# Strength of Thin-Walled, Butt-Welded Steel Tube

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## Abstract

Fabrications made from thin-wall steel tubing are frequently used for high-performance structures such a bicycle and aircraft frames. Cold-drawn seamless alloy steel tubes, often made of 4130 or similar alloys, provide good strength, rigidity, and toughness, with relatively low weight. Tungsten arc welding (GTAW) is frequently used to join thin-walled steel tubes. This study investigates the strength of butt-welded joints made from 4130 seamless tube with a diameter of .75 inches and a wall thickness of .035 inches. Both tensile strength and fatigue strength were measured. The fatigue test used is derived from ASTM F2711, a standard for fatigue testing bicycle frames. Tensile tests compared the strength of ER70, ER80, and stainless steel filler rod to unwelded specimens. In all cases, the welded strength was within 1% of the unwelded tube strength. There was no statistically significant difference between the welded and unwelded specimens, nor between any of the types of filler material. A statistically significant difference was found between two batches of tubing ordered from the same supplier on two different occasions (4.04% difference, p = .0032). Flexural fatigue tests were also conducted on butt-welded tubes with ER80 and stainless steel filler rod. The fatigue strength were very similar, with the ER80 specimens exhibiting a slightly greater fatigue strength at high loads (low cycles) and the stainless filler rod specimens exhibiting a slightly greater fatigue strength at low loads (high cycles). The strength of butt-welded, thin-walled steel tube in either flexural fatigue or tensile loading does not significantly vary with ER70, ER80, or stainless steel filler material

**Background**

Light Alternative Vehicles (LAVs) comprises a class of vehicles dominated by bicycles, but which also includes electric bicycles, velomobiles, and similar vehicles. LAVs are small, and powered either by human muscles or auxiliary power up to 750W[1]. These vehicles provide transportation, recreation, competition, and exercise for people around the globe. As a transportation alternative, LAVs are inexpensive, efficient, and often non-polluting. In urban areas, significant use of LAVs may provide a more sustainable transportation option.

Due to very limited power, minimizing weight is an important factor in LAV design. Consequently, optimizing frame geometry is also important, and preventing fatigue failure is a significant design task. There is a need for fatigue information on light alternative vehicle frames, particularly for custom manufacturers, because fatigue data on frames is not readily accessible to engineers outside of large manufacturing environments.

A previous study investigated the applicability of ASTM F2711, a standard for bicycle frame fatigue that includes both a horizontal and vertical fatigue test as the basis for an improved early design stage method for design against fatigue failure in LAV frames[2, 3]. A testing apparatus (fatigue tester) capable of vertical fatigue tests on either upright or recumbent bicycle frame was designed and constructed during the 2012/2013 academic year by Grove City College seniors. ASTM F2711 is shown to be a less conservative test for fatigue failure – valuable for early fatigue life design and frame optimization in both recumbents and upright bicycles.

When a load case is used to design a frame, such as the load case adapted from ASTM F2711, the area of greatest concern is usually the joints. Historically, frame members were joined using cast, machined lugs, but in recent decades notched, welded construction has become the method of choice for most manufacturers. The most common material for the tubes of a bicycle frame is carbon steel, usually found in low-end bicycles. Higher performance Chromoly steel is frequently used in higher performance bikes as well as in the automotive and recreational vehicle industries[4]. Several weld filler are commonly recommended for welding thin wall Chromoly tubing including: ER70S-2, ER80S-D2, and austenitic stainless steel fillers[5]. This study investigates the effect of weld filler materials on the fatigue and tensile behavior of thin-walled Chromoly steel structures. Tensile testing and flexural fatigue testing is performed on butt-welded tube specimens to compare the relative performance of filler materials.

**Methodology**

*Tensile Testing*

Tensile specimens were made from two, 4-inch lengths of 0.75" OD by 0.035" wall 4130 Chromoly[6] steel tubes butt-welded together using the TIG welding process. Samples were welded with one of three filler rods: ER70, ER80, or CRES. After being welded, 1.5" on each end of the 8" long specimens was crimped and marked with a unique ID number. The specimens were then tested to failure in an Instron 5584 tensile testing system at a constant load rate. A second round of testing with ER70 filler material was done using specimens made from a separate batch of 4130 Chromoly steel tubing. Five unwelded control specimens and five ER80 specimens were also tested.

