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Strength and Behavior of Cold-Formed HSS Columns

by

Reidar Bjorhovde

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Department of Civil Engineering

THE UNIVERSITY OF ALBERTA

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1. INTRODUCTION

Extensive studies have been conducted on the strength and behavior of centrally loaded columns over the past 25 years.[1] Much of this work was directed towards the hot-rolled and welded built-up wide-flange and box sections, and the column design rules that now are used in various countries mostly have been derived from such investigations.

Over the last decade, however, the use of mill-manufactured tubular sections has increased significantly, recognizing the inherent advantages of such shapes for several structural purposes. Since the manufacturing methods for tubes may vary from one producer to another, depending on equipment, technical preference, and intended applications, among others, a host of products of this kind are presently available. For this reason, and also due to the fact that formed tubes possess structural characteristics that set them apart from the built-up ones, experimental and theoretical studies have been carried out to determine their strength and behavior when used as columns, as well as for other purposes. In Europe, much of the work has been conducted under the auspices of CIDECT, and further studies in Japan have enlarged the data base. Research performed in North America has been somewhat limited, with the result that tubes produced on this continent presently are designed on the basis of requirements that originally were developed for other shapes. Differences between North American and other countries' manufacturing procedures make the acceptance of the design rules of such countries a nonviable solution.

In view of the above facts, the American Iron and Steel Institute in 1974 initiated a survey of all research work that had been conducted on tubular shapes, including design procedures and methods of analysis. The findings of the study were published in 1976[2], and a set of tentative design criteria for tubular structures were proposed. Presenting the column design rules in the usual format of column strength versus slenderness ratio, it was recognized that the available data showed significant differences between the average strength of hot-formed and cold-formed tubes. The AISI recommendations[2] therefore proposed that two column curves be used: one for hot-formed (Class H) and the other for cold-formed (Class C) tubes. Given as allowable stress curves, they were derived from curves representing the average test strength of circular and rectangular tubes.

Of the test data reported in Reference 2, approximately 40% pertained to rectangular shapes (297 tests), and about 40% of these dealt with cold-formed shapes (132 tests). The experiments were all performed under CIDECT sponsorship, primarily in Europe, and therefore represented an array of different manufacturing processes. Although the test data for hot-formed and cold-formed tubes both exhibited significant scatter, and therefore overlapped to a certain extent, it was clear that the average strength of the latter type fell below that of the hot-formed shape in the medium and higher ranges of slenderness ratios. Differences of up to 20% were found.

Test results for North American cold-formed tubes are limited, and most of the work that has been done relates to round tubular columns[3]. Since these studies also were conducted relatively early (1958), it is believed that changes in, as well as new manufacturing methods make the data representative of current practice only to a limited extent. However, because of the lack of specific information on the strength and behavior of North American rectangular tubes (hollow structural sections, HSS), the most recent Canadian structural steel design standard(4) observed that its column design rules (Section 13.3) could not be used for the design of cold-formed HSS columns. Although it is known that certain types of heat treatment will improve their performance(5), economic considerations at times make this infeasible. On this basis it was deemed necessary to conduct a study of Canadian-produced cold-formed HSS columns, with the goal of developing a set of design criteria for such members.

2. SCOPE OF INVESTIGATION

In order to obtain as broad and representative a set of data as possible, yet to maintain a reasonable number of tests and types of tests, certain constraints had to be imposed at the outset of the planning phase. It therefore was decided to perform physical tests of the following kinds:

1. Full-size, long column tests
2. Stub column tests
3. Mechanical property tests
4. Cross-sectional and overall straightness measurements.

Due to the excessive cost and time requirements associated with residual stress measurements, which, in case such were to be done, would have to be performed for every type of cross section that would be tested as a column, it was decided to eliminate such an investigation from the program. Since stub column tests were to be done, data regarding the level of the maximum compressive residual stress could be obtained. In terms of column behavior, this is one of the major factors of interest.

The long columns would be tested in the pinned end condition, aligning the member geometrically in the testing machine. This procedure is similar to that used for column tests in North America, Europe, and Japan, and provides for a rational comparison with other results. Similarly, using the standard stub column testing procedure, these short members were to be investigated through a flat-ended test, thus eliminating the possibility of overall buckling. Including the determination of the static (zero strain rate) yield load for the stub column, the test would provide a complete stress-strain curve for the full cross section, as well as the low slenderness ratio end-point for the column curve.

Recognizing that mechanical properties normally are specified on the basis of tension tests, and that the properties also are a function of location within the cross section, a detailed and systematic investigation of quantities such as yield stress and elongation at fracture would be needed. This is particularly important for welded, cold-formed rectangular shapes, where corner and weld areas might be expected to exhibit characteristics quite different from those of other parts of the shape. For example, studies have shown that the yield stress increases and the ductility decreases when typical mild structural steel is subjected to cold-forming operations (cold rolling, press brake forming, etc.). The tension test data also would provide a check of some of the stub column findings.

It was noted that the producers' catalogs specified cross-sectional measurements (wall thickness, overall height and width of shape) as well as areas, moments of inertia, and other relevant data. Accurate recording of these properties would be needed for the analysis of stub column and long column test results. By the same token, and since long column strength is heavily influenced by initial out-of-straightness, measurements of the magnitude and distribution of same were required. The importance of these data is further enhanced by the fact that column curves for use in limit states design[1,4] explicitly incorporate a maximum initial crookedness of 1/1000. The same limitation is imposed by specifications for the delivery of structural steel.

In view of the absence of residual stress measurements, theoretical computations of column maximum strength could not be performed. The number and variety of long column tests therefore were purposely enlarged in order to give a reasonable basis for statistical evaluations. To a certain extent, this is also the basis for the limit states design rules, and it was noted that improved comparison between old and new test data thus could be achieved.

3. TESTING PROGRAM

3.1 Choice of test sections and steel grade

It was decided that the shapes to be tested should be chosen among typical, commercially available, hollow structural sections. The catalog of the producer, Prudential Steel, Ltd., Calgary, Alberta, includes a total of 64 different square shapes, ranging in overall size from 2x2 inches to 8x8 inches, with wall thicknesses varying from 0.095 inches to 0.5 inches. 152 rectangular shapes also are listed, varying in overall dimensions from 2.5x1.5 inches to 10x6 inches, with wall thicknesses similar to those indicated for the square shapes. The tubes are produced in a number of steel grades, with minimum specified yield strengths ranging from 39 ksi (ASTM A500-75, Grade A) to 55 ksi (CSA G40.21, Grades 55W and 55T). The steel grade most commonly used for structural purposes is CSA G40.21, Grade 50W, and the sections are categorized as Class C because of the use of cold-forming in the manufacturing process. On the basis of this information it was decided to use steel grade CSA G40.21-50W-Class C for all column specimens, and these would be supplied from the regular warehouse stock of the producer.

With the large number of HSS types that is available, it was immediately recognized that only a limited number of shapes could be tested. Noting that a rectangular shape generally will buckle in the weak (minor) axis direction, and that square shapes with overall dimensions equal to the smallest side of most rectangular sections are available, it was decided to confine the column tests to square shapes only. For example, it might be expected that the strength of an HSS 6x6x1/4 would be only slightly less than an HSS 8x6x1/4, provided the two had the same slenderness ratio. At the same time, it was considered important to cover the full range of shape dimensions, and with these items in mind the following shapes were selected.

Test series A:	HSS 2x2x1/4
Test series B:	HSS 4x4x1/4
Test series C:	HSS 4x4x1/2
Test series D:	HSS 6x6x1/4
Test series E:	HSS 6x6x1/2
Test series F:	HSS 8x8x1/4
Test series G:	HSS 8x8x1/2

In addition, at a later stage it was decided to add series H, designating a group of HSS 8x8x1/4 columns that had been stress-relieved (annealed). This was done to provide a comparison with the regular, cold-formed columns of series F, and thus obtain an indication of the true effects of full heat-treatment.

3.2 Cross-sectional measurements

Complete and detailed cross-sectional data would be needed for the evaluation of the stub column and long column test results. For each section, therefore, a set of four separate measurements were prescribed for overall height and width, and eight measurements for wall thickness. In addition carbon-paper imprints would be made of the full cross section, such that the area could be accurately recorded by means of a planimeter. Three planimeter sweeps were to be done for each imprint.

Arithmetic averages of the above data then would provide the bases for comparisons with the properties given in the producer's catalog.

3.3 Out-of-straightness measurements

North American specifications for the delivery of structural steel shapes require that certain overall straightness criteria be met. For HSS products these state that the maximum camber and sweep for a given length shall not exceed 1/8 inch times the length in feet, divided by 5. In terms of maximum out-of-straightness, e_{max}, divided by length, L, this may be expressed as:

$$\frac{e_{max}}{L} \leq \frac{1}{480} \approx \frac{1}{500}$$

It must be noted that the out-of-straightness requirement for hot-rolled wide-flange shapes, for example, is different ($e_{max}/L \leq 1/960$).

Out-of-straightness measurements therefore were planned for all long column specimens. Using a high-resolution theodolite and scales with an accuracy of ± 1/128 inch, four sets of out-of-straightness data were to be taken for each of the two areas of the cross section, and values of e were to be recorded at up to 8 points along the length. This procedure would ensure that the magnitude and location of the maximum out-of-straightness could be found, as well as determine the corresponding axis. As will be seen in Section 3.6, each long column would be installed in the testing machine with the axis of maximum crookedness located such that the recording and observation of deflections and other relevant data would be the most convenient.

3.4 Mechanical property tests

As noted earlier, mechanical property data normally are based on the results of tension tests. For the steel chosen, CSA G40.21, Grade 50W, the nominal minimum specified values are:

Yield strength	:	$F_y = 50$ ksi
Tensile strength	:	$F_u = 65$ ksi
Percent elongation at failure (2 inch gage length	:	22%

These minimum values are representative of the steel in its virgin condition, that is, before any welding or cold-forming has taken place.

In view of the fact that during the HSS manufacturing process, a flat sheet of steel is taken from a coil, formed into a circular tube and resistance welded, and then cold-formed into the proper HSS, several regions of the cross section might be expected to undergo significant changes as far as stress-strain characteristics are concerned. For example, experience has shown that the cold-working that takes place during the shaping of the corners of a section normally produces an increase in the yield strength and a lowering of the ductility (elongation at fracture, e.g.)at these locations.

With some consideration for the overall size and wall thickness of the shape to be studied, it was decided to take samples for tension testing under the following guidelines:

a) One sample to include weld area.

b) One sample to be taken from each of the four corners (1/2" wall thickness) or as close to the corners as possible (1/4" wall thickness).

c) One sample to be taken from the wall opposite the one containing the weld, and at the same relative location as the weld sample.

d) Within reason, as many samples as possible to be taken from other areas of the cross section (center of flats, close to corners, etc.)

On this basis, tension test specimens were to be taken from each of the column sections as follows:

Series	A:	2x2x1/4	4 samples
"	B:	4x4x1/4	8 "

Series C:	4x4x1/2	7	samples	
" D:	6x6x1/4	9	"	
" E:	6x6x1/2	12	"	
" F:	8x8x1/4	12	"	
" G:	8x8x1/2	8	"	
" H:	8x8x1/4	24	"	(= 2x12)

The series A shape was so small that no more than 4 specimens could be obtained. This was because the specimen and testing procedure specification that was used, ASTM A370, prescribes certain minimum dimensions for standardized tests.

The relatively large number of samples from series H requires some explanation. These column sections had been fully stress relieved, and original sampling plans called for 12 specimens, just as required for the comparable series F shapes. The column test results for two of the H-specimens seemed unreasonably high, and it was decided to sample their material properties as well. This will be discussed further in Section 4.3 of the report.

Tension testing procedure and specimen layout was prescribed in accordance with the requirements of ASTM standard A370. The specimen thickness was set equal to the full wall thickness in all cases, except for those that were to be taken from within the corners. Cutting and machining of these samples, as well as the existence of the corner curvature, allowed a maximum thickness of only 3/8".

3.5 Stub column tests

By making full-size column specimens so short that overall buckling is precluded, a stub column test provides the stress-strain characteristics for the cross section as a whole, including the effect of residual stresses, and also gives the low slenderness ratio end-point for the column curve. Of particular importance is the magnitude of the yield load, P_y, which, when determined for a testing strain rate equal to zero, gives an accurate representation of the yield strength of the material in the cross section when it is being used as a compression member.

In the development of maximum strength column curves, the accepted manner of presentation relates relative column strength to slenderness ratio (dimensional or non-dimensional). Due to length effects, the normal failure mode for a long column is overall (flexural) buckling. By making a member so short that this mode is excluded, the failure of a stub column essentially may be regarded as that of a column of zero length.

The strength and behavior of stub columns, as well as testing procedures for same, have been examined in detail[1,6]. As a result, standardized testing procedures have been developed[1], and these were used in the testing of the stub columns for the present program. The procedures include data on specimen preparation, end support conditions, alignment and alignment loads, specimen instrumentation, loading rates, attainment and definition of yield load, and interpretation of results.

Since all column specimens of the same cross section were to be supplied from the same heat, it was decided to limit the number of stub column tests to one per type of shape. Thus, a total of 8 stub columns were prepared, one for each of series A through H.

3.6 Long column tests

Considering the variety of HSS types to be tested, as well as the need to obtain column strength data for as large a range of slenderness ratios as possible, it was decided to limit the number of tests to one per slenderness ratio per shape. Although this decision was made for purely practical reasons, it was noted that this would not give any information regarding the statistical (random) variation of the strength of a column with a given length and shape. Certain of the tests therefore were expanded to obtain some data on the scatter of strength that might typically be expected. Similarly, only a few tests were planned for the longest of columns. It was anticipated that buckling would be essentially elastic for the longer of the columns, and thus illustrate that the distribution of residual stress (in other words, the influence of the manufacturing process) would be irrelevant for such members. As will be seen later in this report (Section 4.5), the assumption of elastic buckling for the two columns with the highest slenderness ratio proved to be correct.

With all of the foregoing in mind, Table 1 (see Chapter 8 for all tables and figures) illustrates the final schedule of long column tests, giving a total of 30 specimens.

Many studies have examined testing techniques for long columns[1,7], and standardized procedures have been developed[1]. To achieve uniformity, as well as to be able to compare the results of the above tests to those of other investigations, the pinned-end, geometric alignment procedure described in Appendix 4 of Reference 1 was prescribed. This procedure includes data on end fixtures, instrumentation and measurements to be made, specimen preparation and installation, loading rates, attainment and definition of static maximum strength, and interpretation of results. It should be noted that this, the SSRC Column Testing Procedure[1], now is being used throughout the world.

4. TEST RESULTS

4.1 Cross-sectional measurements

Table 2 shows the results of the cross-sectional measurements for the specimens included in the program. It can be seen that overall dimensions and wall thicknesses correlate well with the nominal values that are given in the producer's catalog, and also that they satisfy the tolerance requirements. Thickness measurements were not made at weld locations, since the pressure that is applied during resistance welding has a tendency to create a "swelling" of the shape at this point. This phenomenon has no effect on the strength and behavior of the shape as a structural member.

Differences between nominal and measured cross-sectional areas are larger, primarily on the low side (i.e. actual area less than nominal area). The maximum deviation is -12.5%, which was found for the series H (stress-relieved) 8x8x1/4 shapes. No explanation will be offered for this occurrence, which, in all probability, has only a minor effect. Although the area per se enters into the stress calculations for stub columns, for long column strength the distribution of the area (e.g. the moment of inertia) is more significant, at least until the appearance of the first local yield.

There can be no doubt, however, that the product as supplied is consistent with the producer's catalog to within very close tolerances for dimensional accuracy.

4.2 Out-of-straightness measurements

The most important of the results for the out-of-straightness measurements are illustrated in Figure 1. As noted in Section 3.3 of the report, such measurements were made about both major axes of the column specimens for up to 8 points along the length, and four sweeps were made for each axis.

The results shown in Figure 1 are keyed to an axis reference system that is schematically explained by the insets in the figure. In brief, the side of the specimen containing the weld was referred to as the "North" side, and all other sides and measurements were made in reference thereto. In an attempt to detect whether there might be systematic differences between the out-of-straightnesses observed for the NS- and EW- directions, separate frequency distributions (histograms) for each have been included in Figure 1. Finally, the fully drawn lines refer to the frequencies obtained by combining the measurements obtained for the two axes.

As a first and general observation it must be noted that none of the column specimens investigated had out-of-straightnesses in excess of the maximum allowable. In fact, the largest value found in any single member was 1/730. The most frequently encountered values were between 1/2000 and 1/5000, but a significant number of columns had out-of-straightnesses well below 1/10,000. More refined measurements would have been possible with instruments of higher resolution, but it is doubtful whether such would produce noticeable changes in the data distribution. One of the specimens was found to be perfectly straight (EW-direction), which was to be expected for a statistical population of this size[8].

Combining all measurements, the mean initial out-of-straightness was computed as 1/6384, which is an order of magnitude less than the specified maximum allowable value. The highly skewed frequency distribution confirms the findings for other types of structural shapes[8], and the out-of-straightness magnitudes compare well with those found in other studies of HSS shapes[5]. In contrast to the production of hot-rolled wide-flange shapes, however, it is important to observe that overall straightening (rotorizing or gagging) of the HSS members is not applied at any time during or after the manufacturing process.

The average initial out-of-straightnesses for the NS- and EW-directions were calculated as 1/5116 and 1/7651, respectively. Despite these numbers, an examination of the detailed measurements as well as the frequency distributions pertaining to the data for the two axes (see Figure 1) reveal no systematic preferences. It therefore appears that the existence of a resistance weld has no noticeable influence on the magnitude and axis of the largest initial out-of-straightness. This is contrary to the results of other studies[5].

The above observations apply only to the HSS types included in the program. However, it would appear reasonable to assume that all square tubes manufactured by the same process would exhibit similar characteristics. An extension to rectangular tubes is not warranted at this time.

In general, the maximum value of the out-of-straightness was found within the center quarter of the length of the specimen, and the distribution along the length was reasonably symmetric. A few specimens, almost all of which belonged to series H, exhibited some initial twist, as well as having out-of-square cross sections (slightly rhomboid, or outwards "bow" of the sides). It is believed that uneven heating and cooling during the stress-relief operation for the series H specimens must have been the cause of these distortions. As will be discussed further in Section 4.5 of the report, particularly the outwards "bow" of the cross-sectional sides may have had an effect on the overall behavior and strength of some of the long columns.

4.3 Mechanical properties

Figure 2 gives a detailed illustration of the locations of the tension test specimens in the HSS types included in the program. As previously noted, the 1/4 inch wall thickness of the sections of series A,B,D,F and H made it impossible to cut ASTM A370 standardized specimens from certain areas of the shapes. It was attempted to alleviate this shortcoming by taking samples as close as possible to the cold-worked corners. Similarly, it is obvious that many more samples could have been obtained, particularly from the larger shapes, but a balance had to be struck between cost, time requirements, and desired accuracy of the results. It was felt that the chosen sampling procedure would yield the optimum outcome.

Table 3 presents an overall view of the tension test results. Included in the table are the CSA specified minimum values of yield strength, tensile strength (= ultimate tensile strength) and elongation at fracture, measured over a 2 inch gage length. Also shown are the same characteristic properties as given by the mill test certificates that were supplied by the producer along with the HSS specimens, as well as the average values of the tension test data obtained in the laboratory.

Before commenting on the test results, it must be observed that both the CSA requirements and the mill test values are based on tension tests that are run at a specified (constant), non-zero strain rate from start to finish of the experiments. This is more a practical, convenience-oriented procedure than anything else, assuring uniform conditions for all materials. In real life, a structure is subjected to loads that are static or essentially so, implying that a zero strain rate would be more representative. Further, research has shown that apparent yield strength increases with increasing strain rate[9]. The accepted manner of reporting mechanical property data therefore has become the use of "zero-strain-rate-properties", or static values as is the common designation. This effect has no influence on the total elongation at fracture. For this measure a standardized gage length of 8 inches or 2 inches must be used, and the latter formed the basis for the tension tests of the HSS program.

Observing the yield strength data in Table 3, it is seen that both the mill test results and the average tension test values exceed the CSA minimum specified property by relatively wide margins. In particular, the series C specimens gave yield strengths approximately 50% higher than required, but the other shapes also performed very well. The lowest value was found for series D (6x6x1/4), which still provided a number about 10% above minimum. The fit between the mill tests and the tension tests varies, which can be explained by the fact that the mill values were obtained from specimens of the sheet steel in its original, pre-production, condition. Other factors may also play a role.

