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MATERIALS AND FRACTURE INVESTIGATIONS IN THE FEMA/SAC PHASE 2 STEEL PROJECT

James O MALLEY[1] And Karl FRANK[2]

SUMMARY

The 1994 Northridge, California earthquake caused significant widespread damage to a large number of welded steel moment resisting frame buildings. As a result of this damage, a large effort has been undertaken to understand the potential causes of the damage, and to develop improved practices that will mitigate the same type of damage in future events. Phase 2 of the FEMA/SAC Steel Project includes a series of investigations of the properties of rolled shape materials used in moment resisting frame structures. The results of these materials investigations will be summarized in this paper.

INTRODUCTION

Significant changes in the steel making and rolling practices have occurred in the steel industry since 1970. In 1974 the majority of steel was produced in open-hearth furnaces. No wide flange shapes were rolled from steel made in electric furnaces. All of the producers in 1974 were integrated mills that produced their steel either solely from blast furnace iron in an open-hearth furnace or from a mixture of iron and scrap steel in a basic oxygen furnace. Most of the current producers of structural shapes available in the U.S. market use electric furnaces for the production of steel. The changes in steel making have caused changes in the chemistry of the steels. The advent of continuous casting has reduced the amount of segregation in the final product and reduced the amount of hot working the steel in the rolling process. The new electric furnace steels typically have a lower carbon content then the steels produced at integrated mills. Older steels had carbon contents in the range of 0.15 to 0.25% while the electric furnace steels typically have carbon contents of 0.08 to 0.15%. The lower carbon increases the toughness of the steels and improves the weldability of the steel. The reduction in strength that would normally occur from the reduction of the carbon content is offset by the alloy additions, which came from the scrap steel used in the charge in the electric furnace. The new specification for structural shapes, A992, was developed specifically for electric furnace steels.

The base materials in steel structures that undergo extreme seismic events will be subjected to strain demands well beyond those of typical structural loads. Understanding the characteristics of the base materials is critical to developing guidelines for seismic design. No comprehensive information was available for the steel wide flange materials that presently are being produced. A series of investigations was undertaken to better characterize these materials and to develop information needed for seismic design guidelines. Some of the major issues dealt with in these investigations will be discussed below.

Yield Strength of Steels

A sampling of current rolled shape production was undertaken to determine the tensile properties of these shapes, to determine the variability of the properties within and among the shapes, and relationship between the results reported in the mill report and the laboratory tests. The properties measured during the tension tests included the following:

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[1] *Senior Principal, Degenkolb Engineers, San Francisco*

[2] *Professor of Civil Engineering, The University of Texas, Austin*

E= elastic modulus assumed as 29,000 ksi

F_{uy} = upper yield point, ksi

F_y = dynamic yield strength, ksi

F_{sy} = static yield strength, ksi

F_u = tensile strength, ksi

ε_{sh} = strain at strain hardening

ε_u = strain at maximum stress

E_{sh} = strain hardening modulus, ksi

The tensile specimens were taken from both the web and the flanges of the sections. Six specimens were taken from each section, three from the web and two from each flange. This multiple sampling allowed the variation of the strength within the cross section to be determined. The static yield strength was measured by stopping the loading of the test specimen during the tests and measuring the load after holding the deformation. All sections were ordered as A572 Gr. 50 steel. Many of the sections met the requirements of both A36 and the new grade 50 steel. The sections supplied by Trade ARBED were QST steels produced in accordance with A913.

Effect of Coupon Location Upon Yield Strength

The webs of rolled sections normally have higher yield strengths than the flanges, due to greater hot working of the thinner web material during the rolling process. With previous mill practices, the yield strength was expected to be 4-7% higher in the web than in the flange. Modern shape production starts with a near net shape cross section, reducing the differences in hot working between the web and flange. Mill test coupons have traditionally been taken from the web until recent changes in the ASTM specifications that now require flange testing. The effect of the coupon location was studied to find overall trends, as well as differences between individual producers. The ratio of $F_{yflange}/F_{yweb}$ was calculated by dividing the average from the four flange tests by the average of the three web tests of each section. The average dynamic yield strength was used for this comparison. The distribution of $F_{yflange}/F_{yweb}$ for the entire set of coupons is shown in the figure below.

