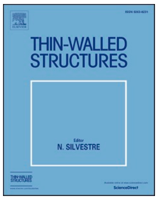
Thin–Walled Structures 228 (2026) 115124

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws



Review

Instability mechanism transitions in imperfect internally restrained thin-walled cylindrical shells

Jing Liu [a,b], Wenlin Jing [b], Jingguo Cao [a,*], Kangfu Sun [a,c,**]

[a] Tianjin University of Science & Technology, Tianjin 300457, China
[b] China Construction Infrastructure Co. Ltd., Beijing 100044, China
[c] Ningbo Water Meter (Group) Co., Ltd., Ningbo 315000, China

ARTICLE INFO

Keywords:
Thin-walled composite cylindrical shells
Buckling instability
Imperfection sensitivity
Interface restraint
Boundary-controlled instability
Cured-in-place pipe (CIPP)

ABSTRACT

Thin-walled composite cylindrical shells with internal restraint exhibit instability behavior highly sensitive to geometric imperfections, interface restraint, and boundary conditions. Unlike idealized shells governed by a single critical buckling load, such systems may experience transitions in governing instability mechanisms during service, evolving from load-controlled buckling to imperfection- or boundary-controlled failure. Experimental, numerical, and analytical evidence shows that degradation of interface restraint, stiffness incompatibility, and time-dependent material behavior alter shell-level stability, leading to imperfection amplification, loss of composite action, and displacement-controlled response. These mechanism transitions explain delayed instability and localized failure observed even when conventional buckling-based design criteria are satisfied. This review presents a mechanism-based reinterpretation of instability in internally restrained thin-walled composite shells, identifies key factors governing instability mechanism transitions, and examines their implications for existing buckling-based design frameworks. By interpreting failure as a transition between instability mechanisms rather than exceedance of a critical load, this study provides a mechanics-based perspective on the long-term stability of imperfect composite cylindrical shells.

1. Introduction

Thin-walled cylindrical shells subjected to external pressure exhibit instability behavior that is highly sensitive to geometric imperfections and boundary conditions, particularly during long-term service. While the present study primarily focuses on instability under external pressure, liner instability may also occur in pressure pipelines, where internal pressure and combined loading conditions can influence stability through different mechanisms. Internal restraint forms a composite cylindrical shell governed by stiffness compatibility and interface restraint. Reinforced concrete pipes rehabilitated with CIPP linings provide a typical example of such systems [1–5]. In this study, the term “composite shell” refers to the pipe–liner system as a whole, while “liner” specifically denotes the CIPP inner layer.

Cured-in-place pipe (CIPP) systems can be regarded as a representative form of internally restrained thin-walled composite cylindrical shells, with governing instability mechanisms defined at the shell level. Owing to liner–host interaction and interfacial restraint, such composite shells exhibit structural responses and failure modes fundamentally different from those of standalone shells. Their behavior is governed by stiffness compatibility and interface conditions, leading to enhanced circumferential stiffness in flexible systems (e.g., corrugated polymeric pipes[6]) and pronounced stress redistribution in rigid systems (e.g., reinforced concrete pipes [7]).

Existing studies on CIPP-formed composite shell systems have mainly focused on buckling stability, liner material properties, and composite structural response. However, delayed buckling, leakage, and localized rupture are frequently reported in practice despite compliance with prevailing design standards, indicating a clear discrepancy between observed service-time failures and conventional buckling-based predictions. Experimental and numerical studies demonstrate that geometric imperfections, interface conditions, and residual host–shell confinement significantly influence the stability and failure behavior of the composite shell system[8–11], including modifications to buckling modes and load redistribution[12,13]. Nevertheless, how interface restraint and composite action jointly govern transitions in dominant

---

[*] Corresponding author.
[**] Corresponding author at: Tianjin University of Science & Technology, Tianjin 300457, China.
E-mail addresses: cjg@tust.edu.cn (J. Cao), skf@tust.edu.cn (K. Sun).

https://doi.org/10.1016/j.tws.2026.115124
Received 12 January 2026; Received in revised form 7 May 2026; Accepted 12 May 2026

instability mechanisms during service remains insufficiently understood [14–16].

CIPP liners are typically composed of resin-based composite materials whose mechanical properties evolve during long-term service due to creep, stress relaxation, and environmental exposure [17,18]. The coupling between time-dependent material degradation and initial geometric imperfections progressively alters instability response, challenging design approaches based solely on short-term properties or a single long-term reduction factor.

This study develops a failure-oriented framework to interpret instability in CIPP-formed composite shells. Failure is defined as a transition between load-controlled, imperfection-controlled, and boundary-controlled regimes, governed by interface restraint and evolving imperfections. As illustrated in Fig. 1, the framework categorizes instability behavior into two regimes: imperfection-controlled (Regime 1) and boundary-controlled (Regime 2). The transition between these regimes is governed by key parameters such as the D/t ratio and interface conditions, providing a mechanistic basis for understanding failures associated with unmodeled transitions in internally restrained thin-walled shells.

The transitions between instability regimes can be further interpreted in a semi-quantitative manner through the relative dominance of key dimensionless parameters, including the diameter-to-thickness ratio (D/t), normalized imperfection amplitude (Δ/t), interface stiffness ratio, and boundary-induced displacement level. These parameters jointly determine whether the structural response is governed primarily by external load, geometric imperfections, or imposed boundary deformation.

In this framework, load-controlled behavior serves as the idealized reference state, whereas service-time instability is interpreted through transitions toward imperfection-controlled and boundary-controlled regimes.

The main contributions of this review can be summarized as follows: (1) a mechanism-based reinterpretation of the stability behavior of internally restrained thin-walled composite cylindrical shells; (2) identification of interface restraint as a key factor governing stiffness compatibility, load transfer, and instability evolution; (3) clarification of delayed instability as a shell-level phenomenon rather than a material- or component-level failure; and (4) systematic identification of mismatches between governing instability mechanisms and assumptions in prevailing buckling-based design frameworks, explaining why service-time failures may occur even when code-based criteria are satisfied.

2. Buckling-based design assumptions for internally restrained thin-walled shells

Buckling-based design methods for internally restrained thin-walled shells are based on idealized load-controlled instability assumptions, neglecting the evolving effects of interface restraint, geometric imperfections, and boundary conditions during service. While this study focuses on instability under external pressure, liner behavior in pressure pipelines may involve different mechanisms due to internal pressure and combined loading. These design approaches can be interpreted as engineering implementations of classical shell stability theories [19,20]. This section examines the underlying mechanical assumptions of such approaches, including the free ring model, host-shell confinement, and

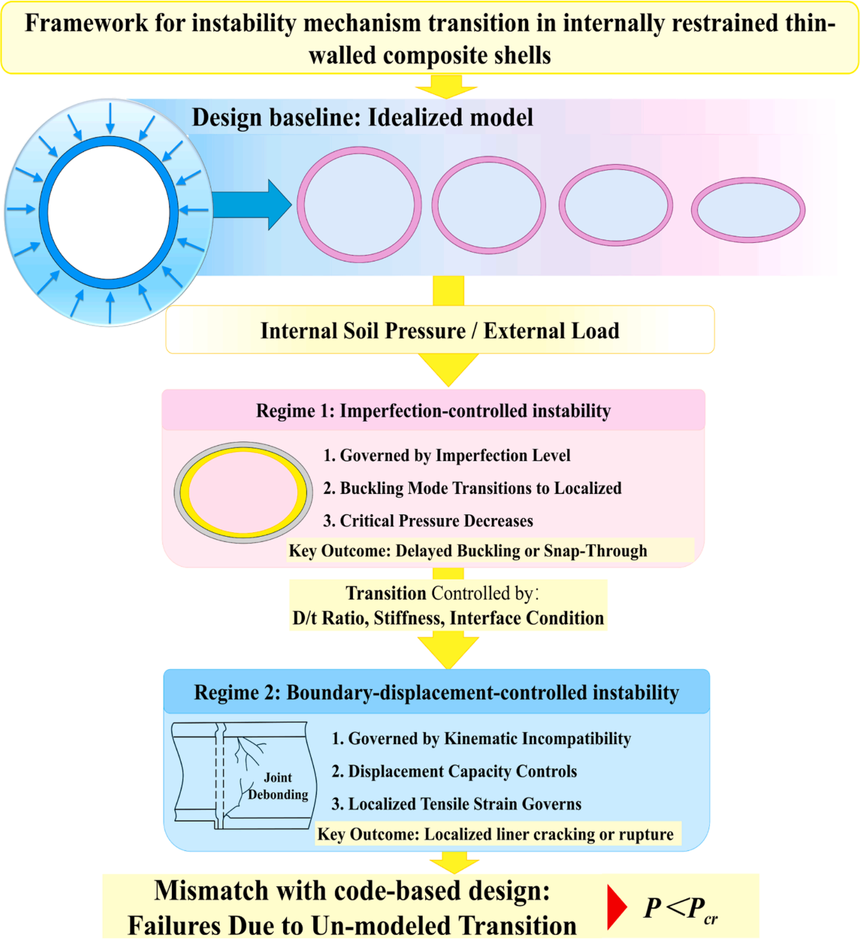


Fig. 1. Conceptual framework for the instability mechanism transition in internally restrained thin-walled composite shells, illustrating the shift from imperfection-controlled (Regime 1) to boundary-controlled (Regime 2) instability modes.

imperfection sensitivity, and evaluates their applicability in relation to governing instability mechanisms. As shown in Fig. 2, the instability behavior evolves from load-controlled buckling to confinement- and imperfection-controlled modes. Geometric imperfections, such as annular gaps and initial ovality, induce non-uniform deformation and stress concentration, leading to a transition from global to localized instability.

Different buckling modes correspond to distinct instability characteristics, spanning from global load-controlled behavior to localized imperfection-driven response. As loading progresses, interactions between these mechanisms drive transitions in instability modes, leading to post-buckling responses ranging from stiffness degradation to localized failure.

