HYBRID COMPOSITE REPAIR for OFFSHORE RISERS

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SUMMARY

An innovative design based on integrated computational models and full-scale tests is presented to address the viability of reinstating capacity to offshore steel pipelines and risers. Simple carbon-fiber composite repair system is developed based on limit analysis and strain-based design methods and validated with prototype tests.

Key words; riser, repair, composite

APPROACH

Risers are critical components in offshore operations as they extend the wellhead from the mud line to the surface and are subject to degradation mechanisms including external corrosion and mechanical damage due to contact with outside forces. Conventional repair techniques incorporate external steel clamps that are either welded or bolted to the outside surface of the riser creating challenges mobility, welding and installation costs. Alternative solutions such as composite repair sleeves provide an attractive option, as they are relatively inexpensive, lightweight, do not require welding, and are relatively simple to install.

One of the challenges in developing a repair system that possesses adequate strength and stiffness to reinforce a given pipe involves determining the acceptable stress and strain fields. This may be resolved by defining an optimum design relative to allowable conditions in the steel and composite materials through i. determining the maximum acceptable strain in the steel subject to appropriate pressure, tension, bending loads, and ii. defining the maximum allowable stress in the composite material.

Limit state design methods based on strain limits are used to address combined loads as well as assess the integral performance of three different materials (i.e. steel, E-glass, and carbon). The detailed simulations are realized through the proposed limit design approach that was integrated with the finite element method. The CRA prototype of Figure 1 was designed with rigorous computational models to understand the load paths, interaction between layer orientation and thickness, length of bonding zone, processing induced residual stresses and potential damage mechanisms [1]. This approach enabled the assessment of shear stress at the steel-composite bond line; and evaluating strain in both the steel and a composite material at different load states including design and plastic collapse conditions.

The primary design requirements are generated to determine the composite architecture and geometric options of the repair by *i.* preventing bulging of the corroded pipe section due to excessive circumferential strains during pressurization, *ii.* provide sufficient reinforcement so that strains induced during bending do not exceed a specified design strain and *iii.* select length to maintain integrity of the interface bond between the repair and steel.

The secondary requirements are selected to assess how the repair functions and performs in situ such as ease of installation, economic viability, quality control and design to ensure structural integrity during installation, impact resistance and finally that it does not cause corrosion or form a galvanic cell.

LIMIT STATE DESIGN for HYBRID COMPOSITE REPAIR

The principal goal is to reduce loads carried by the repaired member. Upon repair, the load path is no longer carried just by the original steel tubular but is shared with the composite reinforcement. We selected strain as our metric to assess this load sharing. Figure 2 shows the steps for establishing strain limit on the steel. Note that if the stresses in the composite are beyond an acceptable level, it is possible that overload of the steel carrier pipe will occur due to failure of the composite to function as originally designed. The sequence of determining limit loads and design margins are as follows;

Determine the Limit Load for Undamaged Risers considering all primary loads (pressure, tension, and bending for the splash zone region of the riser) including the plastic analysis collapse load.

Calculate Design Load Using an Acceptable Design Margin after the limit load is determined. A reasonable conservative value is selected as 2.0, implying that during normal operation the load in the steel is limited to one-half the load required to achieve plastic collapse of the structure.

Determine the Design Strain Limit based on the lower bound collapse load. It is estimated as 0.2 percent.

Similar to discussions on limiting strain the reinforced steel, it is necessary to limit stresses or strains in the composite reinforcing material. In a search of applicable codes, standards, and papers, there are a variety of limitations placed on composite materials used to reinforce steel and aluminum pressure containing structures. Recognizing that if the reinforcing material is properly designed to ensure that strains in the steel remain below the designated design limit a design margin for the reinforcing composite of 2.5 is acceptable. Provided below are several design margins expressed in the open literature that relate to the discussion of riser repair.

ASME PCC-2 Repair Standard (Article 4.1, Non-Metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications): For continuous loads where the axial elastic modulus of the composite material is less that one-half the elastic modulus in the circumferential direction, that design margin of circumferential and axial strain are 4 and 10, respectively.

ASME Boiler & Pressure Vessel Code, Case 2390-1 Composite Reinforced Pressure Vessels Section VIII, Division 3, 4.0 DESIGN, 4.1 Rules for CRPV (i): The primary membrane circumferential stress in the laminate layer shall not exceed 36% of the ultimate tensile strength of the laminate at design conditions. The primary membrane circumferential stress in the laminate layer shall not exceed 60% of the ultimate tensile strength of the laminate under the hydrostatic test load.