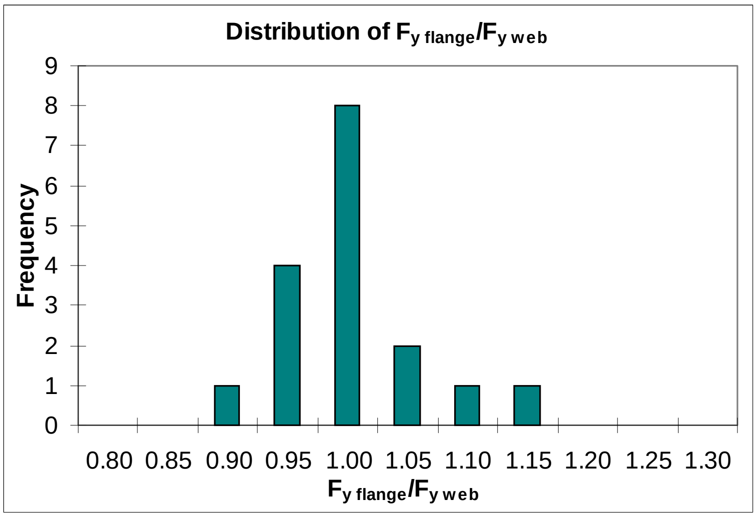
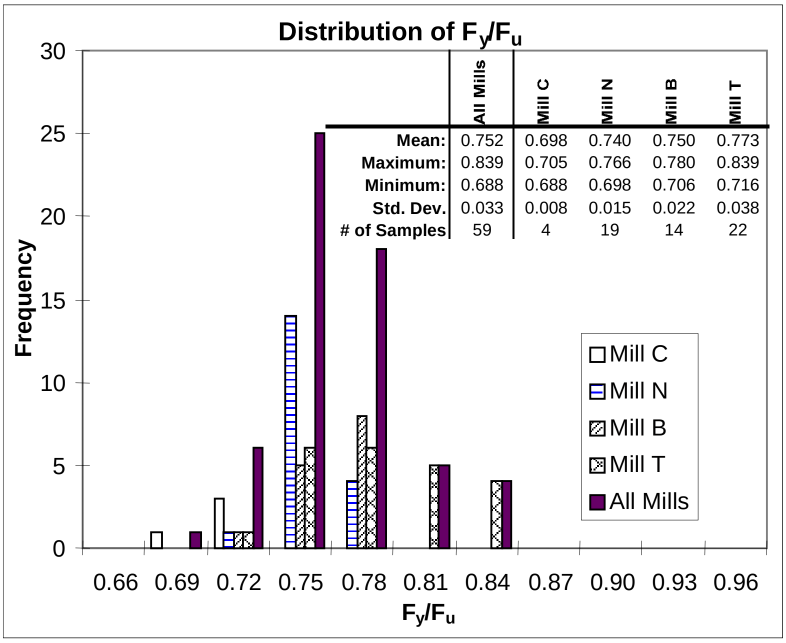


Figure 1 – Distribution of $F_{yflange}/F_{yweb}$ for All Sections

The average ratio was 98%. Since the average ratios of $F_{yflange}/F_{yweb}$ of most of the sections were less than unity and showed a high degree of variability overall, the yield strengths of the flange and web were considered fundamentally different. The traditional ratio 0.95 remains a reasonable estimate of the flange to web yield strength.

Yield to Tensile Strength Ratio

The frequency distribution of the ratio of F_y/F_u ratio for flange coupons is shown in Figure 2. The new A992 specification specifies a maximum ratio of 0.85. All of the specimens met this requirement. The mean values from each mill were similar.