2.1. *Free ring buckling assumption and associated limitations*

The free ring buckling model represents the fundamental shell mechanics assumption for analyzing instability of CIPP liners under external pressure, derived from classical elastic stability theory for thin circular rings. Under linear elastic and small deformation conditions, the critical buckling pressure of a geometrically perfect, homogeneous, and unconstrained ring is given by Eq. (1), serving as an idealized load-controlled reference solution [21].

$$P_{cr} = \frac{2E}{1-\mu^2}\left(\frac{t}{D}\right)^3 \tag{1}$$

where D is the mean pipe diameter (mm); μ is Poisson's ratio; t is the average shell wall thickness; E is the elastic modulus of the liner material (MPa); and P_{cr} is the critical buckling pressure (MPa).

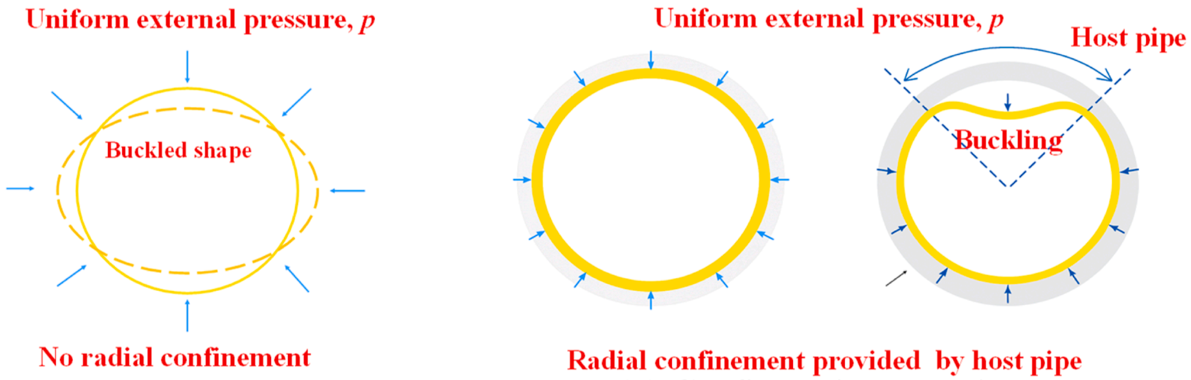
Due to its simplicity, the free ring model is widely used for preliminary instability assessment of CIPP liners. However, it neglects host-shell confinement, interface restraint, and imperfection effects. In practice, these factors significantly alter instability behavior, leading to deviations from free ring predictions. Therefore, the model should be regarded as a lower-bound reference applicable only under ideal load-controlled conditions.

2.2. *Host pipe confinement effects and modifications to buckling models*

In CIPP rehabilitation, the liner is typically subjected to radial confinement from the host shell, which restrains deformation and enhances buckling resistance. Glock [22] showed that rigid host-shell confinement can significantly increase the critical buckling pressure of a liner, and Aggarwal and Cooper [23] further demonstrated that ideal confinement substantially enhances buckling stability. This concept was subsequently incorporated into ASTM F1216 [24] through an empirical support factor that modifies the free ring buckling pressure by implicitly assuming effective liner host-shell contact. However, annular gaps and local defects often weaken confinement in practice, limiting the applicability of such models. While confinement increases apparent buckling resistance, it does not alter the governing instability mechanism, making predictions highly sensitive to interface contact conditions.

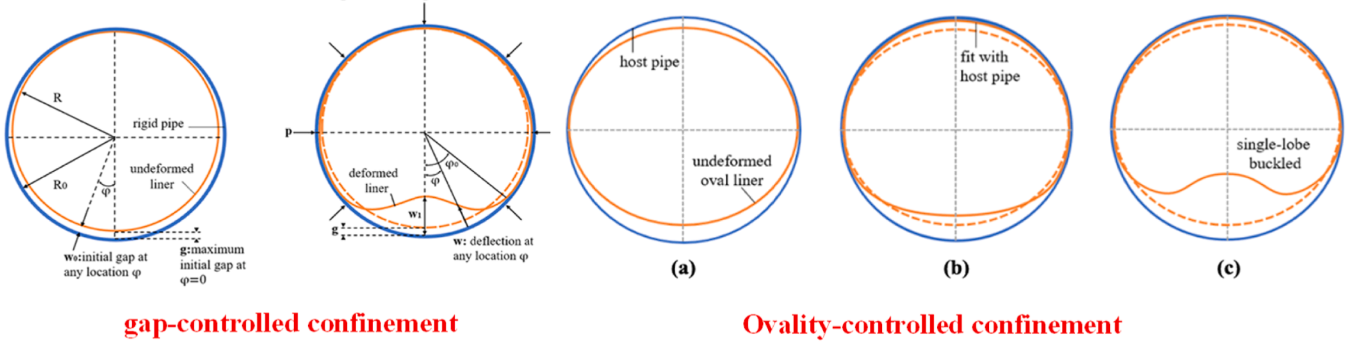
2.3. *Effects of initial imperfections on liner buckling performance*

Initial geometric imperfections are widely recognized as critical factors governing the buckling instability of CIPP liners. El-Sawy [25] identified typical installation induced imperfections in ultraviolet cured CIPP liners, including liner ovalization, local curvature reversal caused by host-shell protrusions, and annular gaps between the liner and the host shell. Among these, annular gaps are generally the dominant factor, promoting global ovalization and localized buckling, with critical pressure highly sensitive to gap size [26–30]. Initial ovality induces cross sectional stress non uniformity and premature local instability, reducing buckling capacity [31,32], while additional defects such as



(a) Free-standing Ring

(b) Confined ring buckling



(c) Annular gap

(d) Initial ovality

Fig. 2. Buckling mechanisms of thin-walled composite cylindrical shells formed by CIPP linings under uniform external pressure:(a) free ring controlled buckling;(b) host-shell confinement controlled buckling;(c) annular gap controlled buckling; and(d) initial ovality controlled buckling. [13].

wrinkles or wall-thickness variation further exacerbate instability through localized stress concentrations, motivating the introduction of imperfection parameters into free ring and Glock based models [33,34]. However, most existing models consider only single imperfections, whereas combined defects introduce strong nonlinearity and significantly reduce prediction accuracy [35].

Overall, geometric imperfections shift instability from global to localized or multi-mode behavior, and their coupled effects remain insufficiently characterized.

2.4. Applicability and limitations of buckling based design methods

Buckling-based design methods for CIPP liners have clear mechanical relevance under external pressure-dominated conditions with good liner–host contact and are suitable for preliminary stability assessment. However, these approaches rely on idealized assumptions such as geometric perfection, continuous interface contact, and negligible imperfection effects. In practical rehabilitation scenarios involving annular gaps, initial ovality, or interacting imperfections, the governing buckling mechanisms and instability modes can deviate substantially from idealized predictions[36,37]. From a design perspective, buckling stability should therefore be regarded as a necessary but not sufficient condition for CIPP liner design[20,38]. Under non ideal confinement or significant imperfections, buckling based criteria alone are inadequate to characterize the structural response. Instead, the behavior should be interpreted within a composite structural framework that considers load sharing and deformation compatibility between the liner and the host pipe [39,40].

3. Structural performance characterization of CIPP liners and its design applicability

3.1. Ring stiffness based performance characterization of CIPP liners

Performance-based indices such as ring stiffness implicitly assume independent liner action and small-deformation behavior, whereas the governing response of internally restrained composite shells is often controlled by instability and deformation compatibility. Experimental studies show that CIPP rehabilitation enhances circumferential deformation resistance, while the effective stiffness contribution of the liner depends on both material properties and liner host-shell interaction [41,42]. Interface bonding further influences the measured ring stiffness, motivating the introduction of reduction factors in engineering evaluations [43]. Nevertheless, ring stiffness based approaches are inherently limited to pre instability deformation response and are unable to capture crack development, interface slip, or instability driven failure mechanisms.

3.2. Strength and load bearing capacity evaluation under independent liner action

Strength based evaluation methods commonly treat the thin-walled liner as an independently acting component, although noticeable discrepancies may exist between this assumption and actual load bearing conditions in rigid flexible composite rehabilitation systems. Within such frameworks, liner thickness is typically determined based on circumferential stress, with stresses induced by external loads, temperature effects, and deformation superimposed and checked against material strength criteria. Brown *et al.* [44] proposed strength based failure equations for CIPP formed shells with pre existing defects under unfavorable loading.

Even under the independent liner assumption, geometric imperfections remain critical to strength controlled failure. Experimental and numerical studies by Ampiah *et al.* [45] showed that wrinkling defects readily induce localized stress concentrations, leading to significant reductions in crack load and ultimate load capacity, indicating that imperfections govern failure initiation even at the component level [46].

Engineering inspection results further reveal the limitations of strength based evaluation. Bosseler *et al.* [47] reported that CIPP liners with different service ages exhibited through wall defects and leakage due to installation related deficiencies, while statistical analyses of samples from multiple European rehabilitation projects indicated progressive degradation of mechanical performance with service time.

Overall, strength and ultimate limit state based methods can provide reasonable estimates of material and component level capacity when the thin-walled shell is treated as an independently acting element. However, in practical rehabilitation, host shell confinement, interface interaction, and construction related defects are commonly present, introducing substantial uncertainty into predictions based on the independent action assumption. Consequently, such approaches remain insufficient to describe system level load transfer and deformation compatibility, motivating subsequent analyses from a composite shell instability perspective.

4. Composite load bearing mechanisms and initial capacity characteristics of CIPP-rehabilitated pipelines

Table 1 synthesizes the major instability and failure modes by linking observed phenomena with their triggering mechanisms and associated limitations in prevailing design assumptions.

