Effect of the Number of Broken Wire Wraps on the Structural Performance of PCCP with Full Interaction at the Gasket Joint

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Abstract: Broken prestressing wire wraps are the main cause of failure in prestressed concrete cylinder pipes (PCCP). The effect of the number and location of broken wire wraps on the structural performance of PCCP is investigated using advanced numerical modeling that considers full interaction between the spigot and bell ends of adjacent pipes. The stresses and strains in the various components of PCCP are evaluated with increasing internal pressure. A sensitivity analysis is performed to understand how manipulating the severity of the damage through varying the number of broken wire wraps affects the internal fluid pressure that causes failure. A 244 cm (96-inch) embedded cylinder pipe (ECP) is modeled with 5, 35, 70, and 100 broken wire wraps. The results obtained show that the internal fluid pressure required to cause failure can be as much as 14% lower when the damage is at the joint, and that the internal pressure that causes yielding of the wire wraps decreases about 65% as the severity of the damage increases from 5 to 100 broken wires.

CE Database Subject Headings: Concrete Pipes; Pipe Joints; Prestressed concrete cylinder pipes; Numerical Analysis; Earth Pressure; Water Pressure; Finite Element Method.

Introduction

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Prestressed Concrete Cylinder Pipe (PCCP) was first manufactured in 1942 as Lined Cylinder Pipe (LCP). Another type of PCCP, known as Embedded Cylinder Pipe (ECP), was developed in 1952 and had concrete encasement of the steel cylinder on both sides and prestressing wire wrapped around the outer concrete core. The design and manufacturing standards of PCCP in the United States were gradually developed beginning in 1943, with the first tentative consensus standard for PCCP being approved by the American Water Works Association (AWWA) in 1949. The AWWA C301 *Standard Specifications for Reinforced Concrete Water Pipe - Steel Cylinder Type, Prestressed* (AWWA C301-52) was revised multiple times, with the latest revision being released in 2007 (AWWA C304-2007).

PCCP consists of a concrete core, a steel cylinder, high tensile prestressing wires, and an outer mortar coating layer. The concrete core is the structural load-bearing component with the steel cylinder acting as a water barrier between inner and outer core concrete layers. The prestressing wire is an important component of the PCCP that produces a uniform circumferential compressive stress in the concrete core that offsets tensile stresses in the pipe. The mortar coating protects the prestressing wires from physical damage and external corrosion. Rupture of presstressing wires around the concrete core can be the result of damage due to unnoticed installation damage, post-installation excavation damage, corrosion, hydrogen embrittlement, overloading, or manufacturing defects. As a result of this loss of circumferential compressive stress around the pipe, tensile stresses will develop that can lead to cracking of the concrete core and cause leakage or damage in the pipe.

While ultrasonic tomography methods—such as the one described by Abi Shdid and Hajali (2014)—and direct inspection by robotic equipment can detect damage, they can be prohibitively expensive. Other available, and similarly expensive to use, methods are: zoom camera,

electroscanning, digital scanning, laser profiling, and sonar (Selvakumar et al. 2013). Some researchers have attempted to solve this by proposing quantitative methods to judge if a concrete pipe displays corrosion, cracks, or breakage. He and Koizumi (2012) proposed such quantification method that is based on various pipe factors, including pipe diameter, number of years since installation, type of road and foundation, overburden, and pipe slope. However, such quantification methods can only predict the likely extent of damage to an existing sewage pipe system, and fall short of an accurate modeling of the damage based on internal and external loads. Thus, numerical modeling remains to be the most efficient method available to analyze and assess the structural condition of PCCP.

Background

The knowledge surrounding the behavior of PCCP under combined internal and external loading has been gradually amassed since the mid-1950s, and the various investigations into PCCP failures have led to the evolution of the design standards to follow PCCP failures. Despite the significant improvements in the design and manufacturing of PCCP, the inclusive understanding of the structural behavior and performance of damaged PCCP is still under investigation. Xiong et al. (2010) used a nonlinear FEM to study the correlation between the degree of prestressing stresses during manufacturing of PCCP and their associated resultant stresses in the concrete core and prestressing wires. The study also compared the resultant stress obtained with another FEM model that replaces the effects of tensile stresses in prestressing wires with an equivalent radial pressure around the pipe. The results obtained from the equivalent radial pressure model were within a 10% deviation of the proposed model (Xiong et al. 2010).

Rauniyar (2013) performed full-scale experimental tests as well as numerical modeling of ECP under three-edge bearing conditions. The study utilized three-dimensional nonlinear finite element analysis for the numerical modeling, and used composite material with complex stress phenomenon due to prestress and interaction between the various component layers of the ECP. The model accounted for the contribution of each component, the manufacturing process, and the simultaneous effects of shrinkage, creep and relaxation (Rauniyar 2013). More advanced models have been used in recent studies to investigate the behavior of PCCP using an extended form of the finite element method (XFEM). Alavinasab et al. (2011a) used XFEM to study crack initiation, growth, and life prediction analysis of damage in Prestressed Concrete Noncylinder Pipe (NCP). Nonlinear FEM has been used not only in static analysis of PCCP, but also in the dynamic response of PCCP. Alavinasab et al. (2010, 2011b) used FEM to evaluate the natural frequencies and mode shapes for Structural Health Monitoring (SHM) of PCCP.

Najafi et al. (2011) proposed an appropriately designed rolled groove joint that could be incorporated into AWWA C303 bar-wrapped concrete pressure pipe. The study used three-dimensional nonlinear numerical finite element modeling, analysis and design optimization to arrive at a viable joint with an optimal stab depth and appropriate rodwrap termination design in both the bell and spigot to provide sufficient stiffness. Experimental results from full-scale testing of rolled groove joint incorporated into a bar-wrapped concrete pressure pipe manufactured to AWWA standard C303 specifications were presented that showed that pipes with such joints can sustain transient internal pressures in excess of 2 MPa without displaying any signs of joint leakage or pipe deformation (Najafi et al. 2011).

Wilson (2011) presented a general analysis using a mathematical model for the failure of a buried steel pipeline under simultaneous hoop tension and transverse loading. The developed

model is based on classical energy and beam theories. The model was validated using a case study where such tensile and transverse loads on a buried pipe were developed from pipe undermining due to an adjacent excavation collapse (Wilson 2011). Coghill (2013) presented an example decision-making tool used by the Asset Management Program team at the San Diego County Water Authority used to ensure the continued safe and reliable water supply to its customers. The study examined the factors that require consideration when rehabilitating PCCP (Coghill 2013).

The structural performance of damaged PCCP is not only dependent on the number of broken prestressing wire wraps, but also on the location of the break regions along the length of the pipe. Alavinasab et al. (2013) studied the effect of the location of broken wire wraps on the strength of PCCP using advanced computational modeling. The study compared three different locations for the defect: at the spigot joint, at the bell joint, and in the barrel of the pipe. The study did not however consider the interaction between the bell end and spigot end of the pipe. The results found that the strength reduction for a low to medium number of wire wrap breaks at a joint was about 20%, and the study concluded that cracking in the pipe will occur at lower pressure when the defects occurred at the joint rather than in the middle of the pipe. Alavinasab and Hajali (2014) studied the effects of broken wire wraps at the joint in the safe operation of an adjacent pipe.

Nasser and Saleh (2008) developed a PCCP wire breaks prediction model using Artificial Neural Networks trained on real-world acoustic monitoring data. The developed model takes as input: the monitoring period, pipe age, soil resistivity, design pressure, design soil density, design soil cover, type of pre-stressing wire wrap, wire diameter, and wire pitch; and predicts the number of wire breaks as an output (Nasser and Saleh 2008). Another approach was developed

by Kleiner et. al.(2004) to model the deterioration of buried PCCP using a fuzzy rule-based, non-homogeneous Markov process. The model yielded possibility of failure at every point along the life of the pipe. However, adequate and sufficient data to validate the model were not provided (Kleiner et. al. 2004).

Problem Statement and Main Contribution

PCCP Joints

The rigid construction of PCCP makes the joint an important component of the pipe system. The function of a pipeline generally determines the performance requirements of the joints. In addition to making installation easier, joints are designed so that when sections are laid together they will make a continuous line of pipe with an interior free from irregularities. Joints are normally designed to provide soil-tightness, water-tightness, the ability to accommodate lateral and longitudinal movement, and the strength to handle shear that causes vertical movement.

Joints in PCCP consist of a spigot ring, a bell ring, a rubber gasket, and grout on the exterior of the joint between the two pipes. Spigot and bell rings are welded to each end of the steel cylinder. Joints are designed to allow a pipe to deflect during installation and operation while maintaining a watertight seal. Rubber gaskets are used between the steel rings to facilitate both flexibility and the sealing of the joint. When joined, the bell and spigot ends compress the rubber gasket into a groove to form a high pressure seal as shown in Figure 1. Such a joint provides high shear strength, excellent water tightness, and flexibility. A layer of mortar or cement paste is placed on the inner side of the bell ring and on the external side of the spigot end

of the pipe. The exterior of the joints are subsequently grouted to protect the steel joint rings from deterioration.

Figure 1. Schematic of the joint in PCCP

Theoretical and Practical Motivation

Once over tensioned, concrete begins to crack and its load carrying capacity decreases with additional strain. At high tensile strains, the load carrying capacity of the concrete core becomes negligible, and the loads are transferred through other components of the PCCP. This load transformation differs at the joints due to the interaction between the pipe's spigot ring, rubber gasket, and bell ring. The interaction between adjacent pipes thus affects the performance of PCCP.

The effects of the location of broken prestressing wire wraps on the performance of damaged PCCP has not been thoroughly investigated, and the few studies available in the literature have not considered the effect of the interaction at the joints between adjacent pipes when investigating the relationship between the location of broken wire wraps and the failure pressure of PCCP. Broken wire wraps in PCCP can occur near the joint or in the barrel (middle) of the pipe, as shown in Figure 2. The objective of this study is to investigate how the location of wire wrap breaks affects the strength of the PCCP while considering full interaction between the bell and spigot ends of the adjacent pipes. Such understanding is critical to owners and inspectors in evaluating both the short- and long-term performance of a pipeline system.

Approach

Evaluating the structural performance of a damaged PCCP at a joint is a complex nonlinear problem due to the interaction between not only the broken prestressing wire wraps and the end of the pipe, but also because of the relative displacement and rotation between adjacent pipes. A 244 cm (96-inch) ECP was considered and modeled for this purpose, and the stresses and strains developed in the prestressing wire wraps, concrete core, and steel cylinder were compared for the cases of wire breaks at the joint and in the middle of the pipe. The structural performance of the PCCP was evaluated using four (4) different measurements: micro cracking, visible cracking, yielding of wire wraps, and rupture stress of wire wraps.

Figure 2. Broken wire wraps at different locations in PCCP

Finite Element Modeling

A numerical model of a 244 cm (96-inch) diameter Class 125-14 ECP with a length of 6.1 m (20 feet) is constructed using three-dimensional nonlinear finite elements with consideration given to the manufacturing process in order to incorporate the creep and shrinkage effects of the concrete. The ECP section is modeled using a composite element with five (5) layers representing the inner concrete core, the steel cylinder, the outer concrete core, the prestressing wire, and the mortar coating. Care is taken when modeling the prestressing wire wraps and the joint rings to ensure that a realistic behavior of the ECP was achieved. The model predicts the performance of a PCCP, utilizing the tensile strengths of the prestressing wire, the steel cylinder, and the concrete core, as well as a plasticity algorithm that simulates concrete crushing in compression regions. The model assumes perfect interface between the prestressing wires and the concrete. A four-node quadratic shell element, in which each node has six degrees of

freedom, is used in modeling the undamaged and damaged portions of the pipe. An eight-node linear brick element, in which each node has three translational degrees of freedom, is used for modeling the joint ends of the pipe. The finite element model of the bell end of the pipe is shown in Figure 3.

