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Review Article

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Conjoint Influence of Nature of Loading and Environment on Residual Strength of an Alloy Steel

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Abstract

In this paper, the influence of nature of loading, i.e., tensile strength and compressive buckling, severity of environment and time of exposure to environment on strength and response of an alloy steel is presented and briefly discussed. The nature, extent and severity of environment-induced degradation, or corrosion, on loss of strength experienced by the alloy steel structure is highlighted in light of the concurrent and mutually interactive influences of length of exposure time to the environment and nature of loading.

Keywords Alloy steel, Environment, Exposure time, Degradation, Strength

1. Introduction

Steel is often a preferred material for use in the construction industry due to its superior mechanical properties. Steel is essentially an alloy of iron, carbon and a few other elements and offers an excellent strength-to-weight [σ / ρ] ratio. High strength low alloy steels are generally chosen for use in ship structural elements, such as hull and frames, which often comprise of a network of stiffened panels. A stiffened panel often consists of a combination of plates, small beams (stiffeners), and girders [1].

To understand the influence of exposure to an aggressive environment on a stiffened panel, it is important to study the influence of the environment on different elements of a panel. The primary objectives of this research study was to determine the residual strength of ASTM A-572 grade 50 ksi steel using:

(a) Steel coupons subject to uniform environment-induced damage, and

(b) Steel plates that were subject to both uniform damage and pitting damage.

The nature, extent and severity of environment-induced degradation, or corrosion, on loss of strength experienced by the alloy steel structure is presented considering the mutually interactive influences of length of exposure time to the environment and loading.

2. Test Procedure for the Steel Coupons and Plates

2.1 Methodology or Approach

Two types of damage processes were used for the purpose of laboratory simulation of corrosion. The chosen alloy steel coupons were initially corroded to induce uniform corrosion. The steel test specimens were also subject to uniform corrosion or pitting corrosion.

2.1.1 ASTM B117 Q- Fog Chamber Method

The ASTM B 117 is a standardized method that is often used in corrosion studies for the purpose of simulating the actual corrosion process. Details and specifics of this test method can be found elsewhere [3]. The temperature during the test and test rate were maintained in accordance with specifications detailed in this standard ASTM B 117.

For purpose of uniform damage, the uncoated test specimens were placed in a "Q" Fog chamber. For the purpose of pitting corrosion, a protective coat of paint was used to prevent damage to the test specimen that was exposed to an aggressive aqueous environment. The pits on the test specimen surface were continuously exposed to a fog chamber environment. The test specimens were thoroughly cleaned once every day with the prime objective of exposing new and fresh surface of the test specimens to ensure continued exposure to an aggressive aqueous environment. The pits were carefully cleaned so as to not damage the paint in the immediate vicinity of the pits.

2.2 Test Specimen Series

To study the effect of both uniform damage and pitting-induced damage on mechanical response of the chosen high strength alloy steel, the dog-bone shaped test specimens and the plates were deformed both in tension and in compression. The steel plates and coupons were divided into three series based on the severity of damage resulting from exposure to the aggressive aqueous environment within the fog chamber.

2.2.1 Series 1 Uniformly Corroded Steel Coupons

Series 1 was used to evaluate the tensile capacity of the uniformly corroded steel specimens. The Series 1 samples were further divided based on the extent and/or severity of damage induced due to exposure to the aqueous environment to be (a) 5 percent, (b) 10 percent, (c) 15 percent, and (d) 20 percent. For each percentage of damage induced, four test specimens were tested with the primary objective of obtaining accuracy in the test results. A Standard ASTM test sample was used for the tensile tests.

2.2.2 Series 2Uniformly Corroded Steel Plates

Series 2 was used to evaluate the compressive buckling capacity of the uniformly corroded steel plates. The Series 2 was further divided into three types, and these are the following:
(a) 5 percent damage due to uniform corrosion,
(b) 10 percent damage due to uniform corrosion, and
(c) 15 percent of damage due to uniform corrosion.
For each percentage of damage, four samples were deformed in tension to ensure accuracy in the test results.

2.2.3 Series 3 Pitting Corrosion of Steel Plates

Steel plates measuring 4.5-inch x 4.5 inch, were used for the Series 3 tests. The thickness of a steel plate was 0.187 inch. Also, the test plate was checked to ensure alignment with the stress axis, i.e., load axis, of the test machine coupled with the presence of defects on the surface.

