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Strength and Ductility of A572 (Grade 65) Steel Structures

La résistance et la ductilité des structures en acier A572 (grade 65)

Festigkeit und plastische Verformungsfähigkeit der Stahlkonstruktionen aus Stahl A572 (Grad 65)

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1. Introduction

A572 (Grade 65) steel, a low-alloy columbium-vanadium steel, is the highest strength steel for which the use of plastic design method is permitted by the American Institute of Steel Construction Specification. The properties of this steel are specified in ASTM Specification A572-74b which covers all six grades of the A572 steel with minimum yield values of 42, 50, 55, 60, and 65 ksi.

Many of the problems encountered in the design of building frames using high strength steels relate to buckling or to instability phenomena; namely, local buckling of cross sections, instability of beam-columns, lateral-torsional buckling of beams and beam-columns, and overall instability of frames. These problems occur in structures made of low carbon steel also but become more dominant as the yield stress of the material increases.

Consider local buckling as an example. Local buckling can occur either in the flange or in the web of a cross section, depending on the width-to-thickness ratios of the elements. For steels up to 50 ksi yield, limiting ratios have been developed in order to ensure that large strains can take place without buckling. This, in turn, assures adequate deformation capacity which is one of the requirements for plastic design. The formula defining the limiting ratios, derived primarily for lower strength steels, have been extended to include high strength steels. Experimental data are needed to confirm this extension.

A research program has been carried out at Lehigh University to study the mechanical properties of the steel and the behavior of some simple structures in the inelastic range with emphasis on local and lateral buckling.

2. Tensile Properties

The required minimum tensile properties (mill tests) of A572 (Grade 65) steel are: yield point σ_y = 65 ksi, tensile strength σ_u = 80 ksi, and elongation = 15% over an 8" gage. As part of the research program, 52 tension tests were conducted, the details of which have been documented elsewhere (1).

Figure 1 shows the stress-strain curve obtained from plotting average values of the significant quantities. The static yield stress σ_{ys} is the most important property of steel and plays a significant role in plastic design. It is the yield stress value at zero strain rate. In the tests, the machine was stopped for five minutes at a strain of approximately 0.005 in/in and σ_{ys} was recorded. Its average value was 62.1 ksi. The corresponding dynamic yield stress σ_{yd} at the testing speed of 0.025 ipm was found to be 64.6 ksi. Simulated mill tests at 0.5 ipm gave an average value of 69.3 ksi. The tensile strength σ_u averaged 85.7 ksi. The value of strain ε_{st} at which strain-hardening commenced was 0.0186 in/in which is about 9 times the yield strain ε_y. The average value of percentage elongation in 8" gage length and percentage reduction of cross-sectional area were 21.5 and 51.0 respectively.

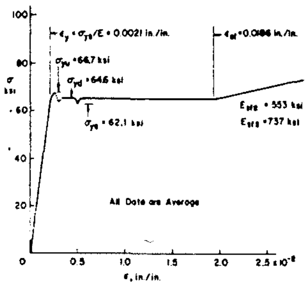

FIG. 1 IDEALIZED STRESS-STRAIN CURVE FROM TENSION TEST

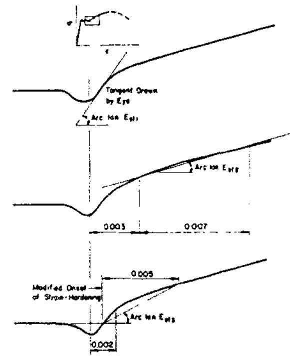

FIG. 2 SKETCH DEFINING E_{st1}, E_{st2} and E_{st3}

3. Strain-Hardening Modulus

The value of strain-hardening modulus E_{st} is important in the study of inelastic buckling of structural members. Three approaches have been used to evaluate E_{st} in this series of tests, as shown in Fig. 2. The modulus E_{st1} is the instantaneous value as measured by a tangent to the curve at the point where strain-hardening commences. This tangent is often difficult to determine consistently. Values of E_{st1} from different tests for the same material are likely to exhibit a wide scatter.

