The Behavior of A514 Steel Tension Members

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RECENT STUDIES into the behavior of bolted joints of high strength steels[1,2] have pointed out the importance of the net-to-gross cross-sectional ratio (A_n/A_g) upon the deformation behavior of such members. In particular, these studies show that because of the low ratio of ultimate vs. yield strength levels, usual detailing practice commonly will lead to the situation wherein the member will fail through the net section of the joint before yield is reached in the gross section. It is hypothesized that in this situation, wherein the main portion of the member is still elastic, fracture will occur before any significant amount of ductility is exhibited. Although tension members are commonly designed on an elastic basis,[3] it is nevertheless considered desirable that as this level is exceeded and the structure proceeds towards its ultimate load, capacity for distortion should still exist in the member.[4] In materials such as aluminum, where it is recognized that this capacity cannot be attained, a rather higher factor of safety is demanded.[5]

Although there is no reason to question the above hypothesis, all the reported tests on A514 steel tension members have been primarily concerned with joint behavior and not with the overall behavior of a member which contains a joint. Accordingly, a series of tests has now been carried out on members of A514 steel, each of which contains a joint. The ratio of net-to-gross cross-sectional area is the principal variable, and the tests show the effect of this ratio (A_n/A_g) upon member ductility. As an important preliminary to these tests, a considerable number of carefully controlled tension coupon tests on A514 steel were performed and these are also reported.

STANDARD COUPON TESTS

All material for the tests came from the same heat of steel. This was supplied by Canadian Heat Treaters Ltd. as their grade CHT 100. This meets all the requirements of ASTM A514 Grade C up to 1¼ in. and Grade K up to 2 in. thick, as well as ASTM A517 Grade C up to 1¼ in. and Grade K up to 2 in. thick. The plate used in these tests was ¼-in. thick. The specified physical properties of A514 steel plate up to 2½ in. thick are 100 ksi minimum yield strength, 115 to 135 ksi ultimate tensile strength, and 18 percent minimum elongation in a 2-in. gage length.

As has been well established,[6] the yield point and yield strength of structural steel are affected directly by the rate of straining. Furthermore, specifications commonly used[7] do not take account of the size effect of the coupons or of differences in testing machines. The only practical way of eliminating these variables and obtaining reproducible test values is to perform a static test in the plastic portion of the stress-strain response of the coupon. This is accomplished by stopping the crosshead movement of the testing machine to record the static yield stress level. This value is obtained for several points in the plastic range. Full details of the procedure are available elsewhere.[6]

A summary of the coupon test results is given in Table 1. A total of 22 tests were conducted, six at a rate of crosshead separation of 0.0020 in./min, 14 at 0.0040 in./min, and two at 0.0120 in./min. The highest of these values is approximately 1/10 of that permitted under ASTM A370.[7] The various rates of testing used herein did not result in any significant differences in the quantities reported and the results from all 22 coupons are, therefore, lumped together.

Table 1. Test Results—A514 Steel Tension Coupons

	Mean (ksi)	Standard Deviation (ksi)
Proportional Limit	115.67	3.64
Upper Yield Point	119.54	1.27
Lower Yield Point	119.00	1.11
Dynamic Yield Level	119.06	1.19
Static Yield Level	116.13	1.30
Ultimate Tensile Strength	124.96	1.49
Modulus of Elasticity	30.2×10^3	1.83×10^3
Strain-hardening Modulus	169.1	13.7

