CYCLIC RESPONSE OF STRUCTURAL STAINLESS STEEL PLATE UNDER LARGE INELASTIC STRAINS

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ABSTRACT

Contemporary seismic design of steel braced systems is based on dissipating earthquake energy through significant inelastic deformation in the bracing members under cyclic excursions. The structure is designed such that the first significant yield occurs at ground intensity levels that are at or above the design earthquake forces. Thus, delaying the yielding of brace elements is deemed a good design but it could also lead to subsequent loss of stiffness and strength, large residual deformation or even dynamic instability and collapse. To enhance the post-yield performance of the brace system, a steel component with high strain hardening character may be required. The stress-strain behaviour of structural stainless steel, the austenitic 304L type, shows an early deviation from linearity at a much lower stress level than carbon steels, but with a much stronger strain hardening character. In this study, the austenitic 304L stainless steel material is characterised under large inelastic cyclic strains. Coupons were carefully designed and machined from 304L stainless steel and 350WT carbon steel plates, and were tested under constant cyclic strain amplitudes. Results of these tests have shown that 304L stainless steel exhibits greater cyclic hardening with maximum cyclic stress values up to nearly three times the yield stress. However, the carbon steel showed greater low-cycle fatigue life.

Keywords: Structural stainless steel, carbon steel, inelastic cyclic strain, cyclic hardening, low cycle fatigue.

1. INTRODUCTION

The hysteretic characteristics of a structural system play an important role in many contemporary approaches to seismic design and analysis. Hysteresis refers to the path-dependence in the force versus deformation response of a structural system. The hysteresis loop offers vital information which must be well understood in order to develop appropriate design tools to mitigate structural damage under extreme seismic load reversals. For instance, the hysteretic characteristics can lead to an understanding of the structure’s degradation and nonlinear response behaviour under cyclic loading. These characteristics can be used as basis for developing numerical models to predict collapse response and mechanism. Experimental cyclic testing is an effective tool for evaluating the hysteretic characteristics.

Concentrically Braced Frames (CBF) have proven to be an economic way of designing steel structures while maintaining a desirable lateral stiffness compared to Moment Resisting Frames (MRF). For CBFs, the lateral response is dominated by the inelastic behaviour of the bracing members. These members are designed to yield in tension and buckle in compression. Traditional brace hysteretic behaviour is unsymmetric in tension and compression, and typically exhibits substantial degradation of strength and stiffness when subjected to monotonic compression or when loaded cyclically. Under reversed cyclic loading, brace members are expected to buckle in compression and yield in tension. After brace buckling, plastic hinges may develop and could lead to permanent plastic deformations and deterioration of brace capacity (Jain et al. 1978, Tremblay 2002).

Buckling-restrained braces (BRBs) have evolved as efficient in the use of the ductility of brace elements by developing their full axial yield strength both in tension and compression, as a result of a buckling-restrained
mechanism provided by an outer restraining medium to a ductile steel plate core (Sabelli et al. 2003, Fahnestock et al. 2007). Although it exhibits stable hysteresis behaviour with balanced hysteresis loops, the BRB frame is prone to low post-yield stiffness and consequently large residual drift (Black et al. 2002, Tremblay et al. 2006). Residual drifts are the permanent deformations in the structure after a seismic event and are closely related to structural damages and the cost of repairs after the event under earthquake ground shaking, yielding of the BRB steel core element can provide significant inelastic energy dissipation. The post-yield stiffness of the brace component would be enhanced if the core material possesses considerable strain hardening character.

The use of stainless steels for structural application has received significant attention in the last decade (Annan 2013). The stress-strain behaviour for the austenitic stainless steel type 304L (EN 1.4301 European designation) have shown an early deviation from linearity at a much lower stress level than for carbon steels, but with a much stronger strain hardening character (Gardner 2005, Baddoo 2008). A previous study on the use of stainless steels in CBFs showed that the material’s strain hardening character leads to delayed inelastic buckling and consequent improvement in structural overstrength (DiSarno et al. 2008). The austenitic stainless tubular grade has also shown greater ductility with a good energy dissipation capacity under axial cyclic loading (Nip et al. 2010). These characteristics are desirable for the steel core plate material in a BRB component. It is worth noting that, for structural applications, the austenitic stainless steel grade is fabricated by methods similar to those used for regular carbon steels.

