Time Effects on the Characteristics of a Steel WF in Pure Bending up to Strain Hardening

by

Paul C. Paris

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IN PURE BENDING UP TO STRAIN HARDENING

Introduction

For the sake of analysis the "collapse" of a structure is usually considered to be independent of the time required during this phenomena. It is the purpose of this work to investigate the effects of this assumption on plastic design. In order to examine time effects it is necessary to define the time variables of "collapse" in the following manner:

1. The rate at which "collapse" is progressing.
2. The elapsed time during which collapse has progressed since it commenced called age.

In an element of a beam under pure bending the first variable may be measured as the time rate of change of curvature ($\dot{\phi}$). The second variable may be measured directly as the clocked time since curvature was initiated. Since time elapses continuously, and since the curvature at any time is the quadrature of the rate of curvature during the elapsed time, the rate itself is the only truly independent variable.

In the test descriptions to follow the rate was controlled in all cases to be a constant or zero during specific intervals of time or curvature. Data was recorded as the loading on the member at some curvature (or time) with a given rate occurring.
Theoretical Considerations on Rate of Curvature Effects

The strain rate in any fiber of a beam is known to be approximately proportional to the rate of curvature occurring at the cross section in question. Therefore, it is of practical importance to know if the effect of strain rate in coupon tests will correlate with the effect of rate of curvature in a beam; if so the effects of "rate of collapse" of a structure may be successfully predicted with coupon testing.

It has been shown by several authors\(^1\) that the effect of rate of strain on the coupon yield strength of steel is but a few percent for rates less than \(10^{-3}\) in./in./sec. (ASTM permissible maximum) and is negligible for rates less than \(10^{-5}\) in./in./sec. In the test descriptions to follow the feasible range of rates of curvature was limited to those corresponding to strain rates of \(10^{-7}\) in./in./sec. to \(10^{-5}\) in./in./sec. (The bounds were set by the limitations of a hydraulic testing machine and the ability of the human recording data). Since coupon tests showed no effect due to rate for rates comparable to those used herein, it is encouraging to find that the author observed no effects of rate in the beams tested.

Theoretical Considerations on Aging Effects

The observation of an upper yield point phenomena in a simple tension test illustrates the fact that the occurrence of first yield in the media is fundamentally different from succeeding yielding. This fundamental difference must be introduced by the existence or non-existence of previous yielding. Considering this, it is evident that yielding starts
with a stress comparable to the upper yield stress and new yield zones are the growth of this original "initial yield line" at a stress comparable to the lower yield stress level. For the sake of simplicity one may think of this as yielding starting at a point with this point growing until the whole specimen has yielded.

In considering the effects of aging one should primarily be concerned with effects on the growth boundary of a yield zone. If the strain rate in the media considered is other than zero, the growth boundary is a moving surface.

Thus if a yielding member is being strained continuously (no matter how slowly) the time during which the growth boundary does not remain at any given location for more than an infinitesimal time. The conclusion to be drawn from this is that: as long as the strain rate in a member is other than zero aging will have no effect. The tests of this program indicate that this conclusion is at least qualitatively correct.

If, after a yield zone has grown in a media, the specimen is unloaded and allowed to remain for a time with zero rate of strain in the body, the growth surface of the yield zone remains at a given position during this time. During this time a phenomena occurs which might best be labeled "healing" of the growth boundary. (The residual stresses in virgin material adjacent to the yield zone are relaxed by creep). Upon healing higher stresses are necessary to induce the yield zone to grow. In the tests it was observed that in a two day stop at room temperature a particular specimen (Test No. 1)
healed sufficiently to raise by 3% the stress required to cause further growth of the yield zone. Other healings (up to nine days at room temperature) increased the stress of perpetuation of growth by various amounts up to 5%.

Often healing might cause the perpetuation stress of a yield zone to be higher than the stress necessary to cause a new yield zone and thus a new zone is started on commencement of straining.

In conclusion of the consideration of healing it would be expected that: if a member with a yield zone is aged for a period of time at zero strain rate healing will increase the stress necessary to induce further yielding in the member, but this increase in stress can be no greater than that necessary to start a new yield zone.

If a yield zone has been initiated into a media, allowed to heal, and by some increased stresses is induced to start yielding again the yield zone will again begin to grow. With growth the growth boundary will move on to new material and therefore further perpetuation of growth occurs under the same conditions regardless of whether healing has or has not occurred at some time in the yield zone growth phenomena. Thus: the stresses necessary to perpetuate yield zone growth which is already initiated should be relatively independent of previous history. This theoretical observation is in agreement with the test data which showed less than 1% difference in "perpetuation of yield" stresses before and after healing had taken place in a member.
It must be remembered that the foregoing theoretical considerations are based on a wholly qualitative concept of the yield phenomena and are thus meant to be propounded only to speculate on the qualitative aspects of time effects on the "collapse load" of a steel structure. They may be useful to plastic design insofar as to give relatively accurate concept of the error committed in ignoring certain time effects. The conclusions drawn are useful to the test engineer in interpreting specific data.