The composite response is governed by stiffness and deformation compatibility between the host shell and the liner. Depending on the material properties of the host shell and the liner, the rehabilitated system may behave as a rigid system, a flexible system, or different forms of composite structures, each associated with distinct failure controlling mechanisms. As illustrated in Fig. 3, different composite structural types exhibit distinct load-bearing mechanisms. It can be observed that flexible–flexible systems are dominated by deformation compatibility, whereas rigid–flexible systems exhibit stress redistribution and interface-controlled behavior. Composite action is therefore conditional rather than universal, and the governing failure mechanism is primarily governed by stiffness compatibility and interface restraint.

Table 1
Structural mechanism–design assumption mismatch framework for thin-walled composite shells.

Failure mode	Triggering mechanism	Governing structural factor	Design blind spot
Delayed buckling instability	Creep amplifies initial geometric imperfections	Time dependent stiffness degradation and imperfection sensitivity	Buckling design based on short-term modulus and ideal geometry
Loss of composite action	Progressive degradation of interface restraint	Interface shear transfer and confinement effectiveness	Oversimplified interface assumptions in design models
Localized liner cracking or rupture	Displacement incompatibility at joints or defects	Tensile strain concentration governed by boundary conditions	Load-controlled design neglects displacement driven failure
Interface debonding	Cyclic loading and stress relaxation at the interface	Degradation of interface shear stiffness	Interface behavior implicitly treated or ignored
Progressive stiffness loss	Viscoelastic creep and stress relaxation	Time dependent material behavior of liners	Single long-term reduction factor insufficient
Failure under extreme boundary conditions	Transition from load-controlled to displacement controlled response	Kinematic incompatibility and boundary constraint change	Pressure based design neglects boundary driven failure
Premature failure due to construction defects	Wrinkles, thickness non uniformity, incomplete curing	Local stress concentration and reduced effective section	Construction defects not explicitly included in models

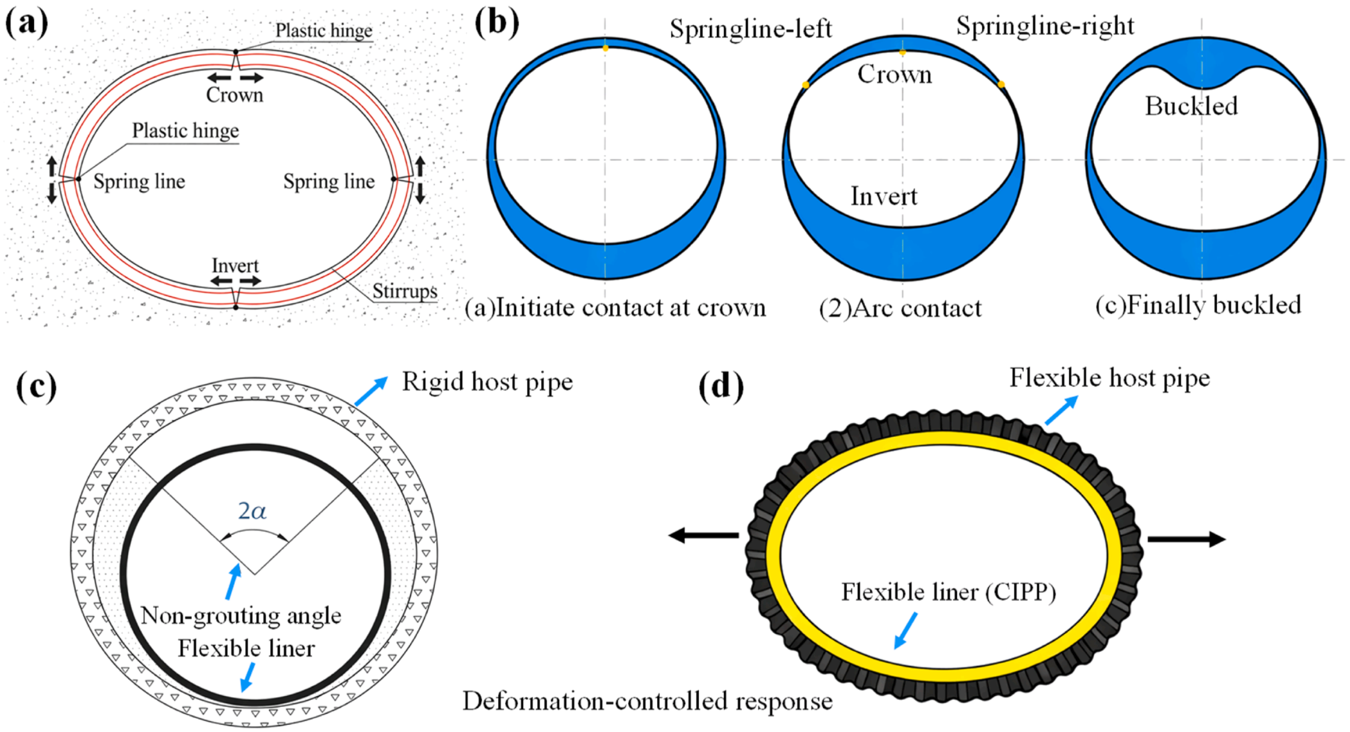


Fig. 3. Typical instability regimes and governing failure mechanisms of thin-walled composite cylindrical shells formed by CIPP linings under different structural interaction conditions:(a) rigid pipe [48];(b) flexible pipe [49];(c) rigid-flexible composite rehabilitation system [50];(d) flexible-flexible composite rehabilitation system.

To validate the aforementioned theoretical models and illustrate differences in load bearing evolution among composite shell systems

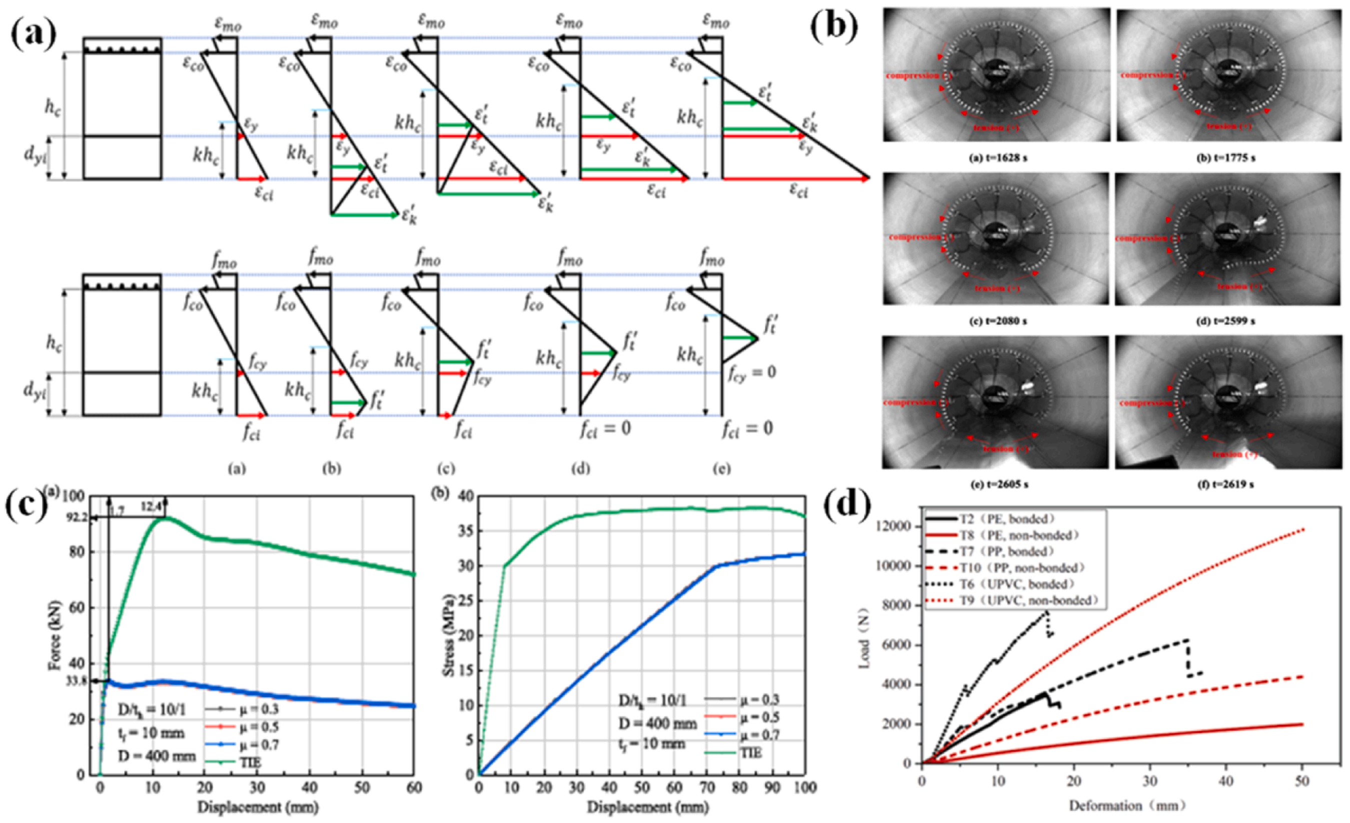


Fig. 4. Representative response characteristics illustrating transitions in instability mechanisms of internally restrained thin-walled composite cylindrical shells under varying interaction and boundary conditions:(a) stress-deformation modes [51];(b) pipe deformation under external pressure [13];(c) load–displacement curves [52];(d) force–deformation responses [14].

under service conditions, Fig. 4 presents representative response characteristics under varying interaction and boundary conditions. It can be observed that stress distribution, deformation patterns, and load–displacement responses evolve significantly with changing confinement and boundary conditions. This indicates that instability mechanisms are not fixed but transition depending on structural interaction and loading conditions.

4.1. *Composite structural types and their cooperative load bearing mechanisms*

After CIPP rehabilitation, the liner and host shell form a composite structural system whose structural response is governed by deformation compatibility, stiffness interaction, and interface restraint. Depending on the relative stiffness of the liner and host shell, CIPP formed systems are commonly classified as flexible-flexible or rigid-flexible composites, each exhibiting distinct cooperative load bearing mechanisms.