The present study seeks a better understanding of the cyclic plasticity behaviour of austenitic stainless steels to characterise their hysteresis behaviour, including their low cycle fatigue life and cyclic hardening character. Low-cycle fatigue tests were conducted on plate coupons fabricated from both austenitic stainless steel type 304L and 350WT carbon steel. The cyclic stress-strain behaviours at different inelastic strain levels were evaluated, and the cyclic hardening and low cycle fatigue life parameters were assessed. This was to enable a careful comparison of the hysteretic behaviour of austenitic stainless steels and their carbon counterpart, and to assess their feasibility as alternate steel core plate material for BRB application.

2. EXPERIMENTAL PROGRAM

2.1 Materials description

For the purpose of evaluating the stress-strain behaviour of the 304L type austenitic stainless steel under repeated inelastic strains, and to compare with carbon steels, low-cycle fatigue tests were carried out on two different steel materials. Stainless steel type 304L is a low carbon version of the commonly used 304 grade. These types of steels are usually used in the food and pharmaceutical industries where corrosion resistance is the primary required property. For better ductility and low yield stress, the annealed condition was selected for the test material, at an annealing temperature of about 1040°C. The CSA G40.21 350WT carbon steel was selected for testing. Thus carbon steel type is known to be more resilient than the commonly used CSA G40.21 350W, and it is mostly used in the bridge industry.

Table 1 contains the chemical composition and mechanical properties for these two steel types. The austenitic stainless steel has a yield stress of 252 MPa compared to 364 MPa for the G40.21-350WT carbon steel. The elastic modulus is 195 GPa, which is nearly identical to that of the carbon steel. The value of the ultimate stress ($F_u$) shown in the table for 304L stainless steel is obtained from the mean value of 5 tensile tests and the values of the yield stress ($F_y$) shown for both types of steel are found to be the average of 5 different values obtained by the offset method on tensile tests for the stainless steel and on the first quarter cycle of the cyclic tests for the carbon steel.

2.2 Specimen specification and test setup

Test specimens in the form of round coupons with reduced effective section were machined from 1¼” steel plates with the longitudinal axis of the coupon carefully selected to be in the rolling direction of the plate. This is to account for the anisotropy of the material. A numerically-controlled metal lathe was used to machine the specimens, and care was taken to achieve a good consistency in different specimens, especially in the gage section. Sand paper grade 325 was used to polish the gage section to ensure smooth finish without visible machining marks.
The gage length was chosen to be 28 mm to make room for the 25 mm extensometer to be used. For the diameter of the gage section, the standard ASTM E466 recommends a ratio gage length to diameter equal to less than 2.0. For this ratio, buckling was found to be important at around 6% strain amplitude when subjected to cyclic loading increasing amplitude by 1% every 2 cycles (Dusicka et al. 2007). Based on these, a gage diameter of 16 mm was selected to obtain a length-t-diameter ratio of 1.56 and to ensure that buckling would not be a problem. Based on the ASTM E606 standard, a grip diameter of 30 mm was chosen, to get a value lower than twice the diameter which is required for a ductile material, and the radius between the gage and grip section was chosen to be 22 mm, as the lower limit specified by the code, to minimize the unrestrained length as much as possible. The grip length was chosen to leave a space of 25 mm between the hydraulic grip end and the start of the reduced section, in order to avoid local stresses building up near the grip area which has potential to influence readings in the gage section. The designed specimen dimensions are shown in figure 1.

