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Effects of the legacy pipe ends on the behaviour of pipe-in-pipe repair systems under internal pressure

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ABSTRACT

Pipe-in-pipe (PIP) has become an acceptable system for the rehabilitation and repair of natural gas distribution networks. Damaged host pipes usually contain defects such as circumferential cracks which can affect the performance of the PIP systems. Under internal pressure, the PIP system will be in contact with the damaged pipes and may have an adverse effect on its structural performance. This paper investigates the effect of the sharp edge of the legacy pipe opening on the PIP systems under the internal pressure. The effect of several design parameters including the bonding condition of the PIP to the host pipe, the material properties of the PIP system, and the level of sharpness of the host pipe ends are evaluated. The numerical results show that without bonding of the PIP to the host pipe, the stress concentration is minimised as the PIP can deform around the edge of the host pipe. The use of high strain PIP material systems and rounding the edge of the host pipe also contribute to reducing stress concentration. The irregular opening of the legacy pipe represents the practical situation in which both unbonded and rounded factors are found effective in terms of stress concentration relief. The outcomes of this work provide useful information on minimising stress concentrations on PIP systems, which can be effectively utilised in repairing damaged pipes with a circumferential crack under the internal pressure loading.

1. Introduction

Natural gas is one of the primary sources of energy in many parts of the world. In the USA, natural gas powers approximately 41 % of industrial, 42 % of residential, 38 % of commercial, and 4 % of transportation sectors and in total provides 34 % of primary energy consumption source [1]. After oil and coal, natural gas is the third highest energy source in Australia [2] and in the world [3]. Gas utilities provide natural gas service to hundreds of millions of residential and commercial customers. Natural gas distribution began operating in the early 1800 s through the service line network of cast iron. Cast iron pipes have low operating and maximum allowable pressures, typically 20 kPa (3 psi) and 250 kPa (36 psi), respectively. In 1900 s, bare steel pipe started replacing cast iron for higher operating and maximum allowable pressures of 400 kPa (60 psi) and 1400 kPa (200 psi), respectively [4]. Both cast iron and bare steel

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pipes, collectively referred to as legacy pipes, compose substantial percentages of millions of kilometres of utility pipelines. In some areas, the legacy pipes in the natural gas distribution system can be more than 100 years old. They have deteriorated over their service life and accounted for several leaks and failures.

An increasing number of studies have investigated pipe failures from gas distribution networks. This is because pipe failures can create an operating safety risk, reliability concerns, and a negative impact on the financial performance of the system owners as well as the gas consumers [5,6]. Legacy pipes are usually connected by mechanical joints which can develop leaks during service due to several reasons such as fracture connection of flanges, degradation of material, environmental corrosion, and bolt-nut failure [7]. The metallic legacy pipe barrels themselves can also fatigue, corrode, and fail over time, typically as circumferential cracks, fractures, and wall loss. Leakage, bursting, fracture, and high cycle fatigue failure due to static and cyclic internal pressure are some possible failure modes of oil and gas steel pipelines [8-17]. The pipeline can be identified as functionally failed after leakage develops and as structurally failed after it bursts through loss of strength [11]. The failure modes of the pipe under internal pressure can also be classified either as ductile or brittle. The ductile failure is characterized by sudden creeping expansion, starting from the weakest point of the pipe, under the high internal pressure while the brittle failure is associated with a slow growing crack under the smaller internal pressure [12]. For gray cast iron pipes with a small diameter (less than 380 mm (15 in.) diameter), circumferential cracking is one of the most common failure modes as illustrated in Fig. 1 [7]. Typically, the circumferential crack is generated when the pipe is subjected to bending forces, similar to a twig snapping. As a result, the crack propagates across the circumference of the pipe. Additionally, soil movement potentially produces the tensile failure and causes the circumferential cracking. Similarly, joints in cast iron pipes could experience bell splitting under thermal expansion and contraction because of the mismatching between coefficients of thermal expansion (CTE) of the joint sealant, leadite, and the pipe [7]. In addition, the material loss in the cross section of the legacy pipe due to excessive corrosion can lead to circumferential failure. Pipe diameter to wall thickness (D/t) ratio, material grade and property, wall thickness, length, depth, angle, and location of crack [8-17] are identified as the critical parameters that have significant effects on the performance of the metallic pipelines under internal pressure. Effective repair systems should however be developed for legacy pipelines with circumferential cracks for their continuous service and safe operation.

There is a growing interest in natural gas system modernisation and the replacement of legacy cast iron and bare steel pipelines. The common approach for addressing legacy pipes is to excavate and replace them, typically with high density polyethylene pipes. However, the cost of pipe replacement can be very expensive, especially in urban areas due to the complexity of underground structures, buildings, and road congestion [18]. Rehabilitation of legacy natural gas pipes using pipe-in-pipe (PIP) systems is a relatively new technology. One of the earliest patents on the PIP technology was submitted by Eric Wood on 21st August 1970 in the UK [19]. Over the past two decades, the PIP system has been proven a well-established technology in which resin-saturated tubes are inserted and cured in existing pipelines [20]. The PIP technology not only increases the service life of legacy pipelines but also eliminates expensive and disruptive work of excavation and restoration. The PIP repair system provides continuity of the pipeline flow, prevents leakage, as well as reinforces structural strength of the legacy pipelines. Due to these advantages, the PIP has significantly attracted efforts in design, installation, and development [21] as a low-cost pipe rehabilitation solution for deteriorated and damaged legacy cast iron and bare steel pipelines.

The performance under internal pressure loading is one of the most important design criteria for PIP systems, as they should be able to handle the internal pressure alone in a region of large discontinuities in the legacy pipeline, such as when the deterioration of the host pipe is so severe that the entire section of its wall can give way [22,23]. Legacy pipes with circumferential cracks can have an adverse effect on the PIP system because of the high stress concentration developed at the interface between the PIP and the legacy pipe [22]. The edge of legacy pipes is typically sharp such as edge of pipes cut in field servicing or edge of pipes experiencing the circumferential cracking [24]. Knowledge on the effect of the sharp edge of the host pipe on the internal repair system is still limited and should be investigated. Henceforward, the objective of the paper is to investigate the sharp edge effect of the legacy pipe opening on the PIP liner under internal pressure loading. First, a finite element analysis (FEA) model is developed to evaluate the end effect of the legacy pipe opening on the PIP linear under internal pressure. Then, a detailed parametric study is conducted to investigate the effect of different scenarios of PIP systems, considering effect of a bonded versus unbonded region, PIP stiffnesses, high strain and low strain tolerance PIP materials, and roundness on the edge opening of the host pipes. Finally, the performance of PIP systems, implementing high strain and low strain tolerance PIP materials, with an irregular circumferential cracked legacy host pipe is investigated as a practical situation. The contributions presented in this paper will improve the understanding of the behaviour of the PIP systems with circumferentially cracked legacy pipelines under internal pressure. It will also be beneficial to the development of new and cost-effective PIP systems as well as the performance enhancement and longevity of existing gas pipeline infrastructure.

2. FEA modelling and validation

A numerical FEA model is developed by using the modern and widely used ANSYS/Mechanical FEA software [25] to investigate the

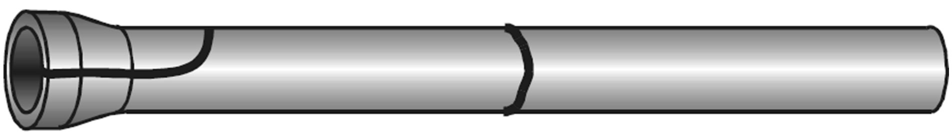


Fig. 1. An illustration of bell splitting at the end and circumferential cracking at the middle of gray cast iron pipelines.

edge effect of legacy host pipe with circumferential crack on PIP repair system. A damanged legacy pipe which has a circumferential crack and repaired by a PIP system is presented as a typical repair scenario. Quarter symmetrical modelling technique and optimal element mesh sizing are utilised to reduce the simulation time while maintaining high quality results. Numerical simulations are done with a DELL computer with specifications of Intel(R) Xeon(R) W-1270 CPU at 3.40 GHz 3.41 GHz and 64 GB RAM. The modelling technique is validated by comparing numerical results with analytical ones.

Details of the FEA model and analysis

Fig. 2 shows a typical case where the legacy pipe has a full circumferential crack i.e., the legacy pipe completely broken into two halves. The common nominal diameter of 300 mm (12 in) cast iron pipe system is considered in this work as it is reported that there are approximately 32000 km (20000 miles) of cast iron pipeline in US gas distribution mains based on the Pipeline and Hazardous Materials Safety Administration (PHMSA) database [26]. The legacy pipe has an outer diameter of 323.85 mm (12.75 in) with a thickness of 6.35 mm (0.25 in) while the PIP system has an outer diameter of 311.15 mm (12.25 in) and a thickness of 3.175 mm (0.125 in) [26]. The PIP thickness of 3.175 mm (0.125 in) is considered as this thickness is found suitable to resist internal pressure up to 1400 kPa (200 psi) for PIP alone based on the previous works by the authors [26]. The legacy pipe opening is set to be 914.4 mm (3 ft) wide. The wide opening is considered to ensure the PIP system fully bears the maximum allowable internal pressure of 1400 kPa (200 psi) at which it deforms up to its nonlinear isotropic range. For the worst-case scenario, the maximum allowable internal pressure of 1400 kPa (200 psi), used for the bare steel pipelines, is considered throughout the paper based on the previous study at Cornell University [27]. The nonlinear static structural FEA modelling, using the full Newton-Raphson solution procedure, is conducted to simulate the material nonlinearity of both the host pipe and the PIP system. Large deformations and plasticity are also allowed in the analysis. The PIP repair system runs the full length of the host pipe, i.e. 1,524 mm (5 ft) and it is fully bonded to the legacy pipe. Both ends of the PIP repair system (including the legacy pipe and PIP liner) are fixed in all degrees of freedom to represent a long continuous pipe. The circumferential crack is assumed to be 90-degree sharp as illustrated in Fig. 3. For simplification, a quarter of the system is modelled with the symmetry boundary conditions applied in longitudinal and transverse directions. Surface mesh sizes of 4 × 4 mm and 2 × 2 mm are chosen for legacy pipe and PIP liner, respectively, while the number of elements in the thickness direction is three for both legacy pipe and PIP as shown in Fig. 4.

