Residual strength and epoxy-based grout repair of corroded offshore tubular members

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Residual Strength and Epoxy-Based Grout Repair of Corroded Offshore Tubular Members

by

Michael F. Hebor

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Nomenclature

A = Area, in²

A = Coefficient Matrix for Regression Analysis

a_i = Various Individual Regression Coefficients, i = 1, 2, 3, etc

B = Matrix of Regressors for Regression Analysis

COV = Coefficient of Variation

c = Circumferential Dimension of a Corrosion Patch, in.

c_i = Various Constants, i=1, 2, 3,etc

D = Outside Diameter, in.

D_ave = Average Measured Outside Diameter, in.

D_max = Maximum Measured Outside Diameter, in.

E = Modulus of Elasticity, ksi

E_{sh} = Strain Hardening Modulus, ksi

e_x = Eccentricity in X direction, in.

e_y = Eccentricity in Y direction, in.

F = Known Independent Variable Vector

F_y = Yield Stress, ksi

F_{cr} = Critical Local Buckling Stress, ksi

h = Dimension of a Corrosion Patch along the Length of a Member, in.

h_{crit} = Critical h dimension at which One Half-Wave Local Buckle may Form, in.

I_x = Moment of Inertia about x axis, in⁴

I_{xy} = Product of Inertia
\[ I_y = \text{Moment of Inertia about y axis, in}^4 \]
\[ i = \text{Integer Counting Variable} \]
\[ L = \text{Length, in.} \]
\[ M_x = \text{Moment about X Axis} \]
\[ M_y = \text{Moment about Y Axis} \]
\[ n_i = \text{Segment Designation for Simplified Method} \]
\[ \text{LVDT} = \text{Linear Voltage Displacement Transducer} \]
\[ \text{OOR} = \text{Out-of-Roundness, percent} \]
\[ \text{OOS} = \text{Out-of-Straightness, } \delta/L \]
\[ P = \text{Load, kips} \]
\[ P_{ib} = \text{Local Buckling Load, kips} \]
\[ P_u = \text{Ultimate Load, kips} \]
\[ P_y = \text{Full Yield Load of a Specimen, kips} \]
\[ R = \text{Radius, in.} \]
\[ r = \text{Radius of Gyration, in.;} \]
\[ R = \text{Regression Approximation Function (Chapter 4)} \]
\[ r_i = \text{Coordinate Function, } i = 1,2,3, \text{ etc} \]
\[ s = \text{Sleeve Length, in.} \]
\[ t = \text{Unreduced Wall Thickness, in.} \]
\[ t_r = \text{Minimum Reduced Thickness of a Corrosion Patch, in.} \]
\[ x = \text{Arbitrary Distance in x Direction, in.} \]
\[ y = \text{Arbitrary Distance in y Direction, in.} \]
\( \alpha \) = Nondimensionalized Parameter for Code Equations

\( \beta_i \) = Angle between Origin and Segment \( i \) for Simplified Method

\( \theta \) = Angle Subtended by Corrosion Patch, with Origin at Center of the Cross Section.

\( \delta \) = Initial Out-of-Straightness, in.

\( \varepsilon \) = strain, in./in.

\( \varepsilon_{sh} \) = Strain at onset of Strain Hardening, in./in.

\( \nu \) = Poisson’s Ratio

\( \sigma \) = Stress, ksi

\( \sigma_b \) = Bond Stress, psi

\( \sigma_r \) = Residual Stress, ksi

\( \sigma_u \) = Ultimate Stress, ksi

\( \sigma_y \) = Yield Stress, ksi

\( \phi \) = Correction Factor

\( \Omega_i \) = Label for Element \( i \) in Finite Element Model
Abstract

The results are presented from an experimental and analytical study of the residual strength and repair of corroded steel offshore tubular members. Steel tubular test specimens with nominal diameter-to-thickness (D/t) ratios of 34, 46 and 64 were inflicted with a single patch of non-uniform corrosion damage, which was simulated by mechanical removal of portions of the wall thickness over a controlled area of the surface. The ratio of corroded wall thickness-to-original thickness, t/t, and the angle, θ, subtended by the corrosion were used as parameters to define the severity of the corrosion. Length-to-radius of gyration (L/r) ratios for the specimens ranged from 10 to 19, with corresponding length-to-diameter (L/D) ratios ranging from 3.5 to 6.4. The low L/r ratios of the specimens ensured that the mode of failure would be local buckling and not overall global buckling in the corroded specimens. The experimental test matrix consisted of 12 specimens, and included non-corroded stub-columns; "corroded" specimens; and repaired "corroded" specimens. The experimental specimens were separated into two series. Series 1 examined the affect of the D/t ratio of the tubular and the corrosion parameters t/t and θ on the local buckling strength of the member when subjected to pure compression. Series 2 examined the effectiveness of repairing a corroded member with steel sleeves and an epoxy-based grout. The experimental study was accompanied by appropriate analytical analyses and a parametric study using nonlinear finite element modeling of 29 damaged specimens. The results of the parametric study were used to obtain a semi-empirical parametric expression for the residual strength of a patch corroded
tubular by multi-variable regression analysis. The finite element model and analytical analyses were verified by the experimental results and found to be in good agreement.

The experimental test results showed a capacity reduction of up to thirty two percent for corrosion damaged specimens having $t/t=0.50$ and $\theta=311^\circ$. The reduction in strength was largest for specimens with larger patch dimensions and reduced wall thickness. The verified finite element model exhibited possible capacity reductions over sixty percent for severe patches of corrosion, i.e. $t/t=0.33$ and $\theta=311$. The behavior and performance of the repaired specimens was found to be influenced by the bond strength of the grouting material. However, the repair was determined to be successfully implemented with relatively low bond strength grout.

The results of this research study will have direct application to the repair and rehabilitation of deteriorated offshore structures. The study provides vital information about the residual strength of corroded steel tubes, as well as a design basis for repair of the corrosion damage with a sleeve and epoxy-based grout technique.
1. Introduction

1.1 STATEMENT OF PROBLEM

Offshore structures of tubular construction, such as the one shown in Figure 1-1, are subjected to extremely corrosive marine conditions. Despite the use of protective coatings and cathodic protection systems, corrosion damage to these structures has been recognized and reported for many years. Corrosion deteriorates the capacity of a tubular member by reducing the wall thickness, thereby increasing its susceptibility to local buckling in the corroded areas. In recent years, the effects of corrosion of offshore tubular members have become a growing concern as more offshore platforms remain in service past their original design life. In addition, these offshore structures are now being required by the United States Government to be reassessed and requalified.

Corrosion can be generally classified into two types: (1) uniform corrosion; and (2) non-uniform or patch corrosion. Uniform corrosion, as shown in Figure 1-2, consists of a relatively constant reduction of wall thickness around the entire circumference, either over the full or partial length of the tubular. The effects of this type of corrosion are relatively simple to analyze because the member acts essentially as a non-corroded member of a thinner wall thickness. The equivalent wall thickness may be determined from the reduced wall thickness and used to determine the local buckling strength of the corroded tubular from existing local buckling code equations (API RP-2A (1989), DnV (1982), AISI (1986) BS5950 (1990)). Uniform corrosion will not be examined extensively in this study.

Compared to uniform corrosion, the effects of patch corrosion are more difficult
to evaluate. With patch corrosion, only a portion of the circumference has the wall thickness reduced by the corrosion, as shown in Figure 1-2. Therefore, the cross section of the tubular is no longer symmetric, resulting in a shift of the center-of-gravity of the cross section and creating an internal eccentricity. This type of corrosion will be addressed in this study, and any further mention of corrosion will refer to patch-type corrosion.

Several structural changes occur due to the corrosion reduction of the wall thickness on only one side of a tubular member. First, there is an overall reduction of the gross area of the member. This gross area reduction increases the overall axial stress in the member. Second, the patch corroded area has a reduced local buckling strength due to the local reduction in wall thickness. Finally, as noted previously, there is a shift of the center-of-gravity of the cross section directly away from the patch of corrosion, resulting in an eccentricity between the geometric center and the center-of-gravity of the corroded cross section. An internal moment is created by this eccentricity which causes additional compressive stress in the area of the corrosion patch. The combination of these structural changes creates the undesirable situation where the nominal applied axial stress is amplified at a patch of corrosion by the reduced cross section and internal moment, while the local buckling strength of the corroded area is reduced by the thinner wall thickness. In addition, the variation in wall thickness can create a stress concentration in the corrosion patch. Furthermore, there is the tendency for plane sections to not remain plane due to local buckling. It is clear that patch corrosion can create a severe threat of local buckling at a load far below the intended capacity of the non-corroded member, and
that the analysis of a member with non-uniform corrosion can be difficult.

1.2 LOCAL BUCKLING

1.2.1 Theory of Tubular Local Buckling

For tubular compression members used in offshore structures \((D/t < 100)\) the local buckle shape is a classic ring bulge. Higher \(D/t\) tubulars will often buckle locally with a symmetric pattern of diamond shaped local buckles. Energy methods can be used to determine the elastic critical buckling load for a short tubular subjected to compression. The method involves setting the work done by the external applied load at buckling equal to the internal strain energy of the member. The internal strain energy is attributed to the strain of the pure axial shortening before buckling initiates, and also circumferential and bending strains after buckling initiates. The change in strain energy \(\Delta U\) in the tubular member after buckling initiates is given by Timoshenko and Gere (1961) based on a unit strip of the wall (as shown in Figure 1-3) as:

\[
\Delta U = -2\pi h E v \epsilon_0 \int_0^l A \sin \frac{m \pi x}{l} dx + \frac{\pi A^2 Eh l}{2a} + A^2 \frac{\pi^4 m^4}{2l^4} \pi a l D \quad (1-1)
\]

Where:

\(A\) = Cross-sectional Area

\(D\) = Flexural Rigidity; = \(Eh^3/12(1-v^2)\)

\(E\) = Young’s Modulus

\(N_{cr}\) = Critical Applied Load per Unit Length of Circumference
\[ a = \text{Radius} \]
\[ h = \text{Thickness} \]
\[ l = \text{Length} \]
\[ m = \text{Integer Number of Half-waves} \]
\[ x = \text{Arbitrary Distance along Length} \]
\[ \varepsilon_0 = \text{Axial Strain Prior to Buckling} \]
\[ \nu = \text{Poisson's Ratio} \]

and the work done \( \Delta T \) by the compressive applied load is given as:

\[
\Delta T = 2\pi N_{cr} \left[ \nu \int_0^l A \sin \frac{m\pi x}{l} dx + \frac{A^2}{4} \frac{m^2 \pi^2}{l} \right]
\]  (1-2)

equating \( \Delta U \) to \( \Delta T \), the elastic buckling stress \( \sigma_{cr} \) for a tubular shell with no imperfections is obtained as:

\[
\sigma_{cr} = D \left( \frac{m^2 \pi^2}{hl^2} + \frac{E}{a^2 D m^2 \pi^2} \right)
\]  (1-3)

Assuming \( \sigma_{cr} \) is a continuous function of \( (m \pi/l) \), and that many waves form along the length of the tubular during buckling, the minimum value of \( \sigma_{cr} \) can be obtained as:

\[
\sigma_{cr} = \frac{Eh}{a \sqrt{3(1-\nu^2)}}
\]  (1-4)
which occurs at:

\[ \frac{m \pi}{l} = \frac{4 \sqrt{\frac{Eh}{a^2 D}}}{l} \]  (1-5)

Therefore, according to this formulation, local buckling of the tubular is a function of the material properties \( E \) and \( \nu \) and the geometric properties \( a \) and \( h \). Note that this solution assumes a uniform buckling mode shape around the circumference.

This energy method works well for tubular members which have constant wall thickness because the strain energy is distributed evenly throughout the entire wall. This uniform strain distribution results in a uniform buckled shape (either a ring bulge for low \( D/t \) tubulars or lobular buckles for high \( D/t \) tubulars), and no overall bending stresses (i.e. there are only longitudinal compressive stresses in the wall). In contrast, when the wall thickness of a tubular is reduced by corrosion the strain distribution is no longer uniform and bending stresses are induced by the internal moment which is generated. The corrosion patch will buckle first and "soak-up" internal strain energy while other areas will give up strain energy. While the concept of external work equaling internal strain energy is still valid, the non-uniformity of a corroded tubular makes applying this theory difficult. The buckled shape of the tubular is also no longer symmetric and lateral deflections are induced. Because the buckled shape is no longer symmetric about the longitudinal axis, a unit strip of the wall can no longer be used. In addition, inelastic buckling may occur, in which case the above equations are not valid.

Experimentally, local buckling can be identified as the separation of strains on two
sides of the wall of the tubular caused by the local bending of the wall at the local buckle. Sometimes local buckling is identified as the point on the load-displacement plot where the curve starts to significantly deviate from the linearity or near-linearity. Unfortunately, determining the local buckling load is somewhat subjective because the point of local buckling is not always obvious.

1.2.2 Local Buckling Design Criteria for Non-corroded Tubulars

There are many different steel design codes which define limiting stress values for local buckling of circular tubular sections of uniform wall thickness. Presented below are some that are applicable.

1. API (American Petroleum Institute, RP-2A (1989))

\[
\frac{F_{cr}}{F_y} = 1.0 \quad \text{for } \frac{D}{t} \leq 60 \quad (1-6)
\]

\[
\frac{F_{cr}}{F_y} = 1.64 - 0.23 \sqrt[4]{\frac{D}{t}} \quad \text{for } \frac{D}{t} \geq 60 \quad (1-7)
\]

2. DnV (Det Norske Veritas. In an adapted form presented by Ostapenko et. al. (1993))

\[
\frac{F_{cr}}{F_y} = 1 - \frac{1}{3} \left( \frac{1.5 + 0.001 \left( \frac{D}{t} \right)^2}{\alpha} \right) \quad (1-8)
\]
Where:

\[
\alpha = \frac{E/\sigma_y}{D/t}
\]  \hspace{1cm} (1-9)

3. AISI (American Iron and Steel Institute: Specification for the Design of Cold-Formed Steel Structural Members (1986))

\[
\frac{F_{cr}}{F_y} = 1.0 \quad \text{for } \alpha \geq 9.1
\]  \hspace{1cm} (1-10)

\[
\frac{F_{cr}}{F_y} = 0.665 + 0.0368 \alpha \quad \text{for } 2.27 \leq \alpha \leq 9.1
\]  \hspace{1cm} (1-11)

Where:

\[
\alpha = \frac{E/\sigma_y}{D/t}
\]  \hspace{1cm} (1-12)

In the above equations, \(F_{cr}\) is the critical local buckling stress; \(F_y\) is the yield stress; \(E\) is the modulus of elasticity; \(D\) is the diameter; and \(t\) is thickness. The above API and the DnV equations are commonly used in the design and assessment of offshore structures in U.S. waters and the North Sea. All the local buckling equations listed above were developed and intended to be used for tubular members with constant wall thickness. Therefore, as described in Section 1.1, these equations could be used for a uniformly corroded tubular member. In the case of uniform corroded members, the wall thickness
around the circumference is corroded somewhat evenly and an equivalent thickness can be determined and used in these local buckling formulas. However, these equations are not applicable for use when the tubular member is damaged by patch corrosion. It is clear, therefore, that there is a definite need for an equation which provides the residual strength of a corrosion damaged tubular member based on the corrosion parameters.

Note that, except for the API code specification, all of the above local buckling equations are dependent on the yield strength of the steel. This is because the API local buckling specification is limited to members with D/t less than 300, and the local buckling strength of tubulars with D/t less than 300 are generally unaffected by varied yield stress. This study is only considering the tubular members which are most commonly used by the offshore industry in fixed offshore platforms, which are tubular members with a D/t ratio less than 100. Therefore, this study does not consider variations of yield strength.

1.3 PREVIOUS CORROSION RESEARCH

Extensive experimental and analytical research studies have been performed to analyze the residual strength and repair techniques for dent damaged tubular members. Some of the more recent work includes that by Ricles et. al. [1994]; Landet et. al. [1992]; Taby [1986]; Ostapenko et. al. [1993]. Few studies, however, have examined the residual strength and repair of corrosion-damaged tubulars. Ostapenko et. al. [1993] conducted concentric axial tests on two patch-corroded offshore tubular members salvaged from Gulf of Mexico platforms which were decommissioned after an estimated twenty
to thirty years of service. The corrosion on these tubular members is shown schematically in Figure 1-4. These tubulars had diameter-to-thickness (D/t) ratios of 33 and length-to-radius of gyration (L/r) ratios of 80 (Specimen C1) and 58 (Specimen C2). These tests showed that the most severely corroded area can cause local buckling to govern member strength. The strength of the specimens were found to be reduced by approximately 50 percent (Specimen C1) and 27 percent (Specimen C2) when compared with their non-damaged strength.

Once the residual strength of a corroded tubular member has been determined to be at a critical level, repair options must be reviewed. Total member replacement is usually neither feasible nor necessary. Non-welding underwater repair techniques for dent damaged tubulars have included the studies by Ricles et. al. [1993], Billington [1987], Parsenejad [1987, 1992]. These techniques include both external steel sleeve and full or partial internal grouting. These repair methods use relatively low bond strength cement-based grout to confine the dent damage and prevent the dent from growing. By preventing the dent from growing, primarily through radial stiffness provided by the grout or sleeve, the original capacity of less severely damaged tubular members can be restored. However, repair of corrosion damage is influenced by load transfer across the corroded patch. The external steel sleeve concept is considered in this study to provide this load transfer. A cement-based grout, which fills the annulus, is replaced with epoxy-based grout having a much higher bond strength in order to develop a stronger bond stress load transfer mechanism across the corrosion patch. This epoxy-based grout sleeve repair also restores the lost gross section and minimizes the corrosion induced internal moment by
reducing the eccentricity in the corroded cross section. Using a high bond strength epoxy-based grout will allow for the use of much shorter steel sleeves as compared to the sleeve length using a lower strength cement-based grout. Specifics of the repair will be discussed in more detail in Chapter 5.