The modulus E_{st2} was measured as the chord slope between strains ε_{st}=0.003 and ε_{st} = 0.010. This specific range was chosen as it confines measurements to a fairly linear and stable range of the stress-strain curve and eliminates the initial erratic portion. Since measurements are made at a greater value of strain than in other methods, E_{st2} provides a conservative value.

In the "Column Research Council approach" (2), the modulus E_{st3} is the average value in the range ε_{st} to ε_{st} + 0.005, where ε_{st} is defined as the strain corresponding to the intersection on the stress-strain curve of the yield stress level in the plastic range with the tangent to the curve in the strain-hardening range. This tangent is drawn as the average value in an increment of 0.002 in/in after the apparent onset of strain-hardening. The attempt is to eliminate the effect of the frequently encountered drop in load immediately prior to the apparent onset of strain-hardening. E_{st3}, however, includes the effect of the steep initial slope and is hence less conservative than E_{st2}.

E_{st1} values varied, in this series, from 393 ksi to 9825 ksi. The straining process in the region of strain-hardening and the inherent difficulties in determining this function have contributed to the wide scatter of values. E_{st2} values averaged 553 ksi (min. 322 ksi, max. 775 ksi). E_{st3} values ranged from 382 ksi to 1160 ksi with an average of 771 ksi.

4. Compressive Properties

Compression tests were performed on ten specimens whose dimensions were generally in accordance with ASTM standards. Minor deviations, however, were necessary in order to be able to test the full thickness of the flange or web element and still use a special strain-recording instrument of fixed gage length 0.5" in the plastic range (3).

A typical stress-strain curve is shown in Fig. 3. The average values for the three most significant quantities are: σ_y = 65.14 ksi, ε_{st} = 0.0086 in/in, E_{st2} = 820 ksi. For comparison, three additional tests were performed on A441 steel specimens. The corresponding average values are: σ_y = 55.8 ksi, ε_{st} = 0.0147 in/in, E_{st2} = 815 ksi.

In general, strain ε_{st} is smaller than in tension tests while modulus E_{st2} is larger. The higher modulus is partly due to Poissòn's ratio effect since the cross-sectional area in a compression test increases. However, the increase in E_{st} is not fully accounted for even with the assumption of 0.5 for Poisson's ratio in the inelastic range.

5. Residual Stresses

Residual stresses, determined by the method of sectioning (3), in a W12 x 19 shape are shown in Fig. 4. The stresses are seen to relatively small and there is no evidence of cold-straightening. In A36 steel, it has been found that the maximum residual stress at flange tips is about 0.3 σ_y or approximately 10 ksi (4). The present study shows that the magnitude of the maximum residual stress does not increase with yield stress level. This was also found to be true for other types of high strength steels.

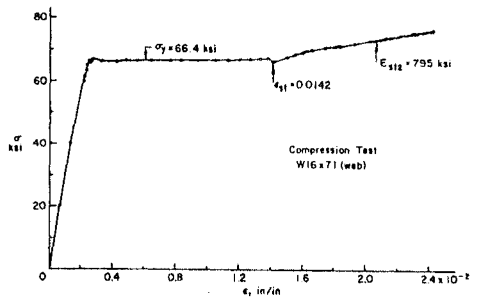

FIG. 3 STRESS-STRAIN CURVE FROM COMPRESSION TEST

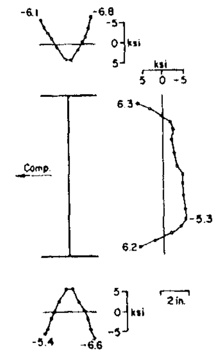

FIG. 4 RESIDUAL STRESS DISTRIBUTION IN W12 x 19 SHAPE

6. Stub Column Tests

Stub column tests were used to examine the local buckling characteristics of the plate elements under uniform compression (2). Previous research on lower strength steels has based the geometry of the plate elements on the criterion that the shape must undergo a strain at least equal to the strain-hardening strain without their buckling locally (5). The relevant formulas have been extended to include A572 (Grade 65) steel. Using these formulas and assuming σ_y = 65 ksi, E_{st} = 600 ksi, Poisson's ratio ν = 0.3 and E = 29,000 ksi, the required flange slenderness ratio b/t is 11.8 and the web slenderness ratio d/w is 30.6. For the first test, a W16 x 71 shape was selected since its listed properties b/t = 10.75, d/w = 33.2 are fairly close to the requirements. The actual ratios were 10.72 and 32.50 respectively. Web buckling was, therefore, anticipated to precede flange buckling.