The above comments generally apply to the tensile strengths as well, with the exception of series D, where the average tension test value of 60.6 ksi fell below the minimum specified figure (65 ksi) by 6.8%. A slight discrepancy is also observed for the specimens from series B (4x4x1/4), but this is not significant. However, since the tensile strength as a rule is a less reliable measure than the yield strength, and because very significant variations may be expected for this property (e.g. CSA standards provide for an allowable range of 65 to 90 ksi for the tensile strength of grade 50 steel), a pattern of variation as expressed by the tensile strength data in Table 3 may be regarded as normal. Furthermore, and although it has not been systematically investigated, it is believed that the magnitude and variation of the (ultimate) tensile strength of steel have no bearing on column strength and behavior.

The required elongation at fracture, or, in other words, a measure of the ductility of the steel, has been well satisfied on the basis of the mill test data. As might be expected, the series A value just fulfills the requirement of 22% elongation in a 2 inch gage length. This is because of the small size of the shape, for which it might be anticipated that the production operations that take place prior to any of the forming processes (cutting or shearing of the sheet from the coil, for example) could lead to local changes of the material characteristics. On the other hand, the laboratory test data show that the CSA elongation requirements were not met by the series A (2x2x1/4) and C (4x4x1/2) specimens. In general, all of the laboratory values were below those of the mill tests, but they still satisfied the specification requirements (with the two exceptions noted above). All of these findings can be explained by the fact that the tension specimens were cut from the cold-formed tubes, and the effects of cold-working therefore would come into play.

Examining the test data for single specimens from the various tubes reveals the above tendencies quite clearly. Thus, the tension specimens that contained the weld areas as a rule exhibited higher strengths and lower ductilities than those cut from the "flats" of the cross section. These differences were particularly pronounced for series A, B and D, where the weld specimen strength was up to 10% higher than it was for the "flats". At the same time the elongation at fracture was as low as 15.5% (series A) and 16.1% (series C). All other weld specimens met the CSA ductility criteria.

No significant differences could be found between tension specimens cut from the middle of the "flats" and specimens taken from areas as close to the corners as possible (series B,D, F and H). It therefore appears that any cold-working effect is confined strictly to within the corner ("bent") area. This statement is borne out by an examination and comparison of corner specimens (series C and E) to samples from other locations within the same cross section. As a rule, all corner specimens had yield and tensile strengths approximately 10% higher (on the average) than those from the "flats", and their elongation at fracture was about 16 to 18%. It is important to note, however, that these observations do not apply to the heaviest HSS of all, namely, the 8x8x1/2 of series G. For example, although the elongations at fracture for samples 4 and 5 (see Figure 2) were 24% and 33%, respectively, they both obviously satisfied the CSA minimum requirements. By the same token, it appears significant that the same relative magnitude of spread was found within the series F (8x8x1/4) section, where no specimens were taken from within the corner areas. It is therefore believed that as far as the material behavior per se is concerned, the larger (e.g. height and width) the section, the less overall influence of corner cold-working. This also appears to be substantiated by the column test results (see Section 4.5 of the report).

A comparison of the test results for series F and H indicate the influence of the stress-relief that was applied to the latter. The important conclusion is reached that although the series H specimens exhibited greater uniformity in strength and ductility than those of series F, the average yield strength and tensile strength of the H-samples were approximately 8% higher. The elongations at fracture were different, but not sufficient to warrant any clear-cut conclusions either way. In terms of strength, of course, normally the opposite of what was observed here will happen, that is, a stress-relieved material will have significantly lower strength and higher ductility than what was the case before the heat-treatment. It is not possible to explain the present occurrences on the basis of the available information. Figure 3 shows stress-strain diagrams for tension specimens for a weld area, for a typical "flats" location, for a corner test, and for a stress-relieved sample. Note the absence of the typical yield plateau in all but the stress-relieved material. Thus, only the latter gives a well-defined yield strength, and for all other tests the yield strength that has been recorded corresponds to the 0.2% permanent deformation definition. This is the standard procedure for a material without a yield plateau, but it corresponds well to the strain that is recorded as ε_y + 0.2%, where ε_y is the yield strain.

Fracture toughness data are not required for CSA G40.21, Grade 50W, steel. However, the mill test reports included such figures for standardized Charpy V-Notch tests, and the values have been included in Table 3 for information only. It is well worth noting the very high toughnesses recorded, particularly in view of the low test temperature (-20°F = -29°C).

4.4 Stub-column tests

The pertinent stub-column test data for all specimens are presented in Table 4 and Figures 4 through 12. Of particular interest are the general shapes of the stub-column curves, as well as the loads at which first yield was observed and the yield loads.

The shape of the stub-column curve, when viewed together with the information regarding the attainment of first yield, is an indication of the level of the maximum compressive residual stress in the cross section. Typically, earlier tests with rectangular cold-formed tubes indicated a magnitude of residual stress in the order of 50 to 75 percent of the material yield stress[(2)]. This was attributed to the manufacturing process, whereby the cold-forming introduces significant stresses in the corner areas. Furthermore, it was found that the residual stresses may vary significantly through the wall thickness, and therefore compounding the detrimental effects on column strength. However, these findings were primarily based on studies of shapes that had been produced by widely different methods of manufacture, and that also differ from that utilized by the producer of the shapes for this research program in important details.

In general it was found that the load at first sign of local yielding varied between 58% (series A) and 80% (series D) of the static yield load for the cold-formed shapes (series A through G). The stress-relieved stub-column of series H did not exhibit yielding until 89% of the static yield load was reached. This was to be expected, since full stress-relief annealing, when executed properly, will reduce the residual stresses to near zero everywhere in the cross-section. Under perfect conditions, annealing theoretically should eliminate all built-in stresses, but this is not a reasonable result in practice.

Without the benefit of actual residual stress measurements, the first yield condition indicates maximum compressive residual stresses, σ_{rc}, in the test sections as follows:

A - HSS 2x2x1/4 : $\sigma_{rc} = 0.42\ \sigma_y = 32.9$ ksi

B - HSS 4x4x1/4 : $\sigma_{rc} = 0.26\ \sigma_y = 17.9$ ksi

C - HSS 4x4x1/2 : $\sigma_{rc} = 0.34\ \sigma_y = 26.8$ ksi

D - HSS 6x6x1/4 : $\sigma_{rc} = 0.20\ \sigma_y = 11.8$ ksi

E - HSS 6x6x1/2 : $\sigma_{rc} = 0.36\ \sigma_y = 26.5$ ksi

F - HSS 8x8x1/4 : $\sigma_{rc} = 0.30\ \sigma_y = 18.6$ ksi

G - HSS 8x8x1/2 : $\sigma_{rc} = 0.38\ \sigma_y = 27.0$ ksi

H - HSS 8x8x1/4 : $\sigma_{rc} = 0.11\ \sigma_y = 7.3$ ksi
(stress-relieved)

The smallest section (2x2x1/4) appears to be unique because of its relatively high level of residual stress. However, this may be explained by the fact that due to its small overall size and comparably thick wall, the cold-working that takes place is likely to influence the entire cross section. This observation is further borne out by the tension specimens that were taken from the A-shape, namely, that all of them behaved very much like those taken from within corner areas of other shapes.

Apart from the series A test, remarkable similarities may be observed for all specimens with the same wall thickness (excluding the stress-relieved series H, for obvious reasons). Thus, the levels of residual stress in the shapes with 1/4 inch wall thickness (series B, D, and F) are reasonably comparable (approximately 12 to 18 ksi). By the same token, the maximum compressive residual stresses in the sections with 1/2 inch wall thickness (series C, E, and G) are all very similar (between 26 and 27 ksi). It is possible to explain these results by observing that the amount of cold-working that takes place in thicker material will be more significant, and thus give rise to higher built-in stresses. At the same time it is clear that overall shape size is important, as illustrated by the findings for the series A specimen. The available data are not sufficient to determine limiting sizes and thicknesses for one or the other of these effects.

The stress-relieved specimen behaved as expected, exhibiting low residual stresses. Its HSS designation is the same as that of series F, and a comparison between the results for these two stub-columns provides additional insight. Whereas the residual stress for specimen H was only about one third of that for specimen F (7.3 ksi versus 18.6 ksi), their actual yield loads were identical (440 kips), and both failed in the same manner (sudden local buckling of walls; little or no warning of impending collapse). Due to differences in cross-sectional area, the yield stress for the H-stub-column was about 6% higher than that of the series F specimen. However, a similar yield stress differential is found in the average tension test data for the two shapes (see column 6, Table 4), and it therefore may be concluded that the H-specimen actually was somewhat stronger. This is not an important finding, however, since otherwise identical shapes of the same nominal steel grade may exhibit random strength variations of the same order of magnitude.

All of the above observations are confirmed by Figure 12, which shows the stub-column curves for series A through H in the same diagram. Relatively speaking, specimens C (4x4x1/2) and E(6x6x1/2) display the least desirable behavior. However, in the initial stages of loading the differences between the best- and worst- behaved specimens are not unduly high.

The average tension test yield strength is consistently less than the yield strength determined by the stub-column test, as shown in column 6 of Table 4. The largest difference was found for specimen H (14%), but in general the tension test results were within approximately 10% of the stub-column data. This is explained by the fact that the tension tests represent but samples from within the shape, and particularly that the higher strength corner areas are not included as much as they could have been. In any case, for overall column strength the stub-column result is the governing factor, and this is what has been used in the long column analyses of this report.

4.5 Long column tests

Table 5 gives the pertinent details for all of the long column tests, and Figures 13 through 20 illustrate the load-deflection curves for the tests. The latter are non-dimensionalized with respect to the load axis, that is, the ordinates represent the ratios of the load at a given instant, P, to the yield load, P_y. The abscissa axis indicates mid-height deflection of the column. It must be noted that the load-deflection curves are based on dynamic load measurements. The true, static maximum column strength, P_{max}, was obtained in every instance by recording the maximum load at zero strain rate (no movement of testing machine crosshead or lateral deflection increase). The differences between the dynamic and the static maximum strength varied considerably for the columns included in the test program, but this deviation is of little interest.

As observed previously (Section 3.6), the long column tests were run as pinned-end specimens, aligned geometrically in the MTS 1500 kip universal testing machine of the Structural Engineering Laboratory at the University of Alberta. Spherical end-fixtures were designed and fabricated, and during the test end-rotations were monitored to ascertain whether the fixtures actually allowed pinned-end rotations to occur. It was found that such was the case; - in no instances did the fixtures prevent rotation. Of course, it must be recognized that it is practically impossible to obtain absolutely perfect pinned ends, since some friction and other resistance always will be present. Such resistance is of particular concern for lower load levels, P/P_y, but as the applied force increases the importance of the minor rotational restraint will vanish.

Overall shortening and mid-height deflections were recorded for every load level, utilizing LVDT units. Recognizing that a square column may buckle in any of the two principal directions, mid-height deflections were recorded for both the NS- and EW- axes. In general, however, it was clear already before testing that the column would buckle in the direction of the axis containing the largest initial out-of-straightness, and this was confirmed in all cases but one (test D2).

The load-deflection curves for all columns in the same series are shown in the same diagrams (Figures 13-20), to permit a direct evaluation of the length effect. The maximum dynamic strength is represented by the peak of each curve, and the maximum static strength was obtained at the same level, by reducing the testing machine load to the point where no further midheight deflection and crosshead movement were recorded. This stabilization process in general was completed within 3 minutes, and the static load was determined as the one maintaining a constant deflection for at least one minute. Having achieved this load, the loading process was resumed at the same rate as was used before the machine was "stopped". A few more load-deflection data were subsequently obtained, to determine a part of the descending portion of the load-deflection curve. The instrumentation was then removed to prevent any damage from occurring during the failure process of the column, and the loading continued until buckling took place. Computer monitoring of deflections, shortening, and rotations was done continuously throughout the test, as well as careful visual inspection of whitewash. The latter was done to determine the initiation and spread of local yielding.

The load-deflection curves for the series A columns (Figure 13) exhibit perfectly normal characteristics. The effect of any initial out-of-straightness is virtually negligible for the shortest specimen (A21), making its behavior comparable to that of a stub-column to a certain extent. Extensive yielding had occurred by the time any of the three A-columns failed through overall buckling. Similar observations apply to the series B results, shown in Figure 14.

The test results for the C-columns are illustrated in Figure 15. The shortest specimen behaved in the typical fashion, comparable to the findings for the corresponding A- and B- members. The three geometrically identical tests, C3-1 through C3-3, exhibit differences in behavior and strength that are within the band of random variation that has been determined for other types of columns[1,8]. The spread can be attributed to factors such as minor variations in yield stress and geometrical size and shape. However, the magnitude of the initial out-of-straightness is the major contributing factor: e/L for specimen C33 was only one half of that of the other two. Nothing unusual was observed for test C41. For specimen C51, however, which was one of the two long columns in the entire program with the highest slenderness ratio, overall failure occurred through fully elastic buckling. No signs of local yielding could be found, and the member regained its original shape after unloading. The nonlinear load-deflection curve thus is wholly attributable to the presence of the initial out-of-straightness, which for this specimen was 1/730. This e/L- value was the highest recorded for any of the test specimens in the entire program.

Specimen D21 achieved a very high dynamic maximum strength, but the static value was below P_y, as should be expected. Column D31 initially started bending in one direction, but as the maximum strength was approached, the deflections reversed, and the column failed in the typical manner. Just as observed for test D21, the difference between the dynamic and the static maximum strength was high (approximately 20%). The deviation normally lies between 5 and 10% of the dynamic value, and there is no obvious reason why these two specimens behaved as shown. Test D41 yielded perfectly normal data, as shown in Figure 16.

For test series E, specimen no. E21 exhibited normal short column behavior. Although the load-deflection curves and maximum dynamic loads for tests E31 and E41 were relatively close, the static loads turned out to be realistically different. The closeness of the two curves can be explained by the fact that the initial out-of-straightness for specimen E41 was less than one half of the e/L value for E31. Just as found for test no. C51, column E51 buckled elastically. This test therefore confirmed early expectations as well.

The test results for the series F columns are displayed in Figure 18. Specimen F21 was initially extremely straight, and therefore showed very little sign of lateral deflection prior to buckling. The negative deflections illustrated are but a sign that the member started bending in the direction <u>defined</u> as negative. The member failed through a rather sudden, overall buckling, and yielding was extensive along the full length. Specimens F31 and F41 exhibit typical characteristics; - the only worthwhile additional piece of information is represented by the fact that F41 showed very few signs of local yielding, and did not obtain the typical local buckles in the wall due to the failure.

The load-deflection curves for tests G21 and G31, shown in Figure 19, exhibit normal characteristics, provided it is observed that the initial out-of-straightness of the latter was only one half of that of E21. This is the reason for the relative closeness of the results. Test G41 behaved in the typical long column fashion, and only very limited local yielding was observed at the time of failure.

The results for the stress-relieved, series H, columns are given in Figure 20. Tests H31 and H32 were geometrically identical (nominal size), and their maximum strengths are very close. The strange shape of the load-deflection curve for specimen H32 cannot be explained rationally by the available data, with the possible exception that the cross section was clearly out-of-square (rhomboid). The magnitudes of the maximum strengths are high, as might be expected for stress-relieved shapes. However, the difference between the strengths of columns F31 and H31/32 is not more than approximately 5%, or, in other words, less than what might be expected to accrue from a stress-relief operation. Apart from specimens H41 and H43, tests H42 and F42 gave identical maximum strengths, which indicates that for this type of shape the stress-relieving had little or no beneficial effect. It is believed that the high b/t-ratio for the walls of 8x8x1/4 sections is the cause of this (b/t $\approx$ 30). Although these columns all failed through overall (flexural) buckling, the collapse in all instances seemed to have been precipitated by local wall buckling. It is known that plate buckling is not nearly as sensitive to residual stresses as is overall buckling, since geometry and plate edge support conditions overshadow other influences.

Although specimen H43 had a very small initial out-of-straightness (e/L = 1/10,000), neither the result for this test nor for that of column H41 are reasonable. In fact, in the column curve evaluation presented in Section 5.2, it is shown that the points for these two tests fall above the Euler curve. The only plausible explanation for this behavior appears to be founded on the fact that both of these shapes had walls that were significantly "bowed" outwards. This kind of deviation from a square cross section can lead to drastically different behavior. Any further explanation cannot be offered at this stage.

5. INTERPRETATION OF TEST RESULTS

5.1 Mechanical properties

To provide further insight into the relationship between tension test results and the yield stress data obtained by stub-column tests, Figures 21 through 29 illustrate yield strength ratios for series A to H. Specifically, the ordinates give values of σ_{yt}/σ_{ys}, where σ_{yt} is the yield strength obtained by a tension test at a specific location, and σ_{ys} is the yield strength given by the stub-column test for the corresponding HSS. To facilitate illustration, the length of the horizontal axis represents the "length" of the cross section if it were folded out into one plane. For example, Figure 21 gives the data for the 2x2x1/4 shape, and the horizontal length is equal to 4x2=8 inches in this case. To ease drawing efforts, all shapes, regardless of size, have been pictured using the same axis length. Tension specimen locations and corresponding yield strength ratios are indicated on the horizontal axes, as well as locations of corners and welds.

Figures 21 to 27, giving the results for series A to G, show ratios of dynamic yield stress (o.2% permanent deformation definition) for the tension specimens to the stub-column static yield stress. Fully static ratios are approximately 4% lower. The data expand on what was observed in Section 4.3 of this report, namely, that the tension test results as a rule tend to give only an approximate measure of the material performance as far as column behavior is concerned. Thus, it might be anticipated that tension test data would vary some ± 10% in comparison with the stub-column yield strength, depending on the location of the tension specimen. Although the limits of variation are somewhat farther apart than ± 10%, in general this observation is found to be correct. It is believed that if tension specimens could be cut from entire shapes, the average σ_{yt}/σ_{ys} - value would be 1.0.

To include dynamic as well as static yield strength ratios, Figures 28 and 29 give typical examples of the level of variation that was found throughout given shapes. Again, as a rule, the tension test strength can only be regarded as an approximation of the true material characteristics for column behavior, but a sufficiently large number of tension specimens will give very good results. As an example, the average static yield strength for the 24 H-specimens was found to be exactly equal to the stub-column static yield strength value.

The strength-variations that occur throughout a given section due to welding, cold-working, and the like, are discussed in detail in Section 4.3. Figures 21 to 29 emphasize these very characteristics, namely, that the yield strength as a rule is higher for weld and corner areas than elsewhere in a given shape.

5.2 Column tests

Figure 30 provides the typical non-dimensional column curve diagram, where ordinates are given by the ratios of static maximum column strength to static yield load, (P_{max}/P_y), and the abscissa is the non-dimensional slenderness ratio, λ. The latter is introduced in order that columns of different material properties may be compared in the same diagram, since λ is a function of the yield strength, thus:

$$\lambda = \frac{1}{\pi} \cdot \sqrt{\frac{\sigma_y}{E}} \cdot \frac{L}{r}$$

For these computations a value of E=29,000 ksi was assumed.

The original testing program called for specimens with slenderness ratios of 30, 60, 90 and 120 (see Table 1). Due to the relatively significant variation of material properties that was found for the test specimens (e.g. yield strength values between 59 and 79 ksi, as shown in Table 4), the λ- values displayed a correspondingly large spread. However, the overall performance picture is not clouded by these variations.

Also included in Figure 30 are the column curves prescribed by CSA Standard S16.1-1974 (without the performance factor, ϕ), and the uppermost of the multiple column curves recommended by the Structural Stability Research Council (SSRC)[1,8]. The CSA curve is the same as SSRC Curve 2, with a minor variation for the very low slenderness ratio range ($0 \leq \lambda \leq 0.15$). It must be observed that neither of the two SSRC curves were based on data for hollow structural sections.

As might be expected for a variety of cross sections and shapes as those included in this testing program, the spread between high and low column strength values for each λ- range is fairly significant. In agreement with other test data [1,2,8], the scatter is larger in the intermediate range of slenderness ratios ($L/r \approx 60$ in Figure 30). However, it is of the utmost importance to note that not one of the test points fall below the CSA column curve ($\approx$ SSRC Curve 2). In fact, most of the column strength data would indicate that those sections can be categorized as belonging to SSRC Curve 1. This observation is based on the fact that the SSRC multiple column curves were statistically developed as approximate average curves. The HSS column strength data shown in Figure 30 all fall within the 95% confindence interval for SSRC Curve 1[1,8], with the possible exception of three of the test results for the lowest L/r - values.

The test results for specially heat-treated (not stress-relief annealed) HSS columns[5] exhibit less scatter than what was found for the columns of series A through H, and their average relative strength is slightly higher than that indicated by the test points of Figure 30. Such heat-treated shapes are presently tentatively approved for design, using the CSA limit states standard[4]. On the basis of the test results for the type of HSS columns that was investigated in the present research program, it would appear that such members can be designed through the same requirements.