1.4 OBJECTIVES

The need for assurances of platform reliability and safety necessitates the development of techniques to evaluate the residual strength and repair of corroded tubular offshore members. A current lack of information puts practicing engineers at a disadvantage when they must assess the residual strength and repair of corroded tubular members without a clear indication of the effects of patch corrosion. This research study was conducted to enhance the knowledge base of the behavior of corroded tubular members and to assess sleeve type repair techniques.

The objectives of this study were:

1) Experimentally investigate the residual strength and behavior of short, patch corroded tubular steel bracing members subjected to concentric axial loading;

2) Parameterize patch type corrosion and develop a working model of patch corrosion based on the most sensitive parameters;

3) Perform an analytical investigation using nonlinear finite element analysis to determine the applicability of the method for predicting the residual strength of corrosion damaged
members;

4) Formulate a strength equation which provides the residual strength of a concentrically loaded, patch corroded short tubular member based on measurable corrosion parameters;

5) Experimentally investigate the use of a prototype epoxy-grouted exterior sleeve repair technique to increase the residual strength of corroded tubular members.

1.5 SCOPE OF STUDY

A detailed description of all facets of this study is included in the following chapters. Chapter 2 discusses the characterization of corrosion and how it is modeled in this study. Chapter 3 describes the experimental study of corrosion damaged tubular members. Chapter 4 describes the analytical study of corrosion damaged tubular members. Chapter 5 describes the repair of corroded tubular members. A summary, conclusions and recommendations for future work are presented in Chapter 6.
Chapter 1

Figures
Figure 1-1. Typical Offshore Structure Composed of Tubular Members.
[T. Dawson, Offshore Structural Engineering, 1983]
Uniform Corrosion

Equivalent uncorroded tube with wall thickness based on reduced wall thickness of corroded tube.

Local buckling stress determined from existing code requirements.

AP1 RP2A  DNV
AISI  EuroCode

Patch Corrosion

Analytical database of finite element analysis results verified with experimental results.

Local buckling stress determined from multi-variable nonlinear regression analysis.

\[ \frac{\sigma}{\sigma_y} = f(D/t, \text{Corrosion Parameters}) \]

Figure 1-2. Analysis of Uniform and Patch Type Corroded Tubulars.
Figure 1-3. Typical Elastic Buckled Shape of an Undamaged Tubular Member.
Figure 1-4. Corrosion of Two Tubular Braces from Gulf of Mexico Offshore Platforms [A. Ostapenko et. al. 1993]
2. Characterization of Corrosion

2.1 GENERAL

Section 1.1 defined patch corrosion and the qualitative effects it has on a tubular member (reduced gross area, shifting of cross section centroid inducing internal moments, and reduced local buckling resistance of corroded wall). In order to investigate and quantify these effects, a model of a corrosion patch must be developed which behaves similar to actual corrosion. This chapter describes how this study idealized a patch of corrosion in order to apply this model to actual corroded tubular members.

2.2 GEOMETRY OF PATCH CORROSION

This study will concentrate on strength reduction due to one individual patch of corrosion. An individual patch of corrosion is defined as an area of corrosion which originates from one single point or line and propagates radially from that origin. This corrosion progression results in a circular or elliptic shaped patch of corrosion, as shown in Figure 2-1(a). This definition of patch corrosion is representative of one form of corrosion found in the field. Inspection of the salvaged, patch corroded tubulars tested by Ostapenko et. al. (1993) has confirmed this definition of a patch of corrosion (See Figure 1-4).

2.2.1 Corrosion Patch Idealization

For this study, the shape of a patch corrosion was idealized as an ellipse. It will
be shown later that this elliptical shape is a reasonable approximation because the residual
strength of the tubular is more sensitive to the major axis (width) of the corrosion patch
as opposed to the minor axis (height) of the corrosion patch. It will also be shown that
the true shape of the corrosion patch is not as important as the critical parameters of the
idealized geometry of the corrosion patch (the critical corrosion parameters will be
defined in Section 2.3).

Since corrosion is a random process, the thickness reduction around the
circumference can be very irregular. However, by considering the point of origin of the
corrosion as being the most severely corroded (because it has been corroding the longest)
and the edges of the corrosion patch as the least corroded (because it has just started to
corrode) and assuming axis symmetry of the corrosion, we can develop a thickness
reduction distribution. By considering the slope of the thickness profile to be zero at the
point of origin and at the edges of the corrosion patch, the thickness reduction distribution
takes the form of a half sine wave starting at the origin of the corrosion and ending at the
edge of the corrosion patch, as shown in Figure 2-1(b). This half-sine wave thickness
distribution was used as the assumed thickness distribution for this study.

It should be noted that both the assumed shape and thickness profile were used
to maintain consistent corrosion geometry while the sensitive corrosion parameters were
varied and examined. The effects of minor changes in the shape and profile are minimal
compared with minor changes in the critical parameters, and it is noted that any assumed
shape or profile can only approximate the true random geometry of the corrosion patch.

The dimensions of the elliptic patch of corrosion can be defined by the following
parameters: the circumferential dimension 'c' (major axis) of the corrosion patch; the longitudinal dimension 'h' (minor axis) of the corrosion patch; and the minimum reduced wall thickness \( t_r \) in the patch of corrosion (See Figure 2-2). These three dimensions and the thickness profile will be used to idealize any size and severity of actual patch corrosion. Idealization of corrosion will be discussed further in Section 2.4.

### 2.3 CRITICAL PARAMETERS OF PATCH CORROSION

Of the dimensions presented, 'c' and \( t_r \) are the sensitive dimensional parameters. Finite element analysis has shown that the 'h' dimension (the height dimension of the corrosion) is not a sensitive parameter, provided there is a certain minimum critical \( h_{crit} \) dimension provided. This minimum \( h_{crit} \) dimension has to be large enough to allow for at least one local buckle half-wave to form (See Figure 2-3). If \( h \) is less than \( h_{crit} \) the wall surrounding the corrosion patch constrains the reduced wall and restrains the local buckle from forming. Consequently, if \( h \) is equal to or greater than \( h_{crit} \) the residual strength of the member is sensitive to the cross sectional thickness reduction, and not sensitive to the reduction along the length of the tubular member. This study used a constant \( h \) of one radius for all experimental and analytical investigations. Applying the results of this study to cases when \( h \) is less than \( h_{crit} \) would provide a conservative result. The effects of \( h \) less than \( h_{crit} \) on the member capacity was left for future studies.

The circumferential width dimension \( c \) of the corrosion (major ellipse axis) is a parameter which can be non-dimensionalized by dividing it by the radius \( (c/R) \) of the cross section, resulting in the non-dimensionalized parameter \( \theta \). The \( \theta \) angle is
subtended by c and has its origin at the geometric center of the cross section. The reduced thickness of the tube wall $t_i$ can also be non-dimensionalized by dividing by the original thickness $(t_i/t)$. Thus, this non-dimensionalized parameter gives the reduced thickness as a percentage of the original thickness. The sensitive parameters are shown schematically in Figure 2-2. The other parameter affecting the residual strength to be considered is the $D/t$ ratio of the member.

All tubular members considered in this study were made of steel. Therefore, the modulus of elasticity, $E$, will be considered constant $(E=29500 \text{ ksi})$. The yield strength of the steel, $F_y$, has an influence on local buckling for tubulars with $D/t$ ratios greater than 100, but has little or no effect for tubulars with low to moderate $D/t$ ratios in the range of 30 to 90, such as those used for offshore structures. These trends have been confirmed by finite element results and by the API RP-2A code requirement for local buckling, which is only dependent on the $D/t$ ratio. Therefore, $F_y$ will not be considered as a sensitive parameter for residual strength, which restricts the results of this study to be applicable for tubular members with $D/t$ ratios of less than 100.

Hence, with the above three parameters selected to define a corrosion patch, the objective of this study was to formulate an expression for the local buckling strength $P_{lb}$ as a function of $\theta$, $t_i/t$, and $D/t$.

\[
P_{lb}/P_y = f(D/t, t_i/t, \theta)
\]

Where:
\[
\theta = c/R
\]
2.4 IDEALIZATION OF ACTUAL CORROSION

Since corrosion is a natural process it can actually take any shape, and not necessarily the elliptical shaped used for this study. Fortunately, as described previously in Section 2-3, the longitudinal dimension \( h \) is not a sensitive parameter as long as the minimum critical dimension \( h_{\text{crit}} \) is provided. This limiting \( h_{\text{crit}} \) dimension allows one to use a 'corrosion block' of height \( h_{\text{crit}} \) to define a simplified corrosion patch shape for irregularly shaped corrosion patches. The \( h_{\text{crit}} \) dimension is kept constant and only the circumferential dimension \( c \) is varied until the largest \( c \) dimension is found for a specific patch of corrosion, as shown in Figure 2-4.

For tubulars with multiple patches of corrosion, several of the most severe patches would have to be analyzed to determine which patch governs the local buckling capacity of the tubular. This study is not considering multiple patches of corrosion, however, it has been demonstrated by Ostapenko (1993) that the most severe patch of corrosion ('most severe' being defined by the combination of the \( \theta \) and \( t/t \) parameters for a given tubular member) will control the capacity of the member. The most severe corrosion patch will buckle first and cause a reduction in strain energy taken by all the other corrosion patches, thus, preventing them from buckling.

In an actual patch-corroded tubular member the thickness \( t_r \) can be determined in one of two ways. A conservative approach would be to use the minimum measured thickness for \( t_r \). Determining \( t_r \) in this way would produce the thickness distribution shown in Figure 2.5(a), where the assumed thickness distribution is a lower bound of the actual profile. A less conservative assumption for \( t_r \) would be to use the average of the
thickness values over the most severely corroded area of the corrosion patch. This averaging method would produce the thickness distribution shown in Figure 2.5(b), where the assumed thickness distribution forms a mean through the actual thickness profile. For field corrosion assessment of in-situ tubulars it is recommended that the minimum thickness measurement be used until further studies can be performed.
Chapter 2

Figures
Figure 2-1. (a) Elliptic Shape of Corrosion Patch Used in this Study. (b) Half Sine Wave Profile of Thickness Used in this Study.
Figure 2-2. Stub-Column Patch Corrosion Parameters.
Figure 2-3. (a) Thickness reduction with $h$ equal to $h_{\text{crit}}$ and (b) Thickness reduction with $h$ less than $h_{\text{crit}}$. 
Figure 2-4. Critical Corrosion Width and Height for Various Shapes and Orientations of Patch-Type Corrosion.
Figure 2-5. Assumed Corrosion Profile and Arbitrary Actual Profile (a) Using Minimum Measured Thickness for $t_r$ (b) Using Averaged Thickness for $t_r$. 

Conservative Profile: Use Minimum Measured Thickness for $t_r$

(a)

Averaged Profile: Use Average Measured Thickness for $t_r$

(b)
3. Residual Strength of Corroded Tubular Members - Experimental Program

3.1 GENERAL

The results from the experimental test program of patch corroded tubular offshore members is presented in this chapter. The general test matrix for this work is shown in Table 3-1. The objective of this study portion of the study was to experimentally investigate the residual strength and behavior of patch-corroded tubular offshore members.

To accomplish the objective, newly manufactured large-scale steel tubulars were inflicted with simulated 'corrosion' conforming to the assumed elliptic shape and half-sine wave profile presented in Section 2.2. Corrosion of the tubular members was simulated by mechanically grinding the wall of the tubular over a specified area. The corrosion patch was ground on the opposite side (180° line) of the cross section from the longitudinal weld of the tubular. During the grinding operation, measurements were taken using templates and ultrasonic methods to ensure the proper profile and dimensions of the corrosion. An isometric depiction of the ultrasonically measured surface from the grinding operation for Specimens 34-33-58 and 34-33-95 are shown in Figure 3-1(a), and the profile of the corrosion for Specimens 46-33-95 and 46-67-95 are shown in Figure 3-1(b). Measured corrosion parameters for all specimens are summarized in Table 3-2.

Specimen names were based on the D/t ratio and corrosion geometry with which
they have been inflicted. For example, Specimen 46-33-95 is a tubular member with a D/t ratio of 46, minimum wall thickness reduced to 33 percent of the original thickness in the corroded area (i.e. t,t/0.33), and the width of the corrosion patch subtended a θ angle of 95°.

The results from experimentally testing 'corroded' tubular members was used to calibrate the finite element model of corroded tubulars. The finite element analysis will be discussed in-depth in Chapter 4.

3.2 SPECIMEN TEST MATRIX

The test matrix for corrosion damaged tubular members is summarized in Table 3-1. All specimens tested were made from 8.625 inch outside diameter ERW steel structural pipe. Three different wall thicknesses were tested: 0.25 inch; 0.1875 inch; and 0.135 inch. These three wall thicknesses corresponded to a radius-of-gyration of approximately 3.0. The length L of the corroded specimens was 55.5 inches, which corresponded to a slenderness ratio (L/r) of 18.5 for all specimens. The specimens intentionally had a low slenderness ratio to ensure that local buckling would be the controlling mode of failure as opposed to overall global buckling. Actual dimensions of each test specimen are listed in Table 3-2. The non-corroded specimens were stub columns having a length of 30 inches. The non-corroded specimens are discussed in more detail in Section 3.3 - Material Properties.

All specimens were checked for out-of-straightness (OOS) and out-of-roundness (OOR). All specimens were within 0.00054 L out-of-straightness and 0.46 percent out-of-
roundness, and consequently were within API RP-2A (1993) tolerances. Maximum
imperfections for each corroded specimen are listed in Table 3-3.

3.3 MATERIAL PROPERTIES

3.3.1 General

All specimens were supplied as electric resistance welded (ERW) structural pipe
with an ASTM A53 Type B specification. This specification mandates a minimum yield
stress of 34 ksi, however, it does not specify a maximum yield strength. Because of the
recent manufacturing process used by the mills for these hot rolled tubes, the yield
strength of all tubes of these dimensions is commonly from 55 to 60 ksi. Tensile coupons
taken from the tubulars confirmed the mill reports as having a yield strength of 60 ksi and
a tensile strength of 70 ksi with virtually no yield plateau and 23 percent elongation. This
material was not representative of the steel commonly used at the time of construction of
most corrosion damaged platforms. Most corrosion damaged offshore platforms are ten
or more years of age, and were constructed of mild A36 grade steel, having a yield stress
in the range of 36 to 42 ksi; yield plateau to a strain of approximately 10 times the yield
strain; and twenty-five to thirty-five percent elongation. Tubulars with these material
properties and the required dimensions were not readily available from any supplier,
therefore, it was necessary to have the tubulars annealed to create material properties
more representative of the in-situ structures.

Several test coupons were annealed and tested to confirm the annealing procedure
to be used. The tubulars were then annealed in a vertical hanging position by heating
them to 1650° F followed by furnace cooling (turning off the furnace and allowing it to cool very slowly over a period of 24 hours) to below 750° F. After annealing, the steel possessed a yield strength of approximately 40 ksi and a tensile strength of 60 ksi. The steel also had a yield plateau to a strain of ten times the strain at yield and an elongation of 34 percent. Figure 3-2 shows typical stress-strain curves of pre- and post-annealed tensile coupons. The annealed steel was more representative of the in-situ material of offshore platforms.

In addition to changing the stress-strain material properties, the annealing process relieved all residual stresses from within the tubular. The post annealing stub columns showed that there were essentially no residual stresses remaining in the tubulars. The removal of residual stresses may not be representative of the in-situ tubulars which do possess some amount of residual stresses, however, the effect of residual stresses was analytically assessed and will be discussed in Section 4.2.3 - Finite Element Analysis Results.

3.3.2 Tensile Coupons

Tensile properties of the specimens were determined by conducting tensile coupon tests. The specimens were fabricated according to the ASTM (American Society for Testing Materials, 1991) standards having a width of 1.5 inches and gage length of 8 inches. The coupons were taken from the end portions of the annealed tubulars. Two coupons for each D/t specimen were cut from the longitudinal direction of the tubular.

The coupons were tested according to SSRC Technical Memorandum B.7
(Galambos, 1988) in a 120 kip Tinius-Olsen (Tinius-Olsen Machine Co., Willow Grove, PA) displacement controlled universal testing machine. An eight inch extensometer was used to measure strain in the gage length of the coupons. The coupons were tested with a strain rate of 0.0025 in/min for the dynamic measurements. Static readings were taken in the yield plateau by holding the axial displacement and allowing the load maintained by the specimen to stabilize. Several static readings were taken in the yield plateau to establish the static yield stress. Final area and elongation measurements were then taken after testing. A typical stress-strain plot for the coupons is shown in Figure 3-2 (post-annealed coupon).

3.3.3 Stub-Columns

Stub-columns for each D/t were also annealed with the specimens. The purpose of the stub-column tests was to determine the level of residual stresses and the compressive material properties. In addition, the stub-column tests also served as control tests of non-corroded tubes. Each of the 30 inch long stub-columns had a 10 inch gage length. All stub-column ends were saw cut. Cardboard bearing material was used at both ends to eliminate any stress concentrations due to imperfections of the saw cuts. Each specimen was placed directly on the pedestal of a 600 kip Satec (Satec Systems Inc., Grove City, PA) universal testing machine. A machined plate was placed on the top of each stub-column. A wet Hydrostone (Hydrostone Gypsum Cement, United States Gypsum, Chicago, Illinois) grout mixture was placed on top of the plate and the machine head was lowered until the Hydrostone grout squeezed out from all sides of the plate,
leaving approximately 1/16 to 1/8 inches between the machine head and the plate. There was no metal-to-metal contact between the head and the machined plate. Using the Hydrostone in this manner assures there is no stress concentrations due to out-of-squareness of the specimen saw cut and assisted in properly aligning the stub-column.

Instrumentation of the stub-columns consisted of four +/- 1 inch LVDTs (Linear Voltage Displacement Transducer - G00, G90, G180, G270) placed on the gage length at four opposite sides. Head travel and load were read directly from the machine. Data was recorded with the DATACQ 3.1 automated computer controlled data acquisition system. The stub-column test setup and instrumentation are shown in Figure 3-3.