In flexible–flexible systems, experimental and numerical studies show that CIPP liners primarily enhance the deformation resistance of flexible host pipes through increased circumferential stiffness and deformation compatibility, rather than acting as independent load bearing elements [16,53–55]. Cooperative behavior in these systems is dominated by deformation compatibility, with the liner redistributing stresses and limiting excessive deformation under external pressure.

In rigid-flexible systems, the host pipe generally remains the primary load bearing component, while the CIPP liner provides secondary strengthening through load sharing and stress redistribution [56–58]. Studies on reinforced concrete pipe CIPP systems further indicate that tensile cracking of the host pipe and interfacial debonding may develop concurrently, underscoring the role of interface interaction in controlling load transfer and damage evolution [59]. Accordingly, cooperative load bearing in rigid-flexible composites is governed by stress redistribution and interface mechanics, with the liner acting mainly as a stabilizing element.

Overall, CIPP formed composite shell systems cannot be interpreted as a simple superposition of stiffness contributions. Their cooperative capacity depends on structural type and is controlled by interface restraint, deformation compatibility, and load transfer paths, while long-term evolution is further influenced by time dependent material behavior and interface degradation.

4.2. *Effects of interface restraint conditions on cooperative load bearing*

In CIPP formed composite shell systems, interface restraint conditions between the liner and the host shell determine whether cooperative load bearing can be activated. Interfacial bonding governs deformation compatibility and load transfer paths, thereby controlling composite stiffness and structural response.

Numerical analyses by Y *et al.* [60] showed that effective bonding enables deformation compatibility and joint load bearing, whereas interfacial gaps or degraded restraint promote independent liner behavior and a non cooperative response. Model tests by Kuliczkowski and Mogielski [61] further demonstrated pronounced variability in bonding performance among different host shell materials and established quantitative relationships between interface bonding, composite capacity, and ring stiffness.

By examining the evolution of the interface parameter K_1, Ti *et al.* [50] indicated that current ASTM design approaches are primarily based on the conservative assumption of an annular gap. Under conditions of strong liner host-shell interaction, such as well compacted grouted interfaces, the applicability of these standards becomes limited. To address this limitation, a non grouted angle α was introduced to represent partial contact conditions and refine stability evaluation.

$$E_l I = \frac{P_{cr} N D^3}{8 \times (66404\alpha^{-2.001})C} \quad 0 < \alpha < 90^{\circ} \tag{2}$$

Where $E_l I$ is the flexural rigidity ($N{\cdot}mm^2$), N denotes the number of active coils, α is the helix angle (°), and C is the dimensionless correction factor.

Overall, interface restraint acts as a load bearing “switch” in CIPP formed composite shell systems, determining whether cooperative mechanisms can be mobilized and defining the validity of related design models. Approaches that neglect interface conditions and consider only the liner or the host shell are therefore insufficient.

4.3. *Structural response under multiple service loadings*

CIPP formed composite shell systems are commonly subjected to multiple concurrent actions, including soil overburden, traffic loading, internal water pressure, and foundation deformation, resulting in a multi field coupled structural response dominated by load interaction and redistribution.

Traditional buried pipeline design, such as the M-S theory proposed by Spangler [60], idealizes soil-pipe interaction as an external pressure dominated problem. While widely used in culvert engineering, this framework is insufficient to capture load redistribution and interface effects in rehabilitated composite systems under combined service actions.

For pipelines with structural defects, Fang *et al.* [62] showed through full-scale tests and numerical analysis that traffic loading above misaligned joints can significantly amplify longitudinal bending moments, while CIPP liners mitigate this amplification by regulating local load transfer paths. Similarly, Yang *et al.* [63] demonstrated that soil loading primarily governs circumferential stress and bending, whereas traffic loading has a stronger influence on vertical deformation and liner stress, with internal water pressure playing a secondary role.

Overall, these studies indicate that under multiple service loadings, the structural response of CIPP formed composite shell systems is highly condition dependent and cannot be described by single load assumptions. Mechanically, multiple service loads redistribute existing load sharing interactions by modifying stress states and interface response, rather than introducing new load bearing mechanisms.

5. Long-term service performance and multi-field coupled response of CIPP rehabilitation systems

Results derived from short-term mechanical performance tests or instantaneous loading conditions are often insufficient to accurately represent the actual structural response of CIPP-formed composite shell systems under long-term service conditions. These time-dependent material effects govern the evolution of load-sharing mechanisms, interface restraint efficiency, and structural stability. During prolonged service, CIPP liners exhibit complex time-dependent behaviors, including tensile creep, flexural creep, cyclic fatigue, and delayed failure. As illustrated in Fig. 5, these mechanisms can be systematically characterized through their corresponding response patterns and failure modes.

Specifically, Fig. 5(a) shows the typical three-stage tensile creep behavior, highlighting the transition from stable deformation to accelerated failure. Fig. 5(b) demonstrates the progressive damage accumulation under cyclic loading, where stiffness degradation becomes evident with increasing cycle number. Fig. 5(c) illustrates the time-dependent flexural deformation, indicating continuous stiffness reduction under sustained loading. Furthermore, Fig. 5(d) reveals that imperfection-induced stress localization governs the initiation and development of instability and failure.

5.1. *Time dependent mechanical response during long-term service*

The long-term stability of CIPP-formed composite shell systems is governed not only by their initial mechanical properties but also by

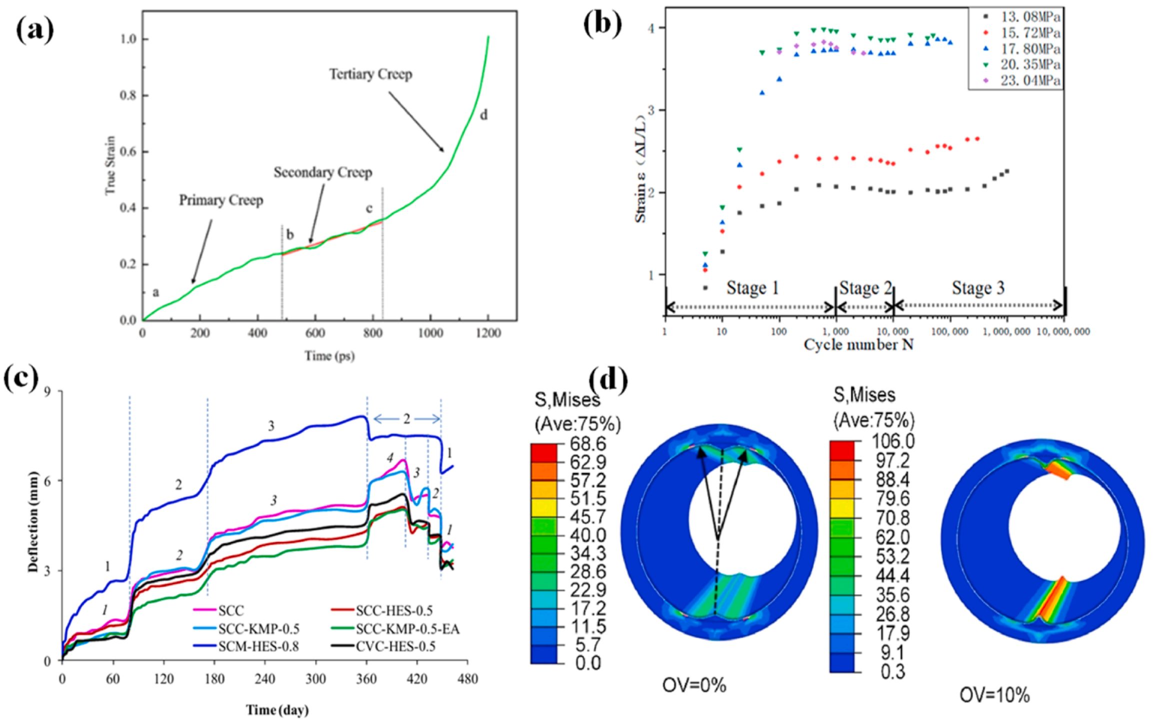


Fig. 5. Long-term mechanical behavior and failure mechanisms of CIPP liners under different loading conditions: (a) typical tensile creep response showing primary, secondary, and tertiary stages[64]; (b) fatigue-induced deformation evolution under cyclic loading[65]; (c) flexural creep behavior characterized by time-dependent deflection[66]; (d) representative instability and failure modes influenced by imperfection levels[20].

time-dependent material behavior. As resin-based composite systems, CIPP liners exhibit viscoelastic responses under sustained external pressure or groundwater loading, leading to creep deformation and progressive stiffness degradation. Experimental studies indicate that, over a 50-year service life, the effective modulus of certain CIPP material systems may decrease to well below 50% of the initial value, depending on material composition and loading conditions [67]. This 50-year design life assumption is primarily associated with conventional thermosetting resin-based CIPP systems, as adopted in standards such as ASTM F1216, while its applicability to other liner systems, such as fiber-reinforced CIPP, may differ depending on their material characteristics. In practical applications, installation defects, environmental exposure, and interface degradation may further reduce the effective service life compared with the nominal 50-year design assumption. As a result, structural performance may continue to evolve even when initial design requirements are satisfied.

Current design standards typically address creep effects through a single long-term modulus reduction factor. For example, ASTM F1216 adopts a reduction factor of approximately 0.5 to represent long-term degradation over a 50-year design life. However, experimental evidence shows that this empirical treatment is insufficient to capture the wide variability in creep behavior associated with different resin systems, fiber reinforcements, and loading histories [1,68,69].

From a failure analysis perspective, creep plays a critical role in delayed instability by amplifying initial geometric imperfections. Buckling resistance is highly sensitive to defects such as ovality and annular gaps [70]. During long-term service, creep-induced radial deformation effectively increases imperfection levels, driving the transition from load-controlled behavior to delayed instability with reduced critical pressure. Once creep deformation exceeds a threshold under sustained external loading, systems initially deemed stable may experience delayed buckling or snap-through instability [71,72].

