

The Analysis of Pipe Elbows and Tees When Designing Geohazard Resistant Steel Pipe (GRSP) Subjected to Extreme Ground Displacement

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ABSTRACT

Using advanced finite element simulation tools, the paper investigates the structural response of pipe elbows (bends) and outlets (Tees), which are important components of a geohazard resistant steel pipe (GRSP) system. Numerical results are reported for two typical 84-in. diameter steel mitered elbows and two typical 90° pipe outlets. Special emphasis is given on the deformation capacity of the fittings with respect to a well-documented maximum strain criterion. In all cases, the effect of internal pressure on structural behavior and deformation capacity of the fittings is also examined. The paper addresses some important structural features of steel pipe fitting design and provides improved analysis methods of fittings in GRSP systems under extreme loading towards safeguarding the functionality of steel water pipelines subjected to extreme ground displacements.

INTRODUCTION

The research summarized in the present paper is motivated by the need for determining the strength and the deformation capacity of welded steel pipelines for water transmission, constructed in geohazard areas. In such areas, the pipeline should be designed to sustain extreme permanent ground deformations, resulting from fault rupture, liquefaction-induced lateral spreading, soil subsidence, or landslide action. Those extreme ground-induced actions deform the pipeline and its components well beyond the stress limits associated with normal operating conditions (Karamanos *et al.* 2017), potentially causing loss of containment.

Towards safeguarding pipeline structural integrity, the structural performance of lap-welded joints had been identified as a potential issue and has been investigated extensively in previous publications of the authors (Sarvanis *et al.*, 2020; Keil *et al.*, 2022). The present research extends the above research on joint systems and refers to the mechanical performance of pipe fittings (bends and outlets), all of which assures that there will be no loss of containment in Geohazard Resistant Pipe System (GRSP) water transmission pipelines. The paper reports numerical results on typical mitered elbows and Tees, subjected to extreme structural loading in the presence of internal pressure, with the main purpose of determining their deformation limits.

Previous work on the structural performance of steel pipe elbows has mainly focused on “smooth” elbows, fabricated mainly through “induction bending”, widely used in industrial piping applications (e.g., chemical/petrochemical industries or power plants). This extensive

research has demonstrated that smooth elbows exhibit a unique behavior under structural loading, characterized by significant flexibility and stress intensification, constituting “weak spots” of the piping system under extreme loading. Based on this research, rules for the structural design of smooth bends have been developed in ASME B31 standards. For an overview of smooth elbow mechanical behavior, and an extensive literature review on this topic, the reader is referred to the review paper by Karamanos (2016).

Mitered bends have received significantly less attention than smooth bends. In industrial piping, mitered bends are designed and fabricated according to the relevant provisions in ASME B31 standards, which are based on Rodabaugh (1975), but their use is limited to applications with relatively low operating pressure, as alternative to smooth elbows, whenever the use of latter may not be feasible or cost-effective. On the other hand, large-diameter steel water pipelines employ almost exclusively mitered bends, which are manufactured according to AWWA C200, and designed according to AWWA C208 and M11. Figure 1a shows the configuration of typical mitered pipe bends used in water transmission pipelines. Nevertheless, despite their extensive use for water transmission, the mechanical behavior of mitered steel pipe bends has received very little attention in comparison with the one of smooth bends.



Figure 1. (a) Mitered steel pipe bend for large-diameter pipeline; (b) reinforced 90-deg steel pipe outlet (photos by Spyros Karamanos).

Pipe outlets, often referred to as “Tees”, are also widely used in pipeline systems (Figure 1b). Previous research on Tees is rather limited and focuses mainly on “wrought butt welded Tee fittings”, according to ASME B31 and B16.9, which are used in piping systems for industrial applications and power plants. The research was aimed at developing flexibility and stress intensification factors (Wais *et al.*, 1999), as well as in assessing the response of those fittings under extreme loading (Nakamura, 2025). On the other hand, steel pipelines for water transmission use welded Tees (unreinforced or reinforced), designed and constructed according to AWWA C208 and M11. Similar rules also exist in ASME B31 standards. However, the design provisions for welded Tees in both standards refer to pressure loading only, and do not account for extreme structural loading conditions, which is still an open research question.

The present study reports a nonlinear finite element simulation of the structural performance of internally-pressurized large-diameter mitered steel pipe bends and Tees. Results are presented for two typical mitered pipe bends with outside diameter $D_o = 86$ in, one 22.5-deg bend and one 90-deg bend, subjected to closing and opening bending, and for two typical 86-inch-to-43.875-inch outside diameter Tee outlets (one reinforced and one

unreinforced). The deformation capacity of those fittings is of particular importance and is determined using a maximum strain criterion. Special attention is given to local strain developed at critical locations of the fittings, where strain intensification occurs.

ASPECTS OF STRUCTURAL BEHAVIOR OF PIPE FITTINGS

Pipe elbows

The mechanical behavior of pipe elbows is quite unique. The elbow is significantly more flexible than a straight pipe segment of the same cross-section and length. It develops higher stresses and strains, associated with cross-sectional “ovalization”, shown schematically in Figure 2. Because of their flexibility, “smooth elbows” are widely used in “expansion loops” of industrial piping to accommodate expansions/contractions due to temperature and pressure variations and absorb other externally-induced loading. They are critical components for the structural integrity of piping systems because of stress and strain intensification. Their bending response is characterized by a biaxial state of stress and strain (Figure 2) in both and direction (axial σ_x and hoop σ_θ), as opposed to uniaxial stress state in straight pipes.