Figure 3. Spigot and bell ends of the PCCP numerical model

The ECP section was modeled based on the tensile strength of concrete and a plasticity algorithm that facilitated concrete crushing in compression regions. The concrete was modeled using a three-dimensional composite axi-symmetric element with additional adjustments made to predict the failure of brittle materials. Cracking and crushing were determined by a failure surface, which formed the boundary between the undamaged zone and failure (damaged) zone. Once the failure surface was reached, cracking or crushing occurred. The nonlinear plastic-damage behavior of concrete, Lubliner et al. (1989) and Lee and Fenves (1998), is defined by the multi-linear stress-strain relationships governed by scalar damaged elasticity as shown in Equations 1 and 2 (Hajali and Abi Shdid (2013)).

$$\sigma = D^{el}:(\varepsilon - \varepsilon^{pl}) \quad (1)$$

$$D^{el} = (1-d)D_0^{el} \quad (2)$$

where D_0^{el} is the initial (undamaged) elastic stiffness of the material, D^{el} is the degraded elastic stiffness, and d is the scalar stiffness degradation variable, which can take values from zero (undamaged material) to one (fully damaged material). Damage associated with the failure

196 mechanisms of the concrete (cracking and crushing) therefore results in a reduction in the elastic
197 stiffness.

198 $$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{pl} \quad (3)$$

199 where $\dot{\varepsilon}$ is the total strain rate, $\dot{\varepsilon}^{el}$ is the elastic component of the strain rate, and $\dot{\varepsilon}^{pl}$ is the
200 plastic component of the strain rate.

201 The average wall thicknesses of the inner and outer concrete core are 4.93 cm (1.94 inches)
202 and 11.43 cm (4.5 inches), respectively. The average thicknesses of the steel cylinder and mortar
203 coating are 0.15 cm (0.0598 inches) and 2.30 cm (0.904 inches), respectively. The center-to-
204 center spacing of prestressing wire wraps is set to be 1.10 cm (0.434 inches). The lengths of the
205 bell and spigot ends are considered to be 14 cm (5.5 inches) and 19.05 cm (7.25 inches),
206 respectively. The average wall thicknesses for the bell ring and spigot ring are 0.635 cm (0.25
207 inches) and 0.95 cm (0.375 inches), respectively. By virtue of symmetry, only half of each pipe
208 section is modeled with fixed displacement boundary condition in longitudinal direction
209 considered at the intact pipe side, thus allowing the damaged pipe to move in longitudinal
210 direction. In order to have a realistic behavior for the gasket joint, interface elements are used at
211 the joint to allow small movement to occur. An efficient approach developed by Mayer (2005) is
212 used to model the contact interfaces of joints with segment-to-segment contact elements like thin
213 layer or zero thickness elements used between spigot and bell ends.

214 The model was subjected to loads corresponding to internal fluid pressure, pipe and fluid
215 weights, and external earth loads as per the pipe dimensions and internal pressure and backfill
216 ratings defined by (AWWA C304-2007). The number of broken wire wraps was varied as shown
217 in Figure 4 in order to evaluate the cracking of the concrete core and the yielding of the

prestressing wires with increasing internal fluid pressure and number of broken wire wraps. The lengths of damaged ECP sections corresponding to the various numbers of wire breaks considered for the joint and the barrel are shown in Table 1. Three (3) different broken wire wrap scenarios were modeled: starting from the spigot end and continuing along the pipe length, starting from the bell end and continuing along the pipe length, and in the barrel of the pipe.

Figure 4. PCCP model with 5, 35, 70, and 100 broken wire wraps

Table 1. Damaged Pipe Length Corresponding to Number of Wire Breaks (WB)

Material Properties

The material properties used in the PCCP model are obtained from the current AWWA C304 - 2007. The concrete core is modeled with a 28-day compressive strength of 31 MPa (4,500 psi). The Young's Modulus, density, and Poisson's Ratio used in the various components of the PCCP model are shown in Table 2. The modulus of elasticity of the core concrete is calculated from Equation 4 and modulus of elasticity of the mortar coating evaluated using Equation 5. The stress-strain behavior of the concrete core and mortar coating are modeled based on the AWWA C304 - 2007.

$$E_c = (0.074)\gamma_c^{1.51}\left(f_c^{'}\right)^{0.3} \quad (4)$$

$$E_c = (0.074)\gamma_m^{1.51}\left(f_m^{'}\right)^{0.3} \quad (5)$$

where γ_c is the concrete density, taken as 2,323 kg/m^3 (145 lb/ft^3); f'_c is the 28-day compressive strength of concrete, taken as 31 MPa (4,500 psi); γ_m is the mortar coating density, considered as

2,242 kg/m^3 (140 lb/ft^3); and f'_m is the 28-day compressive strength of mortar coating, taken as 37.9 MPa (5,500 psi).

Table 2. Material Properties of PCCP Based on AWWA C304 Standard

The gross wrapping stress, f_{sg}, which is the stress in the prestressing wire during wrapping, is considered as 75 percent of the specified minimum tensile strength of the wire, as shown in Equation 6. The yield strength of wire, f_{sy}, is taken as 85 percent of the specified tensile strength of the prestressing wire, as shown in Equation 7.

$$f_{sg} = (0.75) f_{su} \tag{6}$$

$$f_{sy} = (0.85) f_{su} \tag{7}$$

The prestressing wire used is a 6-gage, Class III wire, with an ultimate strength, f_u, of 1,737.5 MPa (252 ksi). The Modulus of Elasticity of the wire, E_s, after wrapping at f_{sg}, for stress levels below f_{sg} is taken as 193,050 MPa (28,000 ksi). The stress-strain relationship for the prestressing wire, after wrapping at f_{sg}, is given in Equation 8.

$$f_s = \varepsilon_s E_s \qquad \text{for} \quad \varepsilon_s \le f_{sg} / E_s$$

$$f_s = f_{su}\left(1 - \left[1 - 0.6133(\varepsilon_s E_s / f_{su})\right]^{2.25}\right) \qquad \text{for} \quad \varepsilon_s > f_{sg} / E_s \tag{8}$$

Where ε_s is strain in prestressing wire.

The yield strength of the steel cylinder in tension is taken as 227 MPa (33,000 psi), and the strength of the steel cylinder at failure is taken as 310 MPa (45,000 psi). Density and Poisson's Ratio of the prestressing wire and steel cylinder used in the model are shown in Table 2. The

compressive strength of the mortar coating, based on AWWA C304 standard, was 37.9 MPa (5,500 psi) (AWWA C304-2007).

Results and Discussion

The effects of the location and number of broken wire wraps in a damaged PCCP with full interaction at the gasket joint are evaluated by examining the stresses and strains developed in various components of the pipe. Two main pipe failure indicators are considered: the onset of micro and visible cracking in the concrete core and yielding and rupturing of the prestressed wire wraps.

Cracking of Concrete Core

Cracks are the first sign of deterioration in PCCP; micro cracks appear in the concrete at a hoop strain of 2.0E-4, while visible cracks appear at a hoop strain of 1.46E-2. Once concrete in tension begins to crack, its load carrying ability begins to decrease with additional strain. The strain developed in the inside concrete core of the damaged ECP at the barrel of the pipe was compared to the strain developed at the spigot and bell ends. Figure 12 shows an example contour plot of the hoop strain in the concrete core of a PCCP with 70 wire breaks at the spigot end when the internal fluid pressure reaches 862 kPa (125 psi). The results show that, under the same level of damage, the hoop strain inside the concrete core at the invert of a Class 125-14 PCCP reaches the limits of micro cracking and visible cracking at much lower internal fluid pressures when the damage occurs at the spigot end, compared with pipes having wire breaks at the barrel and bell end of the pipe.

Figure 5. Hoop strain in concrete core of PCCP with 70 WB at spigot end with 862 kPa (125 psi) internal pressure

Yield and Ultimate Strength of Prestressing Wires

As additional internal fluid pressure loads are applied on a damaged PCCP with broken prestressed wire wraps from corrosion or other causes listed earlier, the stress level in these wires increases beyond the yield limit, and eventually the ultimate strength limit, thus leading to additional wire breaks. This second failure indicator is investigated by monitoring the stresses in prestressing wires in order to determine the internal fluid pressures which will cause them to reach their yield and ultimate strength limits. The impact of growing number of broken prestressing wire wraps on these stresses is also analyzed, and the results summarized in Table 3. Figures 6 and 7 show the stress in the prestressing wires for PCCP with five (5) and thirty five (35) broken wire wraps, respectively. Figures 8 and 9 show the stress in the prestressing wires for PCCP with seventy (70) and hundred (100) broken wire wraps, respectively. Figures 6 through 9 compare the stresses in the prestressing wires when the damage occurs at various locations of the PCCP: spigot end, bell end, and barrel.

Table 3. Internal Pressure Required to Yield or Rupture the Prestressing Wire Wraps

Figure 6. Stress in prestressing wires with five (5) broken wire wraps

Figure 7. Stress in prestressing wires with thirty-five (35) broken wire wraps

Figure 8. Stress in prestressing wires with seventy (70) broken wire wraps

Figure 9. Stress in prestressing wires with one hundred (100) broken wire wraps

It is clear from Figures 6 through 9 that when considering gasket-jointed ECP with full joint interaction, the stress in the prestressing wire wraps reaches their yield limit at lower internal fluid pressures when the wire breaks are at the spigot or bell end than when wire breaks are at the barrel of the pipe. Figure 6 shows that for 5 wire breaks, yielding of the prestressing wires occur at an internal fluid pressure of 1,979 kPa (287 psi) when the defect is at the barrel of the pipe, compared to only 1,807 kPa (262 psi) when the defect is at the spigot end. In effect, the internal fluid pressure that will result in yielding of the prestressed wires is 9% lower when the defect is near the spigot end than when the defect is in the middle of the pipe. When considering the complete rupture of the prestressing wires, this same difference becomes as much as 12.5%.

Figure 7 shows that the prestressing wire wraps of a PCCP with 35 wire breaks reach their yield stress limit state at an internal fluid pressure that is 14.7% lower when the defect is at the spigot end than when it is in the barrel of the pipe. This difference in internal pressure continues to diverge until it reaches 16.3% at the ultimate (rupture) stress. The same can be said about PCCP with 70 and 100 wire breaks where the yield-inducing internal pressures are 11% and 10% lower at the spigot end, respectively, and the rupture-causing internal pressures are 11% and 13% lower at the spigot end, as shown in Figures 8 and 9.