The test results are shown in Fig. 5. The web buckled at a strain of 0.0073 in/in, followed almost immediately by flange buckling at a strain of 0.0079 in/in. These strains are much lower than ε_{st} in tension (0.0186 in/in) but close to ε_{st} in compression (0.0086 in/in). However, the load continued to be sustained until the strain reached 0.038 in/in.

Results of two other tests on modified W10 x 54 shapes are shown in Fig. 6. The flanges were machined down to yield b/t ratios of 11.8 and 13.3 for the two tests, while the web ratio d/w was maintained at 27.5. In the test with b/t = 11.8, the flanges buckled at a strain of 0.010 in/in and the webs at 0.015 in/in. Strain-hardening was evident later (E_{st} = 950 ksi) and the load began to drop off past the strain of 0.025 in/in. The third test with b/t = 13.3 showed nearly the same trends. Web buckling began at 0.006 in/in followed by flange buckling at 0.007 in/in with other details identical.

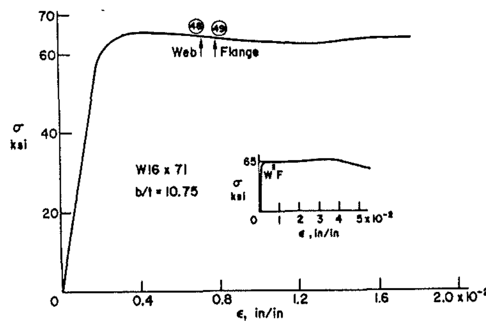

FIG. 5 STRESS-STRAIN CURVE FROM STUB COLUMN TEST - W16 x 71 SHAPE

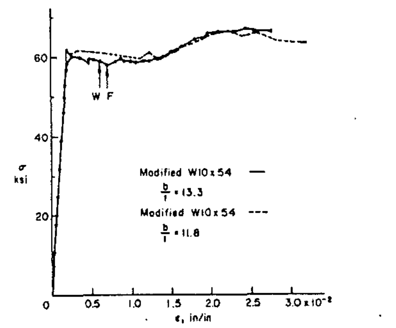

FIG. 6 STRESS-STRAIN CURVE FROM STUB COLUMN TEST - W10 x 54 SHAPE

The results show that local buckling occurred in Grade 65 steels at a strain smaller than that predicted by the theories developed for lower strength steels. Buckling, however, did not precipitate failure and resulting reduction in strength.

7. Beam Tests

Two beams fabricated from a length of W12 x 19 shape were tested, one under moment gradient and the other under uniform moment. Details are given elsewhere (6). Available theories indicate that the slenderness ratios b/t and d/w should be limited to 11.2 and 52.1, respectively, for σ_y = 65 ksi and E_{st} = 600 ksi. The W12 x 19 shape is one of the few having nearly these same ratios.

The beam under moment gradient had a simply supported span of 10'-5" and was loaded at the center. Lateral braces were provided at midspan, supports and at 37.5" on either side of midspan, as against the requirement of 46 r_y or 38.5" according to available theories (7).

The non-dimensionalized moment M/M_p against midspan deflection δ/δ_p is given in Fig. 7. The terms M and δ are the moments and deflections, M_p is the theoretical plastic moment, and δ_p is the deflection at $M = M_p$, assuming ideal elastic behavior. Strain-hardening setting in soon after the plastic moment was reached at the center. Local buckling in the compression flange near midspan was visible at load No. 9. The compression flange also displaced laterally at load No. 13.