On the other hand, the structural behavior of mitered bends has received much less attention. Following, the work by Rodabough (1975), a very small number of papers have been published on this topic, which demonstrated that there exist several similarities with smooth elbows, in terms of ovalization and stress intensification. The latter occurs primarily at the corners between adjacent segments, which are expected to accentuate those local phenomena and differentiate substantially the mechanical behavior of the fittings under consideration compared to smooth elbows, in terms of their structural capacity.

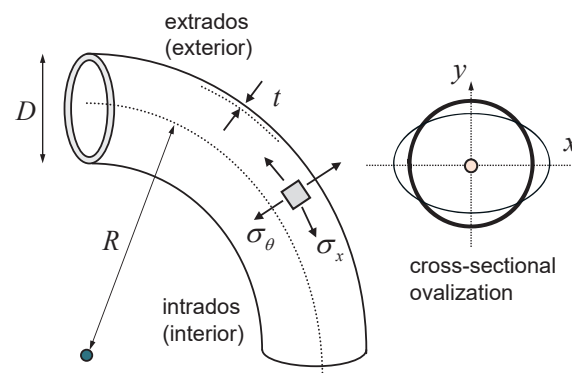


Figure 2. Schematic representation of geometry and ovalization of a pipe elbow.

Pipe outlets

Welded pipe outlets are “joints” between the main pipe and the branch pipe. However, this type of “joint” is far from being a rigid joint; it is characterized by significant local flexibility primarily due to the local deformation of the main pipe at the vicinity of the welded connection. Figure 3 shows schematically the mechanical behavior of a Tee under axial compression, axial tension and bending. In all three cases, the deformation of the main pipe,

associated with pipe wall bending, leads to high stresses at the welded connection and constitutes a key issue for understanding the mechanical behavior of pipe outlets.

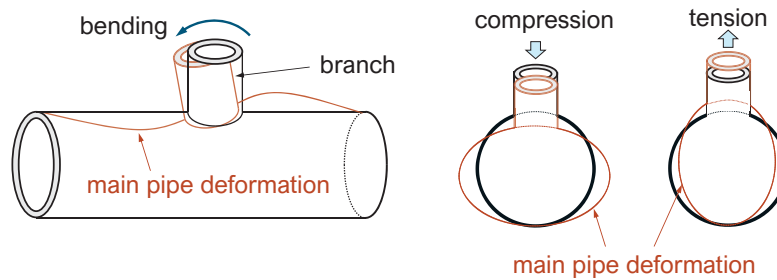


Figure 3. Deformation of a welded pipe outlet; the deformation of the main pipe is a key issue for its mechanical behavior.

DESCRIPTION OF FITTINGS AND MATERIAL CONSIDERATIONS

Two mitered bends with angles 22.5 deg and 90 deg are examined under bending loading. The bends have outside diameter $D_O = 86$ in, wall thickness $t = 0.5$ in ($D/t = 172$) and bend radius $R = 2.5D$. The 90-deg bend has 5 segments, according to AWWA C208. Two $5D$ -long straight pipe segments (430-inch) are attached on either side of the bends. Two welded outlets (unreinforced and reinforced) are analyzed under in-plane bending, axial tension and axial compression loads. Each outlet has mainline outer diameter D_O and wall thickness t_0 equal to 86 in and 0.5 in respectively, whereas the outlet pipe has $D_1 = 43.875$ in and $t_1 = 0.375$ in. The mainline length is $5D_0$, and the outlet was positioned in its center.

The elastic-plastic material curve of Figure 4a is employed to describe steel Grade 42 material, generated with the methodology in Annex-3D of ASME B&PV Code VIII Div.2, using Young's modulus 200 GPa (29,000 ksi), yield strength 297.2 MPa (43.1 ksi) and ultimate strength 437.1 MPa (63.1 ksi). The curve is obtained from tensile tests on specimens extracted from coil used for fabricating similar bends and Tees to those considered herein.

Throughout each numerical analysis conducted in the present study, the strains developing due to the applied loading were monitored and assessed to verify that they do not exceed the critical strain limit at any location of the fitting. According to ASME VIII Div.2, the critical strain at each material point can be expressed as follows:

$$\varepsilon_L = \varepsilon_{Lu} \cdot \exp \left[- \left(\frac{\alpha_{sl}}{1 + m_2} \right) \left\{ \left(\frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e} \right) - \frac{1}{3} \right\} \right] \quad (1)$$

where $\sigma_{1,2,3}$ are the principal stresses and σ_e is the equivalent (Von Mises) stress. The value of strain limit from Eq. (1) refers to local strain at the vicinity of a critical location (e.g., the weld toe), which is calculated with the use of an appropriate finite element model, and represents in a proper manner material behavior under a multi-axial state of stress. This approach is very different from the “2% strain limit” used in estimating the strain capacity of girth welds in straight pipelines, which refers to a global strain measure in the weld area. Using ASME VIII Div.2, for steel Grade 42, one readily calculates $\varepsilon_{Lu} = 0.331$, $m_2 = 0.192$, and $\alpha_{sl} = 2.2$. Figure 4b shows the variation of strain limit ε_L in Eq. (1) with respect to local stress triaxiality, i.e., the ratio of mean principal stresses over the equivalent stress.

