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Final Report

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Introduction

The development of high-toughness linepipe materials is reducing the relevance of current material test methods and their application to design. Current fracture mechanics models, plastic collapse schemes and test methods are inadequate to determine the crack arresting capacity of a steel alloy/linepipe component. Furthermore, relatively inexpensive tests that are quick to perform are simply not available to accurately assess the fracture behavior of today's high-strength and high-toughness linepipe steels.

NIST proposed to identify the stress/strain/crack velocity conditions for unstable ductile crack propagation found in a full-scale pipeline burst test and duplicate those conditions in a medium scale test. NIST proposed modeling to validate conditions and assumptions used in reducing the scale of the tests. Ultimately the goal is to develop a new medium-scale test, which can elucidate material property data necessary to qualify high-toughness materials based on the correlation to large scale tests. A further aim is to parametrically determine the material properties governing fracture propagation or arrest ability, with the goal of determining a small-scale test or tests that provide sufficient information for material selection, design, reliability, and integrity and risk assessment.

This project takes a phased approach with complementary research in successive phases beginning with a road map to systematically fill gaps in knowledge and understanding of the problem of high-rate ductile running fractures in pipelines.

This report is structured to highlight the problem statement with respect to current state of the art understanding, defining gaps and the plan and progress toward meeting the objective. The following sections specifically cover the effort to develop and inform a constitutive material model necessary for the structural model of the medium-scale test. The material testing required to inform the constitutive material model and the testing required to validate the structural model of the medium-scale test are also presented. Conclusions of this phase of the project are also presented in addition to the proposed work in Phase II of the project.

1.1. Background

Ductile running fracture in gas-transmission pipelines has economic, social as well as health and safety impacts that require designers and operators to preclude the event with a high degree of certainty. To be clear, running fracture is the dynamic axial crack propagation along the pipeline pressurized with natural gas or other hazardous fluids whose decompression is time delayed and produces a pressure wave in the fluid that precedes the running fracture. The conditions that influence full-scale response are phenomenologically complex. The fuel medium, operating pressure, pipeline design, material selection, installation variables (backfill, supports, etc.) and environment all have an influence on the full-scale response. Intentional design against these events has relied on full-scale demonstration experiments and have been coupled with fundamental and semi-empirical models.

1.1.1. Problem Statement

The advancement of modern high-toughness steels and their use in pipeline designs have confounded the available models which is further exacerbated by high-strength high-toughness steels. Early semi-empirical models such as the Battelle Two-Curve Model (BTCM), the Battelle simplified model (calibrated to Grade 448 (API 5L-X65)) and more recent correction factor variants are problematic for high-strength high-toughness steels. These limitations are primarily associated with evaluating fracture resistance by use of the Charpy V-Notch (CVN) test. More recent developments especially with respect to crack tip opening angle (CTOA) being used as a measure of propagating fracture resistance have spawned several test designs and geometries. Regardless of

how fracture resistance is measured or characterized, it is not uniquely controlling the condition of propagation or arrest of high-strength high-toughness steels, suggesting that other properties contribute to the arrest ability of modern high-strength and high-toughness steels.

Pursuing this logic, it is presumed that all influences other than material properties must be well controlled in the design of a medium-scale experimental program, and that the experimental conditions must mimic the full-scale condition. The ductile running fracture is preceded by a process zone whereby the material undergoes plastic deformation. Characterizing as-received material, whose strain history is significantly different than that of the material in the plastic process zone (*i.e.*, the crack propagates through material with different mechanical properties) and determining arrest ability based on as-received properties presents the first order problem for this project. Further, the tensile-traction controlled fracture is a function of the tensile properties which are in turn a function of the strain history and stress-state of the material at the point of fracture. The second order problem for the project is to determine what material properties govern the formation of the plastic process zone. Formation of the plastic process zone effectively removes energy from the pressure wave preceding the running fracture. One hypothesis is that the material resistance to through-thickness thinning controls the extent of plastic deformation in the process zone. This flow-controlled behavior is a function of the thickness (constraint), microstructure and crystallographic orientation or grain texture gradients in the through-thickness direction.