In addition, time dependent stress relaxation and environmentally induced plasticization can further reduce the effective restraining capacity of composite shell systems and promote interfacial degradation during service [73,74]. Consequently, evaluations based solely on initial properties or a single reduction factor are inadequate for assessing the long-term stability and failure risk of CIPP formed composite shell systems under realistic underground conditions.

The creep-induced amplification of imperfections can be explained within a viscoelastic framework. Classical models, such as the Kelvin–Voigt and Burgers models, describe time-dependent deformation and stiffness degradation under sustained loading.

From a stability perspective, stiffness reduction leads to a decrease in buckling resistance, consistent with time-dependent stability (creep buckling), where the critical condition evolves with time [75,76]. This process continuously amplifies initial imperfections and increases instability sensitivity. This coupling between viscoelastic deformation and buckling response provides a mechanistic basis for imperfection growth in internally restrained thin-walled shells [77].

5.2. Structural response under extreme conditions and multi-field coupling

Under realistic service environments, CIPP formed composite shell systems may be subjected to extreme or non routine boundary conditions in addition to multiple concurrent actions such as soil overburden, groundwater pressure, traffic loading, internal pressure, and ground deformation. Under these conditions, structural response often departs from linear superposition assumptions and becomes governed by displacement and restraint controlled mechanisms, limiting the applicability of traditional load based models. Unlike the general multi-load scenarios discussed in Section 4.3, the emphasis here is on extreme boundary changes that trigger nonlinear reconfiguration of load bearing paths.

Field monitoring and numerical studies show that environmental coupling can significantly amplify structural response even when external load magnitude remains unchanged. Hu *et al.* [78,79] demonstrated that abrupt temperature drops during extreme cold wave events markedly increase pipeline stress, which is further amplified by traffic loading, particularly for shallow burial and at joint locations.

More fundamentally, recent studies indicate that under extreme conditions the governing response is controlled by boundary induced displacement rather than load amplification. Moore [80] showed that axial joint opening caused by ground deformation, as well as joint rotation and shear displacement, can shift liner behavior from a load-controlled regime to a boundary-controlled regime, with deformation capacity strongly dependent on initial joint gaps and restraint conditions. In such cases, tensile strain at critical locations often governs failure when exceeding typical limits for polymer-based liners (on the order of 1–3%). Similar displacement driven mechanisms have been observed for joint rotation, cracking, and offset misalignment, where localized tensile strain concentrations govern failure under combined traffic loading and ground deformation, motivating the use of local tensile limit states as controlling criteria [81,82].

In complex geological settings, extreme events such as fault dislocation further alter pipe–soil interaction boundaries and drive CIPP formed composite shell systems into strongly nonlinear response regimes. Numerical analyses by Zhai *et al.* [83] showed that fault induced displacement leads to coupled deformation and stress redistribution within the liner host-shell system, significantly increasing the susceptibility to buckling and localized instability, causing early attainment of local damage thresholds, typically associated with critical strain or curvature limits beyond which localized cracking or instability initiates [84,85].

Overall, extreme and multi-field coupled conditions, particularly those involving joint deformation (axial opening, rotation, and shear) and geological hazards such as fault movement, commonly induce a transition from load-controlled behavior to displacement- and restraint-controlled response in CIPP-formed composite shell systems. This transition is characterized by localized response amplification and load path reconfiguration. It is typically reflected in measurable indicators such as strain concentration, displacement localization (e.g., millimeter-level joint opening), and nonlinear load–displacement response, indicating the onset of instability beyond conventional load-based criteria.

These indicators provide a practical basis for identifying the onset and progression of instability under extreme boundary and multi-field coupled conditions.

6. Mechanics-assumption mismatch in current design frameworks

6.1. Buckling-based design assumptions and their mechanical implications

Current design frameworks for internally lined cylindrical shells are characterized by a fundamental mismatch between assumed load-controlled stability models and the mechanism-governed instability behavior observed under imperfect restraint and evolving boundary

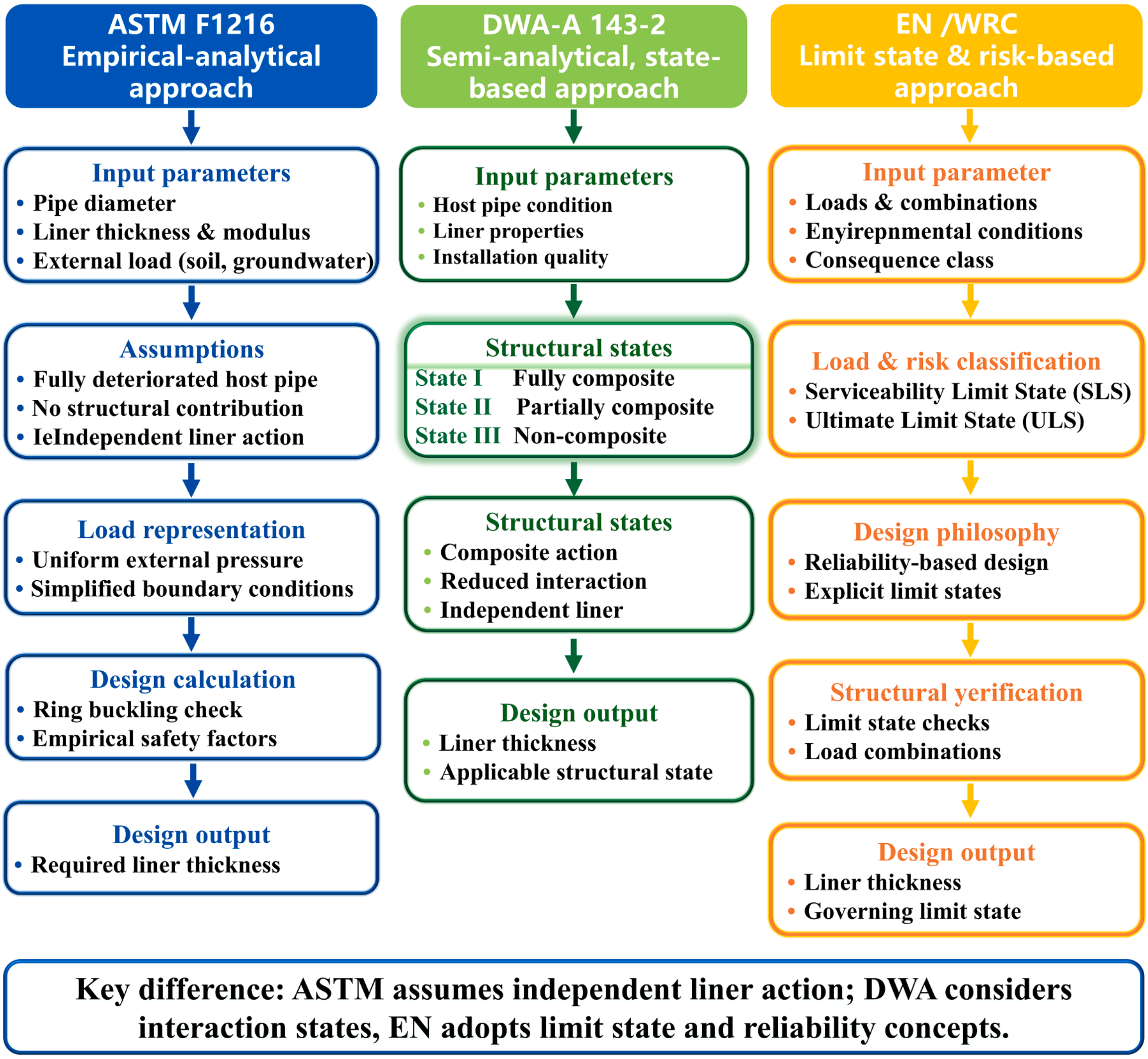


Fig. 6. Comparison of design logic and underlying mechanical assumptions in different international standards for internally restrained thin-walled composite cylindrical shells, highlighting differences in stability evaluation approaches.

conditions. Representative standards include ASTM F1216, DWA-A 143–2 (Germany) [86], EN ISO 11296–4 (Europe) [87], WRc SRM (UK) [88], and CJJ/T 210 (China) [89]. These standards reflect different regional interpretations of composite shell structural response. As illustrated in Fig. 6, different design standards are based on distinct mechanical assumptions, which may conflict with the governing instability mechanisms under service conditions.

ASTM F1216, the most widely applied CIPP design guideline worldwide, is fundamentally based on Timoshenko's external pressure buckling theory, in which the liner is idealized as an independently acting thin-walled circular ring [90]. Although empirical modification factors (e.g., the enhancement factor *K*) are introduced to account for host-shell restraint, the framework remains essentially a load controlled buckling model, with interface effects treated in a simplified or implicit manner. In contrast, the German DWA-A 143–2 standard adopts a more mechanics oriented framework by classifying rehabilitation systems into three structural states (State I-III), representing progressive degradation of host-pipe capacity. By modeling the liner, host shell, and surrounding soil as a coupled nonlinear system, DWA-A 143–2 evaluates stability under non uniform lateral pressure using a semi analytical approach. This framework is more consistent with composite shell interaction mechanisms discussed in Section 4, particularly with respect to confinement and load redistribution.

The European standard system, pioneered by the UK WRc and further developed in EN ISO 11296, emphasizes risk based defect classification and limit state design. In this framework, load effects and material resistance are treated separately using partial safety factors, enabling a more refined treatment of complex load combinations. Compared with the single global safety factor adopted in ASTM-based methods, this approach provides greater flexibility in addressing non uniform loading and degradation scenarios.