The rotation capacity of a beam is usually defined as $R = (\theta/\theta_p)-1$ where θ is the sum of the end rotations at which the moment drops below $0.95\ M_p$ and θ_p is the rotation at $M = M_p$. The R value is 3.1 in this test. A precise comparison of R with those obtained in other tests (for lower strength steels) is difficult, since different shapes and unbraced spans have been used. However, it can be said that the rotation capacity of Grade 65 steel beam is less than that for other beams.

The beam under uniform moment was loaded at quarter points over a simple span 15' long. Lateral braces were spaced, in close accordance with present theories (8), at load points, supports and approximately 13" apart between load points. Outside the uniform moment region, two braces were used, 37.5" from each load.

The results are shown in Fig. 8. The discontinuity of the curve between load Nos. 6 and 11 is due to a slip in a lateral brace and subsequent repair. Local buckling was visible at load No. 15 and the compression flange began to deflect laterally. At load No. 16, the lateral deflection was about 0.6 in. Unloading was caused by severe lateral buckling as a result of local buckling of the compression flange. The computed rotation capacity R in this test was 4.8, a value smaller than in comparable structures of lower strength steels.

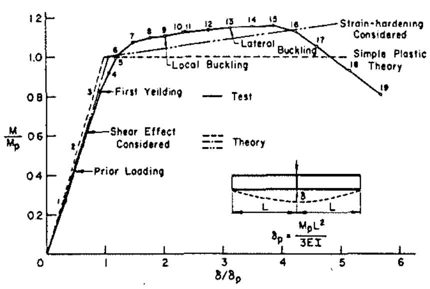

FIG. 7 BEAM UNDER MOMENT GRADIENT

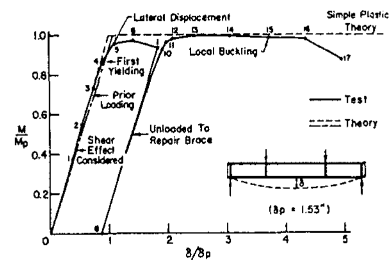

FIG. 8 BEAM UNDER UNIFORM MOMENT

8. Conclusions

A572 (Grade 65) steel exhibits mechanical properties in the inelastic region similar to those of structural carbon steel. The use of E_{st2} for strain-hardening modulus represents a new approach to obtain a more realistic, as well as conservative, value of this property for use in situations where the material is strained into the strain-hardening range. The value of E_{st} in compression is higher than in tension. Since buckling phenomena are associated with compression, a compression test appears to be the appropriate way of obtaining this modulus.

Residual stresses in shapes of higher strength steels are nearly the same in magnitude as in lower strength steels, and are thus independent of yield stress level. Hence, the influence of residual stresses decreases with increase in yield stress.

It was possible to extend the available theories developed for local and lateral buckling to Grade 65 steel although the assumptions of the theory are not fully borne out. This is because the post buckling strength of Grade 65 steel is considerable and reliable to the extent that it offsets any loss of strength as a consequence of premature buckling. Reference 9 contains the design recommendations developed for structures made of this steel.

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SUMMARY

The results of a study of the mechanical properties of ASTM A572 (Grade 65) steel and of the behaviour of simple structures made of this steel are presented. A new approach to define strain-hardening modulus is proposed. This modulus is significantly higher when it is determined from a compression test than from a tension test. Results of experiments on stub columns and beams show substantial post-buckling strength in the inelastic range.

RESUME

Les résultats d'une étude sur les propriétés mécaniques de l'acier désigné par ASTM A572 (grade 65) et sur le comportement de structures simples construites avec cet acier sont présentés. Une nouvelle méthode pour définir le module d'écrouissage est proposée. Ce module déterminé par des essais de compression est nettement plus grand que celui obtenu par des essais de traction. Les résultats des essais sur des colonnes courtes et sur des poutres indiquent que la résistance au flambage est importante dans la région inélastique.