1.1.2. Current Approaches

Structural integrity is assured by the prevention of unstable crack extension. By way of traditional fracture mechanics, this is achieved through the design of structural components such that the stresses will not exceed the limits of the material, imposed by flaw size and material properties. Unfortunately, material properties such as strength and toughness are typically determined on materials and in environments (temperature, stress and strain rates) that have limited applicability to in-service conditions or imposed mechanics during a failure event. Simply, the current approaches to studying unstable ductile failure are not similar enough to in-service full-scale events or conditions to provide a reliable and economically feasible means of preventing unstable crack extension.

The full-scale burst test is arguably the most useful, and in some cases the essential test to evaluate and manage the resistance to ductile failure propagation in gas pipelines. This test can provide critical data necessary for design validation. However, the variables are great in number and uncertainty is high, making it a problematic test for comprehensive predictive models. Another significant drawback of full-scale testing is the cost in time and currency, making the usefulness of the test limited to specific design variables where a large test matrix is prohibitively expensive. A number of laboratory-scale tests have been in use for decades to qualify materials, and attempts have been made to correlate full-scale performance with laboratory-scale tests.

The prevailing favorite is the notched bar impact test, the most common being the Charpy V-Notch (CVN) test. This test is useful to determine the ductile-to-brittle transition temperature of the steel and the relative fracture energy differences between brittle fracture and ductile failure. This test is quick and simple, and has successfully been applied to a range of steel grades but is less relevant for modern high-strength and high toughness steels. The test works fine to determine the ductile-to-brittle transition temperature but has difficulty with providing valid results in tough, ductile steel where the absorbed energy is dissipated by mechanisms other than creating new fracture surfaces (*i.e.*, large scale plasticity and friction). High-strength and high-toughness steels may additionally require high capacity impact machines. Ongoing research with this test method has produced several correction factors that can be used to predict arrest or propagation in the full-scale condition, but the method remains inadequate to describe and mimic the failure mechanics in the full-scale.

Other methods attempt to determine a fracture parameter that can then be compared to full-scale tests and structural models. While there are several such laboratory-scale tests that can determine a fracture parameter (*e.g.*, crack tip opening displacement (CTOD), crack tip opening angle (CTOA) and *J*-integral) there are experimental parameters that limit their application. These experimental parameters are generally related to specimen geometry or environment (*e.g.*, constraint, temperature and strain rate).

1.1.3. Literature Review

Ductile fracture, ductile shear, and propagating shear are all terms that have been used to describe a phenomenon known to occur in modern high toughness steels. Ductile fracture is characterized by a crack, propagating at speeds typically indicative of brittle failure events, which propagates as a function of traditional large-scale plasticity (ductile) mechanisms. Ductile fracture occurs because of a propagating plastic wave triggered by an initial rupture event. The wave causes damage in the form of large scale plasticity, characterized by through-wall thinning of the pipe. For ductile fracture to occur, the damage caused by the plastic wave is a necessary precursor to crack extension. That is, if a crack were to extend through a pipe not having initially been damaged by the plastic wave, the crack surface would have brittle morphology and would be indicative of a brittle fracture. In this case, Linear Elastic Fracture Mechanics (LEFM) would be wholly applicable to the event. Furthermore, the fracture toughness has been shown to be a good metric of crack propagation/arrest in these instances. On the other hand, if a plastic wave precedes the running crack, large scale plasticity occurs (on the order of centimeters in front of the crack tip), and traditional fracture theory is applicable. As such, the traditional determination of go/no-go for material acceptability are also inapplicable, *e.g.* Battelle Two-Curve Model (BTCM), Charpy impact results, Drop weight tear results, etc. This phenomenon and the resulting consequences of the plastic deformation on ductile shear mechanisms, testing, and modelling, have been well documented in [1].

Traditionally, modelling of ductile fracture has been performed by use of a damage-mechanics type approach. Specifically, micro-mechanics approaches which capture damage in the form of void initiation, growth, and coalescence [2-5], and phenomenological approaches which predict failure events as a function of accumulated damage *(e.g.,* cohesive zone model) [6-8]. Given that the ductile fracture event results in the manifestation of large scale plasticity in an orthotropic material (transversely isotropic at best), preceding a running crack, damage accumulation modelling is insufficient to capture the coupled, time-dependent phenomena.