2.3 Mechanical Testing

To understand the behavior of the corroded structural member both tensile tests and compression tests were performed on the as-corroded test samples. The steel coupon was subject to a tensile test while the steel plate was deformed under the influence of compressive loading. The environment-induced damaged test specimen was deformed in tension on a fully-automated servohydraulic test machine [Model: MTS] in conformance with the procedures detailed in the Standard ASTM E8 [6]. The test speed was in conformance with specifications detailed in Standard ASTM E8. Details and specifics of a compression test on sample of a metallic material is described in the Standard ASTM E9 [7]. The buckling test is critical for the case of plates that are often chosen for use in a ship hull, which often experiences a compressive load during service. The plates that were subject to damage due to the conjoint influence of uniform damage and pitting-induced damage were examined for the critical buckling load.

3.Experimental Results and Discussion

The results obtained from the experimental tests are described in this section. The results are divided into three sub-sections.

3.1Tensile Test of Uniformly Corroded Steel Coupons

Uniform corrosion of the steel coupons was achieved by the ASTM B-117 Q fog chamber method. The modulus of elasticity (E), yield strength (σYS), and ultimate tensile strength (σUTS) was determined for all percentages, or degree of environment-induced damage, as a direct consequence of exposure to an aggressive aqueous environment. Summarized in Table 1 are the room temperature mechanical properties obtained from the tensile test. The stress versus strain curves are summarized in Figure 1 for the test coupons following varying degree of corrosion-induced damage. This figure shows an observable loss in the yield stress for test specimens that experienced a higher level of environment-induced damage, or corrosion. The modulus of elasticity (E), or slope of the stress versus strain curve, was essentially constant and reveals minimal influence of environment-induced damage or corrosion. The ultimate tensile strength, or tensile strength, decreases with an increase in damage caused by exposure to an aggressive aqueous environment. The morphology of the chosen test specimens subsequent to being deformed in tension and upon failure is shown in Figure 2.

3.2 Compressive Buckling of Uniformly Corroded Steel Plates

A near uniform environment-induced damage, or corrosion, of the plates of the chosen high strength steel was achieved by the ASTM B-117 Q fog chamber method. The modulus of elasticity (E) and ultimate buckling load (PU) was determined for all four degrees of environment-induced damage. The critical buckling load was obtained from the load versus deflection curve. Once the alloy steel plate is bent, or buckled, it can take no further compressive force and the load versus deflection curve takes the trend of a gradual decrease in slope once the peak is reached.

In Figure 3 (Left) is shown the load versus deflection curves for steel plates that were subject to varying degree of damage due entirely to environment-induced damage. The figure reveals a substantial loss in the ultimate buckling load for the test samples that experienced higher percentages of damage induced by the aggressive aqueous environment. Further, the slope of load versus deflection curve decreases as the degree of environment-induced damage increases. The uncorroded test sample had higher stiffness but lower ductility. The ductility of the chosen alloy steel was observed to increase with an increase in the percentage of environment-induced damage. Under compressive loading the thickness of the steel plate decreases with a concurrent increase in the slenderness ratio thereby causing an observable reduction in the critical buckling load.

3.3 Compressive Buckling of Steel Plates Subjected to Pitting Corrosion

The pitting corrosion of a steel plate was achieved with the aid of precise cuts made using a computer numerical control [CNC] machine. The modulus of elasticity (E) and ultimate buckling load (PU) was calculated for the chosen four series of pitting corrosion. In Figure 3 is shown the load versus deflection curve for varying degree of pitting corrosion-induced damage in the test specimens. The graphs reveal a substantial loss in the ultimate buckling load for the higher percentages of damage caused by exposure to an aggressive aqueous environment. Slope of the load versus deflection curve failed to reveal any consistency. As the pitting corrosion is highly complex in nature, the formation and presence of numerous stress concentration sites [or 'pits'] did significantly influence both the ductility and ultimate buckling load capacity of the plate.

Test Specimen	Elastic modulus (ksi)	Yield stress (ksi)	Ultimate stress (ksi)	Yielding load (Kips)	Average yielding load (kip)
Uncorroded	29666	59.81	70.65	5.58	5.57
Uncorroded	29765	60.45	70.53	5.55	
Uncorroded	29546	60.35	71.41	5.64	
Uncorroded	29626	59.42	71.27	5.54	
5% A1	30002	60.01	70.101	5.35	5.36
5% A2	29795	62.02	72.35	5.33	
5% A3	29664	61.68	71.98	5.4	
5% A4	29631	61.52	72.04	5.38	
10% E1	29620	62.21	72.46	5.16	5.09
10% E2	30042	62.56	72.64	5.19	
10% E3	29979	59.56	70.27	4.94	
10% E4	29415	61.12	70.67	5.07	
20% B1	30339	60.55	70.66	4.53	
20% B2	30433	60.668	70.54	4.52	4.49
20% B3	27118	60.21	71.23	4.49	
20% B4	29096	60.16	70.89	4.43	
25% F1	29777	59.57	69.52	4.25	4.13
25% F2	28252	58.54	69.17	4.17	
25% F3	30788	56.28	66.65	4.01	
25% F4	30125	57.66	68.82	4.11	

Table 1: Room temperature (27oC) tensile properties of both the uncorroded and corroded test samples of the chosen high strength low alloy steel.