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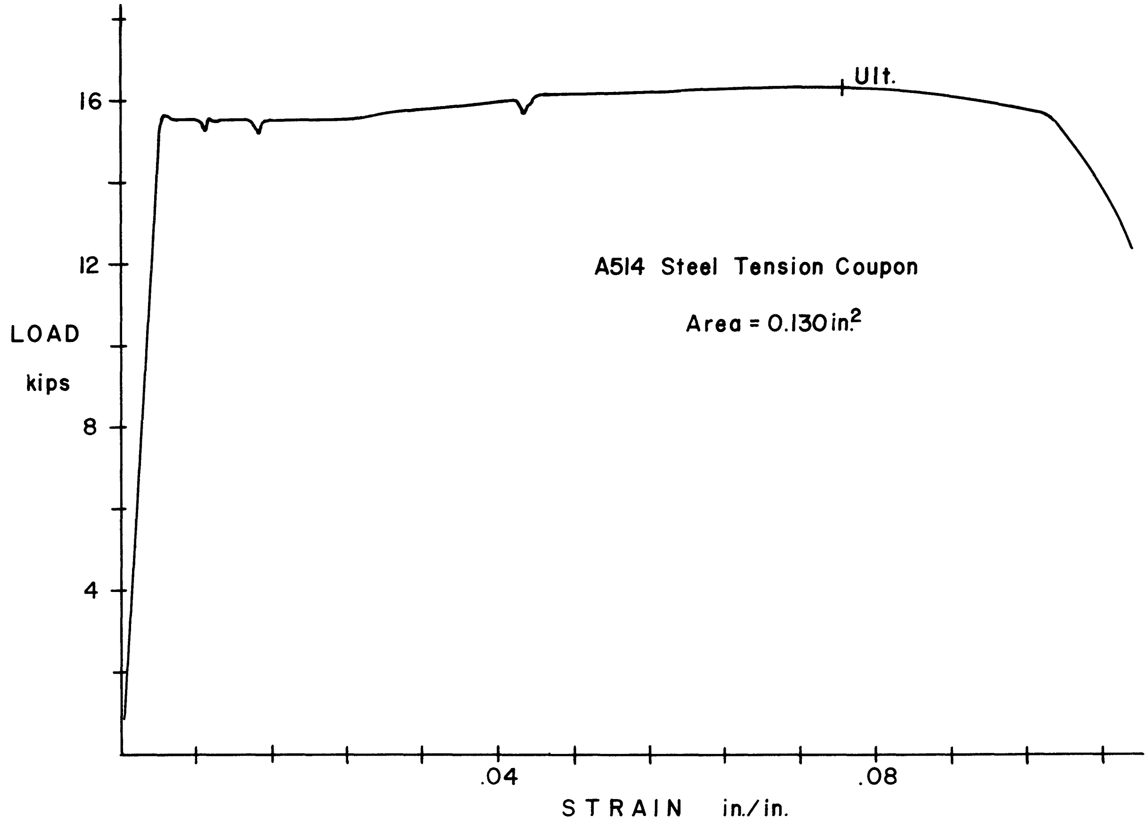

Fig. 1. Typical load-strain curve for tension coupon.

By trial, it was found that for the coupon size and machine size involved, and for these testing speeds, static values of yield stress level could be obtained by stopping the machine for ten minutes in the plastic range. At least two stoppages were made in the plastic range and usually one was taken in the strain-hardening range. As specified in ASTM A514,[8] the elongation of the standard tensile coupons was measured over a 2-in. gage length. A typical stress-strain curve is shown in Fig. 1. Notable is the fact that almost all coupons exhibited an upper yield point, even at these very slow testing speeds. Published curves[9] and test data from Lehigh University (unpublished) generally do not show an upper yield point. In addition, the published curves show the existence of little, if any, plastic zone; that is, strain-hardening starts immediately after initial yielding. For the tests reported herein, the strain at the onset of strain-hardening is approximately 5.8 times that at yield. The strain-hardening modulus is very low, however, the mean value being only 169.1 ksi. Figure 2 shows a stress-strain curve in which the record of stress was taken at a scale five times that of Fig. 1.

TESTS OF A514 STEEL MEMBERS

Member tests were conducted on four specimens, each made from the same heat of steel as used for the standard tensile coupons. The length of the member was 15 in. and each member contained a joint 2 in. long. The ratio of joint length to member length is thus of the same order of magnitude as could be expected in full-size structures.

