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ASSESSMENT OF CODE PROVISIONS FOR STRENGTH DETERMINATION OF ALUMINIUM STRUCTURES BY TESTING

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Abstract: Annex A14.1 of the CSA S6 Canadian Highway Bridge Design Code contains a formula and table for determining the design yield strength of unidentified structural steel by testing. The formula includes a 28 MPa correction for the difference between the "dynamic" and "static" yield strength. For aluminum structures, the American Aluminum Design Manual and the CSA S157 design code have similar formulas and tables for determining the ultimate strength of aluminum components by testing. The aluminum tables are believed to be inherently conservative in that they are established for a nominal aluminum strength based on a 99% survival probability, even though aluminum structures are then designed with a resistance factor that is the same as the one used for steel structures. CSA S6 Annex A14.1 and the associated resistance factors assume a 95% survival probability in establishing the nominal yield strength of the steel. Against this background, this paper presents results of tension coupon tests used to investigate the existence of a difference between static and dynamic strength in aluminum using 6061-T6 alloy 9.5 mm thick plates. The results of tests like these will be used in a planned series of simple structural reliability analyses aimed at assessing the effects of the conservative assumptions made in the American Aluminum Design Manual and CSA S157. Given this information, a new formula and table will be proposed for establishing the strength of aluminum structures by testing.

1 INTRODUCTION

When predicting the performance of a structural component, designers may not always be able to rely on standard design formulas. This is often the case when designing components making use of proprietary or new technology or when assessing existing structures with unknown properties. In these cases, testing is often the only reliable method of evaluating the component's properties, including its strength. Design standards offer methods to obtain a nominal strength based on testing, in order to ensure a consistent level of reliability to the one assumed in the standard's calibration. However, for aluminium, where resistance factors similar to steel have been used historically, with minimal effort in terms of material specific calibration efforts, it is suspected that the current approach may lead to a high degree of conservatism.

A challenge with testing structural components is the influence of strain rate on the measured strength. In 1966, Rao, Lohrmann and Tall established basic relationships between the yield strength of steel measured at a certain strain rate, and the true "static" yield strength. This relationship was used both in the calibration of performance factors in Canada (Kennedy & Gad Aly 1979) (Schmidt & Bartlett 2002) and in the provisions for testing the yield strength of steel in Annex A14.1 of *CSA S6-14: Canadian Highway Bridge Design Code*. It is generally assumed that the strain rate does not affect the ultimate tensile strength of steel.

For aluminium testing in Canada, there are currently no provisions for the effects of strain rate. There is ample literature on the effects of high strain rate on strength from the automotive and aeronautical industries, but at low strain rates there is very little information on the effects on strength.

2 BACKGROUND

2.1 Current methods to evaluate nominal strengths by testing

Currently in Canada, the only standard for the evaluation of aluminium structures by testing is *CSA S157-17: Strength Design in Aluminium* (Section 22). These provisions ae based on *CSA S408-11: Guidelines for the development of limit states design standards* and are similar to those in the American *Aluminum Design Manual*. When evaluating a sample, the nominal resistance is given by the following formula:

[1] $R_m = X_m - k\sigma$

where R_m is the nominal resistance, X_m is the mean resistance from the tests, k is a factor based on the number of tests to achieve the 99th percentile resistance at a 95% confidence, and σ is the standard deviation of the test results. The k-value rewards a higher numbers of tests, with its value for 3 samples being 10.55, and 7 samples being 4.64. This nominal resistance is then used with the strength ϕ-factors provided by the code. If the observed failure mode is brittle, then a value of $\phi_u = 0.75$ would be used, if the failure is in a fillet weld, $\phi_f = 0.67$, etc. These factors are based on the calibration of the steel standard, which is based on a 95th percentile resistance, thus potentially bringing additional conservatism.

For steel, *CSA S6-14: Canadian Highway Bridge Design Code* provides a method for the evaluation of steel structures in Appendix A14.1. In this case, only a formula for the nominal yield strength of steel is given:

[2] $f_y = (\overline{f}_y – 28) \exp(-1.3k_sV)$

where f_y is the nominal (95th percentile) yield strength in MPa, $\overline{f}_y$ is the mean yield strength from the tests in MPa, k_s is a coefficient of variation factor, based on the number of samples, and V is the coefficient of variation of the test results.