6. CONCLUSIONS AND RECOMMENDATIONS

In comparison to other experimental studies of the strength and behavior of columns, the present HSS column program represents a significant addition to the overall statistical population. It has been found that for the shapes manufactured by the process utilized by Prudential Steel, Ltd., the initial out-of-straightnesses are very small, and that cross-sectional tolerances are satisfied to within very close tolerances. Due to the in-line resistance weld and localized heat-treatment of same, as well as the promptly succeeding HSS forming, the residual stresses that are found in these sections are significantly smaller than those of most other cold-formed shapes. Also contributing to the improved column behavior of these HSS types may be the existence of a certain amount of "stretch" - stress-relief as the squaring of the cross section takes place through several sets of rolls in the mill. A certain level of latent heat remaining in the shape after the circular forming and resistance welding also will tend to reduce the residual stresses.

For the particular type of stress-relieved section that was investigated (8x8x1/4), very little benefit seemed to accrue from the heat-treatment. This conclusion cannot be extended to cover all HSS types, since it appears that local wall buckling is of major importance for sections with high b/t- ratios.

Based on an analysis of the column test data in the typical non-dimensional column curve diagram, it is clear that this type of HSS column can be designed safely on the basis of the requirements of CSA Standard S16.1 - 1974. All of the test results were located above the basic column curve. In actual design a performance factor, ϕ, is also applied, which covers any random strength variations that may occur.

It is therefore recommended that HSS columns that are manufactured through this type of process be recognized for design by the CSA limit states design code[4].

7. TABLES AND FIGURES

TABLE 1

Schedule of Long Column Tests

Series	HSS(1)	Number of tests for L/r ≈			
		30	60	90	120
A	2x2x1/4	1	1	1	-
B	4x4x1/4	1	1	1	-
C	4x4x1/2	1	3	1	1
D	6x6x1/4	1	1	1	-
E	6x6x1/2	1	1	1	1
F	8x8x1/4	1	1	1	-
G	8x8x1/2	1	1	1	-
H(2)	8x8x1/4	-	2	3	-

(1) All sections CSA G40.21, Grade 50W, Class C

(2) Stress-relieved (annealed) sections

TABLE 2

Measured Cross-Sectional Dimensions

Series	Nominal Dimensions (in) [1]	Average Width (in) [2]	Average Height (in) [2]	Average Thickness (in) [2]	Average Area (in^2) [3]	Nominal Area (in^2) [1]	Area Difference (%) [4]
A	2x2x0.250	2.01	1.99	0.234	1.51	1.54	-1.9
B	4x4x0.250	4.04	4.02	0.240	3.35	3.54	-5.4
C	4x4x0.500	4.02	3.99	0.499	6.42	6.14	+4.6
D	6x6x0.250	6.01	5.99	0.249	5.20	5.59	-7.0
E	6x6x0.500	6.03	6.03	0.463	9.64	10.36	-6.9
F	8x8x0.250	7.97	8.01	0.247	7.10	7.59	-5.1
G	8x8x0.500	8.02	8.06	0.472	13.35	14.36	-7.0
H [5]	8x8x0.250	8.02	8.02	0.237	6.64	7.59	-12.5

(1) For permissible variations, refer to the Prudential Steel, Ltd., HSS catalog.

(2) Widths, heights and thicknesses measured to an accuracy of ± 0.001 inches.

(3) Areas measured to an accuracy of ± 0.001 sq. in.

(4) Area difference = $\frac{\text{Average area} - \text{Nominal area}}{\text{Nominal area}} \cdot 100$ (%).

(5) Fully stress-relieved (annealed) shapes.

TABLE 3

Comparison of Mechanical Properties for Test Shapes (1)

Series	HSS	Yield Strength (ksi)			Tensile Strength (ksi)			Elongation in 2" (%)			Fracture (2) Toughness (Charpy) (ft-lb)
		CSA Min.	Mill Test Cert.	Av. (3) of Tension Tests	CSA Min.	Mill Test Cert.	Av. (3) of Tension Tests	CSA Min	Mill Test Cert.	Average of Tests	
A	2x2x1/4	50	67.8	67.7	65	79.0	69.9	22	22.0	15.5	-(4)
B	4x4x1/4	50	57.5	60.3	65	70.4	64.3	22	34.0	30.6	82
C	4x4x1/2	50	65.8	76.0	65	84.7	81.2	22	26.0	19.1	134
D	6x6x1/4	50	54.5	54.4	65	65.6	60.6	22	27.0	25.5	-(4)
E	6x6x1/2	50	60.9	68.8	65	74.7	73.6	22	28.0	25.3	136
F	8x8x1/4	50	56.3	58.5	65	71.8	69.1	22	39.0	28.1	61
G	8x8x1/2	50	67.9	62.9	65	78.3	71.0	22	35.0	28.6	206
H(5)	8x8x1/4	50	-(4)	63.7	65	-(4)	71.1	22	-(4)	30.0	-(4)

(1) For numbers and locations of tension test specimens in test shapes, see Figure 2.
(2) Fracture toughness values are not required for Grade 50W steels, but are shown here for information only. These data are mill test values, generally the average of 3 tests. Test temperater was -20°F (-29°C) in all cases.
(3) All test values for yield and tensile strength are based on zero strain rate, which is not used for standard mill tests.
(4) Data not available.
(5) Stress-relieved (annealed) sections.

TABLE 4

Stub-Column Test Data

Series	HSS	Load at first yield (P/P_y) (1)	Yield load, P_y (kips) (2)	Yield Stress, P_y/A (ksi) (2)	Tension (3) test yield (ksi)
A	2x2x1/4	0.58	118.0	78.4	67.7
B	4x4x1/4	0.74	230.5	68.8	60.3
C	4x4x1/2	0.66	505.5	78.8	76.0
D	6x6x1/4	0.80	306.5	59.0	54.4
E	6x6x1/2	0.64	711.0	73.7	68.8
F	8x8x1/4	0.70	440.0	62.0	58.5
G	8x8x1/2	0.62	947.3	71.0	62.9
H (4)	8x8x1/4	0.89	440.0	66.2	63.7

(1) Observed during test as first indication of whitewash flaking. Data are non-dimensionalized with respect to the yield load, P_y.

(2) These are static (zero-strain-rate) values.

(3) Average tension test yield stress (refer to column 5 of Table 3).

(4) Stress-relieved (annealed) specimen.

TABLE 5

Long Column Test Results

Specimen No.	Length (in)	r (in)	L/r	Area(1) (in^2)	σ_y(2) (ksi)	P_{max}(3) (kips)	P_{max}/P_y	λ(4)	Remarks
A21	20		29.4			106.2	0.90	0.50	
31	40	0.681	58.7	1.505	78.4	82.0	0.70	0.99	
41	55		80.8			59.7	0.51	1.34	
B21	45		29.9			214.5	0.93	0.46	
31	90	1.504	59.8	3.351	68.8	165.3	0.72	0.93	
41	117		77.8			139.1	0.60	1.21	
C21	41		30.1			484.0	0.96	0.50	
3-1	82		60.2			400.0	0.79	1.00	
3-2	82	1.363	60.2	6.415	78.8	379.5	0.75	1.00	
3-3	82		60.2			444.0	0.88	1.00	
41	110		80.7			229.0	0.45	1.34	
51	144		105.6			155.0	0.31	1.75	Elastic buckling (C5).
D21	52		22.3			301.0	0.98	0.32	For test D2: L/r is approximate;
31	134	2.330	57.5	5.196	59.0	265.0	0.86	0.83	buckling occurred perpendicular
41	196		84.1			205.0	0.67	1.21	to fixture rotation direction.
E21	66		29.9			642.8	0.90	0.48	
31	132	2.208	59.8	9.643	73.7	481.0	0.68	0.96	
41	178		80.6			365.0	0.51	1.29	
51	260		117.8			200.0	0.28	1.89	Elastic buckling (E5).
F21	94		29.9			422.0	0.96	0.44	
31	188	3.147	59.7	7.096	62.0	365.0	0.83	0.88	No local
41	276		87.7			257.0	0.58	1.29	Minimal local yield(F4).buckling.
G21	91		30.1			830.0	0.88	0.47	
31	182	3.026	60.1	13.349	71.0	768.0	0.81	0.95	
41	273		90.2			412.0	0.44	1.42	
H3-1	188		59.7			380.1	0.86	0.91	
3-2	188		59.7			390.0	0.89	0.91	
4-1	268	3.147	85.2	6.642	66.2	360.0	0.82	1.30	Dubious test:Sides out-of-flat.
4-2	268		85.2			256.7	0.58	1.30	
4-3	268		85.2			395.5	0.90	1.30	Dubious test:Sides out-of-flat

(1) Average measured area (see Table 2).

(2) Static yield stress based on stub-column test.

(3) Static (zero strain rate) value.

(4) $\lambda = \frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \cdot \frac{L}{r}$ (E = 29000 ksi)

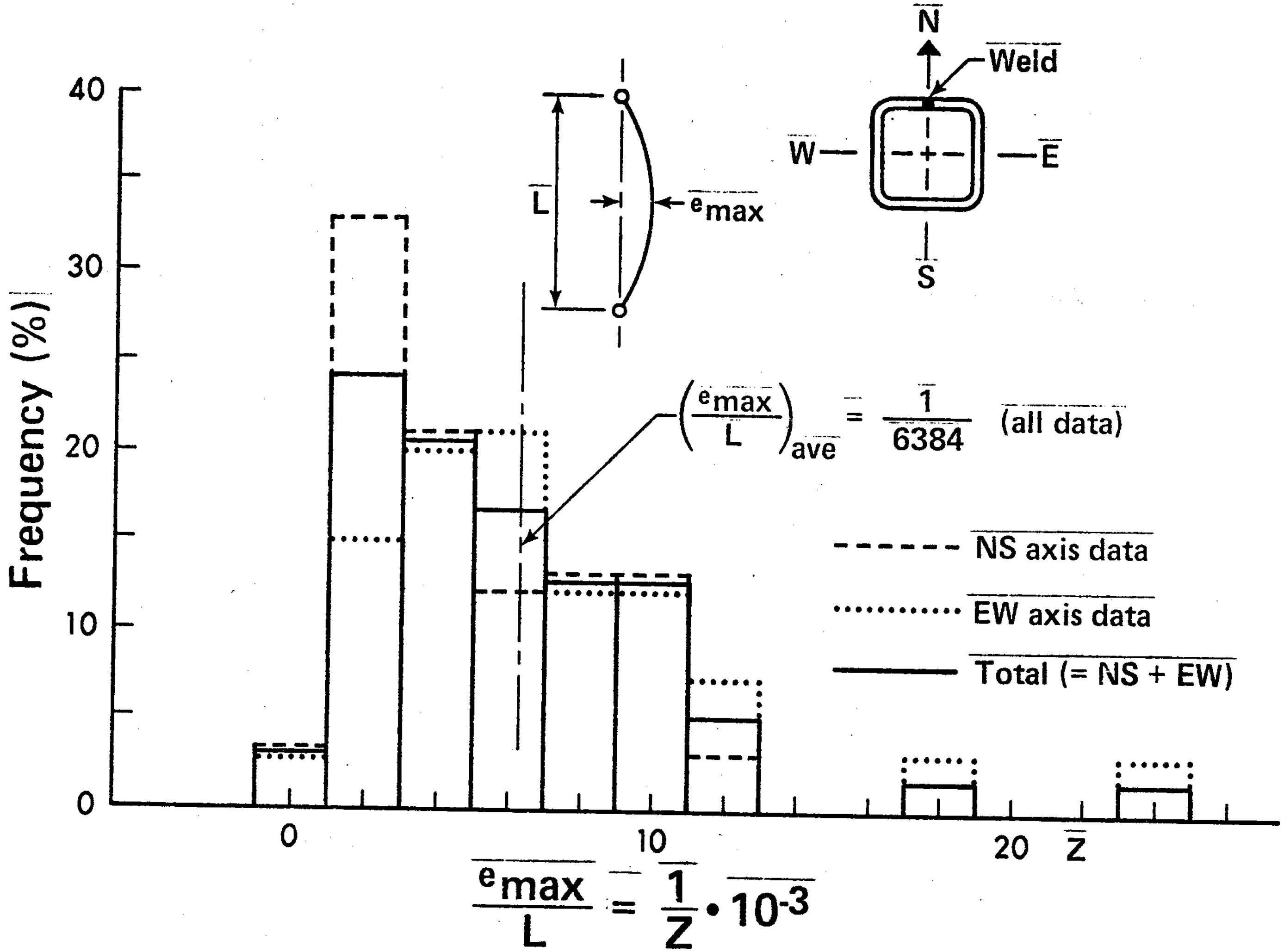

Figure 1 Frequency Distributions for Measured Out-of-Straightness Data (30 specimens, 2 axes, separately and combined).

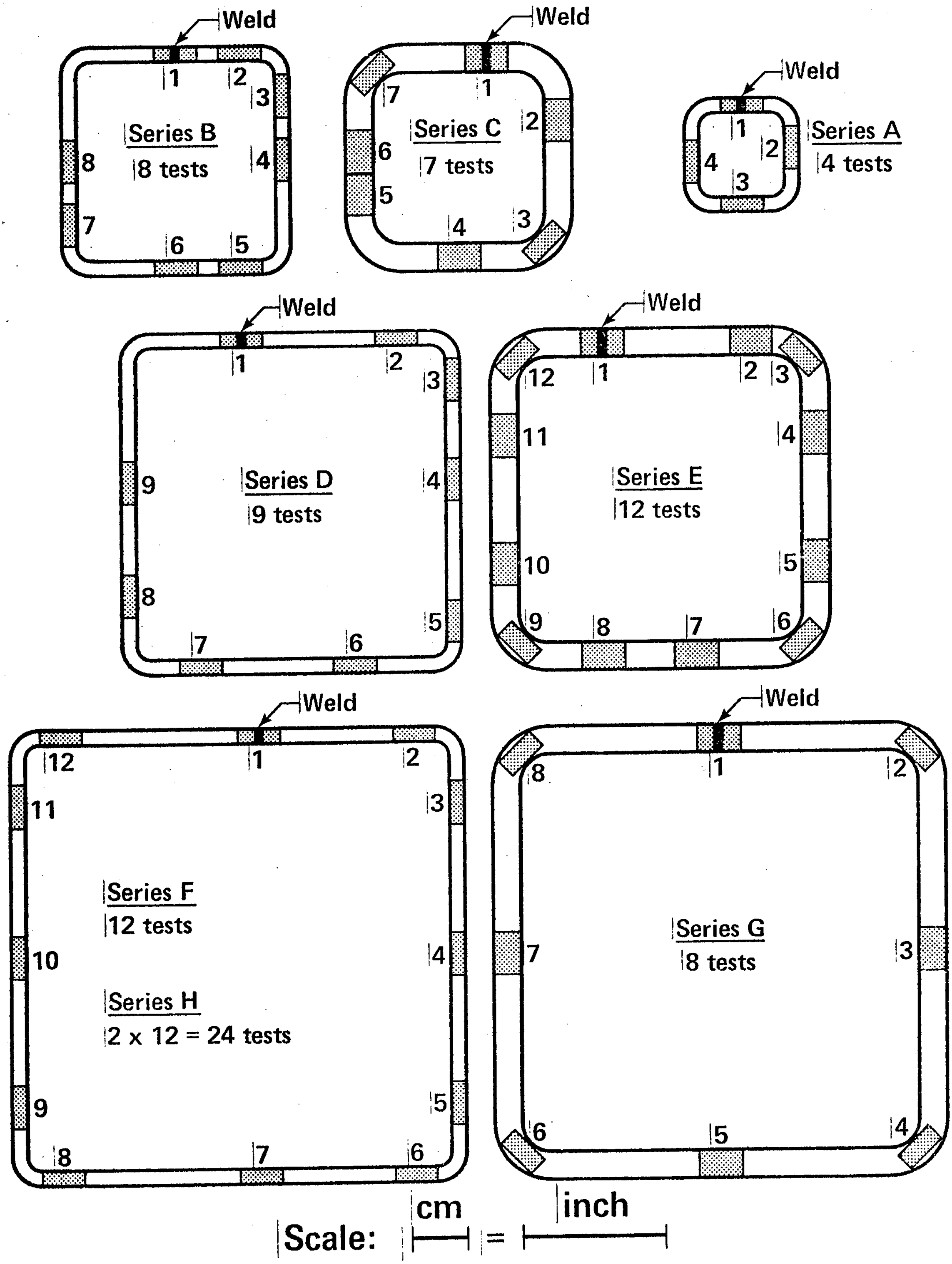

Figure 2 Tension Specimen Locations in HSS Series A through H (cross-hatched areas and numbers indicate locations and specimen nos.).

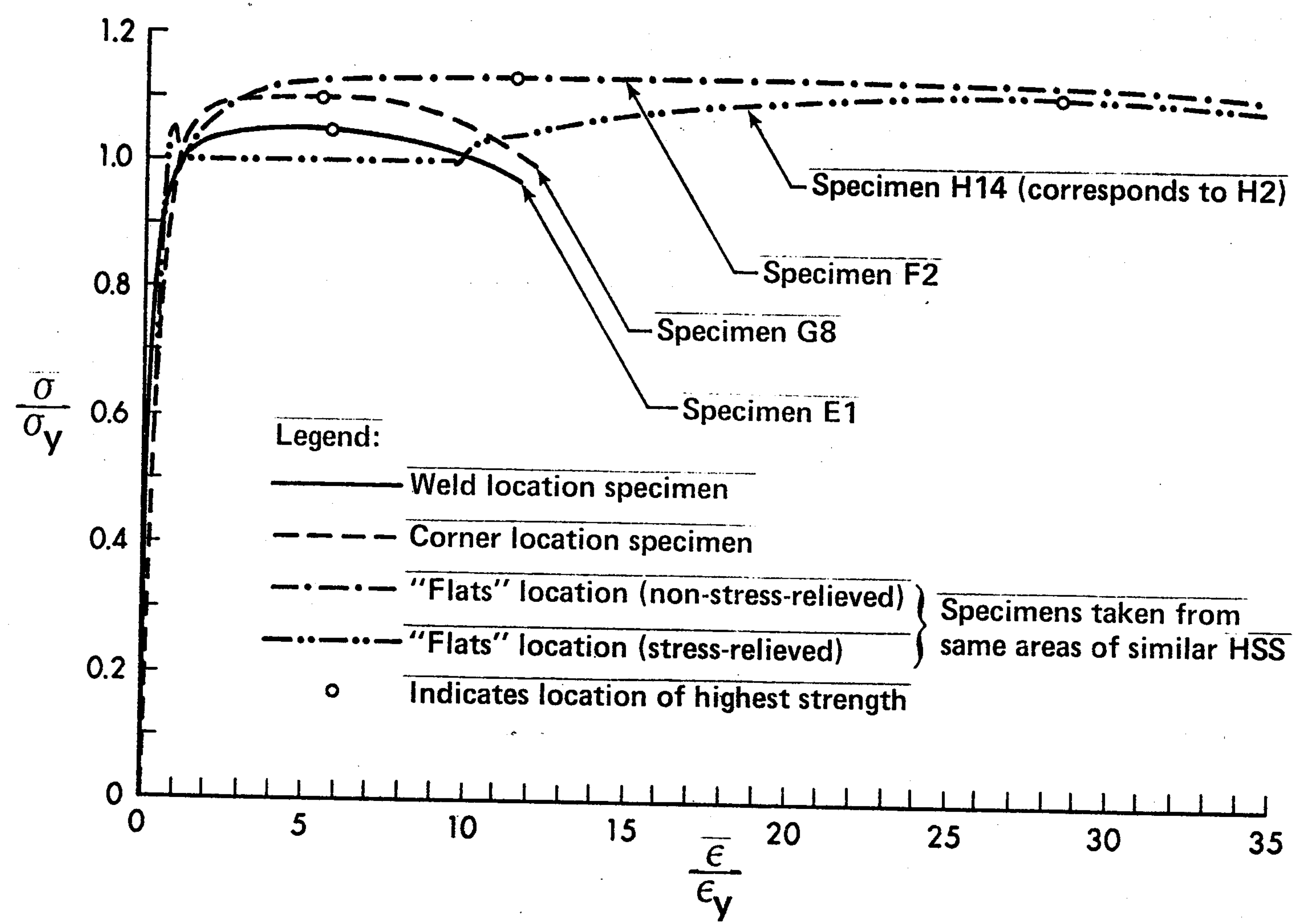

Figure 3 Non-Dimensional Stress-Strain Curves for Some Typical HSS Tension Specimens (refer to Fig. 2 for locations).

