Residual stresses, yield stress, and column strength of hot-rolled and roller-straightened steel shapes

RESIDUAL STRESSES, YIELD STRESS, AND COLUMN STRENGTH OF HOT-ROLLED AND ROLLER-STRAIGHTENED STEEL SHAPES

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ABSTRACT

An investigation of mechanical properties, residual stresses, and column strength of roller-straightened ("rotorized") steel shapes is reviewed briefly. Rotorizing small to medium-size wide-flange members is used in the production line routine at modern structural steel mills, yet most previous investigations of column strength have been concerned with as-rolled members only.

The investigation, being both experimental and theoretical, included a comparison of residual stresses, mechanical properties, and column strength of four lots of HE 200 A shapes, all taken from the same heat but rotorized in various ways. The experimental program included chemical analysis, determination of grain size, tensile specimen tests, as well as stub column and full-length column tests. A theoretical analysis was carried out to study the formation of residual stresses in the manufacturing process, including both the thermal stresses due to cooling, and the stresses due to rotorizing which superimpose upon the cooling stresses. The maximum ("ultimate") column strength in plane buckling was studied theoretically, taking into account the effects of non-symmetrical residual stresses, variable yield strength, initial out-of-straightness, and eccentricities.

In addition to the systematic experiments on HE 200 A shapes, several residual-stress measurements and tensile specimen tests were made on various hot-rolled steel shapes taken from local material suppliers, that is, in the as-delivered condition. Some of these specimens probably were gag-straightened, while others were rotorized.

The investigation showed that the maximum column strength may be increased by about 20 percent due to a suitable rotorizing procedure. It is suggested that the improved column strength of rotorized rolled members be considered in the scheme for assigning proper column curves if multiple column-curve systems are adopted.

1. INTRODUCTION

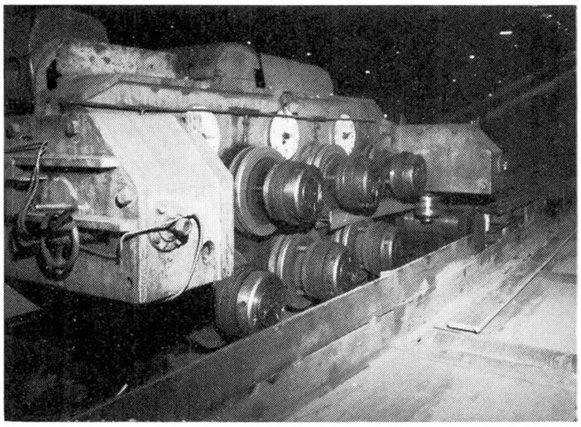
To fulfill the straightness requirements of hot-rolled shapes, most members have to be straightened after rolling and cooling in the mill. The straightening is performed in a roller-straightening ("rotorizing") machine in the production line routine at modern structural steel mills for small to medium-size wide-flange shapes. In rotorizing, the member is deflected back and forth between a number of rollers adjusted in such a manner as to cause plastic deformations in the member, see Fig. 1. For other members, the straightening may be carried out in a gag press. In gagging the member is placed on two supports and loading is applied locally -- the process may be repeated several times along the member to produce a sufficiently straight member.

While practically all delivered wide-flange members thus have been straightened, most research in the past on column buckling of wide-flange shapes has been focused on as-rolled members. Since there was no complete assurance that a delivered member had been straightened, the thermal residual stresses in the as-rolled member were considered, assuming this to be on the safe side.

The fact that residual stresses in a member are affected by an applied bending moment has been known for over 100 years. Wöhler, in his famous investigations of the fatigue strength of railroad car axles, discussed in 1860 residual stresses resulting from a bending which produces plastic deformations [1]. His assumed theoretical model for the formation of residual stresses after bending is essentially the same as used in more recent theoretical investigations of the effect of straightening [2, 3, 4, 5]. Several observations of residual stresses as measured in straightened members have been published in the literature, see for instance Refs. 2 through 9.

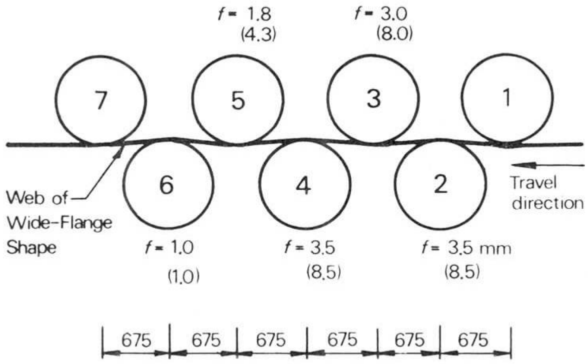
However, there appeared to be a need for a truly experimental study to investigate the effects of the straightening process on residual stresses, mechanical properties, and column strength. ("Experiment" is used here as defined in the behavioral sciences, that is, as opposed to an "observation".) This paper is a brief review of some results of such an experimental program, with additional theoretical studies of the formation of residual stresses as well as of the column strength. The paper is based upon three progress reports in Swedish [10, 11, 12]. In addition to the systematic experimental study, several supplemental residual stress measurements and tensile specimen tests were made on various hot-rolled steel shapes taken from local material suppliers, that is, in the as-delivered conditions [10, 13, 14]. While no account is available as to the detailed straightening procedure used for these supplemental test members, yield lines indicate that some of the members were probably gag-straightened and others rotorized.

A specific objective of the study reported here was to find out whether different column curves should be used for as-rolled as compared to rotorized members, if a multiple column curve system is adopted. Since rotorized columns



(a)

(b)



(c)

Fig. 1 Rotorizing. (a) Wide-flange shape HE 200 A entering the machine. The rollers above the beam are fixed, those below adjustable. (b) Detail at entering rollers. (c) Dimensions and deflections used in the experiments on HE 200 A shapes. Deflections in brackets are for modified rotorizing, see sec. 2.1.

constitute a large share of the total bulk of columns used in structures, the economical benefit from including the favorable effect of a controlled rotorizing should be substantial.