It can also be seen from the numbers of Table 3 and plots of Figures 6 through 9 that these internal pressures that cause yielding and the eventual rupture of the wire wraps drop as the number of respective wire breaks increase from 5 to 100. Figures 10 through 12 therefore, compare—for each location of defect—how the internal pressure that causes failure of the prestressing wires varies with the length of the defect, which corresponds to a different number of broken wire wraps. When the wire breaks occur at the barrel of a PCCP, the prestressing wire wraps reach their yield stress limit at internal fluid pressures of 1979 kPa (287 psi), 1310 kPa

(190 psi), 931 kPa (135 psi), and 731 kPa (106 psi) for 5, 35, 70, and 100 wire breaks, respectively. Similarly, the onset of rupture for the prestressing wire wraps occurs at internal fluid pressures of 1806 kPa (262 psi), 1117 kPa (162 psi), 827 kPa (120 psi), and 655 kPa (95 psi) for 5, 35, 70, and 100 wire breaks, respectively. These translate to a 63.5% drop in the internal fluid pressure required to both yield or rupture the prestressing wires, as the defect worsens from 5 to 100 wire breaks at the barrel of a PCCP. Similar numbers are obtained for when the wire breaks occur at the bell end and the spigot end of the PCCP, as shown in Figures 11 and 12, respectively.

Figure 10. Stress in the prestressing wire –broken wire wraps in the barrel of the pipe

Figure 11. Stress in the prestressing wire –broken wire wraps at bell end

Figure 12. Stress in the prestressing wire –broken wire wraps at spigot end

Conclusions and Recommendations

In this paper, the effect of broken wire wraps on the structural performance of a damaged PCCP was investigated using a three-dimensional numerical response model that accounted for full interaction between the spigot and bell ends of adjacent pipes. A sensitivity analysis was presented to give a better understanding of how the location and number of broken prestressing wire wraps affect the failure pressure of the pipe. Three different locations of defects were considered: spigot joint, bell joint, and barrel; as well as four different numbers of broken wire wraps that varied from 5 to 100. The failure of the pipe was investigated by examining two indicators: yielding of prestressed wire wraps in the vicinity of the damage and cracking of the concrete core.

The results showed that wire wrap breaks at the joints— specifically the spigot joint— decrease the overall pressure capacity of PCCP more so than wire breaks located at the barrel of the pipe. The results indicate over 16% strength reduction for a low to medium number of wire wrap breaks occurring at the spigot joint when compared to the barrel. In addition, the results showed that if wire wrap breaks occur at the joint, it is anticipated that cracking in the pipe will occur at much lower internal pressures than if the breaks occurred in the barrel of the pipe. These internal pressure limits can also drop by as much as 65% with increased number of wire breaks. It is therefore argued that the location and the number of broken prestressing wire wraps have a significant effect on the structural performance of PCCP.

The results presented are significant for owners, operators, and inspectors of PCCP pipeline systems alike. The conclusions arrived at will help these stakeholders better access the risk of certain pipe defects for the purpose of more efficient and on-time replacement of these facilities. While several issues regarding the structural performance of damaged PCCP with gasket joints were discussed in this paper, there are many open questions and issues that need to be researched. Future research into the structural performance and monitoring of PCCP should include full-scale experimental models of PCCP as well as modeling PCCP with harnessed joints.

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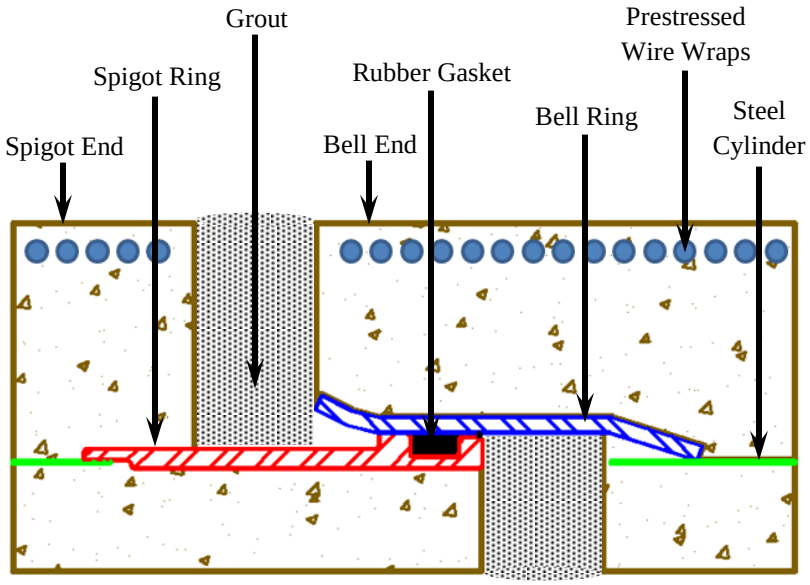

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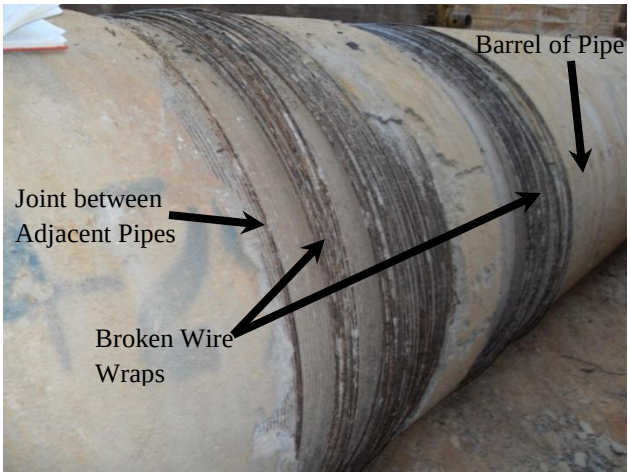

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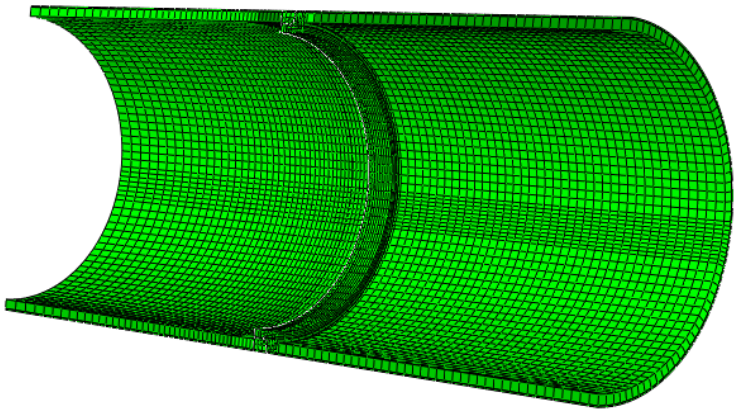

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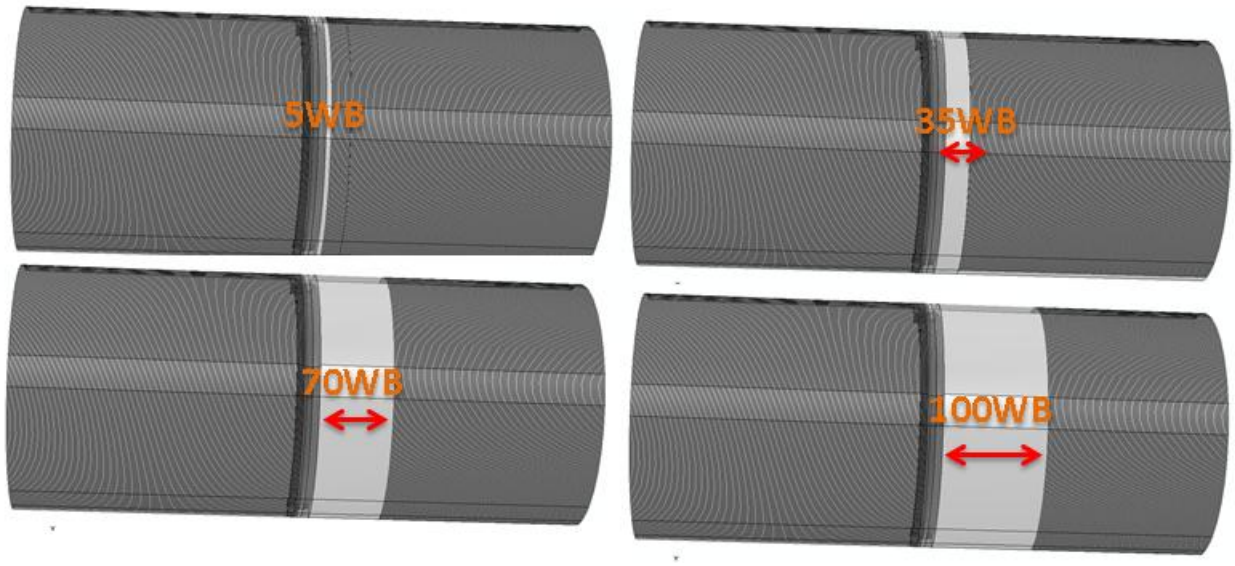

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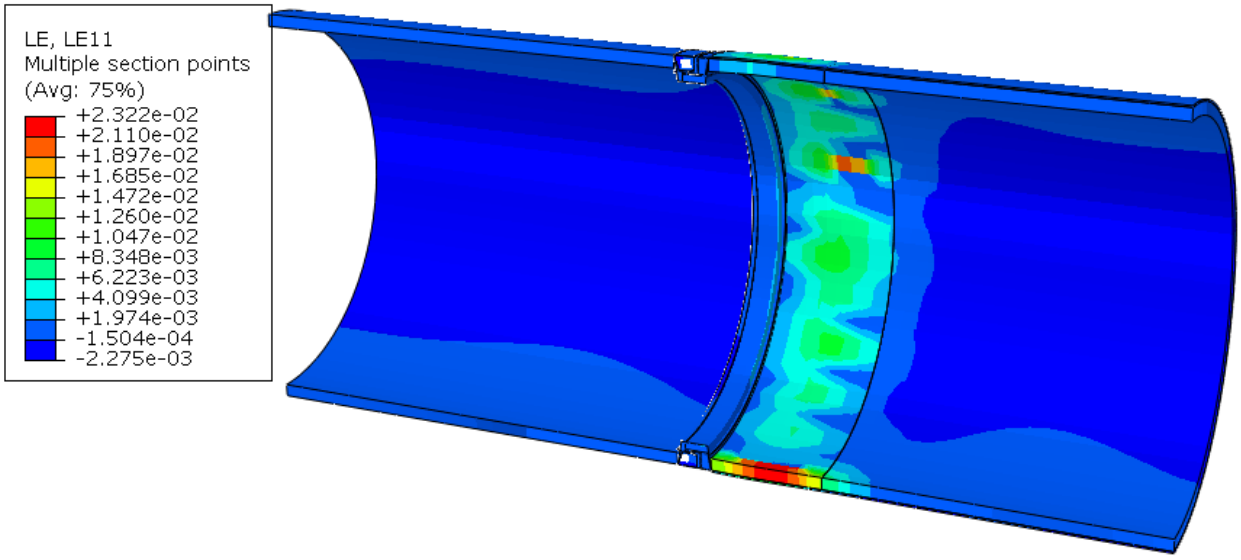

