Residual Performance of Structural Steel after Plastic Deformation and Strain Aging

Shaoqi YANG
Candidate for the Degree of Master of Engineering
Supervisor: Dr. Taichiro Okazaki
Division of Architectural and Structural Design

Introduction

Steel is very well suited for sustainable construction owing to its recyclable and durable properties. Today, nearly all steel products are reused after their service life. However, because the recycle process requires abundant energy consumption and associated carbon-dioxide emission, sustainable steel construction can be further promoted by establishing reuse: procuring steel components as a structure is being demolished, refurbish and then reuse in a new structure. To do so, the performance of used steel must be evaluated. The effect of plastic work, due to earthquake or fabrication among other causes, need to be quantified.

Therefore, research was conducted to understand the residual performance of common Japanese structural steel after plastic deformation and strain aging. This research program includes monotonic tension coupon tests, cyclic tests and cyclic beam tests. At the time of writing, only monotonic tension coupon tests were completed. This thesis reports a background review, experimental methodology and conclusions at current stage.

Literature Review

Bauschinger observed an increase in the maximum load-carrying capacity of a piece of steel after it was tested to inelastic range and retested after some time [1]. This phenomenon, now known as strain-aging, is significantly affected by chemical composition and the method and duration of curing. Cottrell and Bilby [2] explained that strain aging of low carbon steel is caused by segregation of interstitial atoms, mainly carbon and nitrogen, to form atmospheres around dislocations. Ono et al. [3] highlighted the role of titanium on reducing strain aging.

Based on literature review, Baird [4] summarized that strain aging results in increased yield strength, recovery of a sharp yield point, and reduced ductility and toughness as illustrated in Figure 1. Extensive study on strain aging has been conducted in the field of welding and manufacturing. Based on a review of over 30 types of steel, Pense [5] stated that strain-aging can occur in any steel. Inelastic strain introduced at ambient temperature causes strain aging, but the effect may be relaxed depending on curing temperature, i.e., the temperature maintained over the duration when strain aging takes effect: temperatures up to 426°C has no relaxing effect; temperatures between 482 and 649°C can relax ductility loss; temperatures above 649°C can relax the change in yield and tensile strength and elongation but not to the original properties.

Table 1 listed experimental studies on strain aging and tension properties [4, 6-9]. Wilson and Russell reported for low-carbon rimmed steel that changes in yield strength and elongation is controlled by grain size and content of dissolved carbon and nitrogen and that the effect saturates after one week at 60°C [4]. Succop et al. [6] observed for pressure-vessel steel A533 and A516 that even a small, 1.25% pre-strain can cause 75% increase in yield strength after 3,000 hours at 260°C. They also suggested that 260 to 343°C is the most detrimental curing temperature. Kaufmann et al. [7] studied the properties of the k-area of rolled I-sections of A572, A913, and A36 steel to address the change in milling process from blast furnace to electric arc furnace in the 1980's. In the range of 2 to 12%, larger pre-strain caused larger increase in yield strength, from 20 to 40%. In steel cured after 12% pre-strain, which stressed the material to near the necking point, the yield plateau reappeared but strain hardening was negligible. Yamada et al. [8] observed for SS400 steel that strain aging may saturate at 3 months under ambient temperature. They also observed from cyclic-loading tests of beam-to-column connections made of SS400 steel that strain aging can result in a favorable distribution of tension properties to promote yielding in regions away from critical welds. Mojtaba [9] observed for SN490B steel that increase in yield strength was independent of the amount of pre-strain and that strain hardening rate did not change with aging.

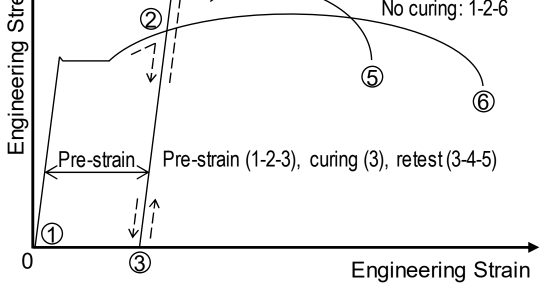

Figure 1. Typical strain aging effect

Table 1. Earlier experiments on strain aging

Author	Steel	Pre-strain	Curing	Observations
Wilson and Russell [4]	Low carbon steel	4%	60℃ / up to 2 months	Changes in yield strength and elongation was influenced by grain size; Strain-aging saturated at 1 week.
Succop et al. [6]	A533, A516	1.25%	93 - 593℃ / up to 1.5 months	260 to 343℃ was the most detrimental curing temperature; even small strain can be detrimental if curing time is long enough.
Kaufmann et al. [7]	A572, A913, A36	2 - 12%	93 - 204℃ / 10 hours	Yield and tensile strengths were nearly identical after curing if pre-strained 12%.
Yamada et al. [8]	SS400	2.5 - 10%	Room Temperature / up to 1 year	Strain-aging saturated at 3 months.
Mojtaba [9]	SN490B	0.8 - 10%	100 - 200℃ / up to 10 hours	Increase of yield strength was independent of amount of pre-strain.