*ASME STP/PT-005 Design Factor Guidelines for High Pressure Composite Hydrogen Tanks***:** This document was developed to provide for industry a technical basis for determining appropriate design margins for composite-wound tanks (typically involving an aluminum liner with an E-glass wrap). According to Section 7 Recommended Short-term (static) Design Factors for Composite Tanks), for transport tanks the stress ratio must be less than 40 percent of the working pressure for hoop-wrapped tanks. The stress ratio is defined as the ratio of the stress in the reinforcing fibers at working pressure to the initial ultimate (tensile) strength of the fibers, as demonstrated by the short-term burst tests.

CRA COMPOSITE CLAM SHELL

The optimal solution is reached by placing E-glass as inner and outer layers. The inner layer acts to protect the pipe from potential corrosion due to carbon interaction with steel, while the outer layers protect the carbon fibers. Circumferentially oriented carbon fibers are placed in the region of corrosion. Next layers are composed of axial layers to accommodate bending and tension. Total length of repair section was limited to 60 inches. The schematic of the lay up is presented in Figure 1.

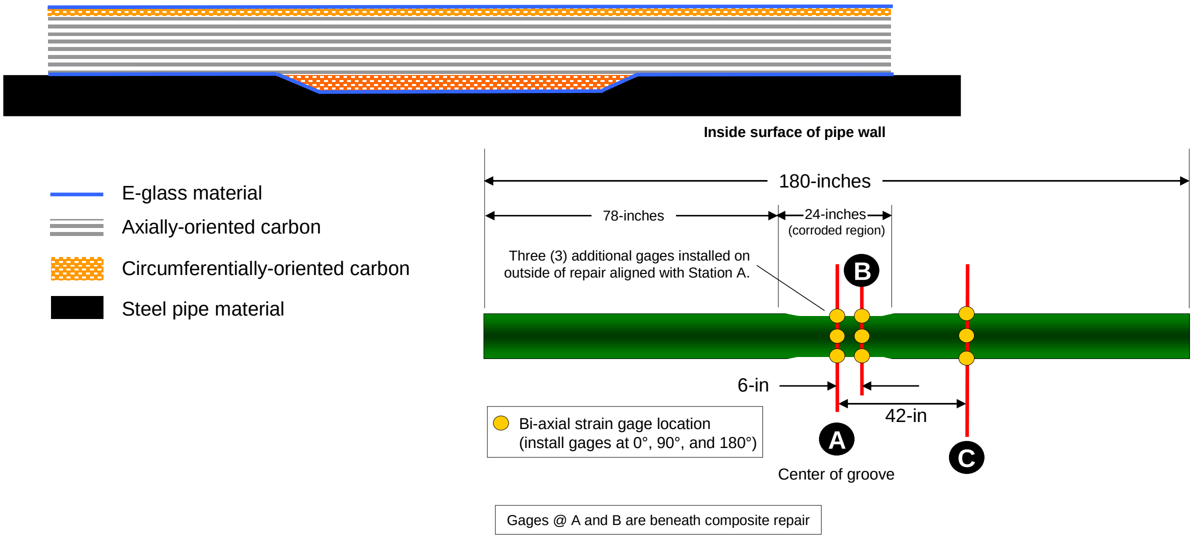


Figure 1 Optimized E-glass/composite repair and test samples

Three sets of E-glass/carbon half shells were fabricated for testing. The tests demonstrated that CRA shell provided adequate structural reinforcement to ensure that excessive strains are not induced in the steel when subjected to internal pressure, axial tension, and bending design loads. The results clearly demonstrate that the computational models, along with selective full-scale tests, can indeed assess performance of the repair both locally and globally. As noted in Figure 3, the practical outcome is to assure that strain in the steel is maintained below an acceptable value and, secondly, that strain in the composite material does not exceed a value acceptable for long-term performance.