ZUSAMMENFASSUNG

Die Ergebnisse eines Studiums über mechanische Eigenschaften des ASTM A572 (Grad 65) Stahles und das Verhalten der einfachen Konstruktionen aus diesem Stahl beschrieben. Es wurde ein neuer Versuch zur Definition des Verformungsmoduls dieses Stahles im Verfestigungsbereich vorgeschlagen. Dieser Modul ist wesentlich höher, wenn er aus Druckproben, jedoch nicht aus Zugproben bestimmt wird. Die Ergebnisse der Untersuchungen an kurzen Säulen und Balken haben gezeigt, dass der Stahl wesentliche überkritische Reserven im nichtelastischen Bereich aufweist.

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La Resistance et la Ductilite des Structures en Acier A572 (Grade 65)

Festigkeit und plastische Deformationkapazitat der Konstruktionen aus Stahl A572 (Grad 65)

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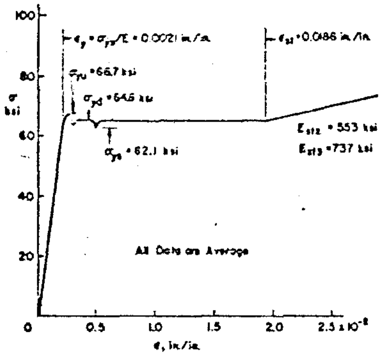

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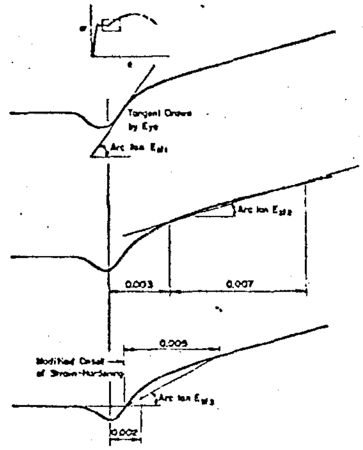

FIG. 2 SKETCH DEFINING E_{st1}, E_{st2} and E_{st3}

3. Strain-Hardening Modulus

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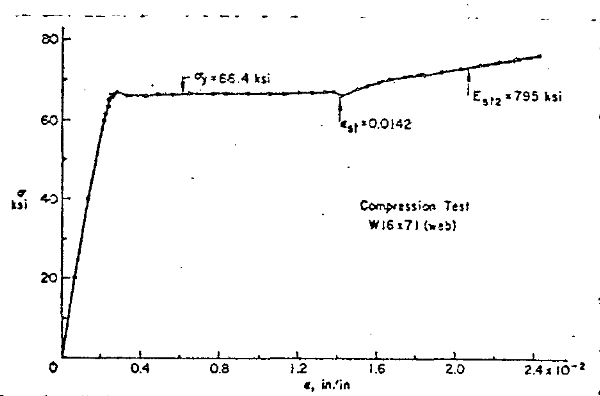

FIG. 3 STRESS-STRAIN CURVE FROM COMPRESSION TEST

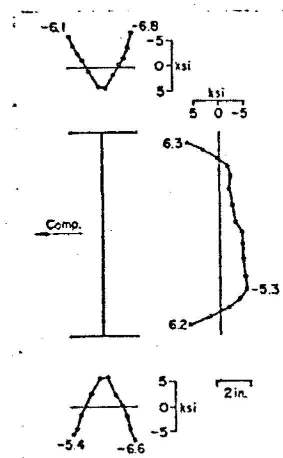

FIG. 4 RESIDUAL STRESS DISTRIBUTION IN W12 x 19 SHAPE

6. Stub Column Tests

Stub column tests were used to examine the local buckling characteristics of the plate elements under uniform compression (2). Previous research on lower strength steels has based the geometry of the plate elements on the criterion that the shape must undergo a strain at least equal to the strain-hardening strain without their buckling locally (5). The relevant formulas have been extended to include A572 (Grade 65) steel. Using these formulas and assuming σ_y = 65 ksi, E_{st} = 600 ksi, Poisson's ratio ν = 0.3 and E = 29,000 ksi, the required flange slenderness ratio b/t is 11.8 and the web slenderness ratio d/w is 30.6. For the first test, a W16 x 71 shape was selected since its listed properties b/t = 10.75, d/w = 33.2 are fairly close to the requirements. The actual ratios were 10.72 and 32.50 respectively. Web buckling was, therefore, anticipated to precede flange buckling.