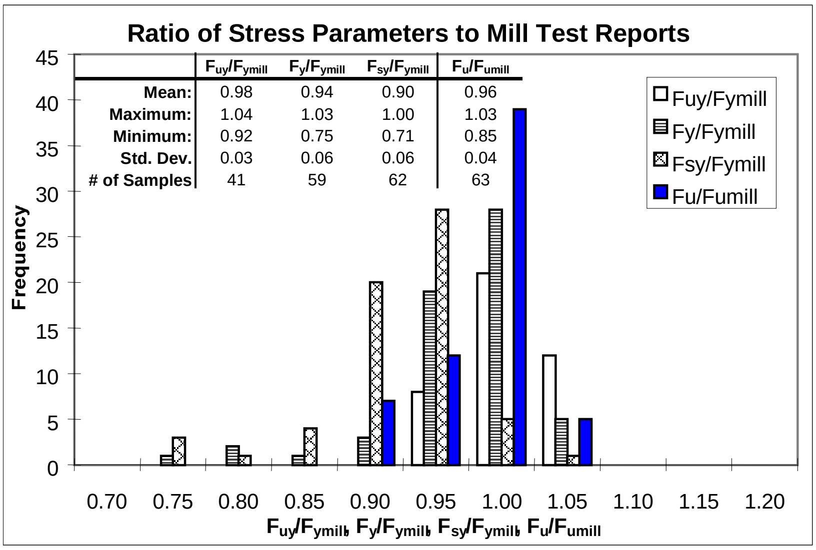


	All Mills	Mill C	Mill N	Mill B	Mill T
Mean:	0.752	0.698	0.740	0.750	0.773
Maximum:	0.839	0.705	0.766	0.780	0.839
Minimum:	0.688	0.688	0.698	0.706	0.716
Std. Dev.	0.033	0.008	0.015	0.022	0.038
# of Samples	59	4	19	14	22

Figure 2 – Distribution of F_y/F_u

Relationship Between Mill Test Report Values and Laboratory Test Results

The relationships between the measured strength parameters and the reported mill test values were determined. Figure 3 shows the distribution of F_{uy}, F_y, and F_{sy}, relative to F_{ymill}, and F_u relative to F_{umill}.



	F_{uy}/F_{ymill}	F_y/F_{ymill}	F_{sy}/F_{ymill}	F_u/F_{umill}
Mean:	0.98	0.94	0.90	0.96
Maximum:	1.04	1.03	1.00	1.03
Minimum:	0.92	0.75	0.71	0.85
Std. Dev.	0.03	0.06	0.06	0.04
# of Samples	41	59	62	63

Figure 3 – Comparison of Mill Tests and Coupon Tests

The histogram represents flange material only.

The average values of F_y/F_{ymill} and F_{sy}/F_{ymill} were 0.94 and 0.90, respectively, suggesting that good estimates of F_y and F_{sy} are approximately 95% and 90% of F_{ymill}. The observed value of F_u/F_{umill} was also about 95%.

Influence of Dual Graded Steels On Expected Strength

Dual grade steels, those that meet the strength requirements of A36 and A572 Gr. 50, have been marketed during the past ten years. This practice tends to skew the yield expected yield strength toward the minimum specified yield strength of 50 ksi. The distribution of yield strength from the mills only producing single graded steels had a more normal distribution and a higher average. The average yield stress is lower for the dual grade producers and about 25 per cent of their dual and grade 50 steel has a yield stress within 2 ksi of the minimum specified. The single grade producers had only 3.6% of their values within 2 ksi of the limit. The truncation of the histogram for yield strength exhibited by the dual grade producers also produced a skewed distribution of the A36 steel yield strengths. The steel not meeting the 50 ksi minimum yield point of grade 50 steel was classified as A36. This is the steel on the tail of the curve below 50 ksi. The result is high strength A36 steel from the dual grade producers and a more normal distribution from the single grade producers. The mean yield point of the dual grade producers is 50.4 ksi with a standard deviation of 4.53. The mean yield point of the single grade producers is 46.8 ksi with a standard deviation of 4.84 ksi. The yield point is reasonably normally distributed about the mean value for both sets of producers. The high strength of the dual grade producers must be considered when evaluating the relative strength of different members of the seismic force resisting system.

