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Use of Scaled Models to Evaluate Reinforcement Efficiency in Damaged Main Gas Pipelines to Prevent Avalanche Failure

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ABSTRACT: This research extends ongoing efforts to develop methods for reinforcing damaged main gas pipelines to prevent catastrophic failure. This study establishes the use of scaled-down experimental models for assessing the dynamic strength of damaged pipeline sections reinforced with wire wrapping or composite sleeves. A generalized dynamic model is introduced for numerical simulation to evaluate the effectiveness of reinforcement techniques. The model incorporates the elastoplastic behavior of pipe and wire materials, the influence of temperature on mechanical properties, the contact interaction between the pipe and the reinforcement components (including pretensioning), and local material failure under transient internal pressure. Based on these parameters, a finite element model was developed using ANSYS 19.2 to enable parametric studies. The accuracy of the proposed model was verified by comparing the simulation results with the experimental findings. Pipeline section samples containing non-penetrating longitudinal cracks were subjected to comparative analyses and transient pressure until critical failure. The unreinforced and steel wire-wrapped sections were investigated. The results confirm the feasibility of applying the computational model to study the dynamic strength of reinforced damaged pipe sections. Furthermore, pipelines with longitudinal cracks reinforced using circular composite overlays with orthotropic mechanical properties were examined, and recommendations are provided for selecting the geometric parameters of such overlays.

KEYWORDS: Composite overlay; crack-like defect; finite-element; local failure; multiscale modeling; pipeline safety; structural integrity; thin-walled structure

1 Introduction

Ensuring the operational reliability and structural stability of defect-containing main steel gas pipelines remains a priority challenge in contemporary engineering mechanics. This issue is particularly critical in seismically active regions and areas subject to substantial temperature fluctuations, where extreme operational conditions can cause localized damage and accelerate the propagation of crack-like defects into penetrating cracks, ultimately resulting in catastrophic failure.



This study continues a series of research initiatives aimed at developing methods for strengthening damaged main gas pipelines to prevent catastrophic failure [1–4]. The authors' previous investigation included a comprehensive set of numerical and experimental studies on various aspects of pipeline structural integrity. Zhangabay et al. [1] used the finite-element (FE) modeling method to analyze the dynamic behavior of a thin-walled steel pipe with a crack-like defect under internal pressure. This model simulated a section of the Beineu-Bozoy-Shymkent gas pipeline in the Republic of Kazakhstan. This study demonstrated that a longitudinal crack-like defect exceeding half the wall thickness under increasing internal pressure from operating to critical levels leads to the formation of a penetrating crack. This crack propagates longitudinally due to localized material failure induced by plastic deformation at the crack tips. Zhangabay et al. [2] examined the influence of ambient temperature (-40°C to $+50^{\circ}\text{C}$) on crack growth. The previously developed dynamic model of deformation and failure of a full-scale pipeline section was extended to account for the temperature dependence of the mechanical properties pipe material. Zhangabay et al. [3] proposed methods for preventing longitudinal crack growth by wrapping steel wire. A combined numerical model—building upon the frameworks established in Zhangabay et al. [1] and Zhangabay et al. [2]—was developed and further enhanced with a wire wrapping component. Numerical simulations enabled the evaluation of multiple wrapping parameters, such as wire diameter, pretensioning force, winding method, and pitch. In addition, simulations of catastrophic pipe failure at varying ambient temperatures provided critical insight into the effectiveness of different structural reinforcement strategies. The reliability of the proposed protection methods against catastrophic failure in damaged pipelines was validated through experimental testing. Zhangabay et al. [4] conducted an experimental assessment of various wire wrapping techniques using a 1:5 scaled model developed according to the theory of mechanical similarity and affine modeling of a full-scale gas pipeline. Collectively, the findings from these studies [1–4] provide the foundation for the present research.

Currently, wire wrapping, composite overlays, and steel sleeves are used as reinforcement techniques. Research in this field is generally classified into four categories based on field data: experimental investigations, analytical approaches, numerical simulations, and case studies. Numerous studies have highlighted the critical importance of preventing avalanche-type failure in damaged main gas pipelines. Considerable attention has been devoted to the numerical modeling of defective regions to assess their influence on the structural integrity of pipelines [5,6]. A standard practice is FE analysis of the stress-strain state of pipelines under internal pressure. This approach accounts for complex contact interactions, nonlinear material responses, and dynamic loading conditions [7,8]. Evidence shows that even small defects can trigger catastrophic failure under certain circumstances, leading to extensive damage [9]. Hara et al. [10] and Li et al. [11] reported on the experimental and numerical investigations of pipeline failure, with a particular focus on the effects of temperature. Lowering the temperature significantly reduces the ductility of steel and increases the risk of brittle fracture. For accurate failure modeling, a comprehensive analysis that integrates temperature fields, material microstructure, and defect geometry is essential [12]. A range of structural strengthening techniques has been developed to localize or arrest damage propagation in pipelines, and these approaches are frequently documented in the literature. Common strategies include installing circumferential reinforcement rings on both sides of the defect zone, applying spiral wrapping with high-strength wire [13,14], and using external composite overlays fabricated from glass or carbon fibers [15–17]. These reinforcement methods differ not only in terms of efficiency but also in terms of weight, costs, and implementation complexity. However, their effective use requires numerical validation, particularly to evaluate energy absorption during defect growth [18]. In recent years, considerable advances have been made in composite repair technologies, particularly with the development of fiber-reinforced polymer (FRP) systems and hybrid composite sleeves. These new technologies offer enhanced adhesion, toughness, and

resistance to high temperatures. Experimental studies have confirmed that modern FRP composites can effectively restore the structural integrity of corroded pipelines under complex loading conditions, including axial compression and offshore environments [19]. Comprehensive literature reviews further underscore the increasing role of advanced composite materials and modeling techniques in evaluating the residual strength of repaired pipelines [20]. These advancements point to the need for updated numerical methodologies capable of accurately capturing the mechanical behavior of composite reinforcements under dynamic and thermal loading. Studies investigating the use of scaled pipeline models for the numerical analysis of failure and reinforcement processes are of particular interest [21–23]. Scaling allows for a substantial reduction in computational costs while preserving the qualitative behavior of mechanical responses. Studies have shown that appropriately scaled models can closely reproduce the results of full-scale simulations [24]. Moreover, scaled models are particularly valuable for simulating complex reinforcement configurations, which require comprehensive, multilevel validation of computational models through experimental testing [25–27].

This study investigates the use of scaled-down models for the experimental assessment of the dynamic strength of damaged pipeline sections reinforced with wire wrapping or composite sleeves. A dynamic numerical model is specifically developed to evaluate the effectiveness of these strengthening methods. The model accounts for several factors: the elastoplastic behavior of pipe and wire materials, the influence of temperature on material mechanical properties, contact interactions between pipe and reinforcement, including prestressing effects, and local material failure under transient internal pressure. The model's reliability is verified by comparing it with experimental data obtained from a scaled gas pipeline section [4]. Furthermore, dynamic deformation and failure simulations are qualitatively compared between scaled and full-size numerical models [1–3]. Three reinforcement configurations are considered: circumferential elements on both sides of the defect, spiral wire wrapping with specified pitch, and composite overlays exhibiting orthotropic properties. This study introduces an integrated methodology that combines geometrically scaled physical models with validated FE simulations to evaluate the dynamic strength of reinforced gas pipelines containing longitudinal cracks. Unlike traditional methods relying on full-scale testing or static loading assumptions, this approach provides a more efficient and realistic assessment of failure mechanisms under transient internal pressure. This integrated framework enables the investigation of fracture behavior using reduced-scale specimens, significantly reducing testing costs and complexity. The proposed model incorporates elastoplastic material behavior, pretensioned reinforcement interaction, and localized failure, offering a more realistic and efficient alternative to conventional static or simplified models. This approach is particularly valuable for optimizing reinforcement strategies in safety-critical pipeline applications.