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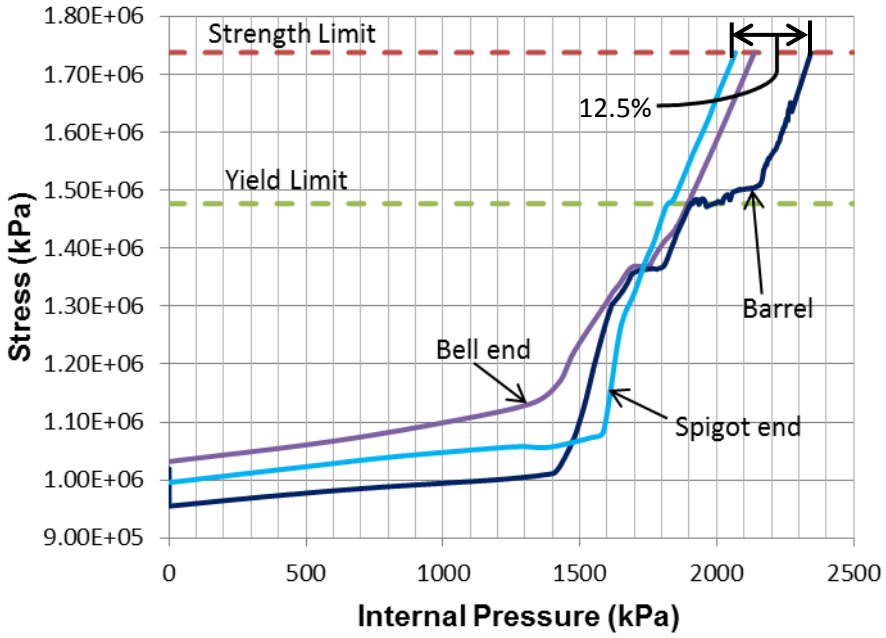

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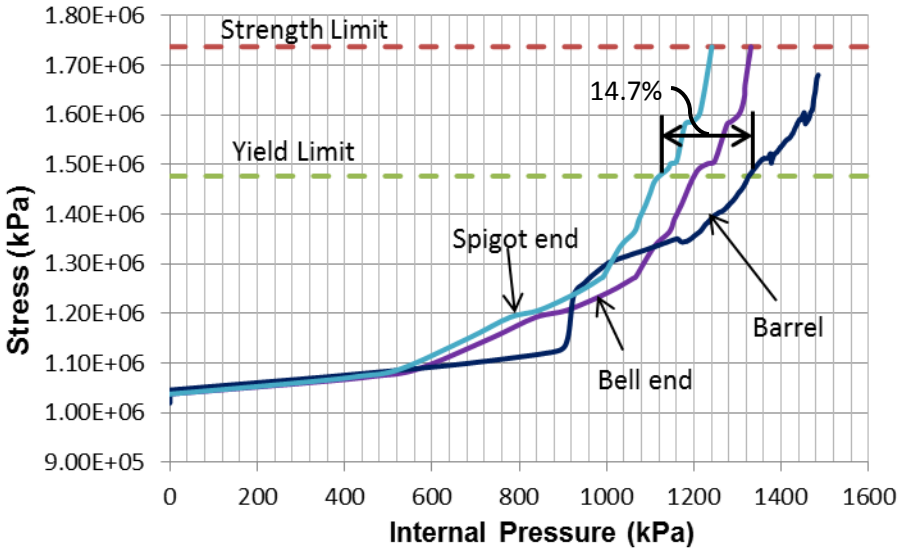

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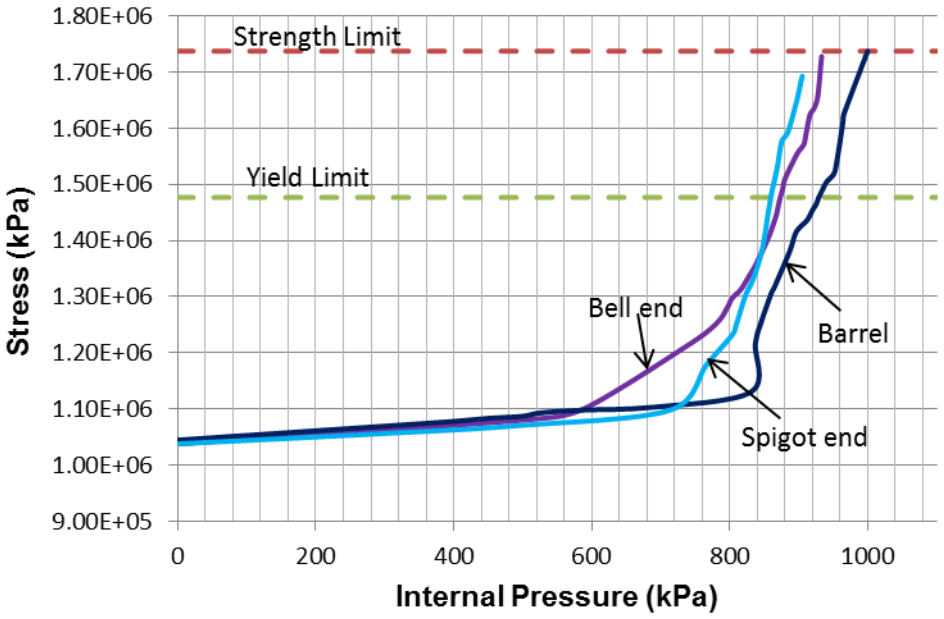

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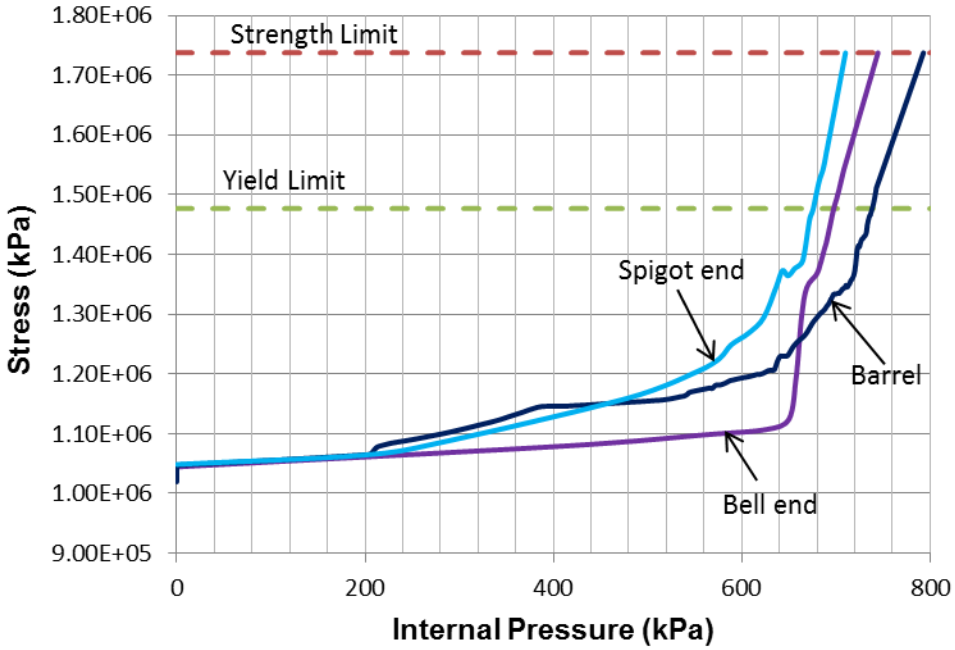

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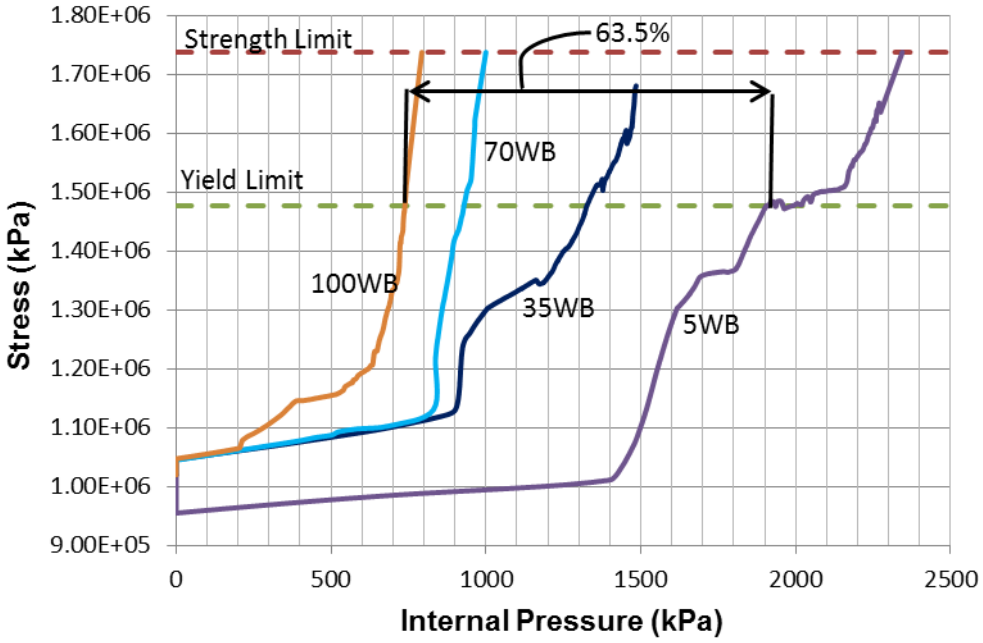

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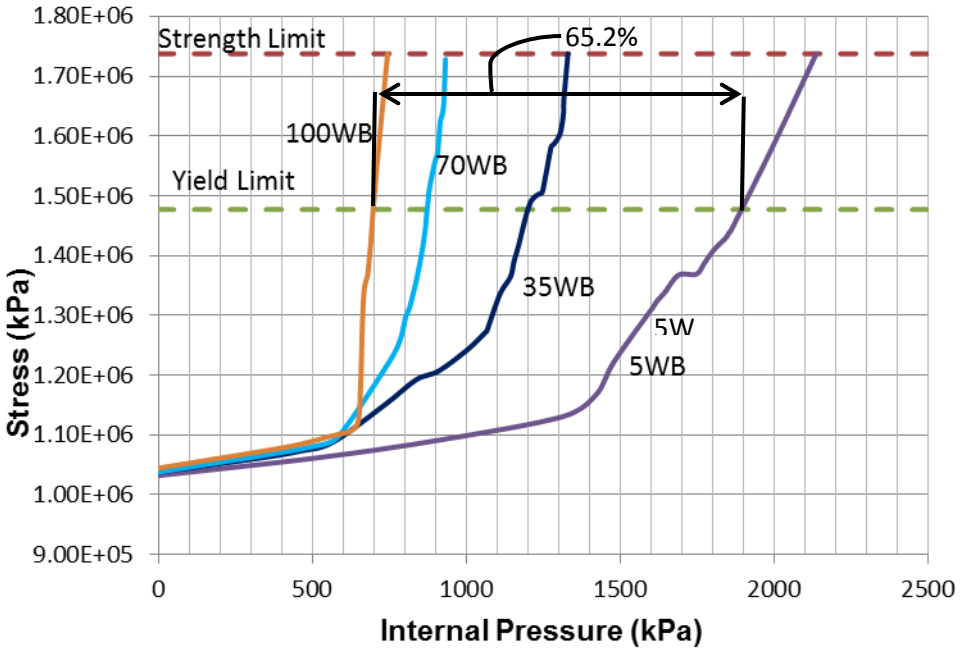