The test procedures in SSRC Technical Memorandum B.3 (Galambos, 1988) were followed for the testing of the stub-columns. A loading rate of 0.01 in/min was used for the dynamic measurements. Several static readings were taken by stopping the loading and holding the displacement until the load maintained by the specimen had stabilized.

Typical stress-strain plots for the different D/t specimens are shown in Figure 3-4. The stub column test results confirmed that there were no residual stresses present in the annealed tubulars, and also confirmed the yield stress obtained from the tensile coupon tests. Yield stress values from the stub-column tests were used for all analytical analyses. The compressive yield stress for each specimen is summarized in Table 3-4.

The stub-column specimens are identified in Table 3-1 as Specimens 34-100-0, 46-100-0, and 64-100-0 for use as the undamaged control specimens. These specimens were used in comparison with the corrosion damaged specimens to indicate a loss of strength due to the corrosion.
3.4 Test Setup

The unrepaired test specimens were tested in a 600 kip Satec universal testing machine. The machine was a hydraulic controlled machine which can be used for load control or displacement control through a computer. A fixed machine head configuration was used, which prevented any rotation of the ends of the specimen in any direction.

The specimens were installed in the testing machine as follows: a specimen was installed upright with the 'A' end at the top. The specimen was positioned with the 315° degree line facing forward. This allowed for better visibility of the corroded patch (0° line) as well as the side of the specimen (270° line) from the front and back of the testing machine. The 'B' end, or bottom of the specimen was placed on the machine pedestal with a dense cardboard bearing material used to prevent metal-to-metal contact. As in the stub-column setup, the bearing material was used to prevent stress concentrations at the end due to minor imperfections of the saw-cut ends. A second piece of cardboard bearing material was then placed on top of the specimen, and a 2 inch thick bearing plate, milled on both sides, was placed on top of the bearing material.

To eliminate any stress concentrations due to out-of-squareness of the ends of the specimen, Hydrostone cement-based grout was used, placing it between the milled bearing plate and the machine head. The Hydrostone grout was placed by first lining the milled plate and the machine head with a thin plastic to eliminate bonding of the grout to these surfaces. The grout was mixed to a paste-like consistency and placed in a mound on top of the plastic lined bearing plate. The machine head was then lowered until the grout
squeezed out from all edges of the milled plate, and there was approximately 1/16 to 1/8 inch between the milled plate and the machine head. Therefore, there was no metal-to-metal contact between the machine head and the milled plate on top of the specimen. The Hydrostone grout was allowed to cure for approximately one hour before testing. During this time the instrumentation was installed, and the specimen was white-washed to highlight yield lines. Figure 3-5 shows a schematic of the test setup, with a photograph of the test setup given in Figure 3-6.

3.5 Instrumentation

All data from the instrumentation was collected using the DATACQ 3.1 computer-controlled data acquisition system. Typically, four channels of LVDTs (Linear Voltage Displacement Transducer) and twenty-four channels of strain gages were used for each corrosion damaged specimen. Two more channels were used to record the load and head travel from the machine. The system was protected with a backup power supply, and the load and head travel were also recorded by the computer in the Satec overhead test machine as an additional backup.

Figure 3-7 is a schematic of the instrumentation setup for the corrosion damaged specimens. The LVDTs used were four +/- 1" transducers. Two LVDTs, Vert1 and Vert2, were positioned vertically at the 0° and 180° lines respectively to measure axial shortening of the specimen. These LVDTs were attached to the bottom of the specimen with magnetic bases, and a wire extended from each to the top of the specimen, where each wire was attached to the specimen with clamps. The other two LVDTs, Lat1 and
Lat2, were positioned horizontally at mid-height on the 0° and 180° lines respectively to measure the lateral displacement of the specimen at mid-height.

Uni-axial, 120 ohm strain gages were used. Eight of these strain gages were utilized as alignment gages and were positioned in groups of four at two levels: one level at one-quarter height; the other level at three-quarter height. Around the circumference, the alignment gages were positioned at the 0°, 90°, 180°, and 270° lines. These gages were used to check to make sure the load was being applied concentrically, i.e. the strains in these gages should be uniform at low to moderate elastic load levels.

Eight more of the strain gages, M1 through M8, were used at the mid-height of the specimen. Around the circumference, these gages were positioned at the 0° (center of the corroded patch), 33°, 60°, 90°, 180°, 270°, 300°, and 327° lines. For the specimens with θ=95°, the 0°, 33° and 327° line strain gages were within the corroded patch, while for the specimen with θ=58° only the 0° line gage was inside the corroded patch.

The remaining eight strain gages, L1 through L8, were positioned around the circumference identically to the M series of strain gages, however they were positioned at a level either one radius above or below the mid-height.

Note that Specimen 34-50-311 used two additional strain gages at mid-height in order to capture the strain distribution through the relatively large corrosion patch (θ=311°). These gages, M9 and M10, were positioned at the 135° and 225° lines at mid-height.
3.6 Typical Specimen Response

Typical response of a corroded tubular to concentric axial load began with linear elastic behavior at low load levels. As axial shortening increased the load-deformation plot became gradually more non-linear as yielding and local buckling occurred. The strains in the corrosion patch gradually become more nonuniform with increased axial deformation. Yielding initiated in the center of the corrosion patch, and gradually extended around the circumference. This yielding continued until a local instability was formed at the corrosion patch. The corrosion patch buckled locally, as stresses redistributed around the circumference. The load-deformation curve softened as the local buckle formed. Axial load on the tubular increased an additional 3 to 5 percent above the local buckling load before it began to deteriorate. This typical behavior is clearly exemplified by Specimen 34-50-311 in Figure 3-18(a).

For all specimens, except Specimen 34-33-58, the buckle formed an asymmetric ring-bulge. This bulge initiated at the corrosion patch and gradually propagated around the circumference with increased axial displacement beyond the ultimate load. Specimen 34-33-58 buckled inward at the center of the corrosion patch. The inward buckle was induced because the corrosion patch had a c dimension very close to h (i.e. c/h=1.0). The other specimens had c values greater than h (c/h=1.67 to 5.47), causing an outward ring bulge to occur. Figure 3-8 shows photographs of both the inward and outward buckling modes, as well as the yield line patterns in the vicinity of the corrosion patch.

The occurrence of local buckling for the outward buckling mode can be determined by the longitudinal strains at mid-height. The longitudinal strain gages are
on the outside wall surface of the tubular, therefore, before local buckling occurs the
gages record compressive strains (positive). However, when outward local buckling
occurs, local bending of the wall creates tensile strains (negative) on the outside wall
surface. Therefore, the formation and propagation of a local buckle can be monitored by
the strain reversal of the mid-height longitudinal strain gages. Figure 3-9 shows a three
dimensional plot of the history of mid-height longitudinal strains around the
circumference of Specimen 34-33-95. The strain history begins at zero and ends at the
ultimate load. The formation and propagation of the local buckle is marked where a
reversal in strain occurs at the center of the corrosion patch. Compressive strains at the
edges of the corrosion patch are shown in Figure 3-9 to become large.

Axial strains at the level one radius above the corrosion patch (not shown)
remained uniform until the post ultimate load range. As axial displacement continues
beyond that corresponding to peak load, the local buckles enlarge at the corrosion. The
axial strains directly above the corrosion patch unloaded, and in some cases completely
reversed to tensile strains. These tensile strains were caused by local curvatures in the
wall due to the local buckle wave.

For the inward local buckle, the mid-height strains did not reverse after local
buckling, but rather increased to the maximum measurable strain of the strain gages. In
the case of the inward buckle, the outside wall surface is the compression face when local
bending of the wall occurs. Consequently, the compressive strains in the gages on the
outside wall surface never experience a strain reversal. The history of the strain
distribution around the circumference at mid-height for Specimen 34-33-58, having an
inward buckling mode, is shown in Figure 3-10. Note that the highest compressive strains develop at the center of the corrosion patch.

The strains at a level one radius above the corrosion remained uniform until displacements beyond the ultimate load were imposed. The area of the wall directly above the corrosion patch reversed strain in the post-ultimate load range, and eventually exhibited some tensile strains.

Yielding of the wall on the side of the specimen opposite the corrosion patch occurred at the top and bottom ends after ultimate load was reached. Characteristic yield lines starting at the ends of the specimen on the 180° side propagated at a 45° angle around the circumference. This yielding was onset by the moments at the fixed ends which are equilibrating the internal moment created by buckling in the corrosion patch. Figure 3-11 is a photograph of typical yield lines formed on the backside of the specimens.

3.7 OBSERVATIONS OF INDIVIDUAL TESTS

The experimental residual strengths for all patch corroded test specimens are summarized in Table 3-4, representing their ultimate capacity.

3.7.1 Specimen 34-33-58

Specimen 34-33-58 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 33 percent of the original thickness and had a subtending angle of θ=58.35°. The full yield load for the specimen was 240.7 kips
based on a measured yield stress of 36 ksi.

The specimen was loaded to 0.195 $P_y$ (47 kips) for an alignment cycle, where $P_y$ is the axial full yield load of the specimen. All strain gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test commenced.

Figure 3-12(a) is the normalized load-axial shortening curve for Specimen 34-33-58. Superimposed onto Figure 3-12(a) is the normalized axial load-shortening curve for Specimen 34-100-00, which represents the undamaged strength for Specimen 34-33-58. Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen and the load displacement plot remained linear elastic up to approximately 0.864 $P_y$ (208 kips). At this point yield lines started forming at the point of minimum wall thickness in the corrosion patch and extended around the circumference.

Visible local buckling of the corroded patch occurred at a load of 0.947 $P_y$ (227.8 kips). The corresponding static load (i.e. displacement held and load allowed to stabilize) was 0.909 $P_y$ (218.8 kips) at local buckling. Excessive yielding at the mid-length was visible at this point. A cross hatch pattern of yield lines formed at the patch of corrosion and extended around the circumference (see Figure 3-8). The specimen reached an ultimate load of 0.954 $P_y$ (229.5 kips), which corresponds to a static ultimate load of 0.916 $P_y$ (220.5 kips).

The mode of failure was an inward buckle of the corroded patch. The wall buckled outward slightly at the edges of the corrosion patch and began to propagate around the
circumference in this manner. Figure 3-8(a) is a photograph of the inward local buckle of this specimen.

After the ultimate load was reached, the capacity of the specimen slightly decreased with continued axial deformation as stresses redistributed from the corroded side of the cross section to the undamaged side. In the post-ultimate load range, yield lines developed on the 180° side of the tubular (the undamaged side) at the top and bottom ends and extended around the circumference at a 45° angle. The specimen lost strength to 0.906 $P_y$ (218 kips) when the final axial shortening of 0.68 inches was achieved.

There was virtually no lateral displacement of the specimen up until the point of local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-12(b).

Figure 3-13(a) is a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M5). These gages were positioned on the outside surface of the wall at the locations indicated in 3-13(b). The inward buckling mode of the specimen caused an increase in compressive strains on the outside wall face, where the strain gages are located. Therefore, this specimen never exhibited strain reversal, rather the compressive strains increased to the measurable limit of the gages.

Initially all mid-height strain readings were uniform (up to 0.4 $P_y$), but with continued axial compression, gage M1 (positioned inside the corrosion patch) increased more rapidly. The strain distribution then consisted of the maximum compressive strain at the center of the corrosion and decreasing around the circumference. This non-uniform
strain distribution at mid-height continued up to the ultimate load of the specimen.

The strain distributions around the circumference at mid-height (from gages M1 to M8) are plotted in Figure 3-14(a) for three different load levels: 0.438 $P_y$ (elastic range); 0.847 $P_y$ (after the local buckling wave initiated); and 0.916 $P_y$ (static ultimate load). This figure shows how the strain distribution remains the same with the maximum strain developing at the center of the corrosion patch. Figure 3-14(b) is the strain distribution around the circumference at a height of 0.5·D above the corrosion patch. This plot shows the strain distributions at 0.438 $P_y$ (elastic), 0.916 $P_y$ (static ultimate load), and 0.874 $P_y$ (post ultimate load). The strain distributions around the circumference are primarily uniform for all load levels below the ultimate load. Elevated strains are not visible in the gages 0.5·D away from the corrosion patch until the post ultimate load range. These strain distributions indicate that the pre-ultimate load effects of the corrosion patch are localized and confined to the length within 0.5·D of the corrosion patch.

3.7.2 Specimen 34-33-95

Specimen 34-33-95 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 33 percent of the original thickness and had a subtending angle of $\theta=95.66^\circ$. The full yield load for the specimen was 241.0 kips based on a measured yield stress of 36 ksi.

The specimen was loaded to 0.216 $P_y$ (52 kips) for an alignment cycle. All strain
gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test commenced.

Figure 3-15(a) is the normalized load-axial shortening plot for specimen 34-33-95. Superimposed onto Figure 3-15(a) is the normalized axial load-shortening curve for Specimen 34-100-00, which represents the undamaged strength for Specimen 34-33-95. Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen and the load displacement plot remained linear elastic up to approximately 0.688 $P_y$ (165.8 kips). At this point yield lines started forming at the point of minimum wall thickness in the corrosion patch and began to extend around the circumference.

Visible local buckling of the corroded patch occurred at a load of 0.834 $P_y$ (201.1 kips). The corresponding static load was 0.797 $P_y$ (192.1 kips) at local buckling. Excessive yielding at the mid-length was visible at this point. A cross hatch pattern of yield lines formed at the patch of corrosion and extended around the circumference. The specimen reached an ultimate load of 0.862 $P_y$ (207.8 kips) corresponding to a static ultimate load of 0.825 $P_y$ (198.8 kips).

The mode of failure was similar to a classic ring buckle which originated as a small local buckle at the corrosion patch and propagated around the circumference as the buckle enlarged. The buckle extended around the circumference in response to the redistribution of stresses from the corrosion damaged side of the tube to the undamaged side. Figure 3-8(b) is a photograph showing the yield pattern and the outward local
buckle of this specimen.

After the ultimate load was reached, the capacity of the specimen began to slightly deteriorate with continued axial displacement, as stresses redistributed from the corroded side of the cross section to the undamaged side. In the post-ultimate load range, yield lines developed on the 180° side of the specimen (the undamaged side) at the top and bottom ends and extended around the circumference at a 45° degree angle. The specimen lost strength to 0.783 $P_y$ (188.7 kips) when the final axial shortening of 0.54 inches was attained.

There was virtually no lateral displacement of the specimen up until the point of local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-15(b).

Figure 3-16(a) shows a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M5). These gages were positioned on the outside surface of the wall at the locations indicated in 3-16(b), and read compressive strains up to the point when local buckling waves formed. After local buckling initiated, some of these gages experienced strain reversal as the local buckle formed and propagated around the circumference.

Initially all mid-height strain readings were uniform (up to 0.4 $P_y$), but with continued axial compression strain gage M1 reversed strain and developed tensile strains as a local buckle wave started to form. Strain gage M2 increased compressive strains. These trends continued as the local buckling initiated and loading continued up to ultimate load. At ultimate load, gage M1 exhibited very large tensile strains while gage
M2 exhibited compressive strains. As the axial compression continued into the post-ultimate load range, the local buckle extended around the circumference and gage M2 exhibited strain reversal.

The strain distributions around the circumference at mid-height (from gages M1 to M8) are plotted in Figure 3-17(a) for three different load levels: 0.399 $P_y$ (elastic range); 0.686 $P_y$ (after local waves initiated); and at the static ultimate load of 0.825 $P_y$. Figure 3-17(b) shows the strain distribution around the circumference at a height of 0.5\*D above the corrosion patch. This plot shows the strain distributions at 0.399 $P_y$ (elastic), 0.825 $P_y$ (static ultimate load), and 0.790 $P_y$ (post ultimate load). The strain distributions around the circumference were primarily uniform for all load levels below the ultimate load. Elevated strains were not visible in the gages 0.5\*D away from the corrosion patch until the post ultimate load range. These strain distributions indicated the development of a localized large strain concentration in the pre-ultimate load range, which was confined to the member length within 0.5\*D of the corrosion patch.

### 3.7.3 Specimen 34-50-311

Specimen 34-50-311 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 50 percent of the original thickness and had a subtending angle of 311.0°. The full yield load for the specimen was 237.0 kips based on a measured yield stress of 36 ksi.

The specimen was loaded to 0.211 $P_y$ (50 kips) for an alignment cycle. All strain
gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test commenced.

Figure 3-18(a) shows the normalized load-axial shortening relationship for this specimen. Superimposed onto Figure 3-18(a) is the normalized axial load-shortening curve for Specimen 34-100-00, which represents the undamaged strength for Specimen 34-50-311. Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen and the load-displacement plot remained linear elastic up to approximately 0.50 \( P_y \) (118.5 kips). At this point yield lines started forming at the point of minimum wall thickness in the corrosion patch and began to extend around the circumference.

Visible local buckling of the corroded patch occurred at a load of 0.691 \( P_y \) (163.8 kips). The corresponding static load was 0.666 \( P_y \) (157.8 kips) at local buckling. Excessive yielding at the mid-length was visible at this point. A cross hatch pattern of yield lines formed at the patch of corrosion and extended around the circumference. The specimen reached an ultimate load of 0.709 \( P_y \) (168 kips), corresponding to a static ultimate load of 0.684 \( P_y \) (162.0 kips).

The mode of failure was similar to a classic ring buckle, which originated as a small local buckle at the corrosion patch and propagated around the circumference as the buckle enlarged. The buckle extended around the circumference in response to the redistribution of stresses from the corrosion damaged side of the cross section to the undamaged side.
After the ultimate load was reached, the capacity of the specimen deteriorated with continued axial deformation, as stresses redistributed from the damaged side of the tubular to the undamaged side. In the post-ultimate range, yield lines developed on the 180° side of the specimen (the undamaged side) at the top and the bottom and extended around the circumference at a 45° degree angle. The specimen lost strength to a static load of 0.554 \( P_y \) (131.4 kips) when the final axial shortening of 0.351 inches was attained.