Mesh convergence study

The mesh convergence study on the PIP system is conducted by comparing the solution accuracy between numerical results with the analytical solution. For this purpose, a single pipe, which represents either the legacy or repair system, is constructed using the standard ASTM A36 steel with modulus of elasticity (MOE) of 200 GPa (29008 ksi). Its chemical composition is presented in Table 1. The pipe is subjected to the maximum allowable internal pressure of 1400 kPa (200 psi). The pipe, which is used for the mesh convergence study, has the same dimensions of the PIP system as shown in Section 2.1. Standard SOLID186 ANSYS element [28], which has plasticity, hyper-elasticity, stress stiffening, creep, large deflection, and large strain capabilities, is used throughout the work. The mesh size of three elements is used in the thickness direction while the surface element sizing of the pipe ranges from coarse 30 × 30 mm to very fine 2 × 2 mm.

The hoop or circumferential stress in a pipe under the internal pressure along the length without the contribution of the host pipe is calculated based on the thin plate theory where D_m/t is greater than 20 as follows:

$$\sigma_h = \frac{PD_m}{2t} \tag{1}$$

where P is the internal pressure; t is the wall thickness; and, D_m is the mean diameter of the outer and inner diameters.

Fig. 5 plots the accuracy ratio of numerical and theoretical results versus the mesh refinement. From the mesh size of 8 × 8 mm or finer, it is seen that solution starts converging with an accuracy ratio of at least 1.001. For high accuracy solutions, the surface mesh of 2 × 2 mm is used for the PIP liner while 4 × 4 mm is used for the host pipe in the next sections.

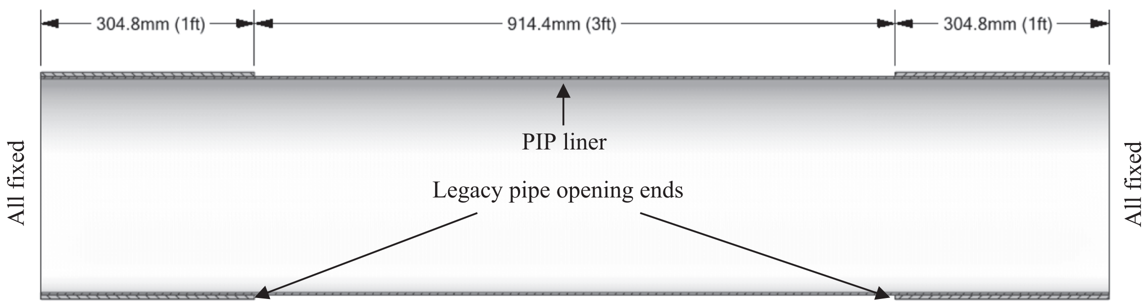


Fig. 2. Dimensions and components of a typical PIP repair system.

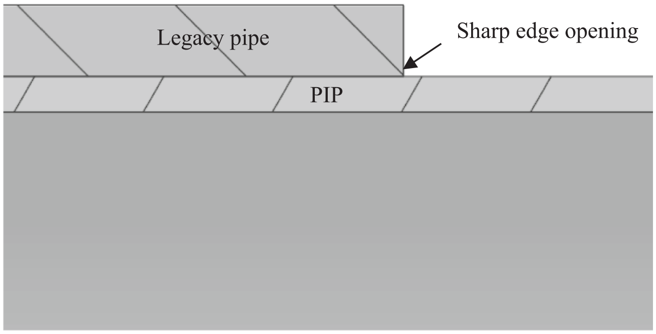


Fig. 3. An enlarged view on the sharp edge opening of the legacy pipe.

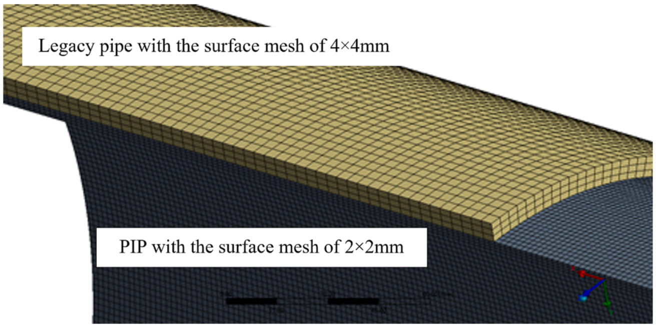


Fig. 4. Meshing configurations of the typical case.

Table 1
Chemical composition of ASTM A36 steel.

Standard	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cu (%)
ASTM A36	0.26	0.40	1.03	0.04	0.05	0.20

Validation of FEA model

The validation of the FEA model with analytical results on one of metallic PIP systems which is the standard steel PIP system is presented in this section. Three typical thicknesses of PIP system, such as 3.175 mm (0.125 in), 6.35 mm (0.25 in) and 9.525 mm (0.375 in), are used for validation [29,30]. The PIP is subjected to maximum allowable internal pressure of 1400 kPa (200 psi). The accuracy ratios of numerical and theoretical hoop stresses versus wall thicknesses are shown in Table 2. The hoop stresses obtained from the FEA models are closely matching with the theoretical results. The mean accuracy ratio between FEA and theoretically

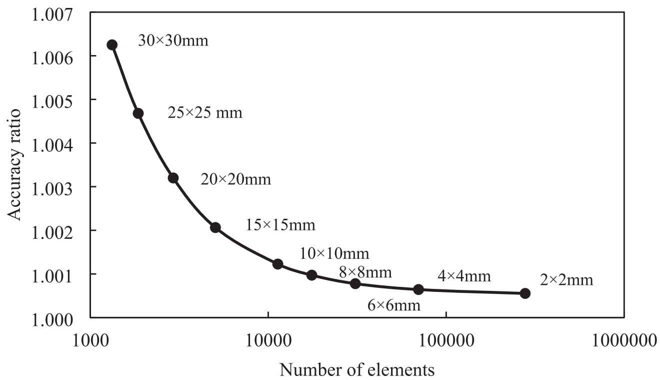


Fig. 5. Mesh convergence study: accuracy ratios versus the number of elements.

predicted hoop stresses is 1.001 which is very highly accurate.

Parametric study

This section presents an analysis on the effect of the sharp end of a circumferentially cracked host pipe on the PIP repair system under internal pressure loading. A thorough parametric study is conducted to investigate the behaviour of PIP systems with different material properties including metallic, composite, and thermoplastics. Different sharpness and shapes of the end of the circumferential cracked host pipe are also considered. Bonded and unbonded conditions between host pipe and PIP liner are studied as well.

Typical case study

A typical case study is implemented to illustrate the host pipe end's effects on the repair system under internal pressure loading wherein the legacy pipe is made of steel while the PIP is made of thermoplastic with MOE of 5 GPa (725 ksi), as the combination of host pipe with high modulus and the PIP with low modulus can simulate most critical edge effect. Because the model is quarterly symmetric, the results are only shown for the first half of the model on the left-hand side for simplicity. The path-line for result extraction starts from the left end to the middle of the pipe. Under internal pressure, the PIP liner undergoes bending as it curves around the opening end of the legacy pipe, resulting in a stress concentration as shown in Fig. 6. In downward bending, the top part of the material is subjected to compression while the bottom part is under tension. It is assumed that the maximum tensile and compressive stresses are equal in magnitude [31]. Consequently, the PIP liner may undergo bending failure due to excessive tensile or compressive stress concentration. For simplicity, this work focuses on the failure due to tensile stress which could potentially develop vertical or flexural cracks in the PIP liner [32,33,22]. The path-line is set in line with the internal surface of the PIP liner where the stresses are captured. Fig. 7 shows the equivalent stress distribution on the PIP liner when subjected to the maximum allowable pressure. It is seen that the stress at the opening sharp end of the legacy pipe is much higher than that of the opening section, i.e., 28 % increment in stress. This means that the PIP will potentially fail due to the stress concentration induced by the end of the legacy pipe before the PIP's design failure pressure.

The equivalent (so called von Mises) stress is described in Equation (2). It is usually used in design work to predict yielding in a ductile material such as those PIP materials considered in this study.

$$\sigma_e = [\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}]^{\frac{1}{2}} \tag{2}$$

where σ_1, σ_2, and σ_3 are the principal stresses in three directions (longitudinal, hoop, and thickness directions, respectively) as shown in Fig. 8 and Fig. 9. It is noted that the stress values in the thickness direction are negligible due to relative thinness of the PIP materials; hence, it is not presented. It is seen that the stress at the concentration region is governed by the longitudinal stress while the stress at the opening region is governed by the hoop stress. This can be due to the bending behaviour, which is governed by longitudinal property of the PIP material around the edge of the host pipe under internal pressure as shown in Fig. 6. For simplicity, hereafter the equivalent stress can be used for comparison between the stresses at the concentration and opening regions in a single plot as demonstrated in Fig. 10.