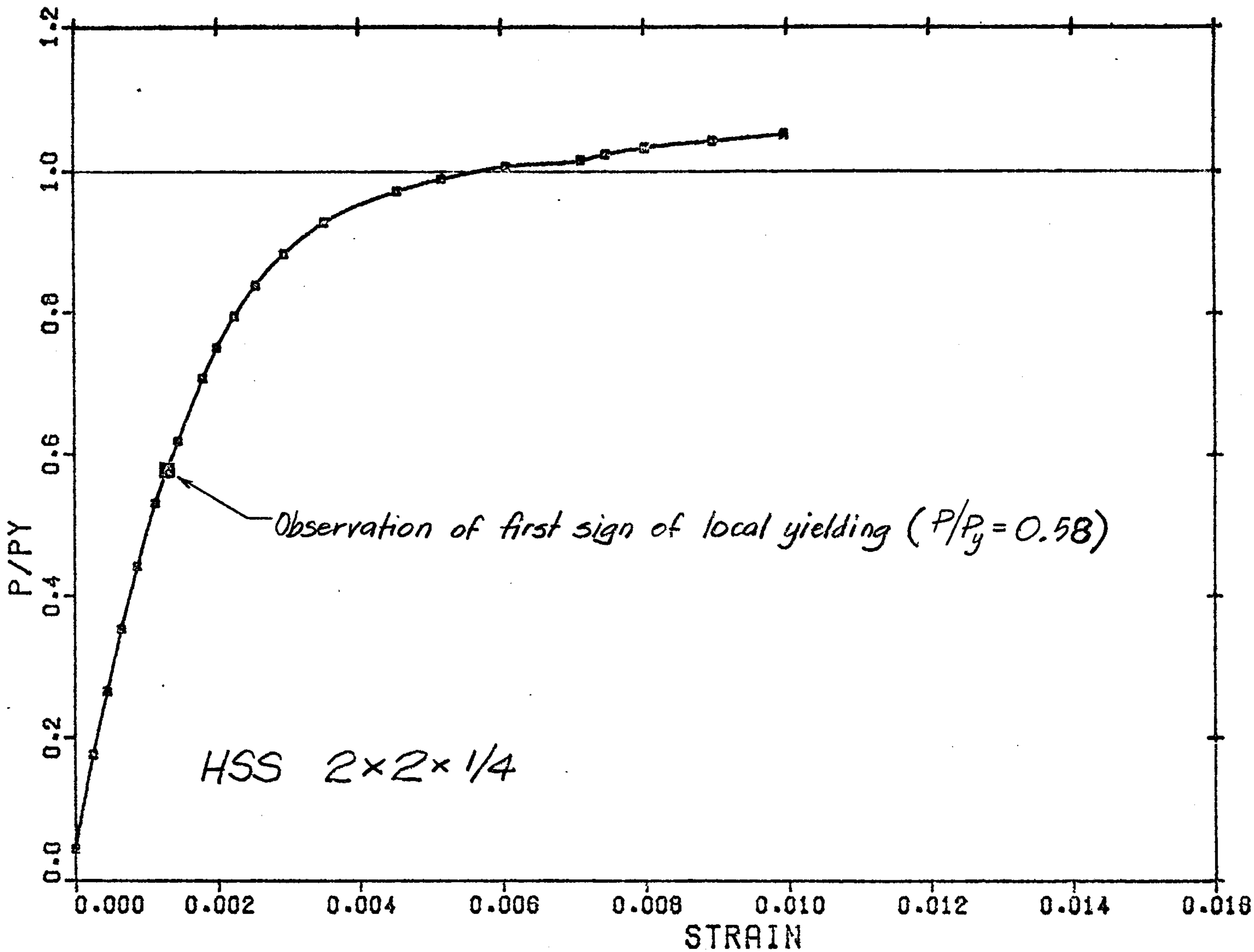

Figure 4 Stub-Column Curve for HSS 2x2x1/4 (Series A).

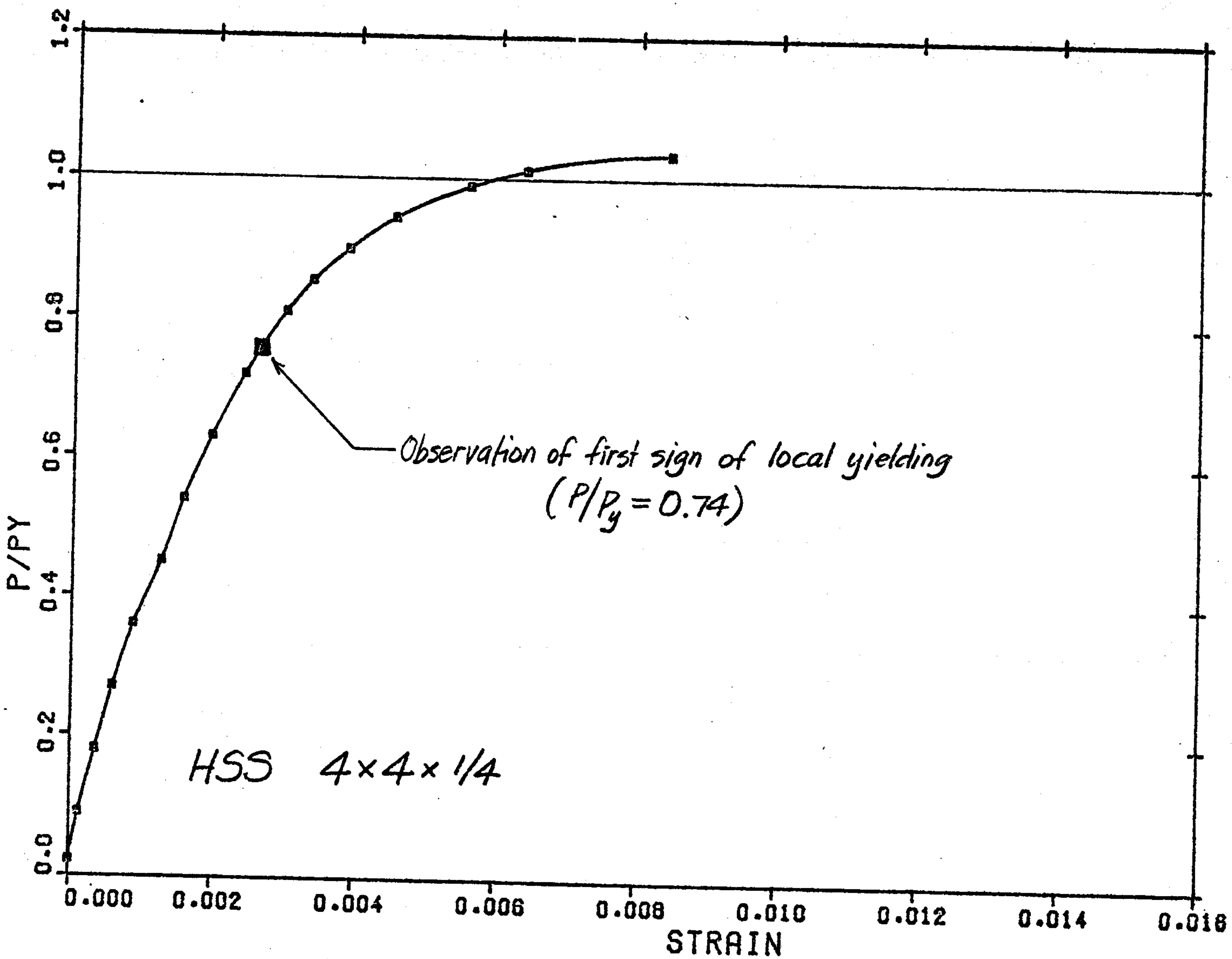

Figure 5 Stub-Column Curve for HSS 4x4x1/4 (Series B).

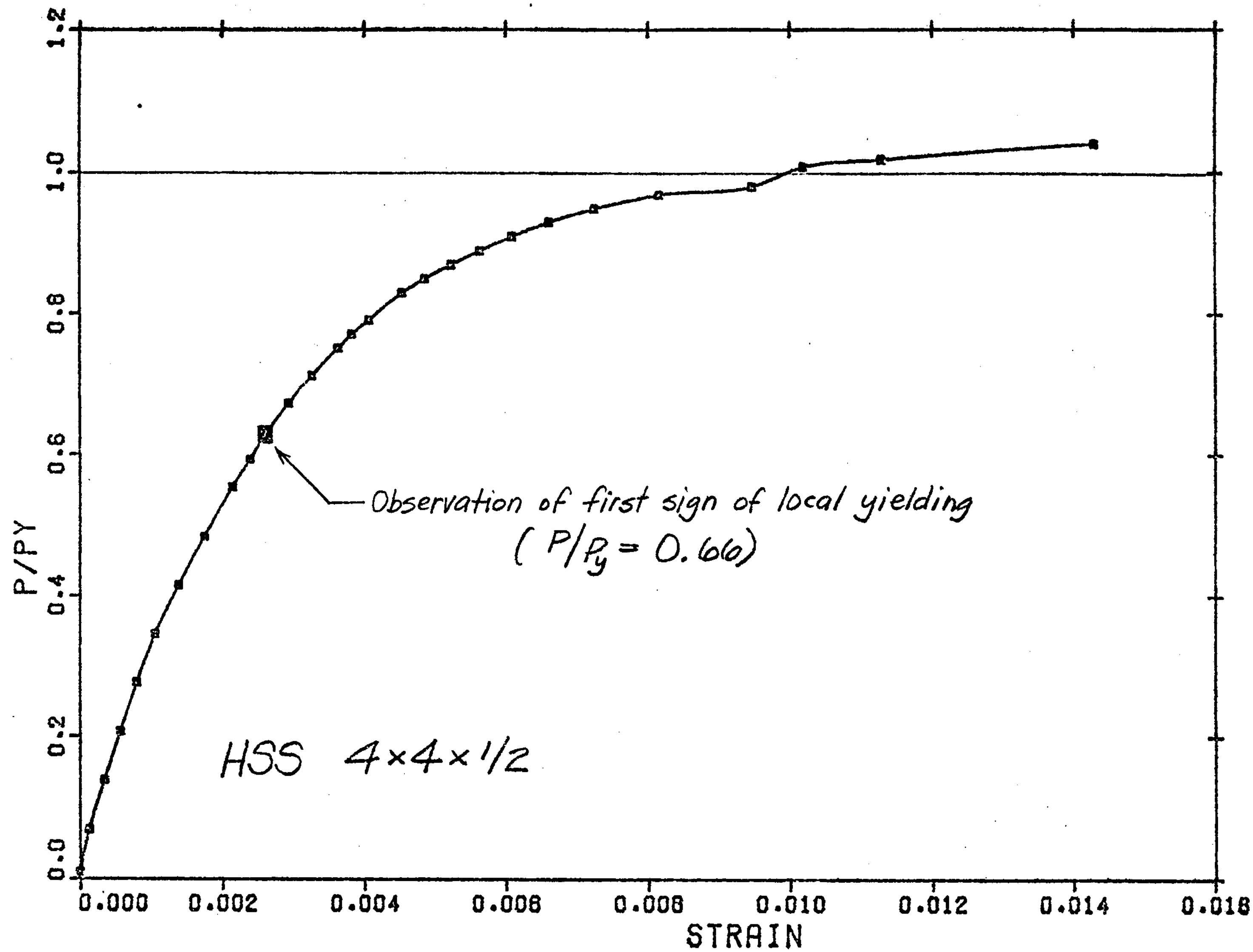

Figure 6 Stub-Column Curve for HSS 4x4x1/2 (Series C).

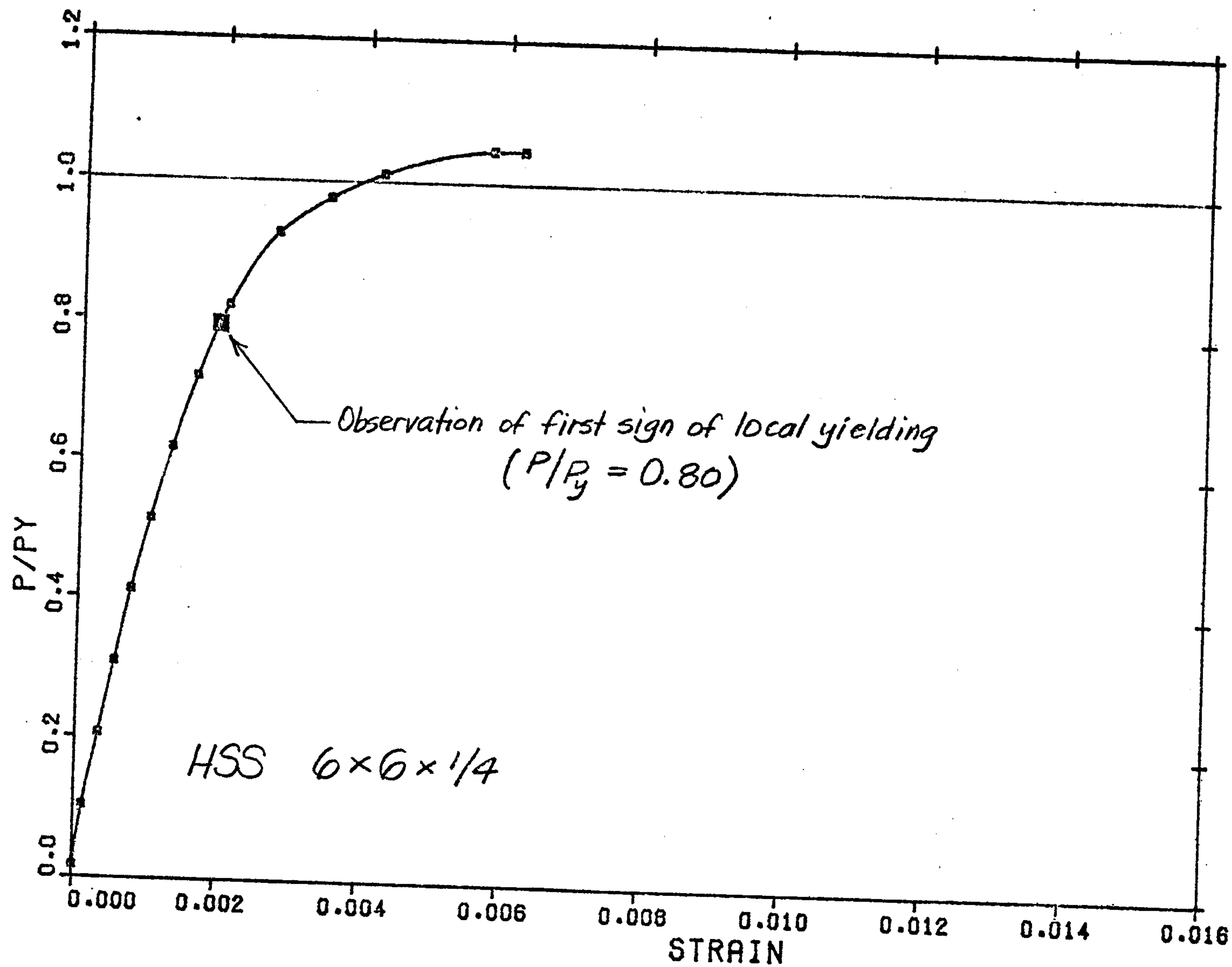

Figure 7 Stub-Column Curve for HSS 6x6x1/4 (Series D).

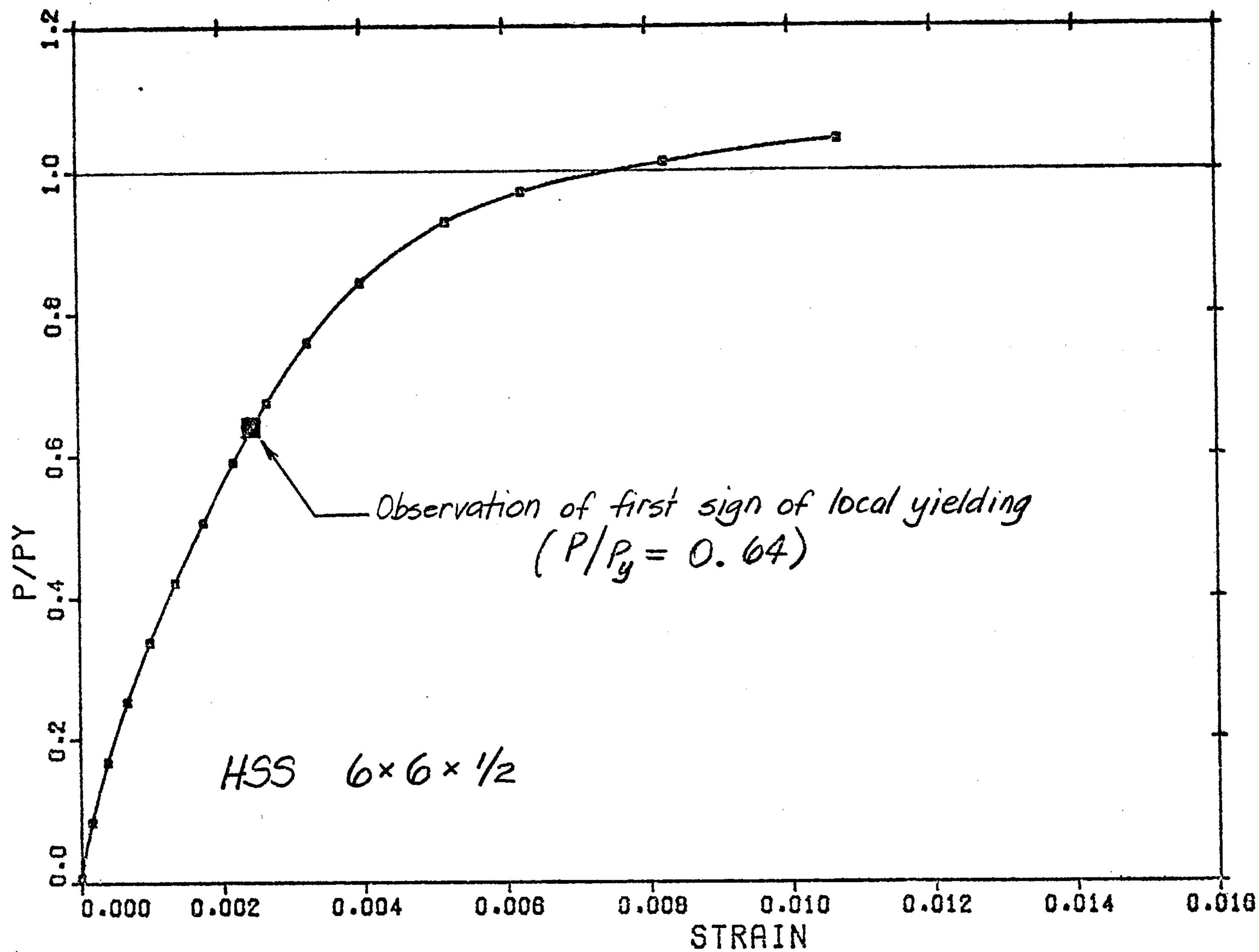

Figure 8 Stub-Column Curve for HSS 6x6x1/2 (Series E).

