

A.4.2. Influence of Geometric Discontinuities

Unequal wall thickness significantly reduces TSC. For X80 pipelines, Chen et al. (2022) reported a 43% reduction in TSC when wall thickness varied from 12.8 mm to 15.3 mm, with further reductions observed under combined misalignment conditions. Guo et al. (2026) conducted full-scale experiments and numerical simulations on X80 girth welds with unequal wall thickness and misalignment. Their results demonstrate that geometric discontinuities significantly elevate crack-tip constraint and fracture driving force, leading to reduced apparent toughness even without changes in intrinsic material properties. Importantly, the study showed that commonly used strain-based assessment methods (e.g., ExxonMobil simplified approach) do not adequately capture this effect—yielding either non-conservative or overly conservative predictions depending on how geometric mismatch is treated.

Misalignment effects are strongly conditional on weld strength matching. Chen et al. (2022) demonstrated a critical interaction: for undermatched welds, misalignment has a secondary effect on TSC; for overmatched welds, misalignment leads to pronounced strain capacity reduction due to intensified strain localization at the weld toe. This non-linear coupling between mismatch and misalignment is not captured by linear superposition approaches commonly used in simplified assessment methods.

A.4.3. Influence of Internal Pressure and Combined Loading

Internal pressure significantly reduces TSC, with non-linear interaction with defect size. Chen et al. (2022) quantified the effect of internal pressure, showing that increasing pressure from zero to moderate levels reduces TSC substantially, while further pressure increases result in a reduced rate of degradation (plateau behavior). Wang et al.(2022) extended this finding by demonstrating that the negative effect of internal pressure is more pronounced for smaller cracks; for larger cracks, TSC is already dominated by defect size, reducing the marginal impact of pressure.

Under combined internal pressure and bending, defect depth has a dominant and non-linear effect on fracture resistance. Zhu et al. (2023) investigated X80 pipe girth welds under combined loading using a damage-mechanics-based numerical framework. Their results show that defect depth has a significantly stronger influence on failure load than defect length. Beyond a critical defect depth threshold, failure load decreases sharply in a non-linear manner.

A.4.4. Influence of Loading Mode and Material Properties

The influence of loading mode and material properties on strain capacity has been widely recognized as critical factors in the structural integrity of vintage pipelines subject to large displacement. Key factors considered include the type of external loading (e.g., tensile, bending, compression) and intrinsic material characteristics (e.g., Y/T ratio and heat-affected zone (HAZ) behavior). Specific findings are discussed as follows.

Tensile loading results in lower strain capacity than bending-dominated loading for otherwise identical welded joints. Yang et al. (2021) conducted full-scale experiments on mismatched X80 girth welds under both tensile and bending loads. Their results demonstrate that strain capacity corresponding to tensile loading is consistently lower than that under bending, indicating that loading mode is a critical factor that must be explicitly considered in SBDA. Complex loading scenarios complicate this further; for instance, Tu and Shuai (2020) showed that under eccentric axial compression, the pipe's buckling capacity is significantly reduced compared to concentric loading due to the induced bending moments. Recent experimental work by Zhang et al. (2024) utilizing curved wide plate specimens has further validated the correlation between these lab-scale results and full-scale fracture behavior, providing critical data on crack propagation paths under large deformation.

Higher base metal Y/T ratio leads to reduced strain capacity. Yang et al. (2021) also showed that base metal Y/T ratio significantly influences strain capacity, with higher Y/T ratios (e.g., 0.93 vs. 0.89) corresponding to reduced strain hardening capability and lower TSC. This finding is particularly relevant to vintage pipelines, where material properties often exhibit elevated Y/T ratios due to legacy steelmaking practices. Zhang et al. (2022) corroborated this for high-strength pipelines, demonstrating that the strain hardening capacity of the girth weld is the dominant factor controlling the overall tensile strain response and failure location.

HAZ softening effects are conditional on weld strength matching. Yang et al. (2021) identified a strong interaction between weld overmatching and HAZ softening: under overmatched conditions, HAZ softening results in noticeable TSC reduction by promoting early strain localization; under undermatched conditions, the relative influence of HAZ softening is less pronounced. Regarding the material source of this softening, Garcia et al. (Garcia et al., 2022) demonstrated that while chemical composition defines minimum potential hardness, the extent of HAZ softening is predominantly controlled by the steel's thermomechanical processing history.

A.4.5. Numerical Modeling Assumptions and Stress Triaxiality

Stress triaxiality (η), defined as the ratio of hydrostatic stress to von Mises equivalent stress, fundamentally governs ductile fracture initiation in welded structures. At elevated triaxiality levels, fracture is primarily driven by void nucleation, growth, and coalescence, whereas lower triaxiality corresponds to shear-dominated failure mechanisms (Bao & Wierzbicki, 2004; Mirza et al., 1996). This parameter has consequently been incorporated into multiple ductile fracture criteria, including the Rice-Tracey void growth model and the Johnson-Cook failure criterion.

In girth-welded pipelines, stress triaxiality and local strain concentration are primarily controlled by geometric features—particularly wall thickness ratio and axial misalignment. When the wall thickness ratio (t_2/t_1) exceeds approximately 1.2, deterioration of stress–strain state accelerates significantly, elevating crack-tip constraint and reducing apparent toughness (Guo et al., 2025). Critically, misalignment and unequal wall thickness interact non-linearly; their combined effect on triaxiality substantially exceeds simple additive predictions, indicating that linear superposition methods are inadequate for capturing this coupling behavior.

Numerical simulation of these geometric effects requires careful treatment of mesh sensitivity and element formulation. The structural strain method has been shown to provide mesh-insensitive solutions at geometric discontinuities, circumventing the singularity issues inherent in local notch stress approaches (Pei et al., 2022). Furthermore, damage models incorporating both triaxiality and Lode angle parameters have demonstrated that weld misalignment accelerates damage accumulation under combined tension-torsion loading, with strain capacity degradation becoming more severe at elevated triaxiality levels (Santos & Sarzosa, 2020). These findings underscore the necessity of explicitly modeling geometric imperfections and adopting appropriate constraint characterization when assessing vintage girth welds, where such features are prevalent.

A.4.6. Local Defects: Dents and Defect Interactions

Local geometric defects, such as dents and their interactions with corrosion, can significantly compromise pipeline integrity by inducing localized plasticity, stress concentration, and premature buckling. Understanding the mechanisms of these defect interactions is essential for accurate strain demand estimation in SBDA.

Constrained dents under internal pressure exhibit severe secondary plastic strain accumulation. Huang & Zhang (2021) investigated the strain response of X80 pipelines with constrained dents subjected to internal pressure. Unlike unconstrained dents that can re-round under pressure, constrained dents cannot recover their geometry, leading to continuous plastic strain accumulation as internal pressure pushes the pipe wall against the constraint. The study shows that peak strain location migrates from dent center (shallow dents) to dent flank (deep dents), and that circumferential dents represent the most critical configuration.

In dent-corrosion interaction scenarios, corrosion depth is the dominant factor controlling buckling failure. Shuai et al. (2020) extended the understanding of corrosion-induced failure, finding that for X80 pipelines under axial compression, the critical buckling load is primarily governed by defect depth and width, with defect length having a negligible effect beyond a specific threshold. Wang et al. (2025) analyzed pipelines containing combined dent-corrosion defects under internal pressure and bending. Their results indicate that corrosion depth-to-thickness ratio (d/t) is the primary factor controlling critical buckling moment—when d/t exceeds 0.3, buckling resistance decreases by more than 50%. Notably, the study found that dent depth has a non-monotonic effect on buckling resistance: shallow dents ($\leqslant$4% D) cause strong strain concentration leading to early instability, while deeper dents ($\geqslant$6% D) enter plastic hardening earlier and may exhibit improved buckling resistance.