If the steel legacy pipe is replaced by the cast iron having an outer diameter of 347.44 mm (13.68 in) with a thickness of 18.143 mm (0.71 in), the two standard legacy pipe systems are believed to have similar strength. The standard A48 Class 20 gray cast iron with modulus of elasticity (MOE) of 70 GPa (10153 ksi) is used for the comparison and its chemical composition is listed in Table 3. Fig. 10 shows the equivalent stress along the PIP system in steel and cast-iron legacy pipes. It is seen that the two systems yield almost identical stress results at the concentration and the opening regions. This can be due to the PIP system having relatively lower thickness and MOE compared to both steel and cast-iron pipes. For simplicity, hereafter all analysis will be conducted using steel as the representative legacy pipe system.

The mesh convergence study is carried on the stress concentration ratio of the PIP liner as shown in Fig. 11. The surface mesh refinement is made from coarse 8 × 8 mm to very fine 1 × 1 mm. It is seen that the mesh starts converging at 2 × 2 mm with the number of mesh 277,749 and there is only 5 % difference in stress ratio value in comparison with that of the mesh 1,138,812. For the sake of computational effectiveness, the optimal mesh size of 2 × 2 mm is used instead of 1 × 1 mm throughout the paper.

Table 2
Validation of FEA results with analytical hoop stress for various thicknesses at the mesh size of 2 × 2 mm.

Thicknesses mm (in)	FEA MPa (psi)	Theory MPa (psi)	Accuracy ratio
3.175 (0.125)	66.916 (9705)	66.879 (9700)	1.001
6.35 (0.25)	33.116 (4803)	33.095 (4800)	1.001
9.525 (0.375)	21.856 (3170)	21.833 (3167)	1.001

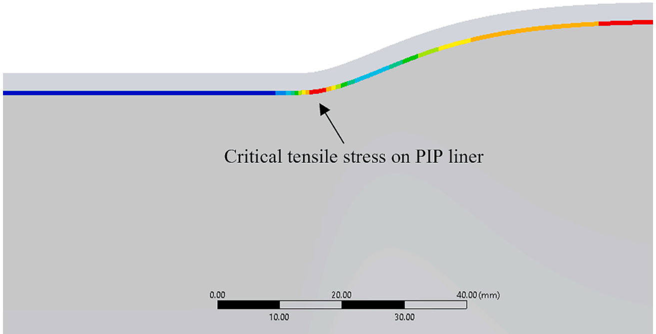


Fig. 6. Path-line setup for result extraction on PIP liner.

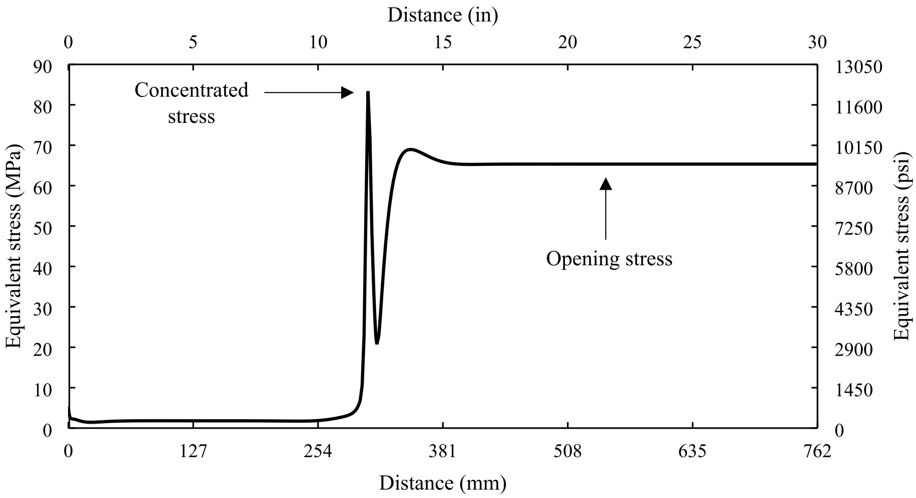


Fig. 7. Demonstration of the equivalent stress at the concentration and opening regions.

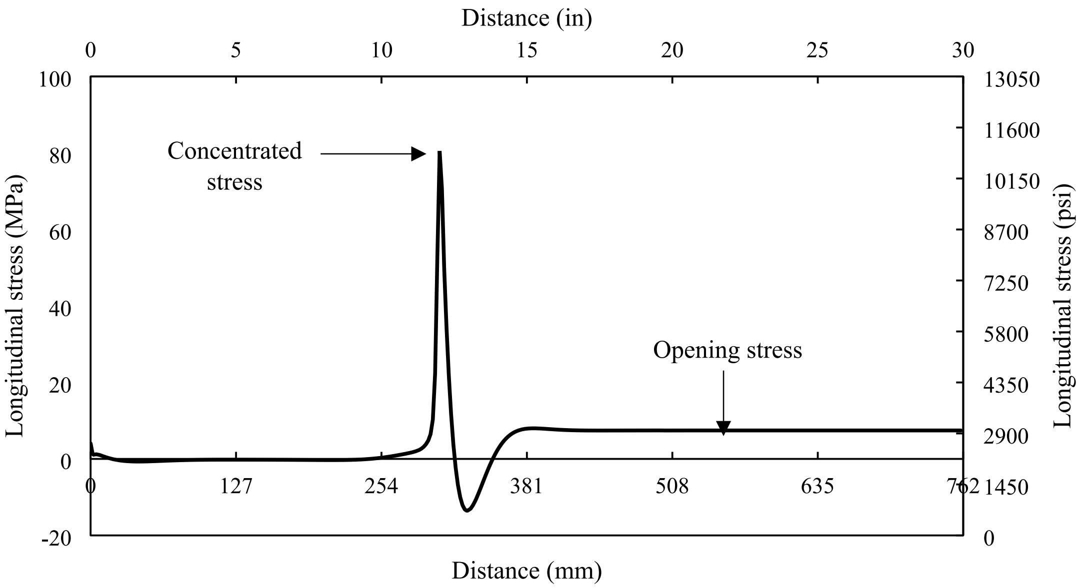


Fig. 8. Demonstration of the longitudinal stress at the concentration and opening regions.

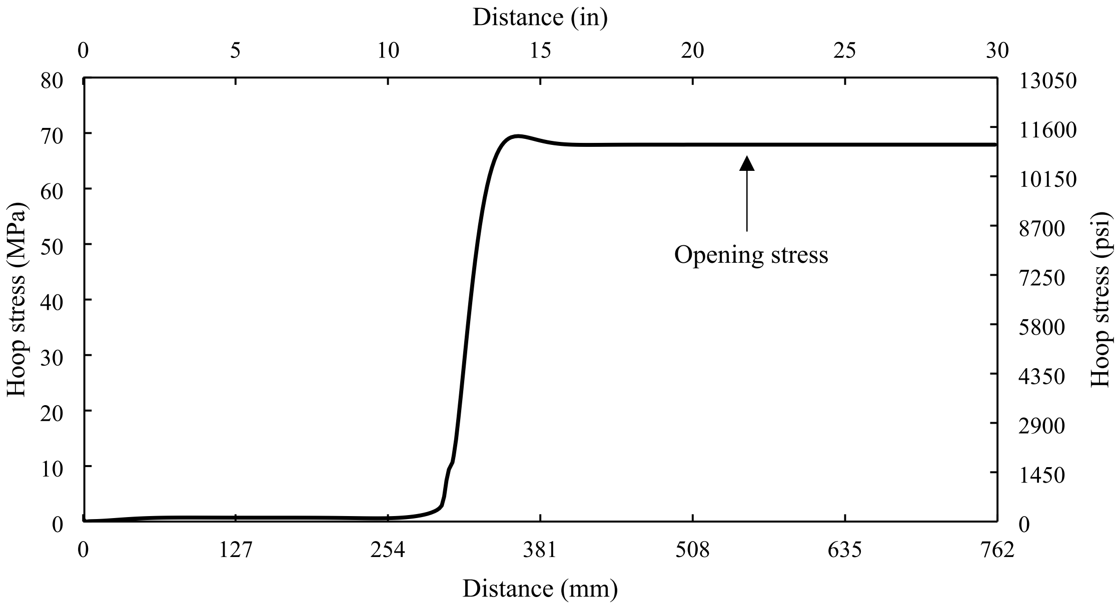


Fig. 9. Demonstration of the hoop stress at the concentration and opening regions.

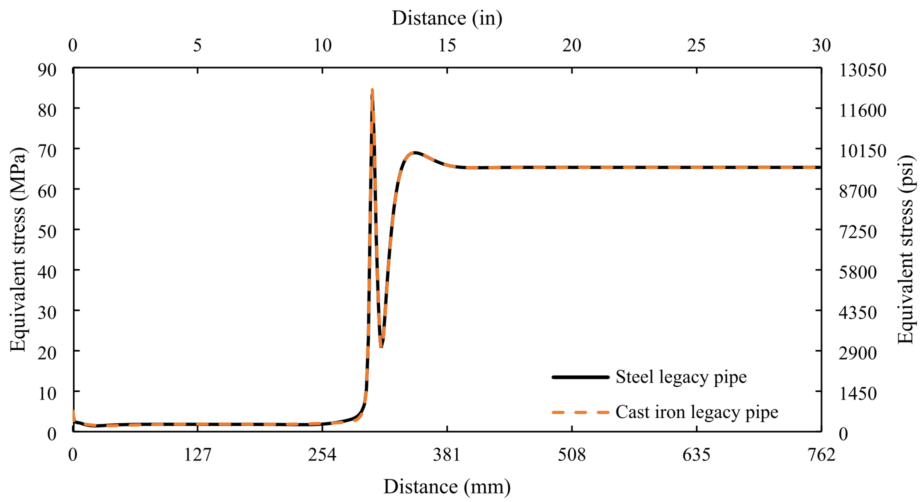


Fig. 10. The comparison of equivalent stress along PIP liner in steel and cast-iron legacy pipe systems.