Stress data in the paper are given in the unit kp/mm^2, as used in the original reports. ($1\ kp/mm^2 = 9.81\ MN/m^2 = 1.42$ ksi.)

2. SYSTEMATIC EXPERIMENTS ON HE 200 A

2.1 Test Material

The systematic study was performed on a wide-flange shape type HE 200 A, corresponding roughly to a W 8 x 31. The test members were manufactured by the Norrbottens Järnverk steel mills at Luleå, Sweden. The steel grade was SIS 1412, a semi-killed steel of IIW Quality B with a specified minimum lower yield stress of 26 kp/mm^2, a nominal tensile strength of 44 to 52 kp/mm^2, and a specified elongation of minimum 23 percent. All test material was taken from the same heat.

The test members were manufactured according to standard practice, except that they were subjected to three different controlled rotorizing procedures. One lot was rotorized in the normal production line, and one was taken twice through the rotorizing machine, using the same roller positions as in the normal production. Another member was straightened with modified adjustments of the rollers, the deflections of the member being approx. 2.5 times larger than in the normal production. The actual deflections at the various rollers are shown in Fig. 1 c. Finally, one lot of material was left as-rolled, that is, without any straightening, and serving as a reference to the rotorized material. In the following, these treatments will be referred to as "as-rolled", "normal rotorizing", "twice rotorizing", and "modified rotorizing". They represent gradually larger energy put into the member being rotorized. This is reflected also in the appearance of the mill scale of the flanges, see Fig. 2. The as-rolled member shown in Fig. 2 displays an undamaged mill scale whereas the number and extension of yield lines in the mill scale of the others is larger the more severely the member was rotorized.

All particulars relevant to the manufacture of test members were recorded and a detailed description may be found in Ref. 11.

Results of chemical analysis at 22 locations over four sections of the specimens and the chemical requirements are summarized in Table I. It may be noted that the variations in chemical contents are very small between the mill test analysis and the check analysis, over each section measured, and between the four sections measured. Thus the material may be considered homogeneous and differences in mechanical properties between the various sections, representing members subjected to different rotorizing procedures, must be attributed to other reasons than variations in chemical analysis.

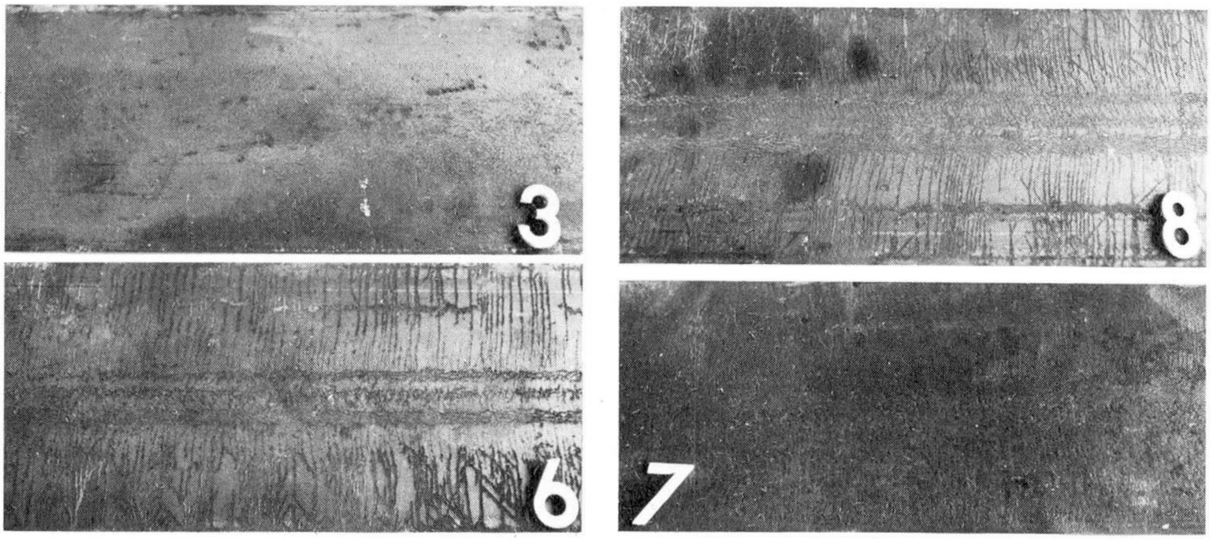


Fig. 2 Mill scale on flange outer surfaces of HE 200 A shapes. As-rolled ("3"), normal rotorizing ("6"), twice rotorizing ("8"), and modified rotorizing ("7").

The grain size was measured at various locations over the cross section of the HE 200 A test shape. The results were as could be expected from the cooling process. The flange tips and the thinner web, cooling faster than the juncture region between flanges and web, had an average grain size of approx. 16 μ, as compared to approx. 30 μ at the junctures.

Table II gives a summary of the test program on HE 200 A designed to determine mechanical properties, residual stresses, and column strength. The results will be discussed in the subsequent sections.

Table I Chemical analysis of test material, HE 200 A. Percent values given (see Fig. 2 for section codes)

Test	C	Si	Mn	P	S	N
Mill test analysis	0,16	0,06	0,94	0,023	0,030	0,006
Check analysis						
Sec. 3	0,16±0,01	0,06±0,00	0,97±0,03	0,022±0,002	0,026±0,003	0,009±0,001
Sec. 6	0,15±0,01	0,08±0,01	0,97±0,01	0,021±0,003	0,027±0,004	0,009±0,001
Sec. 7	0,16±0,01	0,07±0,01	0,99±0,01	0,023±0,001	0,029±0,002	0,008±0,001
Sec. 8	0,17±0,01	0,07±0,00	1,00±0,02	0,024±0,002	0,029±0,003	0,010±0,001
Average	0,16±0,02	0,07±0,02	0,98±0,05	0,023±0,004	0,027±0,005	0,009±0,002
SIS Spec. (SIS 1412)	max. 0,20	approx. 0,05	approx. 0,5-1,1	max. 0,05	max. 0,05	max. 0,009

