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The Modulus of Elasticity of Steel - Is It 200 GPa?

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THE MODULUS OF ELASTICITY OF STEEL - IS IT 200 GPa?

by M. Mahendran*

Summary

In cold-formed steel construction, the use of a range of thin, high strength steels (0.35 mm thickness and 550 MPa yield stress) has increased significantly in recent times. A good knowledge of the basic mechanical properties of these steels is needed for a satisfactory use of them. In relation to the modulus of elasticity, the current practice is to assume it to be about 200 GPa for all steel grades. However, tensile tests of these steels have consistently shown that the modulus of elasticity varies with grade of steel and thickness. It was found that it increases to values as high as 240 GPa for smaller thicknesses and higher grades of steel. This paper discusses this topic, presents the tensile test results for a number of steel grades and thicknesses, and attempts to develop a relationship between modulus of elasticity, yield stress and thickness for the steel grades considered in this investigation.

1. Introduction

The use of cold-formed steel structural members in the building and construction industry has increased rapidly in recent times. Cold-formed steel members have the advantages of being high strength and light weight and they can be used very efficiently in many applications where conventional hot-rolled members are uneconomical. A very good example of this is steel framed housing (see Figure 1).

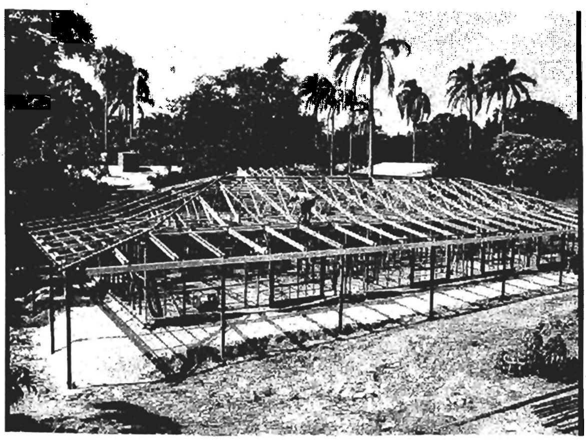

Figure 1. Application of Cold-formed Steel Construction - Steel Framed Housing

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Cold-formed steel members are also used as roof and wall systems of industrial, commercial and farm buildings, steel racks, plane and space trusses, tubular structures and silos (Hancock, 1994). Although the use of thinner and high strength steel in cold-formed steel construction provides a range of advantages, it will cause different failure modes and deformation to those of conventional thicker hot-rolled steels and therefore separate design codes are required (SA, 1988).

In the Australian building industry a range of thin, high strength steels are being used in the cold-formed steel construction. They are manufactured according to AS1397: Steel Sheet and Strip - Hot-dipped zinc-coated or aluminium/zinc-coated (SA, 1993) and AS1163: Structural Steel Hollow Sections (SA, 1991). Table 1 presents the minimum yield stresses and tensile strengths for the steels manufactured to these standards. The AS1163 steels with the highest grade of 450 MPa and the minimum thickness of 1.6 mm are essentially used for hollow sections (circular, rectangular and square hollow sections). On the other hand the AS1397 steels are much higher grades (G550) and thinner steel (0.35 mm) and are commonly used in a range of cold-formed structural applications. The designation of AS1397 steels includes a symbol G to indicate that mechanical properties of these steels have been achieved by in-line heat treatment prior to hot-dipping whereas that of AS1163 steels include a symbol C to indicate cold-forming. It is industry practice to use Base Metal Thickness (bmt), that is, metal thickness without coating in steel specification instead of Total Coated Thickness (tct) which includes coating. Usually the coating thickness is about 0.05 mm and cannot be ignored for steels thinner than 1.0 mm.