Table 3
Chemical composition of ASTM A48 Class 20 gray cast iron.

Standard	C (%)	Si (%)	Mn (%)	P (%)	S (%)
ASTM A48 Class 20	3.2–3.5	1.8–2.4	0.5–0.9	0–0.12	0–0.12

Effect on the PIP system with various elastic moduli and thicknesses

Three general types of materials (steel, cast iron and glass fibre-reinforced polymer (GFRP)) are considered to investigate the performance of PIP repair systems. In addition, the elastic moduli of 24.5 GPa (3553 ksi), 15 GPa (2176 ksi), 10 GPa (1450 ksi), 5 GPa (725 ksi) and 1 GPa (145 ksi) are investigated to cover a wide range of possible polymeric composite PIP material systems (e.g., unreinforced polymers, fibre-reinforced thermosets and thermoplastics polymers, steel/polymer hybrid layers, particulate-filled polymers) as shown in Table 4. Fig. 12 shows the effect of the legacy pipe on the PIP liner with different elastic moduli. Under pressure loading, it is seen that the stress ratio (concentrated stress/opening stress) is lower than 1.0 for elastic moduli from 24.5 GPa

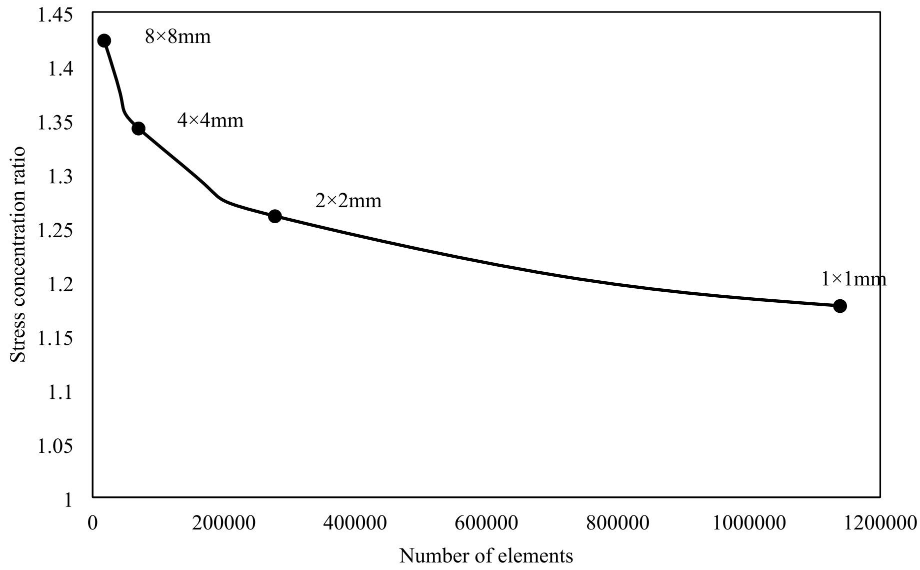


Fig. 11. Mesh convergence analysis on stress concentration ratio of the PIP liner with MOE of 5 GPa (725 ksi).

(3553 ksi) and greater. This also means the end of the legacy pipe has a greater effect on the lower modulus material properties which will be further addressed in the next section.

Fig. 13 shows the effect of the legacy pipe end on the PIP repair system at different levels of internal pressure loading, including 1400 kPa (200 psi), 700 kPa (100 psi) and 400 kPa (60 psi). These pressures are representative for those which are used in cast iron gas distribution mains operating at low pressure e.g. less than 400 kPa (60 psi), as well as bare steel pipelines operating at higher pressure but below 1400 kPa (200 psi) [34]. It is seen that the stress ratios (between the concentration and opening region) are very similar for the three levels of pressure over the range of moduli. When considering a thin section of the PIP repair system along the longitudinal axis, its bending mechanism around the opening edge of the legacy pipe can possibly be explained with the cantilever beam theory as shown in Equation (3). As both hoop stress σ_h and bending stress σ_b are the linear function of the internal pressure P, the stress ratio, σ_b/σ_h is basically independent of levels of the internal pressure.

$$\sigma_b = \frac{FL}{Z} \tag{3}$$

where L is the bending length of the PIP starting from the end of the legacy pipe to the position where the bending finishes as illustrated in Fig. 6; $F = f(P)$ the force at the end of bending length is the linear function of the internal pressure P; $Z = bt^2/6$ is the section modulus; b is the width of the PIP slice along the longitudinal axis; t is the PIP thickness.

Fig. 14 shows the effect of the cracked end of the host pipe on the PIP system at various thicknesses including 3.175 mm (0.125 in), 6.35 mm (0.25 in) and 9.525 mm (0.375 in) under the internal pressure of 1400 kPa (200 psi). The results show that the thicker the PIP, the less the stress ratio because the thickness, t, is inversely proportional to the stress ratio. At 6.35 mm (0.25 in), the PIP with the elastic moduli of 5 GPa (725 ksi) and higher overcome the end effect of the legacy pipe. At 9.525 mm (0.375 in), the PIP suppresses the end effect for the whole range of the elastic moduli considered in the analysis.

Effects of bonding between PIP system and the host pipe on stress concentration

Half of the internal surface of the legacy pipe closer to the opening end is unbonded at a length of approximately 0.5 D_m as shown in Fig. 15 to study the effects of bonding between PIP repair system and the host pipe on stress concentration. The contact condition between the legacy pipe and PIP is considered as frictional with the standard friction coefficient of 0.2 used in the tangential frictional force given in Equation (4) [35]. Under the maximum allowable pressure of 1400 kPa (200 psi), the stress ratios between the concentrated stress and opening stress of unbonded cases are significantly reduced, up to 15 %, in comparison with those of bonded cases for various elastic moduli as shown in Fig. 16. This is because the free/unbonded length of the PIP liner can slide along the host

Table 4
Material properties used for PIP repair system.

Elastic Moduli GPa (ksi)	1 (145)	5 (725)	10 (1450)	15 (2176)	24.5 (3553)	70 (10153)	200 (29008)
Poisson's ratio	0.11	0.11	0.11	0.11	0.11	0.29	0.29
Properties	GFRP	GFRP	GFRP	GFRP	GFRP	Cast iron	Steel

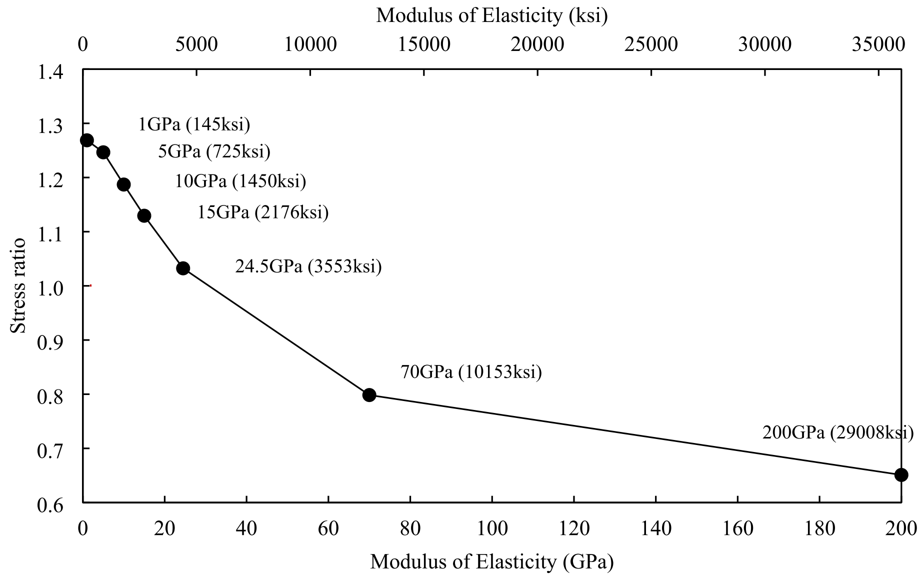


Fig. 12. Stress ratio (concentrated stress/opening stress) on PIP repair system with different elastic moduli.