A.4.7. Implications for Sample Selection and Testing Scope

The reviewed literature shows that tensile strain capacity in pipelines is controlled primarily by localized mechanical response rather than by the global behavior of the pipe body. Across experimental and numerical studies, strain localization and fracture initiation are consistently observed within the girth weld region or the adjacent heat-affected zone under displacement-controlled loading (Chen et al., 2022; Wang et al., 2022; Yang et al., 2021). This indicates that experimental efforts aimed at vintage pipelines should focus on specimens containing girth welds to capture the governing failure mechanisms.

A dominant and recurring theme in literature is the influence of weld strength *mismatch*. Undermatched welds exhibit substantially reduced strain capacity, while the effectiveness of overmatching depends strongly on the presence of geometric discontinuities and material heterogeneity (Chen et al., 2022; Wang et al., 2022; Guo et al., 2026). *Unequal wall thickness* and *axial misalignment*, which are inherent to many as-fabricated pipelines, significantly elevate stress triaxiality and fracture driving force, and their interaction with strength mismatch is strongly non-linear (Guo et al., 2025; Guo et al., 2026). These observations suggest that test specimens should reflect a limited but representative range of strength matching conditions and retain key geometric features where practicable.

Loading conditions further constrain strain capacity and should be considered in the definition of testing scope. Experimental evidence indicates that *tensile loading generally produces lower strain capacity than bending-dominated loading*, and that internal pressure interacts non-linearly with defect size and loading mode (Yang et al., 2021; Chen et al., 2022; Zhu et al., 2023). While full-scale testing offers the most direct representation of pipeline behavior, prior studies have demonstrated that curved wide plate tests can capture critical fracture and strain localization mechanisms consistent with full-scale observations, providing a conservative and practical intermediate testing approach (Zhang et al., 2024).

To maximize the relevance and value of the testing campaign in this project, sample selection should emphasize *vintage pipeline systems*, ideally those constructed more than 50 years ago. These older assets represent a significant portion of the U.S. pipeline infrastructure and are often constructed using phased-out manufacturing and welding techniques such as early shielded metal arc welding (SMAW). The historical PRCI data indicates that welds dating back to the 1920s–1960s exhibit unique characteristics, including limited documentation on material properties, variable weld quality, and legacy seam types (e.g., furnace lap, flash weld, SAWL)(Jia et al., 2019). *This aligns with the need to focus on lower steel grades (e.g., X42, X52)* rather than higher grades (X70–X80), which are already well-studied. Sampling girth welds both with and without known flaws (identified using instruments), and particularly incorporating pre-existing damage such as corrosion, will broaden the insight into how different degradation mechanisms affect strain capacity. *Corrosion, though underexplored in previous studies, represents a realistic and critical threat that could be modeled in terms of material loss and its impact on local ductility and fracture behavior* (Huising & Gasunie, 2020; Clark et al., 2005).

The selection should also take into account the availability of existing NDE results and mechanical characterization data, as found in the PRCI-funded reports (e.g., welds from 1929 to 1964 tested for flaw types, weld heights, ligament remaining thickness, etc.) (Jia et al., 2019;Wang et al., 2023). This allows prioritization of samples with documented flaw types (e.g., root cracks, lack of fusion, porosity) or with confirmed weld techniques of interest. For welds where no flaw data exists, CTOD/CMOD and DIC-based tensile testing can still provide baseline strain capacity metrics. *Where possible, both transmission line and distribution main samples should be considered —*

ensuring applicability across pipeline segments. Consultation of sources like the SIA-1-4 report or coordination with PRCI may help confirm which line types and materials are most accessible. Ultimately, the aim is to develop a balanced test matrix that captures vintage variability in weld processes, degradation states, and mechanical responses.

Finally, the reviewed studies highlight that material variability typical of vintage pipelines, including elevated yield-to-tensile ratios and heterogeneous weld and heat-affected zone properties, can significantly influence strain localization and failure response (Wang et al., 2011). This variability limits the applicability of surrogate or idealized materials and underscores the importance of using real samples that are representative of vintage pipeline materials, where such samples are available.

A.4.8. Key Findings about Critical Factors Influencing Strain Capacity

Key findings about Critical Factors Influencing Strain Capacity are summarized as follows: 1)*Weld strength mismatch* is the dominant factor controlling TSC in girth welded pipelines; undermatched welds exhibit substantially reduced strain capacity. 2) *Geometric discontinuities* (unequal wall thickness and misalignment) significantly reduce TSC by elevating crack-tip constraint and fracture driving force, with combined effects exceeding 50% reduction in severe cases. 3) *Parameter interactions* are strongly non-linear: the effects of misalignment, HAZ softening, and internal pressure are conditional on weld strength matching and defect size—linear superposition approaches are inadequate. 4) *Internal pressure* reduces TSC, with the effect of being more pronounced at lower defect sizes and exhibiting plateau behavior at higher pressure levels. 5) *Defect depth* is more critical than defect length under combined loading, and failure response is non-linear with respect to defect size. 6) *Loading mode* matters: tensile loading produces lower strain capacity than bending for otherwise identical configurations. 7) *Material properties* typical of vintage systems (elevated Y/T ratio, variable HAZ properties) are associated with reduced strain capacity and increased sensitivity to geometric imperfections. 8) *Defect interactions* (e.g., dent-corrosion) exhibit complex, non-monotonic behavior that cannot be predicted through simple superposition of individual defect effects.

A.5. Strain Capacity Testing Approaches for Vintage Steels and Girth Welds

This section reviews experimental and analytical testing approaches used to quantify the strain capacity of vintage pipeline steels and girth welds. Emphasis is placed on methods capable of capturing weld and HAZ heterogeneity, fracture toughness, and strain localization that commonly govern failure in aging pipeline systems. The reviewed techniques span full-scale and laboratory-scale tensile and bending tests, fracture-mechanics-based specimens, and complementary measurement tools used to characterize material degradation, strength mismatch, and crack-driving behavior. Together, these methods form the experimental foundation for evaluating strain capacity and supporting strain-based integrity assessments of vintage pipelines.

A.5.1. Methodologies to Measure Strain Capacity of Pipelines

Different methodologies have been used to investigate the strain capacity of pipelines, which due to the aging have lower toughness and, more importantly, show higher heterogeneous properties, mainly at the girth welds. For this reason, *techniques that are capable of capturing cross-weld* *inhomogeneity and fracture toughness behavior are needed*. The most common techniques are numbered and later discussed: 1) Instrumented cross-weld tensile tests (ICWT) and curved wide-plate tensile (CWT); 2) Standard fracture tests compact tension (CT); 3)Single-edge notched bend (SENB); 4) Pipe ring notched bend (PRNB); 5)Slow strain rate testing (SSRT); 6) Hardness mapping of different welded zones; 7) Charpy test; 8) Drop-weight tear tests (DWTT); 9) Digital image correlation (DIC); 10) Crack tip opening displacement (CTOD); and 11) Crack mouth opening displacement (CMOD).

A.5.1.1 ICWT and CWT

Done in a tensile machine, the samples are taken from the pipeline, containing along its span the weld (including weld metal + HAZ + base material). This test allows identifying from where the necking and/or failure comes from, giving an indication of the weld/pipeline assembly strain capacity. With strain gauges the displacement of the different sections can be obtained, adding more specifics to each of areas' performance. Common ICWT are done with flat cross-weld tensile specimens, while CWT samples are wider specimens with curvature or geometry chosen to better reproduce the hoop/curvature constraint present in a pipe (Biplov Kumar Roy, 2020). Enough replicates are needed to make sure there is no bias on the sample, as geometry, weld and other conditions might have affected the strain capacity measurement. Also, the location and number of strain gauges to identify specific areas is critical.

A.5.1.2 CT

CT specimens have a standardized fracture-mechanics geometry used to measure fracture toughness parameters like J-integral, K_{IC}, and CTOD under controlled crack size and constraint. A fatigue pre-crack is introduced and the specimen is loaded in tension to grow the crack while recording load and crack mouth opening. The advantages of CT specimens is that they are easy to machine from welds and provide standardized information about whether a flaw in a vintage girth weld will propagate under given loads and strains.