1.1.4. Gap Analysis

There are several knowledge gaps apparent when considering a program that can predict propagation or arrest of a ductile running fracture. Firstly, to date the mechanical testing used in failure assessment diagrams (FAD) is performed on as-received pipe material. These tests are performed on specimens taken from actual pipes so the change in properties due to pipe forming is accounted for. However, the plastic process zone that precedes a ductile running fracture has additional strain history that is not accounted for. So, the first knowledge gap can be known by answering the following question. What are the mechanical properties of the steel in all three principal directions inside the plastic process zone? This can be known by testing material adjacent to the fracture edge of a full-scale burst test that resulted in ductile running fracture. One problem with this approach is that the strain history of this post-test material is not the same as the strain history of that material immediately prior to the ductile fracture. Another problem with this approach is that the strain history of the surrounding material is not known.

Secondly, the different mechanical tests will interrogate potentially different material and in different constraint conditions that are not adequate surrogates of the full-scale test. Charpy impact specimens for

example do not encompass the full-thickness average material response. Drop weight tear tests can interrogate full-thickness specimens, but the specimens are typically flattened (adding strain that is not in the full-scale condition of ductile fracture). Crack tip constraint and stable ductile fracture velocity are also very difficult to replicate in laboratory-scale tests.

1.2. Project Overview

NIST proposed to identify the stress/strain/crack velocity conditions for unstable ductile crack propagation found in a full-scale pipeline burst test and duplicate those conditions in a medium-scale test. NIST proposed modeling to validate conditions and assumptions used in reducing the scale of the tests.

1.2.1. Project Objectives

The first objective is to develop a new medium-scale test, which can elucidate material property data necessary to qualify high-toughness materials based on the correlation to large-scale tests. A further goal is to parametrically determine the material properties governing fracture propagation or arrest ability, with the goal of determining a small-scale test or tests that provide sufficient information for material selection, design, reliability, and integrity and risk assessment. An ideal medium scale test should ensure that unstable ductile tearing at a constant (equilibrium) crack velocity is achieved during the test. The goal is to ultimately produce and champion a validated test method in a standards development organization (SDO), but this activity will be the subject of a future task order.

The second objective is to develop an open source model, based on state-of-the-art finite element methods, to parametrically evaluate the crack propagation characteristics of a linepipe section, and to correlate to the results of large scale tests (provided by open literature, DOT, and/or industry). The model is anticipated to be capable of discriminating energy absorbed by fracture, which could then be compared to the energy produced in small scale tests to deduce the energy of deformation and/or friction. The model will be validated with full scale test results in existing datasets. Once successfully developed and validated, the model would be made available in the public domain for use by industry, academia, and government agencies.

1.2.2. Project Scope and Phases

This project takes a phased approach with complementary research in successive phases beginning with a road map to systematically fill gaps in knowledge and understanding of the problem of high-rate ductile running fractures in pipelines. The second phase will determine the structure-property relationship and develop the constitutive material model used in the structural model. The third phase will complete the technical design of a medium-scale high-rate test and conduct the testing to inform and validate the structural model.

1.2.3. Project Milestones and Deliverables

The first milestone under this phase was to develop a technical advisory committee (TAC) that represents multiple relevant industrial interests and expertise. The deliverable for this milestone was to have a functioning TAC with regular meetings to discuss relevant project issues. With the guidance of the TAC, the next task was to identify the type of data generated (*i.e.*, properties measured) and requirements for specimens, test equipment, fixtures, and instrumentation for all available tests. Each of those parameters was then compared to the conditions realized by in-service pipelines. A literature and industry survey was conducted to define knowledge gaps and develop a conceptual test design that prioritizes key parameters that best match in-service conditions. The next milestone was the development of the conceptual test design. Here, the parameter

priorities and the mechanics of the testing will be used to define test equipment, design fixtures and establish performance requirements. Industrial experts and key members of standards development organizations (SDO) were consulted regarding the conceptual test design, method development and analysis. Modeling support will be used for this milestone to design the specimen, define the instrumentation and establish test parameters. Working backwards from the conceptual medium-scale test, key knowledge gaps were defined with a subsequent research plan developed.