2 Materials and Methods

2.1 *Mathematical Model of the Dynamic Strength of a Section between Supports of a Main Gas Pipeline with a Non-Penetrating Longitudinal Crack Reinforced with Various Wire Wrapping or Composite Sleeves*

The dynamic model is developed based on the principles of deformable solid mechanics and comprises the following components:

- Equations of motion for the pipe and reinforcing elements, coupled via contact interaction conditions, and appropriate initial and boundary conditions;
- Constitutive relations describing the elastoplastic behavior of the pipeline and wire wrapping steels, or linear elastic behavior according to Hooke's law in the case of composite overlay;
- Relations connecting strains and displacements;
- Strength and failure criteria governing material response;
- Time-dependent internal pressure function representing operational loading conditions.

The pipeline section between the supports is represented as a cylindrical pipe with an inner radius R , a wall thickness h , and a length L . A non-penetrating longitudinal crack is located on the outer surface and is characterized by length l , depth a , and width $b = R \cdot \psi$. The crack orientation is aligned along the Ox axis. Previous studies [1–4] have shown that cracks of this type constitute the most critical condition for potential catastrophic pipeline failure. A schematic illustration of the pipeline section is shown in Fig. 1.

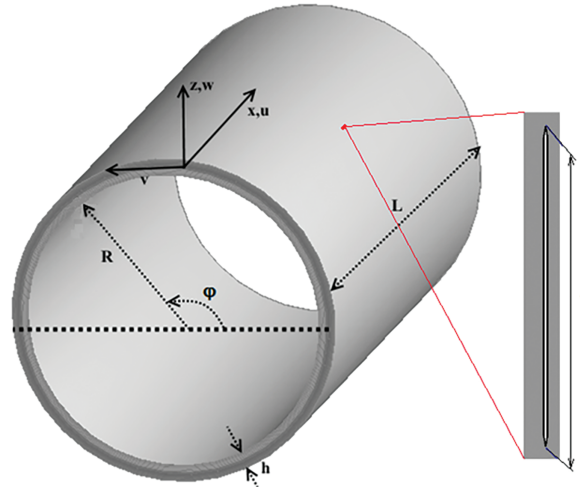


Figure 1: Schematic illustration of the main gas pipeline section

A cylindrical coordinate system (r, φ, x) is employed. A longitudinal crack disrupts the inherent structural symmetry. The dynamic displacements of the pipe are represented by the three components of the displacement vector projected onto the coordinate axes (r, φ, x) : $u(r, \varphi, x, t)$, $v(r, \varphi, x, t)$, $w(r, \varphi, x, t)$. The corresponding equations of motion are expressed as follows [28,29]:

$$\begin{aligned} \frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\phi}{r} + \frac{\partial \tau_{r\phi}}{r \partial \phi} + \frac{\partial \tau_{rx}}{\partial x} + F_r &= \rho \frac{\partial^2 u}{\partial t^2} \\ \frac{\partial \sigma_\phi}{r \partial \phi} + \frac{\partial \tau_{r\phi}}{\partial r} + \frac{2\partial \tau_{r\phi}}{r} + \frac{\partial \tau_{\phi x}}{\partial x} + F_\phi &= \rho \frac{\partial^2 v}{\partial t^2} \\ \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{rx}}{\partial r} + \frac{\tau_{rx}}{r} + \frac{\partial \tau_{x\phi}}{r \partial \phi} + F_x &= \rho \frac{\partial^2 w}{\partial t^2} \end{aligned} \quad (1)$$

where σ_r , σ_ϕ , σ_x are the components of the normal stresses, $\tau_{r\phi}$, τ_{rx} , $\tau_{x\phi}$ represent the components of the shear stresses, u , v , w denote the components of the displacement vector, ρ is the material density, and F_r , F_ϕ , F_x represent the components of the gravitational force.

In conventional analyses of pipe dynamic expansion under transient internal pressure, gravitational forces are often neglected because their magnitude is negligible compared to the primary loading. However, the relative influence of these forces becomes more significant for scaled-down physical models. Therefore, including gravitational effects in the calculations is essential to ensure accurate results.

The initial conditions for the system of Eq. (1) are specified as follows:

$$\begin{aligned} u(r, \varphi, x, 0) &= 0, v(r, \varphi, x, 0) = 0, w(r, \varphi, x, 0) = 0, \\ \partial u(r, \varphi, x, 0)/\partial t &= 0, \partial v(r, \varphi, x, 0)/\partial t = 0, \partial w(r, \varphi, x, 0)/\partial t = 0. \end{aligned}$$

Boundary conditions at the left end of the pipe:

$$u(r, \varphi, 0, t) = 0, v(r, \varphi, 0, t) = 0, w(r, \varphi, 0, t) = 0, \\ \partial u(r, \varphi, 0, t)/\partial t = 0, \partial v(r, \varphi, 0, t)/\partial t = 0, \partial w(r, \varphi, 0, t)/\partial t = 0.$$

The boundary conditions at the right end of the pipe are as follows:

$$v(r, \varphi, L, t) = 0, w(r, \varphi, L, t) = 0, \\ \partial v(r, \varphi, L, t)/\partial t = 0, \partial w(r, \varphi, L, t)/\partial t = 0.$$

The nonzero boundary conditions at the inner surface of the pipe account for the transient internal pressure and are expressed as follows:

$$\sigma_r(R, \varphi, x, t) = -P(t)$$

where $P(t)$ is the transient internal pressure in the pipe.

The nonzero boundary conditions at the outer surface of the pipe simulate the initial stresses generated by the wire wrapping tension or by the interference or shrink-fit conditions of the composite overlay.

The boundary conditions at the contact zone for wire wrapping are expressed as follows:

$$\sigma_r(R + h, \hat{\varphi}, \hat{x}, t) = -P_j(R + h, \hat{\varphi}, \hat{x}, 0) - \Delta P_j(R + h, \hat{\varphi}, \hat{x}, t),$$

where $P_j(R + h, \hat{\varphi}, \hat{x}, 0)$, $1 \leq j \leq N$ is the pressure applied to the outer surface of the pipe due to the initial tension in the j -th turn of the wire wrapping; $\Delta P_j(R + h, \hat{\varphi}, \hat{x}, t)$ represents the time-dependent variation of this pressure resulting from external dynamic loads and deformation of the pipe-wire system; $(\hat{\varphi}, \hat{x})$ denotes the coordinates of the contact surface between the pipe and the j -th turn of the wire.

At the initial moment, $\Delta P_j(R + h, \hat{\varphi}, \hat{x}, 0) = 0$. This value is subsequently determined from the equation of motion for the wire wrapping.

The equations of motion for the centerline of any wire wrapping segment are expressed as follows—A schematic of the segment is shown in Fig. 2.