There was virtually no lateral displacement of the specimen up until the point of imminent local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-18(b).

A plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M6) is shown in Figures 3-19(a) and (b). These gages were positioned on the outside surface of the wall at the locations indicated in 3-19(c). These gages read compressive strains up to the point when a local buckling wave formed. After local buckling initiated, some of these gages experienced strain reversal as the wave of the local buckle formed and propagated around the circumference.

Initially all mid-height strain readings were uniform (up to 0.3 \( P_y \)), but with continued axial compression gages M1, M2 and M3 increased more rapidly. Strain gage M3 showed maximum compressive strains after this point, and gages M1 and M2 already exhibiting strain reversal. At 0.6 \( P_y \), gage M3 exhibited a definite strain reversal as the local buckling wave propagated around the circumference. The local buckle continued to propagate around the circumference causing other gages to exhibit strain reversal.

The strain distributions around the circumference (from gages M1 to M10) at mid-
height are plotted in Figure 3-20(a) for three different load levels: 0.31 \( P_y \) (elastic range); 0.508 \( P_y \) (after local waves initiated); and 0.684 \( P_y \) (static ultimate load). This figure shows how the strain distribution at mid-height for this specimen was much more uniform than the other specimens (note that not all figures are plotted to the same scale). This somewhat more uniform distribution was caused by the large value of \( \theta = 311^\circ \) for this specimen. The large \( \theta \) produced a specimen which was tending toward an undamaged tubular with a thinner thickness, and would have a greater tendency to buckle symmetrically with a uniform stress and strain distribution than the other specimens.

### 3.7.4 Specimen 46-67-95

Specimen 46-67-95 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 67 percent of the original thickness and had a subtended angle of 95.66\(^\circ\). The full yield load of the specimen was 193.5 kips based on a measured static yield stress of 38.45 ksi.

The specimen was loaded to 0.181 \( P_y \) (35 kips) for an alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test commenced.

Figure 3-21(a) shows the normalized load-axial shortening plot for specimen 46-67-95. Superimposed onto Figure 3-21(a) is the normalized axial load-shortening curve for Specimen 46-100-00, which represents the undamaged strength for Specimen 46-67-95. Loading started and was controlled by a displacement rate of 0.01
inches/minute. There were no visible changes in the specimen and the load displacement plot remained linear elastic up to approximately $0.899 \, P_y$ (174 kips). At this point yield lines started forming at the point of minimum wall thickness in the corrosion patch and began to extend around the circumference.

Local buckling of the corroded patch occurred at a load of $0.928 \, P_y$ (179.7 kips). The corresponding static load was $0.892 \, P_y$ (172.7 kips). Excessive yielding at the mid-length was visible at this point. The typical cross hatch pattern of yield lines formed at the patch of corrosion and extended around the circumference. The specimen reached an ultimate load of $0.961 \, P_y$ (186 kips), corresponding to a static ultimate load of $0.924 \, P_y$ (178.8 kips).

The mode of failure was similar to a classic ring buckle which originated as a small local buckle at the corrosion patch, and propagated around the circumference as the buckle enlarged. The buckle extended around the circumference in response to the redistribution of stresses from the corrosion damaged side of the cross section to the undamaged side.

After the ultimate load was reached, the specimen lost strength. In the post-ultimate range, yield lines developed on the $180^\circ$ side of the tubular (the undamaged side) at the top and bottom ends, and extended around the circumference at a $45^\circ$ angle. The specimen lost strength to a static load of $0.651 \, P_y$ (126 kips) when the final axial shortening of 0.44 inches was attained.

There was virtually no lateral displacement of the specimen up until the point local buckling of the corrosion patch. After buckling the lateral displacement gradually
increased, as shown in Figure 3-21(b).

Figure 3-22(a) and (b) shows a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M5). These gages were positioned on the outside surface of the wall at the locations indicated in 3-22(c), and read compressive strains up to the point when a local buckling wave formed. After local buckling initiated, gages M1 and M2 experienced strain reversal as the local buckle wave developed and propagated around the circumference.

Initially all mid-height strain readings were uniform (up to approximately $0.4 \, P_y$), but with continued axial displacement the gages within the corrosion patch (M1, M2, and M3) increased more rapidly. The strain distribution had maximum compressive strain at the center of the corrosion with decreasing compressive strains around the circumference. Because this specimen was not as severely corroded, the local buckle waves did not appear as early as in the other more severely corroded specimens. Strain redistribution of the strain gages did not occur until the load was very close to the ultimate load. The amount of compressive strains taken by the center of the patch was reducing, while the compressive strains at the edges of the patch were increasing. This trend indicated the initiation of a local buckling wave. Strain reversal, or the redistribution of strain, became more pronounced in the post-ultimate load range after the local buckle became more defined and enlarged. Up to the ultimate load strain gages M4 and M5 exhibited only linear strain behavior. The strain distributions around the circumference (gages M1 to M8) at mid-height are plotted in Figure 3-23(a) for three different load levels: $0.385 \, P_y$ (elastic range); $0.908 \, P_y$ (after local waves initiated); and $0.924 \, P_y$ (static ultimate load).

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This figure shows how the strain reversal was reducing the compressive strains being taken by the center of the corrosion patch. Figure 3-23(b) shows the strain distribution around the circumference 0.5·D above the corrosion patch at 0.385 $P_y$ (elastic), 0.924 $P_y$ (static ultimate load), and 0.862 $P_y$ (post ultimate load). The strain distributions around the circumference at 0.5·D are primarily uniform for all load levels below the ultimate load. Slight strain elevations are visible in the post ultimate load range. These strain distributions indicate that the pre-ultimate load effects of the corrosion patch tend to be localized and confined to the length within 0.5·D of the corrosion patch.

3.7.5 Specimen 46-33-95

Specimen 46-33-95 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 35 percent of the original thickness and had a subtending angle of 95.66°. The full yield load for the specimen was 192.79 kips based on a measured yield stress of 38.45 ksi.

The specimen was loaded to 0.130 $P_y$ (25 kips) for an alignment cycle, however, the load application was not adequately uniform and no strains were being recorded in the alignment strain gages T2, B2, T3, and B3 (See Figure 3-7). These gages were on the 90° and 180° line sides. This alignment problem was attributed to improper Hydrostone grout application. The specimen top was grouted again and another alignment cycle was performed. The specimen was loaded to 0.192 $P_y$ (37 kips) for the second alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment gages confirmed that the loading was being applied adequately uniform.
specimen was unloaded back to zero before the test commenced.

Figure 3-24(a) shows the normalized load-axial shortening plot for specimen 46-33-95. Superimposed onto Figure 3-24(a) is the normalized axial load-shortening curve for Specimen 46-100-00, which represents the undamaged strength for Specimen 46-33-95. Loading started and was controlled by a displacement rate of 0.003 inches/minute. There were no visible changes in the specimen and the load displacement plot remained linear elastic up to approximately 0.622 $P_y$ (120 kips). At 120 kips a small local buckling wave started to form in the corrosion patch. At a load of 0.664 $P_y$ (128 kips), the specimen had shortened axially 0.048 inches, and the local buckling wave was growing rapidly. Yield lines started forming at 0.711 $P_y$ (137 kips). The yield lines initiated at the point of minimum wall thickness and extended around the circumference.

Local buckling of the corroded patch occurred at a load of 0.803 $P_y$ (154.9 kips). The corresponding static load was 0.778 $P_y$ (150.0 kips) at local buckling. Excessive yielding at the mid-length of the specimen was visible at this point. The typical cross hatch pattern of yield lines formed at the patch of corrosion and extended around the circumference. The specimen reached an ultimate load of 0.835 $P_y$ (160.9 kips) corresponding to a static ultimate load of 0.809 $P_y$ (156 kips).

The mode of failure was similar to a classic ring buckle which originated as a small local buckle at the corrosion patch and extended around the circumference as the buckle enlarged. The buckle extended around the circumference in response to the redistribution of stresses from the corrosion damaged side of the cross section to the undamaged side.
After the ultimate load was reached, the specimen began to lose strength. In the post-ultimate range, yield lines developed on the 180° side of the tubular (the undamaged side) at the top and the bottom ends, and extended around the circumference at a 45 degree angle. The specimen lost strength to 0.681 \( P_y \) (131.3 kips) when the final axial shortening of 0.6 inches was attained.

There was virtually no lateral displacement of the specimen up until the point of local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-24(b).

Figure 3-25(a) and (b) is a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M5). These gages were positioned on the outside surface of the wall at the locations indicated in 3-25(c), and read compressive strains up to the point when a local buckling wave formed. After local buckling initiated, these gages experienced strain reversal as the local buckle wave formed and propagated around the circumference.

Initially all mid-height strain readings were uniform (up to 0.3 \( P_y \)), but with continued axial displacement the gages within the corrosion patch (M1 and M2) increased more rapidly. Up to approximately 0.65 \( P_y \) the strain distribution showed maximum compressive strain at the center of the corrosion with decreasing compressive strains around the circumference. The local buckle wave which formed at the center of the corrosion patch caused gage M1 to exhibit a strain reversal and strain gage M2 and M3 to develop an increase in compressive strains. The waves in the corrosion patch enlarged and strains in gages M2 and M3 increased until a local instability of the wall was created.
and local buckling initiated. Once local buckling initiated, the local buckle wave extended around the circumference causing M2 to exhibit strain reversal. At ultimate load, strain gages M1 and M2 had developed reversed strains and the maximum compressive strains were at strain gage M3, which is just outside the corroded patch.

The strain distributions around the circumference at mid-height are plotted in Figure 3-26(a) for three different load levels: 0.3 $P_y$ (elastic range); 0.7 $P_y$ (after local waves initiated); and 0.809 $P_y$ (static ultimate load). This figure shows how the strain reversal extends around the circumference as the local buckle wave propagates with greater axial load. Figure 3-26(b) is the strain distribution around the circumference 0.5·D above the corrosion patch. This plot shows the strain distributions at 0.3 $P_y$ (elastic), 0.809 $P_y$ (static ultimate load), and 0.710 $P_y$ (post ultimate load). The strain distributions around the circumference are primarily uniform for all load levels below the ultimate load. Elevated strains are not visible in the gages 0.5·D away from the corrosion patch until the post ultimate load range. As in the other specimens, these strain distributions indicate that the pre-ultimate load effects of the corrosion patch are localized and primarily confined to the length within 0.5·D of the corrosion patch.

**3.7.6 Specimen 46-00-95**

Specimen 46-00-95 was an unrepaired specimen which was inflicted with corrosion that progressed completely through the wall thickness to create a hole. The specimen had a subtended angle of 95.66°. The full yield load for the specimen was 192.79 kips based on a measured yield stress of 38.45 ksi.
The specimen was loaded to 0.182 \( P_y \) (35 kips) for an alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test was started.

Figure 3-27(a) is the normalized load-axial shortening plot for specimen 46-00-95. Superimposed onto Figure 3-27(a) is the normalized axial load-shortening curve for Specimen 46-100-00, which represents the undamaged strength for Specimen 46-00-95. Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen and the load displacement plot remained elastic up to approximately 0.55 \( P_y \) (106.0 kips). The strain gages at the edges of the elliptical hole indicated that yielding had initiated at this load. At this point, the load deformation plot became increasingly non-linear.

Local buckling of the corroded patch occurred at the edges of the hole at a load of 0.792 \( P_y \) (152.7 kips). The corresponding static load was 0.761 \( P_y \) (146.7 kips). A small outward local buckle wave was visible at the left and right edges of the hole. Yield lines formed at the top and bottom on the 180° side of specimen and extended on a 45° angle around the circumference. The specimen reached an ultimate load of 0.814 \( P_y \) (157 kips) corresponding to a static ultimate load of 0.783 \( P_y \) (151.0 kips). The load deformation curve now had a zero slope and started to show a slight decrease in capacity.

The mode of failure was an outward buckle which originated at the edges of the hole and extended around the circumference as the buckle enlarged. The buckle extended around the circumference in response to the redistribution of stresses from the corrosion.
damaged side of the cross section to the undamaged side.

After the ultimate load was reached, the capacity of the specimen deteriorated with continued displacement. In the post-ultimate range the yield lines which developed on the 180° side of the tubular (the undamaged side) intensified at the top and the bottom and extended around the circumference at a 45° angle. The specimen lost strength to 0.670 $P_y$ (129.2 kips) when the final axial shortening 0.420 inches was attained.

There was virtually no lateral displacement of the tube up until the point of local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-27(b).

Figure 3-28(a) and (b) shows a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M3). These gages were positioned on the outside surface of the wall at the locations indicated in Figure 3-28(c). Note that because of the hole in the wall of this specimen strain gage M1 is not in the center of the corrosion patch, but rather at the edge. These gages read compressive strains up to the point when a local buckling wave formed. After local buckling initiated, these gages experienced strain reversal (not shown in plot) as the local buckle wave formed and propagated around the circumference.

Initially all mid-height strain readings were uniform (up to 0.4 $P_y$), but with continued axial displacement gages M1 increased more rapidly. The strain distribution up to ultimate load exhibited maximum strain at the edge of the hole with decreasing compressive strains around the circumference.

The strain distributions around the circumference at mid-height are plotted in
Figure 3-29 for three different load levels: 0.324 P\textsubscript{y} (elastic range); 0.696 P\textsubscript{y} (after local waves initiated); and 0.783 P\textsubscript{y} (static ultimate load). This figure shows the highest compressive strains at the edges of the hole.

### 3.7.7 Specimen 64-60-95

Specimen 64-60-95 was an unrepaired specimen which was inflicted with corrosion that reduced the wall thickness to 60 percent of the original thickness and had a subtending angle of 95.66°. The full yield load for the specimen was 138.05 kips based on a measured static yield stress of 36 ksi.

The specimen was loaded to 0.181 P\textsubscript{y} (25 kips) for an alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment strain gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded back to zero before the test was started.

Figure 3-30(a) is the normalized load-axial shortening plot for specimen 64-60-95. Superimposed onto Figure 3-30(a) is the normalized axial load-shortening curve for Specimen 64-100-00, which represents the undamaged strength for Specimen 64-60-95. Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen and the load displacement plot remained linear elastic up to approximately 0.739 P\textsubscript{y} (102.0 kips). At this point yield lines started forming at the point of minimum wall thickness of the cross section began to extend around the circumference.

Local buckling of the corroded patch occurred at a load of 0.859 P\textsubscript{y} (118.6 kips).
The corresponding static load was 0.832 $P_y$ (114.8 kips). Excessive yielding at the mid-length was visible at this point. Yield lines formed at the patch of corrosion and extended around the circumference. The specimen reached an ultimate load of 0.883 $P_y$ (121.92 kips), corresponding to a static ultimate load of 0.856 $P_y$ (118.12 kips).

The mode of failure was an outward local buckle at the corrosion patch. The local buckle extended around the circumference in response to the redistribution of stresses from the corrosion damaged side of the specimen to the undamaged side.

After the ultimate load was reached, the capacity of the specimen deteriorated as the local buckle extended around the circumference and stresses redistributed from the damaged side to the undamaged side of the specimen. Yield lines also developed on the $180^\circ$ side of the tubular (the undamaged side) at the top and the bottom end of the specimen, and extended around the circumference at a $45^\circ$ angle. The specimen lost strength to 0.514 $P_y$ (71 kips) when the final axial shortening of 0.35 inches was attained.

There was virtually no lateral displacement of the specimen up until the point of local buckling of the corrosion patch. After buckling the lateral displacement gradually increased, as shown in Figure 3-30(b).

Figure 3-31(a) and (b) shows a plot of the strain data recorded at the mid-height longitudinal strain gages (M1 to M5). These gages were positioned on the outside surface of the wall at the locations indicated in 3-31(c), read compressive strains up to the point when local a buckling wave formed. After local buckling initiated, some of these gages experienced strain reversal as the local buckle formed and propagated around the circumference.
Initially all mid-height strain readings were uniform (up to approximately 0.4 $P_y$), but with continued axial displacement the strain readings of the gages within the corrosion patch (M1 and M2) showed an increased magnitude. Up to a load of approximately 0.70 $P_y$, the strain distribution had maximum longitudinal compressive strain at the center of the corrosion with decreasing compressive strains around the circumference. The local buckle wave which initiated at the center of the corrosion patch resulted in gages M1 and M2 developing a reversal in strain, while gage M3 continued to increase. The local buckle wave in the corrosion patch enlarged to where, at ultimate load, strain gages M1 and M2 had reversed strains and the maximum compressive strain was at strain gage M3, which is just outside the corrosion patch.

The strain distributions around the circumference at mid-height are plotted in Figure 3-32(a) for three different load levels: 0.329 $P_y$ (elastic range); 0.755 $P_y$ (after local waves initiated); and 0.856 $P_y$ (static ultimate load). The strain reversal in the corrosion patch after local buckling initiated is evident in this figure. At ultimate load the local buckle had extended to the edges of the corrosion patch, producing the highest compressive strains at the edges of the corrosion patch. This trend of developing an outward local buckling mode was common to most of the test specimens.

### 3.8 ASSESSMENT OF EXPERIMENTAL RESULTS

#### 3.8.1 Effects of $D/t$

Specimen 34-33-95 had a $D/t$ of 34 and suffered an axial capacity reduction of 17.5 percent when compared to its corresponding non-corroded Specimen 34-100-0.
Specimen 46-33-95 had a D/t of 46 and suffered an axial capacity reduction of 19.1 percent when compared to its corresponding non-corroded Specimen 46-100-0. This observation is consistent with the fact that it was found throughout this study that larger D/t tubulars are more severely affected by patch corrosion due to their lower resistance to local buckling.

A tubular with lower D/t ratio has a thicker wall bordering the corrosion patch, which restrains the corrosion patch more than a thinner wall. Consequently, the additional restraint would enable larger strains to develop in the corrosion patch subsequent to local buckling. However, a large angle $\theta$ can counteract this trend. This phenomena is apparent in the behavior of Specimen 34-50-311 which buckled locally at lower strain values than Specimens 34-33-58 or 34-33-95 because the corrosion patch was very wide and had less restraint than the latter two specimens.