Access to relevant materials was a significant obstacle in this phase of the project, and a great deal of time and effort were expended to find and secure the material necessary to perform the tests. In concert with the TAC and other international researchers also working on high-rate ductile fracture, the materials obtained included API 5L X80 (spiral pipe skelp) and API 5L X70 (UOE pipe plate).

1.2.4. Project Team

The research project was led by Timothy Weeks, the Pipeline Safety Project Leader in the Structural Materials Group of the Applied Chemicals and Materials Division at the Material Measurement Laboratory of NIST. In addition to leading the project, Mr. Weeks is responsible for mechanical metallurgy and structural testing. Project team members from the same group include Dr. Robert Amaro who is responsible for the material and structural modelling effort, Dr. Jeffery Sowards who is responsible for physical metallurgy, Mr. Chris McCowan who is assisting with high rate test development, Mr. Ross Rentz and Mr. Kenneth Talley who are conducting mechanical tests and are responsible for specimen preparation and test setup.

1.2.5. Technical Advisory Committee

A technical advisory committee (TAC) was formed to assist the development of the work scope, execution of the work plan, and the review of the work outputs. Members of the technical advisory committee are David Johnson of Paragon Industries, Su Xu of CanmetMaterials, Brian Leis of BN Leis Consultant, Brian Rothwell on behalf of Pipeline Research Council International, Kip Findley of the Colorado School of Mines, Matthew Merwin of US Steel and David Taylor a Technical Consultant to TransCanada.

The members of the TAC were carefully selected to represent key interests in the pipeline industry, steel industry, standards development organizations, government regulators, international collaborators and academia.

1.3. Stakeholder Engagement and Collaborations

Participation in key conferences and meetings allowed face to face communication with members of the TAC, other industry and government representatives as well as international collaborators. Initially the goal was to present the project objectives to as many representatives as possible for general awareness and to solicit specific support. The material source needs were presented heavily, since a source was not identified definitively through the TAC.

Chronologically the following Meetings and Conferences were attended in support of the project.

Host Organization - Purpose	Date	Location
ISOPE - Conference	July 2013	Anchorage, AK
DOT/PHMSA – Pipeline Workshop	September 2013	Alexandria, VA
PRCI – Research Exchange Meeting	February 2014	Atlanta, GA
NIST – Brian Leis Visit	April 2014	Boulder, CO
NIST – Brian Leis/Malcom Gray Visit	May 2014	Boulder, CO
DOT/PHMSA – R&D Forum	August 2014	Chicago, IL
IPC – Conference	October 2014	Calgary, AB Canada
NIST – Brian Leis Visit	October 2014	Boulder, CO
API – Winter Standards Meeting	January 2015	New Orleans, LA
PRCI – Research Exchange Meeting	February 2015	Houston, TX
APPPRC – Semi-Annual Review Meeting	March 2015	Golden, CO
CNPC - Pipeline Conference	April 2015	Xi'an, China
TGRI – Meeting	April 2015	Xi'an, China
NIST – Brian Leis Visit	June 2015	Boulder, CO

2. Constitutive Material Modelling

Ductile fracture of linepipe steels occurs as a progression of the following events: (1) Localized damage is induced in the pipe (*e.g.*, third-party damage) such that the damage behaves as a crack. (2) If the localized damage does not result in a through-wall crack, the crack will propagate to through-wall proportions as a result of intended use. (3) Once the crack has penetrated the pipe wall thickness, the pressurized working fluid within the pipe is released, producing a wave propagating in the longitudinal direction of the pipe. This wave is known as a decompression front. The decompression front induces localized through-thickness necking directly in front of the crack tip. (4) The localized necking immediately in front of the crack tip provides a path of least resistance for crack propagation. The driving force for crack propagation is largely the sudden escaping of working fluid within the pipe. This depressurization tends to deform the pipe into a U-shape in the crack wake. While the driving force for crack propagation and the energy source of the decompression front are intrinsically linked, the two phenomena produce damage that propagates at speeds independent of one another. In order for ductile fracture to occur, the decompression front must precede the running crack, such that it may produce the required through-thickness plasticity which enables crack propagation. Inversely, if the crack travels faster than the decompression wave, the undamaged material that the crack must propagate through will tend to arrest the crack due to its inherent, undamaged, fracture toughness. Finally, the crack propagation surface is indicative of traditional ductile features, including manifesting along a plane at approximately 45° to the applied load, *i.e.*, plane of maximum shear.