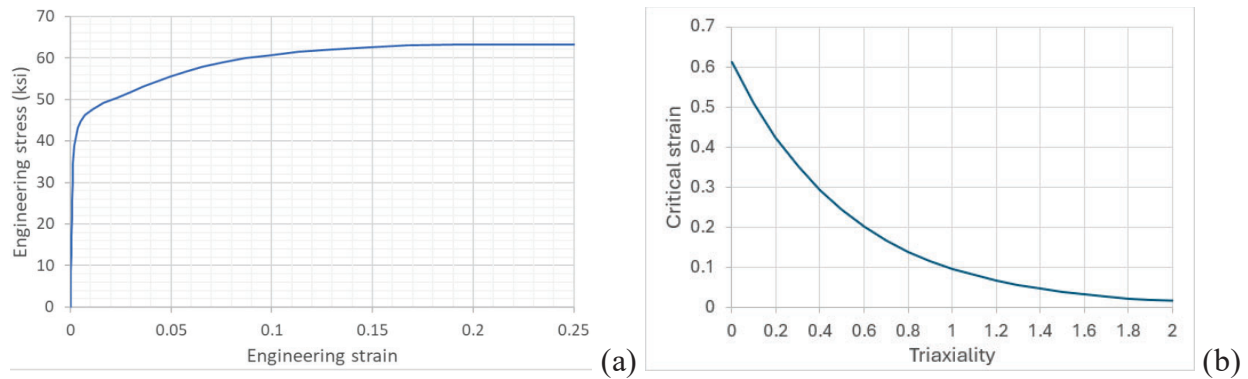


Figure 4. (a) Material stress-strain curve for steel grade 42; (b) critical strain vs. triaxiality

NUMERICAL MODELLING

General-purpose FE software ABAQUS/Standard is employed to model the structural response of the fittings under consideration, accounting for geometrical and material nonlinearities. Due to symmetry, only half of each fitting is modelled, imposing appropriate symmetry conditions. The pipe ends are capped to allow the introduction of end cap forces due to internal pressure. The bends are simulated using three-dimensional 4-node reduced-integration shell elements (S4R) (Figure 5). Around half circumference, 100 elements are used, while an element size of 38 mm (1.5 in) is used in the axial direction, which is sufficient to simulate local buckling formation. The mesh density is slightly coarser away from the critical areas to improve computational efficiency.

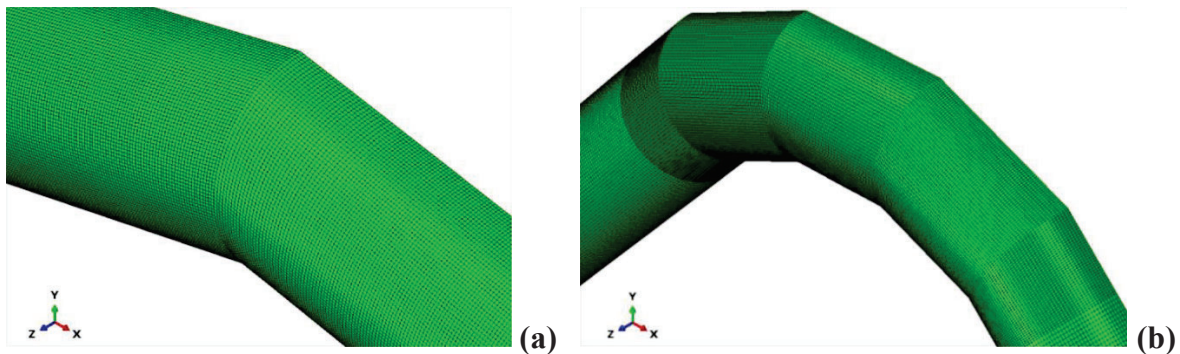


Figure 5. Finite element mesh of mitered bends: (a) 22.5 degrees and (b) 90 degrees.

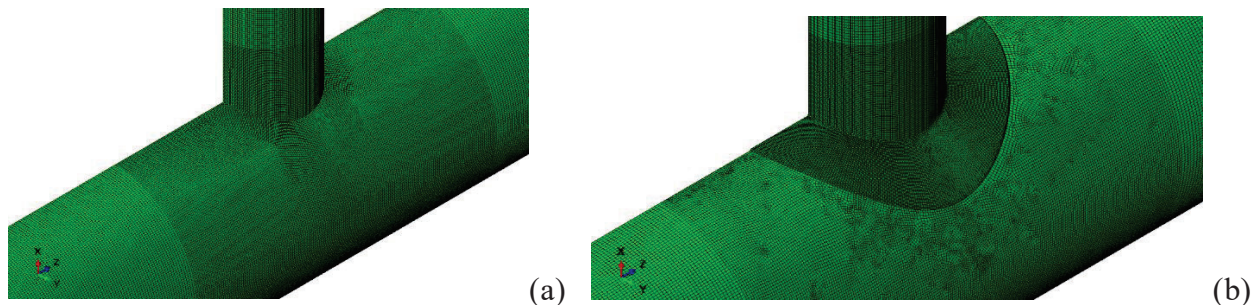


Figure 6. Finite element mesh of (a) unreinforced Tee and (b) reinforced Tee.

Solid 3D reduced integration “brick” elements (C3D8R) are used to simulate the Tees (Figure 6). At critical areas around the welded connection, an element size of 15 mm (0.59 in) was used, while a coarser mesh was used away from the critical areas. Four elements were used in the through-thickness direction in the entire Tee and three elements through the collar thickness.

In the reinforced tee model, a reinforcement collar with outer diameter equal to twice the outlet diameter is assumed, while its thickness is equal to the mainline wall thickness, 0.5 in. The welds connecting the collar to the mainline and the outlet are explicitly modelled. The Tee and the collar are assumed to be connected only at the weld areas, while a frictional contact is introduced between the collar inner surface and the underlying Tee surface, with friction coefficient equal to 0.2.