### 3.8.2 Effects of $t_r/t$

Specimens 46-00-95, 46-33-95, and 46-67-95 were tested to determine the sensitivity of the reduced thickness to the residual strength of the tubular. Specimen 46-00-95 simulated a hole in the wall caused by corrosion (0 percent of wall remained), and suffered an axial capacity reduction of 21.7 percent compared to its corresponding non-corroded tubular (Specimen 46-100-0). In comparison, Specimen 46-33-95 (33 percent of the original wall thickness remaining) and Specimen 46-67-95 (67 percent of the original wall thickness remaining) had only 19.1 and 7.6 percent axial capacity reductions, respectively, when compared with their respective non-corroded tubular
This trend indicates that as more of the wall thickness deteriorates over a certain area of the wall, the axial capacity of the tubular is further reduced.

The reduction of the wall thickness greatly influences the initiation of local buckling. A thinner wall thickness in the corrosion patch causes strain reversal to occur at lower stress levels.

### 3.8.3 Effects of θ

Specimens 34-33-58 had an angle θ of 58.35° and a residual strength of $P_\theta/P_\gamma=0.916$. In comparison, Specimen 34-33-95 had an angle θ of 95.66 degrees and a residual strength of only $P_\theta/P_\gamma=0.825$. This trend shows that increasing the width of the corrosion (increasing θ) reduces the residual strength of the corroded tubular. This trend is associated with the effect discussed above, where a reduced thickness of greater width offers less restraint to local buckling at the corrosion patch.

Larger values of θ also tend to create a more uniform stress and strain distribution than smaller θ values. This trend is based on the fact that smaller values of θ cause more of a discontinuity, where large θ values tend toward a non-corroded tubular with thinner wall thickness. A more uniform distribution of strain can be seen in Specimen 34-50-311 (Figure 3-20). In contrast, Specimen 34-33-58 (Figure 3-14(a)) had a much more nonuniform strain distribution.
Chapter 3

Tables and Figures
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<th>Specimen</th>
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Table 3-1. Experimental Specimen Matrix
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<td>18.5</td>
<td>6.43</td>
<td>4.4</td>
<td>0.084</td>
<td>1.02</td>
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<td>34-33-95</td>
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<td>8.610</td>
<td>0.255</td>
<td>33.76</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
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<td>1.67</td>
<td>95.7</td>
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<tr>
<td>34-50-311</td>
<td>55.5</td>
<td>8.600</td>
<td>0.251</td>
<td>34.26</td>
<td>18.5</td>
<td>6.43</td>
<td>23.4</td>
<td>0.129</td>
<td>5.43</td>
<td>311.0</td>
<td>0.51</td>
</tr>
<tr>
<td>46-100-0</td>
<td>30.0</td>
<td>8.587</td>
<td>0.190</td>
<td>45.11</td>
<td>10.0</td>
<td>3.48</td>
<td>0.0</td>
<td>0.190</td>
<td>0.00</td>
<td>0.0</td>
<td>1.00</td>
</tr>
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<td>46-00-95</td>
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<td>8.590</td>
<td>0.190</td>
<td>45.21</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
<td>0.000</td>
<td>1.67</td>
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<td>0.00</td>
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<tr>
<td>46-33-95</td>
<td>55.5</td>
<td>8.590</td>
<td>0.190</td>
<td>45.21</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
<td>0.068</td>
<td>1.67</td>
<td>95.7</td>
<td>0.36</td>
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<td>44.92</td>
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<td>1.67</td>
<td>95.7</td>
<td>0.67</td>
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<tr>
<td>64-100-0</td>
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<td>8.619</td>
<td>0.136</td>
<td>63.56</td>
<td>10.0</td>
<td>3.48</td>
<td>0.0</td>
<td>0.136</td>
<td>0.00</td>
<td>0.0</td>
<td>1.00</td>
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<td>0.136</td>
<td>63.56</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
<td>0.080</td>
<td>1.67</td>
<td>95.7</td>
<td>0.59</td>
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Table 3-2. Measured Dimensions for Patch Corroded Specimens
<table>
<thead>
<tr>
<th>Specimen</th>
<th>OOS $\delta_{\text{max}}$</th>
<th>OOR $D_{\text{max}} - D_{\text{ave}}$</th>
</tr>
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<tbody>
<tr>
<td>34-100-0</td>
<td>*</td>
<td>0.0012</td>
</tr>
<tr>
<td>34-33-58</td>
<td>0.00036</td>
<td>0.0023</td>
</tr>
<tr>
<td>34-33-95</td>
<td>0.00018</td>
<td>0.0012</td>
</tr>
<tr>
<td>34-50-311</td>
<td>0.00054</td>
<td>0.0035</td>
</tr>
<tr>
<td>46-100-0</td>
<td>*</td>
<td>0.0012</td>
</tr>
<tr>
<td>46-00-95</td>
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<td>0.00036</td>
<td>0.0023</td>
</tr>
<tr>
<td>46-67-95</td>
<td>0.00054</td>
<td>0.0035</td>
</tr>
<tr>
<td>64-100-0</td>
<td>*</td>
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</tr>
<tr>
<td>64-60-95</td>
<td>0.00036</td>
<td>0.0046</td>
</tr>
</tbody>
</table>

OOS - Maximum Out-of-Straightness
OOR - Maximum Out-of-Roundness

* - OOS too small to be measured.

Table 3-3. Initial Imperfections of Test Specimens
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Yield Stress (ksi)</th>
<th>Py (kips)</th>
<th>Pu (kips)</th>
<th>Pu/Py Experimental</th>
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<tr>
<td>34-100-0</td>
<td>36.00</td>
<td>239.5</td>
<td>239.5</td>
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<td>241.0</td>
<td>198.8</td>
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<td>237.0</td>
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<td>0.684</td>
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<td>193.0</td>
<td>1.000</td>
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<td>46-00-95</td>
<td>38.45</td>
<td>192.8</td>
<td>151.0</td>
<td>0.783</td>
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<td>192.8</td>
<td>156.0</td>
<td>0.809</td>
</tr>
<tr>
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<td>38.45</td>
<td>193.5</td>
<td>178.8</td>
<td>0.924</td>
</tr>
<tr>
<td>64-100-0</td>
<td>38.20</td>
<td>138.1</td>
<td>138.1</td>
<td>1.000</td>
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<td>64-60-95</td>
<td>38.20</td>
<td>138.1</td>
<td>118.1</td>
<td>0.856</td>
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</table>

Table 3-4. Peak Static Axial Capacity for Corrosion Damaged Specimens
Figure 3-1. Comparison of Measured Corrosion Dimensions from Test Specimens
(a) Surface Plots of Specimens 34-33-58 and 34-33-95
(b) Cross Section Profile of Specimens 46-33-95 and 46-67-95.
Figure 3-2. Typical Stress-Strain Plots for Pre- and Post-Annealed Tensile Coupons

Pre-Annealed Coupon

\[ \sigma_y = 39 \text{ ksi} \]
\[ \sigma_u = 60 \text{ ksi} \]
\[ E = 29500 \text{ ksi} \]
\[ E_{sh} = 510 \text{ ksi} \]
\[ \varepsilon_{sh} = 15 \varepsilon_y \]
\[ \% \text{ Elongation} = 34\% \]

Post-Annealed Coupon

\[ \sigma_y = 39 \text{ ksi} \]
\[ \sigma_u = 60 \text{ ksi} \]
\[ E = 29500 \text{ ksi} \]
\[ E_{sh} = 510 \text{ ksi} \]
\[ \varepsilon_{sh} = 15 \varepsilon_y \]
\[ \% \text{ Elongation} = 34\% \]
Figure 3-3. General Stub-Column Test Setup and Instrumentation Showing (a) Elevation View, and (b) Plan View.
Figure 3-4. Typical Stub-Column Response for (a) Specimens with D/t = 34, (b) Specimens with D/t = 46, and (c) Specimens with D/t = 64.
Figure 3-5. General Test Setup for Patch Corroded Tubular Member.
Figure 3-6. Photograph of Test Setup for a Patch Corroded Tubular Member.
Figure 3-6. Photograph of Test Setup for a Patch Corroded Tubular Member.
Figure 3-7. General Instrumentation Setup for Patch Corroded Tubular Members.
Figure 3-8. Photographs of Selected Specimens Showing Local Buckling in Corrosion Patch with (a) Inward Buckling Mode of Specimen 34-33-58, and (b) Outward Buckling Mode of Specimen 34-33-95.
Strain reversal at center of corrosion.
Initiation of local buckling.

Strain reversal in this area shows the growth of the local buckle wave around the circumference.

Figure 3-9. Three Dimensional Depiction of Strain Distribution Around the Circumference up to Ultimate Load, Specimen 34-33-95.
Figure 3-10. Strain Distribution Around Circumference for Outward Buckling Mode, Specimen 34-33-58.
Figure 3-11. Typical Yield Lines at Top End of Specimen on Undamaged Side.
Figure 3-11. Typical Yield Lines at Top End of Specimen on Undamaged Side.
Figure 3-12. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 34-33-58 and 34-100-00, and (b) Normalized Load-Lateral Displacement for specimen 34-33-58.
Figure 3-13. Specimen 34-33-58 (a) Mid-height Longitudinal Strains up to Ultimate Load, and (b) Locations of Plotted Strain Gages.
Figure 3-14. Specimen 34-33-58 Longitudinal Strain Around Circumference at (a) Corrosion Patch, and (b) 0.5 D Above the Corrosion Patch. (Compression Positive).
Figure 3-15. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 34-33-95 and 34-100-00, and (b) Normalized Load-Lateral Displacement for Specimen 34-33-95.
Figure 3-16. Specimen 34-33-95 (a) Mid-height Longitudinal Strains up to Ultimate Load, and (b) Locations of Plotted Strain Gages.
Figure 3-17. Specimen 34-33-95 Longitudinal Strain Distribution Around Circumference at (a) Corrosion Patch, and (b) 0.5 D Above the Corrosion Patch. (Compression Positive).
Figure 3-18. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 34-50-311 and 34-100-00, and (b) Normalized Load-Lateral Displacement for Specimen 34-50-311.
Figure 3-19. Specimen 34-50-311 (a) Mid-height Strain Distribution up to Ultimate Load, (b) Same Plot Expanded for Clarity, and (c) Locations of Plotted Strain Gages.
Figure 3-20. Specimen 34-50-311 - Longitudinal Strain Distribution Around Circumference at Corrosion Patch (Compression Positive).
Figure 3-21. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 46-100-00 and 46-67-95, and (b) Normalized Load-Lateral Displacement for Specimen 46-67-95.
Figure 3-22. Specimen 46-67-95 (a) Mid-height Strain Distribution up to Ultimate Load, (b) Same Plot Expanded for Clarity, and (c) Locations of Plotted Strain Gages.
Figure 3-23. Specimen 46-67-95 Longitudinal Strain Distribution Around Circumference at (a) Corrosion Patch, and (b) 0.5 D Above the Corrosion Patch. (Compression Positive).
Figure 3-24. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 46-33-95 and 46-100-00, and (b) Normalized Load-Lateral Displacement for Specimen 46-33-95.
Figure 3-25. Specimen 46-33-95 (a) Mid-height Strain Distribution up to Ultimate Load, (b) Same Plot Expanded for Clarity, and (c) Locations of Plotted Strain Gages.
Figure 3-26. Specimen 46-33-95 Longitudinal Strain Distribution Around Circumference at (a) Corrosion Patch, and (b) 0.5 D Above the Corrosion Patch. (Compression Positive).
Figure 3-27. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 46-00-95 and 46-100-00, and (b) Normalized Load-Lateral Displacement of Specimen 46-00-95.
Figure 3-28. Specimen 46-00-95 (a) Mid-height Strain Distribution up to Ultimate Load, (b) Same Plot Expanded for Clarity, and (c) Locations of Plotted Strain Gages.
Figure 3-29. Specimen 46-00-95 Longitudinal Strain Distribution Around Circumference at Corrosion Patch (Note Hole in Cross Section.) (Compression Positive).
Figure 3-30. (a) Normalized Load-Axial Shortening Relationships for Corroded and Non-corroded Specimens 64-60-95 and 64-100-00, and (b) Normalized Load-Lateral Displacement of Specimen 64-60-95.
Figure 3-31. Specimen 64-60-95 (a) Mid-height Strain Distribution up to Ultimate Load, (b) Same Plot Expanded for Clarity, and (c) Locations of Plotted Strain Gages.
Figure 3-32. Specimen 64-60-95 - Longitudinal Strain Distribution Around Circumference at Corrosion Patch (Compression Positive)
4. Residual Strength of Corroded Tubular Members - Analytical Program

4.1 GENERAL

The results from an analytical analysis of patch corroded tubular members are presented in this chapter. The objective of the analytical program was to develop a functional solution for the residual strength of a patch corroded tubular member. Finite element and regression analysis techniques were used to accomplish this objective. The steps in the analytical analysis, as well as the interaction between the analytical and experimental programs are shown schematically in Figure 4-1.

A finite element model of a patch corroded tubular member, conforming to the corrosion shape and profile presented in Chapter 1, was first developed. (Step 1 in Figure 4-1). This model was used to explore the effects of different parameters (See Chapter 1) to determine which were most critical to the residual strength of a corroded tubular member (Step 2 in Figure 4-1). After the most sensitive corrosion parameters were defined (D/t, t/t, and θ), the experimental test matrix was developed to explore these parameters and formulate an experimental database (Step 3 in Figure 4-1). The experimental testing was performed and the results analyzed (Step 4 in Figure 4-1), and then were used to verify the finite element analysis results (Step 5 in Figure 4-1). Once verified, the finite element model was utilized to conduct a parametric study of the corrosion parameters (Step 6 in Figure 4-1). Twenty-nine finite element analyses were
performed, encompassing the full applicable range of each parameter. The analyses results comprised a database, where each finite element analysis for residual strength defined an entry in the database. A multi-variable linear regression was performed (Step 7 in Figure 4-1) to fit an equation to the database of residual strengths from the finite element analyses. The result is an equation which provides the residual strength of a corroded tubular member as a function of the corrosion parameters $D/t$, $t/t$, and $\theta$.

4.2 FINITE ELEMENT ANALYSIS

4.2.1 Finite Element Model

A finite element model was created and used to analyze patch corroded tubulars. The commercial finite element program ABAQUS was utilized for this purpose on a SUN Sparc station 2. Figure 4-2 shows typical finite element model. Eight node isoparametric shell elements were used, which are based on the updated Lagrangian formulation with Green's strain and second Piola-Kirchoff stress to account for large displacements. A typical mesh had 350 shell elements and 7000 degrees of freedom. The model took advantage of symmetry about mid-height and the longitudinal axis, therefore, only one quarter of the tubular member was modeled. The mesh was refined in the area within one diameter of the corrosion.

The corrosion was modeled to take into account two physical changes. The first change was the reduced thickness of the area. The thickness reduction was modeled by assigning thinner thicknesses to the elements within the corroded area. The second
change was the offset of the midsurface of the elements in the corroded area to account for the fact that only the outside surface of the wall is changed due to the corrosion.

The corrosion was modelled by defining the position of the nodes to coincide with the midsurface of the corrosion profile and assigning the appropriate thickness to each element as shown in Figure 4-3.

Unfortunately, the elliptic shape is an inconvenient shape for use in finite element modeling, where the shell elements used are all rectangular in shape. However, as mentioned in Chapter 2, the exact shape of the patch of corrosion is not as important as the critical parameters of the idealized corrosion patch. Rectangular corrosion patches were used in the finite element model and produced very good correlation with the corresponding elliptical corrosion patches used in the experimental testing.

Boundary conditions for the longitudinal and centerline transverse edges were specified as a symmetric boundary, which is a special boundary condition supported by ABAQUS. The end of the tubular is modeled as a fixed end, where all end nodes were fixed against rotations and were constrained to have equal displacements in the axial direction of the tubular. Only one of the end nodes of the tubular was fixed against transverse displacement, thereby, allowing radial expansion of the ends of the tubular.

In addition to geometric nonlinearities, the finite element model included material nonlinearities. The Von Mises yield criterion was used with the an elastic-plastic stress-strain material which included isotropic strain hardening. The material was representative of a mild steel with a yield stress $F_y = 38.45$ ksi; Young’s modulus $E = 29500$ ksi, Poisson’s Ratio $v = 0.3$; strain hardening modulus $E_{sh} = 113.5$ ksi; strain at the onset of strain
hardening $\varepsilon_{sh} = 0.015 \text{ in./in.}$; as well as a yield plateau which had a length of ten times the yield strain.

Mid-side nodes of the elements at the transition to a refined mesh one diameter away from the corrosion were constrained using the multi-point constraint (MPC) feature of ABAQUS. The MPC feature will constrain a mid-side node of one element to a line formed by the quadratic passing through three adjacent nodes. This feature eliminates the need for transition elements to be used to preserve compatibility at the boundaries of mesh refinements.

### 4.2.2 Solution Procedure

A static nonlinear model was used to mimic the testing procedure in the solution process. The RIKS iteration technique with automatic convergence control was used as the solution technique. The RIKS method uses an arbitrary 'time' step increment as a discrete segment of the load-displacement curve. A 'time' step is a portion of the entire solution process, and is used for the RIKS method because neither the load nor the displacement are held constant for any one step. The RIKS method traces along the load-displacement curve by anchoring the first end of each time increment at the last converged point and, using an axial load and moment convergence technique, creates equilibrium with the load and displacement for points at the other end of each time increment. This new converged point is used for the start of the next increment. The RIKS method is usually used for nonlinear buckling analysis where both the pre- and post ultimate load ranges are of interest. More complete details of the RIKS method are
documented by E. Riks (1979).