Table II Summary of mechanical tests on HE 200 A

Roller-straightening procedure	No. of tensile specimens	No. of residual-stress sections	No. of stub columns	No. of columns $\frac{L}{r} = 60$	No. of columns $\frac{L}{r} = 90$
As-rolled (A)	13	1	2		4
Normal rotorizing (N)	13	1	2	1	4
Twice rotorizing (T)	13	1	2		1
Modified rotorizing (M)	13	1	1		1
Total	52	4	7	1	10

2.2 Tensile-Specimen Tests

A total of 52 tensile-specimen tests were made on HE 200 A shapes, representing various locations over the cross section of the four test groups. The results are summarized in Fig. 3. All specimens were flat, and tested at a strain rate corresponding to max. 1 kp/mm^2-s in the elastic range. The lower yield stress R_{eL}, as defined by ISO [15], the tensile strength R_m, both in kp/mm^2, and the elongation A_5 in percent are given.

The variation of lower yield stress in the as-rolled member is compatible with the measured variation of grain size, that is, the flange tips and the web displays a yield stress which is about 9 percent higher than in the interior of the flange. This is a result of the cooling behavior since no systematic differences could be detected in the chemical contents, see Table I. Similar results were obtained for the rotorized members. This is consistent with previous results obtained on as-rolled members [16].

For the rotorized members there is a tendency of increasing yield stress and decreasing elongation values with increasing rotorizing work. This may be observed in Table III which gives different average values of the individual data values from Fig. 3. Thus, the lower yield stress of the member exposed to modified rotorizing is about 7 percent above that of the as-rolled member. The reduction in elongation is much greater than could be predicted from the strains occurring at straightening, probably because of strain aging. Thus, the ductility requirements will pose a limit to the straightening work that can be used in practice.

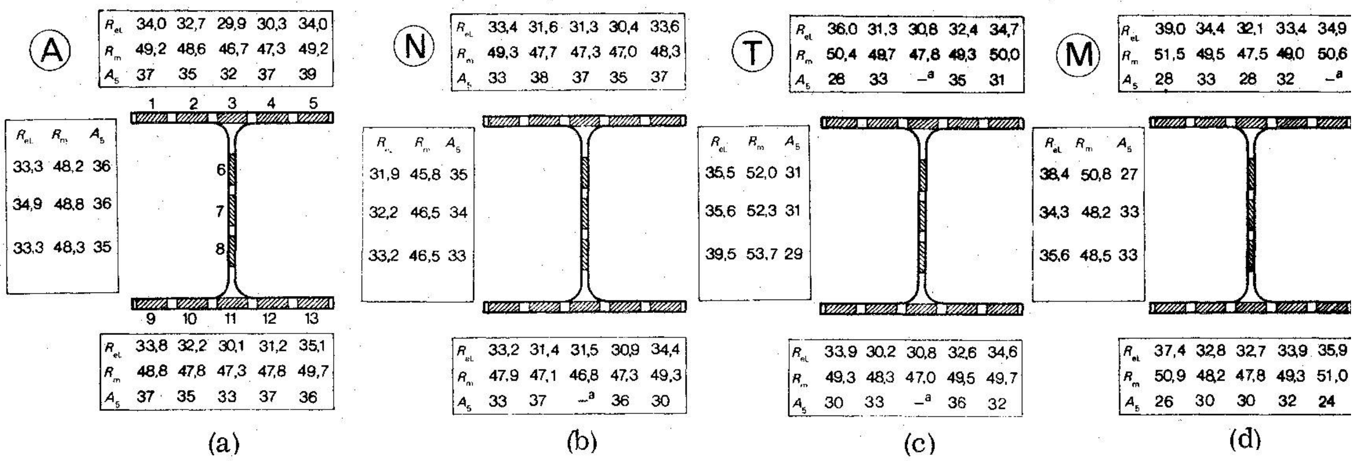


Fig. 3 Results of 52 tensile-specimen tests on HE 200 A shapes being (a) as-rolled and subjected to (b) normal rotorizing, (c) twice rotorizing, and (d) modified rotorizing. The symbol "a" denotes fracture outside gage length.

Table III Average values of tensile-specimen data of Fig. 3. Values given are average of all specimens at each section ("total"), of specimens at flange tips, and of specimens in remaining cross section ("interior")

Roller-straightening procedure	Lower yield stress R_{eL}, kp/mm^2				Tensile strength R_m, kp/mm^2			Elongation A_5, percent		
	Total	Relative to A	Flange tips	Interior	Total	Flange tips	Interior	Total	Flange tips	Interior
As-rolled (A)	32.7	1.00	34.2	32.0	48.3	49.2	47.8	36	37	35
Normal rotorizing (N)	32.2	0.98	34.4	31.6	47.4	48.7	46.9	35	33	36
Twice rotorizing (T)	33.7	1.03	34.8	33.2	49.9	49.8	50.0	32	30	33
Modified rotorizing (M)	35.0	1.07	36.8	34.2	49.4	51.0	47.6	30	26	31

No indications of detrimental Bauschinger effects could be observed in the test results. The yield stress at the flange tips of both sides of the cross section is always higher than in the interior of the flanges.

Strain-hardening properties were not recorded for this series of tensile specimen tests on HE 200 A shapes. Such properties were measured in several specimens from two cold-straightened sections of HE 200 B [10]. It is difficult to compare these results with previous strain-hardening data on as-rolled members because many different definitions have been used in the literature [17]. It is, however, interesting to note that the material, including that from the flange tips, exhibits the usual behavior with an upper yield point and a marked yield plateau. The length of the yield plateau, as measured by the strain ϵ_{sh} at onset of strain-hardening, is approx. 19 ϵ_y (where ϵ_y = strain at first yield) for specimens taken from the flange tips affected most by the cold-straightening, and approx. 15 ϵ_y for specimens from the remaining cross section. These observations do not support the mechanical model used in the literature for representing the material behavior in loading and unloading to yield [18, 19]. According to that model, the yield plateau would occur only in material that is virginal (no yielding) in a particular strain direction.