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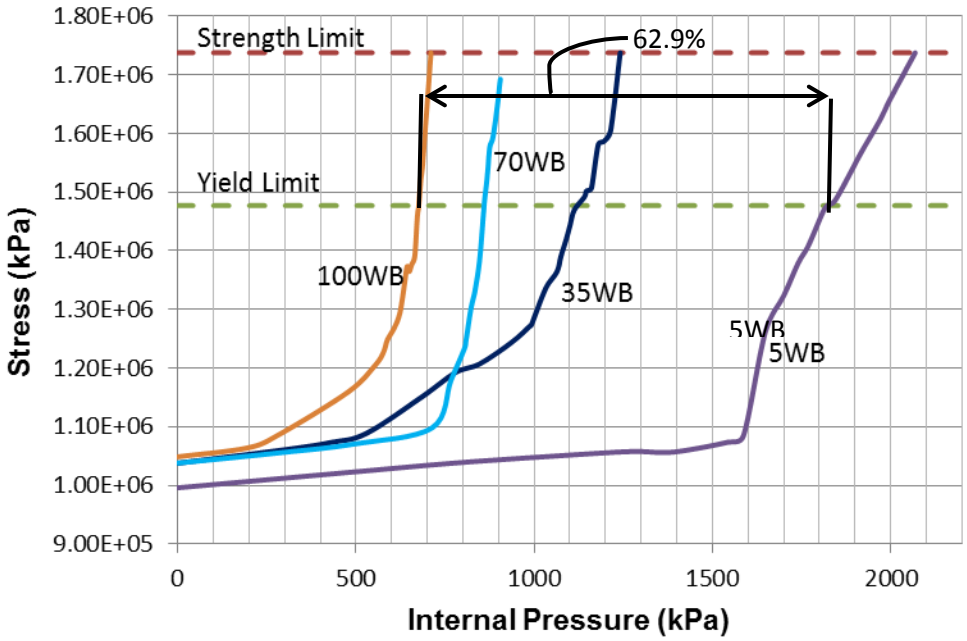

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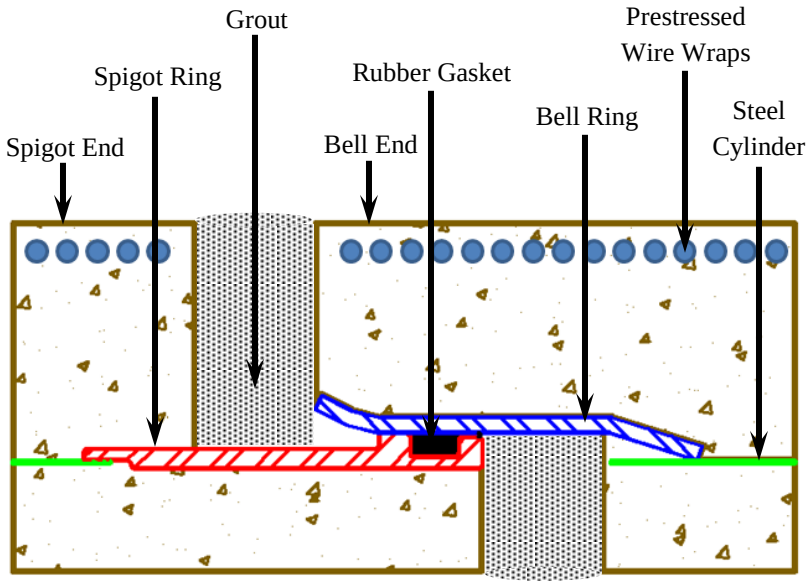

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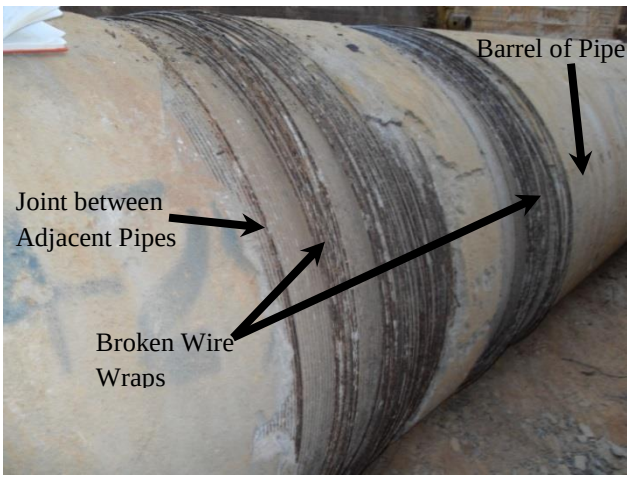

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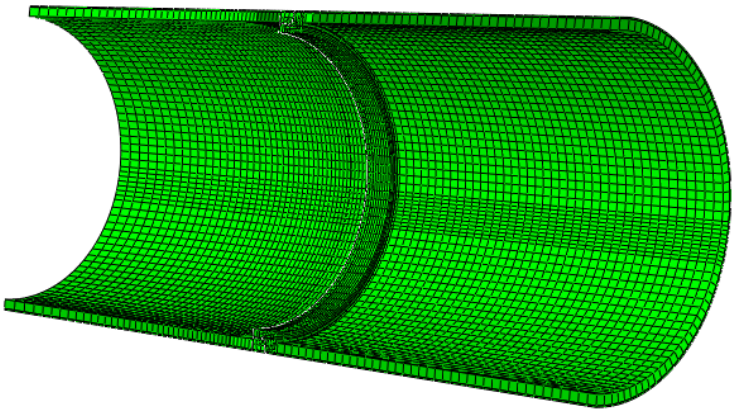

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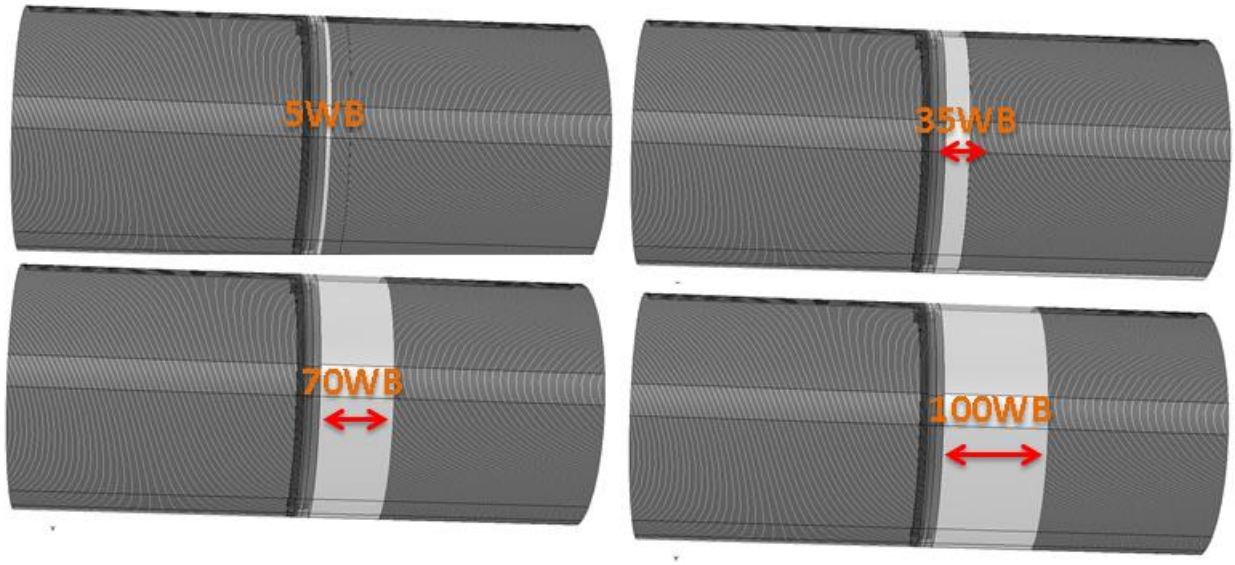

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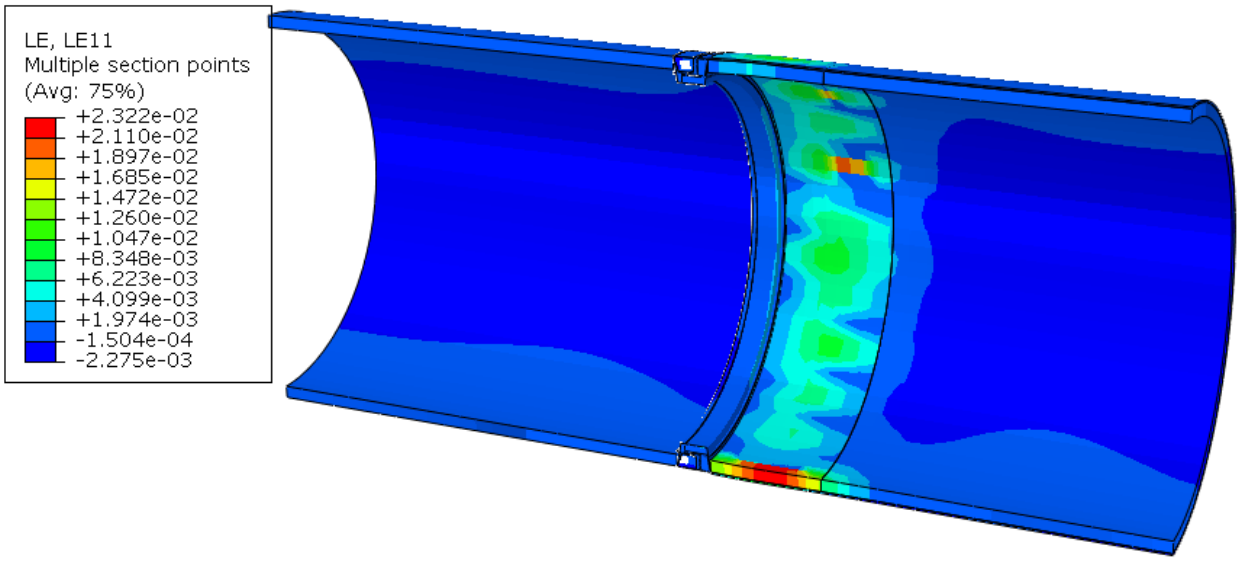

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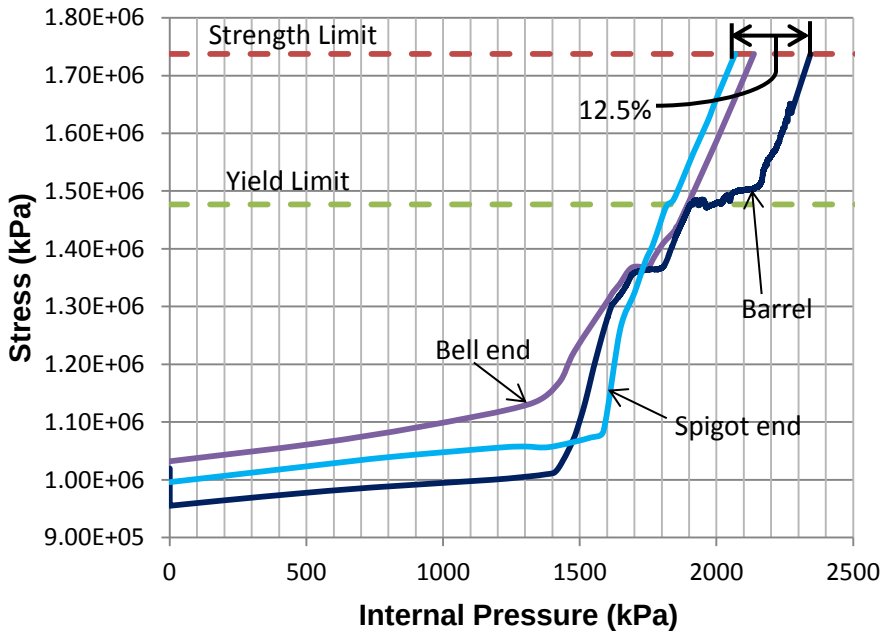