A.5.1.3 SENB

Similarly to the CT testing, SENB is a fracture test that employs a three- or four-point bending to determine the fracture toughness. As the CT specimen, the SENB also contains a fatigue pre-crack and a standardized notch. The difference is that with the bending, the testing can represent through-thickness and it is useful for extracting representative HAZ/weld when plate geometry is not an option.

A.5.1.4 PRNB

Like SENB, the PRNB uses a three- or four-point bending to determine the fracture toughness; however, the specimens are short ring sections of pipeline containing an intentionally notched through-thickness flaw. When loaded in bending, they simulate a circumferential crack in actual pipeline geometry, providing very relevant toughness/propagation data for pipeline integrity work. PRNB is one of the closest tests to real working cases, however as the pipeline diameter increases, the testing becomes more expensive and complicated.

A.5.1.5 SSRT

SSRT uses flat samples under tension, like previously seen for the ICWT, however, the difference is that for SSRT the strain rate is extremely slower, allowing to see the response of the different components (HAZ, welds, bare metal) behave. This type of testing is commonly paired with environmentally assisted cracking. While not directly a tensile strain capacity test, it is a sensitive screening tool for environment-sensitive degradation mechanisms that would lower strain capacity, revealing whether certain welds, HAZ microstructures, or service environments predispose the metal to subcritical crack growth or unexpected brittle behavior.

A.5.1.6 Hardness mapping of different welded zones

Hardness mapping involves taking systematic hardness indents across the weld cross-section to quantify the variation in mechanical resistance from base metal through HAZ to weld metal. For vintage welds, hardness maps reveal HAZ softening, over- or under-matching of weld metal strength relative to the pipe, and steep gradients that can drive strain localization. This testing helps calibrate finite element (FE) models used to predict strain capacity, in addition of being cheap and easy to perform.

A.5.1.7 Charpy test

The Charpy V-notch impact test measures the energy absorbed by a notched specimen when broken by a pendulum, being a rapid, standardized screening of a material's brittle versus ductile behavior as a function of temperature. In vintage pipeline assessments Charpy results help identify low-toughness welds or HAZ regions and set approximate ductile-to-brittle transition temperatures. While Charpy energy is only a screening metric, it is commonly used to prioritize where to perform more mechanistic fracture testing.

A.5.1.8 Drop-weight tear test (DWTT)

DWTT is a quasi-standardized test that uses a notched, sub-size specimen struck by a falling weight to assess ductile fracture propagation resistance and shear-fracture appearance. It is based in energy adsorption as the Charpy test, however it is often used in pipeline practice because it better reflects lateral tearing/cleavage susceptibility in semi-thin specimens. For vintage girth welds, DWTT helps identify welds or HAZ regions prone to brittle or low-energy tearing.

A.5.1.9 Digital image correlation (DIC)

DIC is a non-contact optical technique that tracks a speckle pattern on a specimen surface to produce full-field maps of strain and displacement during mechanical tests. Its high spatial resolution makes DIC especially valuable on cross-weld tensile, CWP, and bending tests where localized strain accumulation like necking and/or HAZ concentration is critical to interpret. For vintage pipeline weld assessments, DIC helps identify where the specimen is concentrating strain before failure, correlating local strain to microstructure/hardness, and providing data to validate/calibrate FE models (Zhihao Zhang, 2025). It is commonly used in combination with any of the tensile or bending techniques.

A.5.1.10 CTOD and CMOD

CTOD quantifies the displacement at the tip of a crack as it opens under load and is a direct, physically meaningful measure of fracture driving force and material resistance to crack initiation and growth. CTOD can be measured in standardized fracture specimens (CT, SENB) or estimated from J-integral values; it is widely used in pipeline assessments because it ties fracture toughness to real crack-tip deformation and can be correlated with ductile tearing and growth. In vintage girth weld evaluations CTOD provides a robust toughness input for ECAs that predict whether a crack will run under imposed strain and pressure conditions.

CMOD measures the opening displacement at the mouth of a cracked specimen (the notch root) and is a convenient, easily recorded parameter in fracture tests (particularly SENB and CT). CMOD is often used as a proxy to monitor crack growth and to calculate fracture parameters (e.g., J or CTOD via calibration) during tests. For pipeline girth weld work, CMOD provides a practical test-control and data stream that, when combined with load and crack length, feeds fracture-mechanics analyses to assess toughness and to support tensile-strain capacity predictions.

CTOD and CMOD differ mainly in what part of the fracture process they represent and how directly they relate to real crack behavior. CTOD measures the opening at the crack tip and is highly sensitive to local plasticity, damage, and constraint, making it a true fracture-mechanics parameter. In contrast, CMOD measures the opening at the crack mouth and reflects the global deformation of the specimen, so it is easier and more repeatable to measure but less sensitive to localized fracture processes. Because CMOD averages the response of the entire specimen, it can mask local brittle or low-toughness behavior that often exists in vintage girth welds and heat-affected zones.

For vintage pipelines, where HAZ softening, local brittle zones, strength mismatch, and microstructural variability are common, CTOD provides a more reliable indicator of fracture resistance and crack-driving behavior under realistic, high-constraint loading. Although CMOD is very useful for test control and for calculating derived fracture parameters, modern integrity practice and regulatory guidance typically rely on CTOD (or J-integral) as the primary acceptance criterion. In practice, CMOD is therefore used mainly as a measurement tool, while CTOD is preferred for engineering critical assessments and strain-based fracture evaluation of vintage girth welds.

A.5.2. Review of Historical Experimental Studies on Strain Capacity and Fracture Behavior of Pipeline Girth Welds

Despite the broad range of experimental programs conducted over the past decades, these studies remain fragmented across materials, weld configurations, defect types, and loading conditions. A focused review of historical experimental evidence is therefore necessary to synthesize key findings, identify consistent trends, and highlight limitations that constrain the application of strain capacity data to vintage pipeline integrity assessment. The following review summarizes representative experimental studies and their key contributions.

Wang studied at full-scale test of X80 pipeline girth welds via four-point bed test, DIC- tensile testing, and SENB, where the four-point bend test gave real pipeline strain capacity under service-like loading, while SENB was used to obtain CTOD and CMOD (Xiaoben Wang, 2025). On the same X80, Guo studied the strain capacity of girth welds with unequal wall thickness and misalignment using CWP tests and FE analysis (Baichen Guo, 2026). Results showed that unequal wall thickness reduces TSC by 27%, and when combined with 4 mm misalignment, capacity drops by up to 51%. On a comparison between ExxonMobil and UGent strain capacity predictive equations for flawed pipeline girth welds on X80, it was found that the CWP testing was more reliable and effective for estimating the strain capacity (Rudi M. Denys, 2013). Similarly, Liu developed and validated a SBDA methodology for pipelines, mainly for X65–X80 grade steels with girth-weld flaws (Ming Liu, 2017). The work combined large-scale full-pipe tests, curved wide plate tests, SENT fracture toughness testing, and FE modeling to quantify tensile strain capacity and the influence of weld properties, geometry, and flaw characteristics.

Zhang studied X70 with large scale CWP with girth welds to measure the CTOD, quantifying ductile tearing behavior, crack-tip blunting, crack-growth patterns, and strain distribution across the weld region (Tieyao Zhang, 2024). Yang used DWTT on X70 to determine how abnormal fracture appearance forms, which of them remains valid for toughness and strain-capacity assessment, and how notch geometry and test conditions influenced fracture behavior in vintage pipelines (Zheng Yang 2008). Chen studied the cracking of girth weld joint for X70 pipelines with near-seam zone by CWP test and SENT, finding that although the specimens of girth weld tensile test cracked in near the seam zone, the CWP test showed considerable strain capacity of about 4% (H.Y. Chen, 2015).