NUMERICAL RESULTS

Results for pipe bends

The structural response of the pressurized 22.5 degrees miter bend under opening and closing bending is summarized in Figure 7. The bending moment is normalized by the plastic moment of the pipe section ($M_p = \sigma_y D^2 t$). The pressure levels are expressed with respect to the yield pressure ($P_y = 2\sigma_y t/D$). Under opening moments (Figure 7a), the increase of internal pressure affects the initial rotational stiffness and the maximum moment reaction. Upon reaching the maximum moment, all diagrams show a descending trend, attributed to local buckling at the central area of the bend. Under closing bending (Figure 7b). Increasing the level of pressure, both initial stiffness and maximum moment increase, and this is consistent with the corresponding response observed in smooth bends (Karamanos, 2016).

For all cases analyzed, the maximum strain at each load increment is monitored and compared with the critical strain of Eq. (1). When the limit strain was exceeded, a marker is added on the corresponding diagram in Figure 7. Critical strain occurs always beyond the maximum moment for both opening and closing bending; and in certain cases, it occurs beyond the rotation range considered.

The deformed shape of the elbow is also affected by the level of pressure. At no pressure, and for opening bending, the flanks buckle inwards, whereas the buckle occurs at the extrados in the presence of pressure (Figure 8). Under closing bending, the buckle occurs at the elbow intrados, and the shape is slightly affected by the presence of internal pressure (Figure 9).

Similar results are obtained for the 90 deg bend (Figure 10). The miter bend response is highly nonlinear and local buckles develop. The critical strain [Eq. (1)] for some cases is reached well after local buckling has occurred. Again, the increase of pressure increases the initial stiffness and the maximum moment.

The deformed bend configuration, with and without pressure is shown in Figure 11 and Figure 12, for opening and closing bending. Under opening bending reverse ovalization occurs, followed by local buckling at the flanks ($P = 0$) or the extrados ($P = 0.3P_y$). Under closing bending, significant ovalization occurs, and its magnitude decreases with increasing pressure. At zero pressure, significantly plastic deformation concentrates at the bend flanks. If internal pressure is present, the concentration of plastic deformation shifts towards the bend intrados.

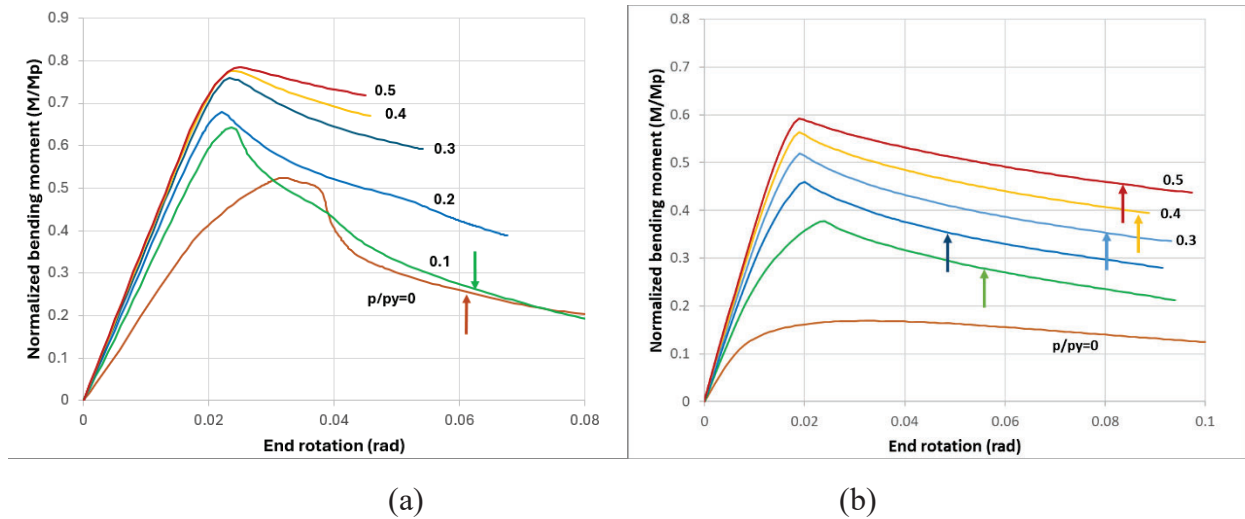


Figure 7. Moment-rotation diagrams for 22.5-deg bend; (a) opening bending; (b) closing bending.

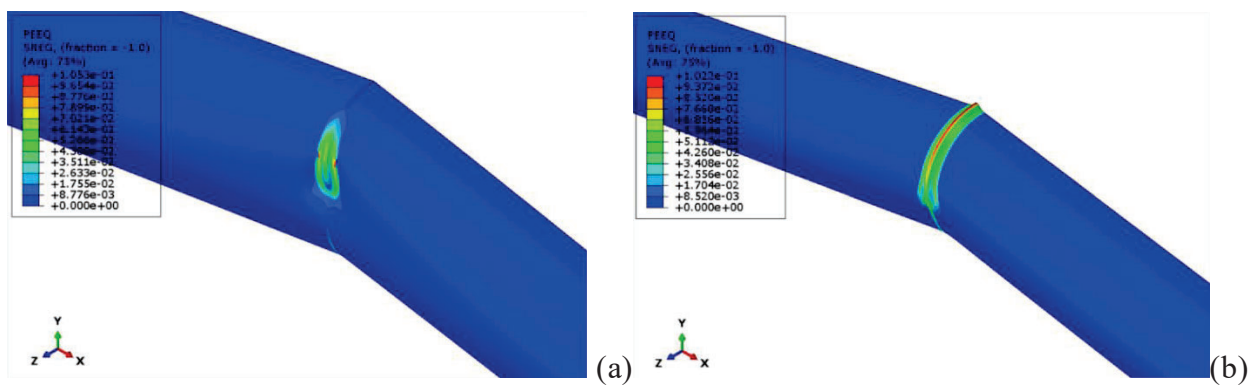


Figure 8. Deformed shape of 22.5-deg bend [opening bending]: (a) $P = 0$; (b) $P = 0.3P_y$.