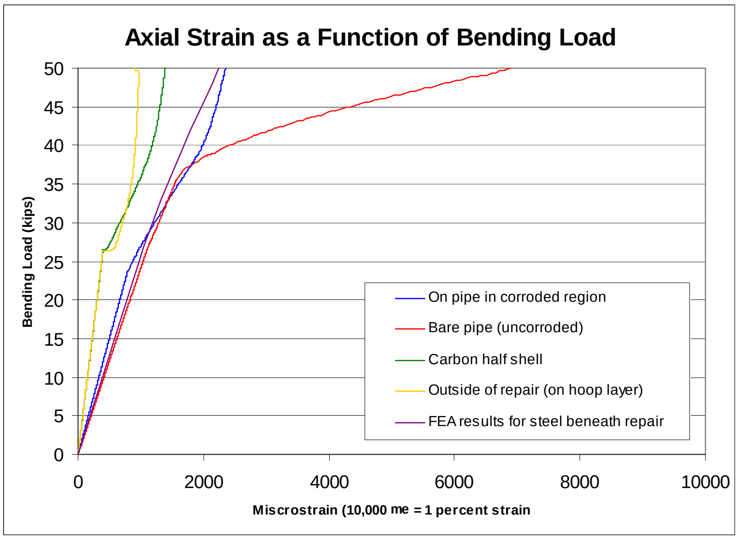


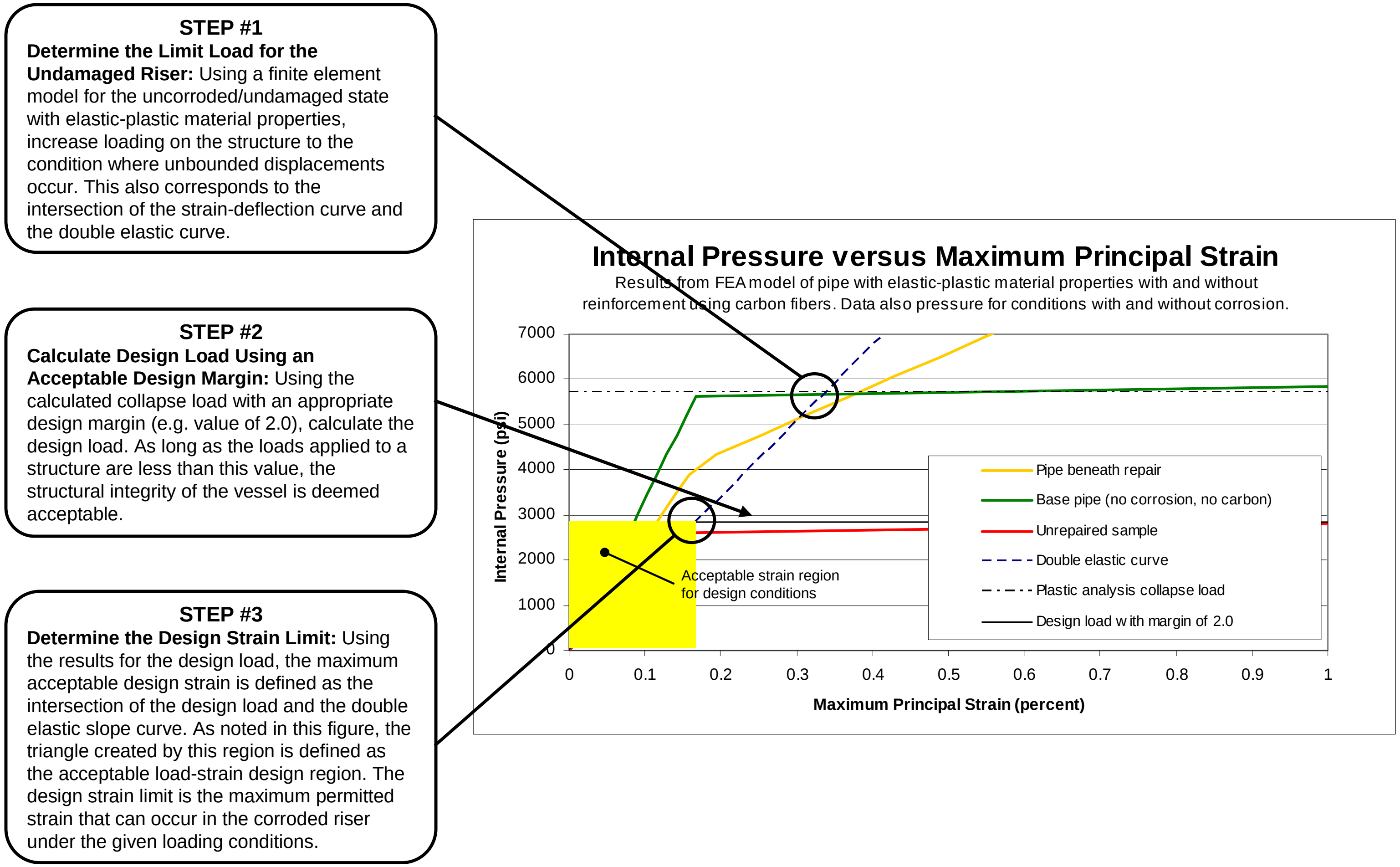
Figure 3 Analysis and testing results for bending coupled with 2,887 psi internal pressure and axial tension of 145 kips.