Any constitutive model which intends to capture the physics of the ductile fracture phenomenon must include the following characteristics, at minimum:

- The inelastic deformation response of the material must be rate dependent. Specifically, the plasticity constitutive relations must be calibrated to loading rates on the order of those seen when a ductile fracture occurs in a linepipe.
- The inelastic deformation response predicted by the model must be transversely anisotropic, due to the lack of isotropy inherent to the process used to create the line pipe. Specifically, a single constitutive model must be able to capture large-scale longitudinal and transverse plasticity having vastly different hardening responses.
- The state of stress and strain produced by the longitudinal decompression front must be captured and used as initial conditions for crack propagation. Specifically, the constitutive model must be history dependent, such that prior damage may be included.
- Volumetric considerations must be accounted for. Specifically, given that the crack propagates on, or very nearly aligned to, the plane of maximum shear, the constitutive model must have the capabilities to incorporate a critical plane theory (*e.g.,* Fatemi and Socie 1988 [9]).

2.1. Current State of the Art

The following theories are commonly used in the constitutive relations for ductile fracture:

- Crack driving force primarily due to the opening of the pipe in the crack wake.
- Fracture predicted by the dynamic fracture toughness of the material, G_d.
- Fracture predicted by crack tip opening angle (CTOA).
- Fracture predicted by energy dissipation rate and critical dissipation energy, R.

2.2. Gap Analysis

The four most common theories used to predict ductile fracture and arrest have been shown to have shortcomings in their implementations. First, the hinging of the material in the crack wake to produce a U-shaped pipe post failure occurs at a time scale that would indicate that it could not precede crack propagation. Furthermore, fracture surfaces do not indicate large scale Mode II characteristics, as this phenomenon would tend to produce. Next, predicting failure by use of a material parameter derived from planar deformation responses, such as G_d and CTOA, does not accurately account for the through-thickness deformation resulting from the propagating decompression front (step 3 above). In this case, the deformation history that enabled the crack propagation is not accounted for. Finally, the use of an energy parameter as a predictor for ductile fracture is promising. However, the use of an energy parameter in conjunction with transversely isotropic large-scale plasticity and history dependent modelling has yet to be performed.

2.3. Project Progress

To address the need for a transversely isotropic large-scale plasticity model, an in-house constitutive model has been created and implemented. The model includes separate, transversely isotropic constitutive models incorporating a Von Mises associated flow rule and isotropic hardening. The implementation of the model ensures deformation history is accounted for in each subsequent time step, and that the energetics of the deformation are summed through all times. The model is currently being calibrated to a “model” steel.

3. Mechanical Testing

This section defines the material testing to determine mechanical properties of the steel in three principal directions and with multiple pre-strain levels. At the time of this report, mechanical tests were only planned and are described below. Procurement of relevant steel plate material was a significant obstacle to making significant experimental progress.

3.1. Material Selection

In conjunction with the TAC it was decided that API 5L X80 would be targeted as representing a modern high-strength and high-toughness grade with significant interest and therefore relevance from the pipeline industry. Based on the conceptual medium-scale test, it was decided that only plate material be sought for the test matrix.

3.2. Material Procurement

The conceptual medium scale test design drove the material source needs and it was quickly obvious to the TAC and to the project team that obtaining API 5L X80 plate material would be difficult. One source of X80 steel was found but the source could not provide plate in the size required for the medium scale test. Instead strips of skelp were delivered to NIST for testing. The material will be useful to inform and validate the material models and structure-property relationships but will not be used to conduct medium-scale tests.

A source of API 5L X70 plate was found with access to the sizes and quantity necessary to conduct the small-scale mechanical tests and the medium-scale test. This steel still represents a high-strength and high-toughness steel relevant to the pipeline industry.

3.3. Experimental Design

The as-received plate material will be tested according to the following tests.