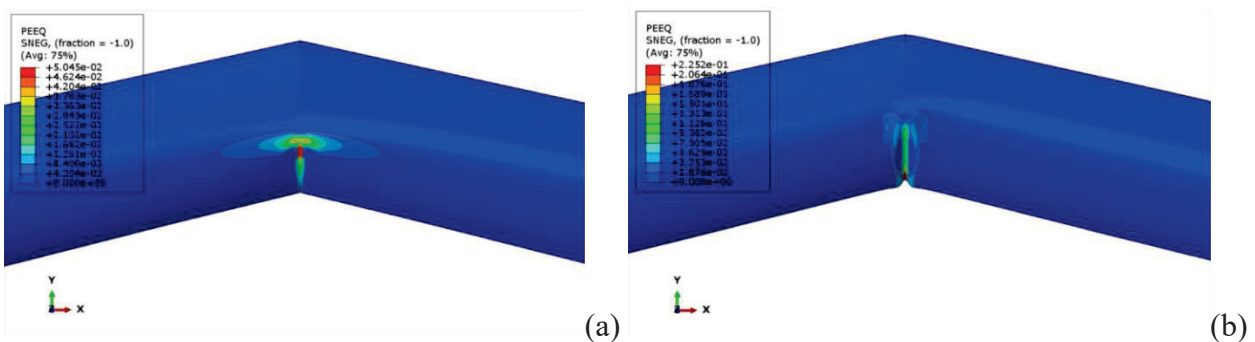


Figure 9. Deformed shape of 22.5-deg bend [closing bending]: (a) $P = 0$; (b) $P = 0.3P_y$.

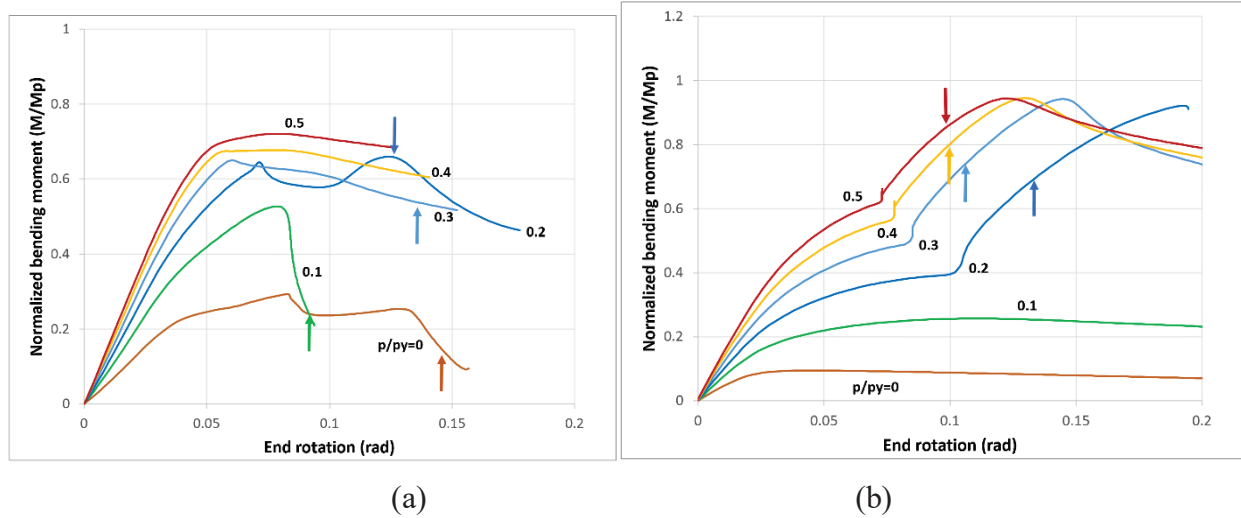


Figure 10. Moment-rotation diagrams for 90-deg bend; (a) opening bending; (b) closing bending.

Results for pipe Tees

The pressurized bending diagrams of the two Tees are shown in Figure 13 and the corresponding deformed shapes are shown in Figure 14. The bending moment is normalized by $M_p = \sigma_y D_1^2 t_1$, where D_1, t_1 are the outlet pipe diameter and wall thickness, and the pressure is expressed with respect to yield pressure P_y of the mainline pipe. The results indicate that increase of pressure higher than $0.1P_y$ results in decrease of initial stiffness, attributed to the substantial amount of plastic deformation developed at the weld area. The point of the diagram where critical strain of Eq. (1) is reached, is also depicted. Finally, reinforced Tees exhibit higher bending resistance and deformation capacity than unreinforced Tees. At higher pressure, critical strains are reached outside the range of bending rotation considered in the analysis.

The response of the two Tees is also investigated under axial tension and compression. The axial force is normalized by the plastic axial force of the outlet pipe ($N_p = \sigma_y \pi D_1 t_1$), and the axial displacements are normalized with the mainline outer diameter D_0 .