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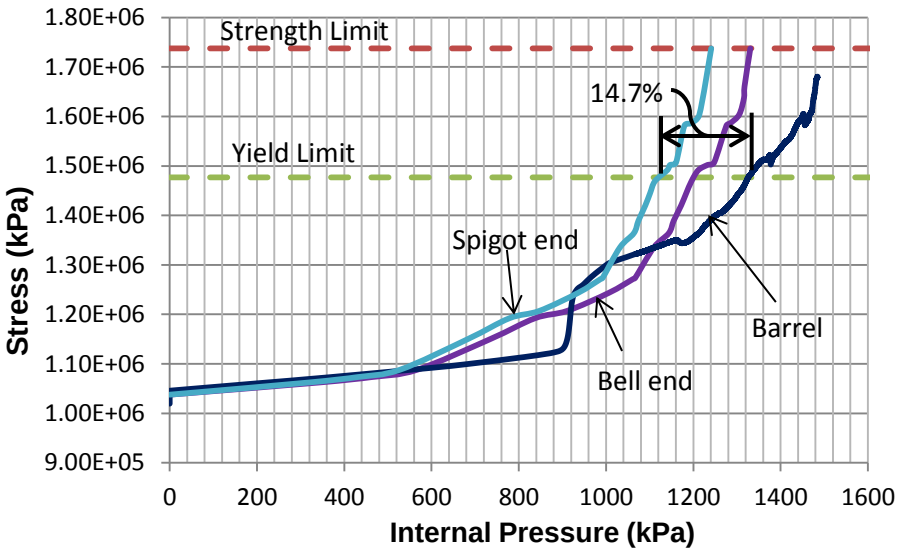

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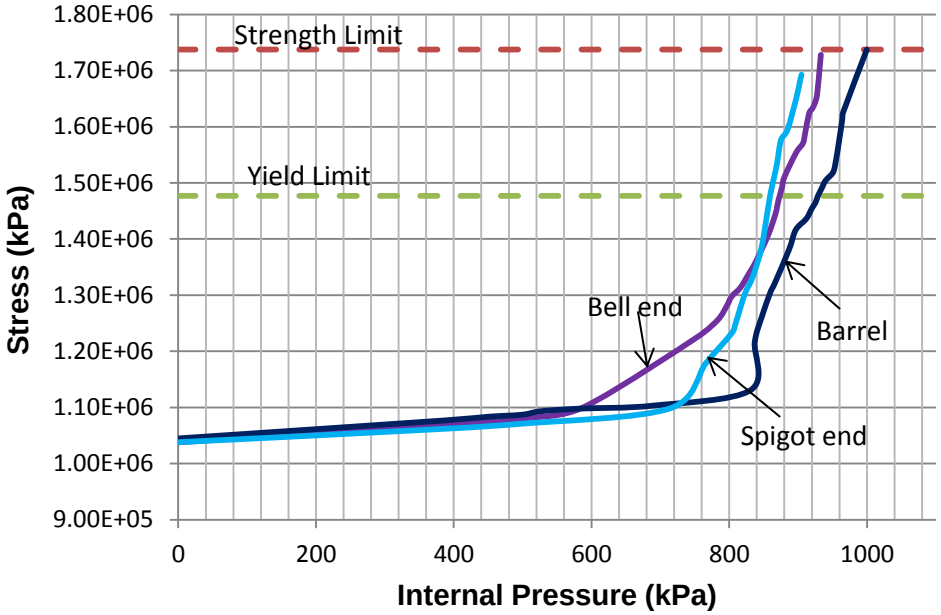

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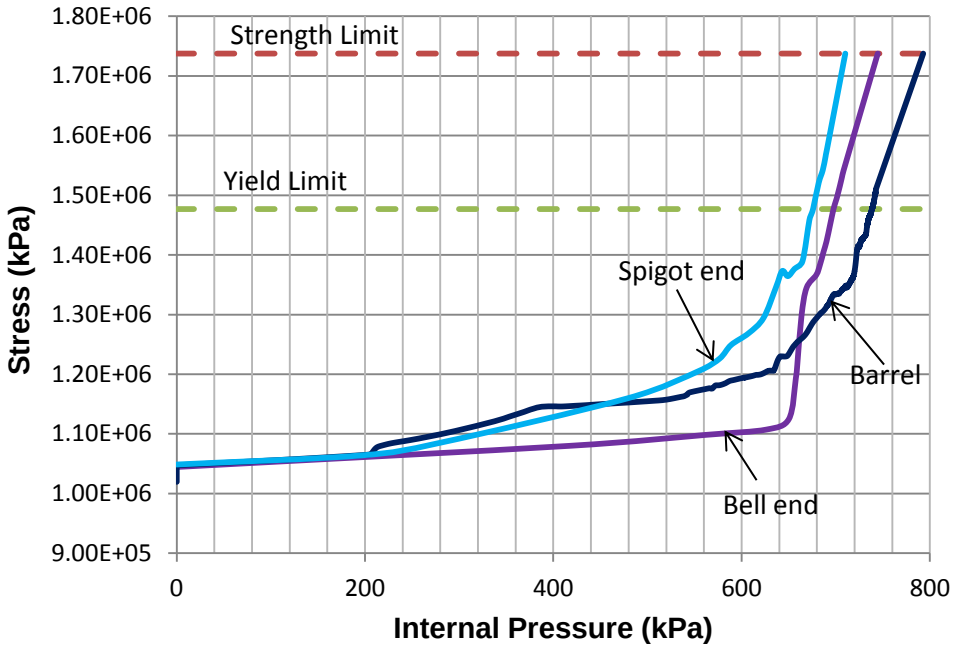

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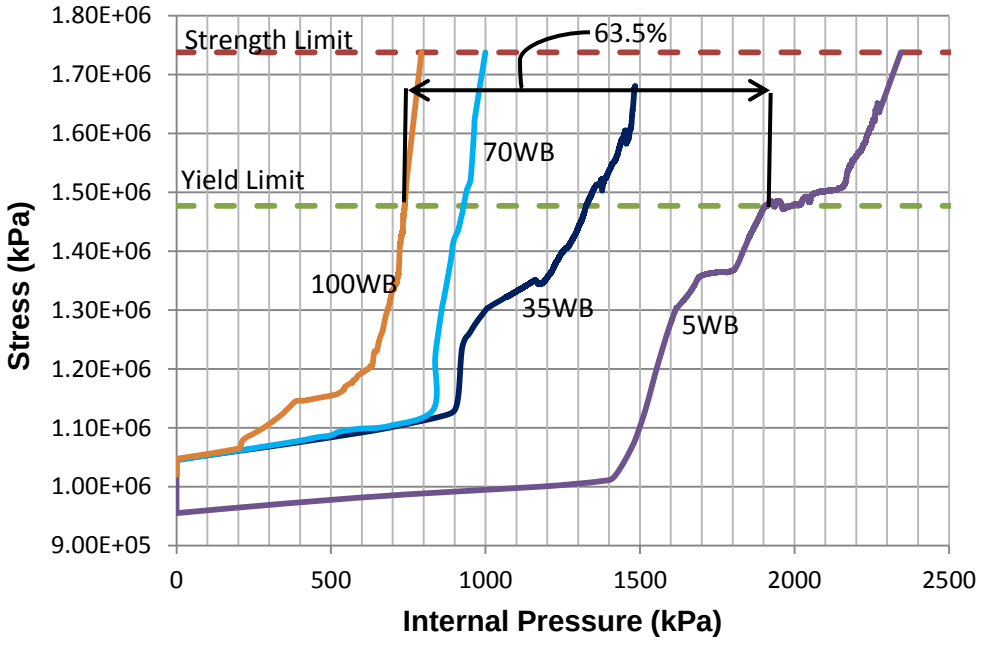

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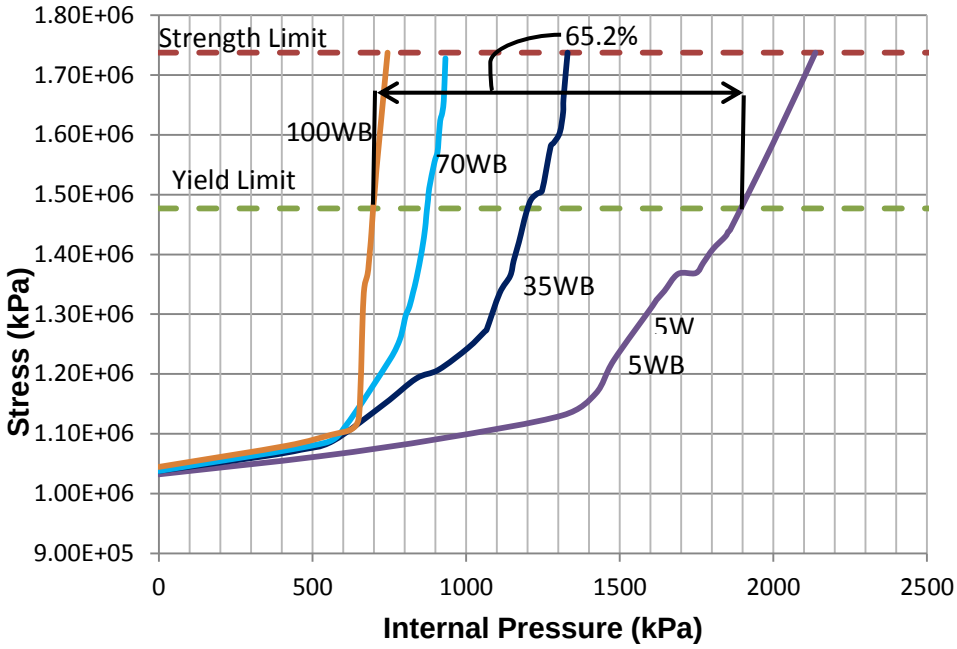

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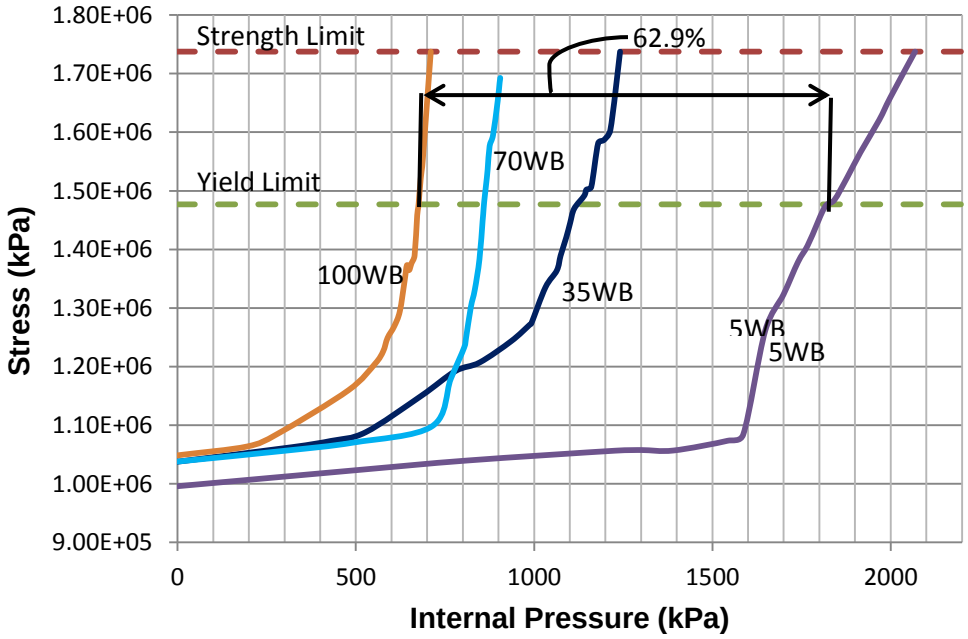