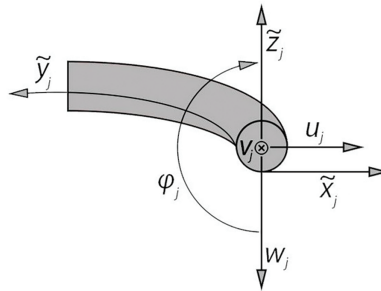


Figure 2: Schematic illustration of the wire wrapping section

The centerline curvature of the j -th wire turn is denoted by R_j . A local coordinate system $(\tilde{x}_j, \tilde{y}_j, \tilde{z}_j)$ is associated with the wire turn. Wire bending in two planes is characterized by the displacements $u_j(\tilde{y}_j, t)$ and $w_j(\tilde{y}_j, t)$, axial tension-compression is represented by the displacement $v_j(\tilde{y}_j, t)$, and the angular rotation function describes torsion $\phi_j(\tilde{y}_j, t)$.

The strains and generalized displacements of the steel wire are expressed as follows:

$$\varepsilon = \frac{\partial v_j}{\partial \tilde{y}_j} - \frac{w_j}{R_j}, \tau = \frac{\partial u_j}{R_j \partial \tilde{y}_j} - \frac{\partial \phi_j}{\partial \tilde{y}_j}, \chi_1 = \frac{\partial^2 u_j}{\partial \tilde{y}_j^2} + \frac{\phi_j}{R_j}, \chi_2 = \frac{\partial^2 w_j}{\partial \tilde{y}_j^2} + \frac{w_j}{R_j^2} \quad (2)$$

where χ_1, χ_2 —change in curvature of the wire centerline, ε —circumferential (axial) strain, and τ is the relative torsional angle.

When reinforcing a damaged pipeline section with a circular composite overlay, system (1) governs the equations of motion for the overlay. The overlay is represented as a thin, anisotropic cylindrical shell with inner radius $R + h$, wall thickness $\tilde{h}$ and length $\tilde{L}$. Because the gravitational force of the overlay is negligible, its projections onto the coordinate axes are taken as zero ($\tilde{F}_r \approx 0, \tilde{F}_\phi \approx 0, \tilde{F}_x \approx 0$) and are therefore excluded from system (1). Boundary conditions are applied only at the contact surface between the pipe and the overlay, specified by the coordinates $(\hat{\phi}, \hat{x})$ at radius $R + h$. These conditions are expressed as follows:

$$\sigma_r(R + h, \hat{\phi}, \hat{x}, t) = -\tilde{P}(R + h, \hat{\phi}, \hat{x}, 0) - \Delta\tilde{P}(R + h, \hat{\phi}, \hat{x}, t)$$

where $\tilde{P}(R + h, \hat{\phi}, \hat{x}, 0)$ denotes the pressure exerted by the overlay on the external pipe surface due to interference or shrink-fit mounting, and $\Delta\tilde{P}(R + h, \hat{\phi}, \hat{x}, t)$ represents the time-dependent variation in pressure caused by external dynamic loads and deformation of the pipe-wrap system. The coordinates $(\hat{\phi}, \hat{x})$ define the contact surface between the pipe and the overlay.

At the initial time, $\Delta\tilde{P}(R + h, \hat{\phi}, \hat{x}, 0) = 0$. As the system evolves, this pressure is determined from the equation of motion for the composite overlay. To capture the thermoelastoplastic behavior of the steel pipe and reinforcing wire, the constitutive relations are expressed in nonlinear form [30]:

$$\sigma_{eq}(t) = \sigma_{eq}(\varepsilon_{eq}(t), \dot{\varepsilon}_{eq}(t), T) \quad (3)$$

where σ_{eq} is the equivalent stress in the material, ε_{eq} represents equivalent strain, $\dot{\varepsilon}_{eq}$ is the strain rate, T denotes the temperature of the steel pipe or reinforcing wire, and t is the time measured from the onset of the transient mechanical pressure.

Dynamic stress-strain modeling, as expressed in Eq. (3), is conducted using a hierarchical system of models that represent three physical states of the material: (1) elastic response, (2) plastic deformation, and (3) local failure.

For elastic deformation, the stress tensor components $\sigma_{ij}(t)$ are related to the strain tensor components $\varepsilon_{ij}(t)$ through Hooke's law:

$$\sigma_{ij}(t) = E(T) \varepsilon_{ij}(t) \quad (4)$$

where $E(T)$ is the elastic modulus as a function of temperature, and T represents the reference (calculated) temperature.

The equivalent von Mises stress σ_{eq} at any time is obtained from the stress tensor components using the following relationship [31]:

$$\sigma_{eq} = \sqrt{\frac{1}{2} \left[(\sigma_r - \sigma_\phi)^2 + (\sigma_\phi - \sigma_x)^2 + (\sigma_x - \sigma_r)^2 + 6(\tau_{r\phi}^2 + \tau_{rx}^2 + \tau_{\phi x}^2) \right]}$$

The influence of temperature on elastic deformation is incorporated by selecting the elastic modulus $E(T)$ corresponding to the calculated temperature T .

The transition from elastic and plastic deformation occurs when the equivalent stress σ_{eq} reaches the dynamic yield strength σ_y^d [32]. The dynamic yield strength is related to the static yield strength σ_y^{st} as follows:

$$\sigma_y^d = \sigma_y^{st} \left[1 + \left(\frac{1}{C} \frac{\partial \varepsilon_{eq}}{\partial t} \right)^{\frac{1}{n}} \right], \quad \sigma_y^{st} = E(T) \varepsilon_y^{st} \quad (5)$$

where C , n is the experimentally determined parameter that characterizes the strain-rate sensitivity of the material, and ε_y^{st} denotes the strain corresponding to the static yield strength.

The use of the dynamic yield strength in Eq. (5) allows the incorporation of the deformation-rate effects on the failure process, which is crucial for modeling avalanche-type failures in pipe structures. Under these conditions, the equivalent stress in the plastic flow region is expressed as $\sigma_{eq} = \sigma_y^d(\varepsilon_{eq}, \dot{\varepsilon}_{eq})$, while the influence of temperature is considered through the temperature dependence of the metal's mechanical properties.

In addition to equal stress, the accumulation of plastic strain ε_{eq}^{pl} in the plastically deformed zone is also tracked. The equivalent strain is calculated using the following equation [31]:

$$\varepsilon_{eq} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_r - \varepsilon_\phi)^2 + (\varepsilon_\phi - \varepsilon_x)^2 + (\varepsilon_x - \varepsilon_r)^2 + 3/2 (\gamma_{r\phi}^2 + \gamma_{\phi x}^2 + \gamma_{xr}^2)} \quad (6)$$

The local failure of the steel pipe and wire wrapping is modeled using the von Mises failure criterion, which is widely applied to plastically deformed isotropic materials: $\varepsilon_{eq}^{pl} \geq \varepsilon_{dstr}$. The structural integrity of the pipe and wire was evaluated by monitoring the accumulated equivalent plastic strain ε_{eq}^{pl} . Failure is assumed to occur when this strain reaches the critical value ε_{dstr} . The next section describes the deformation model of the composite overlay.

High-strength composite overlays with orthotropic mechanical properties are considered in this study. Furthermore, the material demonstrates high thermal resistance. To represent orthotropic behavior, a local coordinate system aligned with the material's orthotropy axes is introduced (Fig. 3). The O_x axis (red) runs along the generatrix of the cylindrical composite overlay, the O_ϕ axis (green) is tangential to the cylindrical surface; and the O_z axis (blue) is normal to the shell surface.