Of important note is that the mean yield strength observed in the tests is reduced by 28 MPa before any adjustments are made. This reduction is based on the work of Rao, Lohrmann and Tall (1966), who established a relationship for the difference between the yield stress obtained at typical loading rates during testing, and the yield stress under fully static loading.

2.2 Effects of strain rate on the strength of steel and aluminium

It is generally understood that metals loaded at higher strain rates exhibit higher strength. However, in structural engineering applications, the loading rate is often assumed to be essentially zero (or very slow loading), except in the case of earthquake loads. However, typical tensile strength tests are usually conducted at rather high strain rates, so they may be performed in a few minutes at most. As such, two measures of stress must be considered: *dynamic stress* and *static stress*. The first corresponds to the test-measured stress, whereas the static stress refers to the stress at a very low strain rate.

To observe the static yield stress, Rao, Lohrmann and Tall (1966) established a procedure where a steel sample is loaded to its yield plateau, after which the strain is held to allow the specimen to relax. After five minutes, the relaxation has mostly stabilized, and the stress is measured as the static yield stress. From this, Rao et al. (1966) establish the following relationship for all steels, independent of strength:

[3] $(F_{yd} - F_{ys}) = 22.1 + 0.007\,\dot{\varepsilon}$

where F_{yd} is the dynamic yield stress measured during testing in MPa, F_{ys} is the static yield stress (i.e. the yield stress at a strain rate of zero) and $\dot{\varepsilon}$ is the strain rate in microstrain/second. They assume that there is no such difference at the ultimate strength level.

The ASTM A370 standard (referenced by CSA G40.20) allows a loading at a rate up to 1/16 in/min per inch of gauge length, equivalent to 1042 microstrain/second. Using this rate in Equation [3], the value of 29 MPa is obtained and forms the basis for the strength reduction in Equation [2] (Kennedy & Gad Aly 1979) (Schmidt & Bartlett 2002).

Most research on this subject in aluminium, such as by Manes (2011) and Hoge (1966), focuses on strain rates many orders of magnitude faster than what is considered in this paper. In Canada, the maximum speed for testing is set by ASTM B557 (referenced by CSA S157-17) as 12 MPa/second in the elastic range, which corresponds to a strain rate in the elastic range of 171 microstrain/second, or less than a sixth of what is allowed for steel. One paper (Huang & Young 2014) looked at three samples of an unspecified aluminium alloy at three different loading rates. Two key points are brought up: the same relaxation phenomenon as with steel occurs in aluminium, and contrary to what is often assumed for steel, the difference between static and dynamic ultimate stresses is higher than at yield.

3 METHODOLOGY

Tests were performed to measure the difference in dynamic stress and static stress (σ_d – σ_s) at various strain rates. In total, five samples of 350W structural steel and eight samples of 6061-T6 aluminium were used. The samples were fabricated per *ASTM E8M-16* using the sheet-type specimen specification, which corresponds to a dog bone specimen with 50 mm gauge length, 12.5 mm gauge width, and in this case the thickness of material was 9.5 mm for all specimen. The loading frame used was the MTS Criterion Model 45 with a 100 kN capacity. Table 1 lists material properties of the analyzed samples.

Table 1: Test Sample Properties

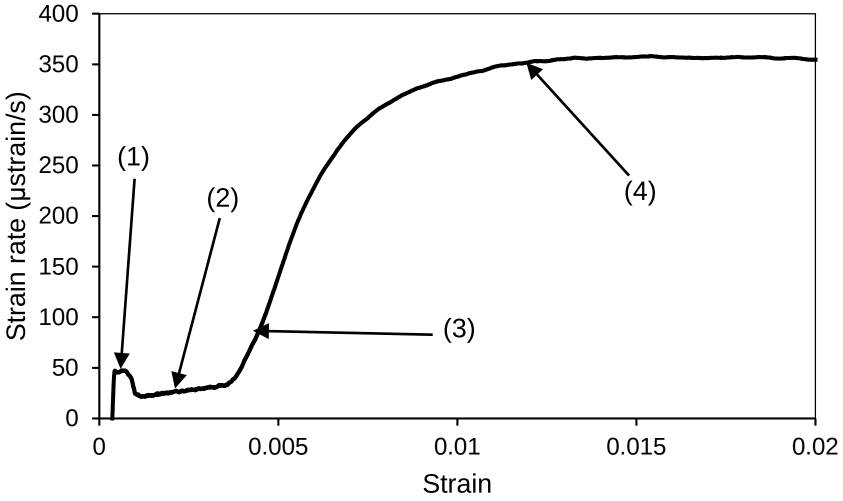
Property	350W Steel	6061-T6 Aluminium
Number of samples	5	8
Yield strength (MPa)	390	280
Ultimate strength (MPa)	540	295