*Fatigue Testing*

Flexural specimens were made from two 6-inch lengths of 0.75" OD 0.035" 4130 Chromoly steel tubes butt welded together using the TIG welding process. Samples were welded with either ER80 or CRES filler rods. A fixture was designed to adapt a bicycle fatigue testing machine (fatigue tester), developed by a team of senior mechanical engineering students at Grove City College, to apply a load similar to a three-point flexural test (see Figure 1). The butt-welded tube was supported at both ends by a pivoting clamp. A sinusoidal load was applied by a two inch wide bracket offset from the weld. The load application during the tests was force controlled, i.e. a load point was maintained, not a stress or strain level. The load ratio, R=0.1, given by Equation (1.1), is the ratio of the force having the lowest algebraic value in the cycle to the force having the highest algebraic value:

$$R = F_{min} \Big/ F_{max} = 0.1 \tag{1.1}$$

Although the capability to record data from strain gages was available, they were not used because this study was only interested in a relative comparison of the filler rods, not an absolute value of the strains (or stresses) sustained.
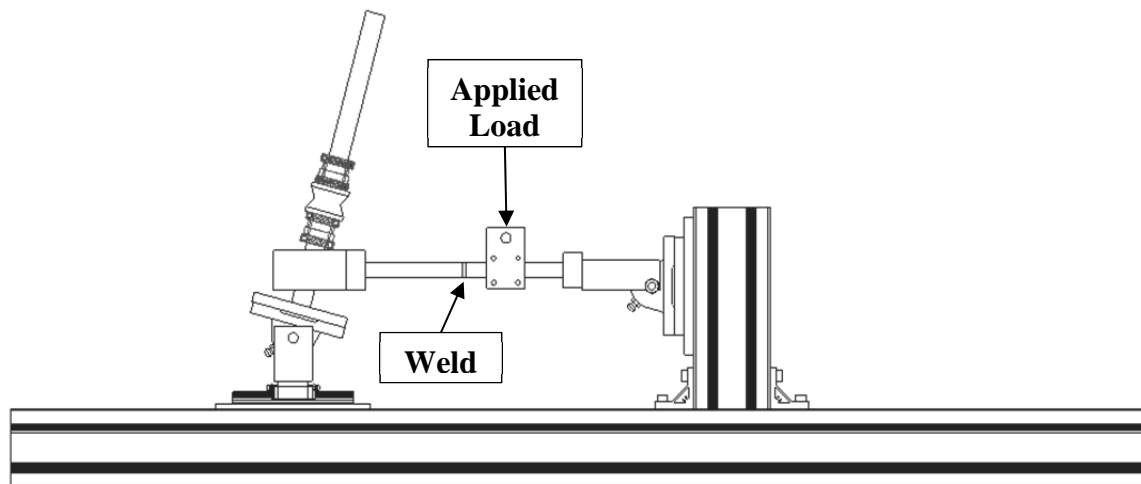


**Figure 1** Fixture for fatigue testing the butt-welded tubes.

An FEA model and hand calculations were used to estimate the stresses and set the load level for the first specimen. The endurance limit was estimated to be half the ultimate tensile strength times the Marin modification factors for surface condition and size (tube diameter, d), as shown in Equations (1.2), using measured values for the ultimate tensile strength:[7]

$$S_e = k_a k_b S_e' = 7,535 \ psi$$
$$k_a = 2.70 S_{ut}^{-0.265} = .121$$
$$k_b = 0.879 d^{-0.107} = 1.01$$
$$S_e' = 0.5 S_{ut} = 61,880 \ psi$$

$k_a$ = surface condition modification factor

$k_b$ = size modification factor

$S_e'$ = rotary-beam test specimen endurance limit

$S_e$ = endurance limit at critical location in condition and geometry of use

(1.2)

S-N curves can be modeled by exponential functions of the form given in Equation (1.3) below:

$$y = Ax^b \tag{1.3}$$

As data was collected, MATLAB's nonlinear regression tools were used to develop load-life relationships for the specimens welded with each filler rod. Load levels were then chosen to get a spread of data from 10^3 cycles to 10^6 cycles. After the testing was completed, MATLAB's statistics toolbox was used to predict 95% confidence intervals for the nonlinear regression models. Those models were then used to determine if one had a statistically higher fatigue strength.