The axial load was applied concentrically to a master node located at the center of the end of the model. The end nodes at the wall were constrained to have the same axial displacement as the master node. Because the RIKS method was used, neither a load nor a displacement increment was applied, rather time increment limits and maximum displacement were specified. The loading process was carried well into the post ultimate load range, at least two to three times beyond the displacement corresponding to the displacement at ultimate load.

### 4.2.3 Finite Element Analysis Results

Tables 4-1 and 4-2, respectively, list the \( \frac{P_j}{P_y} \) from each finite element analyses of the test specimens and in the finite element database from the parametric study. As noted previously, the finite element model was first used to perform a sensitivity study of all parameters which may influence the ultimate load of a tubular member. This parametric study involved 29 analyses. The results from the initial sensitivity study indicated the yield stress of the tubular had little effect on the normalized ultimate load, defined as the static residual strength-to-yield load \( \frac{P_u}{P_y} \) ratio. Finite element analyses for yield stresses of 30 and 60 ksi steels differed by only one to three percent. The sensitivity study also determined that the \( h \) dimension was not critical when it exceeded one radius. (i.e. \( h \geq h_{\text{crit}} \), See Chapter 2). Finite element analyses with \( h \) equal to one radius and two radii had member residual strength predictions that differed by approximately two percent. The finite element analyses did not pinpoint the exact value
of \( h_{\text{crit}} \) because of limitations on the mesh size, however, it did confirm that \( h \) dimensions above one radius did not affect the results. As stated in Chapter 2, sensitive corrosion parameters were limited to \( D/t, t/t \) and \( \theta \).

The effect of residual stresses was also examined using finite element analysis. The segmented straight line approximation for longitudinal residual stresses proposed by Ross and Chen (1976) was used. This residual stress distribution is shown in Figure 4-4, where the tensile residual stress of \( \sigma_y \) is at the longitudinal weld of the cross section of the tubular. When assuming the weld to be centered in the corrosion patch, the high tensile stresses at the weld actually helped prevent the initiation of local buckling. For lower \( D/t \) tubulars, say \( D/t=46 \), there was an ultimate capacity increase of approximately 2 percent. For higher \( D/t \) tubulars, say \( D/t=100 \), the capacity increase was somewhat lower at 1.4 percent. When the weld was assumed to be positioned 180° from the center of the corrosion patch there was approximately a 0.1 percent decrease in ultimate capacity for the lower \( D/t \) tubulars, and a 0.6 percent decrease in ultimate capacity for the higher \( D/t \) tubulars. The higher \( D/t \) tubulars are slightly more adversely affected by the residual stresses, however, all the effects from the residual stresses were insignificant. Figure 4-5 is a comparison of the load-deformation plot for finite element analyses of Specimens 46-33-95 and 100-33-95. Each plot shows the results without residual stresses as well as with residual stresses for both of the assumed weld positions presented above.

A typical buckled finite element mesh exhibiting an inward and outward local buckle is shown in Figure 4-6(a) and (b), and can be compared with the photographs of these buckles from the experimental specimens in Figure 3-8 (a) and (b).
The comparison of finite element results with specific experimental results for member capacity is given in Table 4-1. The ratio of finite element results to experimental results has a mean value of 0.980 with a coefficient of variation (COV) of 0.024. Therefore, the finite element model is on average 2.0 percent conservative, which is an acceptable tolerance. Figure 4-7 is a correlation scatter diagram comparing the finite element results with the experimental results. Perfect correlation lies on the forty-five degree line shown in the plot. The correlation between the finite element and the experimental results appears reasonable and verifies the finite element model as being capable of producing accurate results for single patch corroded tubular members.

Normalized finite element load-deformation plots for each experimental specimen are plotted with their respective experimental results in Figures 4-8 to 4-14. The finite element analyses closely matched the experimental tests in the pre-ultimate load range.

In the post ultimate load range the finite element model showed a general trend of having a lower post-ultimate capacity. This discrepancy is caused by the material properties assumed in the finite element model. The material stress-strain curve used in the FEM analysis was tri-linearized, with a straight line used for the elastic range, yield plateau, and strain-hardening portions of the curve. The strain-hardening of the material strongly influences the post-ultimate capacity of the tubular. The linearized strain-hardening used in the model simulates the average slope of the actual strain-hardening (See Figure 3-2). The linearized strain-hardening does not take into account the steep slope of the stress-strain curve which occurs at the onset of strain-hardening. This steep portion of the stress-strain curve is what causes the discrepancy between the experimental
and finite element load-deformation plots. If the model were "fine-tuned" to have the exact strain-hardening curve as the steel in the experimental specimens, the post-ultimate load discrepancy would be minimized, however, it was more desirable to keep the model general than to conform it to specific case. In short, this shows that a model created with nominal dimensions and properties can still produce sufficiently accurate results.

4.3 MULTI-VARIABLE LINEAR REGRESSION ANALYSIS

As noted previously, a multi-variable linear regression analysis was performed on the finite element database to develop an equation which approximates the residual strength of a corroded tubular based on the most sensitive corrosion parameters.

4.3.1 Multi-variable Linear Regression Analysis

Multi-variable regression analysis was used to approximate the discrete data points from the database for ultimate loads predicted by the finite element analyses. Known values of $P/P_y$ for different finite element analyses were labeled as $f_i$ and assembled in a column vector $F$.

$$F = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix} \quad (4-1)$$
Each value in $F$ is a function of several independent variables ($x_1$, $x_2$, $x_3$, ..., $x_k$). The approximation function $r$ to fit the data in $F$ is taken as a linear form:

$$r = a_1 q_1 + a_2 q_2 + a_3 q_3 ... a_j q_j$$

(4-2)

Where $q_i$ are known regressors, which are products of the independent variables $x_i$ (i.e. corrosion parameters). The regression coefficients, $a_i$, are determined by solving the following matrix equation, which represents a least-squares solution.

$$B^TBA = B^TF$$

(4-3)

In Equation (4-3) $F$ is the known independent variable vector shown previously, and $B$ is a matrix of regressors where each row is the regressors for a particular data point, where

for $n$ data values with $j$ regressors in the approximation function:

$$B = \begin{bmatrix}
q_{11} & q_{12} & q_{13} & \cdots & q_{1j} \\
q_{21} & q_{22} & q_{23} & \cdots & q_{2j} \\
\cdot & \cdot & \cdot & \cdots & \cdot \\
\cdot & \cdot & \cdot & \cdots & \cdot \\
q_{n1} & q_{n2} & q_{n3} & \cdots & q_{nj}
\end{bmatrix}$$

(4-4)

The solution of the above matrix equation produces a vector $A$ containing the values for the $j$ regression coefficients. These coefficients are then substituted into the approximation function to produce the desired equation.
4.3.2 Coordinate Functions

To apply these concepts to the problem of patch corrosion, a general approximation function must be determined. This was done by forming the direct product of the equations which define the influence of each independent variable (D/t, t/t, and θ) on the residual strength. The equations which define the influences of each independent parameter are referred to as coordinate functions. The coordinate functions were developed by holding two of the three sensitive parameters constant and varying the third sensitive parameter. The coordinate function plots based on finite element analyses for D/t, t/t, and θ are shown in Figures 4-15 to 4-17, respectively. Figure 4-15 shows how the residual strength changed as D/t was varied with θ and t/t held constant. Similarly, Figure 4-16 shows how the residual strength changed as t/t was varied, with θ and D/t held constant. And finally, Figure 4-17 shows how the residual strength changed as θ was varied with D/t and t/t held constant. Figures 4-15 through 4-17 indicate that all three coordinate functions were of a linear form. On this basis, the following coordinate functions were proposed:

\[ r_1 = c_1 \left( \frac{D}{t} \right) + c_2 \]  
(4-5)

\[ r_2 = c_3(\theta) + c_4 \]  
(4-6)

\[ r_3 = c_5 \left( \frac{t_r}{t} \right) + c_6 \]  
(4-7)

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4.3.3 Regression Equation

The approximation function for the regression analysis was formed with the direct product of the three coordinate functions.

\[ r = r_1 \cdot r_2 \cdot r_3 \]  \hspace{1cm} (4-8)

Where \( r \) is the \( P_y/P_y \) ratio.

Upon substituting Equations (4-5), (4-6), and (4-7) into Equation (4-8):

\[ r = (c_1 \frac{D}{t} + c_2) \cdot (c_3 \theta + c_4) \cdot (c_5 \frac{t_r}{t} + c_6) \]  \hspace{1cm} (4-9)

Upon expanding and redefining constants, the following result is obtained:

\[ r = a_1 + a_2 \frac{D}{t} + a_3 \frac{t_r}{t} + a_4 \theta + a_5 \frac{t_r}{t} + a_6 \frac{D}{t} \theta + a_7 \frac{t_r}{t} + a_8 \frac{D}{t} \theta \frac{t_r}{t} \]  \hspace{1cm} (4-10)

To simplify Equation (4-10), the last three higher order terms of the approximation equation were eliminated, resulting in the final form of the equation as shown below. This simplification was found to not introduce any significant error.

\[ r = a_1 + a_2 \left( \frac{D}{t} \right) + a_3 \left( \frac{t_r}{t} \right) + a_4 (\theta) + a_5 (\theta) \left( \frac{t_r}{t} \right) \]  \hspace{1cm} (4-11)

The regression coefficient \( A \) can be solved from Equation (4-3) as shown below.
\[ A = (B^T B)^{-1} B^T F \]  

(4-12)

Solving this equation using the finite element database gives:

\[
A = \begin{pmatrix}
0.9998 \\
-0.001014 \\
0.05201 \\
-0.002606 \\
0.002764
\end{pmatrix}
\]  

(4-13)

Therefore, the final version of the regression equation, \( r \), can be written as:

\[
r = \frac{P_u}{P_y} = 0.9998 - 0.001014 \left( \frac{D}{t} \right) + 0.05201 \left( \frac{t_r}{t} \right) - 0.002606(\theta) + 0.002764\left( \frac{t_r}{t} \right)(\theta) \leq 1.0
\]

(4-14)

or,

\[
\frac{P_u}{P_y} = 0.9998 - 0.001014 \left( \frac{D}{t} \right) + (0.05201 + 0.002764(\theta)) \left( \frac{t_r}{t} \right) - 0.002606(\theta) \leq 1.0
\]

(4-15)

Equation (4-15) is valid for the following ranges of \( D/t \), \( t/t \), and \( \theta \):

\[
34 \leq \frac{D}{t} \leq 100, \quad 0.0 \leq \frac{t_r}{t} \leq 1.0, \quad 0.0 \leq \theta \leq 360
\]

(4-16)
4.3.4 Regression Equation Results

Table 4-2 lists the results \( (P_j/P_y) \) from the regression equation for each of the 29 finite element analyses conducted for the parametric study database. Figure 4-18 is a correlation plot of \( P_j/P_y \) from the finite element analysis and \( P_j/P_y \) from the regression equation. Perfect correlation between the two methods would lie along the forty-five degree line. The ratio of \( [P_j/P_y]_{\text{reg}} \) (regression) to \( [P_j/P_y]_{\text{FEM}} \) (finite element) has a mean value of 1.001 and a coefficient of variation (COV) of 0.0344.

The test specimens were analyzed using the regression equation, and the results are listed in Table 4-1. The correlation between the experimental and regression results is shown in Figure 4-19. The ratio of \( [P_j/P_y]_{\text{reg}} \) to \( [P_j/P_y]_{\text{exp}} \) (experimental) has a mean of 0.977 and a coefficient of variation of 0.044. The correlation plot in Figure 4-19 confirms that the regression equation is accurate enough for usage in determining the residual strength of a concentrically loaded, patch corroded tubular member.

A comparison of the reliability of the regression equation indicates that it is as accurate as the finite element method for predicting the residual strength of corroded members, and therefore, can be used in place of finite element analysis. Figures 4-7 and 4-19 illustrate the accuracy of the regression equation relative to the finite element method.

It should be noted that an undamaged tubular has \( \theta=0.0 \) and \( t_r/t=1.0 \), and may be analyzed with this equation, however, there is some variation from code local buckling equations because the linear formulation of the regression equation does not exactly fit the local buckling curves of undamaged tubulars. Figure 4-20 is a comparison plot of the
API RP-2A local buckling equation and Equation (4-15) for undamaged members. Equation (4-15) gives reasonable approximations (i.e. the error is less than one standard deviation) of the local buckling load of an undamaged tubulars, however, it is intended that Equation (4-15) be used primarily for corrosion damaged tubulars. One procedure that could be used to adapt Equation (4-15) to a specific code equations for local buckling would be to use this equation to develop as a correction factor $\phi$, where the local buckling code equations for non-corroded tubular members are multiplied by $\phi$ to take into account the corrosion damage. The correction factor is formulated as:

$$\phi = \frac{r}{f \cdot F.S.}$$

(4-17)

Where $r$ is the strength formula, Equation (4-15), $f$ is a code local buckling equation, and F.S. is an appropriate factor of safety. Chapter 1 gives examples of typical local buckling code equations for non-corroded tubular members. (See Equations (1-6) through (1-12)).

### 4.4 SIMPLIFIED METHOD

#### 4.4.1 Method Formulation

A comparison of a simplified elastic method was used to determine the local buckling load. This simplified method involved discretizing a corroded cross section into 100 units, as shown in Figure 4-21. The centroid of the corroded cross section is then calculated by summing the first moment of each unit about the geometric center of the cross section. The internal eccentricity of the cross section is then determined by the
distance from the geometric center of the uncorroded cross section and the centroid of the corroded cross section. The moment of inertia of the corroded section is calculated as the sum of the second moment of each unit about the geometric center of the cross section. The stress at each unit is then calculated as:

$$\sigma = \frac{P}{A} \left[ \frac{M_y I_x + M_x I_{xy}}{I_x I_y - I_{xy}^2} x + \frac{M_x I_y + M_y I_{xy}}{I_x I_y - I_{xy}^2} y \right]$$  \hspace{1cm} (4-18)

Where:

$$I_x = \sum A_i x_i^2$$

$$I_y = \sum A_i y_i^2$$

$$I_{xy} = \sum A_i x_i y_i$$

$$M_x = P e_y$$

$$M_y = P e_x$$

Where the subscript $i$ ranges from 1 to the number of discrete units (100), $M_y$ is the moment about the Y axis, $M_x$ is the moment about the X axis, $I_x$ is the moment of inertia about the X axis, $I_y$ is the moment of inertia about the Y axis, $I_{xy}$ is the product of inertia, $P$ is the applied axial load, $e_x$ is the eccentricity in the X direction, $e_y$ is the eccentricity
in the Y direction, and $A$ is the area of one unit.

Calculating the stresses at each unit will produce the elastic stress distribution around the circumference. However, this method is not applicable once yielding has initiated. Therefore, the stress computed from Equation (4-18) should be compared to the smaller of the local buckling stress (without corrosion, i.e. Equations (1-7), (1-8) or (1-11)) and yield stress in order to estimate the residual strength, $P_u$, of the member.

### 4.4.2 Simplified Method Results

The test specimens were analyzed with the simplified method ignoring the effect of any moment developed at the fixed ends of the member. These moments, which are reactions, did not develop an appreciable amount until after the peak load was reached in the experiments. The eccentricity in the y direction was computed from the first moment (eccentricity in the X direction is zero due to symmetry of the section). The results, in terms of the ratio of the predicted-to-yield capacity $[P_u/P_y]_{\text{sim}}$ are listed in Table 4-1. A correlation plot of the $[P_u/P_y]_{\text{sim}}$ versus $[P_u/P_y]_{\text{FEM}}$ and $[P_u/P_y]_{\text{exp}}$ is shown in Figure 4-22. This correlation plot indicates that this simplified method produces a reasonable approximation of the residual strength of a patch corroded tubular member. The simplified method was further compared with the finite element results and the experimental results by dividing the $[P_u/P_y]_{\text{sim}}$ (simplified method) by the $[P_u/P_y]_{\text{FEM}}$ (finite element analysis) and by the $[P_u/P_y]_{\text{exp}}$ (experimental). When compared to the finite element results, the ratio $[P_u/P_y]_{\text{sim}}/[P_u/P_y]_{\text{FEM}}$ had a mean of 0.992 and a coefficient of variation (COV) of 0.0615. When compared with the experimental results, the ratio
[P_u/P_y]_sim/[P_u/P_y]_exp had a mean of 0.972 and a coefficient of variation (COV) of 0.048. These results indicate that the simplified method is a reasonable approximation for the local buckling load, which was found to be typically three to five percent below the experimental and analytical ultimate load.

4.5 PROCEDURE FOR DETERMINING THE RESIDUAL STRENGTH OF A PATCH CORRODED TUBULAR MEMBER

Based on the preceding results, a procedure for the evaluation of a patch corroded tubular member subjected to only axial loading is summarized in the following steps. This evaluation is intended to provide an estimate of the residual strength of a member. The case of combined axial and flexural loading is not addressed.

(1) Determine the h_cri dimension for the given tubular of radius R.

(2) Inspect the tubular and determine the most severely corroded areas.

(3) Determine the c dimension of the selected corrosion patches by using the corrosion block concept discussed in Section 2.4 (See Figure 2-4). Convert c dimension to θ angle by dividing by the radius, R, of the tubular and then converting it to degrees.

(4) Record minimum thickness measurements in the corrosion block area to define the
thickness reduction \((t_i)\) for each selected area. Nondimensionalize the reduced thickness by dividing by the original thickness \((t_j/t)\).

(5) Substitute \(\theta\), \(t/j\), and \(D/t\) into the residual strength equation, Equation (4-15), to evaluate the normalized ultimate capacity, \(P_u/P_y\), of each of the selected patch.

(6) From the corroded areas analyzed, select the patch with the lowest local buckling strength as the governing patch of corrosion. Apply an appropriate factor of safety to maintain a margin of safety and arrive at the local buckling "design" load.

(7) Determine the allowable axial load by using this new "design" local buckling load in the appropriate long column design equation.