Damjanovic worked on the correlation between PRNB and SENB with $16Mo_3$ steel, finding that PRNB specimens replicated the fracture behavior seen in standard SENB specimens, important for assessing the strain capacity and fracture resistance of vintage pipelines where pipe curvature and wall thinning made standard specimens difficult to extract (D. Damjanovic, 2017). Yang studied the strain capacity of high-strain marine pipeline welds by comparing crack-growth driving force from FEA with crack-growth resistance from single edge notch tensile (SENT) testing (Kun Yang, 2022). Full-scale girth-weld notch tests were used for validation. Results showed that the FEA-based method predicted strain capacity more accurately, while the failure assessment curve approach was overly conservative. On same SENT testing, Tang refined the SENT specimens to improve the reliability through CTOD measurements, finding that specimens with side grooves produce consistent toughness, deeper cracks and, reduce ductile resistance; while ID vs. OD notch differences arise mainly from material property variation through pipe thickness rather than constraint effects (Huang Tang, 2011).

Agbo performed full-scale pressurized four-point bending tests on 22-inch X42 pipes to evaluate the influence of internal pressure and flaw size on strain capacity, using biaxial strain gauges and DIC to capture deformation and CMOD-based crack growth [Sylvester Agbo, 2019]. It was concluded that internal pressure has no effect on the CMOD failure, however, the level of internal pressure could reduce the TSC by 40% or more depending on the flaw size. Elyasi used an extended FE model (XFEM) to investigate the ductile fracture properties for vintage pipelines made of X52 when subjected to internal pressure (Nahid Elyasi 2021). Regardless of the differences in the pipe and crack dimensions as well as the internal pressure of each model, the XFEM analysis could accurately predict the initiation and propagation of the crack in all eight models. Chen also simulated the effect of internal pressure on vintage pipelines with girth welds, finding that when the internal pressure exceeded 0.5 times of the specified minimum yield internal pressure, the strain capacity decline slowed down significantly (Hongyuan Chen, 2022). While when the design factor was less than 0.5, the internal pressure affected strain capacity proportionally, and if the design factor was greater than 0.5, the effects of internal pressure on strain capacity were limited.

Hertele studied the Structural integrity of corroded girth welds in vintage steel pipelines made from X46 and X60, both types being manufactured between 1967 and 1973, having successfully operated for at least 40 years (Stijn Hertelé, 2016). They used CWP, DIC and hardness mapping to obtain plastic collapse equations that were applied to assess the acceptability of girth weld metal loss in vintage pipelines. The equations covered the effects of pipe and flaw geometry and of weld misalignment. Zhang studied the inhomogeneous strain behaviors of the high strength pipeline girth weld under longitudinal loading via combination of ICWT and DIC, where the tested shielded metal arc welded pipe exhibited under matched girth welds due to high heat input, while gas metal arc welding introduced a narrower weld and HAZ with higher hardness than the base metal, indicative of overmatched girth welds (Zhihao Zhang 2024). It was also found that reinforcement significantly improves the tensile strength of girth welds and effectively prevents failure in the weld region.

A.5.3. Experimental Capabilities and Feasible Strain Capacity Testing for Vintage Pipelines at TAMU

Based on prior strain capacity testing experience and existing laboratory infrastructure, the TAMU team has the capability to perform a comprehensive lab-scale experimental program focused on vintage pipeline steels and girth welds. Pipeline sections can be sectioned using electrical discharge machining (EDM) to extract flat cross-weld tensile specimens while avoiding thermal or residual stress artifacts. These specimens can be configured with weld metal, HAZ, and base metal aligned within the gauge length, enabling direct assessment of cross-weld strain localization and failure initiation (see Figure A.2, left, for example specimen location and dimensions). Specimen testing can be conducted using multiple available load frames, including servo-hydraulic tensile systems and screw-driven universal testing machines, covering a wide range of load capacities suitable for vintage pipeline steels of varying wall thickness and strength levels.

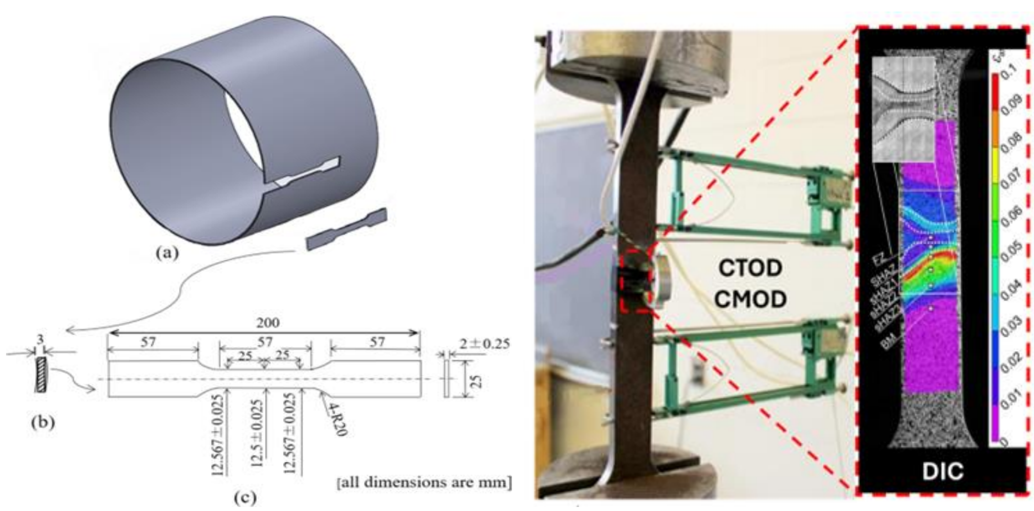

Figure A.2 Left: Example of sample location and dimensions (approx.); right: Example of setup including sensors for CTOD/CMOD and DIC/thermal.

In addition to flat tensile testing, TAMU is equipped to conduct CWT experiments that better represent pipeline curvature and constraint effects. These tests can be performed under both conventional and slow strain rate loading conditions. Full-field deformation can be captured using DIC systems, while complementary thermal imaging cameras enable monitoring of temperature evolution during plastic deformation (see Figure A.2, right, for an example test setup with CTOD/CMOD instrumentation and DIC/thermal sensing). The experimental setup also supports integration of CMOD gauges and CTOD measurements, allowing fracture-driven strain capacity evaluation of girth welds with or without introduced flaws.

Complementary post-test characterization capabilities further support detailed interpretation of strain capacity results. Available facilities include hardness mapping equipment for weld cross-sections, optical microscopy (OM) for metallographic analysis, scanning electron microscopy (SEM) for fracture surface examination, electron backscatter diffraction (EBSD) for microstructural orientation analysis, X-ray diffraction (XRD) for phase and residual stress characterization, and three-dimensional surface topography measurement systems. Together, these experimental and characterization tools allow systematic investigation of vintage pipeline behavior, including the effects of weld heterogeneity, flaw presence, and material degradation due to corrosion and/or mechanical damage. The TAMU experimental framework therefore provides a robust and well-instrumented platform for generating high-quality strain capacity and other relevant data directly applicable to vintage pipeline strain capacity modeling.

These experimental capabilities directly complement the analytical modeling, uncertainty quantification, and risk-metric development efforts led by the other university teams, collectively supporting an integrated strain-based assessment framework for vintage pipelines.

A.5.4. Key findings about Strain Capacity Testing Approaches

Experimental studies demonstrate that strain capacity of vintage pipeline girth welds is strongly governed by weld and HAZ heterogeneity, strength mismatch, flaw geometry, and internal pressure. Large-scale tests (e.g., curved wide plate and full-pipe bending) consistently provide more representative strain capacity than small-scale tensile tests alone. Fracture-based parameters, particularly CTOD, are shown to be more reliable than CMOD for assessing crack-driving behavior in vintage welds. Advanced measurement techniques such as DIC and hardness mapping are essential for identifying strain localization and calibrating numerical models, while internal pressure, misalignment, and corrosion can significantly reduce tensile strain capacity.

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Based on these findings, the available experimental capabilities summarized in Section A.5.3 were evaluated and found to be well aligned with the key mechanisms governing strain capacity in vintage pipelines, providing the necessary testing scale, instrumentation, and measurement resolution to support representative strain-based assessment and model validation.