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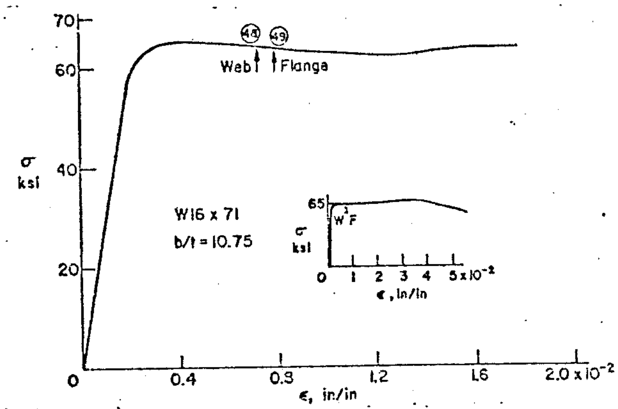

FIG. 5 STRESS-STRAIN CURVE FROM STUB COLUMN TEST - W16 x 71 SHAPE

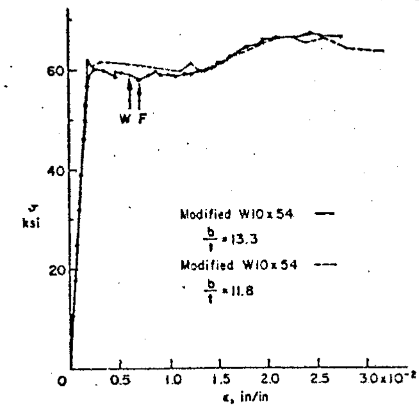

FIG. 6 STRESS-STRAIN CURVE FROM STUB COLUMN TEST - W10 x 54 SHAPE

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7. Beam Tests

Two beams fabricated from a length of W12 x 19 shape were tested, one under moment gradient and the other under uniform moment. Details are given elsewhere (6). Available theories indicate that the slenderness ratios b/t and d/w should be limited to 11.2 and 52.1, respectively, for σ_y = 65 ksi and E_{st} = 600 ksi. The W12 x 19 shape is one of the few having nearly these same ratios.

The beam under moment gradient had a simply supported span of 10'-5" and was loaded at the center. Lateral braces were provided at midspan, supports and at 37.5" on either side of midspan, as against the requirement of 46 r_y or 38.5" according to available theories (7).

The non-dimensionalized moment M/M_p against midspan deflection δ/δ_p is given in Fig. 7. The terms M and δ are the moments and deflections, M_p is the theoretical plastic moment, and δ_p is the deflection at $M = M_p$, assuming ideal elastic behavior. Strain-hardening setting in soon after the plastic moment was reached at the center. Local buckling in the compression flange near midspan was visible at load No. 9. The compression flange also displaced laterally at load No. 13.

The rotation capacity of a beam is usually defined as $R = (\theta/\theta_p)-1$ where θ is the sum of the end rotations at which the moment drops below $0.95\ M_p$ and θ_p is the rotation at $M = M_p$. The R value is 3.1 in this test. A precise comparison of R with those obtained in other tests (for lower strength steels) is difficult, since different shapes and unbraced spans have been used. However, it can be said that the rotation capacity of Grade 65 steel beam is less than that for other beams.

The beam under uniform moment was loaded at quarter points over a simple span 15' long. Lateral braces were spaced, in close accordance with present theories (8), at load points, supports and approximately 13" apart between load points. Outside the uniform moment region, two braces were used, 37.5" from each load.

The results are shown in Fig. 8. The discontinuity of the curve between load Nos. 6 and 11 is due to a slip in a lateral brace and subsequent repair. Local buckling was visible at load No. 15 and the compression flange began to deflect laterally. At load No. 16, the lateral deflection was about 0.6 in. Unloading was caused by severe lateral buckling as a result of local buckling of the compression flange. The computed rotation capacity R in this test was 4.8, a value smaller than in comparable structures of lower strength steels.