The Chinese standard CJJ/T 210 adopts a dual track framework, in which industry standards guide structural design while national standards regulate material performance. Although its analytical structure partially follows ASTM based formulations, conservative parameter calibration and semi empirical correction models derived from extensive field measurements provide practical adaptability under complex service conditions, such as high groundwater levels, soft soil strata, and large diameter shell systems.

Table 2 summarizes the key differences among major international standards in terms of their core mechanical models and treatment of defects, long-term degradation, and applicability.

Collectively, these standards indicate an evolution in CIPP design philosophy from liner strength verification toward assessment of composite shell stability. However, they remain conservative in delineating the applicability between liner independent behavior and pipe-liner cooperative action. This conservatism primarily stems from simplified interface assumptions and the absence of explicit criteria for activating composite action, which explains why instability and localized failures are observed even when code based criteria are satisfied.

6.2. *Consequences of mechanism–assumption mismatch under service conditions*

In addressing the condition of a "fully deteriorated host pipe," current international standards generally adopt the independent load bearing assumption [91]. Under this assumption, once the host shell is considered to have lost its structural integrity, it is treated merely as a load transfer medium, and the liner is required to independently resist the full earth and water pressures as well as surface live loads. However, this mechanical simplification is markedly disconnected from the actual response of pipe-liner composite shell systems and tends to inadequately represent the failure mechanisms of rehabilitated structures.

As discussed in Section 4, even when the host shell exhibits extensive cracking or localized collapse, its physical role as a *confining shell* is not completely lost. Experimental and numerical studies have demonstrated that the lateral restraint provided by the host shell can effectively limit the radial instability displacement of the liner, resulting in a significantly higher critical buckling pressure compared with the case of an independently loaded liner [92]. However, current standards commonly simplify the liner-host shell interface as a fully frictionless or unrestrained decoupled condition, which to some extent diminishes the representation of the overall structural response of the composite system.

Table 2
Comparison of major international CIPP design standards in terms of mechanical models and key design parameters.

Aspect	ASTM F1216 (USA)	DWA-A 143−2 (Germany)	EN ISO 11296−4 (Europe)	GB /T 210 (China)
Theoretical basis	Semi-empirical analytical method based on external pressure buckling theory	Semi-analytical approach considering pipe-soil-liner interaction	Design approach incorporating limit state concepts	Graded evaluation method based on analytical models
Defects	Equivalent defect parameter mainly based on ovality	Explicit consideration of annular gaps and asymmetric deformation	Comprehensive geometric defect correction factors	Reference to ovality and construction tolerances
Long-term reduction	Empirical creep reduction factor (C_L)	Time dependent model based on material classification	Test-based extrapolation according to EN 761	Arrhenius based extrapolation correction
Applicability	Primarily focused on circular pipes	Applicable to various non circular sections	Emphasis on whole life-cycle risk	Applicable to both structural and non structural rehabilitation

The excessive conservatism of this assumption leads to two major adverse consequences. First, for large diameter shell systems, the theoretically calculated liner thickness often results in substantial construction difficulty and disproportionately high costs[93]. Second, the critical contribution of interface bonding quality to the overall structural stability is largely neglected [94]. Therefore, future revisions of design standards should introduce concepts such as an *interface cooperation coefficient* or a *confinement enhancement factor* to quantitatively account for the actual contribution of residual host-shell stiffness and interface friction to load bearing capacity.

The consistency between design assumptions and the underlying instability mechanisms is further examined. Although existing standards (e.g., ASTM, DWA, and EN) provide practical design frameworks, their underlying assumptions do not fully align with the mechanisms identified in this study. ASTM-based methods are predominantly empirical, relying on simplified reduction factors without explicitly capturing the evolution of instability modes or the coupling between creep and buckling. In contrast, the DWA guidelines partially incorporate geometric imperfections and soil–structure interaction, making them more consistent with imperfection-controlled instability (Regime 1), yet they still neglect time-dependent stiffness degradation. The EN standards adopt a conservative, safety-factor-based approach, but do not explicitly address transitions between instability regimes. Consequently, these differences may lead to inconsistencies in design predictions, particularly when the governing instability mechanism shifts, as some assumptions may not fully capture, or may even conflict with, the time-dependent and imperfection-sensitive nature of the instability behavior identified in this study, underscoring the need for mechanism-based design approaches.

From a practical engineering perspective, the limitations of existing design standards indicate that the applicability of different approaches should be evaluated based on the governing instability mechanism. Buckling-based methods are appropriate when the response remains load-controlled and liner–host contact is effective. In contrast, for systems with pronounced imperfections or annular gaps, imperfection sensitivity should be explicitly considered. Under conditions involving joint opening or ground deformation, where boundary-induced displacement governs the response, displacement- or strain-based criteria are more appropriate than global pressure-based checks.

Although the present review focuses on instability under external pressure, liner instability in pressure pipelines may also arise under internal pressure and combined loading conditions. Extending the present mechanism-based framework to pressure pipeline applications therefore represents an important direction for future research.

7. Conclusions and future research directions

7.1. Main conclusions

This study provides a mechanics-based interpretation of instability in internally lined composite cylindrical shells, highlighting the roles of composite action, interface restraint, and time-dependent material behavior.

(1) The structural response of composite shell systems is fundamentally governed by the activation of shell–liner interaction through interface restraint. Loss of interface shear transfer disrupts cooperative behavior and shifts the system toward independent liner action, promoting instability or localized failure.
(2) Delayed instability originates from creep-driven amplification of geometric imperfections, which progressively reduces stability margins and may trigger buckling or snap-through under loads well below short-term critical levels.
(3) Design approaches based on independent liner assumptions are intrinsically insufficient, as they neglect the conditional nature of composite action and interface degradation, thereby failing to capture instability mechanisms that develop during service.
(4) Under multi-field and extreme conditions, failure is governed by boundary- and displacement-controlled mechanisms rather than load-based criteria, with localized deformation incompatibility dominating the structural response.

Overall, stability assessment based solely on a single critical buckling load is inadequate for internally restrained composite cylindrical shells. These findings indicate that future design approaches should incorporate mechanism-based criteria that explicitly account for interface conditions, imperfection effects, and boundary-induced deformation.

7.2. Failure oriented research perspectives

From a thin-walled shell failure perspective, several mechanisms controlling service-time instability in internally lined composite shells remain insufficiently understood under realistic underground conditions.

(1) Most existing studies focus on load-controlled instability under limited ground deformation. However, under displacement-dominated scenarios such as seismic ground movement, fault offset, or soil liquefaction, failure is governed by kinematic incompatibility and interface degradation rather than load magnitude. The underlying mechanisms, including interface debonding, localized instability, and brittle rupture under large imposed displacements, require further systematic investigation.
(2) Constitutive descriptions of CIPP liners are predominantly derived from short-term or single-field conditions and are insufficient to capture delayed instability observed in service. Failure-oriented models that explicitly link time-dependent material degradation, creep-induced deformation, and imperfection amplification to stability loss remain underdeveloped.
(3) Although field monitoring techniques increasingly provide spatially resolved response data, translating non-uniform damage and interface degradation into mechanics-based indicators of impending instability remains challenging. Future efforts should focus on establishing measurable response parameters that correlate with the initiation and evolution of localized shell instability.
(4) Emerging resin systems and low-energy curing technologies introduce additional uncertainty in long-term stiffness retention and imperfection sensitivity. Their implications for creep-driven degradation and delayed instability should be evaluated from a shell-level stability perspective rather than solely through material property characterization.

In addition, instability behavior of liners in pressure pipelines, where internal pressure and cyclic loading may introduce distinct governing mechanisms, warrants further investigation.

CRediT authorship contribution statement

Wenlin Jing: Supervision, Project administration. **Jing Liu:** Writing – original draft, Resources, Methodology, Data curation. **Jingguo Cao:** Writing – review & editing, Supervision, Funding acquisition. **Kangfu Sun:** Writing – review & editing, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] A.M. Riahi, Short-Term and Long-Term Mechanical Properties of CIPP Liners, University of Waterloo,, Waterloo, ON, 2015.
[2] S.M. Yadollahi, K.R. Piratla, A state-of-the-art review on failure mechanisms in buried plastic pipes, Tunn. Undergr. Space Technol. 162 (2025) 106672.
[3] B. Li, H. Fang, H. He, K. Yang, C. Chen, F. Wang, Numerical simulation and full-scale test on dynamic response of corroded concrete pipelines under Multi-field coupling, Constr. Build. Mater. 200 (2019) 368–386.
[4] T. Abel, Laboratory tests and analysis of CIPP epoxy resin internal liners used in pipelines-part II: comparative analysis with the use of the FEM and engineering algorithms, Stud. Geotech. Et. Mech. 43 (3) (2021) 307–322.
[5] J. Hicks, V. Kaushal, K. Jamali, A comparative review of trenchless cured-in-place pipe (CIPP) with spray applied pipe lining (SAPL) renewal methods for pipelines, Front. Water (2022).
[6] Z. Wang, W. Li, S. Li, W. Qiu, W. Ding, Development of an optimum forepole spacing (OFS) determination method for tunnelling in silty clay with a case study, Tunn. Undergr. Space Technol. 74 (2018) 20–32.
[7] J.-M. Hsu, K.-J. Shou, Numerical analysis of the mechanical behavior of separated joints in underground pipelines rehabilitated by cured-in-place pipes, Tunn. Undergr. Space Technol. 125 (2022) 104520.
[8] B. Shannon, G. Fu, R. Azoor, R. Deo, J. Kodikara, Long-term properties of cured-in-place pipe liner material, J. Mater. Civ. Eng. 34 (7) (2022) 04022119.
[9] Y.-d Huang, X.-l Gong, Y.-j Peng, C.-N. Kim, Effects of the solid curtains on natural ventilation performance in a subway tunnel, Tunn. Undergr. Space Technol. 38 (2013) 526–533.
[10] F. Gras-Travesset, A. Andreu-Torras, M.A. Pérez, Thickness optimization of semi-structural CIPP pressure pipe liners: A mathematical modeling approach, Tunn. Undergr. Space Technol. 152 (2024) 105876.
[11] Y. Huang, All-in-One Multifunctional Cured-in-place Structural Liner for Rehabilitating Aging Cast Iron Pipelines, North Dakota State University,, Fargo, ND, USA, 2024.
[12] G.M. Hebeler, R. Cichocki, M. Tara, A. Babazadeh Asbagh, K. Zhai, J. Gumbel, AASHTO LRFD design, installation, and standard practice of testing for cured-in-

place pipe (CIPP) liners, Transportation Research Board, National Academies of Sciences, Engineering, and Medicine, Washington. DC USA (2022).