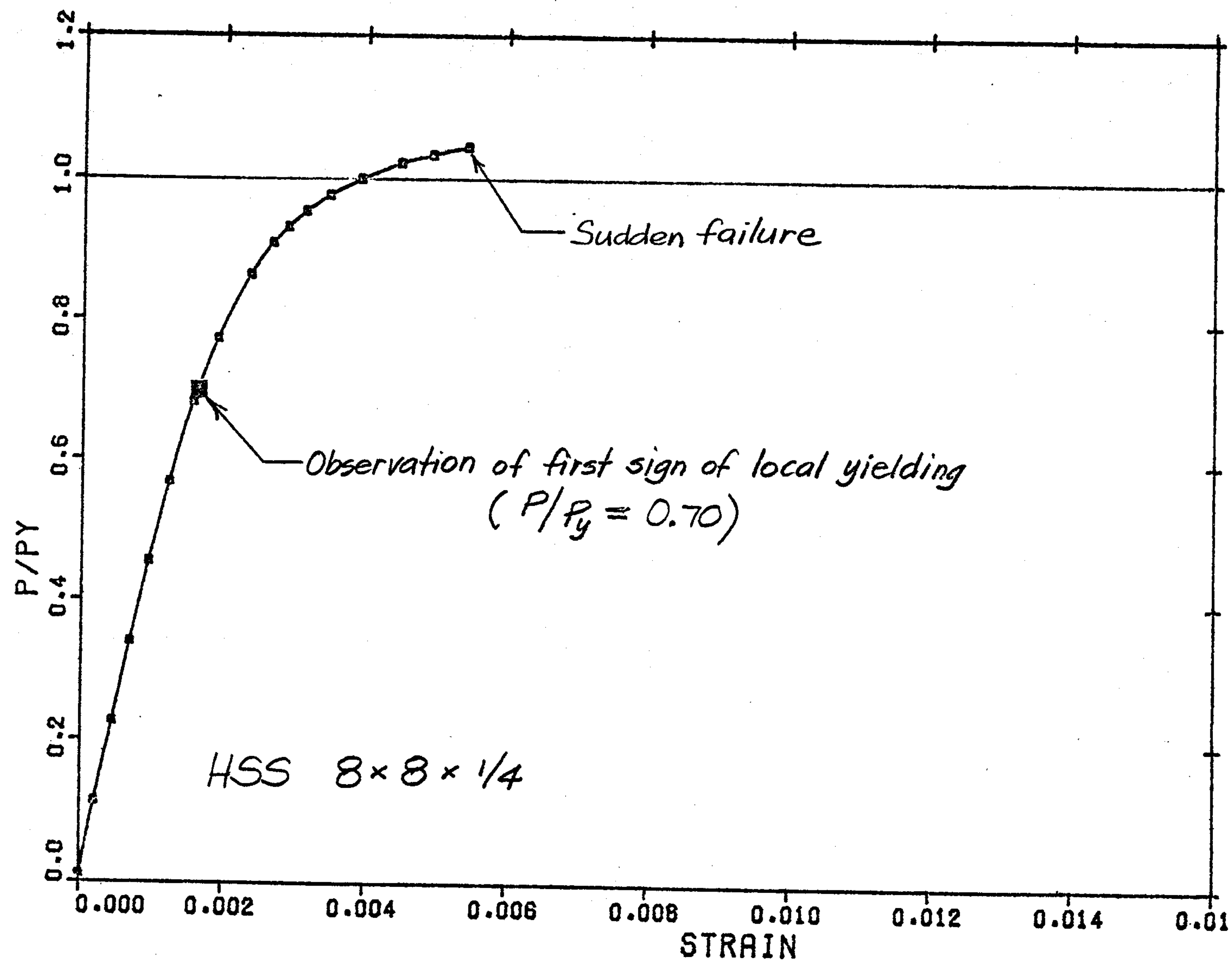

Figure 9 Stub-Column Curve for HSS 8x8x1/4 (Series F).

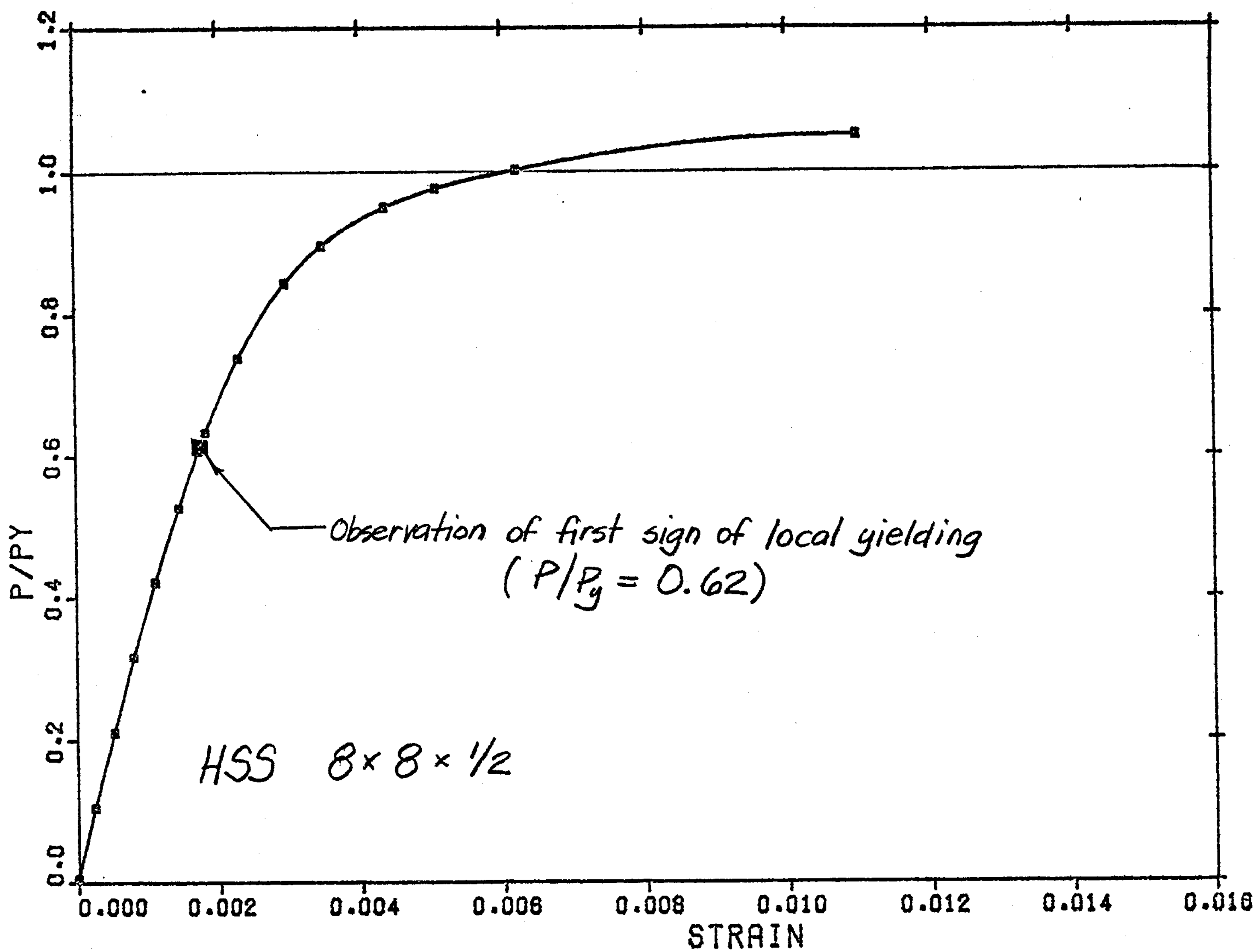

Figure 10 Stub-Column Curve for HSS 8x8x1/2 (Series G).

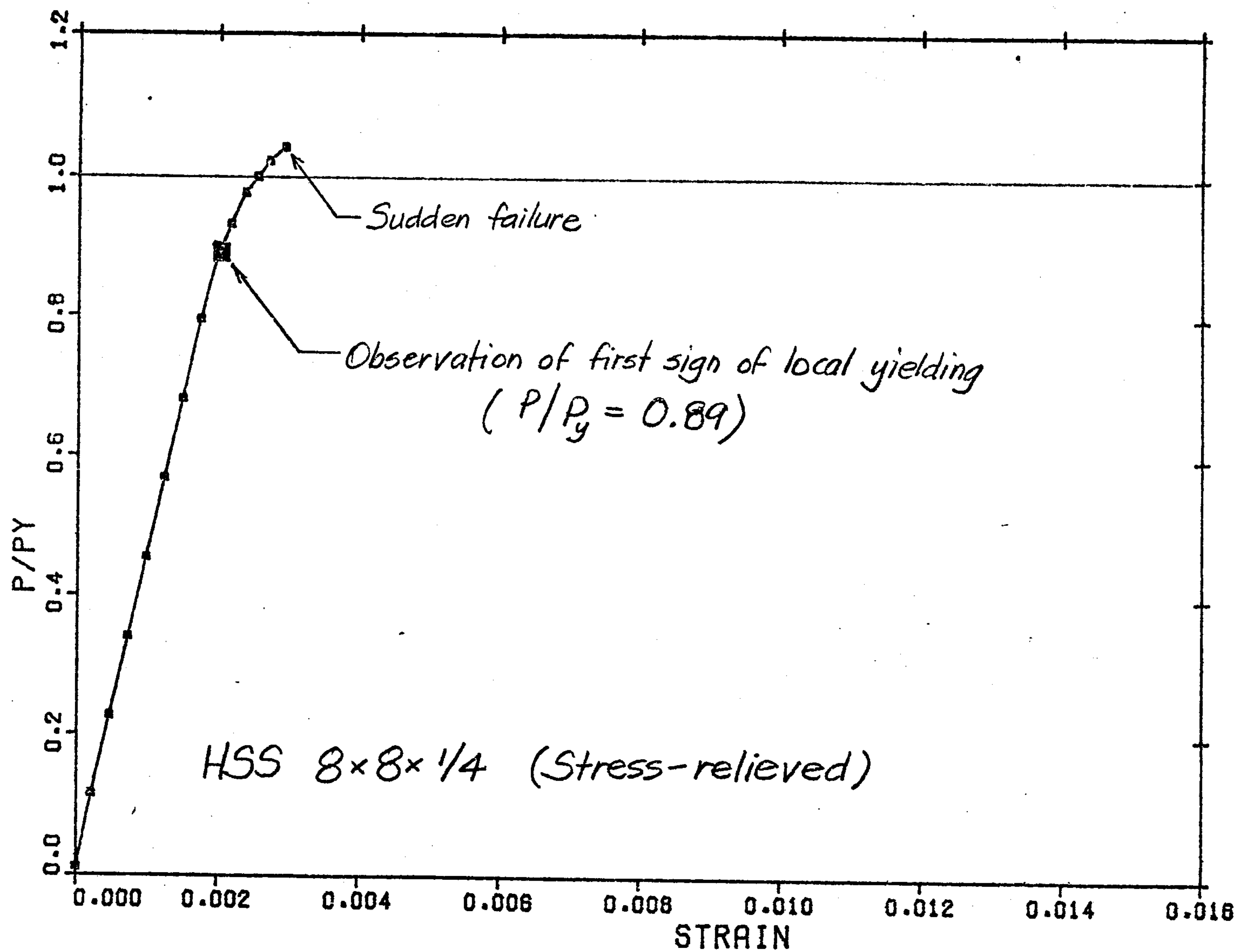

Figure 11 Stub-Column Curve for HSS 8x8x1/4 (Stress-Relieved) (Series H).

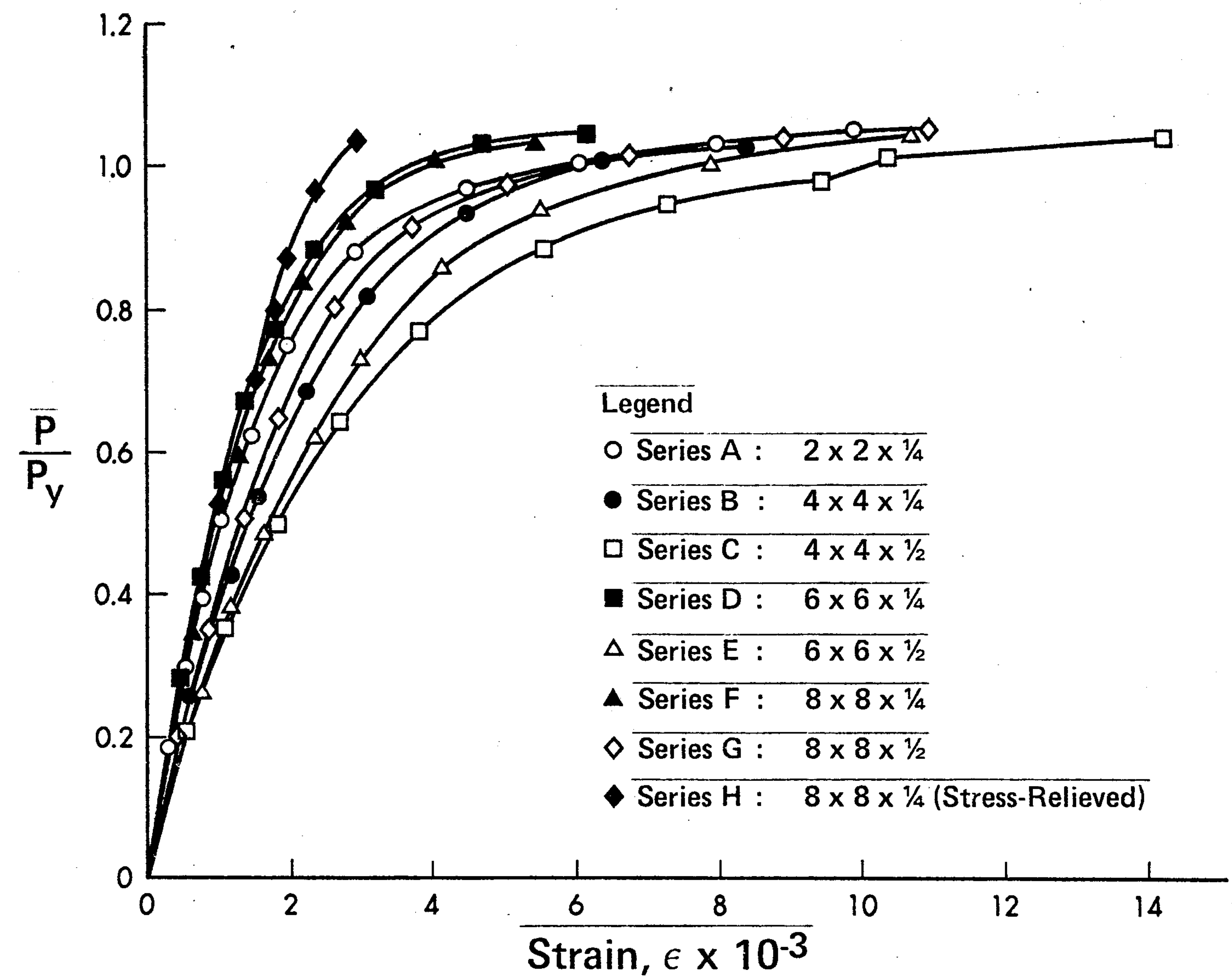

Figure 12 Comparison of the Stub-Column Curves for All Specimens (Series A through H).