A Review of Important Conclusions of Theoretical Observations:

1. Effects of strain rate are negligible up to $10^{-5}$in./in./sec.

2. As long as strain rate is other than zero, aging will have no effect.

3. If a yield zone is aged for a period of time at zero strain rate, healing will increase the stresses necessary to induce further yielding.

4. The increase in yielding stress due to healing can be no greater than the stresses necessary to initiate a new yield zone.

5. The stresses necessary to perpetuate an already growing yield zone are independent of previous history.

The Test Apparatus

Since it is of primary interest to apply the results of this work to assumptions of analysis of steel frame structures, it was decided to go a step further than simple tension or
compression tests to a structural WF section in bending. For the sake of size, local and lateral stability requirements, and economy a 4 WF 13 beam 6 feet in length and loaded approximately at the one-third points was chosen. (see Figure I) A rotation (curvature) indicator was used to measure the angle change in the center 8 inches of the 24 inch section of the beam under pure moment.

Two SR-4 strain gage were used to check the performance of the rotation indicator in the first test. The rotation indicator was found to be sufficiently accurate to omit the SR-4 gages in all further tests. The testing machine used was a 300 kip Baldwin Universal. The only further instrumentation required was a stop watch used to measure rates and age time.

The Programing of Tests

The programing of tests was set up to examine the theoretical conclusions previously discussed in this work.

Upon starting a test the strain rate was held a particular constant until a predetermine curvature (half the way to strain hardening) was reached. At this curvature the beam was unloaded and allowed to age for periods of time from 16 hours to 9 days. The test was then recommenced at a standard constant rate 10^-6 in. per in. per second and run into the strain hardening range. In some of the tests (Nos. 4, 7, 8 & 9) a second stop was introduced in the test previous to the standard stop. These second stops were introduced to examine the effect of stops at various curvatures and also the effect of previous history the standard stop. The initial strain rates
were varied from $0.7 \times 10^{-7}$ to approximately $0.8 \times 10^{-5}$ (in./in. per sec.). Test No. 2 was run at standard rate with no stops in order to establish a control $M-\phi$ curve for the basis of comparison of effects.

Figures 2 thru 11 give the experimental moment-curvature diagrams plotted as dimensionless quantities $M/M_y$ ($M_y$ being the yield moment of the section and $\phi/\phi_y$ ($\phi_y$ being the initial yield curvature of the section). In all cases the strain rate has been recorded on each portion of the curves where it is pertinent and the length of each stop is recorded at each unloaded point.

Observations from Experimental Data

Test No. 1 (Figure 2) shows a fairly typical aging "bump". On reloading after a 2 day stop a 3% increase in stress was necessary to initiate further yield and as yielding progress the curve rapidly reverts to its original yield stress. This curve is a perfect example of the effect of aging as predicted by the preceding theoretical considerations. One may find exactly the same type of phenomena occurring in the other test curves (see Figures 8, 9 and 10).

As was predicted in the theoretical discussion, some specimens after aging showed relatively low or no aging bump at all. This comes about as the result of the starting of a new yield zone after aging, the new yield zone needing only a small increase in stress to be initiated. Examples of this particular phenomena are observed on Figures 4, 5, 6 & 7. In all but Figure 4 the perpetuation stress for further yielding
is the same as that before aging. The only feasible explanation for the change of yield stress in Figure 4 is the difference in strain rate before and after the aging stop.

Figure 12 shows the height of yield "bumps" plotted against the length of stop. This graph shows that the average height of the "bumps" to be about 2% of the total stress. The maximum height observed was 4 1/2% as shown from test No. 9 (Figure 10).

Figure 13 shows the % change in yield zone perpetuation stress before and after an age stop. The average change can be seen to be negligible for all practical purposes having a maximum effect of 1%.

On a statistical basis the foregoing test observations verify the theoretical observations very closely. It is important to emphasize the fact that such a statistical correlation gives one a picture of bounds within which another test would be expected to lie.

Conclusions
1. Of the rates at which beam tests are usually run, none of these affect the yield stress of steel members.
2. As long as strain-rate is other than zero aging has no effect on a member. This result may be drawn from theoretical considerations or conclusion number one.
3. If a yielded member is aged for a period of time at zero strain rate, the stress necessary to initiate further yielding will be raised. From the experimental observations this increase was found to vary from 0 to 5% as a maximum. The fact that this is variable leads to conclusion No. 4.
4. The increase in yield stress due to aging can be no greater than that necessary to initiate a new yield zone.

5. The stress necessary to perpetuate an already initiated yield zone are independent of the previous history of a member.

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References

Figure 6

- 0.8 x 10^{-5} in/in per second
- 10^{-6} in/in per second

2-day stop

Test No 5 - P 4.29-54
Figure 11

Graph showing the change in M/M₀ as a function of time, with two sections marked:
- 10⁻⁶ in/in per second
- 10⁻⁶ in/in per second

Time axis (in days):
0 1 2 3 4 5 6 7 8 9 10 11 12 13

Note: The graph also indicates a 4 day stop at point 5.