Furthermore, the strain-hardening data from cold-straightened HE 200 B sections indicated no significant difference between the strain-hardening modulus E_{st} of the flange tips and that of the remaining cross section. Thus, the reduction of E_{st} due to roller-straightening to between 10 and 28 percent of E_{st} of the virgin material, as anticipated in studies of the effect of rotorizing on the inelastic behavior of beams [18], appears much exaggerated judging from the present data. The average strain-hardening modulus, defined as the secant to the stress-strain curve at strains ϵ_{sh} and 4 percent, is about 300 kp/mm^2 or E/70. Measured over the strain range ϵ_{sh} to (ϵ_{sh} + 0.002), the average E_{sh} value obtained for the HE 200B shape is 590 kp/mm^2 or E/36. This is within the range of E/45 to E/35 reported in the literature for as-rolled structural carbon steels [18,20, and others]. The experimental scatter obtained with the latter definition of E_{st} is so large that there would be no point in comparing values at different locations over the cross section etc.

2.3 Residual-Stress Measurements

Longitudinal residual stresses were measured using a sectioning method. The released strains were recorded with a mechanical extensometer of 165 mm gage length. The total number of measured points, each consisting of two gage marks, was 98 for each cross section. The accuracy in the measured stress was estimated to ± 1 kp/mm^2 [10]. This includes the thermal and mechanical effects of carefully cold-sawing the cross section into strips. Localized residual stresses at cold-sawn surfaces were measured by X-ray diffraction technique for the purpose of estimating this source of error [10].

Figures 4, 5, 6, and 7 show the measured residual-stress distributions in the as-rolled HE 200 A member, and those subjected to normal rotorizing, twice rotorizing, and modified rotorizing, respectively. All residual-stress diagrams are plotted with tension towards the cross section. Open points are measured values at the near surface, solid points at the far surface.

The residual stresses in the as-rolled member, Fig. 4, are distributed with -12 kp/mm^2 in compression at flange tips and -14 kp/mm^2 at the web center. The compressive stresses are balanced by tension in the remainder of the cross section. This stress distribution is typical for the thermal stresses resulting from a free cooling [4]. The residual stresses obtained on both sides of each sectional element are very close, the difference being less than 3 kp/mm^2. The stress at the outside of the flanges is generally about 2 kp/mm^2 below the corresponding inside stress (sign included). While this does not reveal the true through-thickness variation, the fact that the two sides follow each other closely is a good indication of the accuracy of the measurements.

The member rotorized in the production exhibits a completely different distribution, Fig. 5. Although there is still a tendency of compression towards the flange tips and tension in the flange centers, the distribution is more irregular and the stresses are much smaller. There is a large variation across the flanges, the difference being