The simulated joint consisted of a line of holes drilled along the center line of the member. Their diameter was such as to achieve the desired A_n/A_g ratio. For those specimens expected to yield only on the net section, the hole spacing was reasonably close to that occurring in structural practice (spacing was approximately five hole diameters). The fourth specimen, where yielding was expected on both net and gross cross-sections before the ultimate load was reached, had a hole spacing of ten hole diameters. Details of the members are listed in Table 2.

The unit strain occurring over the length of the joint, 2 in. in this case, was recorded using the extensometer attached to the testing machine. A direct plot of load against strain was thus obtained.

The unit strain occurring over the length of the member, 15 in., was obtained on an x-y plotter using a linear transducer which worked against the moving crosshead of the machine. Precautions were taken so that machine response was eliminated. Details of this, as well as other aspects of the test procedure, are available elsewhere.[10]

All member tests were conducted at a rate of crosshead separation of 0.002 in./min. No static readings were taken, as it was felt that this rate was sufficiently slow as to eliminate any appreciable dynamic effects. The readings of member strain were taken continuously until fail-

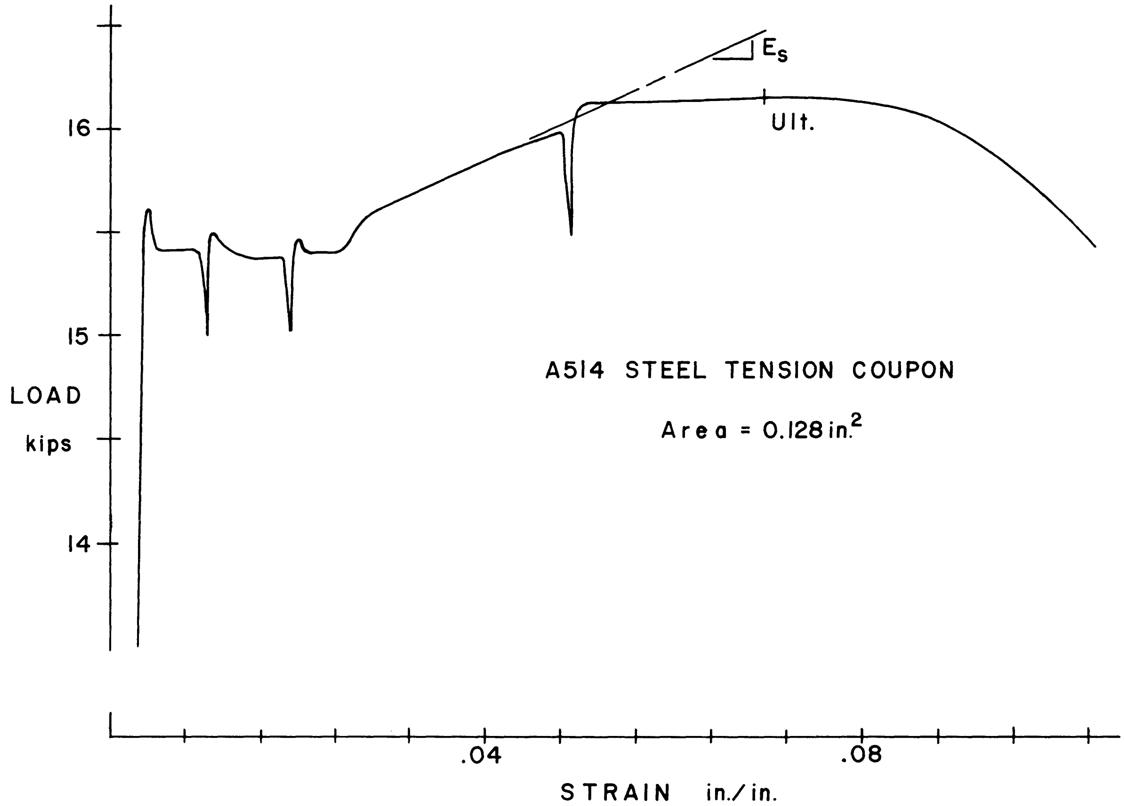

Fig. 2. Expanded portion of load-strain curve.

ure of the specimen. The extensometer measuring strain over the length of the joint was removed before failure on two of the specimens, but on the other two remained on until failure.