Experimental Method

Materials

Three different structural steel grades, JIS SS400, SN400B, SN490B, were selected for testing. Table 2 lists the mechanical properties and carbon content reported in the mill-test reports. Table 3 summarizes the nitrogen content measured based on the thermal conductimetric method according to JIS G 1228: Iron and steel – Methods for determination of nitrogen content and the glow discharge optical emission spectroscopy (GD-OES) method. Since the GD-OES can only measure the relative composition, the nitrogen content listed in Table 3 was based on the carbon content listed in Table 2. The GD-OES results suggested a higher nitrogen content compared to the thermal conductimetric method. The discrepancy may be attributed to the sampling procedure used for the GD-OES.

Monotonic Tension Coupon Tests

JIS 1A tension coupons were sampled from H-500 ×200×10×16 hot-rolled sections at the locations shown in Figure 2. An extensometer shown in Figure 3 was devised to measure engineering strain over the standard gauge length of 200 mm. The extensometer was fixed to the coupon at each gauge marks through four springs. Engineering strain was calculated as the average displacement measured by two transducers divided by the original gauge length. The accuracy of strain measurement in the elastic range was confirmed by comparison against measurements from strain gauges attached to the middle of the gauge length.

Coupons were pre-strained to three different values, 2, 4 and 8%, and then cured at ambient temperature for 30 or 90 days. After the designated curing duration, the pre-strained coupons were tested to fracture. A fourth coupon was tensioned to fracture with no pre-strain to provide data on properties without strain aging. Coupons sampled from location A, B, F and G were used to evaluate the flange after 30 days and 90 days; and location C and E for the web after 30 days.

Table 2. Material properties from mill test report

Steel Type	SS400	SN400B	SN490B
Yielding Strength [MPa]	310	314	364
Tensile Strength [MPa]	454	469	531
Yield Ratio	0.68	0.67	0.69
Elongation [%]	30	29	28
Carbon [wt%]	0.15	0.16	0.16

Table 3. Measured nitrogen content [wt%]

Analysis Method	SS400	SN400	SN490
JIS G 1228	0.0073	0.0031	0.0028
GD-OES	0.0100	0.0073	0.0072

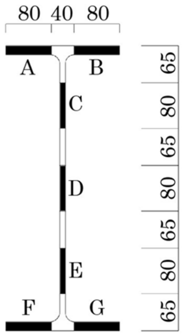

Figure 2. Sample Location

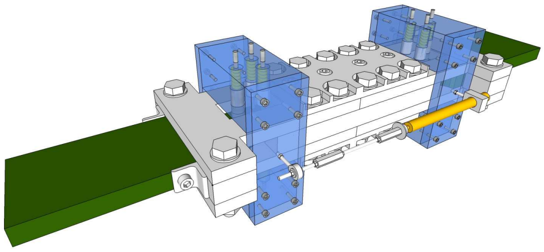

Figure 3. Coupon with extensometer and buckling restrainer

The tests were conducted using a 1,000-kN capacity universal testing machine. The strain rate was controlled at 0.00005 /s until the start of strain hardening, 0.00025

/s until strength drop (tensile strength was measured), and then 0.0005 /s to fracture.

Results and Discussion

Figure 4 shows the strain-stress relationships obtained from all six cases, three steel grades and two sample locations, of monotonic coupon tests. The yield strength was established based on the segment of the yield plateau where the loading rate was 0.00005 /s. Change in tension properties was noticed in all six cases as re-appearance of distinguishable yield plateau, rise in yield strength, rise in tensile strength, and reduction in elongation with respect to the original properties listed in Table 4. For all steel, larger pre-strain resulted in larger change in tension properties. Eight-percent pre-strain resulted in recovery of upper-yield point and yield plateau, and 40 to 60% increase of yield strength. Little change in tensile strength was observed: 8% pre-strain resulted in 4% increase in SS400 and smaller increase in SN400B and SN490B. Little change in elongation was observed: 8% pre-strain resulted in 15% reduction in SS400 but no significant change in SN400B and SN490B. it was noticed that yield and tensile strengths were nearly identical after curing if pre-strained 8% which suggested a total loss of ductility. The result of longer curing times indicates very small difference. The yield strength was further increased around 5% from 30 days to 90 days. The result agrees with Yamada et al. [8] who reported the strain aging of SS400 steel may saturate at three months in ambient temperature.