(8) Compare the calculated column capacity from step (7) with the original design loading to evaluate the margin of safety for the corroded member.
Chapter 4

Tables and Figures
<table>
<thead>
<tr>
<th>Specimen</th>
<th>Pu/Py Experimental</th>
<th>Pu/Py Finite Element Analysis</th>
<th>Pu/Py Regression Analysis</th>
<th>Pu/Py Simplified Method</th>
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<th>([\text{Pu/Py}]<em>{\text{reg}} / [\text{Pu/Py}]</em>{\text{exp}})</th>
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Mean: 0.980 0.977 0.972  
COV: 0.024 0.044 0.048

Table 4-1. Analytical and Experimental Results
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Mean = 1.0010  
COV = 0.0344

Table 4-2. Finite Element and Regression Results
Develop Finite Element Model of a Patch Corroded Tubular Member

Perform Sensitivity Study with Finite Element Model to Determine the Most Significant Corrosion Parameters

Develop Experimental Test Matrix Based on the Most Significant Corrosion Parameters (D/t, t/r, θ)

Verify Finite Element Model with Experimental Results

Perform Testing of Experimental Specimens

Perform Parametric Study with Finite Element Model, and Create Database of Results

Develop Local Buckling Stress Equation using Multivariable Regression Analysis of the Finite Element Database.

\[ P_u/P_y = f(D/t, t/r, \theta) \]

Figure 4-1. Schematic Representation of the Scope of the Analytical Program and Relationship to Experimental Program.
Figure 4-2. Typical Finite Element Model of a Patch Corroded Tubular Member.
8-Node Shell Element

(a)

Corrosion Profile

Wall thickness midsurface

(b)

Finite Element Node

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Figure 4-10. Specimen 34-50-311 Normalized Load Versus Normalized Axial Shortening Plots from Experimental Test and Finite Element Analysis.
Figure 4-11. Specimen 46-67-95 Normalized Load Versus Normalized Axial Shortening Plots from Experimental Test and Finite Element Analysis.
Figure 4-12. Specimen 46-33-95 Normalized Load Versus Normalized Axial Shortening Plots from Experimental Test and Finite Element Analysis.
Figure 4-13. Specimen 46-00-95 Normalized Load Versus Normalized Axial Shortening Plots from Experimental Test and Finite Element Analysis.
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Figure 4-16. Coordinate Function for Influence of \( tr/t \) on Residual Strength
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Figure 4-19. Correlation Plot of Results from Regression Equation and Experimental Results
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Figure 4-21. Schematic of Cross Section Used for Simplified Method.
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5. Repair of Corroded Tubular Members

5.1 GENERAL

The experimental study of the repair of corroded offshore tubulars is presented in this chapter. The objective of this study was to examine a prototype external steel sleeve and epoxy-based grout repair for patch corrosion damaged tubular members. A rendering of how a sleeve of this type would look in practice is shown in Figure 5-1 and cross-sectional views of the repair are shown in Figure 5-2.

Two independent mechanisms occur in this type of external grouted sleeve repair. The first mechanism is the confinement of the cross section, while the second is the load transfer into the sleeve.

Confinement of the cross section is the restraint of the corrosion patch to prevent local buckles from forming. Experimental testing of the unrepaired corroded specimens indicated a tendency for the cross section to buckle outward if the aspect ratio of the corrosion patch (c/h) was greater than one, and inward if (c/h) was close to one. Confinement of an outward buckling mode is accomplished with hoop restraint from the external sleeve. Confinement of an inward buckle would require both hoop restraint by the sleeve and radial tensile stresses in the grout needed to maintain compatibility between the tubular and the sleeve.

With respect to the second mechanism, load transfer, the force in the member must be transferred out of the corroded tubular and into the sleeve through bond stresses and shear stresses in the grout. In order to have good load transfer, the bond strength of the grout must be adequate. The need for proper load transfer prompted the use of a high
bond strength epoxy-based grout with the repair sleeve.

The objective of the repair is to return the damaged tubular to its full, undamaged capacity. Ideally, buckling of the repaired member will occur outside of the repaired segment (i.e. the repaired segment would be stronger than the original tubular).

5.2 REPAIR DESIGN

The required design capacity of the sleeve repair can be bound by two extremes. The first extreme is to repair the corroded tubular for the full undamaged capacity (i.e the corroded tubular would be assumed to have zero residual strength). The other extreme is to repair the member to restore only the capacity which was lost to the corrosion damage. Obviously, in order to pursue the latter method there must be some method of evaluating the residual strength of the tubular, such as the residual strength equation (Equation (4-15)) presented in Chapter 4.

The actual repair should be designed to have a strength between the two extreme bounds presented above. The amount of conservatism built into the design of the repair sleeve would be dependent on the importance of the structure, the importance of the member in the structure, the severity of the corrosion, and the consequences of member failure.

The design of the sleeve for the test specimens was based on the bond strength of the grout used to fill the annulus between the tubular and the sleeve. The sleeve was designed to transfer approximately 50 percent of the full capacity of the tubular, and
hence was a compromise between the two extreme bounds presented above. This resulted in a 100 kip load to be transferred into the sleeve through the bond. The sleeve length was calculated by dividing the 100 kip load by the circumference of the tubular (27.1 inches) and the bond strength of the epoxy-based grout (1.2 ksi). The resulting dimension is the sleeve length needed to transfer 100 kips. This dimension is doubled because the 100 kips must be transferred into the sleeve, past the corrosion, and then back into the tubular. Therefore, the 100 kips must be transferred twice. The critical $h$ dimension, $h_{\text{crit}}$, is added to the sleeve length to span the corrosion patch itself. This procedure is demonstrated by the following sample calculation used for the experimental specimens.

Required sleeve length, $s$,

$$ s = \left( \frac{P}{D \pi \sigma_b} \right)^2 + h_{\text{crit}} $$  

(5-1)

$$ s = \left( \frac{100 \text{kips}}{(8.625 \text{ in.}) \pi (1.2 \text{ ksi})} \right)^2 + (4.312 \text{ in.}) $$  

(5-2)

$$ s = 10.46 \text{ in.} $$

Where:

$s$ = sleeve length

$D$ = outside diameter of tubular

$\sigma_b$ = epoxy-based grout bond strength

$h_{\text{crit}}$ = critical $h$ dimension
The 10.5 inch sleeve dimension was then used directly to create the cement-based grout repaired specimen. This was done so a direct comparison of the effect of a different bond strength could be examined. The load transferable through the bond of the cement-based grout (the cement grout had a bond strength of 158.0 psi, as shown in Section 5.3.3.3) with the given dimensions is 13.2 kips. The capacity of the damaged Specimen 46-00-95, which will be repaired with this sleeve, was reduced by 42 kips. Therefore, if the repair were dependent only on load transfer the cement-based grout repair would not be successful.

5.3 EXPERIMENTAL PROGRAM

5.3.1 General

The experimental program for repair of offshore tubular members consists of the testing of two repaired tubulars. The two repaired specimens were similar to Specimen 46-00-95 in terms of corrosion damage, and this specimen was used to experimentally determine the residual strength of the repaired specimens. With respect to each other, the two repaired specimens were identical except for the grout used to fill the annulus between the sleeve and the damaged tubular. The two repaired specimens and unrepaired Specimen 46-00-95 are shown in Figure 5-3. The specific dimensions of these three specimens, including the inflicted corrosion and sleeve repair, are summarized in Table 5-1 and Table 5-2.

Because the purpose of the testing was to investigate a concept rather than a specific repair, the sleeve was not designed as it would be in practice. The sleeve was
not split into two halves nor were there any clamping brackets, as shown in Figure 5-1. The clamping brackets would introduce another unknown parameter of the clamp stiffness. Therefore, to minimize any possibility of uncertainty, the sleeve was left as one piece and was lowered over the end of a vertically positioned damaged tubular. Form work held the sleeve in placed while the grout was poured in from the top of the sleeve.

5.3.2 Specimen Geometry

The specimens for the external sleeve repair were made from ERW (Electric Resistance Welded) structural steel pipe with an outside diameter of 8.625 inches and thickness of 0.1875 inches (D/t=46). Specimen length was limited to 55.5 inches, and L/r for the specimens was 18.5. The two repaired specimens were inflicted with the same corrosion as specimen 46-00-95 so that a direct comparison of repaired and unrepaired strengths could be made.

The steel sleeve used for the repair had an inside diameter of 10.125 inches, a wall thickness of 0.375 inches, and a length of 10.5 inches (The sleeve length was determined in Section 5.2). These sleeve and tubular dimensions produced an annulus between the tubular and the sleeve of 0.75 inches. To prepare the wall surface of the tubular for the repair sleeve, as well a producing a consistent, standard surface, the grout contact surfaces of the tubular and the sleeve was sandblasted to a consistent roughness of approximately 3 mils.
5.3.3 Material Properties

5.3.3.1 STEEL

The damaged and repaired specimens had the same material properties as the D/t=46 series of specimens. The yield stress for the two repaired tubulars, and Specimen 46-00-95, was 38.45 ksi, which is the compressive yield stress determined from the stub-column tests. Typical stress-strain curves from the tensile coupons for the specimens were shown previously in Figure 3-2. More detailed information about material properties of the damaged tubulars was given previously in Section 3.3.

The sleeve was made from a mild steel with a yield stress of approximately 40 ksi. The sleeve had an area which was substantially larger than that damaged tubular, therefore, failure of the sleeve was not a concern.

5.3.3.2 EPOXY-BASED GROUT

Figure 5-4 is a comparison of the compressive stress-strain plots for the cement-based and epoxy-based grouts. The stress-strain data was obtained from tests of ASTM standard 2 inch grout cubes. Both grouts were plotted at their 28 day strength (Note that the epoxy-based grout reaches full strength in seven days).

The epoxy used in the epoxy-based grout was a typical construction grade epoxy called Sikadur 35. This epoxy is a high-modulus, low-viscosity two part adhesive produced by Sika Corporation, Lyndhurst, New Jersey. The epoxy was made into grout by using a 2 to 1 mix of kiln dried sand (0-00 blend grit) and epoxy. At 28 days, the epoxy-based grout had a compressive strength of 10,000 psi, with a modulus of elasticity
E of approximately 1000 ksi. The epoxy-based grout cube crushed, but did not fracture.

The epoxy-based grout has a relatively short curing time. The grout reaches 80 to 90 percent of full strength in twenty-four hours, and reaches full strength in seven days. Material tests of epoxy-based grout cubes indicated that their compressive strength exceeded 8000 psi after twenty-four hours.

The bond strength of the epoxy-based grout was determined from testing a bond strength specimen. The bond strength specimen was fabricated from short sections similar to the test specimen and sleeve, as shown in Figure 5-5. The tubular and the sleeve were overlapped three inches, and the annulus was filled with epoxy-based grout. The grout was allowed to reach full seven-day strength before the specimen was tested in compression, which causes shear stresses in the grout. Instrumentation was setup to measure axial load and axial movement between the two ends of the bond test specimen.

The bond stress-axial displacement relationship from this test is shown in Figure 5-6. This figure shows that the bond strength and axial displacement had a linear relationship up to the point where slip occurred between the tubular and sleeve. After the slip, the grout rapidly increased bond strength until a brittle fracture occurred. Figure 5-6 shows that the slip occurred at 1200 psi and a grout fracture at 1400 psi. Once fracture occurred, a residual bond strength of approximately 350 psi was maintained by the friction across the fractured grout surface as the tubular and sleeve slide in relation to one another under continued axial compression. Failure was considered to be at the slip, therefore, the bond strength of the epoxy based grout was 1200 psi. It should be noted that the failure mode of the bond test was a shearing failure through the epoxy grout and
not a true bond failure. This is because the epoxy grout mix is weaker than the bond strength of the epoxy alone. According to the manufacturer, the specified bond strength of the epoxy alone was 2800 psi, but the addition of the sand to form an epoxy-based grout for this application limited it to 1200 psi.

5.3.3.3 CEMENT-BASED GROUT

The cement-based grout used for the repair was a cement based grout commonly used by the offshore industry. The design grout mix consisted of 54.1 percent Type II portland cement, 10.8 percent microsilica fume, and 35.1 percent water by weight. The cement-based grout had a 28 day compressive strength of approximately 5500 psi, with a modulus of elasticity \( E \) of approximately 730 ksi. The cement-based grout cube specimen failed in compression with a sudden fracture and a severe loss of strength, as shown in Figure 5-4.

The bond strength of the cement-based grout was determined using a bond strength specimen similar to the epoxy-based grout, as shown in Figure 5-5. The tubular and sleeve were overlapped six inches and the annulus was filled with the cement-based grout and allowed to cure for 28 days.

Figure 5-7 is the bond stress-displacement curve for the cement-based grout. This figure shows the slightly non-linear relationship of the bond strength and axial displacement up to the ultimate bond strength of 158 psi. At ultimate load, bond failure occurred and the test specimen gradually lost strength until the only remaining capacity was the sliding friction of the debonded surface. At this point, the specimen was
unloaded. An examination of the specimen indicated that the mode of failure of the cement-based grout was bond failure between the tubular and the grout. This failure mode was induced because the compressive strength of the cement-based grout was greater than the bond strength of the grout.

The load-axial displacement curve for the cement-based grout bond test specimen was superimposed on the load-axial displacement curve in Figure 5-6. This comparison shows that the epoxy-based grout has a bond strength approximately 7.6 times the cement based grout bond strength, and referring to Figure 5-4, the compressive strength of the epoxy based grout is 1.8 times the cement-based grout.

5.3.4 Test Setup

The test setup for the repaired specimens was identical to that of the damaged, unrepaired specimens. Figure 5-8 is a typical test setup for the repaired specimens. See Section 3.4 for an explanation of the test setup.

5.3.5 Instrumentation

All instrumentation, except for the strain gage configuration, for the repaired specimens is identical to that of the damaged, unrepaired specimens as described in Section 3.5.

The strain gage configuration for the repaired specimens is shown in Figures 5.9 and 5-10. The strain gage configuration consisted of twenty-nine 120 ohm uniaxial gages. All gages were oriented so as to record longitudinal strains. Eight of the strain gages (T1
through T4 and B1 through B4) were used as alignment gages and were positioned in two levels of four gages on the tubular. The first level of alignment gages was at quarter height and the second level was at the three-quarter height. Around the circumference, the alignment gages were positioned at the $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$ lines. Five more of the strain gages (M1 through M5) were used at the mid-height of the damaged tubular. These gages were positioned at the $60^\circ$, $90^\circ$, $180^\circ$, $270^\circ$, and $300^\circ$ lines. (Note that the damaged tubulars had corrosion which reduced the wall thickness to a hole, therefore, no strain gages could be placed between the $330^\circ$ and $30^\circ$ lines) The next eight strain gages (S1 through S8) were positioned on the outside surface of the sleeve at the $0^\circ$, $33^\circ$, $60^\circ$, $90^\circ$, $180^\circ$, $270^\circ$, $300^\circ$, and $327^\circ$ lines around the circumference. Four more gages (C1 through C4) were positioned on the outside surface of the sleeve along the $0^\circ$ line (See Figure 5-10). Two gages were positioned above S1, at 0.5 and 2.375 inches from the top end of the sleeve, and two were positioned below S1, at 8.125 and 10 inches from the top end of the sleeve. The last four gages (U1 through U4) were positioned similar to gages C1 to C4 along the sleeve on the outside surface of the sleeve along the $180^\circ$ line (See Figure 5-10). Again, two of the gages were positioned in line directly above S5 and two gages were positioned directly below S5.

5.3.6 Response of Individual Specimens

The results from the experimental testing of the repaired specimens is summarized in Table 5-2, and includes the results from Specimen 46-00-95 for comparison between repaired and unrepaird specimens.
5.3.6.1 SPECIMEN 46-00-95-C - CEMENT-BASED GROUTED SLEEVE REPAIR

Specimen 46-00-95-C was a repaired specimen with identical corrosion parameters to unrepaired Specimen 46-00-95. Results from the unrepaired specimen are shown in Figures 3-27 through 3-29 and discussed in Section 3.7.6. The unrepaired specimen had a static residual strength of 0.783 $P_y$, which was a capacity reduction of 21.7 percent compared to an undamaged tubular. In addition to the capacity reduction of the unrepaired specimen, it is worthwhile noting the non-linearity of the load-deflection curve in Figure 3-27(a), the lateral displacement shown in Figure 3-27(b), and the extreme non-uniformity of the longitudinal strains around the cross-section shown in Figures 3-28 and 3-29.

The first repaired specimen, 46-00-95-C, was repaired with an external steel sleeve and standard cement-based grout. Full yield load, $P_y$, for this specimen, if it were not corroded, would be 193 kips, based on a yield stress of 38.45 ksi.

The specimen was loaded to 0.182 $P_y$ (35 kips) for an alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded to zero load before the test commenced.