Table 3 summarizes the results of the member tests. Figure 3 shows the stress-strain curves for the two joints (**C** and **D**) where complete records were obtained. Figure 4 shows the stress-strain curves for the members.

As Table 3 indicates, the A_n/A_g ratio of the members varied from 0.80 to 0.90, in steps of 0.05. The main purpose was, of course, to illustrate the effects of this ratio upon the ductility of the member. Based upon minimum specified properties of A514 steel, this ratio should be at least 0.87 (i.e., 100 ksi/115 ksi), if yielding through the gross cross-section is to be attained before the ultimate load of the member is reached. A more accurate determination of the value of the critical ratio can be obtained from the measured material properties, however. Using the yield stress obtained from the coupons when loaded at a rate similar to that used for the members (119.1 ksi) and the measured ultimate strength (125.0 ksi), this ratio is (119.1/125.0 =) 0.95. If the static yield stress is used instead, the ratio would be (116.1/125.0 =) 0.93.

Figure 4 illustrates the very marked effect of the A_n/A_g ratio upon member ductility. Curves for members **A**, **B**, and **C** show that there is only slight increase in member ductility as the A_n/A_g ratio rises from 0.80 to 0.90, but remains below the critical value. As expected,

Table 2. Details of Members

Specimen	No. of Holes	Hole Spacing (in.)	Hole Diameter (in.)	Gross Area (in.^{2})	Net Area (in.^{2})	A_n/A_g
A	4	½	0.104	0.136	0.109	0.80
B	5	⅜	0.076	0.138	0.118	0.85
C	7	¼	0.052	0.139	0.125	0.90
D	7	¼	0.025	0.137	0.131	0.95

Table 3. Test Results of A514 Steel Members

Member	A_n/A_g	Ultimate Stress (ksi)		Ultimate Elongation (in.)	
		Net Area	Gross Area	Member*	Joint**
A	0.80	133.1	106.9	0.168	N.A.
B	0.85	130.6	111.7	0.165	N.A.
C	0.90	128.6	115.8	0.203	0.128
D	0.95	129.1	123.8	0.698	0.181

* Measured over 15-in. gage.
** Measured over 2-in. gage.