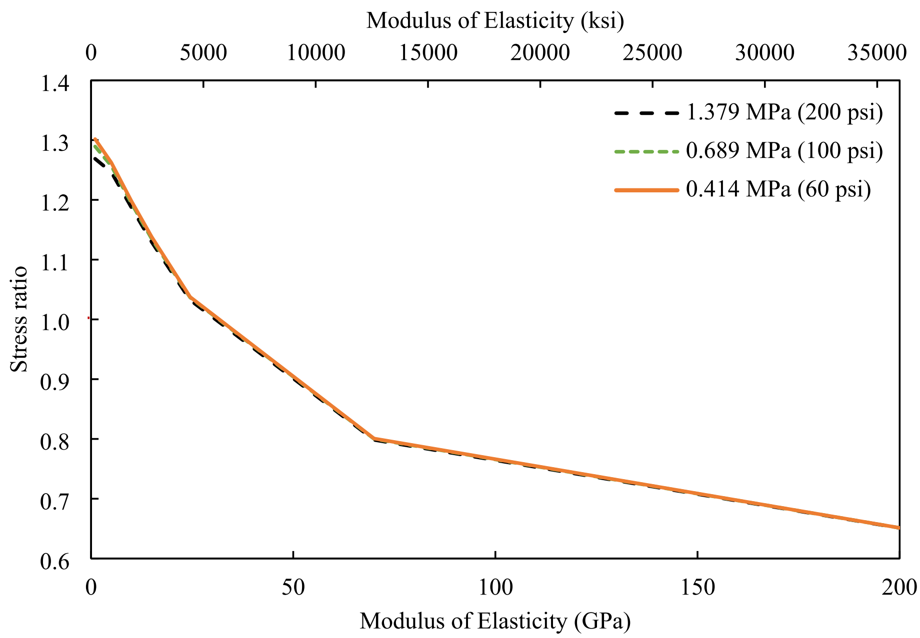


Fig. 13. Stress ratio on PIP repair system with thickness of 3.175 mm (0.125 in) with different elastic moduli at different levels of internal pressure.

pipe and allows it to form more effectively around the edge of the host pipe in comparison with fully bonded PIP systems. Furthermore, when unbonded condition is considered, it is found that the end of the legacy pipe only affects the performance of the material with elastic modulus of 15 GPa (2176 ksi) and lower as shown in Fig. 16. While the end of the legacy pipe affects the performance of the material with elastic modulus of 25 GPa (2176 ksi) under fully bonded condition. The PIP system with unbonded region outperforms the fully bonded one due to the flexibility of PIP around the unbonded region. Next section presents a study on a high strain tolerance material which has equivalent elastic modulus of 5 GPa (725 ksi).

$$F_{fric} = \mu F_N \tag{4}$$

where μ is the friction coefficient and F_N is the normal force.

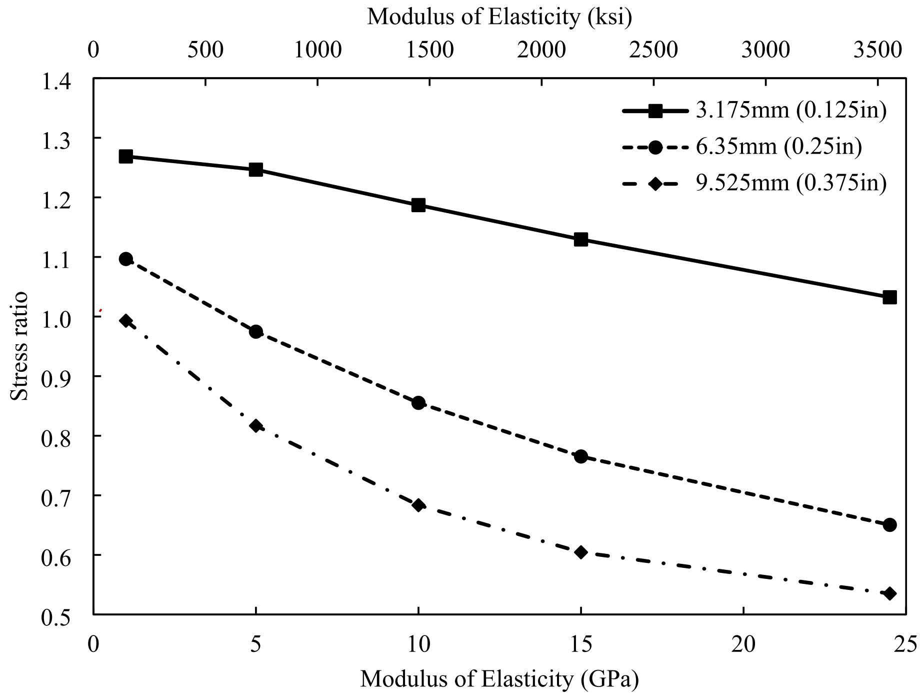


Fig. 14. Stress ratio on PIP repair system with different thicknesses at the internal pressure of 1400 kPa (200 psi).

Fig. 15. A schematic of bonded and unbonded partition considered in the PIP system.

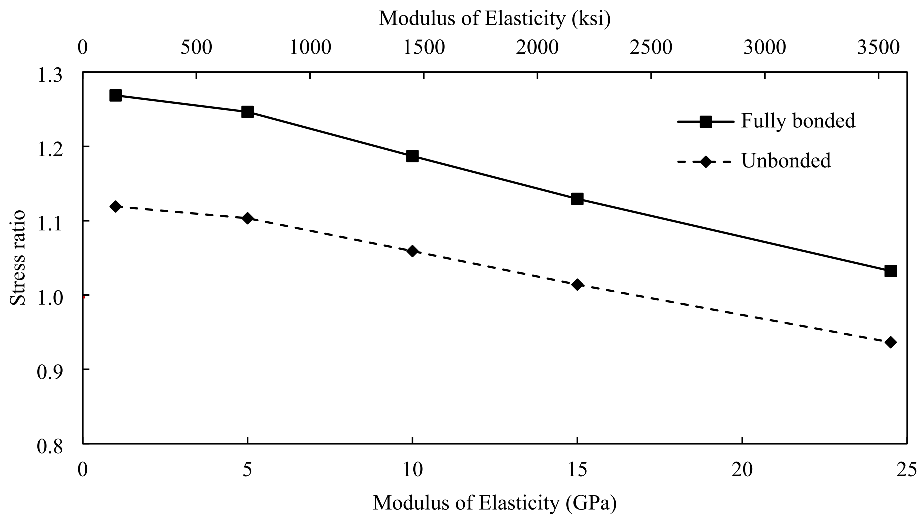


Fig. 16. Stress ratio of bonded and unbonded cases.

High strain tolerance material

Aqua Pipe® (AP) is a high strain tolerance pipe repair material system which can yield high deformation, i.e. over 20 %, upon the application of external forces. AP material is a proven structural liner and widely used to rehabilitate existing water mains [12]. AP-3, which has the elastic modulus of 3.38 GPa (490 ksi), is modelled in this numerical analysis as high strain nonlinear isotropic material. AP-3 has Poisson's ratio of 0.23 and failure strain on 20 % [27]. In the Fig. 17, the stress–strain curve of AP-3 is compared with that of the comparative lower strain tolerance PIP repair material, E5, which is modelled as linear isotropic material and has modulus of elasticity of 5 GPa (725 ksi). The slight difference in moduli of elasticity between AP-3 and E5 has no significant effect on the purpose of performance comparison. Both AP-3 and E5 liners are fully bonded along the contact interface with the host pipe for the worst-case scenario as discussed in Section 3.3. It is seen that the AP-3 material produces much lower stress at the concentration region around the opening edge of the legacy pipe compared to that of the E5, i.e. 59 MPa for AP-3 in comparison with 83 MPa for E5 accounting for 29 % stress reduction, as shown in Fig. 18. This is possibly because the high strain capability of AP-3 allows the higher deformation capability. Therefore, AP-3 lessens the stress concentration effect from the opening edge of the legacy pipe in comparison to the case using the lower strain material of E5 as shown in Fig. 19.

Effects of rounding end of host pipe ends

The opening end of the legacy pipe is rounded at a factor of 0.25 legacy pipe thickness which is equivalent with the roundness radius of 1.5875 mm (0.0625 in) to further investigate on the stress concentration effect. It is noted that both AP-3 and E5 liners are fully bonded along the contact interface with the host pipe for the worst-case scenario as discussed in Section 3.3. Fig. 20 and Fig. 21 show the roundness effect on both E5 and AP-3 materials, respectively. It is seen that the rounded edge eases the stress concentration for both materials. Unlike converting from lower strain to higher strain tolerance PIP material as shown in Section 3.4, the roundness does not have as much of a significant effect on stress concentration relief, i.e. 5 % stress reduction for E5 and 3 % for AP-3.

Host pipe with irregular crack opening

The effect of the irregular edge, shown in Fig. 22 (a), is investigated to evaluate the behaviour of the PIP systems when used in repairing a host pipe with an irregularly circumferential crack. The irregular fracture was captured on a 330 mm (13 in) cast iron pipe by using the iOS photogrammetry app PhotoCatch version 1.1.3 (EOS Innovations LLC) and was converted to STL format using Aspose conversion software (Aspose Pty ltd) as shown in Fig. 22 (b). For numerical work, the irregular fracture is simplified by using multiple linear lines as shown in Fig. 23 (a). Sharp and mild angles are purposely modelled in FEA to visualise their effects on the PIP repair systems. The sharp angle is defined 45° while the mild one is 14° as shown in Fig. 23 (b). The meshing of the irregular model, using the meshing configuration presented in Section 2.1, is shown in Fig. 23 (c). Fig. 24 and Fig. 25 show the effect of the irregular opening of the legacy pipe on PIP systems using E5 and AP-3 materials, respectively. The results show that the PIP system, using either E5 or AP-3 material, yields less concentrated stresses along the irregular edge when the unbonded condition and rounded edge (i.e. Fig. 24 (b) and Fig. 25 (b)) are considered in comparison with the cases of fully bonded condition and sharp edge (i.e. Fig. 24 (a) and Fig. 25 (a)). Between the two materials, it is also seen that E5 PIP material generally produces higher stress concentration along the irregular edge in comparison with that of the opening stress as shown in Fig. 24 (b); while, the AP-3 counterpart, with better flexibility or strain tolerance, overcomes the concentrated stress as shown in Fig. 25 (b).