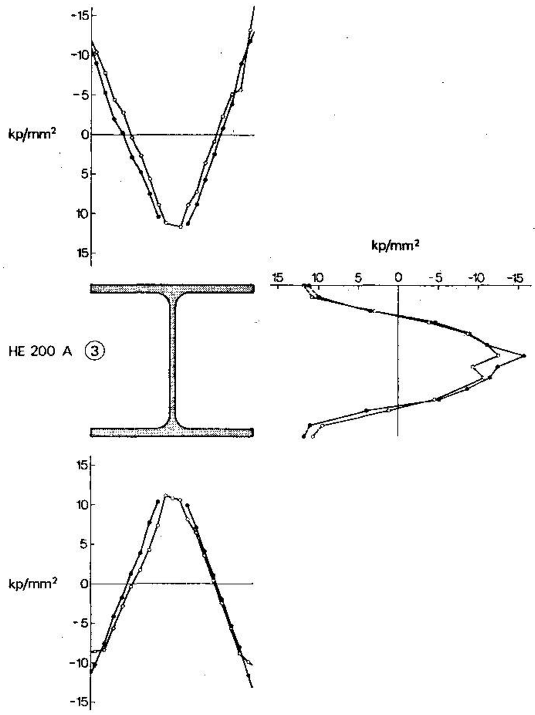


Fig. 4 Residual stresses in an as-rolled HE 200 A shape

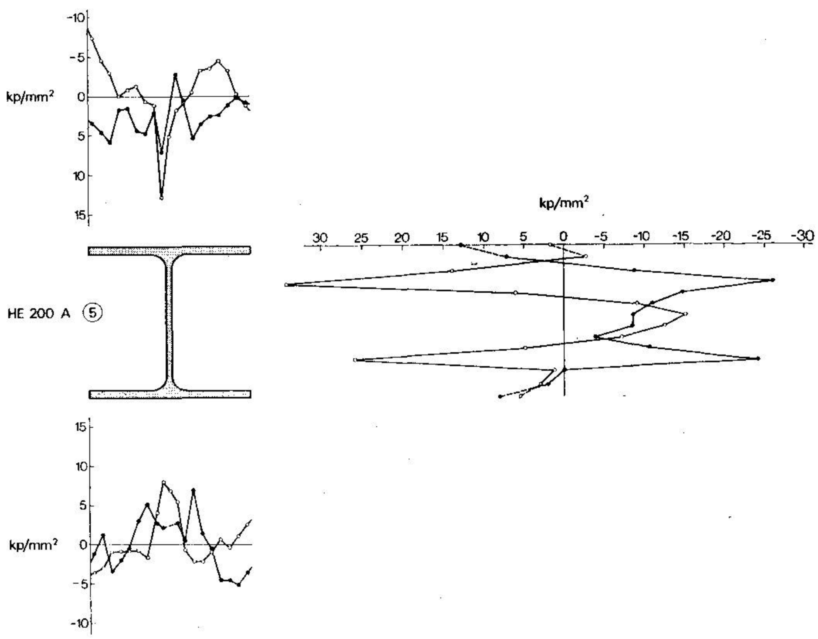


Fig. 5 Residual stresses in an HE 200 A shape rotorized in normal production

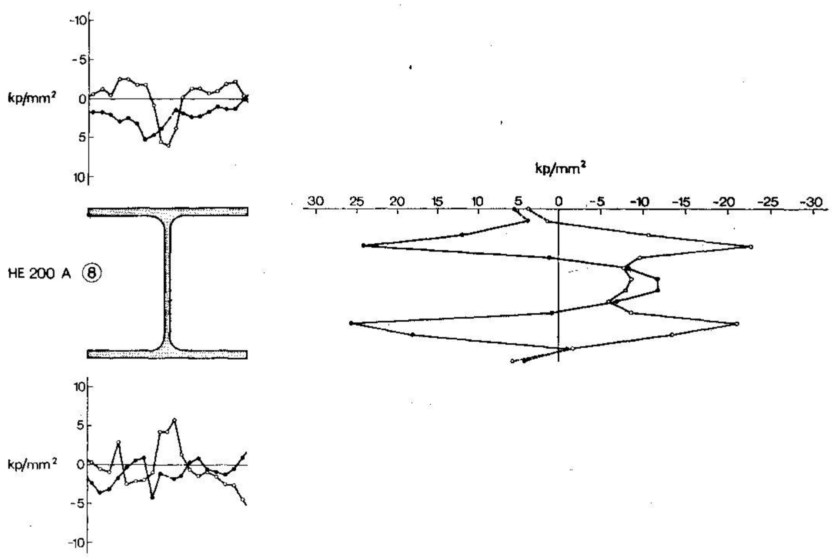


Fig. 6 Residual stresses in an HE 200 A shape rotorized twice

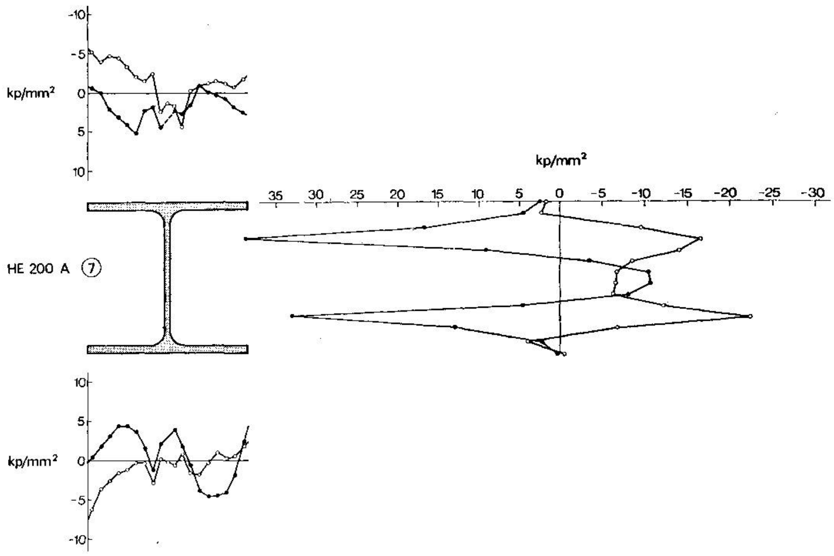


Fig. 7 Residual stresses in an HE 200 A shape rotorized using a modified procedure with larger deflections than in normal production

up to 10 kp/mm^2. This variation is still larger in the web, where differences of up to 60 kp/mm^2 were obtained locally, near the fillets at the flange-web junctures. These stress peaks at yield level result from the local load effects under the rollers in the rotorizing machine.

The residual-stress distribution in the member rotorized twice, Fig. 6, resembles that of Fig. 5. The residual stresses in the flanges have been further smoothened out. The stress in all measured flange points falls between -5 and +6 kp/mm^2. A similar distribution was obtained in the member which was rotorized using larger deformations, see Fig. 7. The stress peaks in the web are at approx. 36 kp/mm^2, to be compared with the recorded lower yield stress of 37 kp/mm^2, see Fig. 3.

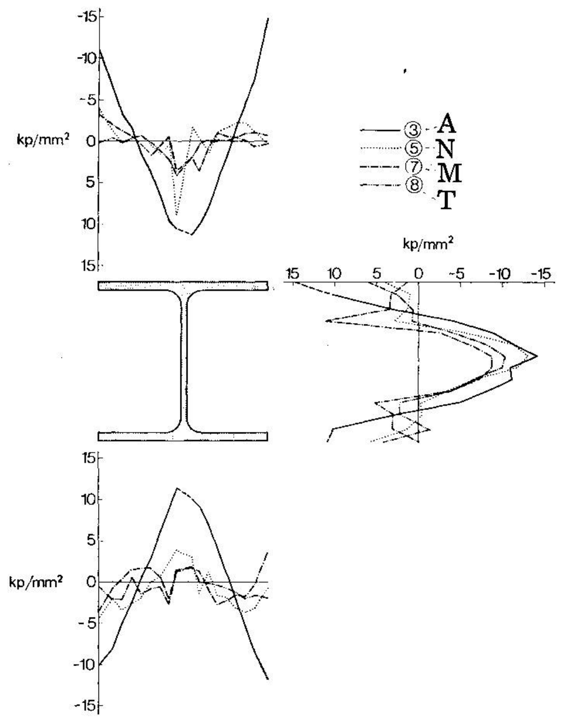


Fig. 8 Residual stresses in HE 200 A shapes. Average stresses across thickness

It is interesting to note that, although the rotorizing procedures used are drastically different, the residual-stress distributions at large in the three rotorized members, Figs. 5 through 7, are quite similar. This is even more evident if average stresses over the thickness are considered as in Fig. 8. When compared with the residual stresses in the flanges of the as-rolled member, the rotorized flange stresses are almost negligible. The average stresses in the web are less affected by the rotorizing as may be seen in Fig. 8. This is because the web is close to the neutral axis in minor axis bending.