On the steel samples, the same method as was employed by Rao et al. (1966) was used to establish σ_d - σ_s. Specimens were loaded to their yield plateau, after which the test was paused and resumed at a few intervals at different strain rates. This was procedure also performed at the ultimate strength level.

For the aluminium samples, since there is no defined yield plateau, the method was slightly modified. Specific strains (0.005, 0.008, 0.02 and 0.08) were established – the first two corresponding approximately to yield stresses, 0.02 strain corresponding to a work hardening stress and 0.08 corresponding to the ultimate stress. Only one pause was taken in the region of the ultimate stress because it was found during trial tests that pauses near the ultimate zone would affect results nearby.

It was observed in pilot tests that the aluminum samples generally reached their stable relaxation point slower than steel. Thus, the steel samples were relaxed for 5 minutes, as was done by Rao et al., and the aluminium samples were relaxed for 10 minutes. These tests were conducted at a variety of head displacement rates, in steel ranging from 0.01 to 0.1 mm/s and in aluminium from 0.002 to 0.08 mm/s. To establish the σ_d - σ_s relationship with strain rate, the strain rate was taken as the rate measured by the extensometer immediately before the test was paused to allow relaxation.

The loading frame was run in stroke-control mode, with a constant head displacement rate to remain consistent with industry practice. It is important to note that a constant head displacement rate will generally not correspond to a constant strain rate once the specimen yields. This is because as the specimen is loaded in the elastic region, the loading frame is also strained by an amount of proportional to the relative stiffness of the specimen and the frame. Once the specimen yields, its stiffness is greatly reduced: for a given increase in displacement, the load increases very little. Thus, almost all of the strain occurs in the gauge length of the specimen, and the effective strain rate in the gauge length is much higher. Figure 1 shows how the strain rate varies as the specimen is strained.



(1) Stabilization as the test starts and the specimen settles in grips
(2) Elastic portion – strain rate remains approximately constant as relative stiffnesses stay constant
(3) The specimen yields and strain rate increases very rapidly
(4) The strain rate stabilizes as work hardening begins and the relative stiffness settles

Figure 1: Strain rate as a function of strain in a 6061-T6 sample.

4 RESULTS AND DISCUSSION

4.1 Steel samples

4.1.1 Yield stress

The steels samples were tested in the same manner as was done by Rao et al. (1966). Figure 2 shows a typical stress strain curve, with the sharp drops in the yield plateau and near ultimate showing where the test was interrupted to allow relaxation to be observed.

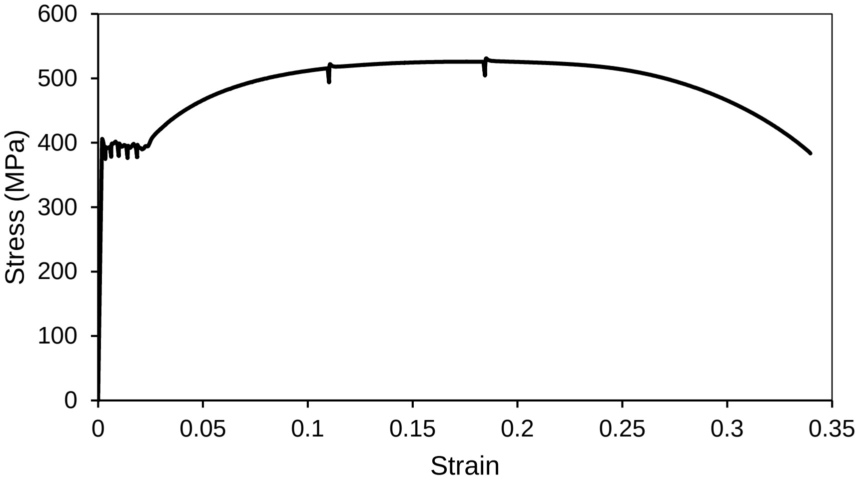


Figure 2: Stress-strain curve for a 350W steel sample (the sharp "ticks" are locations where the test was interrupted to allow relaxation).