[13] X. Wang, Y. Zhao, S.T. Ariaratnam, X. Yan, Study on the impact of ovality defect on structural stability of CIPP liner of drainage pipeline, Tunn. Undergr. Space Technol. 140 (2023) 105338.

[14] X. Wang, X. Yan, S.T. Ariaratnam, B. Ma, Y. Zhao, Investigation on the load-bearing performance and interface stress of plastic pipe–CIPP liner composite structures, Tunn. Undergr. Space Technol. 168 (2026) 107160.

[15] K. Yang, H. Fang, X. Zhang, X. Du, B. Li, K. Zhai, Mechanical evaluation analysis of pipe-liner composite structure before and after polymer grouting rehabilitation, Eng. Fail. Anal. 158 (2024) 108050.

[16] X. Wang, C. Zeng, X. Yan, P. Zhang, Study on the Bearing Capacity of the Polyethylene Pipe–Cured-In-Place Pipe Liner Composite Structure under External Pressure, Buildings 14 (7) (2024).

[17] C.J. Vining, W. Hall, D., Long-term material characterization of a cured-in-place plastic (CIPP) sewer rehabilitation liner material, Elsevier Science Ltd., Oxford, UK,, 2001.

[18] M. Nuruddin, K. DeCocker, S.M.T. Sendesi, A.J. Whelton, J.P. Youngblood, J. A. Howarter, Influence of aggressive environmental aging on mechanical and thermo-mechanical properties of Ultra Violet (UV) Cured in Place Pipe liners, J. Compos. Mater. 54 (23) (2020) 3365–3379.

[19] M.E. Woodbridge, J.R. Cook, Development and Implementation of a Construction Material Information System, Transp. Res. Rec. 1652 (1) (1999) 172–180.

[20] Y. Zhao, P. Ma, Y. Chen, K. Liu, X. Yan, B. Ma, F. Wang, Stability assessment of CIPP liner under varied boundary conditions: A theoretical and simulation study, Results Eng. 22 (2024) 102187.

[21] S.P. Timoshenko, J.M. Gere, Theory of Elastic Stability, Courier Corporation,, Chelmsford, MA, USA, 2009.

[22] D. Glock, Überkritisches Verhalten eines starr ummantelten Kreisrohres bei Wasserdruck von außen und Temperaturdehnung (Post-critical behavior of a rigidly encased circular pipe subject to external water pressure and thermal extension), Der, Stahlbau 7 (1977) 212–217.

[23] S.C.C. Aggarwal, M.J., External pressure testing of Insituform lining, Coventry (Lanchester) Polytechnic, Coventry, UK, 1984.

[24] A. International, ASTM F1216-16: Standard practice for rehabilitation of existing pipelines and conduits by the inversion and curing of a resin-mpregnated tube, ASTM International,, West Conshohocken, PA, USA, 2016.

[25] K.M. El-Sawy, Inelastic Stability of Tightly Fitted Cylindrical Liners Subjected to External Uniform Pressure, Thin-Walled Struct. 39 (9) (2001) 731–744.

[26] X. Tan, W. Chen, G. Wu, J. Yang, Numerical simulations of heat transfer with icewater phase change occurring in porous media and application to a cold-region tunnel, Tunn. Undergr. Space Technol. 38 (2013) 170–179.

[27] Z. Zhiqiang, Y.A. Mansoor, Evaluating the strength of corroded tunnel lining under limiting corrosion conditions, Tunn. Undergr. Space Technol. 38 (2013) 464–475.

[28] X. Yan, X. Wang, C. Deng, Y. Zhao, S. Mei, J. Bai, B. Ma, Testing and analysis of CIPP liner under simulated groundwater pressure, Tunn. Undergr. Space Technol. 152 (2024) 105903.

[29] F. Gu, H. Xiao, H. Wang, Z. Chen, K. Su, Z. Tian, X. Li, Y. Jin, Research on the Nonlinear Confined Buckling Pressure of a Thin-Walled Metal Liner with an Ovality Defect Installed Inside the Composite Overwrapped Pressure Vessels, J. Compos. Sci. 9 (9) (2025) 480.

[30] P. Zhang, F. Gu, Z. Cao, H. Wang, Z. Chen, H. Xiao, X. Wang, G. Ma, Theoretical and experimental research on the critical buckling pressure of the thin-walled metal liner installed in the composite overwrapped pressure vessel, Int. J. Press. Vessels Pip. 212 (2024) 105335.

[31] H. Hernández-Moreno, B. Douchin, F. Collombet, D. Choqueuse, P. Davies, Influence of winding pattern on the mechanical behavior of filament wound composite cylinders under external pressure, Compos. Sci. Technol. 68 (3) (2008) 1015–1024.

[32] R. Lo Frano, G. Forasassi, Experimental evidence of imperfection influence on the buckling of thin cylindrical shell under uniform external pressure, Nucl. Eng. Des. 239 (2) (2009) 193–200.

[33] D. Vasilikis, S.A. Karamanos, Stability of confined thin-walled steel cylinders under external pressure, Int. J. Mech. Sci. 51 (1) (2009) 21–32.

[34] Z. Li, L. Wang, Z. Guo, H. Shu, Elastic buckling of cylindrical pipe linings with variable thickness encased in rigid host pipes, Thin-Walled Struct. 51 (2012) 10–19.

[35] Z. Li, K.-c Shen, X.-h Zhang, G. Pan, Buckling of composite cylindrical shells with ovality and thickness variation subjected to hydrostatic pressure, Def. Technol. 18 (5) (2022) 862–875.

[36] C.R. Calladine, Understanding imperfection-sensitivity in the buckling of thin-walled shells, Thin-Walled Struct. 23 (1) (1995) 215–235.

[37] H.-Y. Choi, E.-K. Park, J.-W. Park, Y.-J. Kim, J.-I. Kim, Quantification of Plastic Buckling Behavior of Steam Generator Tubes with Wear defect under External Pressure, Thin-Walled Struct. (2026) 114904.

[38] M.K. Abadi, M.Z. Kabir, Buckling load prediction and peridynamic-based damage detection in composite structures, Forces Mech. 23 (2026) 100365.

[39] C.-X. Qu, S.-F. Ren, X.-Y. Li, Q. Zhong, M.-L. Qiu, Experimental and numerical study on dynamic buckling of cylindrical shells with initial imperfections subjected to underwater explosion, Thin-Walled Struct. 224 (2026) 114729.

[40] Q. Zhang, D. Liu, Z. Wang, C.G. Soares, Elastoplastic buckling responses of confined aged subsea pipelines under uniform pressure and thermal environment, Mar. Struct. 109 (2026) 104085.

[41] E. Allouche, S. Alam, J. Simicevic, R. Sterling, W. Condit, J. Matthews, A. Selvakumar, A pilot study for retrospective evaluation of cured-in-place pipe (CIPP) rehabilitation of municipal gravity sewers, Tunn. Undergr. Space Technol. 39 (2014) 82–93.

[42] J.-M. Hsu, K.-J. Shou, Experimental study of the separated joint of an underground pipeline rehabilitated by cured-in-place pipe, Undergr. Space 7 (4) (2022) 543–563.

[43] K.A. Mogielski, A. Kuliczkowski, E. Kuliczkowska, Change in Toughness Parameters of Sewer Pipes Rehabilitated with Two Types of Epoxy CIPP Liners, J. Pipeline Syst. Eng. Pract. 8 (4) (2017) 04017015.

[44] M.J.P. Brown, I.D. Moore, A. Fam, Analysis of a cured-in-place pressure pipe liner spanning circular voids, Tunn. Undergr. Space Technol. 101 (2020) 103424.

[45] N.F. Ampiah, A. Moore, I.D, Wavy imperfections and the strength of cast-in-place pressure pipe liners Conference Name: Proceedings of the International Pipeline Conference (IPC), ASME (2008).

[46] C. Wang, L. Guo, Y. Xia, C. Zhang, X. Sang, C. Xu, G. Zhu, H. Ji, P. Zhao, H. Fang, Z. Peng, X. Zhang, Flexural performance and damage evolution of multiple fiberglass-reinforced UV-CIPP composite materials– A view from mechanics and energy release, J. Mater. Res. Technol. 29 (2024) 3317–3339.

[47] B. Bosseler, D. Homann, T. Brüggemann, I. Naismith, M. Rubinato, Quality assessment of CIPP lining in sewers: Crucial knowledge acquired by IKT and research gaps identified in Germany, Tunn. Undergr. Space Technol. 143 (2024).

[48] Z. Zhu, P. Zhang, B. Ma, C. Zeng, Y. Zhao, F. Wang, Z. Li, W. Xiang, S. T. Ariaratnam, X. Yan, Quantitative model for residual bearing capacity of corroded reinforced concrete pipe based on failure mode, Tunn. Undergr. Space Technol. 129 (2022) 104675.

[49] X. Yan, X. Wang, W. Xiang, Y. Zhao, B. Ma, Buckling behavior of Formed-in-Place-Pipe (FIPP) liners under groundwater pressure: An experimental investigation for buried municipal pipelines, Tunn. Undergr. Space Technol. 142 (2023) 105397.