2.4 Column Tests

The extent of the experimental program for testing rotorized HE 200 A columns is shown in Table II. A total of 18 columns were tested, of which seven were stub columns, one was a full-length column with a slenderness ratio of 60, and ten were full-length columns with a slenderness ratio of 90. The purpose of the stub columns was to determine the overall material strength in compression. The slenderness ratio of 90 for most columns was chosen to allow comparisons with previous column-test results [21].

All columns were tested in a universal testing machine of 400 Mp capacity. The columns were fully instrumented. The column testing followed the procedure suggested in Ref. 22. Both "statical" and "dynamical" recordings were taken. The details relevant to the columns tests are given in Ref. 11.

Figure 9 shows stress-strain curves from the stub columns. An average curve was drawn when more than one stub column was tested for each rotorizing procedure. The values given in Fig. 9 are the "static" yield stress level at 0.5 percent strain.

It may be noted that local buckling started on the yield plateau at approx. 0.7 percent strain with some variation. The actual b/t ratio of the flanges is 21 (nominally 20). In one stub column, buckling started even before the yield stress was reached. Thus, the maximum stress attained in the stub columns is not much higher than the yield stress. Table IV summarizes the test results of the stub columns. The yield stress level is increased by 14 percent for a modified rotorizing as compared to the as-rolled member. This is about twice as much as obtained in the tensile specimen tests, see Table III. When comparing the tensile specimen properties in Fig. 3 and Table III with the yield properties in compression in Table IV, it should be kept in mind that the latter are "static" values obtained at a negligible strain rate (see also Fig. 9) whereas the tensile specimens were tested at a strain rate of the order of 1 kp/mm2-s (see Sec. 2.2).

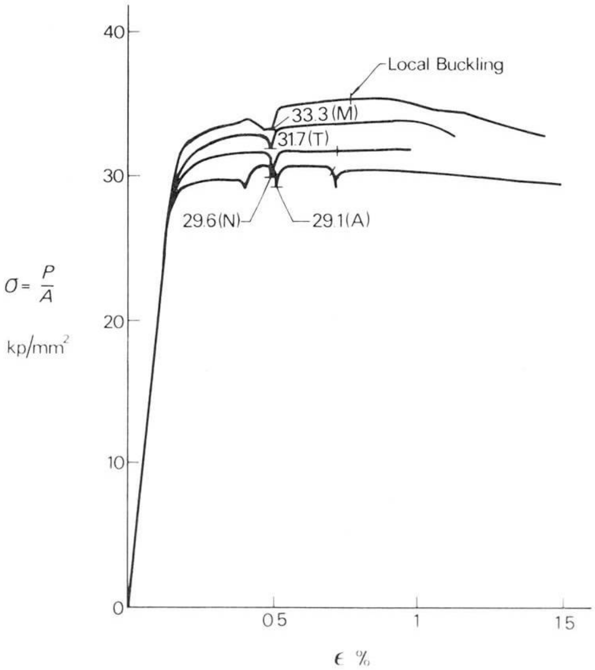


Fig. 9 Stress-strain curves from stub columns. Curves and values shown are average for stub columns with same rotorizing procedure

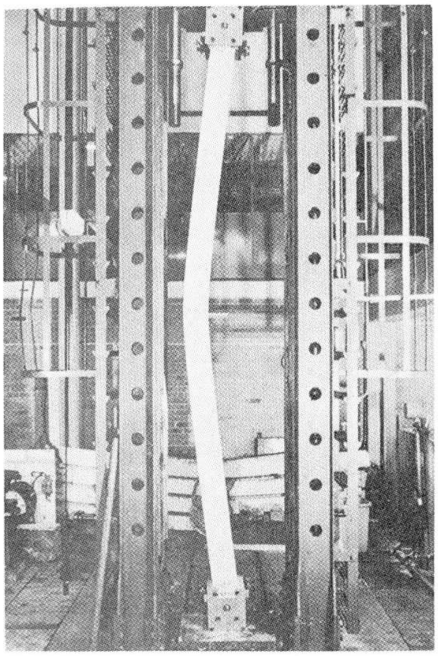


Fig. 10 Column with slenderness ratio of 90 in testing machine

Table IV Stub-column test results (average where more than one stub column was tested)

Roller-straightening procedure	Static yield stress level		Maximum stress	
	kp/mm^2	Relative to A	kp/mm^2	Relative to A
As-rolled (A)	29.1	1.00	31.2	1.00
Normal rotorizing (N)	29.6	1.02	31.9	1.02
Twice rotorizing (T)	31.7	1.09	33.8	1.08
Modified rotorizing (M)	33.3	1.14	35.3	1.13

For a perfectly concentric loading of a stub column with constant strain over the cross section and along the column, the difference between the yield stress level and the proportional limit of the stress-strain curve should equal the maximum compressive residual stress in the column. There appears to be no such correlation between the maximum compressive stresses in Figs. 4 to 7 and the stress-strain curves of Fig. 9. The reason for this is that it was not possible to maintain a perfectly concentric loading, probably because of the thin cross-sectional elements and the effect of early onset of local buckling.

The full-length columns were tested with pinned-end conditions and end rotations permitted about the minor axis. Twisting of the ends was prevented by friction in the cylindrical bearings. Figure 10 shows a column in the testing machine at a late stage of buckling. All columns failed in plane buckling about the minor axis. No appreciable cross-sectional rotation was observed in the test columns, in spite of the fact that residual stresses in the rotorized members were non-symmetrical and, for some columns, the initial deflection of the two flanges were in opposite directions.