Table 1. Material Properties of Steels according to AS1163 and AS1397
(From Hancock, 1994)

Australian Standard	Grade Designation	Minimum Yield Stress (MPa)	Minimum Tensile Strength (MPa)	Min. Elongation (%) on 50 mm gauge length (t < 3 mm)
AS1163	C250, C250LO	250	320	22 (CHS), 18 (RHS)
(1991)	C350,C350LO	350	420	20 (CHS), 16 (RHS)
	C450, C450LO	450	500	16 (CHS), 14 (RHS)
AS1397	G250	250	320	25
(1993)	G300	300	340	20
	G350	350	420	15
	G450	450	480	10
	G500	500	520	8
	G550	550	550	2

Note: Chemical composition of these steels are given as a percentage of Carbon, Manganese, Phosphorus, Sulfur (AS1397: SA, 1993):

G250 - 0.12, 0.50, 0.03, 0.035
G300, G350 - 0.30, 1.60, 0.10, 0.035
G450, G500, G550 - 0.20, 1.20, 0.04, 0.030

As seen in Table 1, the standards do not specify the modulus of elasticity (E) or Poisson's ratio for any grade of steel. They have been conveniently assumed to be 200 GPa and 0.3 in many design and research projects. These values were initially obtained for thicker mild steel plates of Grade 250 or less. A number of text books in this field suggest that these elastic properties of steel are practically the same for all grades of steel (see Figure 2 from Davis et al., 1982). The well-known text book by Gere and Timoshenko (1991) gives a range of 190 to 210 GPa for the modulus of elasticity of steel E. However, researchers have often measured higher E values for thinner, higher strength steels. This has been often attributed to inaccurate testing procedures. But there is a possibility that the manufacturing processes and thin steels which increase the yield stress of steel do increase the E values as well. This project therefore investigated this problem using tension tests of steel sheets manufactured according to AS1397 (SA, 1993), and the results are presented in this paper.

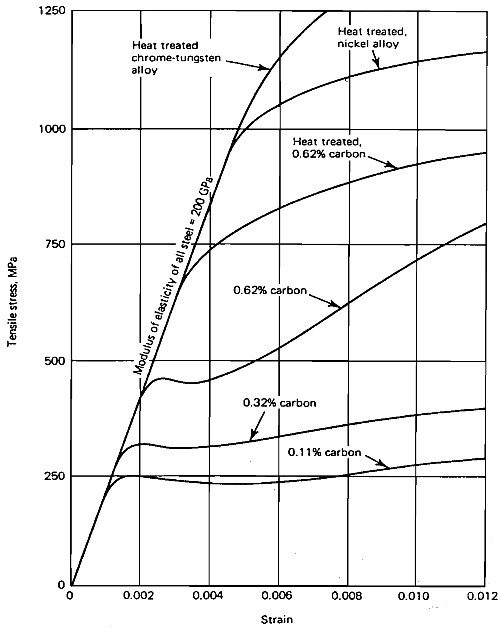

Figure 2. Idealised Stress-Strain Curves for Steel (From Davis et al., 1982)

2. Modulus of Elasticity

This investigation is aimed at determining whether the modulus of elasticity (E) is constant for all grades and thicknesses of steel using laboratory experiments of tensile steel specimens. Table 2 presents the reported results on E values in recent research papers. Some of the reports do not indicate whether the base metal thickness (bmt) or the total coated thickness (tct) was used in their strength calculations or whether coating was removed from tensile specimens before testing. However, Table 2 shows that there is a variation in E values within the range of 190 to 230 GPa.

Table 2. Reported Modulus of Elasticity Values for Steel

Minimum Yield Stress (MPa)	Measured Yield Stress (MPa)	Nominal Thickness (mm)	Modulus of Elasticity E (GPa)			Reference
			bmt	tct	bmt or tct	
550	653	0.6	230	220		Bernard et al. (1992)
550	670	0.75			218	Mahendran (1995)
350	392	6.0			208	Sully and Hancock (1994)
-	324	2.5			206.7	Chen et al. (1994)
-	420	1.3			190	Davies et al. (1994)

Stress-strain curves can be obtained directly from standard tensile tests carried out according to AS1391 (SA, 1991). The slope of the linear region of these curves will then give the required modulus of elasticity (E). However, this procedure may not give accurate answers. Therefore this investigation used tensile coupons which were strain gauged on both sides. Tensile tests were carried out on different grades (G250, G450, G500 and G550) and thicknesses (0.42 to 1.6 mm) of steel using the procedure given in AS1391 (SA, 1991). Tensile coupons were 25 mm wide and 300 mm long. Since the main objective was to determine E values instead of yield stress, a constant width specimen was used. Figure 3 shows a tensile coupon being tested on the Tinius Olsen Testing Machine. A special clamping device was used because of the thin steel specimens. Although there are other methods such as ultrasonic and resonance test methods to determine the E value of thin steel, the method of using strain gauged tensile specimens was used in this investigation because of simplicity of test method and unavailability of specialist equipment.