Among the three grades of steel, SS400 saw the most profound change in tensile properties, while SN400B and SN490B saw very little change. The result correlated with the nitrogen content listed in Table 3: According to the thermal conductimetric method, the nitrogen content of SS400 of 0.0073% was 2.5 times that of SN400B or SN490B. The change in yield strength and elongation for SS400 steel was consistent with the report by Yamada et al. [8]. The rise in tensile strength was notably smaller than the results reported by Yamada et al. [8] and Pense [5].

Conclusion

A literature review on the effect of strain aging on tension properties of steel was reviewed. Strain aging in Japanese structural steel SN400, SN400B, and SN490B was examined through tensile coupon tests conducted in two phases. The change in tensile properties was influenced by the extent of pre-strain and nitrogen content. Among the three steel grades, SS400 with nitrogen content of 0.0073% saw the most profound change in tension properties, while SN400B and SN490B with nitrogen content of 0.003% saw very little change. The strain aging for three steels may saturate by 90 days at ambient temperature.

Future Works

Cyclic Coupon Tests

Coupons sampled from location A, B, F and G will be used to evaluate residual performance of flange when subjected to cyclic and cured 90 days at ambient temperature. A buckling restrainer as shown in Figure 3 was devised to prevent buckling of the coupon about it minor axis during compression. The tests will be conducted by a 750kN dynamic actuator following a displacement control, quasi-statically cyclic loading protocol. It has an initial amplitude of 0.5% and the amplitude increases 0.5% every two cycles. Coupons will be loaded until finish three designated strain levels, ±1, ±2 and ±3%, and then cured at ambient temperature for 90 days. After the designated curing duration, the pre-strained coupons were tested to failure. A fourth coupon will be loaded to failure with no pre-strain to provide data on properties without strain aging.

Beam Tests

A total of twelve H-500×200×10×16 beam specimens were fabricated and will be tested to evaluate residual performance from component level. The steels came from exactly the same heat with the three studied in coupon tests. Detail of the specimen is shown in Figure 5 and test setup is shown in Figure 6. The beam specimens were bolted into a real beam-to-column connection and tested by a revised AISC protocol. Similar to coupon tests, beam tests were conducted in two stages. The beam specimens first went through certain portion of the loading protocol until a designated plastic deformation; cured 90 days under ambient temperature; and tested again after curing period. A 3D reconstruction method using images was developed using software Agisoft PhotoScan. This method will be used to quantify the local buckling of specimen flange.

Reference

[1] A. Momtahan, R.P. Dhakal, and A. Rieder. Effects of strain-aging on New Zealand reinforcing steel bars. Bulletin of NZSEE, Vol. 42, No. 2, September 2009.

[2] A.H. Cottrell, and B.A. Bilby. Dislocation theory of yielding and strain ageing of iron. Proc. Physical Soc., 62(1-349 A), pp. 49-61, 1949.

[3] T. Ono, K. Murayama, K. Masuda, A. Sato and T. Yokokawa. The experimental study on the effect of trace elements onn toughness of steel plate for building structure. *J. Struct Constru Eng*, AIJ, No.536, pp.157-162, 2000 (in Japanese).

Table 4. Measured mechanical properties

Steel Type	SS400		SN400B		SN490B	
Location	Flange (A)	Web (C)	Flange (A)	Web (C)	Flange (A)	Web (C)
Yield Strength [MPa]	300	332	284	322	344	358
Tensile Strength [MPa]	448	462	457	472	521	522
Yield Ratio	0.67	0.72	0.62	0.68	0.66	0.69
Elongation [%]	31.3	28.4	32.9	29.0	28.5	25.3