Because this study is only interested in a relative difference between the filler rod materials, all of the diagrams are presented as force-cycles to failure, or F-N diagrams. Only one specimen is tested at each stress level because of time and cost considerations, giving very little information on the variability or distribution of the fatigue data. In addition, the current method of testing produces a difficult to analyze stress state. Further work is being done to develop a faster method for testing the behavior and quality of welds in thin-walled steel tubes.

**Results**

*Tensile*

Two rounds of tensile tests were done with separately purchased batches of 4130 Chromoly steel tubing. The first round (denoted by an "A" suffix in the results section) consisted of 27 specimens welded with ER70 filler rod, 24 specimens welded with ER80 filler rod, and 27 specimens welded with CRES filler rod. A problem with the preparation of the ER70-A specimens made the data unreliable and was discarded. A second round of testing was done (denoted by a "B" suffix in the results section) consisting of 27 specimens welded with ER70 filler rod, 5 specimens welded with ER80 filler rod, and 5 control specimens with no weld. The sample sizes, mean breaking loads, and standard deviations of each specimen group are summarized in Table 1.

**Table 1** Butt-weld tensile data for both batches of Chromoly tubing

|  | ER80 A | CRES A | Control A | ER70 B | ER80 B | Control B |
|---|---|---|---|---|---|---|
| **Sample Size** | 24 | 27 | 5 | 27 | 5 | 5 |
| **Mean Breaking Load (lbs)** | 9,730 | 9,700 | 9,739 | 10,065 | 10078 | 10149 |
| **Standard Deviation (lbs)** | 168.4 | 218.6 | 140.7 | 91.0 | 67.9 | 25.6 |

There were three failure modes for the specimens:

1. Along the weld in the heat-affected zone (HAF)
2. At the neck of the specimen close to the grips where the specimens are flattened
3. Inside gripped area

The failure modes of the specimens were not correlated with the breaking strength of the specimens in any of the groups presented at a 0.05 significance level.

Figure 2 contains a boxplot comparison of all the tensile data. A statistically significant difference was found between two batches of tubing ordered from the same supplier on two different occasions (4.04% difference, p = .0032) with the second batch of tubing (Batch B) having a higher mean breaking strength. Figure 3 contains boxplots comparing the tensile data from batch A and B separately. The ANOVA test p-values for Batch A and B (p = 0.82 & p = 0.13, respectively) indicate that there is not a statistically significant difference between the breaking loads of the welded specimens and the unwelded control specimens, within each batch.
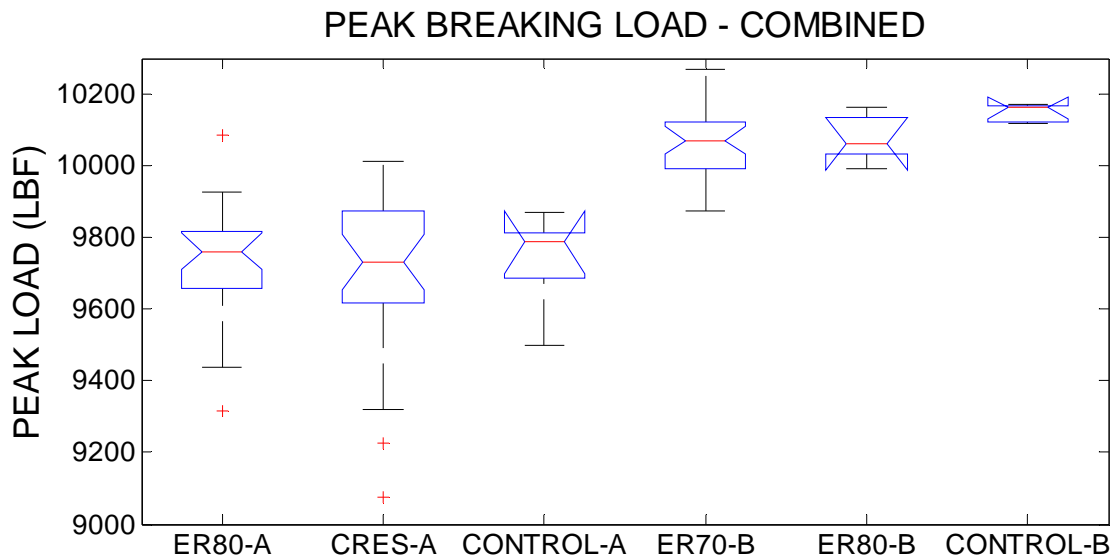