The difference between the dynamic and static yield stresses was plotted as a function of strain rate and compared to the relationships noted in Rao et al. (1966). Figure 3 shows these results.

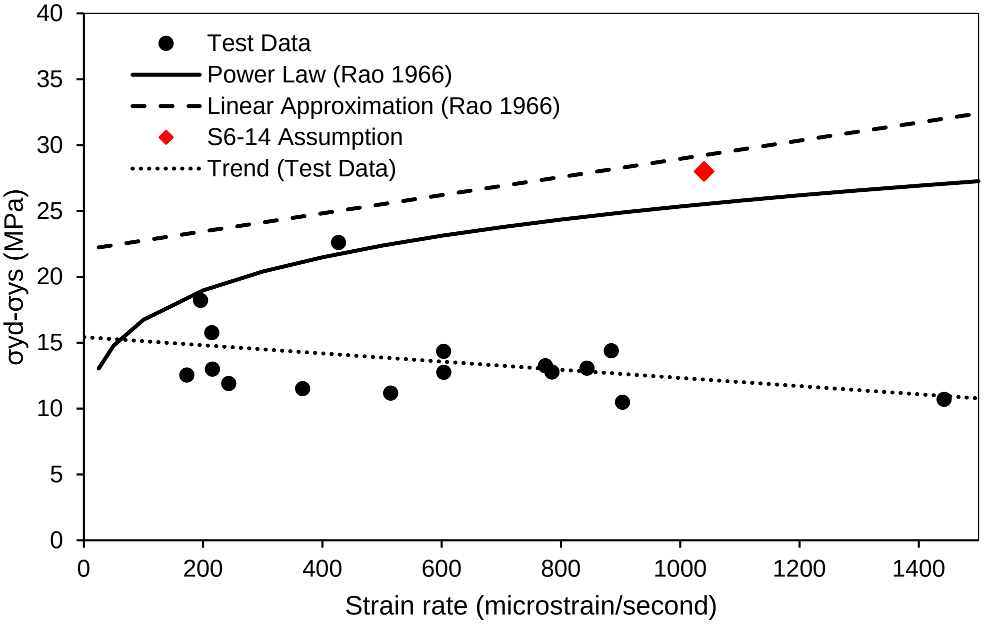


Figure 3: The effect of strain rate on the difference in dynamic and static yield stresses (steel).

It is immediately obvious from Figure 3 that the test data does not correspond well to the observations of Rao et al. Whereas the prediction was that an increase in strain rate would correlate to an increase in $\sigma_{yd} - \sigma_{ys}$, no such trend is visible from the data, in fact a best-fit trend line suggests a slightly negative correlation. In general, the decrease in stress was also much smaller than predicted.

Directly comparing strain rate and the observed dynamic yield stress before pausing also showed very little correlation between the two, as seen in Figure 4.