Table 1: Properties of different steel materials

<table>
<thead>
<tr>
<th>Steel type</th>
<th>304L</th>
<th>350WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.0002</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.0176</td>
<td>0.09</td>
</tr>
<tr>
<td>Cr</td>
<td>18.169</td>
<td>0.05</td>
</tr>
<tr>
<td>Cu</td>
<td>0.524</td>
<td>0.13</td>
</tr>
<tr>
<td>Mn</td>
<td>1.753</td>
<td>1.43</td>
</tr>
<tr>
<td>Mo</td>
<td>0.33</td>
<td>0.01</td>
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<tr>
<td>N</td>
<td>0.0882</td>
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<tr>
<td>Nb</td>
<td>0.041</td>
<td></td>
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<tr>
<td>Ni</td>
<td>8.029</td>
<td>0.05</td>
</tr>
<tr>
<td>P</td>
<td>0.033</td>
<td>0.013</td>
</tr>
<tr>
<td>S</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Si</td>
<td>0.2565</td>
<td>0.22</td>
</tr>
<tr>
<td>Sn</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.004</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>304L</th>
<th>350WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (MPa)</td>
<td>194500</td>
<td>211200</td>
</tr>
<tr>
<td>$F_y$ (MPa)</td>
<td>252</td>
<td>364</td>
</tr>
<tr>
<td>$F_u$ (MPa)</td>
<td>642</td>
<td>503*</td>
</tr>
<tr>
<td>Elongation (%)</td>
<td>58.55*</td>
<td>22.1*</td>
</tr>
</tbody>
</table>

*Value from milltest

All the tests were carried out using an MTS 322 test frame, with a capacity of 500 kN. Hydraulic grips were used to clamp the specimens, permitting to use a cylindrical specimen to get a better alignment than a threaded specimen. To avoid out of plane deformations under cyclic strain excursions, the head of the press needed to be braced by external fabricated brace system to increase its lateral stiffness. The bracing was designed to prevent the head of the
press from moving more than 0.1 mm under a 100kN lateral load and was mounted on bearing rollers to avoid any constraints in the axial direction of the loading frame. The test setup is shown in figure 2.

Figure 2: Experimental setup

2.3 Testing program

All specimens were tested under strain-controlled constant amplitude fatigue, using an extensometer signal. Triangular waveform was used with the first quarter cycle starting in tension. The ratio of axial strain limits is found to be equal to -1, to maintain the fully reversed cycles for all the specimens. The strain rate was chosen to be 0.1%/s, to ensure that no heating occurs in the specimen during the tests, except for the first quarter cycle of every test where it was chosen to be 0.005%/s to reduce the possible transient instability around the time of first yielding.

2 different constant strain amplitudes (1 and 2%) were chosen for each of the 2 steel materials representing standard strain amplitude demand prescribed for BRBs under seismic excitation. In Canadian context, tests on BRBs have indicated that the anticipated strain demand in the core plate would be between 1 and 2% for a ratio of the yielding length to the total length of the core between 0.3 and 0.6 (Tremblay et al. 2006). To obtain a good consistency of the results, 5 stainless steel and 4 carbon steel specimens were used for each strain amplitude and the most representative one was used to present the results.

3. RESULTS AND DISCUSSION

3.1 Cyclic hardening

Different phenomena are observed when a metal is loaded under repeated cycles into the plastic range. Figure 3 shows the hysteresis curve for the first tensile and full cyclic excursion of the 304L stainless steel loaded at ±1% strain amplitude. In the first quarter cycle in tension before unloading, the specimen’s response is similar to observations in uniaxial tensile tests. Firstly, an elastic response then followed by deviation into the nonlinear region. Upon unloading, the same elastic slope as in the loading phase was observed, but due to the Bauschinger effect, deviation from linearity occurred at a lower stress level in compression than that of a uniaxial tension loading. Upon reloading, the same phenomenon is observed and is repeated in subsequent cycles in both loading direction. It is, however, observed that after a complete cycle, the specimen reaches a stress level that is higher than the level in previous cycle. This is an indication of the cyclic hardening character of the test material. The cyclic hardening character depends not only on the type of material but also on the strain amplitude, and it tends to stabilize after a few numbers of cycles to reach a near constant level.