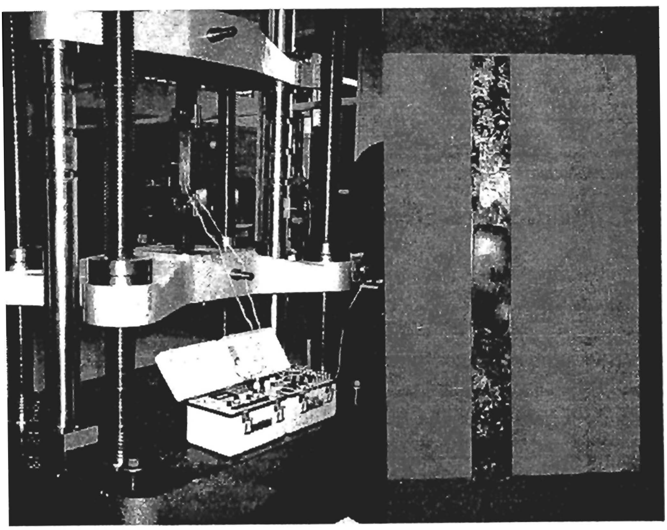

Figure 3. Tensile Test Set-up

For each steel grade and thickness, tensile tests were carried out at a rate of 0.1 to 0.3 mm / minute to 80% of yield stress levels on specimens with and without coating. For the latter case, the zinc or aluminium/zinc coating was removed from the middle of the specimen using Hydrochloric acid before installing the strain gauges. As tensile loading was increased strain gauge readings from both sides of specimens were recorded at regular intervals to give a minimum of 10 readings in each case. Average strain values and measured stresses based on base metal thickness (bmt) were then entered into the Microsoft Excel program and the modulus of elasticity E was calculated using the LINEST function based on the method of least squares. For each specimen, loading was repeated at least once and the modulus of elasticity values obtained were averaged. In most cases, the difference in E values was quite small, which gave confidence in the results obtained. Table 3 presents the results from these non-destructive tensile tests.

Table 3. Results of Tensile Testing

Steel+ Grade	Thickness (mm)			Modulus of Elasticity E (GPa)				
(MPa)	Spec (1)	tct (2)	bmt (3)	Transv. UC/bmt	Transv. C/bmt	Longl. UC/bmt	Longl. C/bmt	Est. Diff.
250 (367)	0.4	0.44	0.39	215	230	211	220	8
250 (365)	0.6	0.59	0.54	215	224	208	218	6
250 (327)	1.0	0.98	0.93	212	217	206,203^{x}	216	3
250 (310)	1.2	1.17	1.13	216	-	-	211	2
250 (290)	1.6	1.56	1.51	209	211	-	210	2
450 (575)	1.6	1.65	1.60	220	224	210	222	2
500 (635)	1.2	1.20	1.15	230	241	217,224^{x}	226	3
550 (726)	0.42	0.46	0.42	239	246	225	239	6
550 (683)	0.60	0.64	0.60	236	240	228	235	4
550 (637)	0.95	0.99	0.95	230	235	220	226	3

Note.
1. + : Steel grade or minimum yield stress (measured yield stress)
2. Spec. : Specified thickness in mm
3. UC / bmt : bmt was used for Uncoated specimen test results
   C / bmt : bmt was used for Coated specimen test results
4. x : Results based on a different method of loading the specimens using standard weights
5. Est.Diff. : Estimated difference in E values for coated and uncoated specimens

It is international practice to test zinc or aluminium/zinc coated sheet with the coating intact, but to calculate the strength on base metal thickness (AS1397: SA, 1993). This is despite the fact that aluminium/zinc coating will add to the strength. However, it is used because the coating also reduces the ductility parameters and these values must be obtained with the coating intact (AS1397: SA, 1993). Despite these, the current practice of using coated specimens and base metal thickness for strength calculations is questionable. However, it is believed that the effect of coating will be accounted for in the quoted strength values provided the calculations for the design of steel structures are also based on base metal thickness. Therefore the E values in Table 3 are based on bmt for both coated and uncoated specimens. This practice gives higher stresses (thus higher E values), particularly for thinner coated steels of 0.6 mm or less. Based on the current practice, the results from coated specimens cut in the longitudinal direction should be used for design purposes.