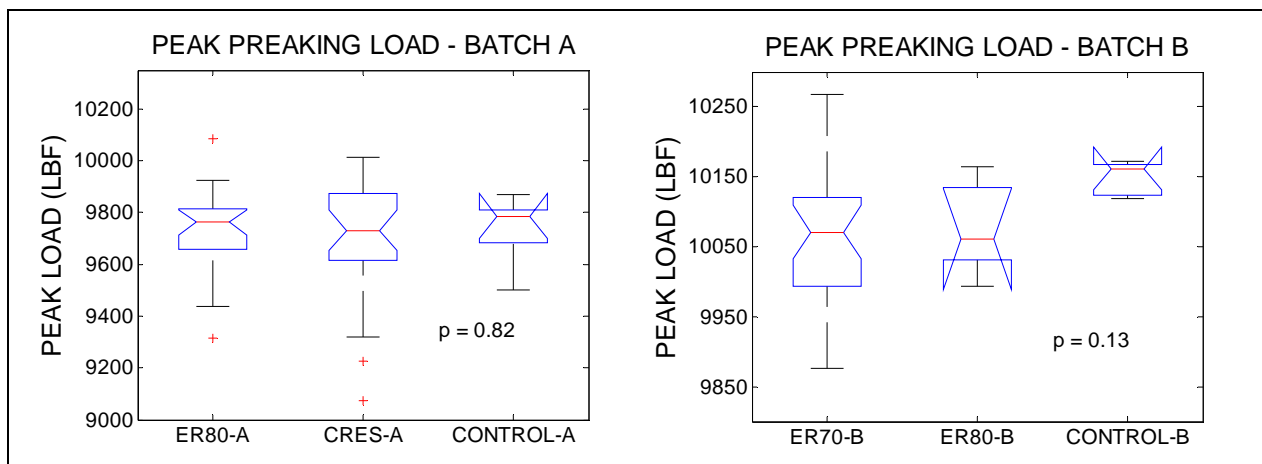**Figure 2** Box plot of all the collected data from Batches A & B.



**Figure 3** Box plot of the tensile data grouped into batches, A and B, with p-values from an ANOVA test shown in the bottom right of the plots.

*Fatigue*

Fatigue tests were performed on 12 ER80 specimens and 14 CRES specimens to develop a load life relationship for each filler rod. The experimentally determined load life relationships with 95% confidence intervals for the ER80 and CRES specimens are shown in Equation (1.4):

$$f_{CRES} = (3170 \pm 979)N^{(-0.200 \pm 0.028)}$$
$$f_{ER80} = (4637 \pm 1812)N^{(-0.231 \pm 0.036)}$$

(1.4)