- Tensile Tests on As-Received (A-R) Plate Steel – Longitudinal to the plate rolling direction
- Tensile Tests on A-R Plate Steel – Transverse to the plate rolling direction
- Tensile Tests on A-R Plate Steel – 45 ° to the plate rolling direction
- Mini-Tensile Tests on A-R Plate Steel – Longitudinal to the plate rolling direction
- Mini-Tensile Tests on A-R Plate Steel – Transverse to the plate rolling direction
- Mini-Tensile Tests on A-R Plate Steel – Through the thickness direction
- Compression Tests on A-R Plate Steel – Longitudinal to the plate rolling direction
- Compression Tests on A-R Plate Steel – Transverse to the plate rolling direction
- Compression Tests on A-R Plate Steel – Through the thickness direction
- Charpy Impact Tests on A-R Plate Steel – Propagation longitudinal to the plate rolling direction
- Charpy Impact Tests on A-R Plate Steel – Propagation transverse to the plate rolling direction
- Charpy Impact Tests on A-R Plate Steel – Propagation through the thickness direction

Additionally, the plate will be pre-strained with three strain ranges and the following tests conducted for each of the three strain ranges.

- Tensile Tests on Pre-Strained (P-S) Plate Steel – Longitudinal to the plate rolling direction
- Tensile Tests on P-S Plate Steel – Transverse to the plate rolling direction
- Mini-Tensile Tests on P-S Plate Steel – Longitudinal to the plate rolling direction
- Mini-Tensile Tests on P-S Plate Steel – Transverse to the plate rolling direction
- Mini-Tensile Tests on P-S Plate Steel – Through the thickness direction
- Compression Tests on P-S Plate Steel – Longitudinal to the plate rolling direction
- Compression Tests on P-S Plate Steel – Transverse to the plate rolling direction
- Compression Tests on P-S Plate Steel – Through the thickness direction
- Charpy Impact Tests on P-S Plate Steel – Propagation longitudinal to the plate rolling direction
- Charpy Impact Tests on P-S Plate Steel – Propagation transverse to the plate rolling direction
- Charpy Impact Tests on P-S Plate Steel – Propagation through the thickness direction

Chemical Analysis will be conducted on the as-received plate steel. Additional analysis will be performed to determine if chemical segregations are obvious from plate processing, understanding that pipe formation and thermo-mechanical control processes after pipe forming may affect the distribution. Phase constituents, distribution and size distribution will be determined on as-received and pre-strained plate steel. Lastly, phase grain boundary angle distribution and orientation will be studied on as-received and pre-strained plate steel. The chemical and microstructural properties of the steel in different principal directions may have quantifiable correlation with mechanical properties. By studying different grades of steel, it may become apparent that a particular structure or distribution of physical properties has an impact on arrest ability of the steel.

The mini-tensile tests are non-standardized specimens that allow for sectioning in the through-thickness direction. Significant test design (specimen, fixtures and instrumentation) has been done on the mini-tensile test.

3.4. Project Progress

As of this report, the X80 and X70 plate materials are at NIST in Boulder. The test matrix has been designed, specimens have been designed and material is in process to section for as-received material specimens. The pre-straining plate and fixtures have also been designed.

4. Structural Modelling

Structural modelling as part of this project includes both medium scale and large-scale modelling of realistic geometries, loading conditions, and boundary conditions. Specifically, medium and small-scale test specimens must be modeled to match all laboratory conditions of interest. Furthermore, the operational pipe geometry, loading conditions, and boundary conditions must also be modeled to provide support for similitude between the laboratory test results and predicted field results.

4.1. Current State of the Art

The current state of the art to perform structural modelling is implemented in any number of commercial finite element packages (e.g. ABAQUS, SolidWorks, COMSOL, etc.).

4.2. Gap Analysis

To the best of our knowledge, there is not a commercially available finite element package that can perform anisotropic inelastic deformation. This is the purview of research scientists and scientific laboratories focusing wholly on anisotropic plastic deformation behavior.

4.3. Project Progress

Finite element modelling has been performed on laboratory specimens to predict deformation response of the tests. Results have been used to design specimen geometries producing homogeneous deformation within sections of interest. The finite element results have also been used in conjunction with the transversely isotropic large-scale plasticity material model, outlined in Section 2, to predict the required test parameters to ensure sufficient plastic deformation during pre-stressing. The pre-stressing is performed to simulate the effect of the propagating decompression front.