A.6. Uncertainty Quantification Limitations of SBDA Frameworks

This section reviews the limitations of current SBDA frameworks in quantifying uncertainty for strain capacity estimation, especially subjected to geohazard-induced loading. The discussion focuses on uncertainty sources in strain demand characterization, model applicability to in-service and vintage pipelines, and the treatment of aleatoric and epistemic uncertainty. Emphasis is placed on identifying gaps that constrain the reliable implementation of SBDA for geohazard management and integrity decision-making.

A.6.1. Strain Demand Characterization Under Geohazard Loading

Geohazards are hazards caused by natural phenomena in the atmosphere and on the ground. Figure A.3 shows examples of different geohazards that can cause pipeline failure. These are significant contributing causes to consider in pipeline industries. Generally, geohazards can be classified as: (1) geotechnical hazards attributed to the movement of soil or rock (e.g., landslide, subsidence, seismic activities) and (2) hydrotechnical hazards caused by extreme water-related events or water-based activities (e.g., flood, drought, erosion, scour). The likelihood of failure and damage potential of a pipeline subjected to geohazards are contingent upon inherent pipeline characteristics, including geometric properties (diameter, wall thickness), material specifications, and the presence of construction-related or operational defects. Key factors, such as material grade, welding procedures, and weld inspection quality, are directly related to the vintage and methodology of pipeline construction (Wang et al., 2023; 49 C.F.R. §191.3 (2023); 49 C.F.R. pt. 195 (2023)).

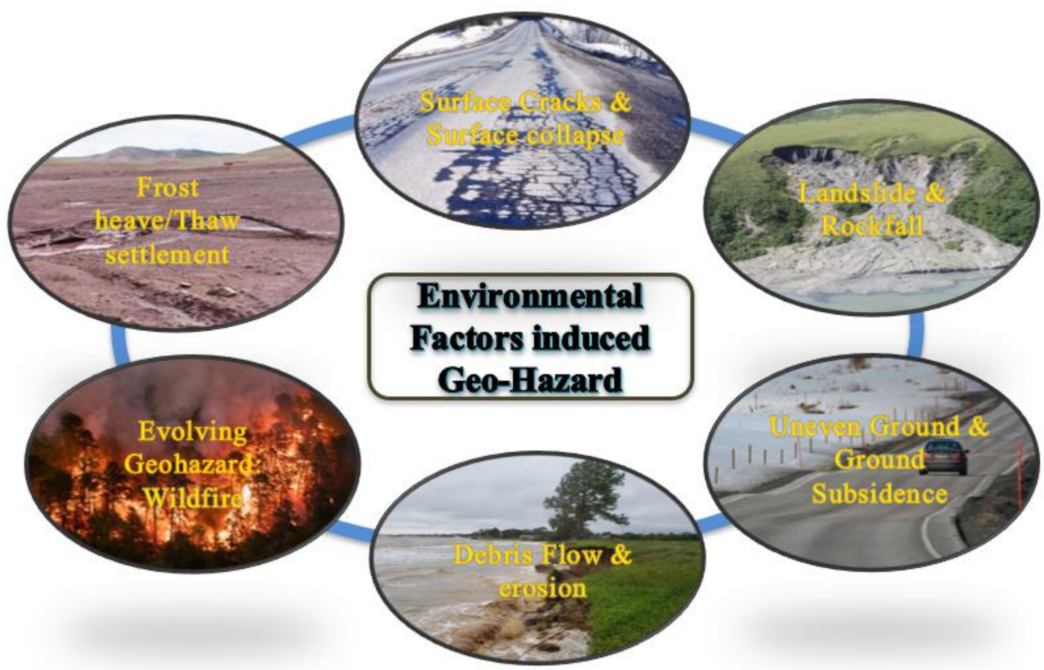

Figure A.3 Examples of different geohazards that can cause pipeline failure.

A.6.1.1. Framework for Geohazard Assessment

Effective strain demand characterization begins with a structured integrity management program for geohazards. This process involves a tiered assessment to refine the strain demand estimate. The comprehensive framework for geohazard management emphasizes three key levels of assessment, each requiring increased data resolution and analytical sophistication. Level 1 assessment (screening) is a desktop review using historical data, satellite imagery, and aerial surveys to identify potentially affected pipeline segments. Level 2 is an intermediate assessment through preliminary site reconnaissance and simplified geotechnical investigations to characterize the specific geohazard mechanism and its approximate magnitude. Level 3 is a detailed assessment that includes site-specific geotechnical studies, NDE, and advanced analysis to quantify ground movements and the resulting pipeline strain demand accurately. This multi-level approach is supported by two mutually reinforcing components: a geohazard-focused assessment which characterizes the ground movement and a pipeline integrity-focused assessment that determines the pipe's response (Wang et al., 2012; Fredj et al., 2019).

Successful application of SBDA relies on two fundamental components: accurately quantifying the pipeline's strain demand (applied load) and predicting the pipeline's strain capacity (maximum resistance). Unlike a loading driven by internal pressure, geohazards such as landslides, subsidence, settlement, frost heave, and seismic events impose large, often displacement-controlled deformations on buried pipelines, resulting in severe axial and bending strains leading to tensile rupture and comprehensive buckling/wrinkling of pipelines. Consequently, leaks and time-delayed failures at locations of buckling/wrinkling may occur, necessitating the development of distinct analytical frameworks (Wang et al., 2012; Lee & Kim, 2020; Schell et al., 2023).

A.6.1.2. Modeling and calculation of strain demand

Strain demand, which is the total longitudinal strain experienced by the pipe wall, is calculated as the superposition of axial strain and bending strain. The accurate prediction of these strain components relies heavily on PSI modeling.

Two primary analytical methods are utilized for this purpose. One is the simplified models (finite difference or analytical): These methods represent the non-linear resistance of the soil using discrete, non-linear soil spring elements (axial, lateral, and vertical). This approach is computationally efficient and suitable for Level 1 and 2 screening, provided that appropriate force-displacement relationships for the soil are selected and calibrated. The other method is an advanced finite element analysis (FEA). For Level 3 assessments, full 3D non-linear FEA is employed to explicitly model the pipeline, the surrounding soil volume, and complex soil constitutive models (e.g., Mohr-Coulomb). This provides a more rigorous prediction of strain distribution and localization, particularly when high-resolution geotechnical data is available for calibration (Wang et al., 2023).

While IMU bending strain sensing is a powerful tool for monitoring and identification, it is important to note that IMU analysis may under-represent the total strain imposed on the pipe segment in certain cases.

A.6.1.3. Link to strain capacity and advanced assessment

The resulting strain demand profile, obtained from rigorous modeling or from in-line inspection (ILI) data, serves as the critical input for the second half of the SBDA framework: strain capacity.

The integrity management process mandates that the calculated strain demand must be reliably compared against the pipeline's capacity to ensure a sufficient margin against failure.

The multi-tier tensile strain model developed by Wang et al. (2012, 2014) provides a suitable capacity framework, offering a rational and statistically sound methodology for predicting the failure strain of high-toughness pipelines, particularly at girth welds. By characterizing strain demand with sufficient accuracy and confidence, operators can utilize such capacity models to make objective fitness-for-service and risk-management decisions under displacement-controlled loading conditions.

The characterized strain demand profile is the critical input for the fitness-for-service assessment, which determines the safety margin between the strain demand and the strain capacity. Strain-based assessment (SBA) has become a powerful, maturing technology for evaluating pipeline integrity when pipelines are exposed to geohazards, especially where longitudinal stresses may exceed the yield strength.

A.6.2. Applicability and Limitations of Current SBDA Frameworks

The practical applicability of current SBDA frameworks is governed by specific technical tiers and inherent data limitations that affect their reliability in real-world scenarios. Early SBDA models—such as those developed by PRCI, ExxonMobil, and others—were primarily validated using modern linepipe materials with consistent mechanical properties, low-strength mismatch, and controlled weld geometry. These frameworks, including the multi-level PRCI SBD models (Wang et al., 2011; Wang et al., 2016), often assume idealized input conditions: planar flaws, predictable strain distributions, and complete material data. While this approach is sufficient for new constructions in uniform terrain, its limitations become apparent when assessing in-service pipelines in regions with complex geohazards.