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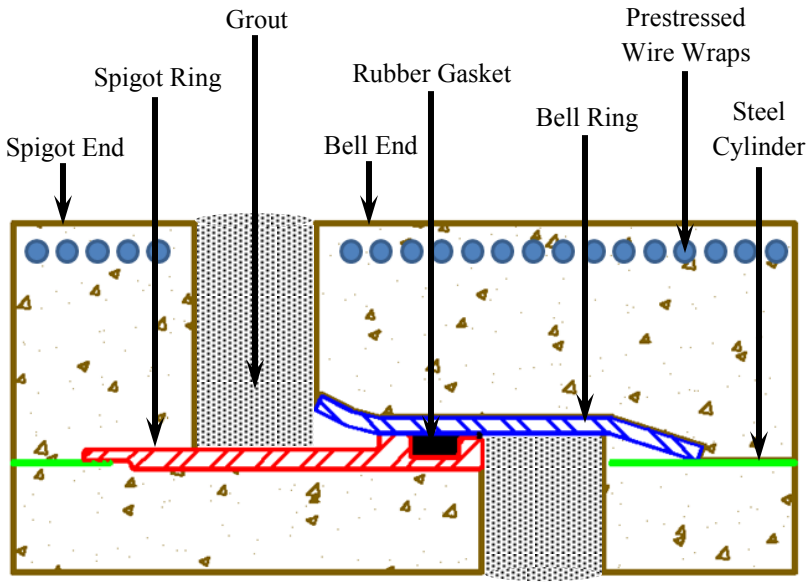

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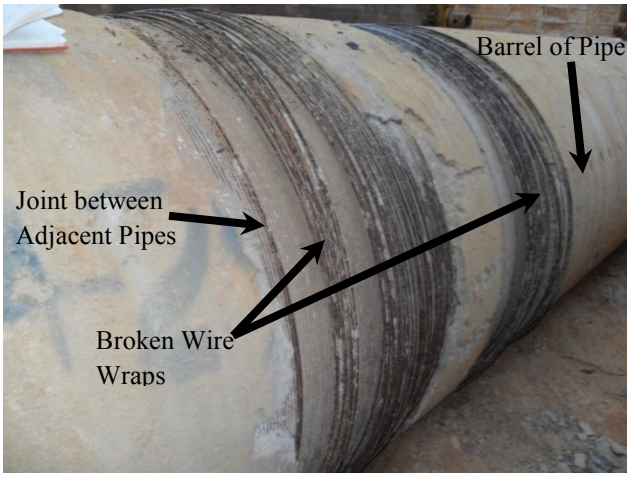

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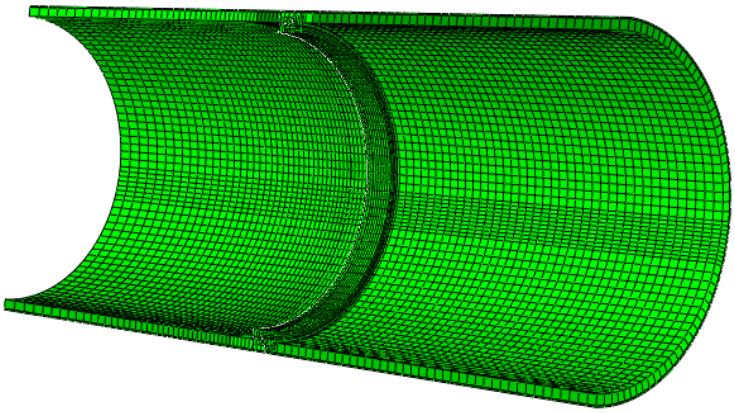

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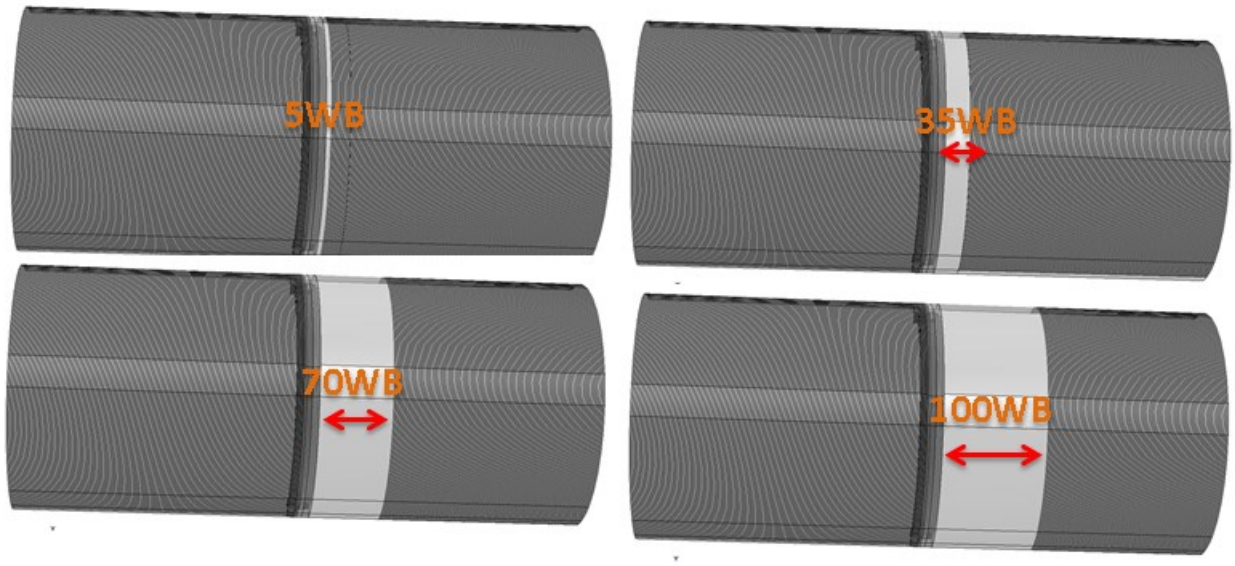

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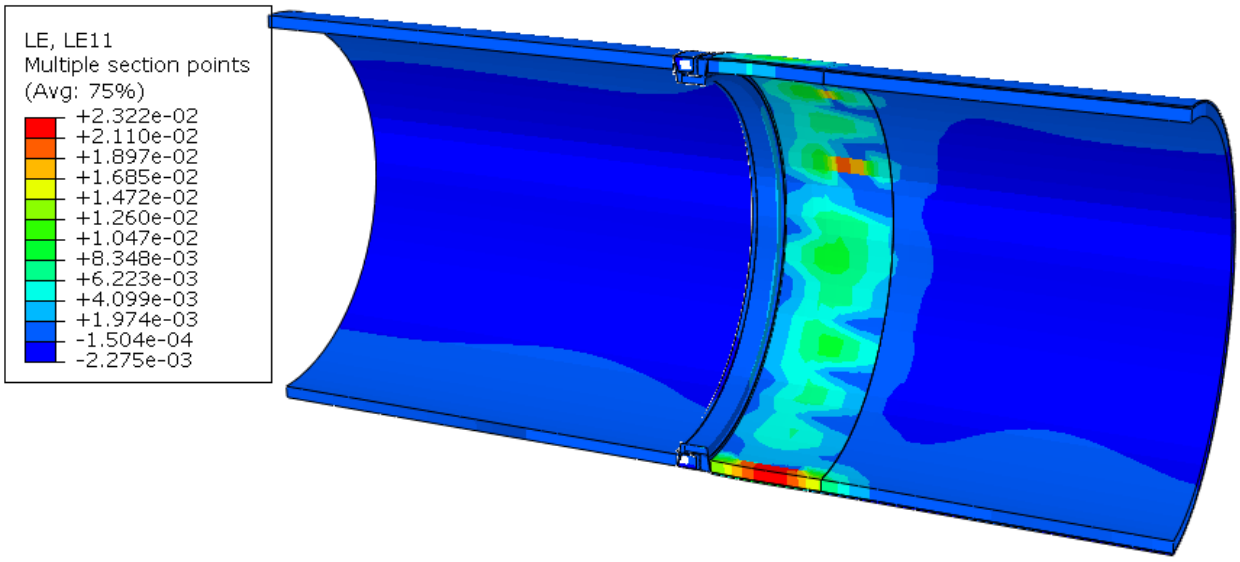

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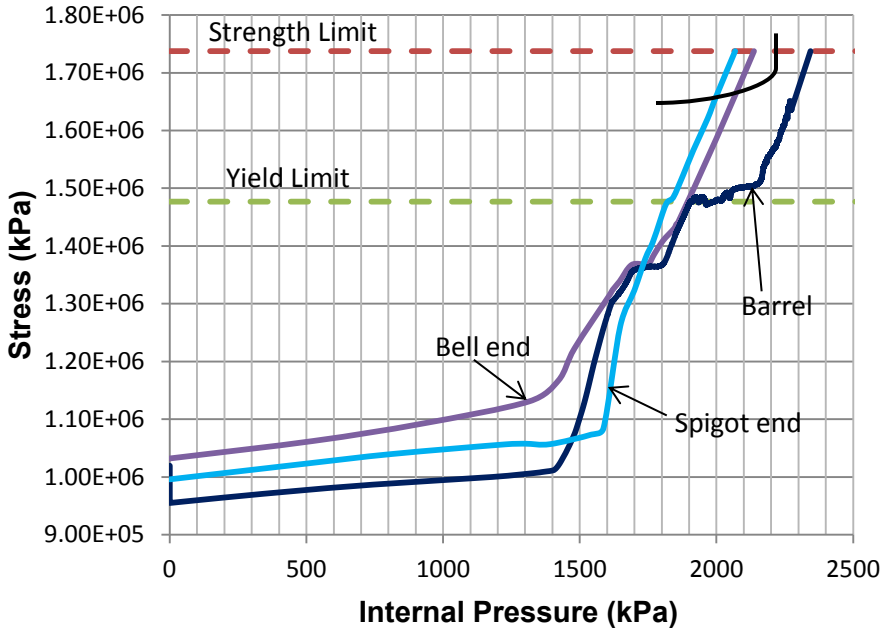