Recommended Changes to the ASTM Specifications

The results of the investigation indicate that the yield point reported in the mill test report over estimates the yield strength of the steel. The yield strength of these steels is sensitive to the strain rate of test. The static yield strength, which is measured after the specimen has been held at fixed strain, is independent of the test machine and test protocol. However, this test is not suitable for mill tests due to the length of time required to perform the measurement. A correlation with the more rapid mill test must be used to estimate the yield strength of the steel. The present ASTM specifications allow the mill to report the upper yield point rather than the dynamic yield strength of the steel. The results of the round robin testing performed among the mills indicated that the yield point measured in accordance with the methods allowed in the present ASTM specifications can result in differences in reported yield points. The correlation with the mill tests would be improved if the steel specifications in ASTM were changed to require a specified yield strength for the structural steels. The yield strength would be determined using an offset method which will reduce the scatter in reported yield strengths/points and provide a statistic which has a better correlation with the actual yield strength of the steel.

Charpy V-Notch Toughness of Rolled Shapes

The Charpy V-Notch, CVN, toughness of the shapes was measured in the flange, the web, the core at the junction of the web and flange, and in some sections at the so called K-line, the intersection of the flange to web fillet and the web. The CVN test is a simple method of estimating the dynamic fracture toughness of steels. The test measures the energy required to fracture a notched beam specimen loaded in single point bending. The notch toughness of particular steel is dependent upon the temperature of the steel when it is tested. The results are typically divided into three regions. The lower shelf is a region of low toughness at low temperature in which the specimen fractures in a cleavage mode with no significant plastic deformation. The upper shelf occurs at higher temperatures. Considerable energy is required to fracture the specimen at the upper shelf temperature, with large plastic deformation. Between the two shelves is a region of rapid change in toughness with temperature. This region is labeled the transition zone and is often characterized by determining the temperature at which the steel attains a certain energy level. The 15 ft-lb. energy level is often used to fix the transition temperature of low strength steel.

In the sections tested in this program, the flange region exhibited a gradual transition, with an estimated transition temperature below -50^{o} F. The upper shelf energy is about 200 ft-lbs. The core region exhibited a very abrupt transition with a transition temperature of approximately 10^{o} F. The average upper shelf energy of the core region was 230 ft-lbs. The web also exhibited an abrupt transition in toughness with a transition temperature similar to the flange. The upper shelf of the web was higher than the flange but comparable to the core. The results from most the sections tested were similar; with the measured toughness being different in each of these three locations. The upper shelf toughness of the core was often equal to the web or flange toughness.

K-Area Properties of Rolled Shapes

The K-area of the web is defined by the “K” dimension given in the AISC Manual as the distance from the outside surface of the flange to the line of tangency of the fillet between the web and flange and the web surface. Service fractures at the end of continuity plate and web doubler plate welds have occurred in the region of the K-area. The cause of these fractures was the low toughness of the region. The change in the properties relative to the other areas of the section was attributed to the contact forces on the web from the rollers during cold roller straightening of the sections. The sections investigated in the SAC studies were evaluated to determine the properties of the sections at the K-line.

Hardness surveys using the Rockwell B scale were performed on the web-flange juncture. The hardness approximately 1/8 in. in from the surface of the sections was measured around the sample. The web showed considerable hardness variation with the highest hardness in the region of the K-line. The shapes from the two producers have very similar hardness. No significant hardness gradients were found in the flanges. The hardness of two additional roller straightened sections produced similar results.

The toughness of the core region was compared to the toughness measured in the flange away from the core. The results are shown in the figure below.