[50] Z. Ti, F. Wang, Y. Zhao, B. Ma, C. Zeng, B. Liao, Theoretical Study on Design of Composite Lining Structure with Rigid-Flexible Combination for Trenchless Pipeline Rehabilitation, Appl. Sci. 12 (11) (2022) 5374.

[51] X. Dong, T. Dou, P. Dong, Z. Wang, Y. Li, J. Ning, J. Wei, K. Li, B. Cheng, Failure experiment and calculation model for prestressed concrete cylinder pipe under three-edge bearing test using distributed fiber optic sensors, Tunn. Undergr. Space Technol. 129 (2022) 104682.

[52] K. Zhai, H. Fang, D. Di, B. Li, J. Lei, M. Li, J. Ma, Mechanical behavior of the rigid pipeline strengthened by CIPP under the action of soil pressure: Analytical solution and numerical simulation, Tunn. Undergr. Space Technol. 166 (2025) 106938.

[53] J.C. Boot, Z.W. Guan, I. Toropova, The structural performance of thin-walled polyethylene pipe linings for the renovation of water mains, Tunn. Undergr. Space Technol. 11 (1996) 37–51.

[54] B. Ma, M. Najafi, Development and applications of trenchless technology in China, Tunn. Undergr. Space Technol. 23 (4) (2008) 476–480.

[55] M.J.P. Brown, I.D. Moore, A. Fam, Performance of a cured-in-place pressure pipe liner passing through a pipe section without structural integrity, Tunn. Undergr. Space Technol. 42 (2014) 87–95.

[56] Y. Takahashi, T. Deguchi, L. Li, A Study on the Bedding Effects of the Deteriorated Existing Pipe on the Flexible Rehabilitated Pipe and Its Mechanism, J. Jpn. Sew. Works Assoc. 39 (471) (2002) 103–115.

[57] J. Gumbel, A. Spasojevic, R. Mair, Centrifuge Modelling of Soil Load Transfer to Flexible Sewer Liners, N. Pipeline Technol. Secur. Saf. UK (2003) 352–362.

[58] G. McAlpine, Rehabilitation of fully deteriorated rigid pipes by flexible and rigid liners. Pipelines 2001: Advances in Pipelines Engineering and Construction, American Society of Civil Engineers,, San Diego, California, United States, 2001, pp. 1–12.

[59] K.J. Shou, C.C. Huang, Numerical analysis of straight and curved underground pipeline performance after rehabilitation by cured-in-place method, Undergr. Space 5 (1) (2020) 30–42.

[60] Y. Kou, S.K. Shukla, A. Mohyeddin, Experimental investigation for pressure distribution on flexible conduit covered with sandy soil reinforced with geotextile reinforcement of varying widths, Tunn. Undergr. Space Technol. 80 (2018) 151–163.

[61] A. Kuliczkowski, K. Mogielski, Results of Laboratory Tests of Concrete, Vitrified Clay and PVC Sewer Pipes with CIPP Liners, Struct. Environ. 4 (3) (2012).

[62] H. Fang, K. Yang, B. Li, Parameter Analysis of Wall Thickness of Cured-in-Place Pipe Linings for Semistructured Rehabilitation of Concrete Drainage Pipe, Math. Probl. Eng. 2020 (2020).

[63] K. Yang, H. Fang, J. Bu, X. Zhang, B. Li, X. Du, Z. Zhang, Full-scale experimental investigation of the mechanical characteristics of corroded buried concrete pipes after cured-in-place-pipe rehabilitation, Tunn. Undergr. Space Technol. 117 (2021) 104153.

[64] X. Li, X. Zhang, J. Chen, L. Huang, Y. Lv, Uniaxial Tensile Creep Behavior of Epoxy-Based Polymer Using Molecular Simulation 13 (2) (2021) 261.

[65] S. Wang, S. Tang, C. He, Q. Wang, Cyclic Deformation and Fatigue Failure Mechanisms of Thermoplastic Polyurethane in High Cycle Fatigue 15 (4) (2023) 899.

[66] F. Kassimi, K. Khayat, Flexural Creep and Recovery of Fiber-Reinforced SCC - Testing Methodology and Material Performance, J. Adv. Concr. Technol. 19 (2021) 67–81.

[67] R.K. Lee, S. Ferry, Long-Term Cured-In-Place Pipe (CIPP) Performance and its Design Implications[J], Water Practice 1 (2007) 1–12.

[68] R. Nassar, M. Yousef, Analysis of creep failure times of cured-in-place pipe rehabilitation liners, Tunn. Undergr. Space Technol. 17 (3) (2002) 327–332.

[69] E. Barbero, S. Rangarajan, Long-Term Testing of Trenchless Pipe Liners, J. Test. Eval. 33 (6) (2005) 377–384.

[70] Y. Zhao, B. Ma, S.T. Ariaratnam, X. Yan, W. Xiang, Z. Zhu, Z. Li, M. Moghbel, Esfahani, Buckling behaviour of internal stiffened thin-walled stainless steel liners under external constraints, Tunn. Undergr. Space Technol. 129 (2022) 104685.

[71] Q. Zhao, Finite element simulation of creep buckling of CIPP liners under external pressure, 1999.

[72] Z. Li, Y. Tang, F. Tang, Y. Chen, G. Chen, Elastic buckling of thin-walled polyhedral pipe liners encased in a circular pipe under uniform external pressure, Thin-Walled Struct. 123 (2018) 214–221.

[73] S. Tomar, B.S. Butola, M. Joshi, The Impact of UV-protective Finish on the Natural Weathering of High-Strength Fabrics used in LTA Applications, Polym. Degrad. Stab. (2026) 112114.

[74] M.S. Song, G.X. Hu, L.J. Hu, Prediction of long-term mechanical behaviour and lifetime of polymeric materials, Polym. Test. 17 (5) (1998) 311–332.

[75] H.-L. Dai, H.-Y. Zheng, Creep Buckling and Post-Buckling Analyses of a Viscoelastic FGM Cylindrical Shell with Initial Deflection Subjected to a Uniform In-Plane Load, J. Mech. 28 (2) (2012) 391–399.

[76] F.W. French, S.A. Patel, B. Venkatraman, Creep buckling of cylindrical shells under axial compression, J. Frankl. Inst. 284 (5) (1967) 320–325.

[77] N. Miyazaki, Creep buckling analysis of circular cylindrical shell under both axial compression and internal or external pressure, Comput. Struct. 28 (4) (1988) 437–441.

[78] M.C. Celina, The Effect of Long Term Thermal Exposure on Plastics and Elastomers, Elsevier,, Amsterdam, 2013.

[79] Q. Hu, O. Ayinde, W. Liu, Mechanical response of buried water pipes to traffic loading before and after extreme cold waves, Transp. Geotech. 49 (2024) 101418.

[80] I. Moore, Response of a polymer liner passing across a pressure pipeline joint opening under axial ground movements, Comput. Geotech. 139 (2021) 104429.

[81] K. Zhai, I. Moore, Bending Response and Design Equations for Gravity-Flow Pipe Liners Passing across Ring Fractures or Joints, J. Pipeline Syst. Eng. Pract. 15 (4) (2024) 04024043.

[82] K. Zhai, H. Fang, D. Di, B. Li, J. Lei, M. Li, J. Ma, Mechanical behavior of the rigid pipeline strengthened by CIPP under the action of soil pressure: Analytical solution and numerical simulation, Tunn. Undergr. Space Technol. 166 (2025).

[83] K. Zhai, D. Hu, K. Wang, H. Fang, N. Wang, B. Li, X. Du, Y. Hu, X. Fan, Mechanical properties of the liner for strengthening steel pipe under the action of normal fault, J. Pipeline Sci. Eng. 5 (1) (2025) 100225.

[84] K. Zhai, H. Fang, N. Wang, B. Li, X. Du, P. Cui, K. Yang, A simplified solution for buried continuous pipe rehabilitated by liner under the effect of surface load and soil void, Can. Geotech. J. 62 (2025) 1–15.

[85] K. Zhai, I.D. Moore, Stress Analysis for a Liner Spanning a Gap between Sections of Rigid Pressure Pipes 17 (1) (2026) 04025105.

[86] DWA, DWA-A 143–2: Rehabilitation of Drainage Systems Outside Buildings – Part 2: Static Calculation for Lining and Assembly Methods, German Association for Water, Wastewater and Waste, Hennef, 2015.

[87] I.Of Standardization, Plastics piping systems for renovation of underground non-pressure drainage and sewerage networks — Part 4: Lining with cured-in-place pipes (CIPP, ISO 11296-4:2018, International Organization for Standardization,, Geneva, Switzerland, 2018.

[88] WRc, Sewer Rehabilitation Manual (SRM), Water Research Centre,, Swindon, 2015.

[89] M.o.H.a.U.-R.D.o.t. PRC, CJJ/T 210—2014 Technical Specification for Trenchless Rehabilitation of Urban Drainage Pipelines, China Architecture & Building Press,, Beijing, 2014.

[90] K. El-Sawy, Ian D. Moore, Stability of Loosely Fitted Liners Used to Rehabilitate Rigid Pipes, J. Struct. Eng. 124 (11) (1998) 1350–1357.

[91] S. Das, A. Bayat, L. Gay, M. Salimi, J. Matthews, A comprehensive review on the challenges of cured-in-place pipe (CIPP) installations, J. Water Supply. Res. Technol. - Aqua 65 (2016) 583–596.

[92] J.-Y. Fu, B.-G. Wu, J.-R. Wu, T. Deng, Y.-L. Pi, Z.-N. Xie, Design sensitivity analysis for optimal design of geometrically nonlinear lattice structures, Eng. Struct. 168 (2018) 915–928.

[93] U.S.E.P.A. (EPA), National database structure for life cycle performance assessment of water and wastewater rehabilitation technologies (retrospective evaluation), U. S. Environmental Protection Agency,, 2014..

[94] NASSCO, Cured-in-place pipe (CIPP) installation: performance specification guideline, Institution, National Association of Sewer Service Companies,, 2023.