Figure 4 shows plots of the maximum tensile stress level reached at the end of each cycle for both 304L and 350WT steels at the two different strain amplitudes. By the definition of straining hardening, these plots represent the cyclic hardening within the life of a representative specimen at the two amplitude levels. For the structural steel grade 350WT, both strain amplitudes showed consistently increasing hardening within the first 3-4 cycles, then a slightly increasing hardening until an almost total stabilisation at around 10 cycles. For the 2% strain amplitude, the maximum stress value exceeded the ultimate tensile strength after about 13 cycles and then stabilises at about 13
MPa above the ultimate tensile strength. In the case of the 1% strain amplitude, the maximum stress reached in the life of the specimen was below the ultimate tensile stress. For the stainless steel type 304L, both strain amplitudes showed significantly greater hardening character than the structural carbon steel grade at the same strain amplitude.

For the 2% strain amplitude, the material showed high hardening rate in the first 5-6 cycles and then continues to harden at a smaller but significant rate until failure. For the 1% strain amplitude, the behavior is slightly different. Significant rate of hardening occurred in the first 5-6 cycles, then it appeared to have stabilized before starting a secondary hardening phase at around 75 cycles until failure. This secondary phase of hardening has been observed for 304L stainless steel tested under fully-reversed conditions at low strain amplitudes of 0.25 and 0.3% (Colin et al. 2010).

Figure 3: Hysteresis curve for first full cycle of 304L stainless steel

Figure 4: Cyclic hardening for different strain amplitudes
In order to compare the amount of cyclic hardening between two materials, the ratio of the maximum cyclic stress to the yield stress can be used. At 1% strain amplitude, this ratio is calculated as 1.26 and 2.0 for the structural carbon steel and stainless steel, respectively, and it is found to be equal to 1.42 and 2.88 for 2% strain amplitude. The main reason for greater cyclic hardening in the austenitic stainless steel, especially the secondary hardening, is the martensitic transformation, where the unstable austenite partially transforms into martensite which tends to improve its mechanical properties.

3.2 Cyclic stress-strain

Cyclic stress-strain curves are useful for describing the cyclic hardening character between strain amplitudes when compared to the tensile response. The Ramberg-Osgood relation (Ramberg and Osgood 1943), given by Eq. 1, can be used to represent the cyclic stress strain curve, and is particularly useful for metals that harden with plastic deformation. The first term on the right hand side represents the elastic part of the strain, while the second term defines the plastic part. In the equation, $\Delta e_1$, $\Delta e_\varepsilon$, and $\Delta e_p$ are the total, elastic and plastic strain amplitudes respectively, $\Delta \sigma$ is the stress amplitude, $E$ is the Young’s modulus, $K'$ is the cyclic strength coefficient and $n'$ is the cyclic strain hardening exponent.

$$\frac{\Delta e_1}{2} = \frac{\Delta e_\varepsilon}{2} + \frac{\Delta e_p}{2} = \frac{\Delta \sigma}{2E} + \left(\frac{\Delta \sigma}{2K'}\right)^{\frac{1}{n'}}$$

In order to derive the cyclic stress-strain curves, the single-step tests method was chosen because of the material’s (stainless steel) dependence on prior loading and the fact that it does not stabilize. This method consists of doing several cyclic tests at different constant strain amplitudes until fracture. The loops representing the stabilized state for each different strain amplitude are superposed and the cyclic stress-strain curve is obtained as the curve that passes through the tips of each loop. Since the austenitic stainless steel does not stabilize, the half-life data is used instead of the stabilized data. To get a representative half-life data, the determination of failure must be consistent, and so the modulus method (ASTM E606) was used to determine the number of cycles to failure.

For the determination of the model parameters, the plastic component of the total strain amplitude must be determined and fitted with the stress amplitude where $\Delta e_p$ is found to be the sum of the absolute values of the positive and the negative strain at zero stress at half-life of the specimen, and $\Delta e_\varepsilon$, the difference between $\Delta e_1$ and $\Delta e_p$. Values of the derived parameters for both the carbon and stainless steels are given in table 2. Figure 5 shows the Ramberg-Osgood cyclic stress-strain curves fitted to the hysteresis loops, as well as the monotonic tensile response for both steel materials. The hysteresis loops shown have been chosen as the most representative specimen from different tests at constant amplitudes.