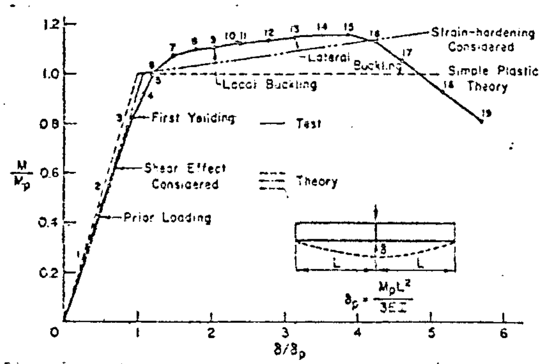

FIG. 7 BEAM UNDER MOMENT GRADIENT

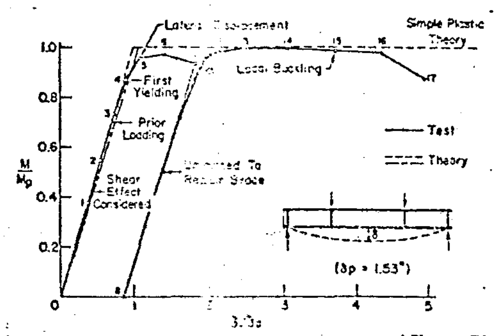

FIG. 8 BEAM UNDER UNIFORM MOMENT

8. Conclusions

A572 (Grade 65) steel exhibits mechanical properties in the inelastic region similar to those of structural carbon steel. The use of E_{st2} for strain-hardening modulus represents a new approach to obtain a more realistic, as well as conservative, value of this property for use in situations where the material is strained into the strain-hardening range. The value of E_{st} in compression is higher than in tension. Since buckling phenomena are associated with compression, a compression test appears to be the appropriate way of obtaining this modulus.

Residual stresses in shapes of higher strength steels are nearly the same in magnitude as in lower strength steels, and are thus independent of yield stress level. Hence, the influence of residual stresses decreases with increase in yield stress.

It was possible to extend the available theories developed for local and lateral buckling to Grade 65 steel although the assumptions of the theory are not fully borne out. This is because the post buckling strength of Grade 65 steel is considerable and reliable to the extent that it offsets any loss of strength as a consequence of premature buckling. Reference 9 contains the design recommendations developed for structures made of this steel.

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Summary

The results of a study of the mechanical properties of ASTM A572 (Grade 65) steel and of the behavior of simple structures made of this steel are presented. A new approach to define strain-hardening modulus is proposed. This modulus is significantly higher when it is determined from a compression test than from a tension test. Results of experiments on stub columns and beams show substantial post-buckling strength in the inelastic range.

Résumé

Les résultats d'une étude sur les propriétés méchaniques de l'acier désigné par ASTM A572 (Grade 65) et sur le comportement des structures simples fabriquées avec cet acier sont présentés ici. Une nonvelle méthode pour définir la module d'écrouissage est proposée. Cette module comme déterminée par des essais de compression est signifiquemment plus grande que celle obtenue par des essais de tension. Les résultats des essais sur des colonnes courtes et sur des poutres indiquent que la résistance au flambage est substantielle dans la région inélastique.

Zusammenfassung

In der Bericht die Ergebnisse eines Studiums über mechanische Eigenschaften des ASTM A572 (Grad 65) Stahles und das Verhalten der einfachen Konstruktionen aus diesen Stahl sind geschrieben. Es wurde ein neuer Versuch der Definition des Moduls dieses Stahles in dem Verfestigungsbereich vorgeschlagen. Dieses Modul ist wesetlich höher, wenn es aus Druckprüfung aber night aus Zugprüfung bestimmt wird. Die Ergebnisse der Untersuchungen der kurzen Säulen und Balken haben gezeight, dass der Stahl nach dem Ausknicken immer eine wessentliche Festigkeit in dem nichtelastischen Bereich aufweist.