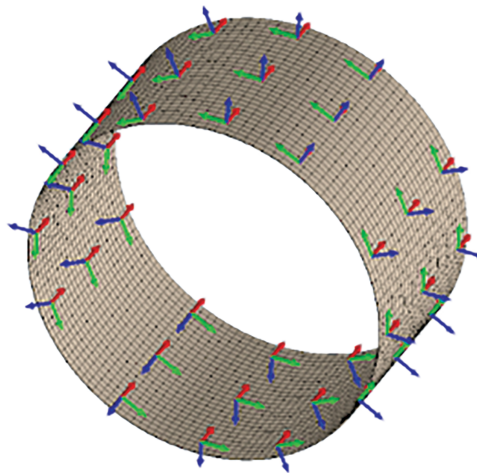


Figure 3: Schematic of the local coordinate system of the composite overlay, showing axes aligned with the material's orthotropy directions

In the (x, φ, z) coordinate system, the generalized Hooke's law for an orthotropic material is expressed as follows [31]:

$$\begin{bmatrix} \sigma_x \\ \sigma_\varphi \\ \sigma_z \\ \tau_{\varphi z} \\ \tau_{xz} \\ \tau_{x\varphi} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_\varphi \\ \varepsilon_z \\ \gamma_{\varphi z} \\ \gamma_{xz} \\ \gamma_{x\varphi} \end{bmatrix} \quad (7)$$

where $\sigma_x, \sigma_\varphi, \sigma_z, \tau_{x\varphi}, \tau_{xz}, \tau_{\varphi z}$ are the components of the stress tensor, and $\varepsilon_x, \varepsilon_\varphi, \varepsilon_z, \gamma_{x\varphi}, \gamma_{xz}, \gamma_{\varphi z}$ represent the components of the strain tensor.

The matrix $\mathbf{C}$ represents the material stiffness matrix and is defined as the inverse of $\mathbf{C}^{-1}$, with components expressed as follows [31]:

$$\mathbf{C}^{-1} = \begin{bmatrix} \frac{1}{E_{11}} & \frac{-\nu_{21}}{E_{22}} & \frac{-\nu_{31}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_{11}} & \frac{1}{E_{22}} & \frac{-\nu_{32}}{E_{33}} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_{11}} & \frac{-\nu_{23}}{E_{22}} & \frac{1}{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad (8)$$

where ν_{ij} represents the Poisson's ratios satisfying the relation; $E_{jj}\nu_{ij} = \nu_{ji}E_{ii}, i \neq j$; G_{ij} denotes the shear moduli.

To model the local failure process, the maximum stress criterion, a classical failure criterion for layered orthotropic materials, is expressed as follows [33–35]:

$$\begin{cases} \sigma_x \geq X_t, \\ \sigma_\varphi \geq Y_t, \\ \sigma_z \geq Z_t, \\ \tau_{x\varphi} \geq S_{x\varphi}, \\ \tau_{xz} \geq S_{xz}, \\ \tau_{\varphi z} \geq S_{\varphi z}, \end{cases} \quad (9)$$

where X_t, Y_t, Z_t represent the tensile strength limits in the respective directions, and $S_{x\varphi}, S_{xz}, S_{\varphi z}$ denote the shear strength limits. The transient load applied to the circumferential overlay acts in the positive O_z axis, including tensile deformation in the overlay. Consequently, the compressive strength limits in the corresponding directions are neglected.

In modeling the transient deformation of a pipe reinforced with wire or a composite overlay, the strain-displacement relationships are expressed in nonlinear form [31,35]. Zhangabay et al. [2] provided a detailed presentation of these relationships, which is not reproduced here due to its complexity. The model is analyzed using the time-dependent behavior of the internal pressure.

Pipeline failure occurs due to the growth of the initial microdefects under high internal pressure. The most critical stage in assessing the dynamic strength of a main gas pipeline is the rapid increase in pressure from the operating level to the critical level. During this phase, significant transient loads act on the pipe wall, potentially causing the formation of penetrating cracks and failure in regions already containing non-penetrating cracks. Consequently, the strength analyses of gas pipelines focus on the transient regime, in which the internal pressure rapidly increases from the operating value to the critical level and then decays [36]. Within this interval, the pressure on the pipeline's inner surface increases to its maximum value at time t^* , where it remains until time t^{**} . During this stage, a non-penetrating crack may evolve into a penetrating crack. Propagation of the penetrating crack is accompanied by gas decompression, which manifests as a decrease in pressure over time in the surrounding pipe region. To describe this behavior, an approximate model of the gas-dynamic pressure acting on both the crack faces and the pipe's inner wall is employed, which has proven effective in simulating dynamic crack propagation [37]. The subsequent pressure decay is represented by an exponential law, consistent with the experimental observations [38]. Based on these considerations, the transient load can be mathematically formulated as follows: the internal pressure acts normally on the pipeline wall as a time-dependent function applied across the entire inner surface of the pipe, including the crack faces.

$$P_z = \begin{cases} \frac{P_{\max}}{t^*} t, & t < t^*, \\ P_{\max}, & t^* \leq t < t^{**}, \\ P_{\max} e^{-\frac{t}{\theta}}, & t \geq t^{**}, \end{cases} \quad (10)$$

where $P_{\max}$ represents the maximum pressure, θ denotes the pressure decay coefficient, t^* , t^{**} are the times corresponding to the maximum pressure onset and decay initiation, respectively.

The dynamic model allows for a comprehensive assessment of local initial stresses in the pipe induced by reinforcement elements, the evolution of material properties during deformation, and the distinct characteristics of internal pressure variation along the inner wall during penetrating crack formation.

2.2 Computational Model for the Dynamic Strength of a Section between Supports of a Main Gas Pipeline with a Non-Penetrating Longitudinal Crack Reinforced with Various Wire Wrapping or a Composite Sleeves

The dynamic strength of a defective section of the main gas pipeline was numerically analyzed using the ANSYS 19.2/Explicit Dynamics software package, which applies an explicit time integration scheme to solve the equations of motion. The FE model simulated a steel pipe segment with fixed ends, a non-penetrating longitudinal crack, and external reinforcement with either wire wrapping or a composite sleeve. The pipe's geometric parameters correspond to typical values for main gas pipelines: outer diameter D , wall thickness h , and segment length L , which were varied according to the model scaling factor [4]. The wire wrapping was characterized by the wire diameter $\tilde{d}$ and spacing between adjacent turns $\tilde{h}$ [3]. The composite sleeve, modeled as an orthotropic material with circumferentially oriented fibers, was defined by its thickness $\tilde{h}$ and length $\tilde{l}$.

The FE model was developed using three-dimensional tetrahedral elements (SOLID164), which are suitable for highly nonlinear problems involving large deformations. The contact interactions among the pipe, crack, and reinforcing layer were simulated using an automatic contact detection algorithm that allowed the separation and sliding between surfaces. The structural materials were described using appropriate constitutive models. The steel pipe was modeled as an isotropic elastic-plastic material with strain hardening based on the Cowper-Symonds model [1–3]. The dynamic yield stress in the model was defined as

follows [26]:

$$\sigma_y = (A + B\varepsilon_{pl}^n) \left(1 + (\dot{\varepsilon}/C)^{1/q}\right) \quad (11)$$

where σ_y represents the yield stress accounting for isotropic strain hardening and strain rate sensitivity, A denotes the initial yield stress at zero plastic strain, B represents the strain hardening coefficient, ε_{pl} is the equivalent (effective) plastic strain, n represents the strain hardening exponent, $\dot{\varepsilon}$ is the strain rate, and C, q are the strain rate hardening parameters.