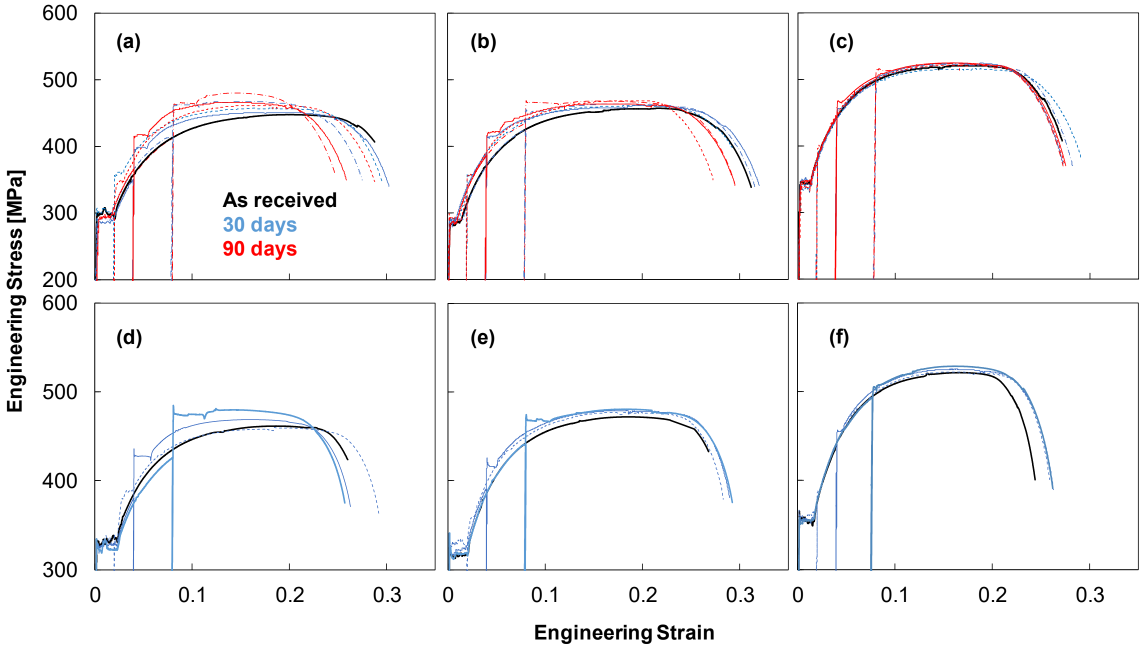

Figure 4. Strain-Stress Curve After One-Month Curing: (a) Flange of SS400; (b) Flange of SN400B; (c) Flange of SN490B; (d) Web of SS400; (e) Web of SN400B; (f) Web of SN490B.

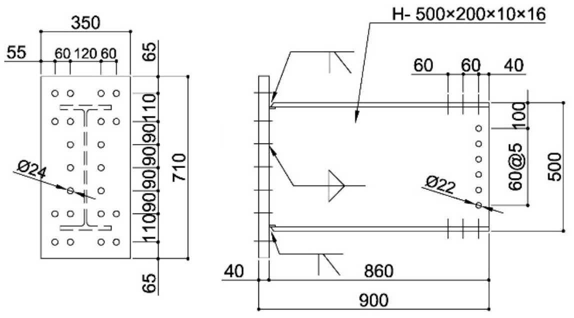

Figure 5. Beam specimen (dimensions in mm)

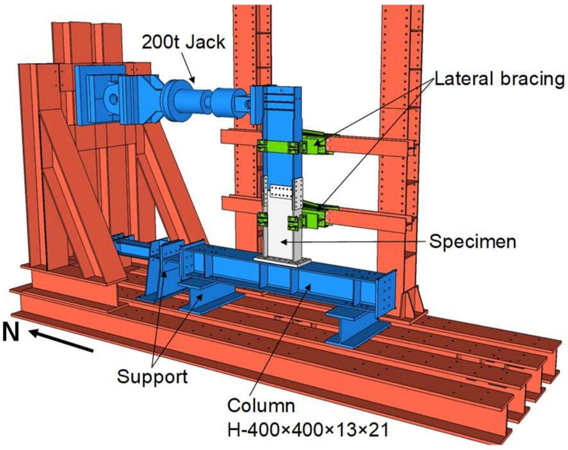

Figure 6. Beam tests setup

[4] J.D. Baird. The Effects of Strain Aging due to Interstitial Solutes on Mechanical properties of Metals. *Met. Rev.*, 5, pp. 1-18, 1971.

[5] A. Pense. HPS corrugated web girder fabrication innovations, Final report, Part 4: Literature and experimental study of strain aging in HPS and other bridge steels. Center for Advanced Technology, Betlehem, PA, 2004.

[6] L.N. Succop, A.W. Pense, and R.D. Stout. The effect of warm overstressing in pressure vessel steel properties. *Welding J.*, 49(8), pp. 354-364, 1970.

[7] E.J. Kaufmann, B. Metrovich, and A.W. Pense. Characterization of cyclic inelastic behavior on properties of A572 Gr. 50 and A36 rolled sections. ATLSS Report No, O1-13, August 2001.

[8] S. Yamada, A. Takeuchi, S. Kishiki, and A. Watanabe. Hysteresis behavior of steel affected by strain aging. Summary of Technical Papers of Annual Meeting, AIJ, pp.927-930, 2006 (in Japanese).

[9] M.A. Mojtaba. Static strain aging in low carbon ferrite-pearlite steel: Forward and Reverse Loading. Electronic Theses and Dissertations (ETDs), University of British Columbia, 2015.