Fig. 26 and Fig. 27 show the stresses at the concentration and opening regions for the regular edge. It is seen that the regular opening can represent the irregular case because both generally yield similar stress concentration. The maximum stress results of irregular edge are higher than those of regular one, e.g. 11 % for bonded E5 to 20 % for bonded AP-3. In irregular cases, the maximum stress happens at the sharp angle as shown in Fig. 24 and Fig. 25. In practice, it is faster and cheaper to prepare the legacy pipe with

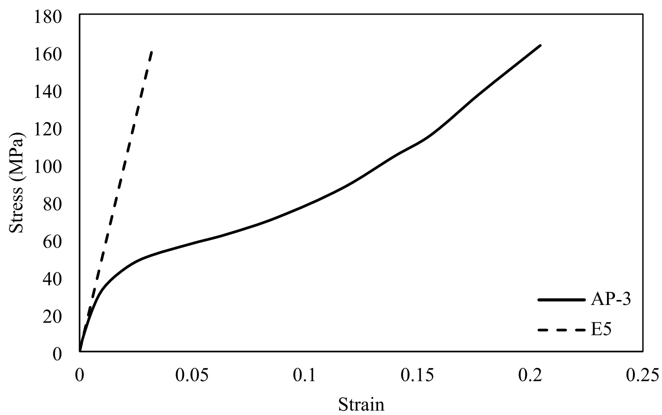


Fig. 17. Stress–strain curve of AP-3 and E5 materials.

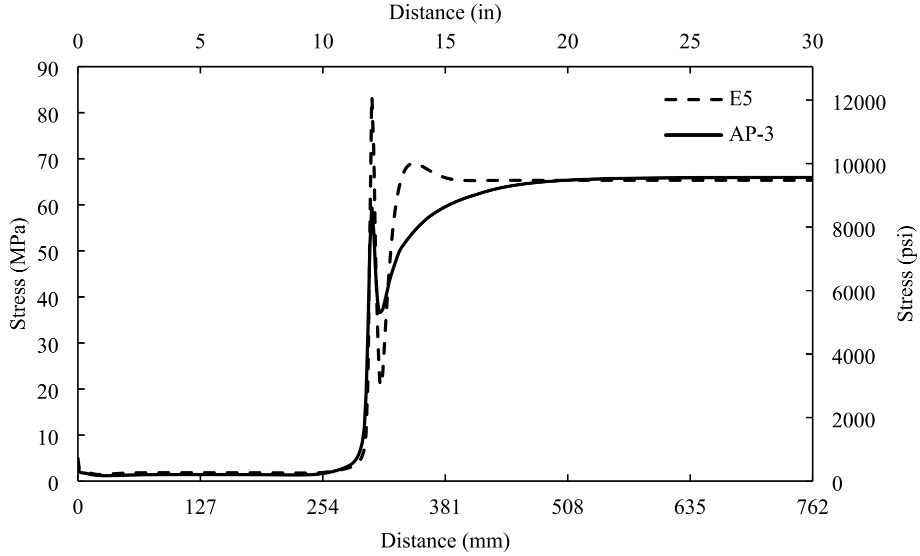


Fig. 18. Stress over the distance for E5 and AP-3 materials.

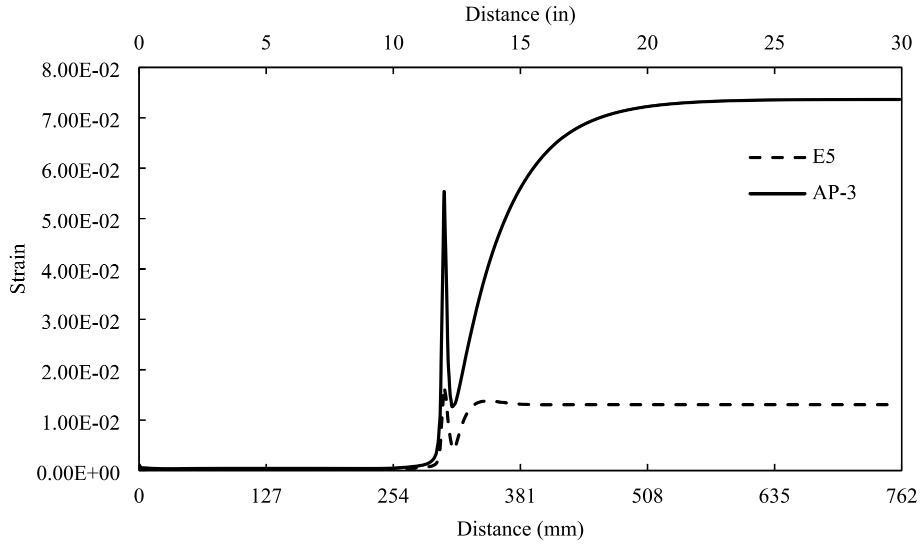


Fig. 19. Strain over the distance for E5 and AP-3 materials.

regular opening for experimental and repairing purposes while it can produce a similar trend of failure as presented in Table 5. Table 6 compares the concentrated stresses between sharp and mild angles, and the regular edge. The sharp angle normally produces higher stress than the mild one does due to harder puncture effect. However, the relative percentage difference is in the rage from 2 % to 11 % depending on the legacy and liner bonding conditions and edge configurations.

Further studies of irregular effects on other liner material properties such as low strain AP-5 and AP-3/5. AP-5, modelled as nonlinear isotropic in FEA, has the elastic modulus of 5.29 GPa (726 ksi) and Poisson's ratio of 0.23 and its stress–strain curve is shown in Fig. 28. While AP-3/5 is assumed to be linear orthotropic with the elastic modulus of 3.38 GPa (490 ksi) in longitudinal direction and 5.29 GPa (726 ksi) in both circumferential and thickness directions as shown in Table 7. It is noted that the AP-3/5 has the characteristic of a brittle material while AP-3 and AP-5 are ductile with their stress–strain curves shown in Fig. 17 and Fig. 28, respectively. Numerical results show that both AP-5 and AP-3/5 material properties do not overcome the stress concentration affected by the host pipe in the way that the AP-3 material does, illustrated in Fig. 29 and Fig. 30. It demonstrates that the high strain capability of AP-3 with over 20 % strain has a significant effect on relieving the stress concentration because it allows the PIP system to highly deform around the opening edge.

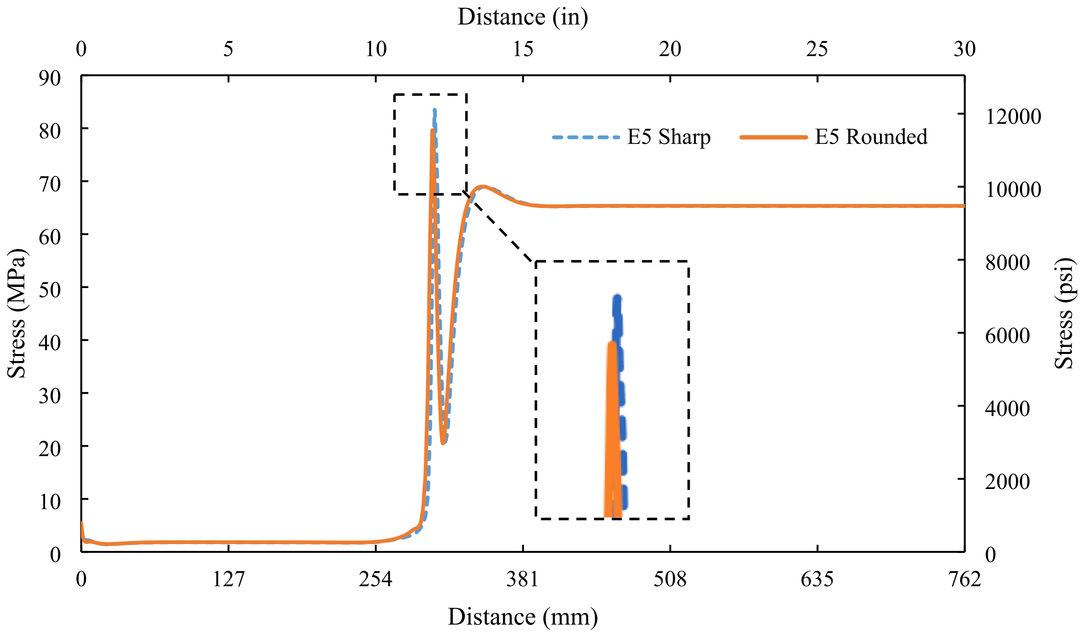


Fig. 20. Roundness effect on the PIP system using E5 liner.