If the constants in the Cowper-Symonds model are expressed using the parameters in Eq. (5), such that $A = E(T_0) \varepsilon_y^{st}$, $C \equiv C$, $q \equiv n$, and the strain-hardening coefficient is set to zero ($B = 0$), the resulting expression for the dynamic yield stress becomes identical to that in Eq. (5) $\sigma_y^d \equiv \sigma_y$. Therefore, both models provide an equivalent definition of the material's dynamic yield stress.

The wire wrapping was represented as an elastic-plastic material with a maximum elongation limit [3,4]. Steel failure was assumed to occur once the critical plastic strain threshold was reached. The composite was modeled as an orthotropic material, and its elastic moduli, strength parameters, and failure behavior were derived from the maximum stress theory [32,33]. In ANSYS Explicit Dynamics, the explicit solver advances the solution without nonlinear iterations at each time step, enabling efficient computation of crack propagation. The governing solution stems from the discretized equation of motion:

$$[M] \{\ddot{u}(t)\} = \{F_{ext}(t)\} - \{F_{int}(t)\} \quad (12)$$

where $[M]$ is the lumped (diagonalized) mass matrix; $\{\ddot{u}(t)\}$ is the acceleration vector; $\{F_{ext}(t)\}$ is the vector of external forces (including pressure); and $\{F_{int}(t)\}$ represents the vector of internal forces dependent on the geometry. Time integration is performed using the central difference method, an explicit scheme that directly updates displacement:

$$\begin{aligned} \{\ddot{u}\}_n &= [M]^{-1} (\{F_{ext}(t)\} - \{F_{int}(t)\}) \\ \{\dot{u}\}_{n+\frac{1}{2}} &= \{\dot{u}\}_{n-\frac{1}{2}} + \{\ddot{u}\}_n \Delta t \\ \{u\}_{n+1} &= \{u\}_n + \{\dot{u}\}_{n+\frac{1}{2}} \Delta t \end{aligned} \quad (13)$$

The simulations used a lumped mass matrix with automatic time-step control governed by stability criteria and allowed the definition of load functions through time-dependent tables. The stepwise data recording enabled the analysis of the evolution of the plastic zone and the damage localization around the crack and reinforcement region.

The time step Δt was calculated automatically according to the Courant-Friedrichs-Lewy (CFL) stability criterion, considering the minimum FE size and the elastic wave propagation speed in the material. The convergence of the numerical solution was verified using the standard procedure of successively halving the minimum element size [32]. This approach enabled the assessment of the effects of mesh refinement on key computed parameters, primarily the maximum displacements, von Mises equivalent stresses, and plastic strains in the defect and reinforcement regions. The sweep method was used for FE mesh generation, providing a regular element structure through the thickness with controlled element size along the length and width. The element size was set using the element size parameter, ensuring adequate geometric resolution while maintaining a reasonable computational cost. The pipe element size was defined as a multiple of its wall thickness, ensuring consistency between the full-scale and scaled computational models.

3 Results and Discussion

3.1 Validation of the Dynamic Strength Model for a Wire-Wrapped Section between Supports of a Main Gas Pipeline with a Non-Penetrating Longitudinal Crack

To verify the accuracy of the numerical results regarding the reinforcement of damaged main gas pipeline sections with wire wrapping or a circumferential composite sleeve, the model described in Section 2 was benchmarked against experimental data reported in Zhangabay et al. [4]. Validation drew on tests conducted with a scaled pipeline span section between supports, containing a non-penetrating longitudinal crack. This defect was examined in specimens reinforced with two types of wire wrapping and reinforced form (scale of 1:5). The similarity conditions were determined according to the theory of mechanical similarity and affine modeling [4]. In total, 12 computational cases were compared with full-scale experimental, using six specimens of varying geometry tested at +20°C and -10°C. The geometric parameters of these specimens are listed in Table 1.

Table 1: Geometrical parameters of cracked pipes reinforced with wire rings, wire wrapping, or unreinforced pipes

No.	Pipe length, L , mm	Pipe diameter, D , mm	Wall thickness, h , mm	Wire wrapping diameter, $\tilde{d}$, mm	Wrapping type	Initial crack length, l , mm	Initial crack depth, a , mm
1	2000	250	0.8	1	No wrapping	100	0.4
2	2000	250	0.8	1	Steel rings, 2 pcs	100	0.4
3	2000	250	0.8	1	Wire wrapping, 250 mm pitch	100	0.4
4	2000	350	0.8	1	No wrapping	100	0.4
5	2000	350	0.8	1	Steel rings, 2 pcs	100	0.4
6	2000	350	0.8	1	Wire wrapping, 250 mm pitch	100	0.4

Table 2 summarizes the material properties of the pipe and wrapping materials. The tensile force applied to the steel rings and wire wrapping was set to $0.05\sigma_U$, where σ_U represents the ultimate strength of the wrapping material. In experimental and numerical analyses, this tensile force was maintained at $N = 0.13$ kN [4].

The computational model developed in the ANSYS 19.2 environment accurately replicates the geometry and loading conditions of the physical experiment described by Zhangabay et al. [4]. Table 3 compares the numerical and experimental results for the six specimens described in Table 1, tested at +20°C, whereas Table 4 provides the corresponding results for the experiments conducted at -10°C. The first column lists the specimen identification number, and the second outlines the geometric parameters that distinguish the pipe structures. The third column reports the experimentally determined critical pressure, which was also used in the numerical simulations. The fourth and fifth columns present the crack opening width after rupture, obtained experimentally and through simulation, respectively, with the sixth column showing the relative error between these values. Similarly, the seventh, eighth, and ninth columns present the crack length results, including the experimental values, numerical results, and the relative error, respectively.

Table 2: Mechanical properties of the pipe and wrapping materials

Material type	Grade	Static yield strength, σ_y^{st} , MPa	Ultimate strength, σ_U , MPa	Relative elongation, δ , %	Strain rate sensitivity of the material	Hardness, HB, MPa
Pipe material	St3kp	238	363	23	42 s^{-1} ; 5	≤ 131
Wrapping material	St2kp	204	324	25	41 s^{-1} ; 5	≤ 116

Table 3: Numerical and experimental results for six pipe structures tested at $+20^\circ\text{C}$ (Table 1)

No.	Pipe diameter, D , mm; wrapping type	Critical pressure, MPa	Crack width after rupture, mm			Crack length after rupture, mm		
			Experiment, mm	Simulation, mm	Relative error, %	Experiment, mm	Simulation, mm	Relative error, %
1	250 No wrapping	1.519	183.3	161.80	11.73	375.6	413.98	9.27
2	250 Steel rings, 2 pcs	1.554	112.5	101.79	9.52	172.2	186.08	7.46
3	250 Wire wrapping, 250 mm pitch	1.598	120.5	107.88	10.47	264.1	289.01	8.62
4	350 No wrapping	1.237	235.4	208.14	11.58	416.4	459.75	9.43
5	350 Steel rings, 2 pcs	1.253	151.2	137.64	8.97	215.4	231.99	7.15
6	350 Wire wrapping, 250 mm pitch	1.319	164.5	147.31	10.45	296.1	324.10	8.64

Table 4: Numerical and experimental results for six pipe structures conducted at -10°C (Table 1)