OPERATIONAL CONSIDERATIONS

To better understand and anticipate the performance of the composite repair, several investigations were conducted using finite element methods to assess the behavior of the composite repair during pressurization (axisymmetric model) and in the case of debonding (shell models). The ability of the repair to provide adequate reinforcement is related to its proper adherence to the steel pipe.

Pressurization

If a compressive stress exists between the inside surface of the repair and the outer pipe surface, the potential for delamination is minimized. To numerically demonstrate that a compressive stress exists, a model was constructed that integrated axisymmetric continuum elements for the steel and axisymmetric shell elements to represent the composite material. An internal pressure of 2,887 psi was applied to the inside surface of the model and the ends of the model were restrained axially. The radial stresses are presented in Figure xx. Note that the data plotted from 0 to 1.0 (X-axis) are for results beneath the repair, whereas data from 1.0 to 1.75 are results outside the repair (the 0 position is at the axial center of the model). As demonstrated, a compressive radial stress exists for all regions beneath the composite reinforcement.



STEP #1

Determine the Limit Load for the Undamaged Riser: Using a finite element model for the uncorroded/undamaged state with elastic-plastic material properties, increase loading on the structure to the condition where unbounded displacements occur. This also corresponds to the intersection of the strain-deflection curve and the double elastic curve.

STEP #2

Calculate Design Load Using an Acceptable Design Margin: Using the calculated collapse load with an appropriate design margin (e.g. value of 2.0), calculate the design load. As long as the loads applied to a structure are less than this value, the structural integrity of the vessel is deemed acceptable.

STEP #3

Determine the Design Strain Limit: Using the results for the design load, the maximum acceptable design strain is defined as the intersection of the design load and the double elastic slope curve. As noted in this figure, the triangle created by this region is defined as the acceptable load-strain design region. The design strain limit is the maximum permitted strain that can occur in the corroded riser under the given loading conditions.

Figure 2 Process for establishing strain limits on the reinforced structure

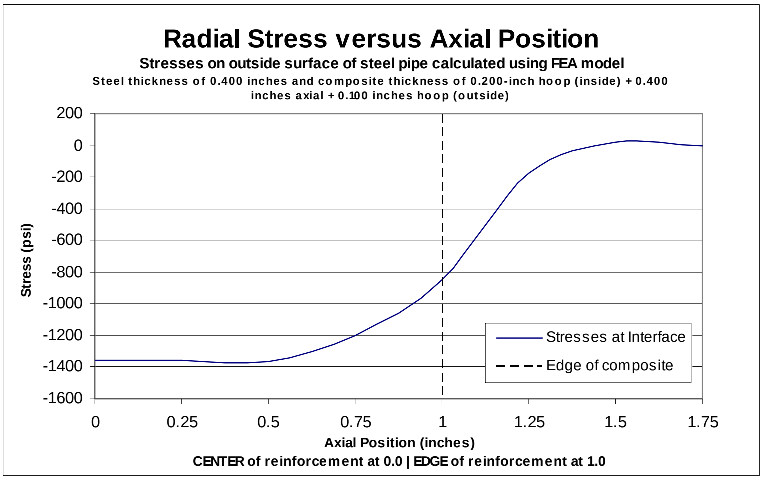


Figure 4 Radial stress at interface between composite and steel

Debonding

The ability of the composite repair to reinforce the damaged pipe or riser is directly related to its interaction with the steel. The effects of surface bond and regions of delamination on the ability of a composite to reinforce a corroded riser pipe. Figure 5 shows the geometry used in the half-symmetry finite element model. The four point bend configuration is selected to take advantage of the constant, shear free bending moment applied across the region between the vertical load points. Shell elements were used to model both the composite and steel materials. However, in regions of debond, contact elements were assigned. The loading on the finite element model included an internal pressure of 2,887 psi, an axial tension load of 145 kips, and an applied bending moment up to 175 kip-ft.