The *Realistic Strain Capacity Models* report (Wang et al., 2013) attempts to extend SBDA tools to more realistic conditions. These frameworks introduce flaw-specific models that account for tensile strain interaction with crack-like defects, including weld centerline (WCL) and HAZ features. For instance, *SIA-1-7* allows assessment of girth weld flaws under tensile loading, calibrated against large-scale testing. Similarly, the TSC model presented by Jia et al. (2020) is explicitly designed for a strain range of 0.2–1.0%, commonly seen in ground movement-affected regions. However, these models require accurate knowledge of flaw size, weld geometry, material properties, and local strain—data that are often unavailable in practice.

Limitations of current frameworks primarily concern input sensitivity and validation scope. Models such as the PRCI Level 3/4 tools are heavily reliant on flaw characterization and toughness data, often derived from Charpy V-notch (CVN) or crack tip opening displacement (CTOD) testing. As noted by Jia et al. (2019), these inputs may not be available for vintage systems or may not reflect actual weld properties due to unknown/uncertain weld mismatch, multiple welding processes, or local embrittlement. Furthermore, most models are built on the assumption of uniaxial loading and neglect potential multi-axial strain states or dynamic soil-pipe interactions. This introduces epistemic uncertainty regarding model applicability beyond the tested parameter space. While conservative screening tools offer practical alternatives, their simplicity often leads to over-conservatism, particularly in displacement-controlled scenarios where high strain does not necessarily imply failure.

A.6.2.1. Evolution and multi-tier frameworks

The current state-of-practice for SBDA, particularly for TSC, is defined by a tiered approach that balances analytical complexity with the availability of material data. This framework typically categorizes assessments into three tiers: Tier 1, Tier 2, and Tier 3. (Fairchild et al., 2012)

Tier 1 (lower-bound assessment) utilizes simplified, conservative equations intended for screening. These models generally require only basic material specifications but provide the lowest predicted strain capacity to ensure safety under high uncertainty. Tier 2 (intermediate assessment) incorporates more specific material properties, such as the uniform elongation (UEL) and the yield-to-tensile (Y/T) ratio. These models provide a more realistic capacity estimate but are sensitive to the accuracy of the tensile testing data. Finally, Tier 3 (site-specific/advanced assessment) involves detailed finite element analysis (FEA) and site-specific material characterization, including crack tip opening displacement (CTOD) or J-integral toughness values. This tier is reserved for critical segments where Tier 1 or 2 results indicate potential failure, yet field conditions suggest higher inherent capacity.

A.6.2.2. Critical sensitivities and applicability

The applicability of these models is heavily influenced by several key parameters identified across recent literatures. These include weld strength mismatch, ductility of a material, and internal pressure. A critical limitation of early frameworks was the assumption of weld strength overmatch. Modern assessments emphasize that weld strength undermatching (where the weld is weaker than the pipe body) drastically reduces strain capacity by localizing plastic deformation within the weld zone. The capacity of a pipeline to resist displacement-controlled loads is fundamentally limited by the material's work-hardening capacity. Models developed by Wang et al. (2012, 2014) demonstrate that UEL is often the most significant predictor of TSC, yet it is also a parameter that shows high aleatoric uncertainty in vintage materials. While geohazards are displacement-controlled, internal pressure introduces a multi-axial stress state that can either increase or decrease tensile strain capacity depending on the pipe's diameter-to-thickness ratio and material grade.

A.6.2.3. Limitations in in-service and vintage systems

The most significant challenge for current frameworks lies in their application to existing (in-service) and vintage pipelines. Unlike new constructions, where material properties are strictly controlled, *vintage systems often lack* (1) *high resolution flaw data* and (2) *toughness data*. Current models, like the TSC equations, are highly sensitive to flaw height and length. In many cases, ILI tools provide insufficient resolution to distinguish between benign anomalies and critical girth weld defects. Additionally, reliable application of SBDA requires fracture toughness values that are rarely available for pipelines installed before the 1980s. This necessitates the use of conservative "default" values, which can lead to excessive and costly remediation efforts for stable geohazard features. (Wang et al., 2023; Kotian and Wang, 2016; Wang et al., 2019)

A.6.2.4. Integration into geohazard management

The CRES framework on geohazard (Wang et al., 2023) addresses these limitations by linking SBA directly to the management lifecycle. It clarifies that the SBA should not be a static calculation, but rather a tool for setting girth weld flaw acceptance criteria and supporting strain demand limits (SDL). By understanding the "strain demand" (how the hazard engages the pipe) alongside the "strain capacity" (determined by the SBDA framework), operators can identify the specific stage of failure—from existing condition to imminent rupture—allowing for more strategic intervention.

A.6.3. Uncertainty Quantification in Strain-based Assessment

A.6.3.1 Sources and classification of uncertainty in SBDA

Uncertainties in pipeline failure arise from a complex interplay of internal pressure, geometric variances, material flaws, and environmental stressors. Uncertainty Quantification (UQ) is therefore central to the validity and defensibility of any SBDA framework. These uncertainties are broadly categorized into aleatoric (inherent variability) and epistemic (knowledge imperfectness).

Aleatoric uncertainties include the natural stochastic variation in mechanical properties, such as yield strength (YS), Y/T ratio, and toughness. As documented in the PRCI report (Jia et al., 2019), vintage girth welds exhibit significant scatter in YS, ultimate tensile strength (UTS), and CVN energy across weld metal and HAZ samples. Similarly, flaw dimensions—particularly depth and length—demonstrate inherent variability even within a single weld due to the stochastic nature of defect morphology and measurement scatter. Epistemic uncertainties dominate when data are sparse or full-scale testing is infeasible. For instance, non-destructive evaluation (NDE) methods like phased array ultrasonic testing (PAUT) often underestimate defect depth, especially for embedded flaws with irregular morphology. To address these limitations, models such as the TSC model described by Wang et al. (2020) often rely on default inputs or approximate apparent toughness values. While this enables modeling in the absence of full-scale test data, it introduces unquantified epistemic uncertainty through reliance on "representative" rather than site-specific values. To mitigate this, Liu et al. (2013) proposed a database-driven methodology where population distributions of input parameters generate conservative yet realistic capacity envelopes.

Model structure also contributes to epistemic uncertainty. Many SBDA tools rely on empirical correlations or finite element simulations calibrated to specific test conditions. When these models are extrapolated to new materials or loading scenarios (e.g., low-toughness vintage girth welds under axial strain and internal pressure), their predictive reliability declines. Wang et al. (2016) noted that current models often fail to account for complex interactions between the flaws, such as offset surface cracks or flaws intersecting weld boundaries. Additionally, epistemic uncertainty in strain demand, compounds capacity uncertainties, making the overall margin-to-failure difficult to define with confidence. Therefore, robust SBDA demands both improved UQ methodologies and conservative model structures that reflect real-world material and flaw behavior.

A.6.3.2 Probabilistic and Bayesian SBDA frameworks

In recent years, researchers have shifted away from purely empirical data and basic modeling toward developing robust UQ frameworks for pipeline SBDA. A central component of this shift is the application of probabilistic risk assessment (PRA), a methodology that quantifies risk as the intersection of event likelihood and its potential impact. By modeling system components—including hardware, software, and human factors—probabilistically, PRA identifies critical risk drivers and highlights areas of limited knowledge (i.e., uncertainty). While standards like ASME B31.8S (2023) and CSA Z662 (2023) provide foundational guidance, the adoption of more data-intensive probabilistic methods offers a higher fidelity of risk management recognized across various engineering sectors.

The shift toward probabilistic SBDA has been driven by the need to explicitly quantify "knowledge gaps" in pipeline integrity, particularly in geohazard-prone regions. Recent studies highlight that while these data-intensive methods require significant time and resources, their results provide a superior basis for decision-making compared to conventional assessments. For instance, Zheng et al. (2023) advanced this field by integrating the finite-difference method (FDM) with Monte Carlo simulations to calculate the probability of exceeding the strain capacity. Their approach allowed the prediction of failure probabilities as a function of time by incorporating the likelihood of ground movement initiation.