No.	Pipe diameter, D , mm; wrapping type	Critical pressure, MPa	Crack width after rupture, mm			Crack Length after Rupture, mm		
			Experiment, mm	Simulation, mm	Relative error, %	Experiment, mm	Simulation, mm	Relative error, %
1	250 No wrapping	1.553	165.2	145.57	11.88	354.8	392.87	9.69
2	250 Steel rings, 2 pcs	1.584	108.8	98.26	9.69	144.5	158.81	9.01
3	250 Wire wrapping, 250 mm pitch	1.618	129.2	115.97	10.24	250.2	275.58	9.21
4	350 No wrapping	1.28	226.6	200.41	11.56	398.7	440.16	9.42
5	350 Steel rings, 2 pcs	1.291	141.1	126.82	10.12	203.5	223.60	8.99
6	350 Wire wrapping, 250 mm pitch	1.275	154.4	137.86	10.71	275.5	303.51	9.23

Analysis of the data in Tables 3 and 4 indicates that the numerical simulation results of the pipe failure process correspond closely with the experimental findings. The relative error between the peak displacement values, defined by the longitudinal and transverse crack dimensions, remains under 12%. For this class of problems, an error margin of 10% to 15% is generally acceptable. This range is consistent with the established practices for model validation in computational solid mechanics, as outlined in the ASME V&V 10-2006 guideline [39].

The computed crack lengths are consistently greater than the experimentally measured values, although the relative error remains below 10%. Therefore, the simulations yield a conservative upper-bound estimate of the crack propagation in the longitudinal direction, which supports the application of the result in engineering decisions on structural reinforcement to prevent catastrophic (avalanche-type) failure.

The crack opening width calculated in the numerical models is smaller than that observed experimentally, leading to elevated stress levels in the crack opening zone during the assessment of the defective pipeline section. When modeling a reinforcing sleeve, this provides a safety margin by reducing the likelihood of under-reinforcement under actual operating conditions, making the numerical results a robust basis for engineering decisions. Furthermore, in all 12 numerical cases, the crack shape at the maximum opening closely corresponds to the experimentally observed shape [4]. Fig. 4 illustrates the results for an unreinforced pipe with a diameter of 250 mm at -10°C , showing the crack profile at maximum opening. A comparison between the numerical results (a) and experimental data (b) [4] demonstrates strong agreement in the crack opening configuration, thereby validating the assumptions of the models, the adopted plastic deformation model, and the adequacy of the selected boundary conditions and material parameters.

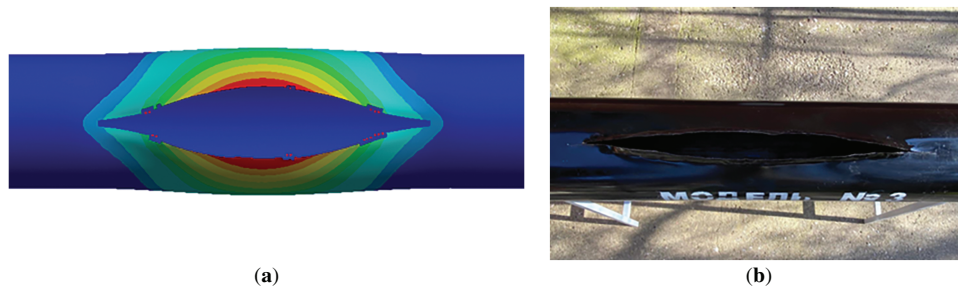


Figure 4: Comparison of crack shapes at the maximum opening for the unreinforced pipe: (a) numerical results and (b) experimental data [4]

Fig. 5 shows the crack profile at the maximum opening in the pipe reinforced with steel rings at the crack edges. Numerical (a) and experimental data (b) [4] indicate good correlation between crack geometry and opening behavior. Steel rings suppress crack growth by redistributing stresses and restricting plastic deformation, confirming their effectiveness in localizing and containing damage.

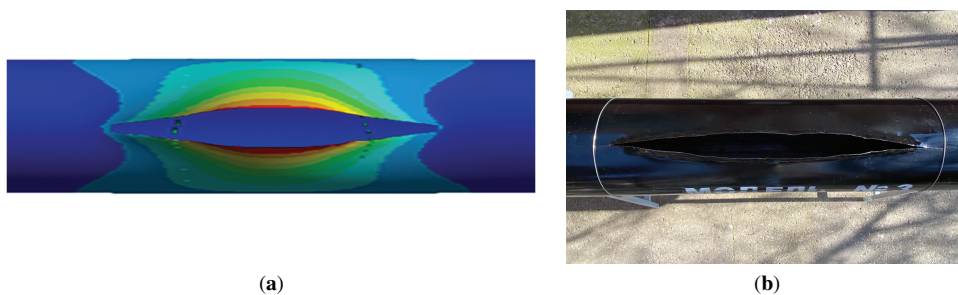


Figure 5: Crack shape at maximum opening in a pipe reinforced with steel rings: (a) numerical results; (b) experimental results [4]

Wire wrapping provides a comparable crack-arrest mechanism by generating circumferential prestressing zones in the pipe, with a similar function as individual steel rings. When a propagating crack encounters a wire turn, the induced compressive stresses counteract the tensile forces driving crack opening, thereby inhibiting further progression. As a result, the prestressed wire wrapping can slow, and in some cases completely arrest, longitudinal crack growth. Experimental studies on scaled models [4] and numerical simulations on full-scale models [3] confirm that regions subjected to wrapping-induced contact stresses exhibit either marked deceleration or complete cessation of crack advances. The choice between steel rings and continuous wire wrapping largely depends on the crack configuration and number. For isolated cracks deeper than half the wall thickness, anchoring with steel rings at the crack edges is recommended. Conversely, continuous wire wrapping is more effective for multiple cracks with depths up to half the wall thickness. In this case, preliminary numerical analysis is essential to optimize the wire turn spacing and tensile force, ensuring uniform stress distribution across the reinforced section. Although wire wrapping effectively limits longitudinal crack propagation and prevents avalanche-like failure, once the opening reaches a critical value, it cannot stop a surface crack from developing into a penetrating crack.

Validation of the proposed numerical model against experimental data confirms its reliability in analyzing the dynamic strength of damaged and reinforced sections of main gas pipelines.

3.2 Comparative Analysis of the Dynamic Strength Calculation Results for a Main Gas Pipeline Section with a Longitudinal Crack Reinforced with a Composite Overlay: Full-Scale vs. Scaled Models

Scaled models used in experimental studies and numerical simulations offer several key advantages over full-scale structures. They reduce material and fabrication costs, shorten testing time, and improve safety when examining failure scenarios. When the principles of physical and geometric similarity are observed, scaled models can accurately reproduce the stress-strain state and failure behavior of real structures. They are effective tools for assessing the dynamic strength of damaged gas pipelines.

A comparative analysis was conducted on the numerical simulations of the dynamic strength of steel main gas pipeline spans containing longitudinal cracks and reinforced with circumferential composite overlays, using scaled and full-scale geometric models. The analysis focuses on the influence of overlay dimensions to evaluate the validity of the scaling approach for modeling deformation and failure behavior in reinforced pipeline sections. The geometric parameters of the scaled model are provided in Table 1. The full-scale geometric model was examined in earlier studies [1–3]. The analyzed pipeline section is 4000 mm in length, with an outer diameter of 1047 mm and a wall thickness of 11.9 mm. The pipe was fabricated from X70 steel, which has the following physical and mechanical properties: density $\rho = 7810 \text{ kg/m}^3$; elastic modulus $E = 2.06 \text{ GPa}$; ultimate tensile strength $\sigma_B = 570 \text{ MPa}$; and yield strength $\sigma_T = 505 \text{ MPa}$. The critical internal pressure is $P_{\max} = 9.8 \text{ MPa}$. The initial crack length corresponds to 5% of the section length (200 mm), while the initial crack depth equals 50% of the wall thickness (6 mm).