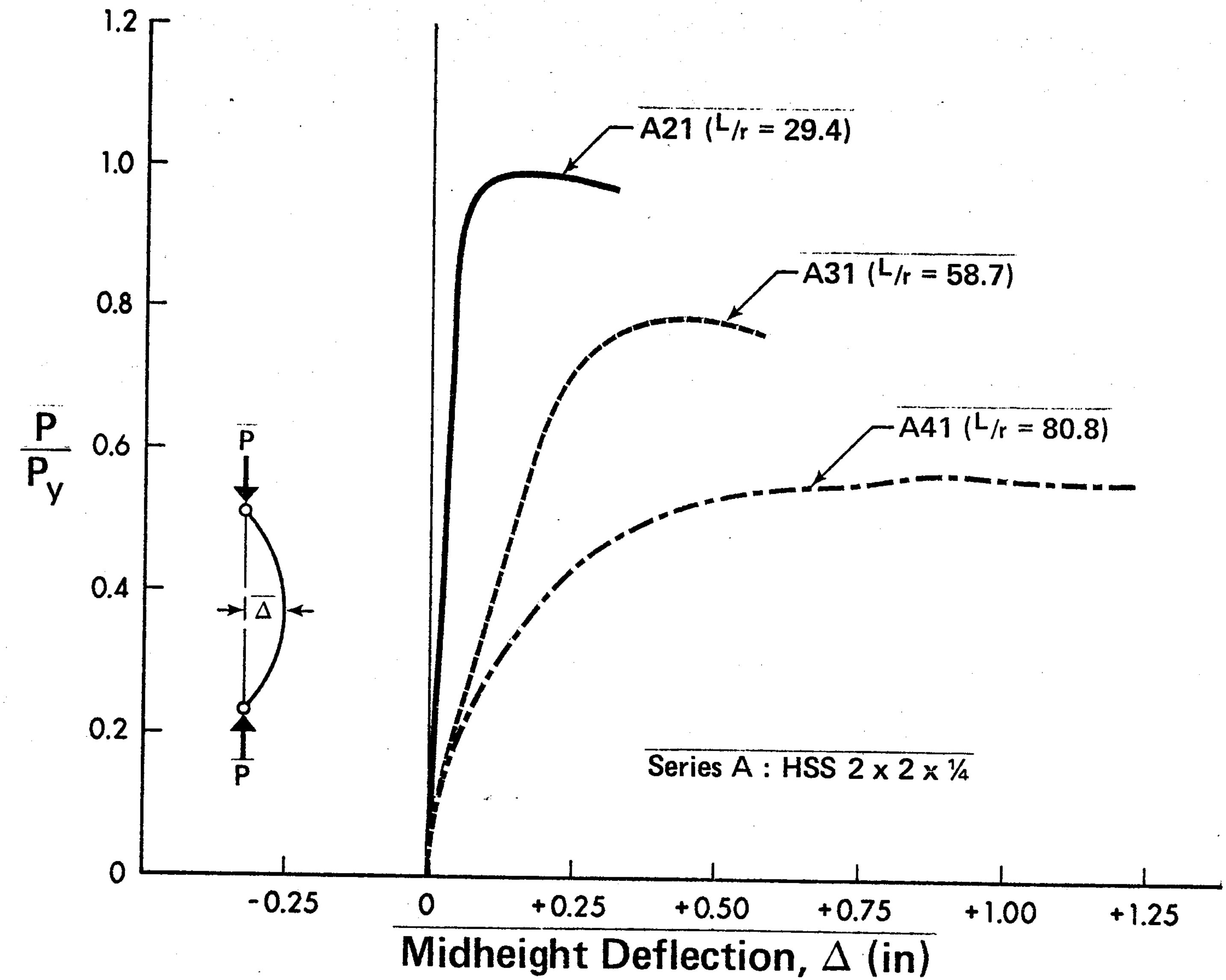

Figure 13 Load-Deflection Curves for Series A Long Columns

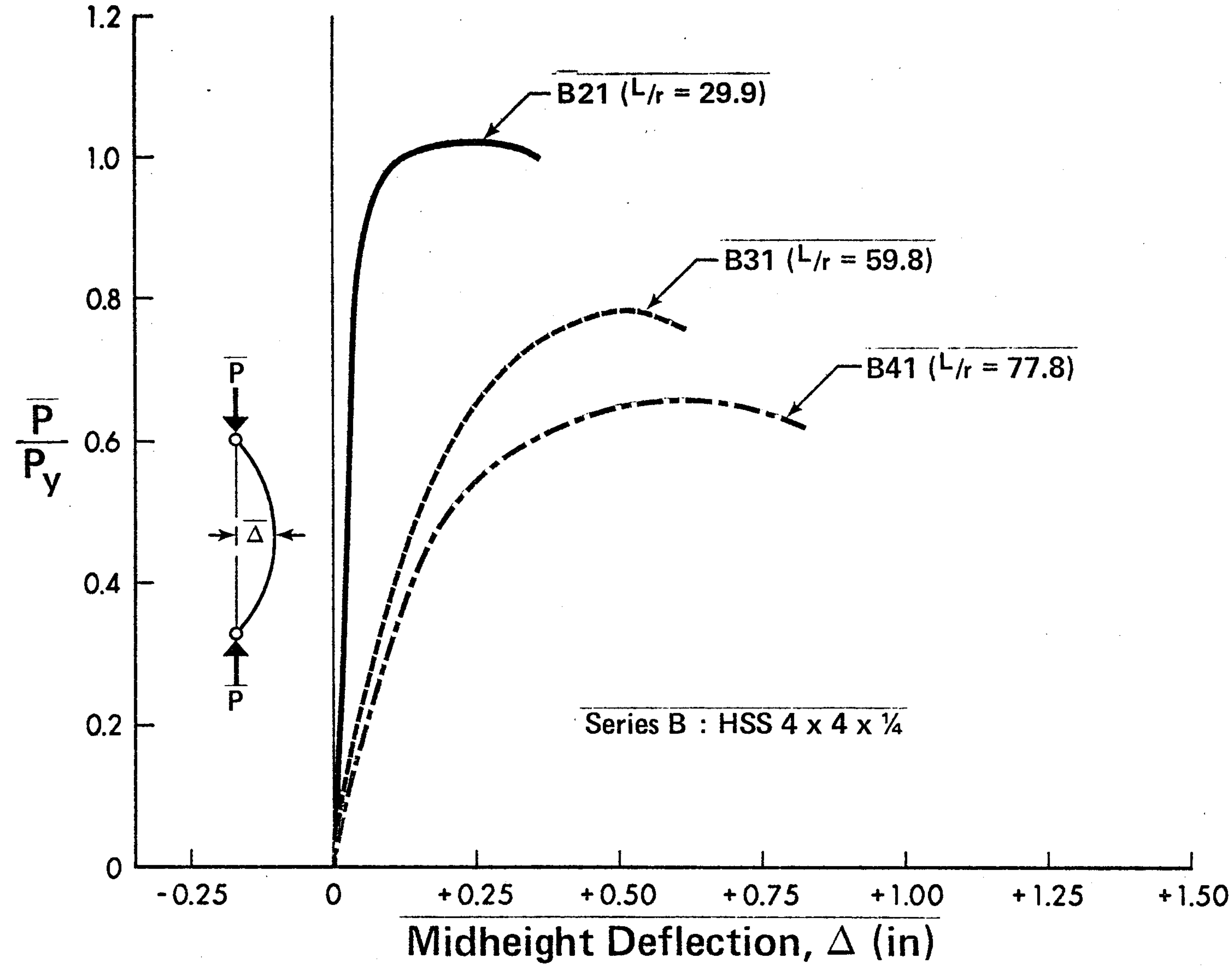

Figure 14 Load-Deflection Curves for Series B Long Columns

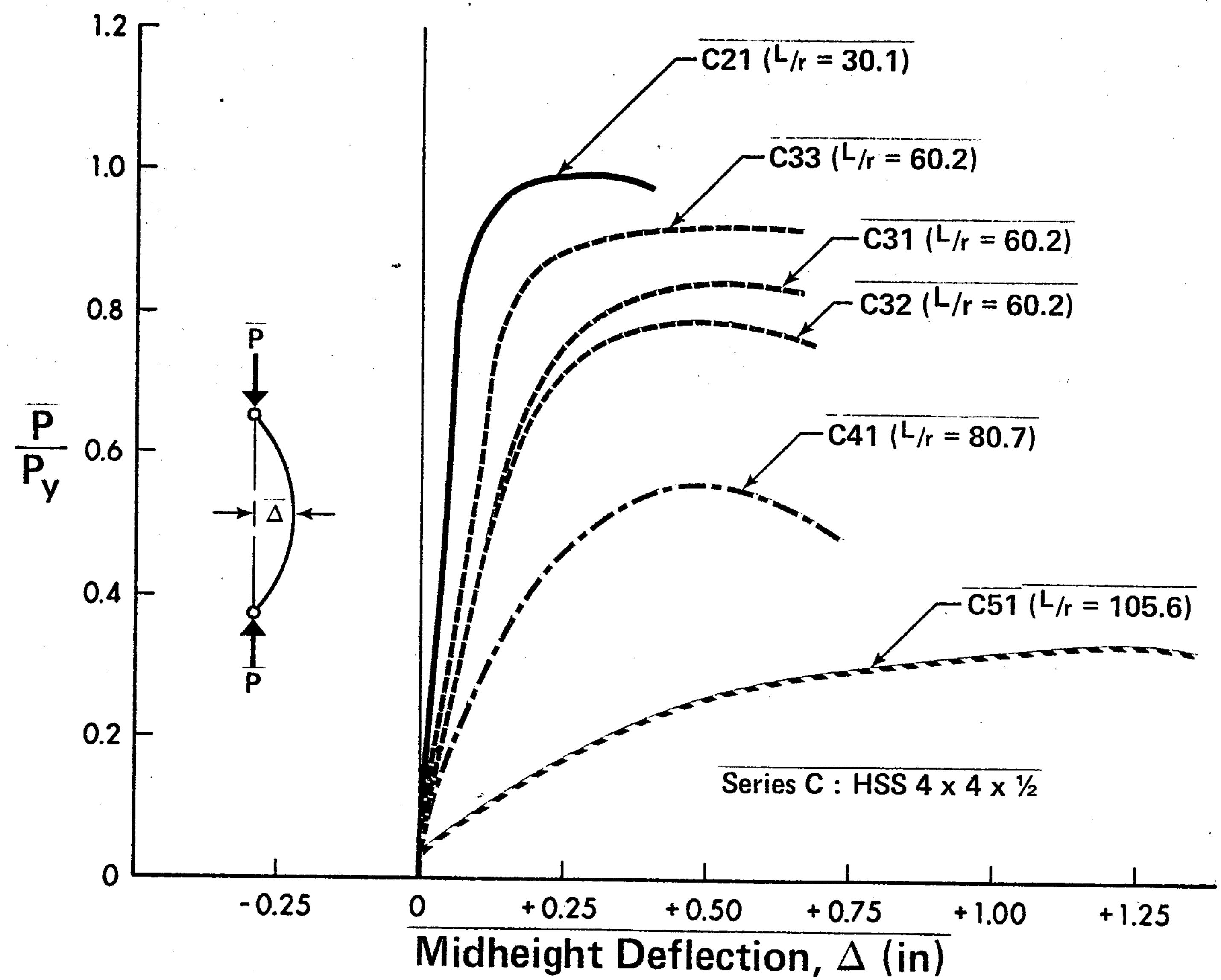

Figure 15 Load-Deflection Curves for Series C Long Columns

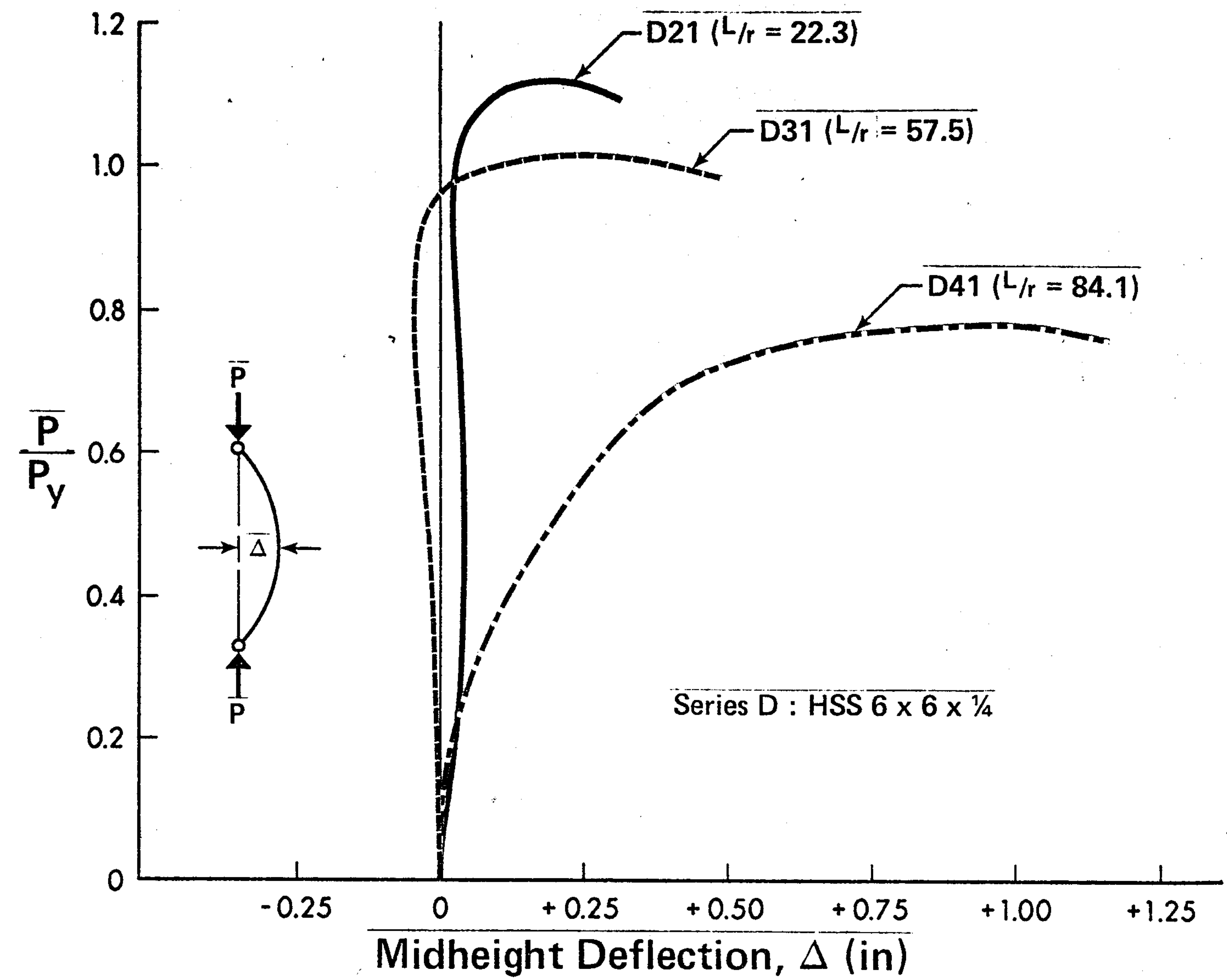

Figure 16 Load-Deflection Curves for Series D Long Columns

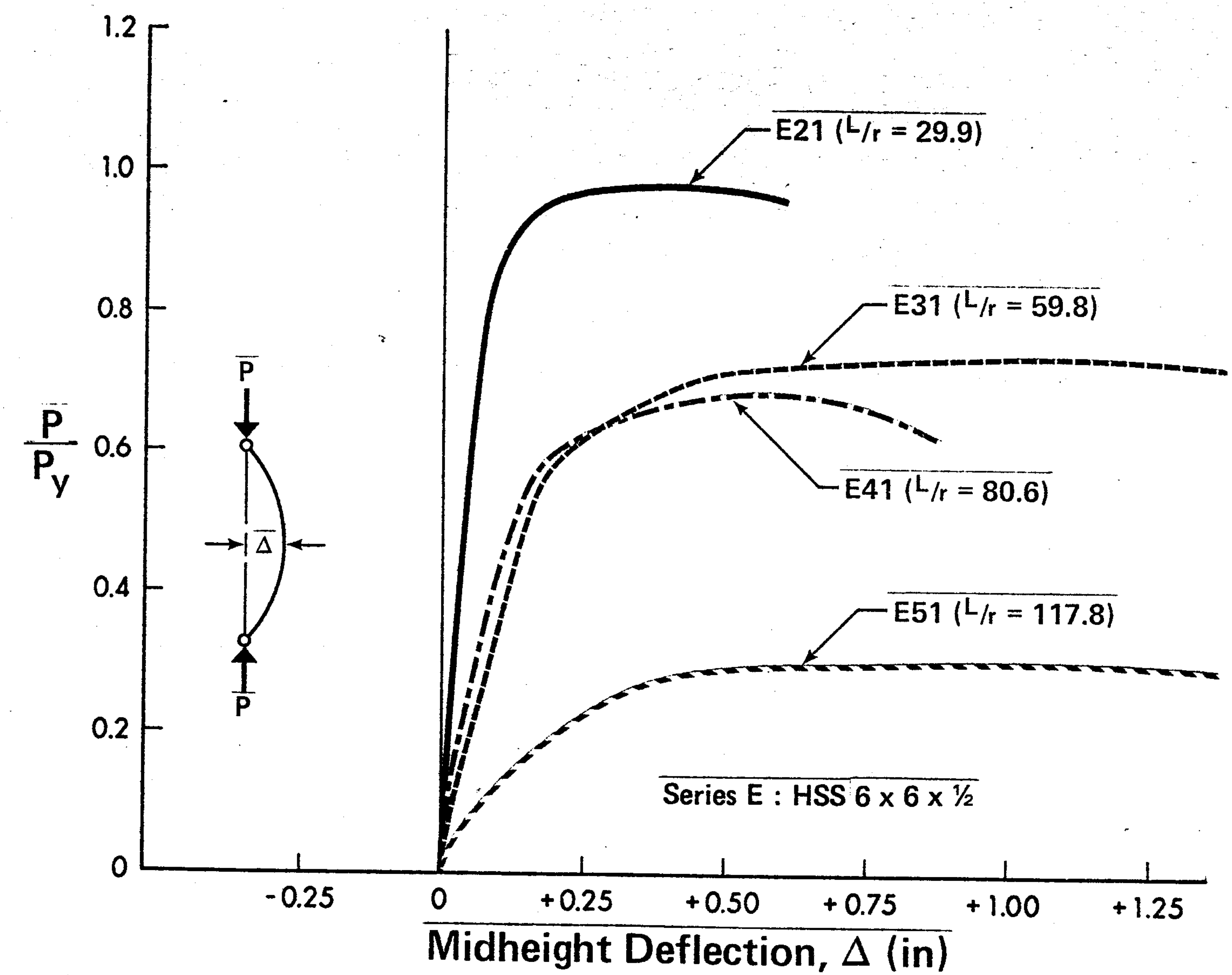

Figure 17 Load-Deflection Curves for Series E Long Columns

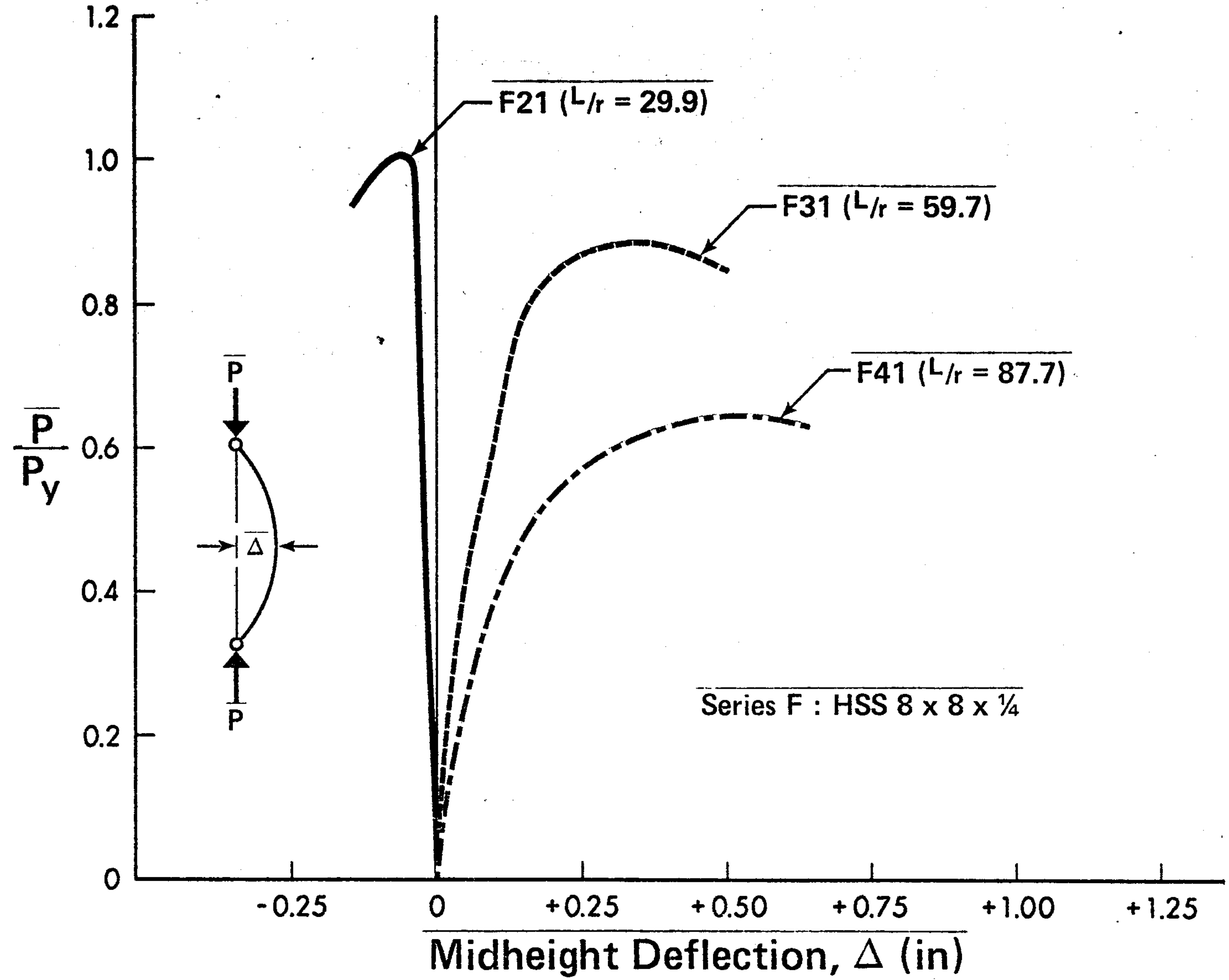

Figure 18 Load-Deflection Curves for Series F Long Columns

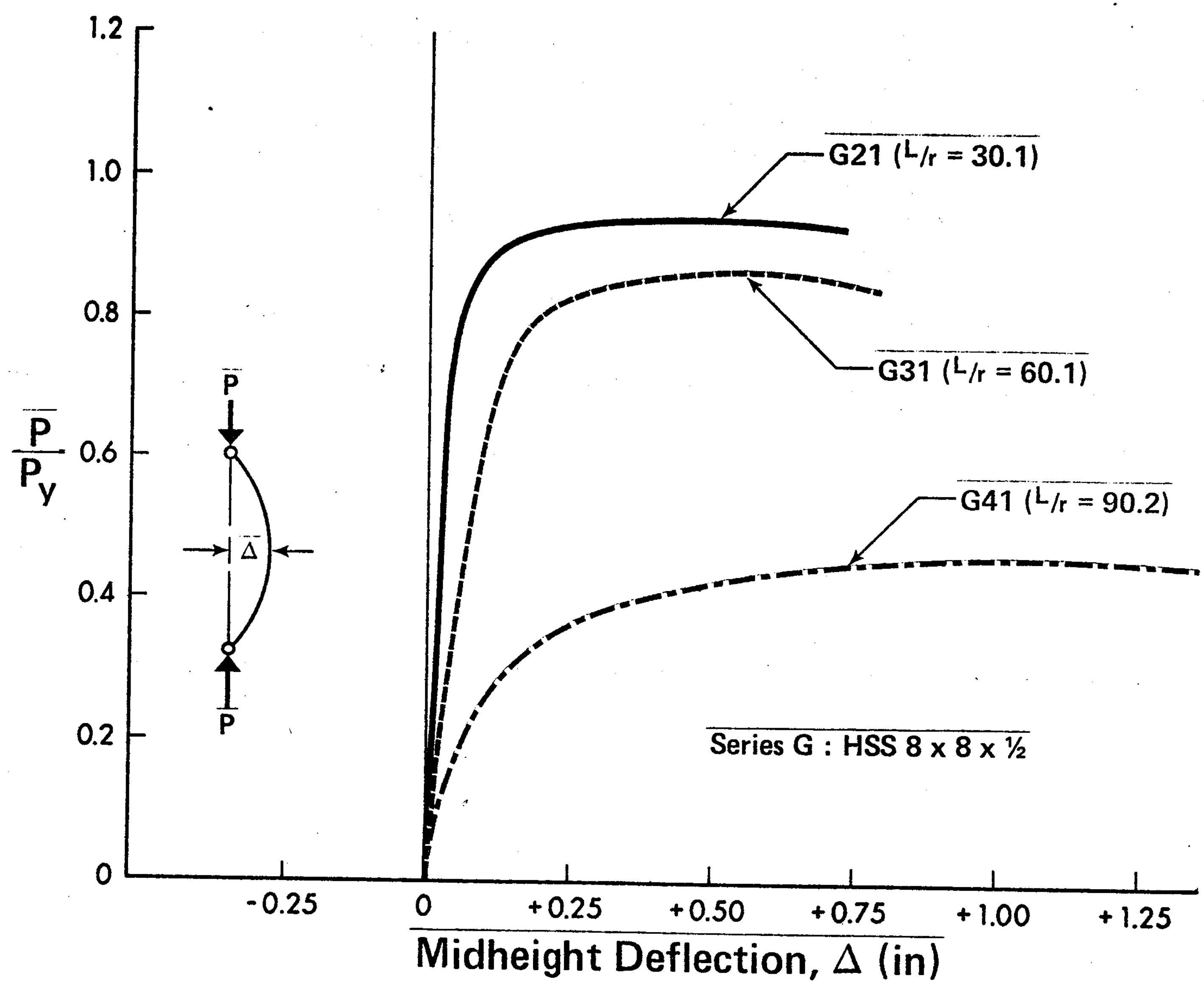

Figure 19 Load-Deflection Curves for Series G Long Columns