These load life relationships are plotted separately with the ER80 and CRES data in Figures 4 and 5, respectively, and then together in Figure 6.
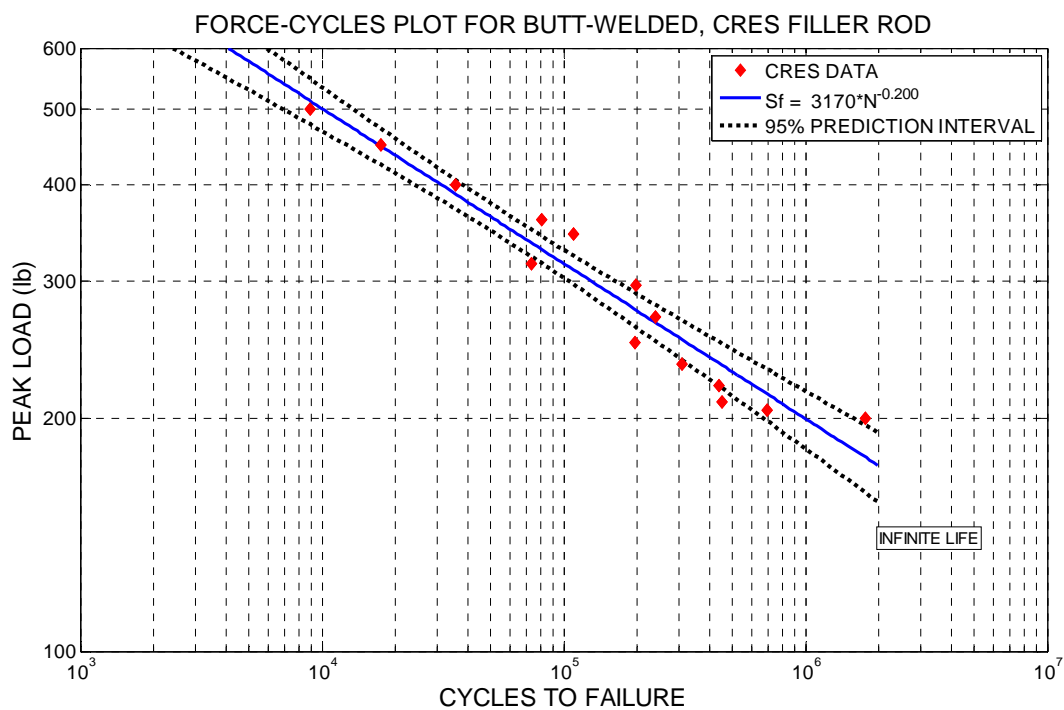


**Figure 4** Force-cycles to failure plot of the CRES butt-welded fatigue specimens with a best-fit line and 95% prediction intervals.
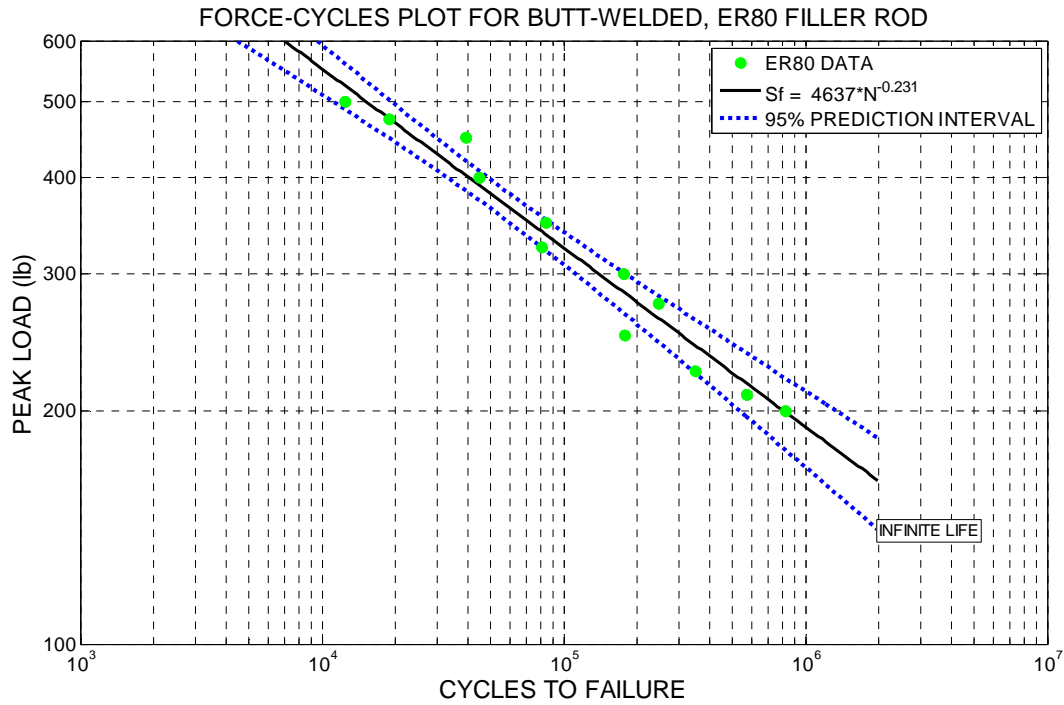
**Figure 5** Force-cycles to failure plot of the ER80 butt-welded fatigue specimens with a best-fit line and 95% prediction intervals.
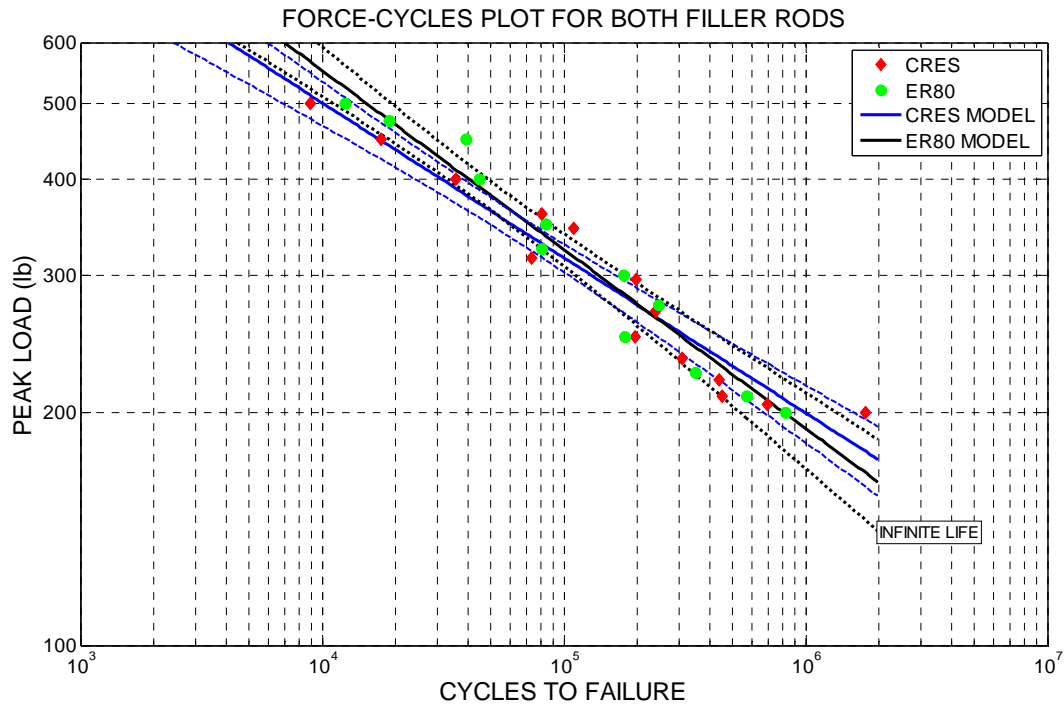