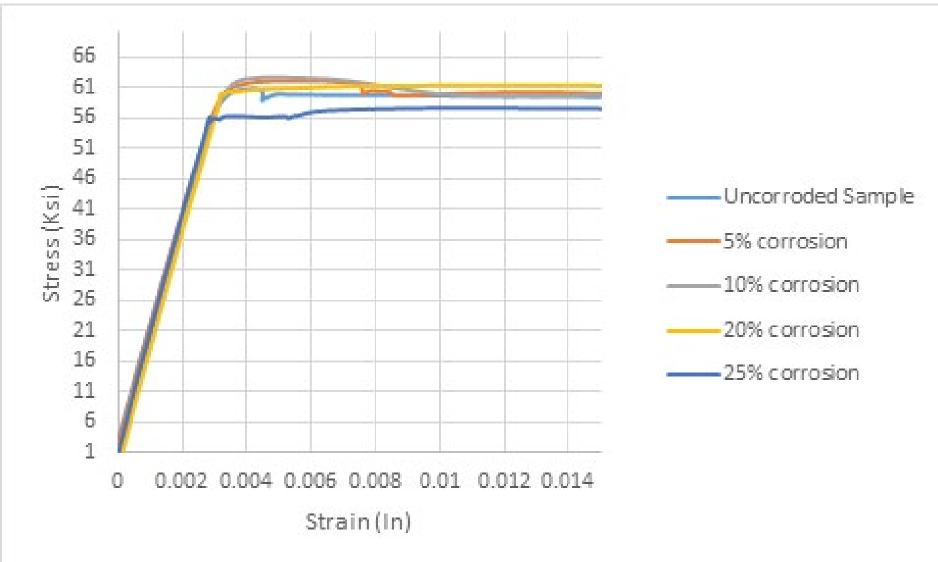

Figure 1; A comparison of the stress versus strain curves for varying degree of damage due to exposure to environment.

Figure 2: The test samples, subject to various degree of environment-induced damage, subsequent to being deformed and failure in tension.

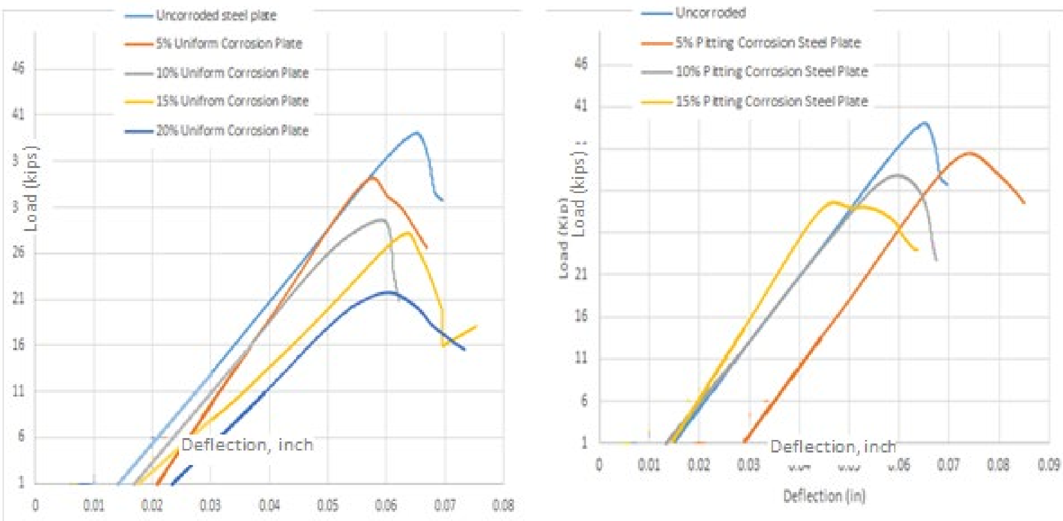

Figure 3: Compressive Load Versus Deflection Curves for Plates Due to Exposure to Environment (Uniform Corrosion on Left and Pitting Corrosion on Right).

4. Conclusions

The following are the key findings from this research study:

(1) The loss in tensile strength of the chosen alloy steel increases when subject to uniform corrosion caused by exposure to an aggressive aqueous environment. This loss is highly non-linear in nature with respect to percentage damage induced due to exposure to an aggressive aqueous environment.

(2) The modulus of elasticity is relatively constant despite exposure to an aqueous corrosive environment.

(3) Compression buckling strength of the chosen alloy steel plates decreases with an increase in uniform corrosion, or pitting corrosion, induced as a direct consequence of exposure to an aggressive aqueous environment.

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