5. Medium-Scale High-Rate Testing

There are no medium-scale high-rate tests that are conducted by the industry to validate structural models and inform risk and failure assessment methods. The definition of medium-scale has some implications in contrast to a full-scale or small-scale test. The intent is to bridge the gap between full-scale and small-scale tests and in the process parametrically separate the structural/geometric influences from material influences. As discussed previously, the small-scale tests do not match the full-scale condition and it is therefore very difficult to predict full-scale behavior with small-scale test data. The medium-scale test, if successful, will be significantly less expensive and faster to conduct, compared to full-scale tests. The economy gained by a successful medium-scale test will allow for the generation of much more test data and will therefore reduce uncertainty and risk.

5.1. Current State of the Art

The conceptual medium-scale test is essentially a middle-crack wide plate tension test on a pre-strained plate. The goal is to get steady-state crack velocities in excess of 300 m/s. Using a middle-crack specimen will ensure symmetric loading and will significantly simplify the mechanical fixture and equipment needs for the test as well as the instrumentation and analysis. The tests are designed with a pre-strained plate that is pre-strained in a manner that simulates the plastic process zone that precedes the running crack in a full-scale test. Once the plastic process zone is formed, there is little difference between a planar process zone and the longitudinally dominated process zone in a pipe. The specimens will be loaded quasi-statically with the middle-crack being guarded by the applied load until the guards are removed and the crack propagates due to severe overload generated by the stored elastic energy in the guards.

5.2. Gap Analysis

The similitude between the medium-scale test and the full-scale test requires that the stress/strain/crack velocity conditions be understood and met. Assuming that a full-thickness plate is used and a target velocity exceeding the arrest velocity known from full-scale tests is used, then the stress and strain states on the crack tip are the remaining unknowns. The conceptual medium-scale test only provides loading in the circumferential direction, that is crack propagation is normal to the direction of loading, which is similar to the full-scale condition but does not include the additional elastic strain placed on the pipe in the longitudinal direction. The plastic process zone is simulated by the pre-strained specimen but an additional loading direction is necessary to fully simulate the full-scale condition. At this point it is proposed to initially limit the test to a single loading direction and only consider the second loading direction if the geometric and material influences cannot be separated and re-applied to the full-scale model.

5.3. Project Progress

As of this report, only a conceptual test design has been determined and no further engineering has been conducted on the test design in favor of completing the small-scale testing and modelling necessary to fully model the medium-scale and full-scale tests.

6. Phase II – Research Proposal

Model Development: The continuation of the project in Phase II will finalize the three-dimensional constitutive model and prepare that model to be input into the structural model of the medium scale test geometry. A ductile running crack is preceded by a large plastic process zone, and knowing the material properties of steel in the plastic process zone, the structural model can be used to predict whether a running crack would have sufficient driving force to propagate. The objective in this phase will be to determine the material properties of the steel in the plastic process zone and inform the constitutive model. The scope for this effort will only include X70 to meet funding and scheduling needs.

Structure-Property Relationships: The constitutive model will require the same small-scale matrix of tests for different grades of steel until a normative empirical relationship between grade and material properties at failure can be developed. This has never been attempted in the literature, but will be very valuable to avoid the need to generate an informed constitutive model from the complex test matrix for each grade and even differences within grades. The objective is to develop a framework for a normative constitutive model and determine the knowledge gaps.

Understanding fundamental material properties that control dynamic plastic collapse is paramount to getting critical data and design requirements to the industry. Chemistry and through-thickness microstructure will be characterized along with development of test methods to obtain critical material properties that are unavailable from conventional mechanical testing. The objective is to develop structure-property relationships and a framework to parameterize material structure influence across grades. The scope for this effort will only include X70 to meet funding and scheduling needs.

The challenge to understand ductile fracture is an international challenge with several organizations involved in collaborative research with NIST. Several of these organizations are a source for relevant steels. We are leveraging independent research with these organizations on the same material so that material variability is normalized out of the results and a true comparison can be made from the results of each organization.

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