<table>
<thead>
<tr>
<th>Type of steel</th>
<th>304L</th>
<th>350WT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramberg-Osgood Coefficients</td>
<td>K'</td>
<td>5166</td>
</tr>
<tr>
<td></td>
<td>n'</td>
<td>0.4981</td>
</tr>
<tr>
<td>Basquin Coefficients</td>
<td>$\sigma'_f$ (MPa)</td>
<td>25820</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>-0.4813</td>
</tr>
<tr>
<td>Coffin-Manson Coefficients</td>
<td>$\varepsilon'_f$</td>
<td>0.01454</td>
</tr>
<tr>
<td></td>
<td>c</td>
<td>-0.2677</td>
</tr>
</tbody>
</table>

As observed from the graphs, the fitting of the Ramberg-Osgood relationship is not passing exactly by the peak points, underestimating it for the compression part and overestimating it for the tension, due to kinematic hardening, described by the translation of the yield surface in stress space. For the stainless steel, the curve started deviating from linearity much early and showed dramatic strain hardening, while the carbon steel hardened but not in a dramatic fashion.
3.3 Low-cycle fatigue life

Low cycle fatigue is associated with localised plastic behaviour in metals. Thus, a strain-based parameter is used to predict this life, which can be obtained from a constant strain amplitude testing. For many ductile metals, low cycle fatigue is characterised by the Coffin-Manson relation (published independently by S.S. Manson in 1953 and L.F. Coffin in 1954) which is linear on a log-log plot of plastic strain range versus cycles to failure. The elastic part of the stress is defined by the Basquin relation (Basquin 1910) which is also linear on a log-log plot of elastic strain range versus cycles to failure. Equation 2 shows the combination of these two relations which are able to satisfy cases where plastic or elastic strain dominates.

\[
\frac{\Delta \varepsilon_p}{2} + \frac{\Delta \varepsilon_e}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c
\]

\(2N_f\) is the number of reversals to failure (\(N_f\) cycles), \(\sigma'_f\) is the fatigue strength coefficient, \(b\) is the fatigue strength exponent, \(\varepsilon'_f\) is an empirical constant known as the fatigue ductility coefficient and \(c\) is known as the fatigue ductility exponent. To derive the model parameters, each power function representing the elastic strain and the plastic strain were fitted separately using mean values of the number of cycles to failure for each strain amplitude.

The empirical coefficients found for each type of steel are presented in table 2 and the two relationships are represented on a log-log scale in figure 6.
Clearly, the carbon steel showed longer strain life than the stainless steel, while both cyclic lives improved with decrease in strain amplitude. The short low-fatigue cyclic life of the stainless steel may be due to the martensitic transformation with plastic loading of the material (Baudry and Pineau 1977).

![Figure 6: Coffin-Manson-Basquin relationship for 2 types of steel](image)

4. CONCLUSION

This experimental study has characterised the cyclic plastic behaviour of the austenitic stainless steel 304L type, including the Bauschinger effect, cyclic hardening, and the symmetric strain controlled low cycle fatigue. Low-cycle fatigue tests were conducted at 1% and 2% strain amplitudes for stainless steel coupons machined from plates, and as a comparative study, coupons from carbon steel were prepared and tested. This following is a summary of observations from the tests:

1. Cyclic hardening occurred in both materials, with stabilization occurring after the first few cycles in the carbon steel and almost absent in the stainless steel but rather a secondary hardening. Maximum cyclic stresses reached values of 1.26 and 1.42 times the yield stress for the carbon steel at 1% and 2% strain amplitudes respectively, and values of 2.0 and 2.88 times the yield stress for the stainless steel at 1% and 2% strain amplitudes. The cyclic hardening rate increased with strain amplitude.
2. Ramberg-Osgood parameters were determined to describe the cyclic stress-strain curves, confirming that the stainless steel showed greater cyclic hardening than the carbon steel with increasing strain amplitude.
3. Low-cycle fatigue life was evaluated by determining the Coffin-Manson parameters. The fatigue strain-life was found to be longer for the carbon steel than for the stainless steel.
4. Both the greater cyclic hardening and the short low-cycle fatigue life observed in the stainless steel are due to the plasticity induced martensitic transformation that occurs in the material under loading.

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REFERENCES