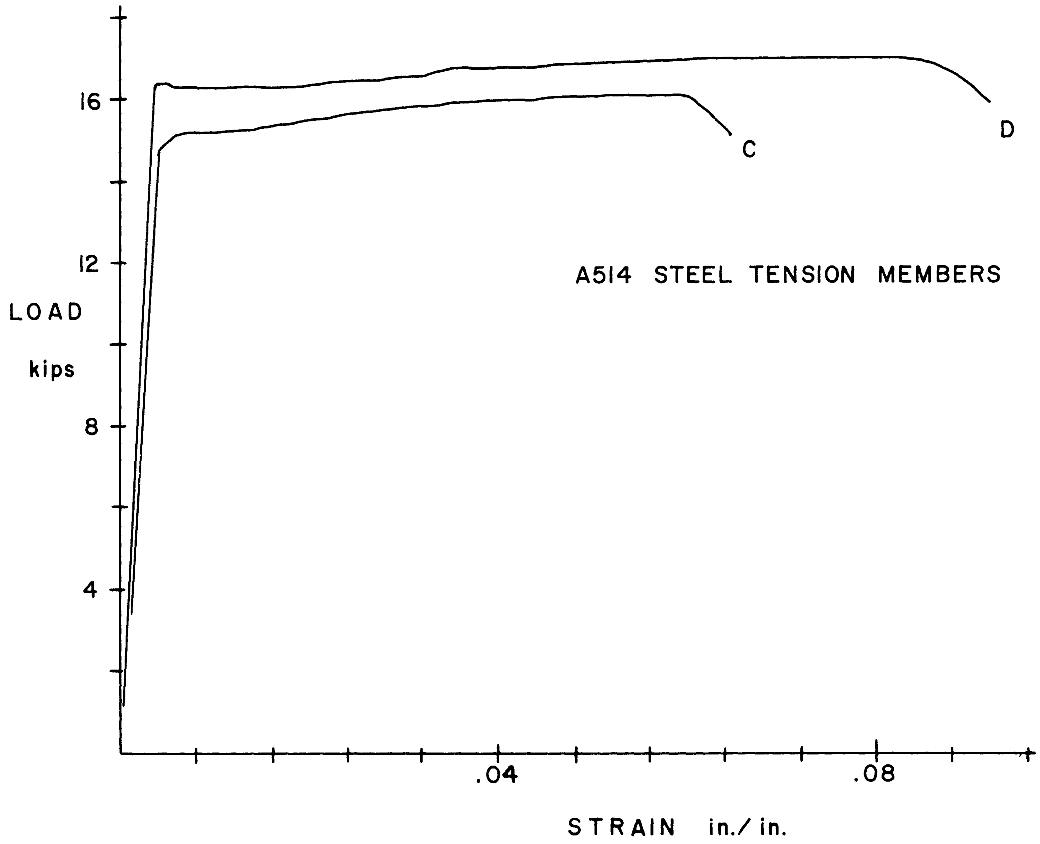

Fig. 3. Load vs. strain – joints.

and as is shown in Table 3, the stress on the gross cross-section of these members did not reach the yield level before the member failed by fracture on the net section.

Specimen **D** (A_n/A_g = 0.95) was proportioned at or near the critical value of A_n/A_g, depending upon which definition of yield stress is used in the calculations. The test showed that the gross section did, in fact, reach yield before the failure on the net section (see Table 3). The increase in member ductility is appreciable, the elongation of member **D** is, for example, 3.44 times that of the next most ductile member, **C**. This increase in member ductility with increasing A_n/A_g ratio is illustrated graphically in Fig. 5.

For the two members in which a complete record of joint strain was obtained, an assessment of the contribution of ductility provided by the joint itself can be made. If this contribution is a large proportion of the total, there might be no need to specify a critical A_n/A_g ratio.

The members on which an evaluation of this point can be made are **C** and **D**, which represent the specimens which bound the critical A_n/A_g ratio. Table 3 shows that the joint elongation was 63 percent of the member elongation for specimen **C** while the corresponding value for specimen **D** was only 26 percent. This indicates that, if member ductility is considered desirable, it is available to the major extent in the member, not in the joint.