**Figure 6** Force-cycles to failure plot of both the CRES & ER80 butt-welded fatigue specimens.

## Discussion

The tensile data in Table 1 and the boxplot of all the breaking loads data in Figure 2 clearly indicate that batch B had a higher average breaking load than batch A. The tubing was from separate lots and, as such, a difference in tensile strength is to be expected. In all cases, the welded strength was within 1% of the unwelded tube strength. There was no statistically significant difference between the welded and unwelded specimens, nor between any of the types of filler material. Thus, the strength under static loading is not a factor when choosing one of the commonly recommended fillers for welding thin-walled Chromoly tubing.

When plotted together on a log-log scale the flexural fatigue tests conducted on the butt-welded seamless tubes with ER80 and stainless steel filler rod are difficult to distinguish from one another. The fatigue strengths were very similar, with the ER80 specimens exhibiting a slightly greater fatigue strength at high loads (low cycles) and the stainless filler rod specimens exhibiting a slightly greater fatigue strength at low loads (high cycles). Given the 95% confidence intervals, the half-percent difference in fatigue strengths at the upper and lower cycle limits is negligible.

## Conclusion & Recommendations.

This study showed that the choice of which common, recommended filler rods to use for welding thin-walled Chromoly tubing is not critical when designing against tensile or fatigue failure, providing good welding techniques are used. Tensile tests compared the strength of ER70, ER80, and stainless steel filler rod to unwelded specimens. In all cases, the welded strength was within 1% of the unwelded tube strength. Fatigue tests failed to show a statistically significant difference between welded and unwelded specimens, nor between the filler materials. The strength of butt-welded, thin-walled steel tube in either flexural fatigue or tensile loading does not significantly vary with ER70, ER80, or stainless steel filler material.

## References

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