The composite overlay was fabricated from heat-resistant Carbon-Fiber-Reinforced Plastic (CFRP). The material properties are as follows: elastic moduli $E_{xx} = 35 \text{ GPa}$, $E_{\varphi\varphi} = 35 \text{ GPa}$, $E_{zz} = 8 \text{ GPa}$, shear moduli $G_{x\varphi} = 6 \text{ GPa}$, $G_{\varphi z} = 30 \text{ GPa}$, $G_{xz} = 30 \text{ GPa}$, Poisson's ratios $\nu_{x\varphi} = 0.01$, $\nu_{\varphi z} = 0.09$, $\nu_{xz} = 0.09$, density $\rho = 1477 \text{ kg/m}^3$.

The selection of parameters for composite reinforcement overlays in pipeline strengthening depends on several key factors. The overlay thickness is primarily governed by the stiffness ratio between the composite layer and pipe wall: insufficient thickness does not provide adequate load-bearing capacity, whereas excessive thickness results in material waste and elevated interface stresses. Two thickness options were evaluated in this study: *Option 1*: One-third of the pipe wall thickness –0.27 mm for scaled models

(250 and 350 mm diameters) and 4.0 mm for the full-scale model. *Option 2*: One-half of the pipe wall thickness –0.4 mm for scaled models and 6.0 mm for the full-scale model.

Overlay length is determined by defect size, the expected plastic deformation zone, and the need for stress redistribution along the pipe axis. To ensure a smooth stress transition from the damaged to the intact region, the overlay length is designed to significantly exceed the crack length. In the numerical simulations, two configurations were evaluated to prevent longitudinal crack propagation. *Option 1*: The overlay length is equal to three times the crack length –300 mm for the scaled models and 600 mm for the full-scale model. *Option 2*: The overlay length is equal to five times the crack length –500 mm for the scaled models and 1000 mm for the full-scale model. In all cases, the circumferential overlay edges were symmetrically positioned with respect to the crack.

The computational model treats the overlay as an element in free contact with the pipe's external surface, without gaps or prestressing, thereby reflecting actual installation conditions. The modeled composite is a carbon fiber-reinforced plastic with an epoxy matrix, characterized by high strength and stable mechanical properties under temperature variations [34]. The analysis considered a temperature range from -40°C to $+50^{\circ}\text{C}$; since these variations have minimal effect on the composite's mechanical properties, and were therefore excluded from the simulation. The steel's mechanical properties within this temperature range and their effect on longitudinal crack propagation are described in Zhangabay et al. [2].

The analysis aimed to evaluate the qualitative agreement between numerical simulation results from scaled and full-scale models. Within the considered temperature range, no qualitative differences were observed; therefore, the results presented correspond to $+50^{\circ}\text{C}$, the most critical temperature for longitudinal growth of penetrating cracks [2]. A reduction in pipe diameter from 350 to 250 mm also had no qualitative effect on the simulation outcomes, so only the results for the 350 mm diameter are shown.

Table 5 summarizes the simulation results for the dynamic strength of a steel pipe with a longitudinal crack reinforced by a composite overlay. The following parameters are used: h —pipe wall thickness; l —initial length of the longitudinal crack. Figs. 6 and 7 illustrate these results for the full-scale model with a diameter of 350 mm, respectively. Reducing the pipe diameter from 350 to 250 mm did not cause any qualitative changes in the results, indicating that longitudinal and radial displacements predominantly govern the deformation process. The simulation results show complete qualitative agreement between the full-scale and scaled models.

Table 5: Defects in a steel pipe reinforced with a composite overlay after a sudden increase in internal pressure to a critical level

No.	Overlay dimensions	Model		
		Full-scale	Scaled model with a diameter of 350 mm	Scaled model with a diameter of 250 mm
1	$0.3 \cdot h, 3 \cdot l$	Overlay rupture. Penetrating cracks on both sides of the overlay.	Overlay rupture. Penetrating cracks on both sides of the overlay.	Overlay rupture. Penetrating cracks on both sides of the overlay.
2	$0.3 \cdot h, 5 \cdot l$	Overlay rupture.	Overlay rupture.	Overlay rupture.
3	$0.5 \cdot h, 3 \cdot l$	Penetrating cracks on both sides of the overlay.	Penetrating cracks on both sides of the overlay.	Penetrating cracks on both sides of the overlay.

(Continued)

Table 5 (continued)

No.	Overlay dimensions	Model		
		Full-scale	Scaled model with a diameter of 350 mm	Scaled model with a diameter of 250 mm
4	$0.5 \cdot h, 5 \cdot l$	No penetrating defects in the reinforced pipe.	No penetrating defects in the reinforced pipe.	No penetrating defects in the reinforced pipe.

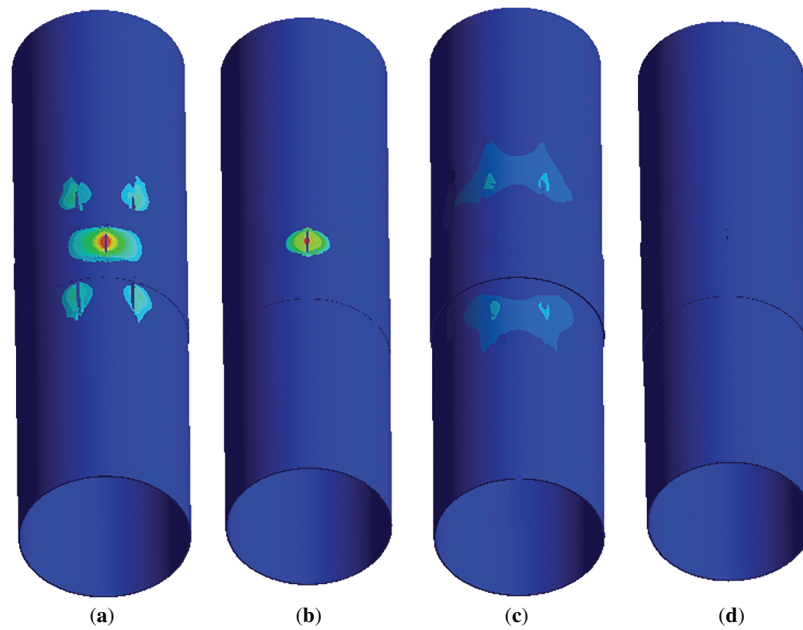


Figure 6: Displacements in the full-scale steel pipe reinforced with the composite overlay under a sudden increase in the internal pressure to the critical value: (a) the overlay with a thickness of 0.3 times the pipe wall thickness and a length of 3 initial crack lengths; (b) the overlay with a thickness of 0.3 times the pipe wall thickness and a length of 5 initial crack lengths; (c) the overlay with a thickness of 0.5 times the pipe wall thickness and a length of 3 initial crack lengths; (d) the overlay with a thickness of 0.5 times the pipe wall thickness and a length of 5 initial crack lengths