This mirrored the analytical techniques proposed by Jean-Pierre et al. (2022), who defined the failure condition as the product of demand and resistance probability distributions. By moving beyond deterministic limit states, these integrated computational models allow operators to enact more effective mitigation measures, aligning with the Quantitative Risk Analysis (QRA) procedures outlined in the CSA Z662 standard. The current frontier of probabilistic SBDA involves the fusion of remote sensing data with structural reliability models to reduce the inherent uncertainties of geotechnical threats.

A.6.3.3 Remote sensing and data fusion for risk-Aware SBDA

As demonstrated by Zheng et al. (2024), integrating interferometric synthetic aperture radar (InSAR) into a Bayesian Network (BN) provides a high-resolution, non-invasive method for quantifying ground movement, which serves as a primary input for estimating probabilistic strain demand. This monitoring approach addresses the spatial challenges of geohazard assessment by replacing localized instrumentation with continuous satellite data.

Complementing these demand-side advancements, Lee and Kim (2020) emphasized the importance of refining strain capacity calculations through the reference strain method, particularly for welded joints. Their research highlights that accounting for strength mismatch effects in girth welds significantly improves the accuracy of engineering critical assessments (ECA), moving away from the over-conservatism of traditional stress-based standards like BS 7910. By synthesizing remote monitoring data with detailed metallurgical modeling within a BN architecture (Schell et al., 2023) the industry is moving toward a holistic "data fusion" model that can evaluate integrity risks across expansive pipeline networks in real-time.

Distinguishing between uncertainty and conservatism is crucial for an effective SBDA. Uncertainty represents the lack of definitive knowledge regarding actual conditions, whereas conservatism is a deliberate safety bias used to mitigate that lack of knowledge. Because early assessments often lack detailed data on geohazards and material properties, they traditionally rely on conservative, deterministic safety factors. While this approach ensures safety, it may not accurately reflect the pipeline's true capacity or the actual risk of failure. The adoption of multi-level frameworks provides a pathway to reduce these uncertainties over time, facilitating more informed and robust integrity management than traditional deterministic methods.

A.6.4. Challenges and Gaps in Applying SBDA to Vintage Pipelines

Implementing SBDA for vintage pipelines presents substantial challenges arising from both inherent technical complexity and pervasive data deficiencies. Most legacy systems installed prior to the 1970s lack reliable documentation of steel grades, welding procedures, post-weld heat treatment, and construction-era inspection practices. Vintage girth welds exhibit pronounced variability in metallurgical properties, hardness distribution, microstructure, and weld-to-pipe strength mismatch (Jia et al., 2019). Welding techniques commonly used at the time, such as oxy-acetylene and early manual SMAW, frequently produced wide weld caps, uneven fusion profiles, and high inclusion content. These characteristics often fall outside the calibrated range of contemporary SBDA frameworks, necessitating modified analytical approaches or bespoke testing programs to ensure safe application to legacy infrastructure.

Accurate detection and sizing of flaws in vintage girth welds remain a major limitation. Despite advances in PAUT and radiography, distributed porosity, slag lines, and small embedded cracks are not consistently identified or reliably sized, introducing substantial epistemic uncertainty into strain capacity assessments. Furthermore, the geometry and spatial distribution of vintage weld flaws often diverge from the idealized planar crack representations assumed in modern capacity models. As emphasized by Jia et al. (2020), strain-based models calibrated using modern, high-quality welds may fail to provide conservative predictions for vintage pipelines, particularly when defects are located within softened heat-affected zones or in regions of weld metal strength undermatching.

These technical challenges are compounded by *pervasive data scarcity*. Many legacy pipelines lack reliable tensile strength and fracture toughness measurements, and available test data are typically sparse and unrepresentative of population-level variability. Because destructive sampling of in-service pipelines is generally impractical, SBDA applications frequently rely on surrogate databases or intentionally conservative default inputs (Kotian and Wang, 2016). The absence of standardized material and flaw characterization data further constrains calibration and validation of advanced SBDA models. To address this gap, Wang et al. (2023) called for the development of standardized databases encompassing vintage weld material properties and flaw characteristics. Until such resources become widely available, SBDA for vintage pipelines will remain constrained by epistemic uncertainty, requiring conservative screening and increased reliance on field observations.

Beyond data limitations, a fundamental gap lies in the *scalability* of current SBDA methodologies. Owing to their heavy dependence on site-specific material and flaw data, SBDA applications are often restricted to isolated pipeline segments. Schell et al. (2023) identified major methodological gaps, including the lack of universal models, insufficient treatment of interacting variables, and persistent data-quality limitations. While finite element–based capacity models provide high fidelity, they are computationally expensive and unsuitable for system-wide integrity management. Converting such models into streamlined analytical formulations would enable more efficient network-scale screening and facilitate integration into holistic risk frameworks. Furthermore, the limited availability and variable quality of geotechnical and ILI data necessitate probabilistic data-fusion strategies, such as Bayesian frameworks, to explicitly propagate data uncertainty and support system-level decision making.

A.6.5. Key Findings about the Uncertainty of SBDA Frameworks

Current SBDA frameworks exhibit strong sensitivity to input data quality, flaw characterization accuracy, and material property variability. While tiered SBDA methodologies provide structured pathways for integrity evaluation, their reliability decreases substantially for in-service and vintage pipelines due to pervasive epistemic uncertainties. These uncertainties stem primarily from sparse fracture toughness data, limited resolution of ILI tools, and non-ideal metallurgical behavior of legacy girth welds that fall outside the calibrated domain of most modern strain capacity models.

Strain demand characterization under geohazard loading further introduces uncertainty through reliance on simplified soil–pipe interaction models and incomplete geotechnical information, which can lead to under- or over-estimation of displacement-controlled loading effects. Conservative default assumptions, while providing safety margins, often result in excessive remediation actions for stable geohazard features and do not reliably represent true failure risk. Recent advances in probabilistic, Bayesian, and data-fusion-based SBDA frameworks demonstrate significant potential to explicitly quantify aleatoric and epistemic uncertainties, integrate remote sensing data such as InSAR, and support scalable, system-level risk management. These approaches are therefore essential for improving the defensibility and practical applicability of SBDA in geohazard-prone pipeline networks.

A.7. Gaps in Risk Metrics for Strain-Based Integrity Assessment of Vintage Pipelines

This section reviews gaps in current risk metrics used within strain-based design and assessment (SBDA) frameworks, with a focus on their applicability to vintage pipelines exposed to geohazard-induced loading. The review examines limitations in translating strain-based results into probabilistic, consequence-informed risk metrics and highlights challenges in integrating SBDA outputs into system-level integrity management and decision-making processes.

A.7.1. Key Challenges and Research Gap

A.7.1.1. Lack of Generalizable SBDA frameworks

A significant gap in current SBDA research is the lack of a generalized and unified framework that is broadly applicable across pipeline types, materials, and loading conditions. While tensile and compressive strain capacity models have advanced, their integration remains inconsistent, and many elements are still treated independently despite their interdependence in real-world conditions. This issue is well-documented in a review that emphasizes the need for a system-level SBDA framework that considers the full lifecycle of pipeline integrity management from design to post-construction monitoring (Wang et al., 2014).

Furthermore, although SBDA has been increasingly adopted in response to geohazards, it still lacks standardization and full integration into risk-based management systems. (Schell, et al., 2023b) note that SBDA methods are often used in isolation, and there is a critical need to formalize a roadmap that links SBDA principles to comprehensive risk frameworks. Most SBDA studies define pipeline safety in terms of exceedance of tensile or compressive strain capacity, using deterministic strain limits as acceptance criteria (Wang et al., 2014; Zhang et al., 2014). While these limits are effective for evaluating local failure potential, they do not constitute formal risk metrics as used in risk-based integrity management, where risk is typically defined as a combination of likelihood and consequence.