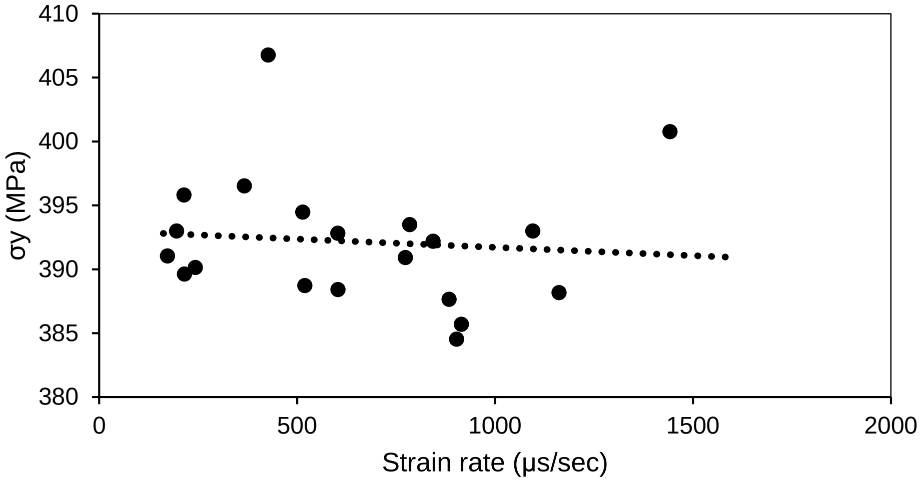


Figure 4: The effect of strain rate on the observed dynamic yield stress (steel), taken just before pausing.

There are a few plausible reasons for this discrepancy. Improvements in the past 50 years on manufacturing and alloying technologies may have reduced the effect of strain rate in this range or improved the relaxation properties of structural steels and thus affect the value of $\sigma_{yd} - \sigma_{ys}$. Additionally, the samples used in the Rao et al. studies were taken from webs and flanges of W-sections, whereas the samples used in this study were taken from hot-rolled flat bar. There may thus have been different amounts of work hardening during the manufacturing process, which can affect the mechanical properties of steel (Kennedy & Gad Aly 1979).

Despite the difference in results, the 28 MPa reduction in yield strength is conservative and may still be justified when testing steel in existing bridges. While modern steels may not be as affected by strain rate effects, there remain many structures with unknown older steels as studied in Rao et al.

4.1.2 Ultimate tensile strength

The tests on 350W steel were also stopped and held at the ultimate tensile stress to visualize the effects of strain rate on the difference in dynamic and static ultimate stress ($\sigma_{ud} - \sigma_{us}$). These were not performed in the 1966 Rao et al. study, as it was assumed that strain rate had little effect on the ultimate strength. In The relationship between strain rate and the ultimate tensile strength is seen in Figure 5.

An apparent negative correlation suggests that strain rate may have an influence on the value of $\sigma_{ud} - \sigma_{us}$, however it appears to be the opposite direction as would be expected for yield strength. It can also be seen that the magnitude of the relaxation drop is slightly higher than at the yield level. The ultimate tensile strength was also directly compared to strain rate, as shown in Figure 6.

The two measures of strain rate effects on strength thus seem to be contradicting each other. An explanation for the discrepancy is that the process of relaxation may not be linked to the same process that governs strain rate effects on strength at the UTS level.

In practice, this suggests that a reduction in measured strength similar to that used in Equation [3] may be warranted for the ultimate tensile strength when determined by testing. A drop in load was observed when the test was paused, in the same manner as was done in the region of the yield plateau.

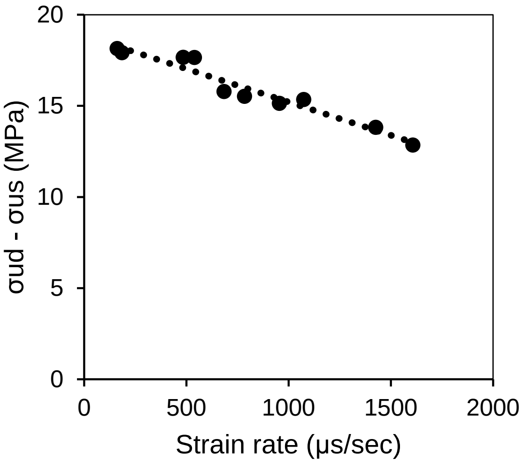


Figure 5: Effect of strain rate on the difference in dynamic and static ultimate stress (steel).

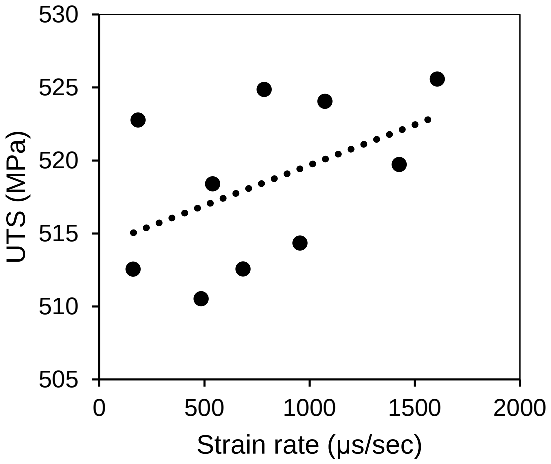


Figure 6: The effect of strain rate on the ultimate tensile strength (steel).