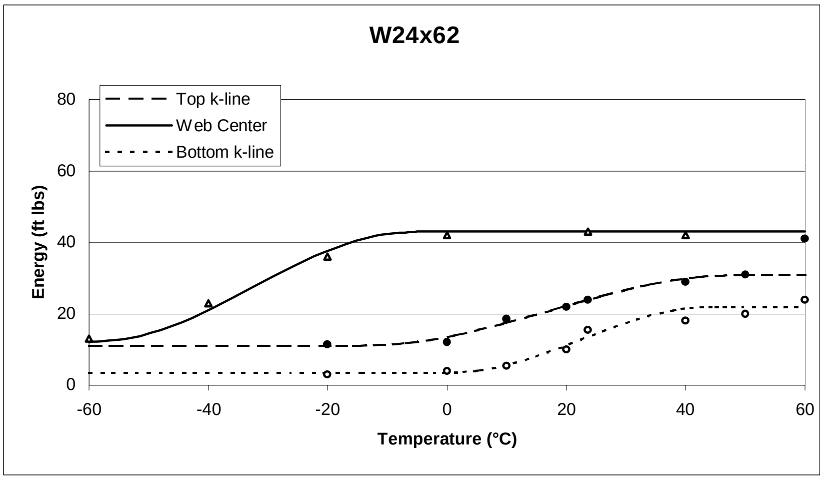


Figure 4 – Charpy V Notch Results of W24x62

The K-area exhibited a dramatic reduction in toughness relative to the center of the web. The 15 ft-lbs transition temperature was at or above room temperature and the upper shelf values were one half the values from the center of the web. The results confirm observations from other investigations of the K-area of roller straightened sections. These K-area regions will have a high hardness, higher yield and tensile strength, and lower notch toughness than other portions of the section.

Strength Variation in A913 steel

The rolled sections from the producer of A913 steel were all produced by the Quenching Self-Tempering , QST, heat-treating process. This process consists of hot rolling the sections to the final geometry and then quenching section within the rolling line and allowing the hot core region of the section to temper the cooler and more rapidly cooled exterior surfaces. The process requires precise control of the steel temperature at the time of quenching which may require cooling hot regions such as the junction of the flange and web. The result of the quenching and self-tempering is a harder and higher strength steel on the surface and a lower strength steel in the interior of the section. To evaluate the distribution of strength within the section, hardness readings were taken in same survey pattern used in the K-area evaluation. The QST sections showed a high hardness, Rockwell B 92-95, on the outside surface of the flanges away from the web and near the K-area of the web. The results of the center of the flange had a lower hardness, Rockwell B 75-78, than the conventionally rolled section. The conventionally rolled section showed almost no hardness variation within the cross section. These results were typical of all the specimens tested.

The areas of high hardness in the web were investigated to determine the notch toughness of the region. The purpose of this investigation was to determine if the high hardness of the K-area region was also a region of low toughness similar to the roller straightened sections. The toughness of these QST shapes was similar at the K-area and the center of the web. The high hardness of this region was not due to roller straightening and did not indicate degradation in toughness. The low hardness in the central part of the flange was correlated with a significant reduction in strength measured in the tensile specimens. The reduced strength of the central part of the flange is due to the reduced cooling rate during the quenching of the steel. Full flange thickness tensile specimens should be used to characterize the strength of these sections.

Through Thickness Strength of Rolled Section Flanges

The through thickness tensile strength of column sections was investigated by Dexter as part of the SAC research program. The purpose of the investigation was to evaluate the ability of the column flange to resist the through thickness forces produced by the beam flange. The through thickness direction, or “Z” direction of hot rolled steel products typically has a lower ductility, fracture toughness, and lower tensile strength than the other directions. The reductions are due to the heterogeneous distribution of the shape of the non-metallic inclusions in the steel. The size, distribution, and shape of manganese sulfide inclusions are the primary variables controlling the through thickness behavior of steels. The steel producer can improve the steel through thickness properties by reducing the number and size of the inclusions, by reducing the sulfur content of the steel or by controlling the shape of the inclusions. Lower sulfur content not only reduces the anisotropy of the steel but also increases the fracture toughness of the steel in all directions. The through thickness properties of the steels are typically evaluated using a through thickness tensile specimen in accordance with ASTM A770. Only two of the steels demonstrated through thickness ductility using this test procedure.