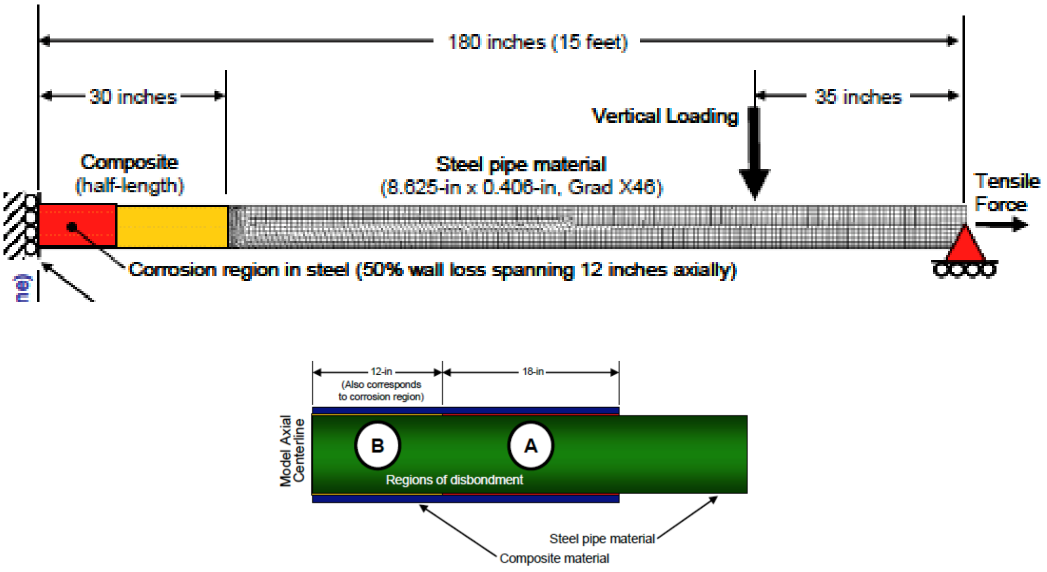


Figure 5 Geometry and boundary conditions for the debond FEA model

The debonded regions are located at the following locations; Case A- outer 18 inches, Case B- inner 12 inches, and Case C- no debonds. From the finite element model strains were extracted in the steel beneath the repair at the axial center of the corrosion. Results are plotted for the three debond cases in Figure 6 for steel and composite. The maximum stress occurs when the outer region debonds (Case A). It should be noted that the maximum stress beneath the repair occurs in the corroded region; however, the reinforcement contribution from the composite material reduces the stresses to levels below stresses calculated in the base pipe outside the repair.

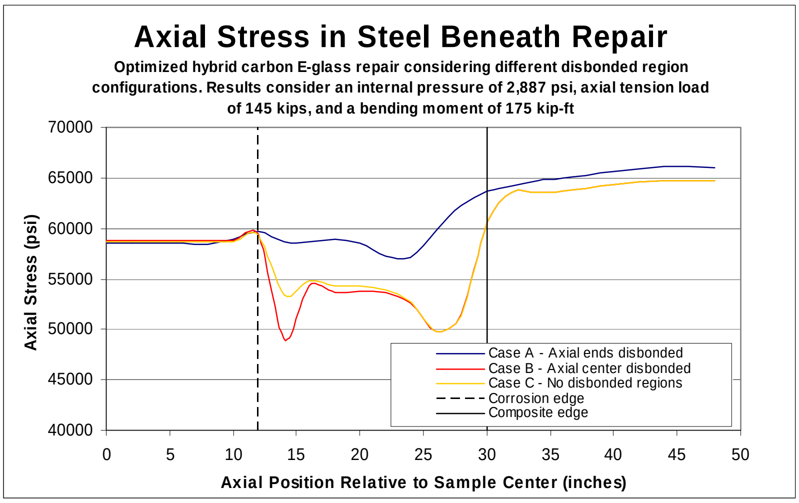
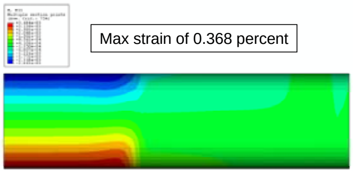
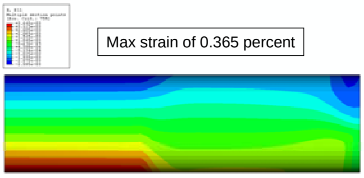


Figure 6 Axial stress in steel and Axial strain in composite shell

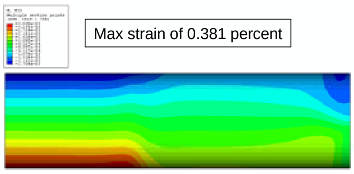


Case A – Axial Strain in halfshell
(outer disbonded region)



Case B – Axial Strain in halfshell
(center disbonded region)

NOTE: Axial strains extracted from inner axially-oriented carbon fibers in halfshell material.



Case C – Axial Strain in halfshell
(completely bonded region)

REFERENCE

[1] C. Alexander, Development of a composite repair system for reinforcing offshore risers, PhD Dissertation, Texas A&M University, 2007.