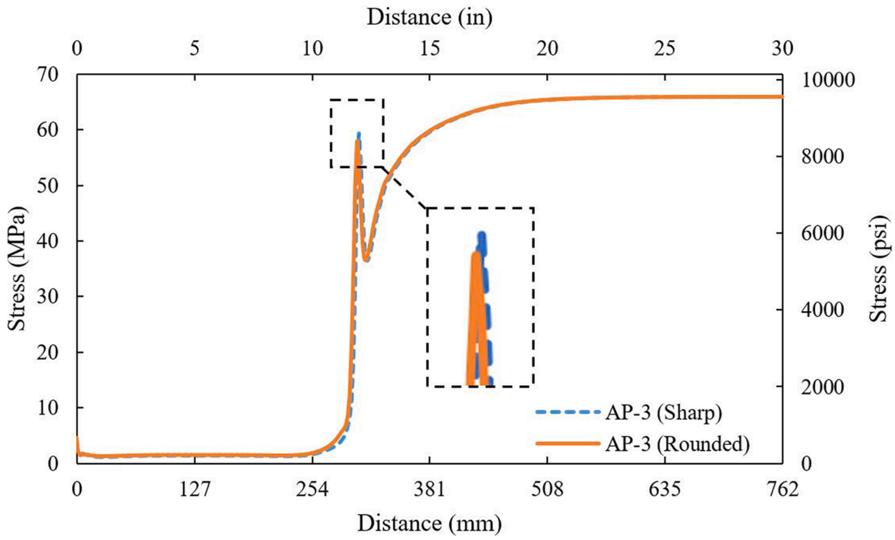
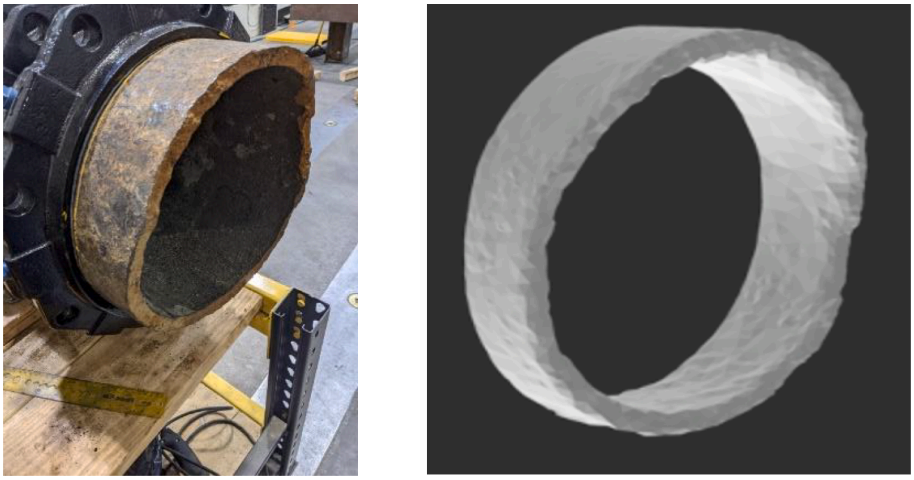


Fig. 21. Roundness effect on the PIP system using AP-3 liner.

Conclusion

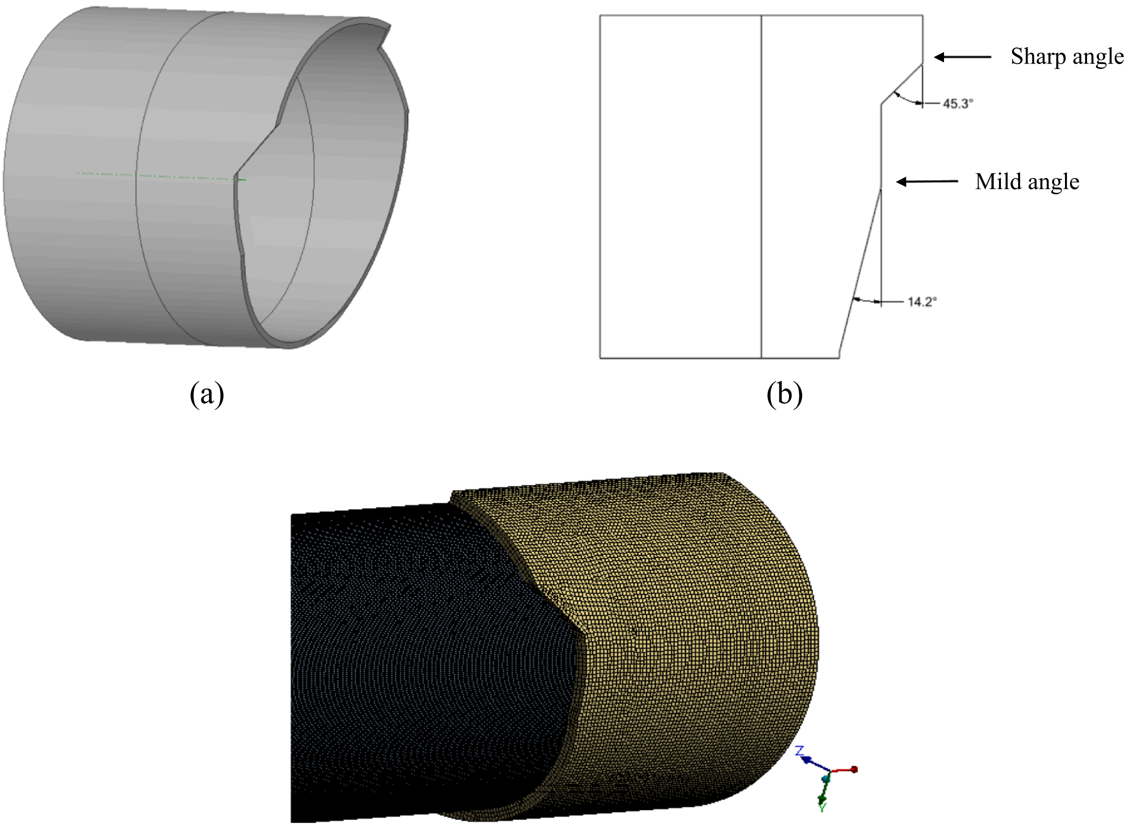
This paper investigates the effect of the sharp edge of the legacy pipe on the pipe-in-pipe (PIP) repair system under the internal pressure loading. Various approaches, including an unbonded region, different material properties such as high strain and low strain tolerance materials and rounded edge, are introduced to eliminate the stress concentration. From the results of the extensive finite element analyses, the following conclusions can be drawn:

- The sharp edge of the legacy host pipes can cause a stress concentration on the PIP repair system by up to 30 %, which could lead to premature failure under the internal pressure service. The premature failure on PIP may occur on the concentrated region where the liner contacts with the edge of the legacy pipe instead of the designed failure on the opening region.



(a) (b)

Fig. 22. Shape of fracture on a cast iron pipe (a) photo of cracked edge and (b) 3D scan of the crack.



(c)

Fig. 23. Shape of irregular fracture used in FEA (a) 3D modelling, (b) schematic of the irregular edge, and (c) meshing of the irregular model.

- Unbonding the PIP system to the host pipe by at least half pipe diameter can lessen the concentrated stress by as much as 15 % as the free/unbonded length of the PIP repair system can relatively slide through the host pipe and allow it to form more effectively around the edge of the host pipe in comparison with the fully bonded case.

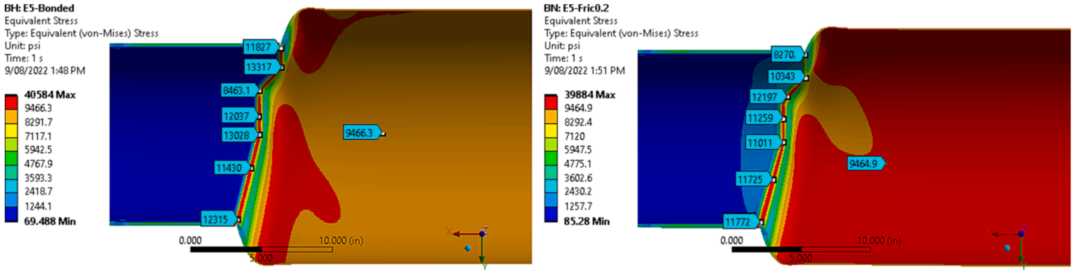
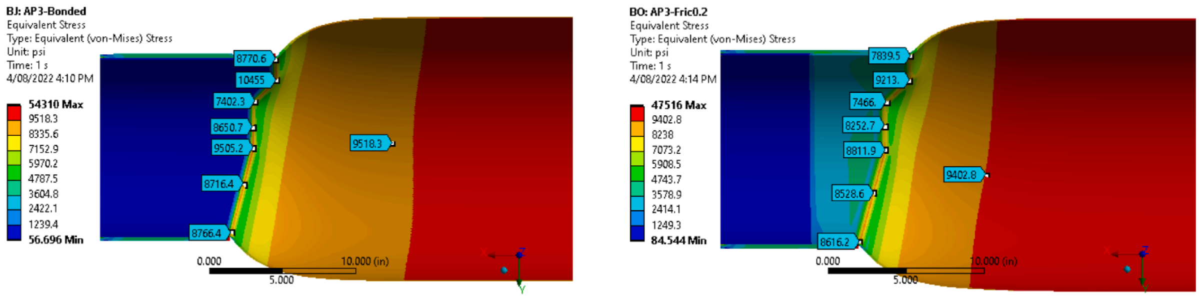
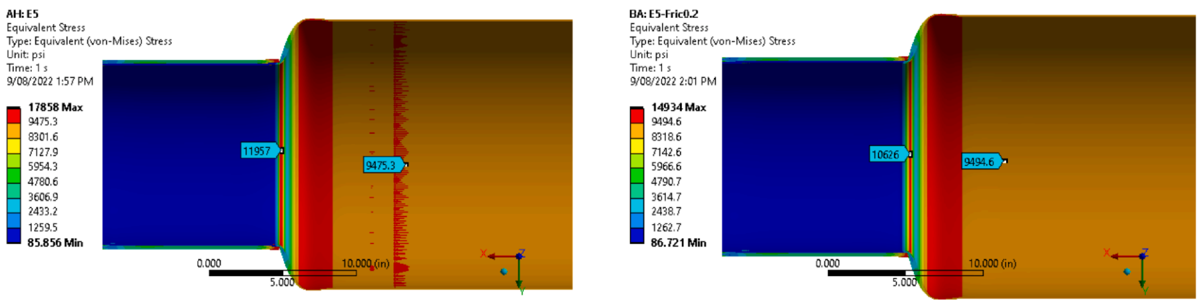


Fig. 24. Effect of irregular opening on E5 material (a) before (b) after considering roundness and un-bonding.