4.2 Aluminium 6061-T6 samples

4.2.1 Yield stress

Similar tests as were performed for the 350W steel were also performed on the aluminium 6061-T6 specimens. Figure 7 shows a typical stress strain curve from this series of tests.

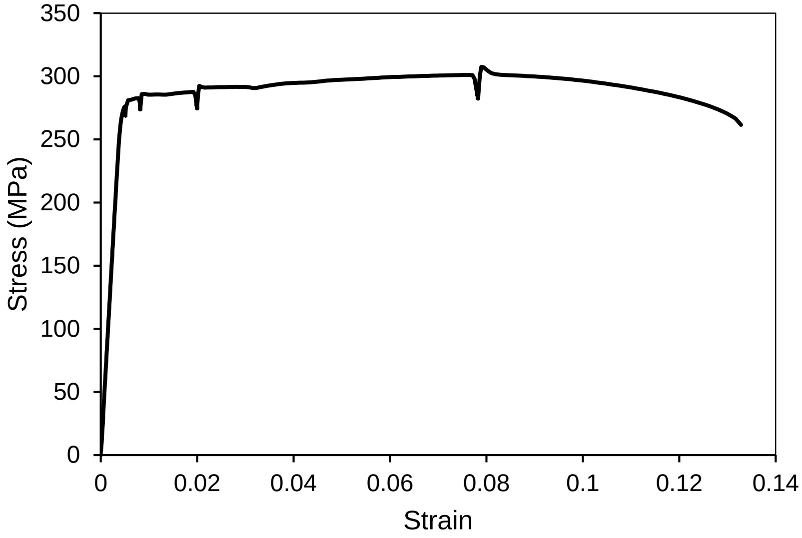


Figure 7: Stress-strain curve for a 6061-T6 aluminium sample.

The relationship between strain rate and the difference between dynamic and static yield stress ($\sigma_{yd} - \sigma_{ys}$) is shown in Figure 8. The magnitude of the stress drop, approximately 6 MPa, is observed to be much smaller than in steel. The strain rate during testing had no significant effect on this value (though considerable scatter may be obstructing such an observation).

The yield stress as a function of strain rate was also plotted and is seen in Figure 9. Again, there is considerable scatter in the data. The strain rate varies significantly near the yield point, and while the immediate strain rate before pausing was taken, such quick changes may affect the “effective” strain rate in the sample. While the samples were all cut from a single flat bar, it is also possible that small variations in the heat treatment or extrusion process are causing this scatter (e.g. samples closer to the edges may work harden differently and heat or cool more rapidly).

These results correspond to literature suggesting that there is very little effect on yield strength due to strain rate in such low ranges (Manes et al. 2011). The same relaxation phenomenon observed in steel is nonetheless present. This suggests that if the CSA S6-14 provisions (equation [2]) are to be used with aluminium, the 28 MPa value may be justifiably reduced to a value near 6 or 7 MPa. This is quite significant, as with some aluminium alloys and tempers, a 28 MPa reduction in yield strength may mean more than a 30% reduction in effective strength.

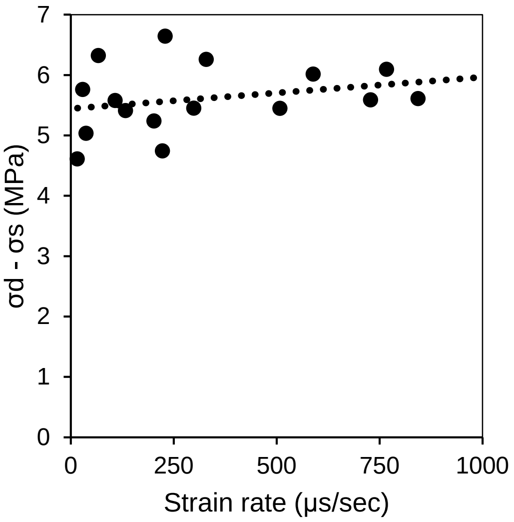


Figure 8: Effect of strain rate on the difference in dynamic and static yield stress (aluminum).