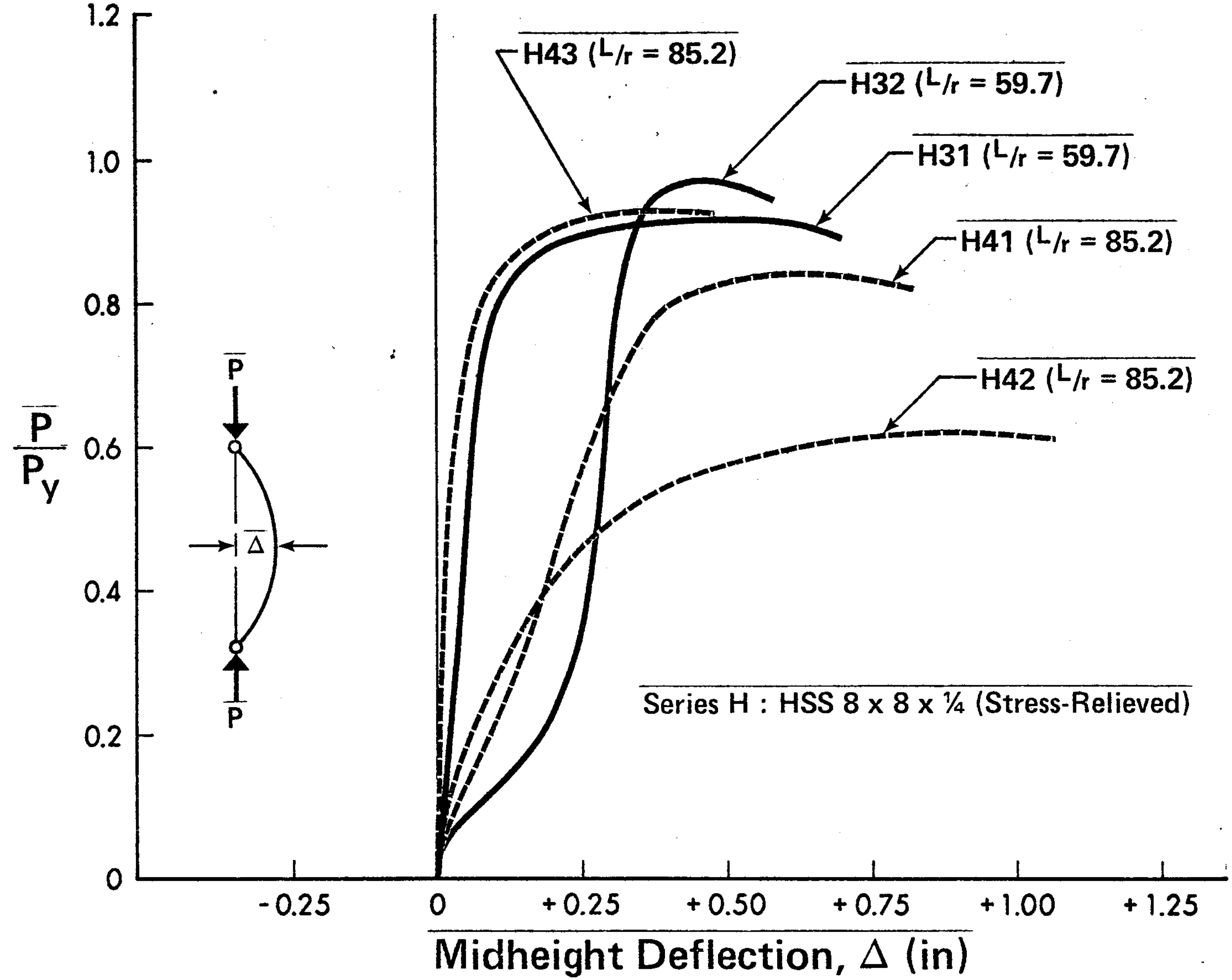

Figure 20 Load-Deflection Curves for Series H Long Columns

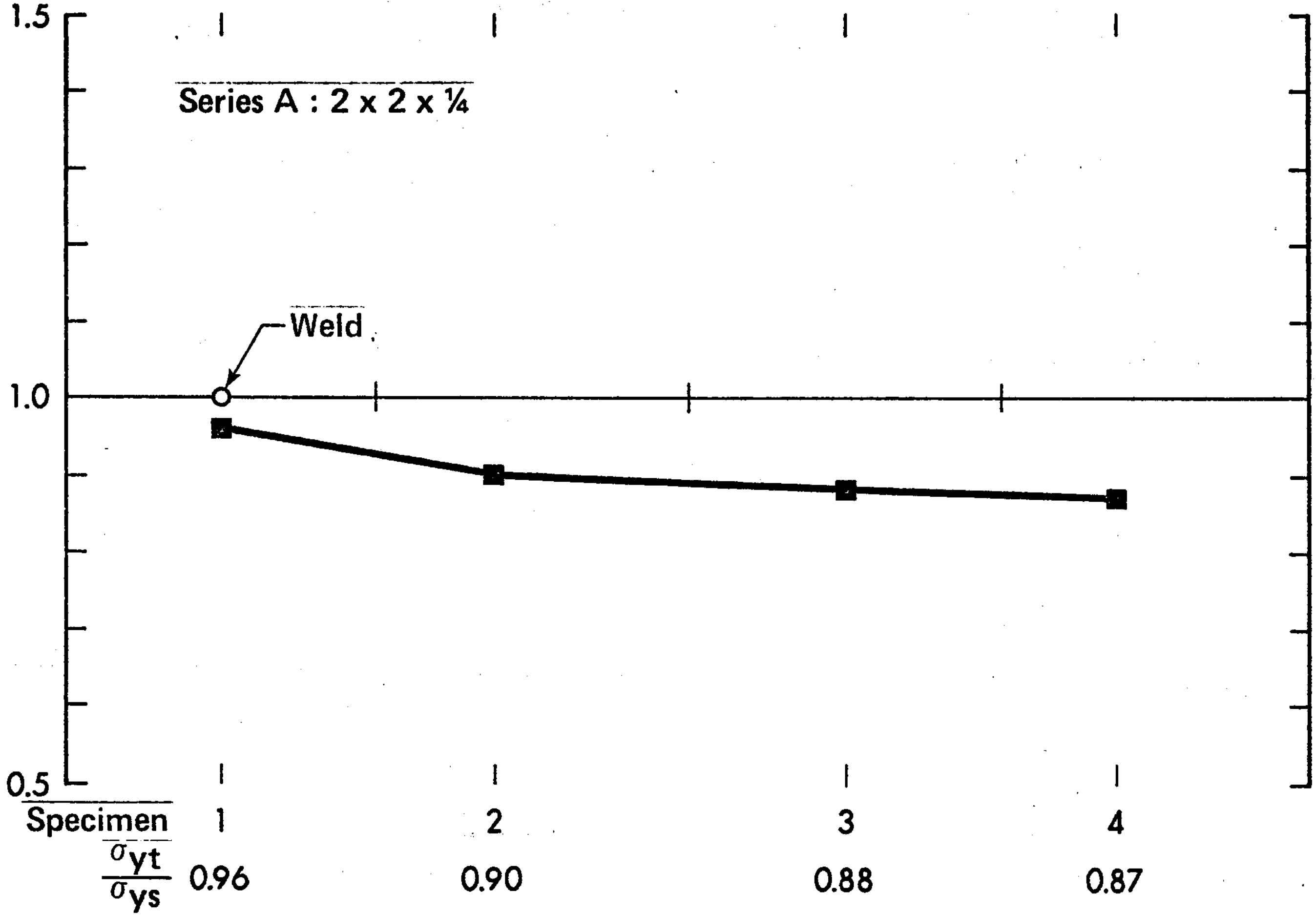

Figure 21 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series A

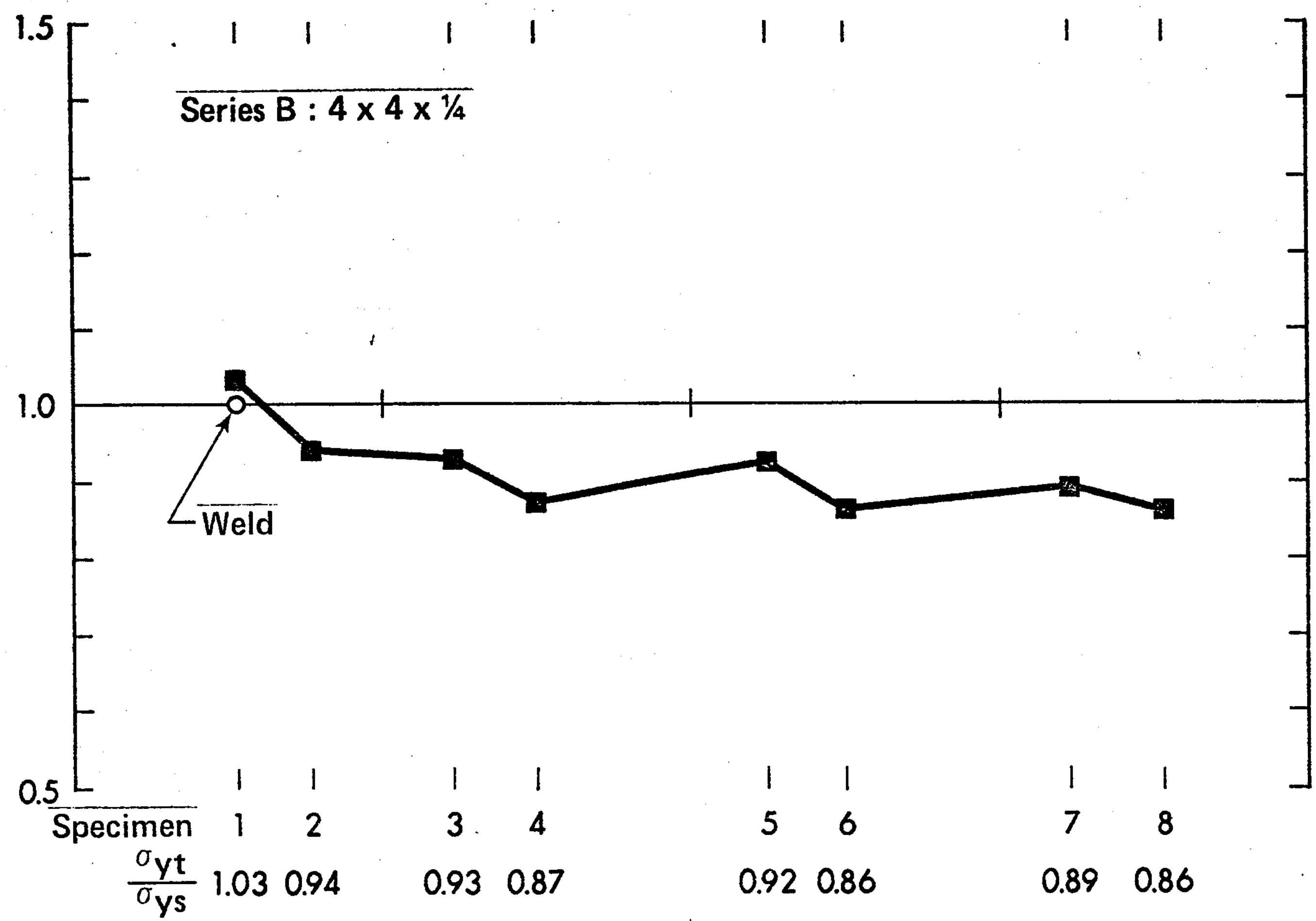

Figure 22 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series B

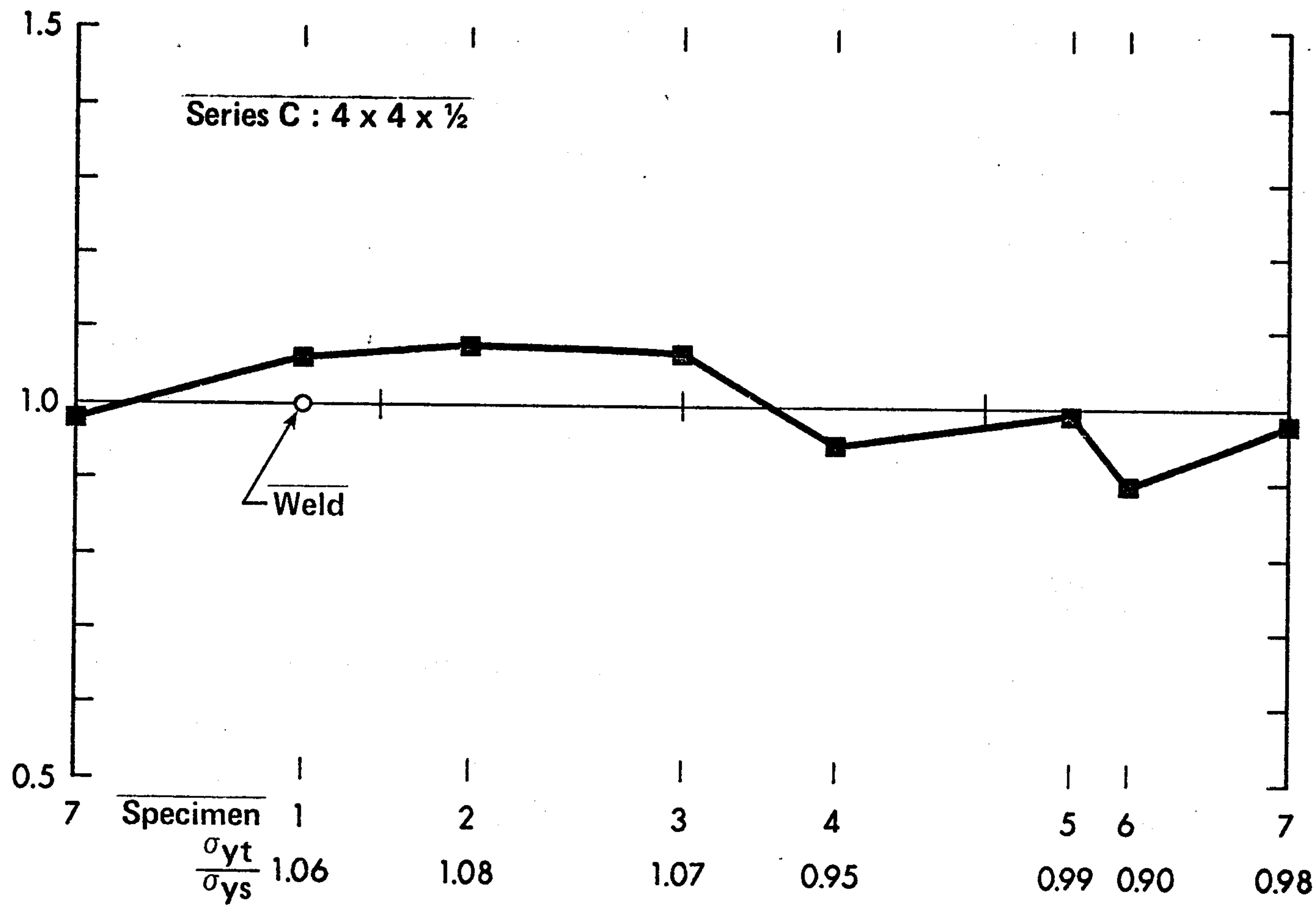

Figure 23 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series C

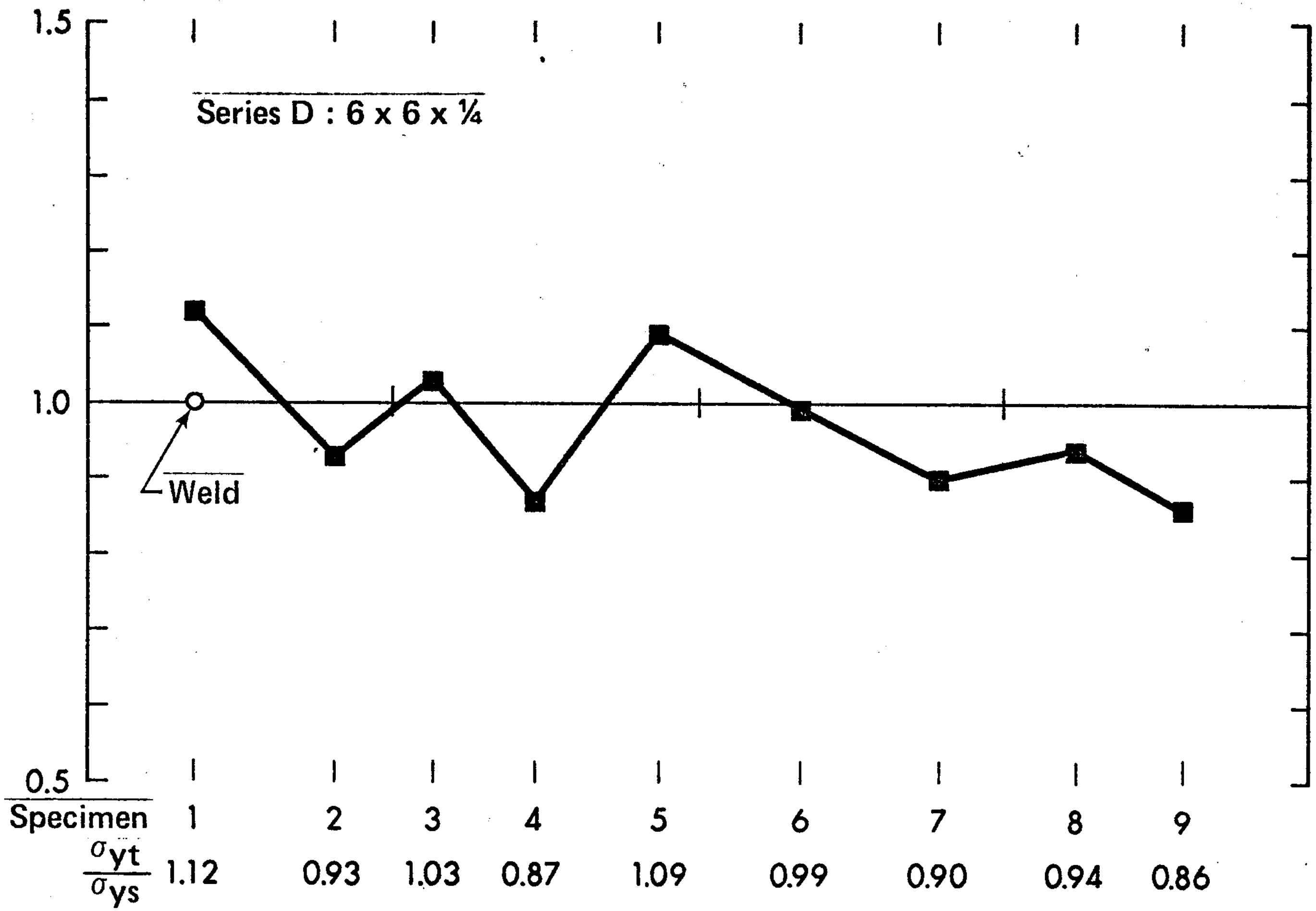

Figure 24 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series D

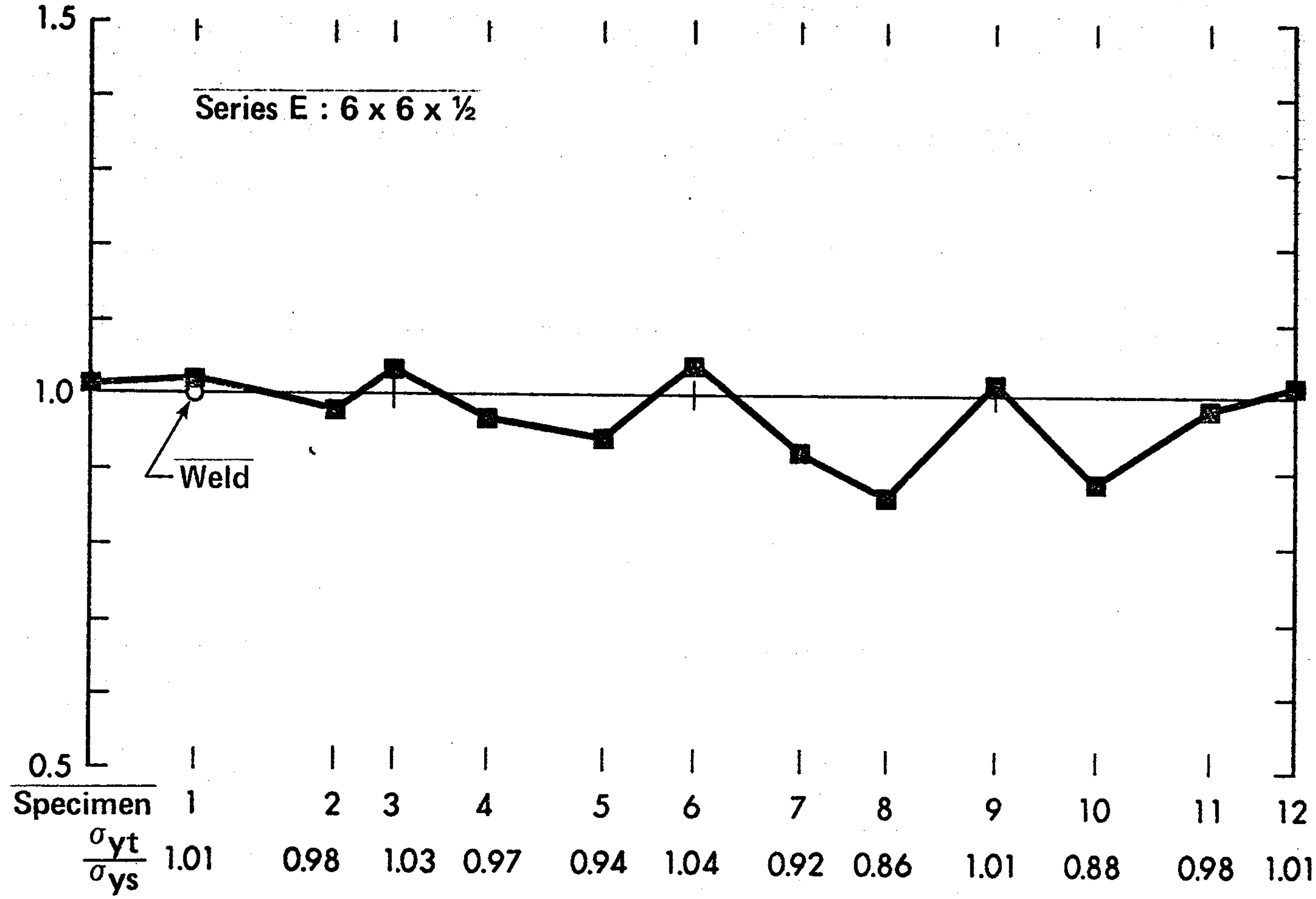

Figure 25 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series E