A.7.1.2. Data and computational needs for probabilistic approaches

The application of SBDA in probabilistic modeling faces two significant challenges: data integration and computational feasibility. As pipelines operate in complex conditions, probabilistic assessments require a large amount of heterogeneous data, including satellite ground movement data (InSAR), strain measurements, defect data, and metallurgical properties. A Bayesian network model proposed by (Schell et al., 2023a) highlights the difficulty of integrating such diverse datasets and identifies the need for improved data structures and algorithms to reduce uncertainty in pipeline risk modeling.

Additionally, even when using high-resolution satellite data, models often fall short in accurately predicting all relevant failure modes, such as bending strain, due to limitations in computational modeling and data resolution. A recent study further stresses that while InSAR data and pipe-soil interaction models are promising, current Bayesian network approaches still require refinement and computational optimization to become practical for widespread industry use (Lever et al., 2024).

A.7.1.3. Reliance on deterministic strain limits as proxies for risk

The reviewed literature demonstrates a strong reliance on deterministic strain thresholds as proxies for pipeline risk. Studies on tensile strain capacity, compressive strain capacity, and corrosion-affected pipelines primarily evaluate whether a critical strain value is exceeded under a given loading scenario (Elyasi et al., 2021; Zhou et al., 2018). While these approaches provide valuable insight into failure mechanisms, they implicitly equate strain exceedance with unacceptable risk without explicitly defining how close-to-limit conditions should be interpreted in integrity decision-making.

This approach is particularly limiting for vintage pipelines, where material degradation, undocumented repairs, and variable construction quality result in a wide spectrum of performance margins. Deterministic strain limits do not adequately capture gradations of risk or support prioritization among assets with differing vulnerability and consequence profiles.

A.7.1.4. Weak integration of consequence considerations into SBDA metrics

Another significant gap is the limited integration of consequence into SBDA-derived risk metrics. Most SBDA studies focus on structural response and failure likelihood at the component level, such as girth weld failure or local buckling, without explicitly linking these outcomes to consequences such as product release, environmental impact, population exposure, or service disruption (Fredj & Dinovitzer, 2014; Liu et al., 2022).

Although SBDA is increasingly applied to geohazard-prone regions and critical crossings, the resulting assessments rarely distinguish between low- and high-consequence segments when defining acceptable strain limits or mitigation thresholds. This disconnect limits the usefulness of SBDA results for risk-based integrity management, where consequence differentiation is essential for allocating resources and selecting mitigation strategies.

A.7.1.5. Limited applicability of existing risk metrics to vintage pipelines

The applicability of existing SBDA risk metrics to vintage pipelines remains insufficiently addressed. Many SBDA methodologies and acceptance criteria were developed based on modern pipeline materials and construction practices, with relatively well-documented properties (Chen et al., 2022; Jang et al., 2019). In contrast, vintage pipelines often exhibit seam weld defects, strength mismatch, material anisotropy, and historical modifications that significantly influence failure behavior (Jia et al., 2020; Wang et al., 2020).

Despite these differences, SBDA risk indicators are often applied uniformly across vintage pipelines, without adjustment for aging-related vulnerabilities. This gap reduces confidence in SBDA-derived risk metrics when applied to older infrastructure and highlights the need for risk representations that explicitly acknowledge vintage-specific failure mechanisms.

A.7.1.6. Inconsistent linkage between SBDA results and integrity management decisions

A further gap lies in the inconsistent linkage between SBDA outputs and integrity management decisions. While several studies demonstrate how strain-based assessments can inform operational or mitigation actions, such as monitoring or pressure reduction, there is limited guidance on how strain-based indicators should be mapped to decision thresholds within existing risk management frameworks (Liu et al., 2022) .

In many cases, SBDA results are used in isolation, rather than being integrated into system-level risk ranking or lifecycle management strategies (Schell et al, 2023a). This limits the scalability of SBDA for large vintage pipeline networks and constrains its adoption as a core component of risk-based integrity programs. Although probabilistic SBDA frameworks have been proposed, they frequently rely on expert judgment due to limited data availability and lack standardized acceptance criteria linking probabilistic outputs to operational or regulatory decisions. Similarly, interactions among multiple degradation mechanisms such as corrosion combined with tensile or compressive strain are not adequately captured, and time-dependent effects including progressive ground movement and cyclic loading remain largely unexplored.

A.7.1.7. Absence of system-level risk metrics derived from SBDA

Finally, the literature reveals a gap in system-level risk metrics derived from SBDA. Most studies focus on localized assessments of strain demand and capacity at specific sites, such as slope crossings or corrosion anomalies. While these site-specific analyses are valuable, they do not readily translate into network-wide risk indicators that enable comparison across multiple threats, locations, and pipeline segments.

Without system-level risk metrics, SBDA remains primarily an engineering evaluation tool rather than a comprehensive risk management methodology. Addressing this gap is particularly important for vintage pipeline systems, where operators must prioritize interventions across extensive networks with limited inspection and historical data.

A.7.2. Key Findings about Gaps in Risk Metrics

The reviewed literature shows that current SBDA practices lack risk metrics that are probabilistic, consequence-informed, and suitable for vintage pipelines. Existing approaches rely heavily on deterministic strain limits, which do not adequately represent uncertainty, gradations of risk, or differences in consequence across assets. Data and computational constraints further limit the practical implementation of probabilistic SBDA frameworks, while existing risk indicators are largely developed for modern pipelines and are not readily transferable to vintage systems. Moreover, SBDA outputs are weakly connected to integrity management decisions and rarely scaled to system-level risk prioritization. These gaps underscore the need for SBDA-based risk metrics that explicitly incorporate uncertainty, consequence, and vintage-specific vulnerabilities.

A.8. Conclusion

The reviewed studies collectively demonstrate that strain capacity of vintage pipelines is governed by localized, highly coupled mechanisms involving weld mismatch, geometric imperfections, loading mode, and material heterogeneity. These interactions invalidate simplified or linearized assessment assumptions and highlight the necessity of specimen- and geometry-representative testing. The findings emphasize that reliable strain-based assessment for vintage pipelines must explicitly account for nonlinearity, constraint effects, and degradation-specific behavior to ensure meaningful integrity evaluation and decision support.

Building on the identified localized mechanisms in vintage girth welds, the reviewed testing approaches show that representative strain capacity characterization relies on geometry-relevant multi-scale specimens, fracture-toughness metrics, and proper measurements. Importantly, the assessed TAMU laboratory capabilities indicate that these requirements are practically achievable, enabling generation of high-fidelity datasets for model calibration, uncertainty treatment, and subsequent risk-metric development.

Extending SBDA from modern, well-characterized linepipe to in-service vintage systems reveals that framework "tiers" are less a maturity ladder than a reflection of data availability, with model reliability becoming dominated by input sensitivity, limited flaw/toughness information, and extrapolation beyond validated domains. Across the reviewed PRCI- and industry-led tools, the central obstacle is not the absence of models but the persistence of epistemic uncertainty in both capacity and demand, which drives over-conservative decisions and hinders network-scale application. The synthesis points toward probabilistic, Bayesian, and data-fusion strategies—including remote-sensing-informed strain demand—as the practical path to make SBDA defensible, scalable, and decision-relevant for geohazard-prone vintage pipeline networks, thereby setting the stage for risk-metric development.

Despite advances in strain capacity testing and SBDA methodologies, a critical gap remains in translating strain-based results into decision-relevant risk metrics for vintage pipelines. Current practice relies largely on deterministic strain limits as proxies for risk, without explicitly incorporating uncertainty, consequence severity, or system-level prioritization. Probabilistic SBDA approaches face data integration and computational challenges, and existing risk indicators are largely derived from modern pipeline assumptions that do not reflect vintage-specific vulnerabilities. These gaps highlight the need for next-generation SBDA-derived risk metrics that are probabilistic, consequence-informed, and explicitly tailored to aging pipeline systems.

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