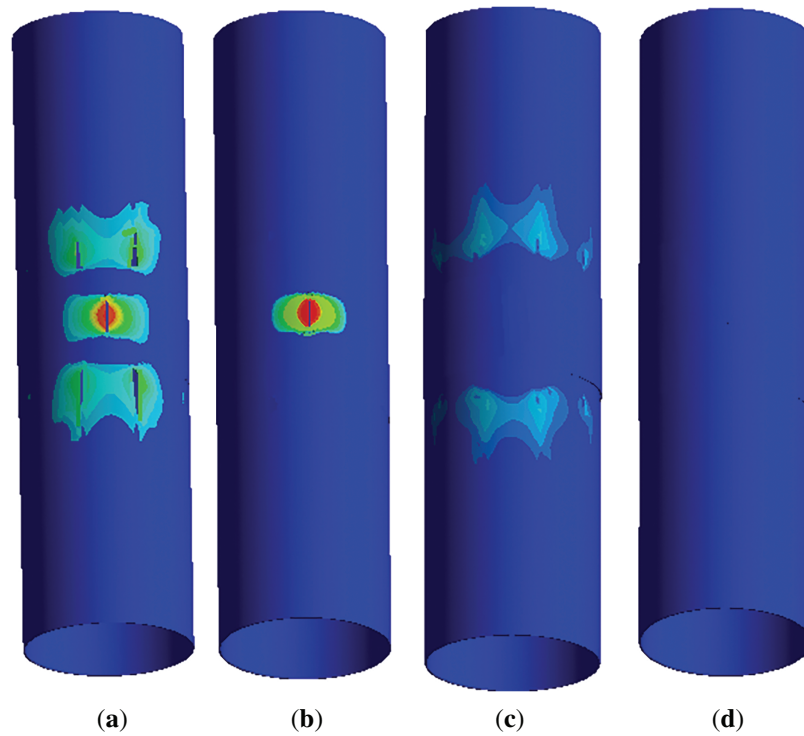


Figure 7: Displacements in the scaled steel pipe reinforced with the composite overlay under a sudden internal pressure increase to the critical value: (a) the overlay thickness equal to 0.3 of the pipe wall thickness and a length equal to 3 initial crack lengths; (b) the overlay thickness equal to 0.3 of the pipe wall thickness and a length equal to 5 initial crack lengths; (c) the overlay thickness equal to 0.5 of the pipe wall thickness and a length equal to 3 initial crack lengths; (d) the overlay thickness equal to 0.5 of the pipe wall thickness and a length equal to 5 initial crack lengths

Table 6 summarizes the FE model parameters used to generate the reported results. Two elements were employed through the thickness of both the pipe and the composite wrap, with the mesh generated using the sweep method. Increasing the through-thickness elements from 2 to 4 had a minimal qualitative effect on the results (<5%) but increased the computation time by more than threefold.

Table 6: Results of the FE mesh convergence studies

No.	Overlay dimensions	Model		
		Nodes	Elements	Time steps
1	$0.3 \cdot h, 3 \cdot l$	145 386	77 324	9.86×10^{-5}
2	$0.3 \cdot h, 5 \cdot l$	151 404	83 532	9.91×10^{-5}
3	$0.5 \cdot h, 3 \cdot l$	145 386	77 324	9.86×10^{-5}
4	$0.5 \cdot h, 5 \cdot l$	151 404	83 532	9.91×10^{-5}

For the overlay with dimensions of $0.3 \cdot h$ and $3 \cdot l$ (Table 5, Row 1; Figs. 6a and 7a), failure occurs through a transverse tension mechanism, indicating insufficient overlay thickness. This is accompanied by the initiation and propagation of penetrating cracks along the pipe and at the reinforced zones. The failure pattern revealed localized stress concentration along the overlay boundaries, indicating that the overlay length was inadequate. In the scaled model, the stress localization zone extends further than in the full-scale

model, enabling a conservative (majorant) evaluation of structural strength based on the scaled geometry. The simulation results from both models indicate that an overlay with these dimensions is inadequate for effective reinforcement.

A comparable failure mechanism occurs in the overlay with dimensions of $0.3 \cdot h$ and $3 \cdot l$ (Table 5, Row 2; Figs. 6b and 7b). Despite the increased length of the overlay, internal forces in the defect area under elevated internal pressure remain insufficiently compensated due to inadequate overlay thickness. Structural failure developed in the reinforced region above the longitudinal crack, accompanied by overlay rupture. Although the increased length allows partial stress redistribution along the pipe axis, reducing edge stress concentration, this configuration does not ensure structural integrity. As in the previous case, the scaled model exhibits a more extended stress localization zone than the full-scale model, providing a conservative (majorant) estimate of structural strength.

Increasing the overlay thickness to $0.5 \cdot h$ enhances stiffness and partially compensates for internal forces in the defect area. However, an overlay length of $3 \cdot l$ (Table 5, Row 3; Figs. 6c and 7c) remains insufficient for effective axial stress redistribution, particularly in the transition zone between reinforced and unreinforced pipe segments. The local stress concentrations in this zone initiate pipe failure at the overlay boundaries. Although the increased thickness improves strength, it is insufficient to prevent progressive failure with the limited overlay length, rendering this configuration ineffective for structural reinforcement.

Only the overlay with dimensions of $0.3 \cdot h$ and $5 \cdot l$ (Table 5, Row 4; Figs. 6d and 7d) achieves a stable stress-strain state, preventing macrocrack initiation in the overlay and the body of the pipe. Displacements in the reinforced pipe remain minimal even when the internal pressure reaches critical values. This geometry provides sufficient length for effective stress redistribution and adequate thickness to compensate for axial forces in the longitudinal crack region. These dimensions effectively prevent defect propagation and pipeline integrity.

The results show a strong agreement between the behavior of scaled models and the full-scale pipe. This confirms that the scaling approach reliably evaluates the effectiveness of reinforcement in damaged main gas pipelines, effectively preventing catastrophic (avalanche-like) failure.

4 Conclusions

This study presents a generalized mathematical model for evaluating the dynamic strength of damaged main gas pipeline sections reinforced with wire wrapping or composite overlays. The model integrates the elastoplastic behavior of pipe and wire steels, temperature-dependent mechanical properties, contact interaction between the pipe and reinforcement, and local material failure under transient internal pressure. Implemented in ANSYS 19.2, the proposed model supports comprehensive parametric numerical investigations. Validation against experimental data showed satisfactory agreement, with discrepancies in crack length and width within 10%–12%, in accordance with ASME V&V 10-2006 guidelines, confirming the FE model as a reliable engineering analysis tool.

A comparative analysis of full-scale and scaled pipe sections reinforced with composite overlay confirmed that scaled models reliably reproduce the essential stress-strain state characteristics and fracture mechanisms. This finding validates their application in experimental investigations and in evaluating reinforcement strategies. This study showed that carbon-fiber composite overlays with a thickness equal to half the pipe wall and a length five times the crack length maintain stable stress-strain conditions in reinforced pipes. Such overlays effectively redistribute stresses and suppress crack propagation even under near-critical internal pressures. Despite these advantages, the approach has certain limitations: the numerical model is confined to axisymmetric reinforcement configurations, and the material models are applicable

only within the temperature range of -40°C to $+50^{\circ}\text{C}$, without accounting for long-term degradation or fatigue. Future studies will address these limitations. Overall, the proposed method provides a practical basis for optimizing reinforcement overlay and wire wrapping parameters and is recommended for designing preventive measures against catastrophic pipeline failures.

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