The behavior of these column steels to resist large through thickness stresses from a simulated beam flange was investigated using large welded specimens in an effort to better simulate the through thickness action on the column shapes. High strength, 100 ksi yield one inch thick plate was used to simulate the beam flange. This high strength plate was welded with a matching high strength, high toughness electrode. The purpose of using the higher strength flange and weld metal was to attempt to produce a failure in the column flange material. The smaller specimens with 4-inch wide flange plates were tested both quasi-statically and at a higher strain rate, to better simulate an earthquake loading rate. The larger width flange specimens, 12 inches wide, could only be tested at a quasi-static loading rate. The variables considered in the study besides plate width and strain rate included producer, yield strength, column foot weight from 174 to 605 lb./ft., flange bending/prying, heat input, and finally weld notches and toughness. In the initial tests no failures occurred in the column flange; the specimens failed by fracture of the high strength pull plates. In later tests the weld reinforcement was removed to increase the local stress and strain demands on the column flange. The only failures to occur outside of the pull plates were in specimens with high heat input, lower toughness welds with defects, low toughness E70-T4 weld root pass with the backing bar left in-place, or no continuity plates. The specimen without the continuity plates produced a divot type fracture at a 92 ksi average weld stress. No evidence of lamellar tearing was observable on the fracture surface of this test. In addition to the tests performed on new sections, one test was done on a W14x455 section removed from a building that suffered damage in the Northridge earthquake. The result was again a failure in the high strength pull plate.

The results of this experimental study indicate that connections with welds without a notch at the root, with reasonable toughness, and uniform distribution of stress across the flange width can sustain through thickness stresses that easily exceed the uniaxial tensile strength of the column flange material. The only indicator typically available to evaluate the through thickness behavior of a steel is the sulfur content of the steel that is reported on the mill test report. Other variables such as the size, distribution, and shape of the sulfide inclusions are also important but are not part of the normal product requirements for structural steel. All of columns had sulfur contents less than 0.035% with the majority below 0.030%. The smaller beam shapes in the test series had much higher sulfur contents. The column section through thickness specimens did not exhibit a reduction in through thickness properties or lamellar tearing. It appears that if the sulfur is limited to 0.030% present mill melting and rolling practices provide steels that will have through thickness performance adequate for welded beam to column connections. Barsom and Korvink presented data that indicated that the through thickness direction may have a 20% reduction in tensile strength and 10% reduction in yield strength from the longitudinal direction. No reduction in strength was evident in the SAC testing. In fact, all sections except one had a higher strength in the through thickness direction. The large scale through thickness tests confirmed that the sections included in Dexter’s tests did not have a weakness in the through thickness direction. Consequently, no reduction in strength is likely necessary for steels with similar sulfur content and rolling and melting practice. Older steels, particularly those with sulfur contents above 0.030%, may exhibit the reduction in strength found by Barsom. Lamellar tearing during welding or an earthquake may also occur. The sulfur content as well as the other elements of the base metal should be checked prior to making repair in older steels. A welding procedure which reduces strains in the through thickness directions should be employed and the column flange should be ultrasonically inspected after welding is completed.

CONCLUSIONS

As part of the FEMA/SAC program, extensive testing of the base materials typically used in moment frame construction in the United States was performed. This testing was performed to generate better understanding of the mechanical properties of structural wide flange shapes, so that this information could be used in the development of design guidelines for seismic actions. Some of the major conclusions from this work include the following:

1. The traditional ratio 0.95 remains a reasonable estimate for the ratio of the flange to web yield strength.

2. All of the test specimens met the A992 material maximum yield to tensile ratio of 0.85.

3. The testing indicates that a good estimates of F_y and F_{sy} are approximately 95% and 90% of $F_{ymill.}$ The observed value of F_u/F_{umill} was also about 95%.

4. The correlation between coupon and mill tests would be improved if the ASTM specifications were changed to require a specified yield strength for the structural steels. The yield strength would be determined using an offset method which would reduce the scatter in reported yield strengths/points and provide a statistic which has a better correlation with the actual yield strength of the steel.

5. The majority of the Charpy V-Notch tests indicated high levels of toughness in the members, except in the K-area, where substantial reductions were noted. No such dramatic changes were noted in A913 steels.

6. The through thickness properties of the column shapes tested indicates that large beam flange forces can generally be resisted without fracture.

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