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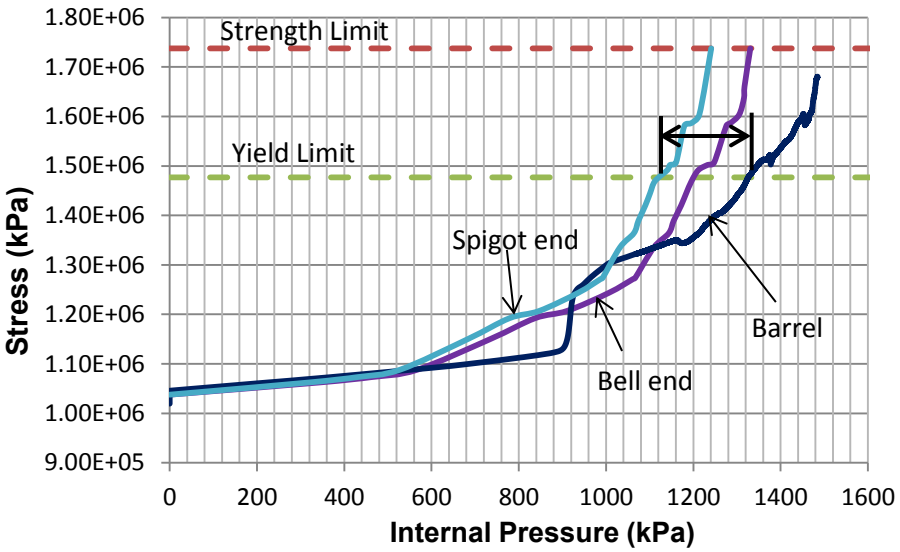

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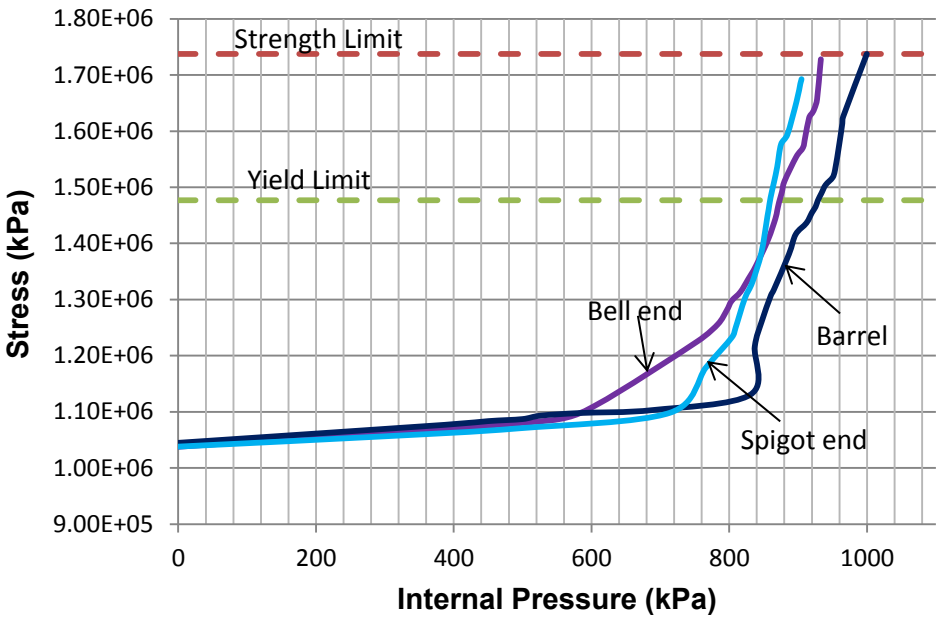

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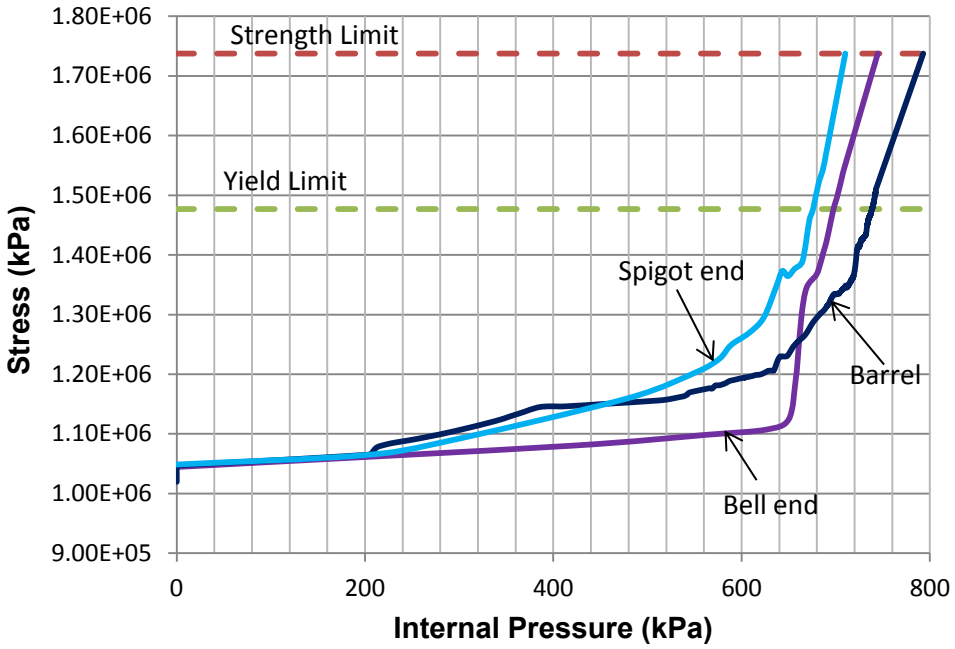

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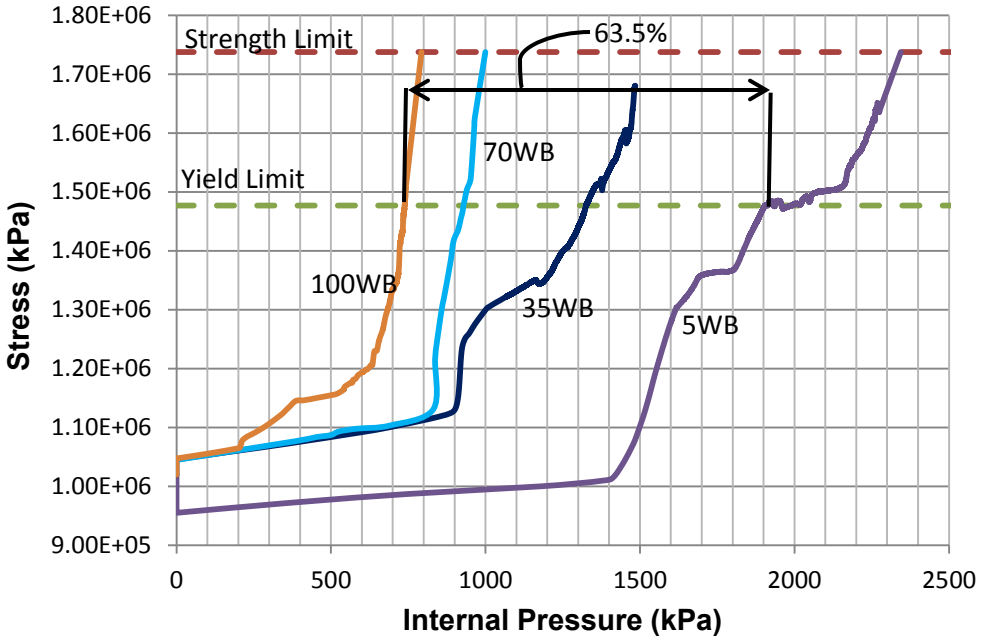

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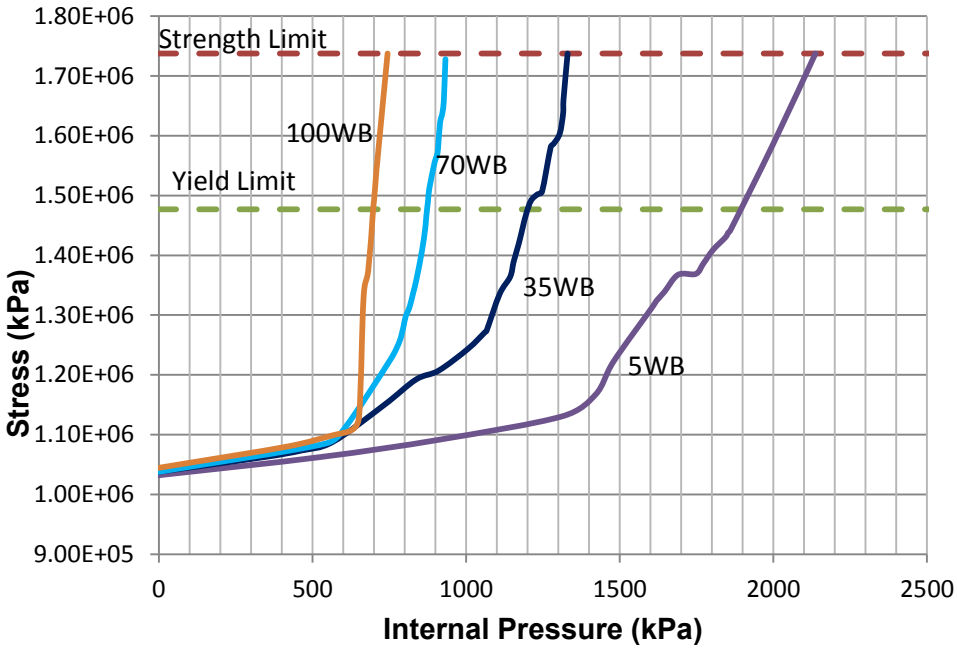

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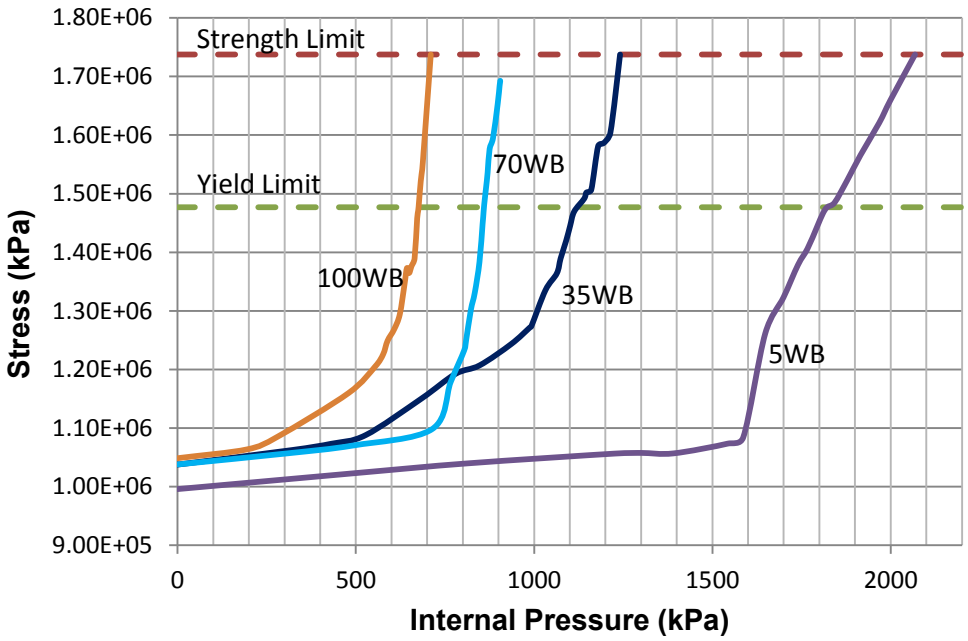

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