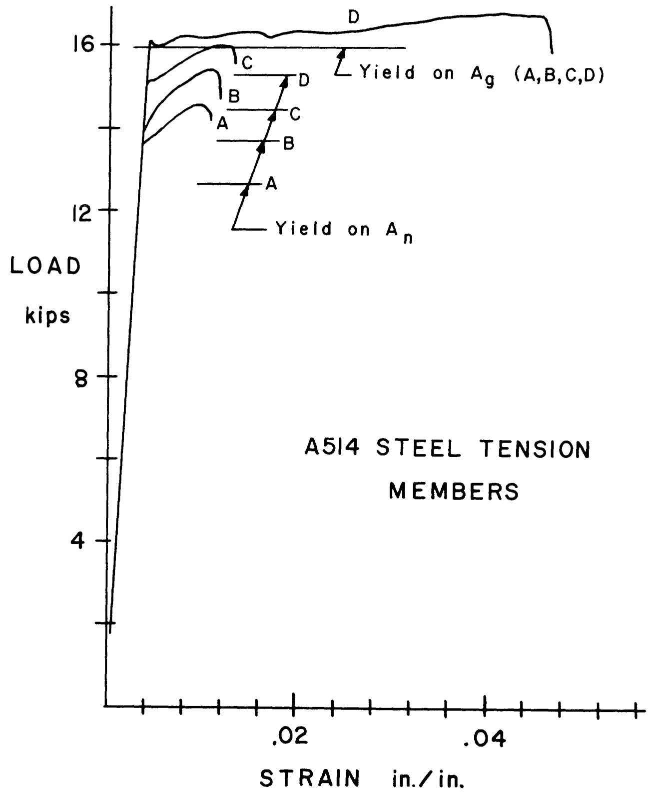

Fig. 4. Load vs. strain – members.

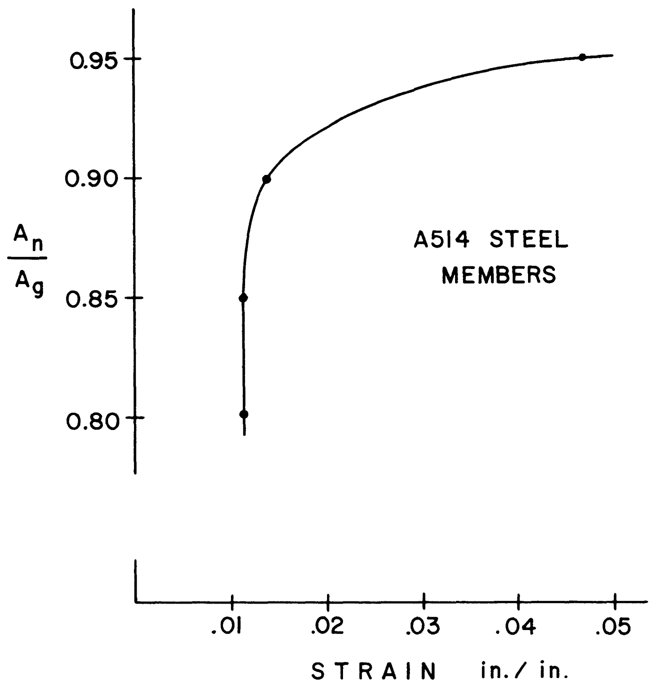

Fig. 5. A_n/A_g vs. strain – members.

It should be further noted from Table 3 and from Fig. 4 that all specimens were able to reach the ultimate strength of the material as obtained from the coupon tests. In fact, due to the strengthening effect of the hole, the coupon ultimate tensile strength was in all cases exceeded in the member test. Although any conclusions drawn from this point must take into account that the hole pattern here is very simple, this information is of considerable importance. If certain critical A_n/A_g ratios must be equalled or exceeded when specifying tension members of high strength steels, it obviously is essential to know whether or not these efficiencies can, in fact, be obtained. The joint efficiency in carbon steel structural joints is commonly limited to 0.85, for example.[11] The test results cited here, although limited to a simple hole pattern, would indicate that they can. Recent tests on full-size A514 steel bolted joints[2] have also shown that high efficiencies are obtainable. A maximum value of 0.91 was obtained in these tests.

SUMMARY AND CONCLUSIONS

The study reported herein has been particularly directed toward an examination of the effect of the net-to-gross area ratio upon the ductility of A514 steel members. Preliminary to this examination, carefully controlled tests on tension coupons were performed on A514 steel plate. The following conclusions are indicated as a result of the study:

1. A514 steel exhibits only a very short region of plastic strain.
2. The strain-hardening modulus of A514 steel is about 170 ksi; strain-hardening can be expected to start at a strain approximately six times the yield strain.
3. The spread between yield strength and ultimate strength of as-delivered A514 steel can be expected to be even less than that indicated by minimum specified values of these quantities.
4. The ductility of an A514 steel tension member is dependent upon the ratio of net-to-gross cross-sectional area. Members proportioned such that their A_n/A_g ratio is less than the ratio of yield strength to ultimate tensile strength of the material show a greatly decreased ductility as compared to members where this ratio is exceeded.

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