A summary of the column test results for slenderness ratio 90 is given in Fig. 11. The static maximum stress obtained is plotted against the equivalent initial deflection of the column. This corresponds to the maximum deflection of a sine curve equivalent with the actual initial deflection. It may be noted in Fig. 11 that the rotorizing results in a 10 to 15 percent increase in column strength for this slenderness ratio. There appears to be no large difference between the normal rotorizing and the member rotorized twice or by a modified procedure. Since only one column each was tested for these latter groups, and because the initial deflection of the column with modified straightening was much larger than for all other columns, no definite conclusions may be drawn as to the effectiveness of various rotorizing procedures. It should also be borne in mind that all columns were of one slenderness ratio only. Further discussion will follow below in connection with theoretical column strength predictions.

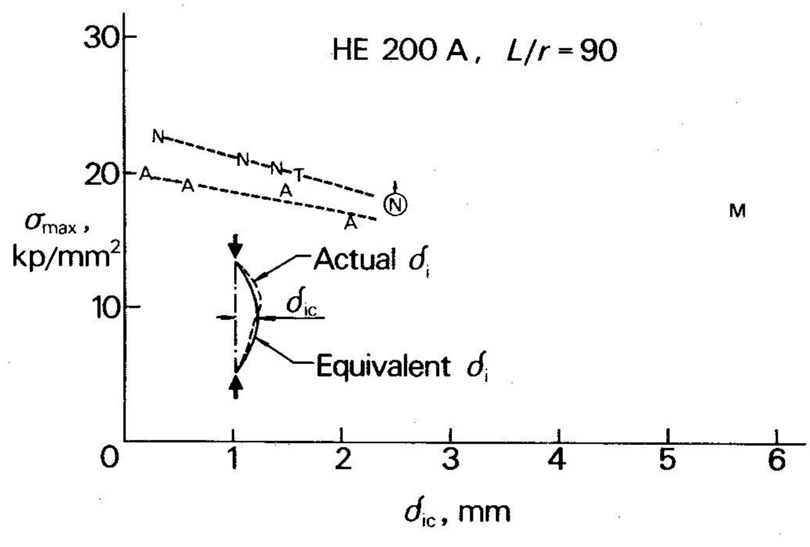


Fig. 11 Summary of test results for columns with slenderness ratio of 90

3. THEORETICAL PREDICTIONS OF RESIDUAL STRESSES AND COLUMN STRENGTH OF ROTORIZED HE 200 A

3.1 Predicted residual stresses in as-rolled HE 200 A

The thermal residual stress distribution in as-rolled shapes may be predicted using a theoretical model to represent the temperature and thermal strain history during cooling on the cooling bed in the steel mill. The simulation model has been described in detail elsewhere [4, 23, 24]. The numerical analysis was performed in a computer.

A calculated thermal-stress distribution is given in Fig. 12. The distribution is to be compared with the measured distribution in Fig. 4. The difference in stress level at the flange-web junctures is due to the effect of the fillet areas not included in the theoretical calculations. For the HE 200 A shape as much as 5 percent of the total cross-sectional area is located in these fillet areas. The residual-stress distribution representing the inside of the flanges is about 2 kp/mm^2 below that of the outside, as was obtained also in the measurements, Fig. 4.

3.2 Predicted residual stresses in rotorized HE 200 A

The mechanical behavior in rotorizing H-shapes was simulated theoretically. A specific purpose was to allow a better understanding of the process and the possible effects of different variables. Furthermore, the calculations were intended to facilitate the interpretation of experimental measurements.

The member was treated as a continuous beam loaded and supported by the straightening rollers, as shown schematically in Fig. 13. Each concentrated load shown in Fig. 13 is actually two concentrated loads closely spaced in such a manner as to achieve a constant moment over the contact surface of each roller. A more detailed account of the calculations is given in Ref. 12.

Several assumptions were made in the simulations:

- Only minor axis bending was considered. Although the principal straightening action is about the minor axis, only small moments need be applied about the major axis to achieve a definite straightening effect because the cross section yielding for minor axis bending produces only slight resistance to major axis bending.

- Plane sections are assumed to remain plane during deformation in the elastic as well as the elastic-plastic region. In actual rotorizing the local loads at rollers will cause deviations from the assumed action. Furthermore, large strains and deformations due to initiated local buckling of compressed flanges may give similar effects.

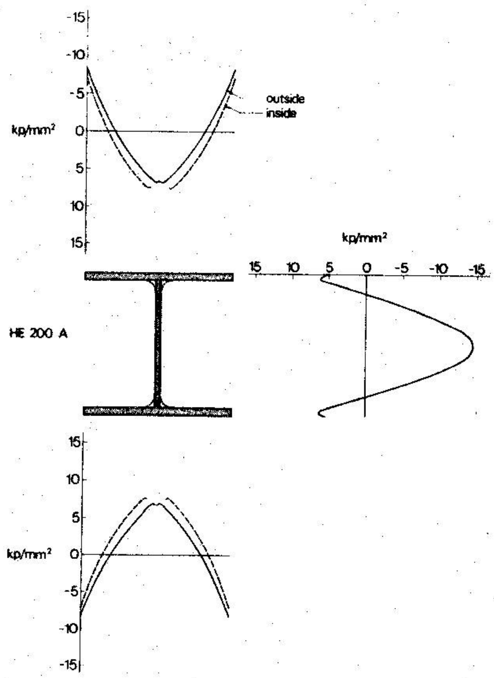


Fig. 12 Thermal residual stresses in as-rolled HE 200 A as calculated from the cooling behavior

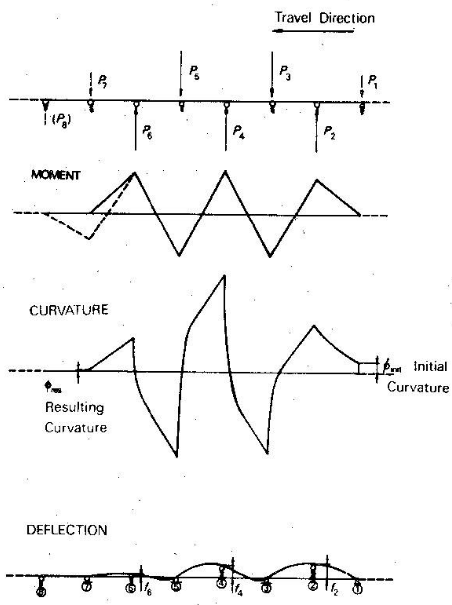


Fig. 13 Calculation of moments, curvatures and deflections in a rotorizing procedure (schematic)

- Only longitudinal stresses are considered. Transverse stresses are, however, created by the concentrated loads from the rollers, and they affect in reality the yield conditions at the sections under the rollers.