Figure 5-11(a) is the normalized load-axial shortening curve for the non-corroded (46-100-0), corroded (46-00-95) and cement-based grout repaired specimens (46-00-95-C). Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen up to a load of 0.600 $P_y$ (115.8 kips) at which
point lateral deflections began to develop at mid-height. Figure 5-11(b) is a plot of the normalized load-lateral displacement curve for specimen 46-00-95-C. The lateral deflection did not influence the linearity of the load-axial shortening curve until the specimen reached a load of 0.850 $P_y$ (164.05 kips). From 0.850 $P_y$ (164.05 kips) to 0.925 $P_y$ (178.53 kips) the load-axial shortening curve exhibited a slight nonlinearity. After 0.925 $P_y$, the load-axial shortening curve exhibited more severe nonlinearity up to the ultimate load of 1.0 $P_y$ (193 kips). No visible local buckling was visible at ultimate load. No yield lines were visible in the area of the repair, however, this portion of the specimen was sandblasted for application of the repair sleeve and no mill scale remained in this area, and therefore, yield lines would not be expected to form. As the specimen reached ultimate load, yield lines did form at the ends of the specimen on the side opposite the corrosion and extended around the circumference at a 45° angle. As axial compression continued the specimen maintained the load of 1.0 $P_y$, yielding of the ends became more extensive, and the lateral deflection became increasingly pronounced. After approximately 0.5 inches of axial compression, an outward bulge formed on the 0° line side (corroded side) of the specimen approximately four inches below the repair sleeve. This bulge became more pronounced with continued axial compression. The specimen was compressed approximately 0.67 inches when loading was stopped and the specimen was unloaded. The specimen had a final axial shortening of approximately 0.62 inches and a lateral deflection of 0.53 inches. The mode of failure was local buckling of the uncorroded wall below the repair sleeve. Also noted was that there appeared to be movement between the repair sleeve and cement grout which indicated a possible bond.
Strain data from specimen 46-00-95-C is shown in Figures 5-12 to 5-16. Figure 5-12 is a plot of the longitudinal strains on the surface of the corroded tubular underneath the repair sleeve at mid-height. This figure shows that the longitudinal strains in the corroded cross section have a similar non-uniform distribution as the unrepaired specimen, however, the non-uniformity of strains occurred at a higher load level. Figure 5-13 is a plot of the longitudinal strain distribution around the circumference at four different load levels. This plot shows the development of the non-uniform strain distribution at higher load levels and that yielding of the corroded cross section occurred at the edges of the hole (yield strain = 1300 microstrains). Inspection of the inside of the specimen showed that the cross section buckled inward at the edges of the hole (see Figure 5-14). The repair sleeve caused the corroded cross section to buckle inward, which is a higher energy buckling mode than the outward mode seen in the unrepaired specimen. Therefore, the nonlinearity of the load-deformation plot (Figure 5-11) was a result of the loss of bond strength between the steel and the grout, which allowed yielding and the inward buckling mode of the corroded cross section. The specimen reached its full yield load because of the confinement provided by the grout and sleeve.

The longitudinal sleeve strains are shown in Figures 5-15 to 5-17. Figure 5-15 is a plot of the longitudinal strains on the outside of the sleeve up to ultimate load. This figure shows that the magnitude of the strains are relatively small, and that they are not uniform around the circumference of the sleeve. The gages on the sleeve in the area of the corrosion patch (gages S1 and S2 as shown in Figure 5-15(c)) had the highest
compressive strains, while the other gages around the sleeve circumference exhibited little compressive strain. The somewhat independent behavior of the sleeve is further displayed in Figures 5-16 and 5-17. Figure 5-16(a) shows the longitudinal strains along the length of the sleeve on the corroded side of the specimen. It is clear that most of the compressive strains are in the central three gages, C2, S1, and C3. Strain gages C1 and C4 exhibited zero strain as a result of the loss of bond strength at the edges of the sleeve. Figure 5-16(b) shows the longitudinal strains along the length of the sleeve on the non-corroded side (180° Side) of the specimen. All strains in these gages recorded essentially zero strains. These zero strains occurred due to the cancellation of the compressive strains by the tensile strains induced by the moment of the laterally displacing specimen. Figures 5-17(a) and (b) compare the strain distribution along the sleeve at different load levels on the corroded (0° side) and the non-corroded side (180° side) of the specimen. These plots show the relatively high strains in the sleeve in the area of the corrosion patch, and the lack of strain at the ends of the sleeve as well as on the non-corroded side of the specimen.

5.3.6.2 SPECIMEN 46-00-95-E - EPOXY-BASED GROUTED SLEEVE REPAIR

Specimen 46-00-95-E was a repaired specimen with identical corrosion parameters as unrepaired Specimen 46-00-95, which was discussed previously. Also noted previously, this unrepaired specimen had a residual strength of 0.783 P_y, which represents a capacity reduction of 21.7 percent compared to its corrosion free capacity.
The second repaired specimen, 46-00-95-E, was repaired with an external steel sleeve Sikadur 35 epoxy-based grout. Full yield load for this specimen, if it were not corroded, would be 193 kips, based on a yield stress of 38.45 ksi.

The specimen was loaded to 0.207 $P_y$ (40 kips) for an alignment cycle. All strain gages and LVDTs were checked, and the strains in the alignment gages confirmed that the loading was being applied adequately uniform. The specimen was unloaded to zero load before the test commenced.

Figure 5-18(a) is the normalized load-axial shortening curve for the non-corroded (Specimen 46-100-0), corroded (Specimen 46-00-95), and epoxy-based grout repaired specimen (46-00-95-E). Loading started and was controlled by a displacement rate of 0.01 inches/minute. There were no visible changes in the specimen until after the ultimate load was attained. Figure 5-18(a) shows that the normalized load-axial shortening curve was linear up to the ultimate load. Figure 5-18(b) is the normalized load-lateral deflection plot. This plots shows that there was no lateral displacement until after the ultimate load was attained, and that there was some lateral deflection in the $0^\circ$ Line direction (negative lateral deflection in Figure 5-15(b)) before the expected lateral deflection forced the specimen in the opposite direction. No visible local buckling was visible at ultimate load. Nor were there yield lines visible in the area of the repair, however, this portion of the specimen was sandblasted for application of the repair sleeve and no mill scale remained in this area, therefore, yield lines would not be expected to form. The specimen load reached and slightly surpassed 1.0 $P_y$, then quickly dropped back down to 1.0 $P_y$. With continued axial compression past ultimate load, the specimen
maintained the load of 1.0 \( P_y \), and yield lines formed at the ends of the specimen which extended around the circumference. The pattern of the yield lines indicated the development of a symmetric "elephant’s foot" mode of local buckling at the top of the specimen. Continued axial compression enlarged a series of symmetric outward bulges at the top and produced another at the bottom of the specimen. Extensive yield lines formed at the top and bottom of the specimen. These yield lines were symmetric and not like the yield lines seen in the unrepaired or the cement-based grout repair. The specimen was compressed to approximately 0.60 inches when loading was stopped and the specimen was unloaded. The specimen had a final axial shortening of approximately 0.51 inches and a lateral deflection of 0.097 inches upon unloading. The mode of failure was a symmetric "elephant’s foot" local buckling of the uncorroded wall at the top and bottom of the specimen. Also noted was the fact that there appeared to be no movement between the repair sleeve and epoxy-based grout which indicated that there was no bond failure.

Strain data from specimen 46-00-95-E is shown in Figures 5-19 to 5-23. Figure 5-19 is a plot of the longitudinal strains on the surface of the corroded tubular underneath the repair sleeve at mid-height. This figure shows that the longitudinal strains in the corroded cross section remained in the linear elastic range. Figure 5-20 is a plot of the longitudinal strain distribution around the circumference at four different load levels. This plot shows that the strain distribution around the circumference was uniform, even at the edges of the hole. These figures also show that there was neither yielding nor buckling of the corroded cross section, even after extensive axial compression (yield strain \( \sigma_y = 1300 \) microstrains). Inspection of the inside of the specimen after testing confirmed
that there was no local buckling of the cross section. Therefore, this repaired specimen behaved as if it were an undamaged stub-column.

The sleeve strains are shown in Figures 5-21 to 5-23. Figure 5-21 is a plot of the strains on the outside of the sleeve up to ultimate load. This figure shows that the strains are uniform around the circumference of the sleeve. Figure 5-21(c) shows the locations of the plotted strain gages. The uniform strain behavior of the sleeve is further displayed in Figures 5-22 and 5-23. Figure 5-22(a) shows the longitudinal strains along the length of the sleeve on the corroded side of the specimen, and Figure 5-22(b) shows the longitudinal strains along the length of the sleeve on the non-corroded side of the specimen. These two figures indicate that the sleeve remained linear elastic and also shows the uniformity of the strains around the circumference of the sleeve. Note that the central portion of the sleeve (gages C2, S1, C3, and U2, S5, U3) exhibit compressive strains while the ends of the sleeve (gages C1, C4, and U1, U4) exhibited tensile strains. These tensile strains are caused by the affect of the high bond strength of the epoxy-based grout. At the edges of the sleeve there is a strain discontinuity between the highly strained tubular, and the end of the sleeve which has zero strain. Compatibility of the tubular and the sleeve end is maintained by the Epoxy-based grout. The bond strength of the epoxy-based grout is high enough that strains in the tubular cause the grout to pull at the ends of the sleeve, causing enough local bending of the sleeve to exhibit tensile strains on the outer surface. These tensile strains occur near the ends of the sleeve where the strain gages (C1, C4, U1, and U4) are located. Figure 5-23(a) and (b) compares the strain distribution along the sleeve at different load levels on the corroded (0° side) and
the non-corroded side (180° side) of the specimen. These plots clearly show the tensile strains produced at the ends of the sleeve, as well as the very uniform strain distribution throughout the remaining part of the sleeve.

5.3.6 Assessment of Specimen Response

It is apparent that both repaired specimens, 46-00-95-C (Cement-based grout) and 46-00-95-E (Epoxy-Based Grout), were successful in the sense that they both attained the full capacity of the undamaged member. The success of both specimens indicates that the strength of the grout is not the most important mechanism for a successful repair. The confinement of the damaged cross section appears to also be an important mechanism for a successful repair. For both of the repaired specimens the sleeve was stiff enough to provide proper hoop restraint to confine the cross section from buckling outward. The higher energy inward mode, which the specimen was forced into, enabled the lower strength cement-based grout specimen to reach its full capacity.

However, there is a definite influence of grout bond strength in the behavior of the repair. The lower strength cement-based grout allowed non-uniform strain distributions, yielding and buckling of the corroded cross section, as well as excessive lateral deflection. These undesirable effects were caused by the lower bond strength of the cement-based grout which could not preserve full compatibility between the tubular and the sleeve. The damaged cross section still possessed an internal eccentricity, reduced gross section and reduced local buckling resistance, however the effects of these problems was minimized by the confinement of the sleeve.
In contrast, the higher bond strength epoxy-based grout had a bond capacity high enough to preserve the compatibility between the tubular and the sleeve. The high bond strength caused the tubular and the sleeve to act more as one symmetric section and prevented yielding and buckling of the corroded cross section. The strain distribution was more uniform throughout the repair and lateral deflections were reduced by over 80 percent in the epoxy repair. The epoxy-based repair effectively eliminated the internal eccentricity and reduced local buckling resistance of the corroded cross section by creating a new, more uniform symmetric section. Apparently, the higher tensile strength of the epoxy-based grout prevented, through radial tension, inward buckling near the edges of the corrosion hole. Figure 5-19(b) shows that the corroded cross section in the epoxy-based repair specimen reached a maximum longitudinal strain of approximately 700 microstrains, and did not exceed the yield strain of 1300 microstrains. In contrast, the cement-based grout repair specimen reached strains of approximately 14,000 microstrains (see Figure 5-12) and locally buckled at the corroded cross section.

Other positive aspects for the use of epoxy-based grout include the curing time and the inertness of the epoxy. The epoxy-based grout reaches 80 to 90 percent of full strength in twenty-four hours (epoxy-based grout cubes exceeded 8000 psi in 24 hours), and reached full strength in seven days. In contrast, cement-based grout attains only minimal strength after twenty-four hours and needs 21 to 28 days to reach full strength. Also, the epoxy-based grout is not influenced by contact with water, and can be used to displace water without detrimental effects. In contrast, the strength of the cement-based grout is highly dependent on the water to cement ratio. Therefore, the quality of the
cement-based grout can be more affected by forcing it to displace water.
Chapter 5

Tables and Figures
Table 5-1. Measured Dimensions for Corrosion Damaged Specimen 46-00-95 and the Repaired Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>L (in.)</th>
<th>D (in.)</th>
<th>t (in.)</th>
<th>D/t</th>
<th>L/t</th>
<th>L/D</th>
<th>c (in.)</th>
<th>tr (in.)</th>
<th>θ (radians)</th>
<th>° (degrees)</th>
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<td>8.590</td>
<td>0.190</td>
<td>45.21</td>
<td>18.5</td>
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<td>0.000</td>
<td>1.67</td>
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<td>0.00</td>
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<td>46-00-95-C</td>
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<td>0.191</td>
<td>44.97</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
<td>0.000</td>
<td>1.67</td>
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</tr>
<tr>
<td>46-00-95-E</td>
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<td>8.590</td>
<td>0.190</td>
<td>45.21</td>
<td>18.5</td>
<td>6.43</td>
<td>7.2</td>
<td>0.000</td>
<td>1.67</td>
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Table 5-2. Repair Dimensions and Test Results for Corrosion Damaged Specimen 46-00-95 and the Repaired Specimens

<table>
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<tr>
<th>Specimen</th>
<th>Sleeve Length (in.)</th>
<th>Sleeve Thickness (in.)</th>
<th>Annulus (in.)</th>
<th>Grout Type</th>
<th>Grout Cube Strength (ksi)</th>
<th>Grout Bond Strength (ksi)</th>
<th>Py (kips)</th>
<th>Pu (kips)</th>
<th>Pu/Py</th>
</tr>
</thead>
<tbody>
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<td>46-00-95 *</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>193.0</td>
<td>151.1</td>
<td>0.783</td>
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<td>0.313</td>
<td>0.75</td>
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<tr>
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<td>5500</td>
<td>158</td>
<td>193.0</td>
<td>193.0</td>
<td>1.000</td>
</tr>
</tbody>
</table>

*Damaged, unrepaired specimen
Figure 5-1. External Grouted Sleeve Repair for Patch Corroded Tubular Members.
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Figure 5-14. Inward Local Buckles at Edges of Hole on Specimen 46-00-95-C (Cement-Based Grout Repair Sleeve).
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6. Summary, Conclusions, and Recommendations

6.1 SUMMARY

Twelve full scale tests were performed to examine the effects of patch corrosion damage to offshore tubular members, and assess the feasibility of a prototype external sleeve repair. The test matrix consisted of three undamaged control specimens, seven simulated patch corroded specimens, and two specimens which were damaged and repaired. The specimens were short segments (L/r=18.5) and were subjected to concentric axial compression. In addition to a direct experimental evaluation of the effects of patch corrosion, the results of this testing confirmed a proposed parameterization of patch type corrosion, and verified appropriate finite element models of patch corroded tubular members. Results from the prototype repair specimens allowed direct evaluation of the repaired strength of a corroded tubular member repaired with an external sleeve, and provided valuable insight into the mechanisms required to effectively repair patch corrosion damage on tubular members.

Finite element and regression analysis, involving 29 models of corroded tubulars, allowed for the development of a larger database of specimen behavior and the formulation of a strength equation which provides the residual strength of a corroded tubular based on the D/t ratio of the tubular and specific corrosion parameters.

6.2 CONCLUSIONS

Based on the results of the study presented here, the following conclusion are
given:

(1) Patch-corroded offshore tubulars can suffer significant capacity reductions from relatively small patches of corrosion.

(2) The D/t ratio, thickness reduction t/t, and subtended angle of the corrosion patch θ are critical parameters for determining the residual strength of a patch corroded tubular member.

(3) The height of a corrosion patch along the member is not a sensitive parameter provided h is at least one radius.

(4) The aspect ratio (c/h) of the corrosion patch can influence the buckling mode of a patch-corroded tubular. Aspect ratios close to one (c/h≈1.0) induce an inward mode of local buckling, while an aspect larger than one (c/h < 1.0) tends to induce an outward local buckling mode in patch corroded tubular members.

(5) Patch-type corrosion can be successfully repaired with a grouted external sleeve.

(6) Confinement of the corroded cross section to prevent outward buckling is the primary mechanism acting in an externally grouted sleeve repair for patch
(7) The bond strength of the grout influences the behavior of the grouted sleeve repair by preserving the compatibility between the tubular and the sleeve in both the longitudinal and radial directions. A higher bond strength grout, such as the epoxy-based grout used herein, preserves the compatibility more effectively than lower bond strength cement-based grouts. Therefore, higher bond strength grouts should be considered for use in a sleeve repair, particularly when the aspect ratio of the corrosion is close to 1.0 \( (c/h=1.0) \), which makes the lowest energy buckling mode for the tubular an inward local buckle.

(8) Nonlinear finite element analyses showed that the method is effective in modeling the behavior and capacity of patch corroded tubular members.

(9) The strength formulation developed by multi-variable regression analysis of the finite element results (Equation 4-15) can closely predict the residual strength of a patch corroded tubular member subjected to pure concentric compression.

(10) Other analytical methods, such as the simplified elastic method presented herein, may produce accurate predictions of capacities of patch corroded tubulars.
tubular members. However, care must be used when applying methods which are valid only in the elastic range because the failure mode of all experimental specimens was inelastic local buckling and the elastic limit and the inelastic capacity of a tubular may not correlate closely for all tubulars.

6.3 RECOMMENDATIONS FOR FUTURE WORK

Based on the results and conclusions presented here, the following areas are recommended for future research:

(1) Practical techniques of assessing and repairing patch corrosion damage in the field.

(2) Further development of residual strength assessment and repair of patch corroded tubulars with experimental testing of other loading conditions. This testing should include, but not be limited to: pure moment members, eccentrically loaded members (beam-columns), pinned ended members, cyclic loading, and fatigue testing.

(3) The critical corrosion patch height, \( h_{\text{crit}} \), should be further examined to better define its limits and influence on specimen behavior.

(4) Development of residual strength assessment should be performed for
multiple patch corroded tubulars as well as other shapes and profiles of corrosion.

(5) Parametric studies of the grouted sleeve repair should examine sleeve stiffness, size of annulus, sleeve length, and bracketing systems.

(6) High performance, non-ferrous, composite materials, such as advanced composite fiber-epoxy laminates, should be examined for their use in underwater repair of corrosion damaged tubular.

(7) Development of appropriate analytical tools for evaluating corrosion damage incorporating the other areas of future work presented here.
7. References


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8. Vita

Michael Francis Hebor, the author and son of Francis and Juliann Hebor, was born on March 8, 1970 in Pottsville, Pennsylvania. He grew up in Eastern Pennsylvania and graduated from the Pottsville Area High School in 1988. His undergraduate studies were conducted at the University of Pittsburgh in Pittsburgh, Pennsylvania. In 1992 he graduated Magna Cum Laude with his Bachelor of Science Degree in Civil Engineering.

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