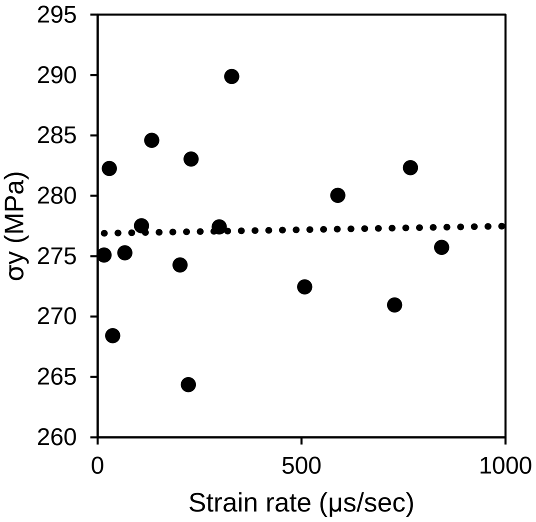


Figure 9: Effect of strain rate on the measured yield stress (aluminum).

4.2.2 Ultimate stress

As with steel, the tests were also paused at the ultimate strain to measure the drop from stress relaxation. This drop is plotted as a function of strain rate in Figure 10. At the ultimate stress level (UTS), the relaxation that occurs is almost twice than observed at yield, which matches past studies (Huang & Young 2014). This is different than with steel where relaxation was observed to increase only slightly at ultimate. There is a slight downward trend here as well, similar to what was observed in the steel. There is also less scatter at this level, which may be explained by a more stable strain rate (Figure 1). The relationship between measured ultimate stress and strain rate was also plotted in Figure 11.

As with the relaxation, a higher strain rate seems to correlate with a smaller UTS, though more samples would be required to confirm the existence of such a trend. In general, the strain rate seems to have little effect on the UTS.

Despite the strain rate having little effect on the relaxation properties or the ultimate tensile strength, there is a significant drop in stress at the UTS when the test is paused, similarly to what was done by Rao et al. (1966). This suggests that a reduction in strength of approximately 15 MPa, should be applied when using the S6-14 method. This is a large reduction, which may be more than 10% in some weaker alloys. Since only the 6061-T6 designation was tested, this value may vary for weaker alloys.

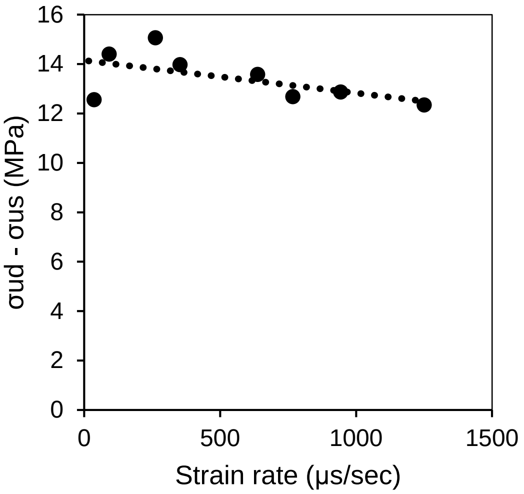


Figure 10: Effect of strain rate on the difference in dynamic and static ultimate stress (aluminum).

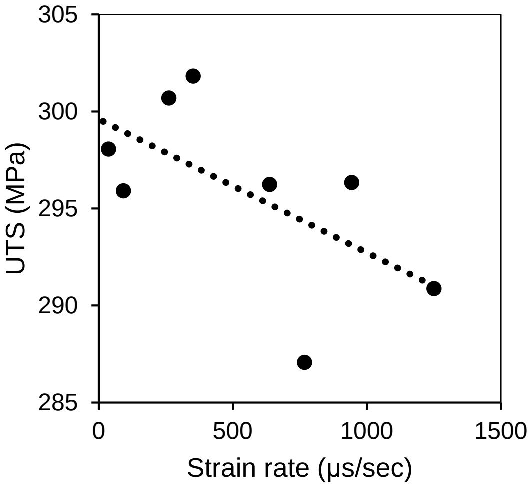


Figure 11: Effect of strain rate on the measured yield stress (aluminum).