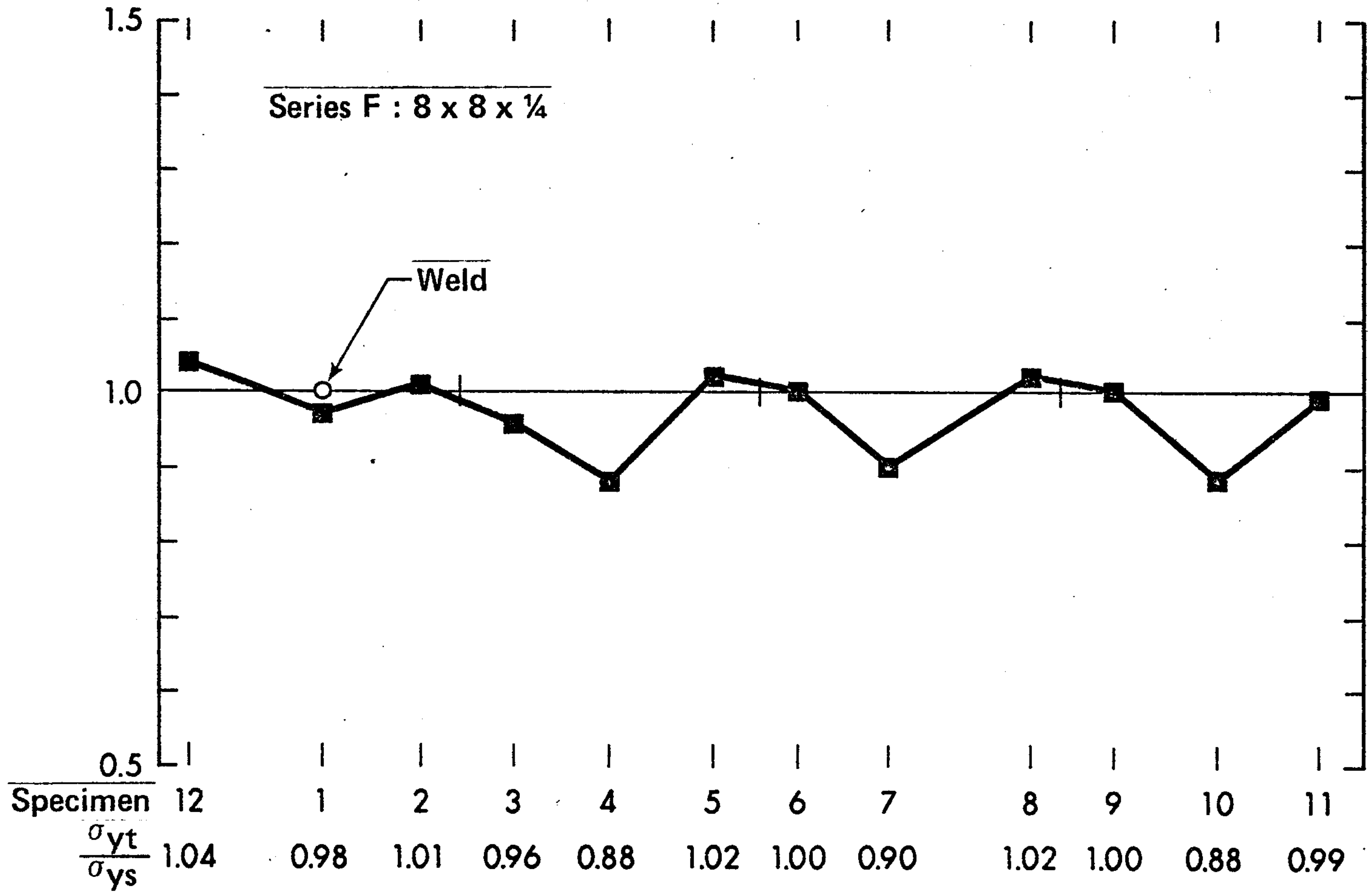

Figure 26 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series F

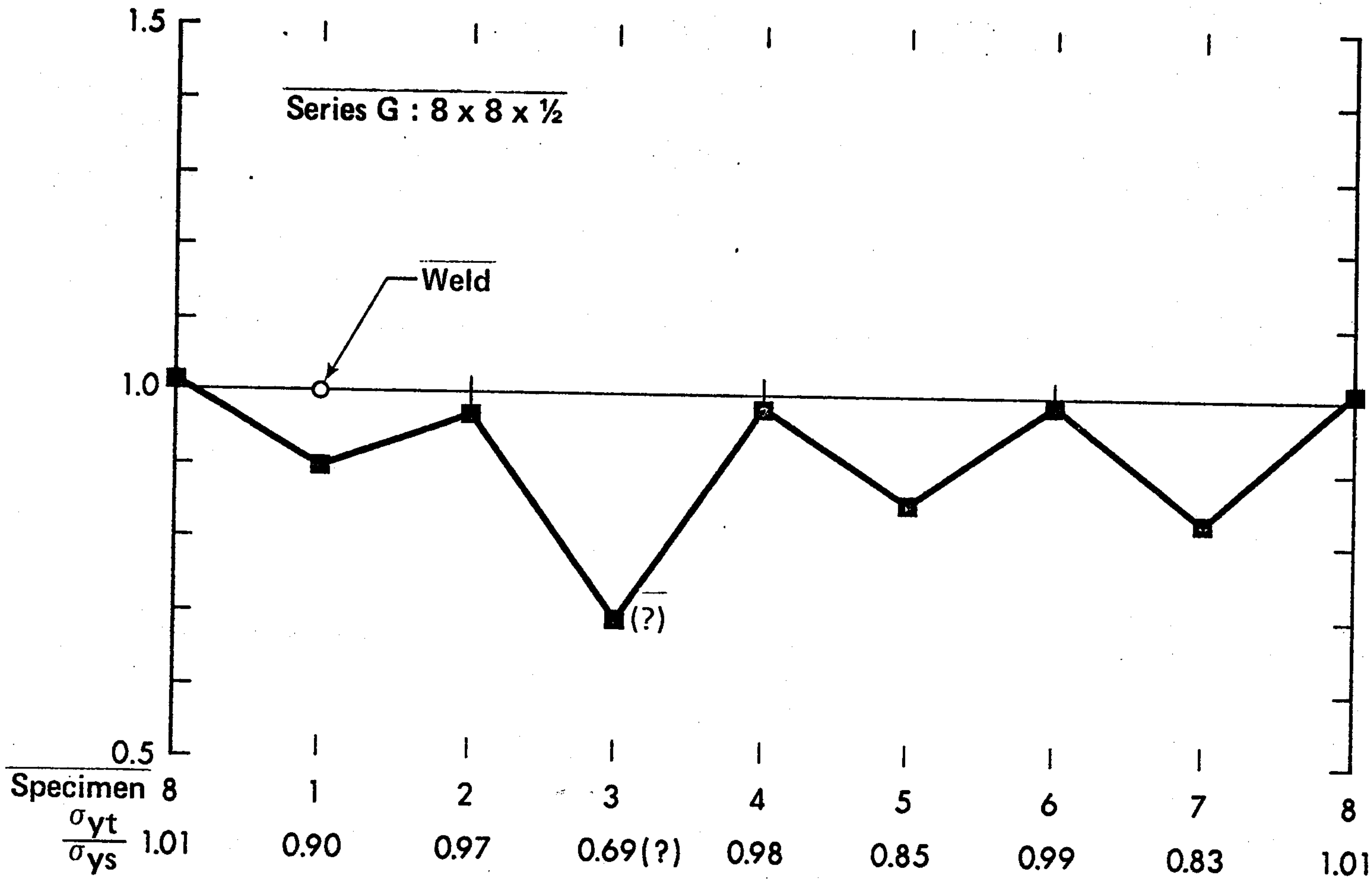

Figure 27 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series G

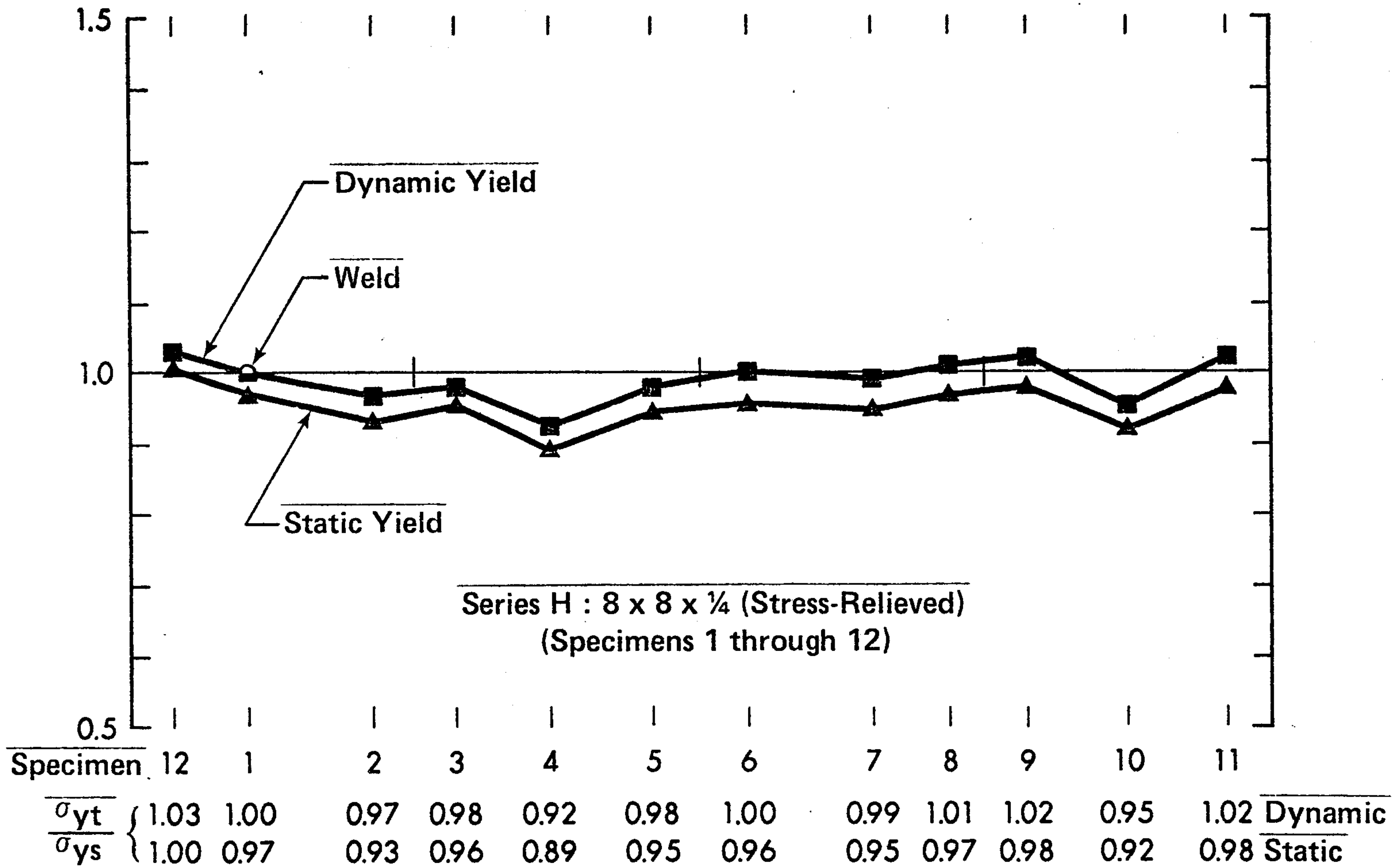

Figure 28 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series H (specimens 1 - 12).

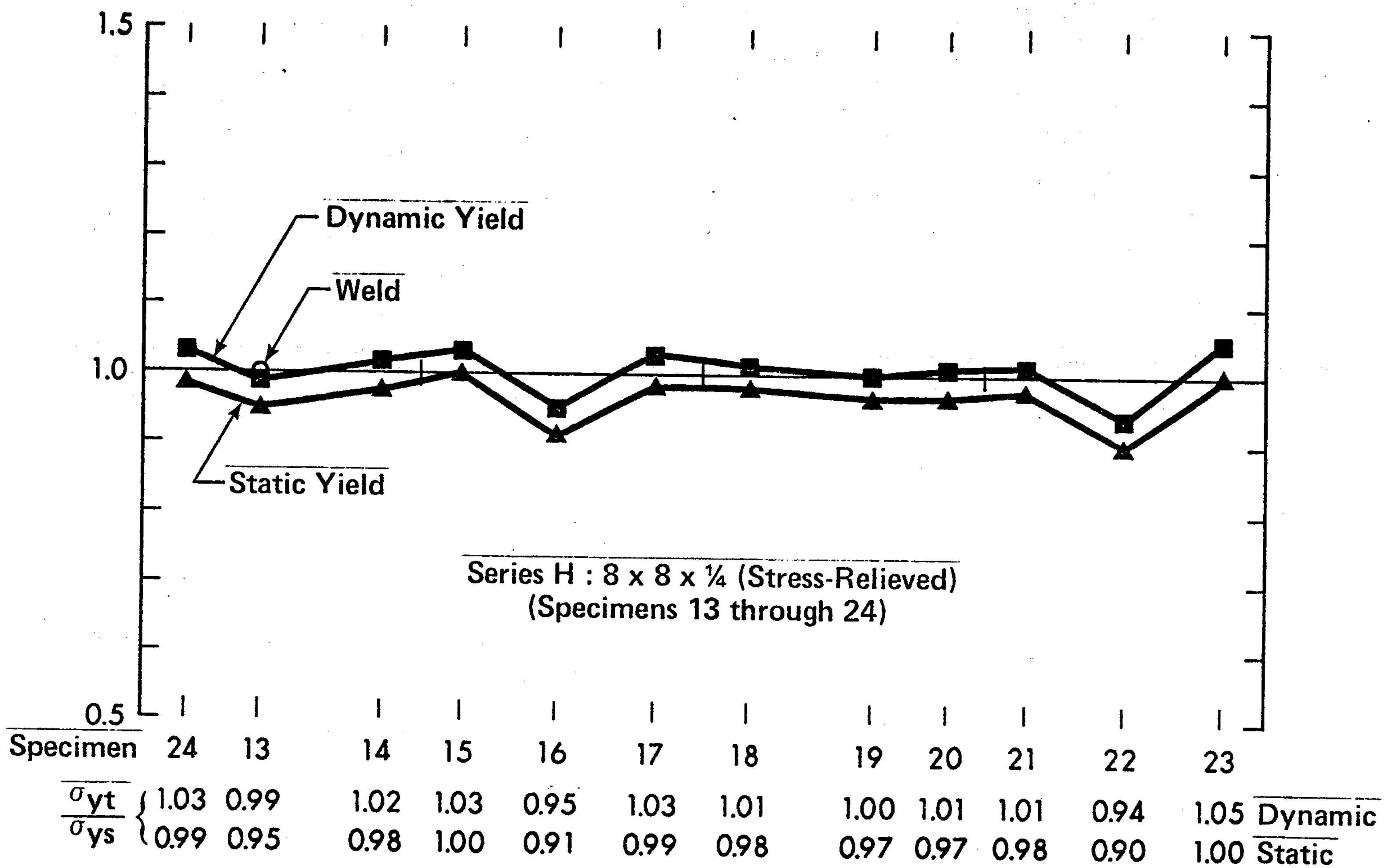

Figure 29 Comparison of Tension Specimen and Stub-Column Yield Strengths for Series H(specimens 13-24).

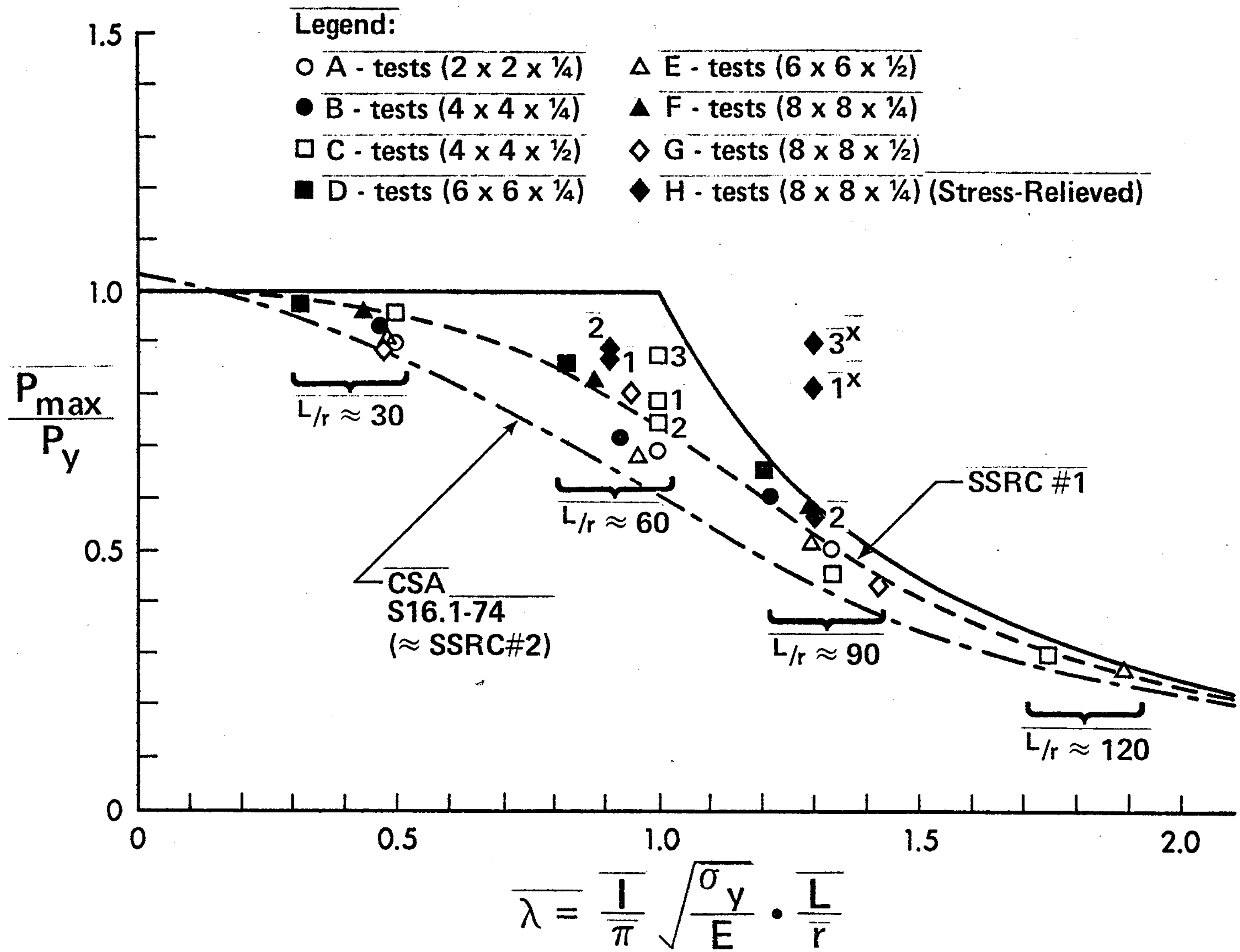

Figure 30 Column Curve Evaluation of HSS Column Strength Data

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