The tests on uncoated specimens can be considered to give the E values of bare steel whereas those on coated specimens give the E values of the coated steel. Using simple mechanics and an approximate E value for aluminium/zinc coating (Ec) of 60 GPa, the difference between the two E values mentioned above can be estimated using (tct/bmt-1) x Ec. The estimated difference in E values is included in Table 3 for each case and appears to agree reasonably well with the corresponding value from the experiments (column 8 - column 7 value and column 6 - column 5 value in Table 3).

Tensile specimens were cut in both longitudinal and transverse directions due to an error in the workshop. AS1397 (1993) stipulates that tensile test pieces shall be cut parallel to the direction of rolling for structural grades G250 to G550. However, tensile tests were conducted on specimens cut in both longitudinal and transverse directions. The E value in the transverse direction was higher than that in the longitudinal direction which is similar to the observation on yield and tensile strengths. The difference between these E values was in the range of 5 to 15 GPa for the steels tested in this investigation.

Table 3 results show that E values are much larger than expected for thinner, low alloy steels used in this investigation. These results contradict the common belief that a large amount of alloy addition is needed to cause a change to the E value of steel. Table 3 results also indicate the increase in the modulus of elasticity both with the decreasing thickness and increasing steel grade. It is believed that these observations may be due to the thinness of steel (0.4 to 1.6 mm). The plane stress problem for thin steel and the associated change of failure mode (shear failure) are considered the possible reasons for the observed higher values of E. However, further studies are needed to investigate this problem.

For the conventional design assumptions, only the results in the last column of Table 3 are needed, and are used in the following discussion. When the thickness was decreased from about 1 mm to 0.4 mm, all grades of steels had an increase in E value by 5 to 13 GPa whereas it was 10 to 19 GPa for all thicknesses when the grade of steel was increased from 250 to 550. It may not be correct to assume that the modulus of elasticity E is constant for all grades and thicknesses of steel and is equal to 200 GPa. This assumption may mean an error of 20%, and thus may also mean the corresponding buckling loads can be in error by similar magnitudes. Although this error leads to a conservative design, it may be appropriate to use exact values of E. The manufacturers may be able to recommend an E value for each grade and thickness steel in a similar manner to yield stress. If not, testing may have to be conducted to determine the E values in each case. This may be essential in research projects where accurate predictions of failure loads are needed. On the other hand a simple formula is more useful to designers and researchers. Therefore attempts were made to develop a simple formula to determine E as a function of bmt (t in mm) and yield stress (F_y in MPa) using the results in the last column of Table 3. Equations (1 a) and (1 b) were thus developed to give the modulus of elasticity of the steel sheet in the direction of rolling using coated steel and bmt in strength calculations. The former was developed based on measured thickness and yield stress values whereas the latter was for nominal thickness and yield stress values.

$$E = 120\ t^{-0.03}\ F_y^{0.10} \qquad (1\ a)$$

$$E = 130\ t^{-0.04}\ F_y^{0.09} \qquad (1\ b)$$

It is to be noted that the above equations are only applicable to structural steel grades manufactured according to AS1397 (1993). The equations are approximate. They were derived using a simple method of fitting the best curve for the data (Table 3) obtained from the limited number of experiments from this investigation. Exact E values can only be obtained by accurate tensile testing of steel.

3. Conclusions

With the increasing use of a range of cold-formed high strength and thin steels in the building and construction industry, a good knowledge of the basic mechanical properties of these steels, namely, the yield and tensile strengths, the modulus of elasticity and ductility parameters is needed. This paper has concentrated on the topic of modulus of elasticity of steels. Tensile tests of steels with different grade and thickness revealed that the current practice of assuming the same modulus of elasticity value of 200 GPa for all grades and thicknesses of steel may be inaccurate. An approximate formula has been developed in terms of thickness and yield stress of steel.

4. Acknowledgements

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