4.2.3 Stress relaxation at 0.02 strain

Upon analyzing the data from pauses at 0.02 strain, it was found that the change in stress trend was essentially in the same as at the ultimate stress level, with the effects of relaxation slightly scaled down, suggesting that as the samples work harden, they progressively become more susceptible to the effects of stress relaxation. Figure 12 displays the phenomenon.

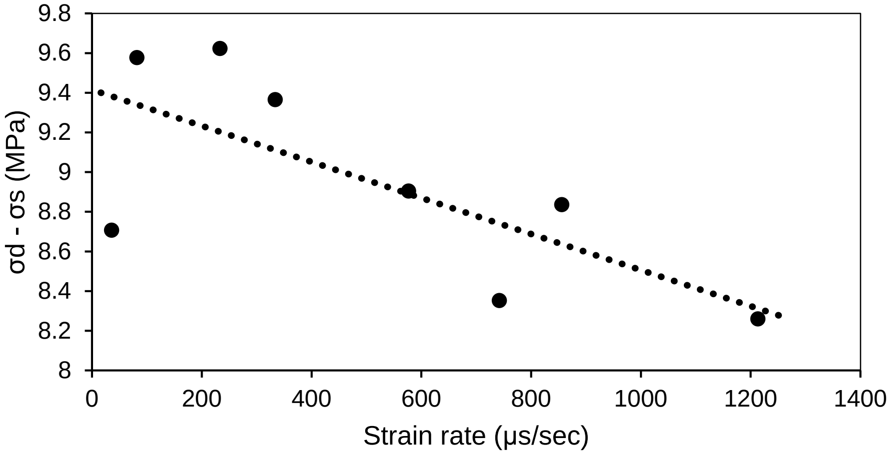


Figure 12: Effect of strain rate on the difference in dynamic and static stress at 0.02 strain (aluminum).

5 CONCLUSIONS

This study confirmed the findings of Rao et al.'s study in 1966 that 350W steel relaxes when a test is paused in the yield plateau. However, it failed to establish the same trend with strain rate as observed in the original report, and the magnitude of the relaxation effect was observed to be smaller. Since this may be attributable to differences in steel alloys and technology, there is no basis to suggest that the yield strength reduction of 28 MPa used in the current version of the *Canadian Highway Bridge Design Code*'s (S6-14) Annex A14.1 is inadequate.

At the ultimate stress level in steel, it was observed that an increased strain rate may correlate to a small increase in strength, but the opposite effect was seen with the amount of relaxation. This suggests that relaxation may not be an adequate measure of the effect of strain rate on strength. Nevertheless, there was a relaxation effect similar to what was observed at yield, and following the reasoning used at yield strength, in may be warranted to also mandate a reduction in the ultimate strength determined by testing.

In the 6061-T6 aluminium alloy, no significant correlation was found between the strain rate and either yield strength or the relaxation at pauses. Relaxation however still occurred, with an approximate drop of 7 MPa. This value is much lower than observed with steel, an important distinction when considering that some aluminium alloys may have yield strengths less than 100 MPa. At the ultimate stress level, the decrease in stress from relaxation was doubled. A small negative correlation with strain rate was observed in both the relaxation magnitude and the UTS, though its significance is doubtful.

The performance factors for aluminium are based on the steel calibration, despite aluminium using the 99th percentile strength and steel using the 95th percentile. Thus, it is believed that Equation [2], used in Annex A14.1 of S6-14, should be valid and conservative with both steel and aluminium, with aluminium using a strength reduction value much less than 28 MPa. It should also be noted that the family of aluminium alloys used in structural applications ranges over a large range of yield and ultimate strengths, with some alloys having very different properties. Further tests on different alloys will be required to establish an adequate value to replace the 28 MPa reduction in equation [2] for aluminium. Further tests on a different test frame and under strain, rather than displacement control, are also recommended, in order to ensure that the findings of this study are applicable to a broader set of testing conditions.

Acknowledgements

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