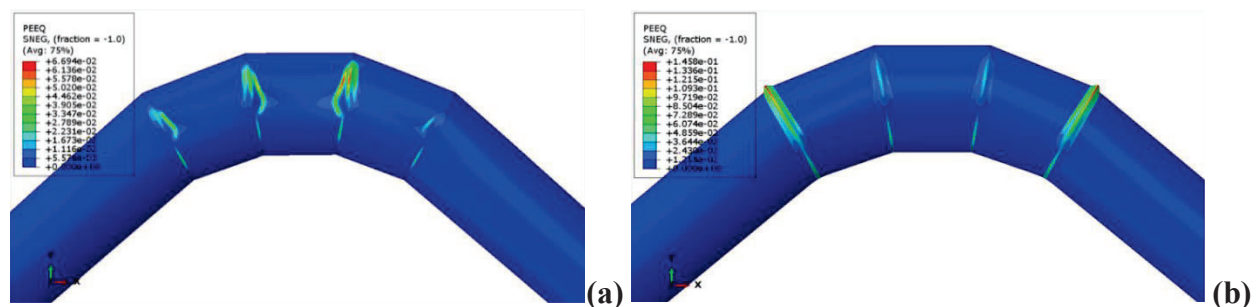


Figure 11. Deformed shape of 90-deg bend [opening bending]: (a) $P = 0$; (b) $P = 0.3P_y$.

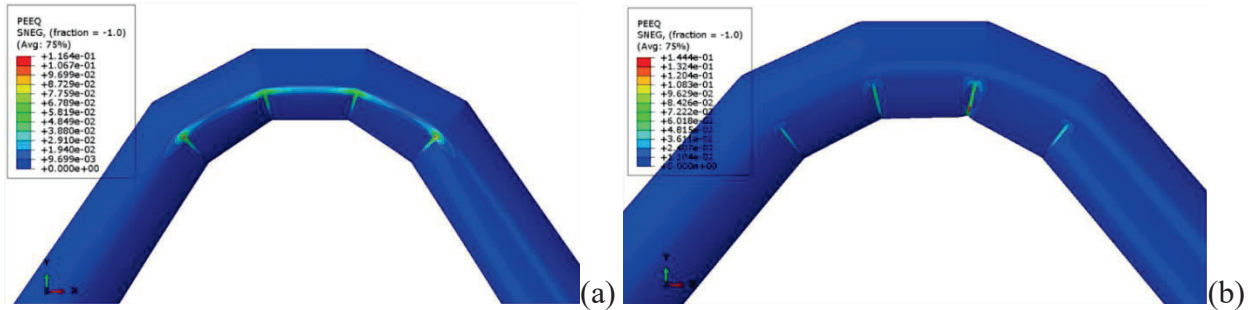


Figure 12. Deformed shape of 90-deg bend [closing bending]: (a) $P = 0$; (b) $P = 0.3P_y$.

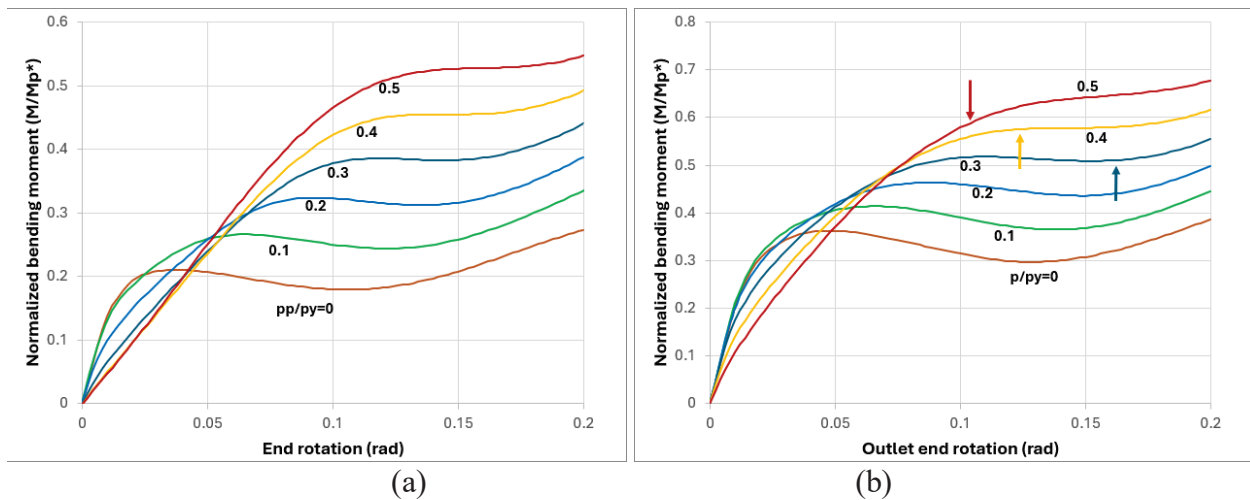


Figure 13. Moment-rotation diagrams for Tees; (a) unreinforced (b) reinforced.

Under axial tension (Figure 15), the critical strain for reinforced Tees is reached at higher load compared to the unreinforced Tees, and the corresponding deformed shapes are shown in Figure 16. Under axial compression, the reinforced Tees exhibit higher load resistance, but the critical strain is reached at smaller displacement compared to unreinforced Tees (Figure 17). The corresponding deformed shapes are shown in Figure 18.