(a) (b)

Fig. 25. Effect of irregular opening on AP-3 (a) before (b) after considering roundness and un-bonding.



(a) (b)

Fig. 26. Effect of regular opening on E5 liner (a) before (b) after considering roundness and un-bonding.

- High strain tolerance PIP material such as AP-3 produces better performance than the comparatively lower strain E5 material by lowering stress concentration by as much as 29 % at the sharp edge of the legacy pipe. This is because high strain tolerance PIP material can deform around the opening edge without being over stressed.
- The rounded edge can ease the stress concentration in the PIP repair system by up to 5 % compared to the sharp edge. However, it does not have as much as effect on high strain tolerance PIP material, i.e., 3 % stress reduction.
- Irregular opening of the legacy host pipe is considered to represent the practical situation where both unbonded and rounded factors show to be effective for PIP repair systems. The sharp irregular edge (45-degree angle) can increase the stress concentration by up to 20 % for high strain PIP materials and up to 11 % for low strain PIP material.

While this study focuses on the 300 mm (12 in) PIP repair system, the developed FEA modelling, and methodology can be extended to other diameters for cast iron and bare steel pipelines. By defining more suitable material properties, pipe thickness and better bonding condition, the PIP system can perform better and has greater longevity. The cost of manufacturing can also be reduced by using optimal thickness. Moreover, microstructural inhomogeneities may also have an effect in stress concentration in the critical PIP

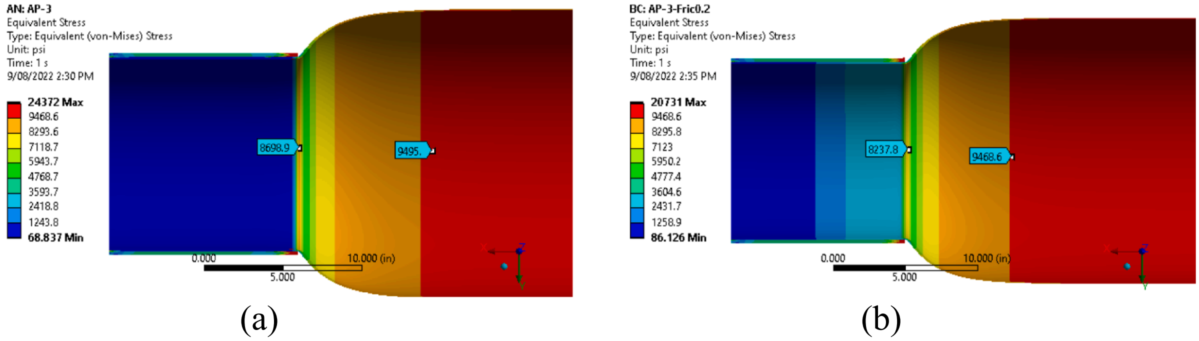


Fig. 27. Effect of regular opening on AP-3 liner (a) before (b) after considering roundness and un-bonding.

Table 5
Percentage difference in stress between irregular and regular edge.

Materials	Bonding	Irregular (MPa) [psi]	Regular (MPa) [psi]	Difference (%)
E5	Bonded	(92) [13,317]	(82) [11,957]	↑11 %
E5	Unbonded	(84) [12,197]	(73) [10,626]	↑15 %
AP-3	Bonded	(72) [10,455]	(60) [8,699]	↑20 %
AP-3	Unbonded	(64) [9,213]	(57) [8,238]	↑12 %

Table 6
Percentage difference in stress between sharp and mild angles compared to regular edge.

Materials	Bonding	Sharp angle (MPa) [psi]	Mild angle (MPa) [psi]	Regular (MPa) [psi]
E5	Bonded	(92) [13,317] ↑11 %	(90) [13,028] ↑9%	(82) [11,957]
E5	Unbonded	(71) [10,343] ↓3%	(76) [11,011] ↑4%	(73) [10,626]
AP-3	Bonded	(72) [10,455] ↑20 %	(66) [9,505] ↑9%	(60) [8,699]
AP-3	Unbonded	(64) [9,213] ↑12 %	(61) [8,812] ↑7%	(57) [8,238]

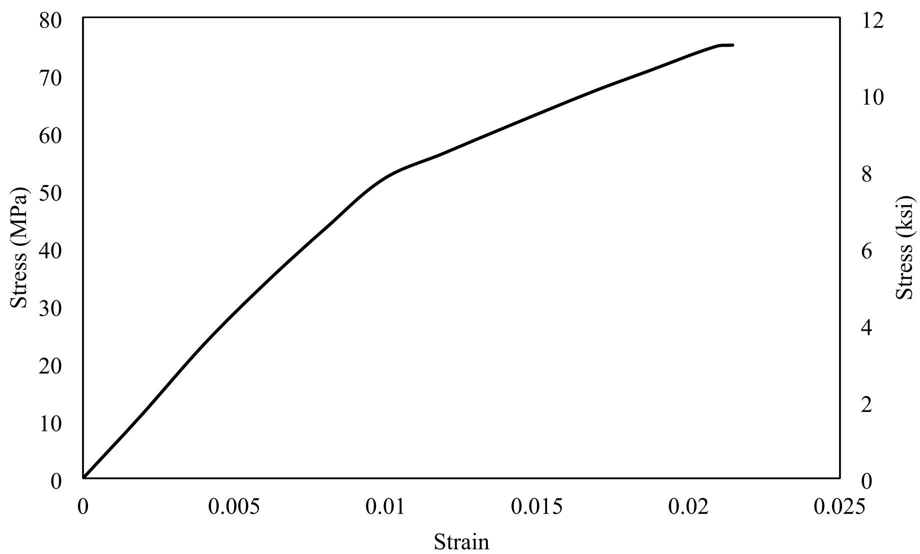
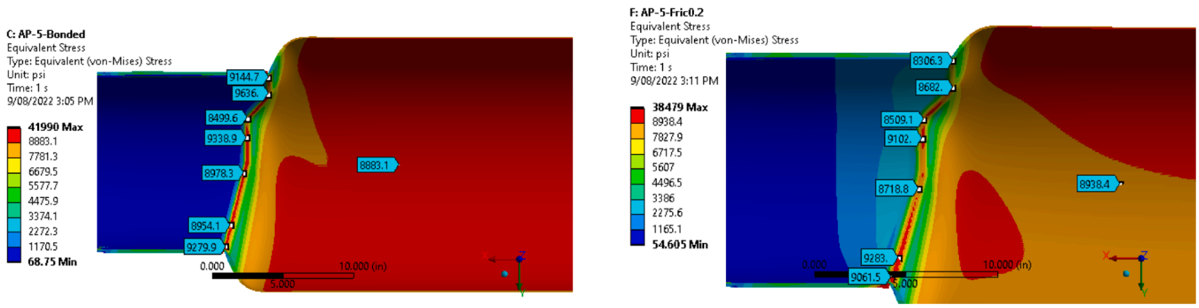


Fig. 28. Stress–strain curve of AP-5 material.

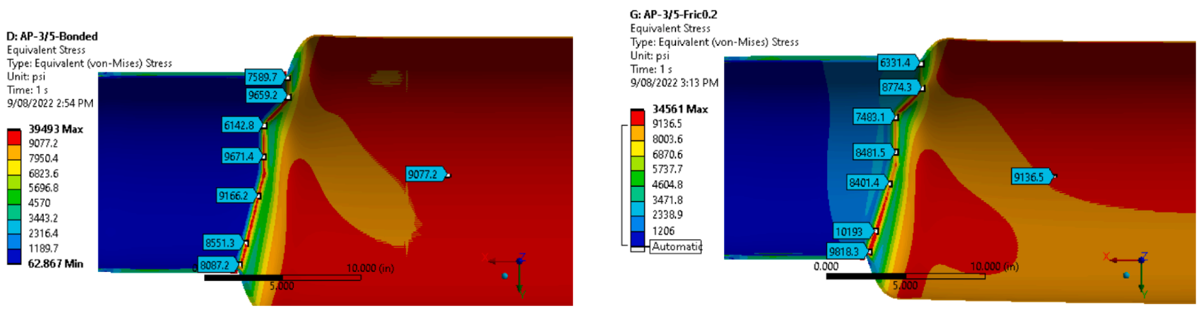
Table 7
Mechanical properties of AP-3/5 material.

Properties	AP-3/5
Elastic modulus in longitudinal direction (GPa) [ksi]	(3.38) [490]
Elastic modulus in circumferential direction (GPa) [ksi]	(5.29) [767]
Elastic modulus in thickness direction (GPa) [ksi]	(5.29) [767]
Shear modulus in longitudinal-circumferential direction (GPa) [ksi]	(1.36) [198]
Shear modulus in circumferential-thickness direction (GPa) [ksi]	(2.13) [309]
Shear modulus in longitudinal-thickness direction (GPa) [ksi]	(2.13) [309]
Poisson's ratio in longitudinal-circumferential direction	0.24
Poisson's ratio in circumferential-thickness direction	0.24
Poisson's ratio in longitudinal-thickness direction	0.24



(a) (b)

Fig. 29. Effect of irregular opening on AP-5 material (a) before (b) after considering roundness and un-bonding.



(a) (b)

Fig. 30. Effect of irregular opening on AP-3/5 material (a) before (b) after considering roundness and un-bonding.

zones, which is suggested to investigate in future studies. Nonetheless, the outcomes of this study contribute new knowledge to the effective design of PIP systems in repairing circumferentially crack legacy pipes under the internal pressure loading.

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.

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