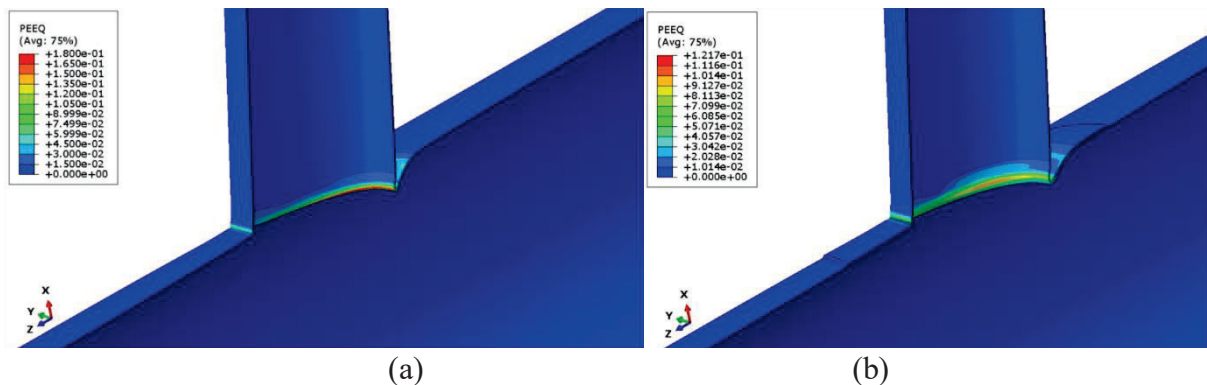


Figure 14. Deformed shape of Tees under bending; (a) unreinforced (b) reinforced.

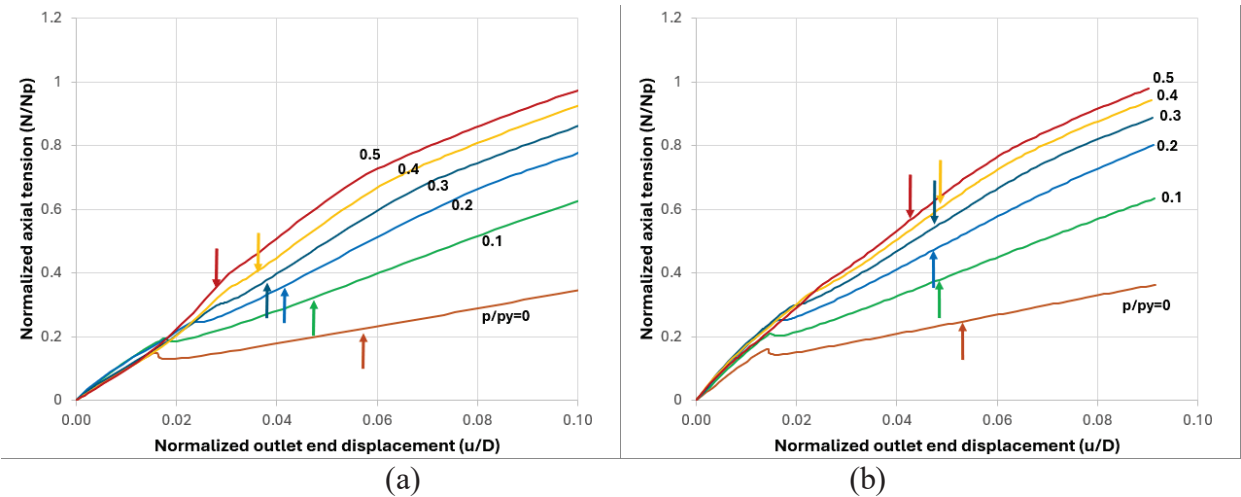


Figure 15. Tension load-displacement diagrams for Tees; (a) unreinforced (b) reinforced.

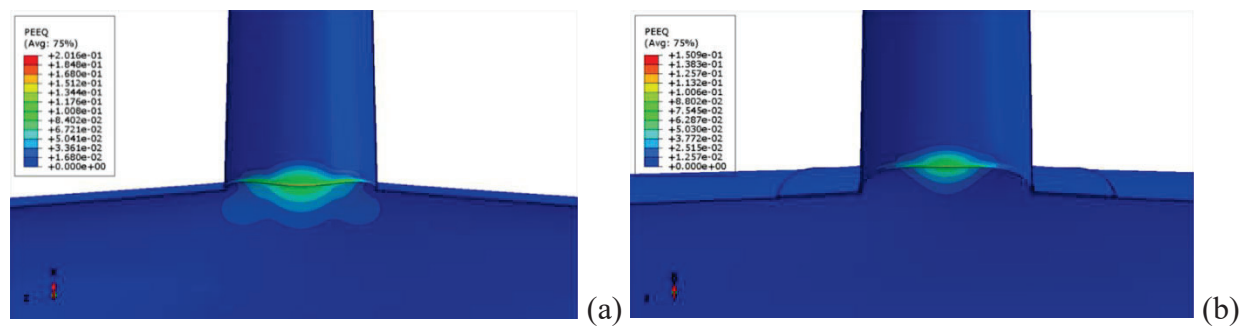


Figure 16. Deformed shape of the Tees under axial tension; (a) unreinforced (b) reinforced.

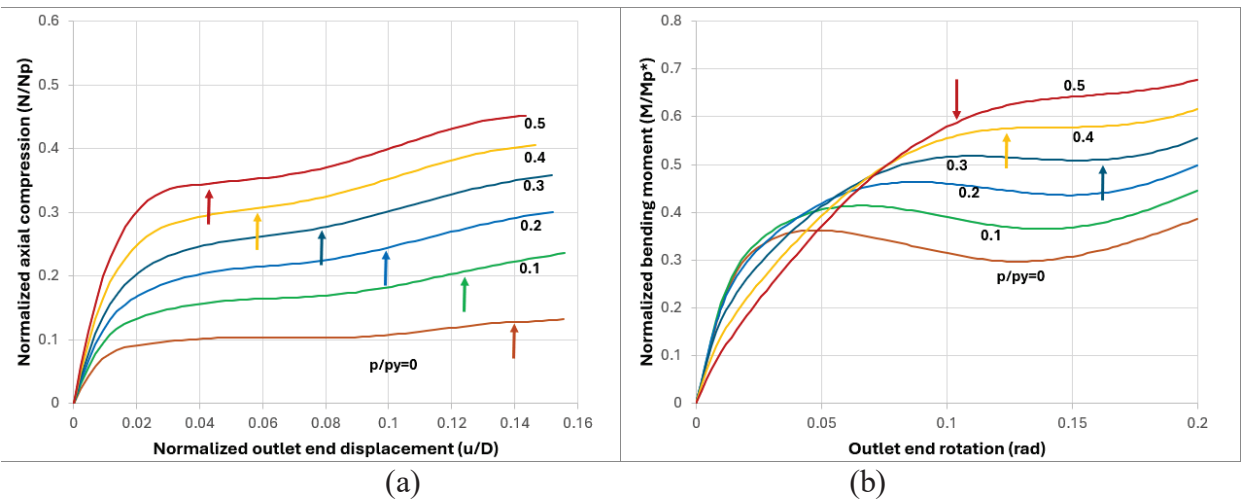


Figure 17. Compression load-displacement diagrams for Tees; (a) unreinforced (b) reinforced.

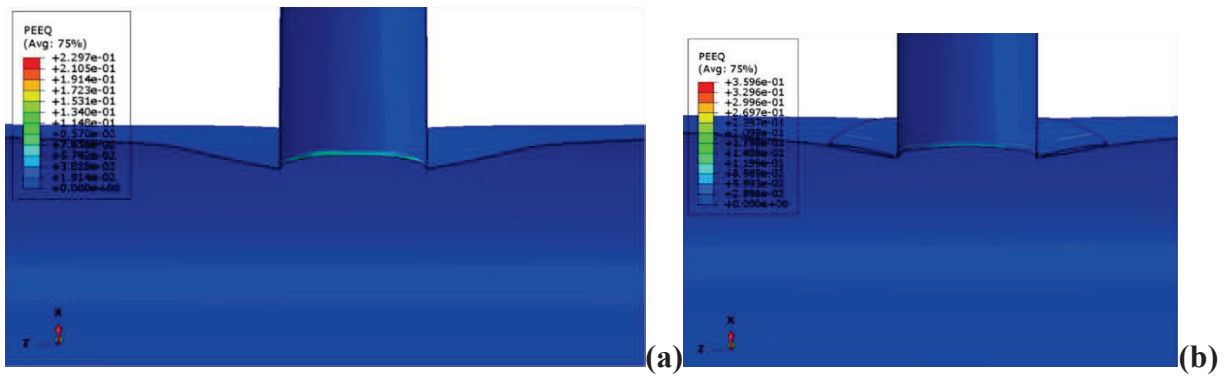


Figure 18. Deformed shape of Tees under axial compression; (a) unreinforced (b) reinforced.

CONCLUSIONS

Motivated by the need for safeguarding the structural integrity of large-diameter steel water pipelines subject to extreme ground displacement, the paper presents numerical results on the mechanical behavior of pipe fittings (elbows and Tees), as part of a Geohazard Resistant Steel Pipe (GRSP) system. The fittings are analyzed with nonlinear finite element tools, capable of describing inelastic response of the steel material as well as possible formation of local buckling in the pipe wall. A simple and efficient criterion for maximum strain is adopted, in order to determine the deformation capacity of each fitting.

First, two mitered pipe elbows (22.5-deg and 90-deg) have been analyzed under opening and closing bending moments. In addition, two pipe outlets have been analyzed, one unreinforced and one reinforced. The main conclusions from the numerical results can be summarized as follows:

Miter bends

- The bending response of miter bends is highly affected by the level of internal pressure, which increases initial stiffness and the maximum bending moment of the bend.
- Upon reaching the maximum moment load, local buckling occurs; the buckled shape depends on the level of internal pressure.
- In all cases, the critical local strain expressed in Eq. (1) is reached well within the plastic range of deformation, and beyond the buckling stage, indicating that miter bends have significant deformation capacity to accommodate large deformations imposed by ground-induced actions.

Pipe outlets

- Under bending conditions, the increase of pressure beyond $0.1P_y$ results in initial stiffness decrease, due to local plastic deformation developed at the welded connection area.
- The increase of pressure consistently increases the maximum moment capacity of unreinforced and reinforced Tees.
- For unreinforced Tees, the critical strains are reached well within the inelastic range for lower pressure levels; at pressure levels higher than $0.4 P_y$, the critical strains are in the elastic range.
- Reinforced Tees exhibit high bending resistance and significant deformation capacity.

- Under axial tension, unreinforced and reinforced Tees exhibit similar load-displacement behavior; the critical strains of reinforced Tees are reached at higher load compared to the unreinforced Tees.
- Under axial compression, the reinforced Tees exhibit higher load resistance; however, the critical strains are reached at smaller displacements compared to the corresponding unreinforced Tees because of inelastic deformation.

As a general conclusion, miter bends and welded Tees (unreinforced and reinforced) used in large-diameter pipeline systems for water transmission, exhibit significant strength and deformation capacity. Through appropriate finite element simulation tools, those fittings can be properly designed as parts of a Geohazard Resistant Steel Pipe system and are capable of accommodating extreme ground-induced actions in geohazard areas with no loss of containment.

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