- Effect of shear deformations are neglected.

- The material behavior is represented by a mechanical model shown in Fig. 14, as used previously in the literature [18, 19]. It was noted above that the tensile-test results did not support some implications resulting from this model. For this reason the Bauschinger effect was neglected in the simulations, that is, R^*_{eL} was assumed equal to R_{eL}. The stress-strain relationship in the strain-hardening range was assumed to follow the well-known Ramberg-Osgood equation

$$\epsilon - \epsilon_{sh} = \frac{\sigma - R_{eL}}{E_{sh}} + K \left(\frac{\sigma - R_{eL}}{E_{sh}} \right)^m$$

The following coefficients were used, and assumed constant over the cross section:

$E = 21\ 000$ kp/mm^2	$\epsilon_{sh} = 1{,}4$ %
$R_{eL} = (R_{eH} =)\ 32.7$ kp/mm^2	$K = 21$
$E_{sh} = 600$ kp/mm^2	$m = 2$

The number of numerical operations involved in the calculations is tremendous, in spite of the simplifying assumptions noted above. The structure is highly statically

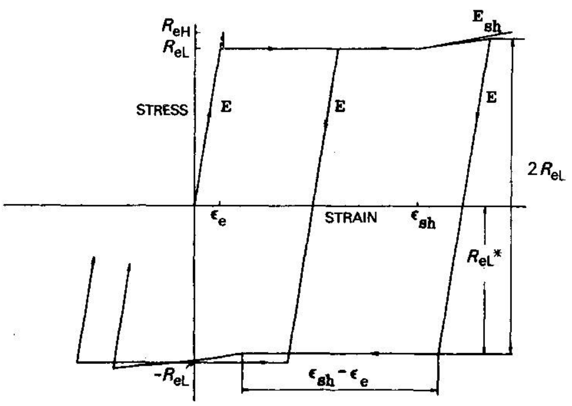


Fig. 14 Stress-strain relationship for yielding and strain-hardening alternating in tension and compression

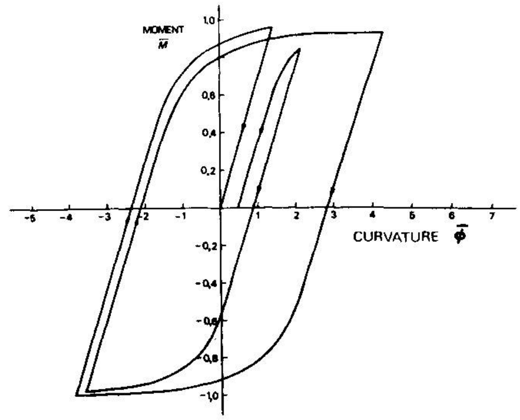


Fig. 15 Typical moment-curvature history as calculated for a simulated rotorizing

indeterminate and the moment-curvature relationship at each point is affected by the complete loading history at previous positions. Since loads are controlled by deflections, this means that all variables are highly interrelated in a complicated way. The problem was solved by an iteration procedure in a computer. Because of all assumptions involved, the simulations must be regarded as qualitative only.

A typical simulated moment-curvature history for a particular cross section moving through the rotorizing machine is shown in Fig. 15. The initial residual stresses were those obtained in measurements on the as-rolled HE 200 A, see Fig. 4. The initial curvature was about $0.5\ \phi_y$, where ϕ_y is the curvature which corresponds to attainment of the yield strain ($= R_e/E$) at the extreme fibers. This curvature is of the order of 10 times larger than allowed in mill tolerances on straightness.

Three different rotorizing procedures were simulated. These correspond to three levels of rotorizing work termed a "weak", a "normal", and a "heavy" rotorizing. The deflected curves from the simulations are shown in Fig. 16. The weak and the normal rotorizing do not produce any strain-hardening. In the heavy rotorizing, the maximum strain was approx. 2.3 percent. From a comparison with Fig. 1 c it is noted that the "normal" and the "heavy" simulated rotorizing relate to the "normal" and the "modified" rotorizing in the experimental study.

Figure 17 shows residual-stress distributions resulting from the three simulated rotorizing procedures. It may be noted that all flange distributions in rotorized members are similar in nature, but quite different from that of the as-rolled

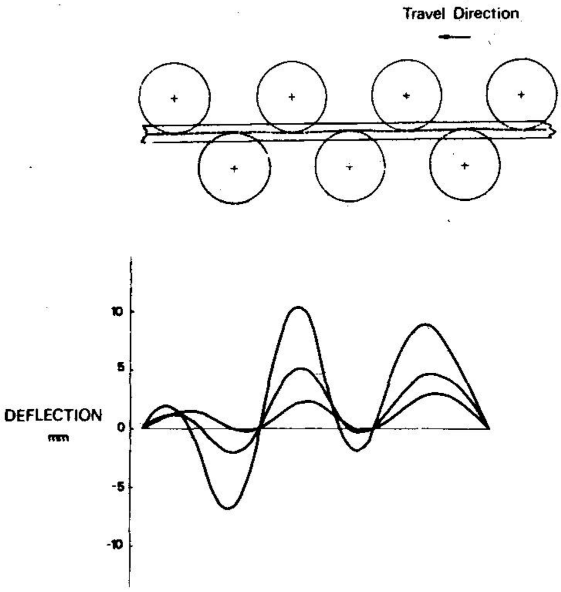


Fig. 16 Deflected curves in simulated rotorizing

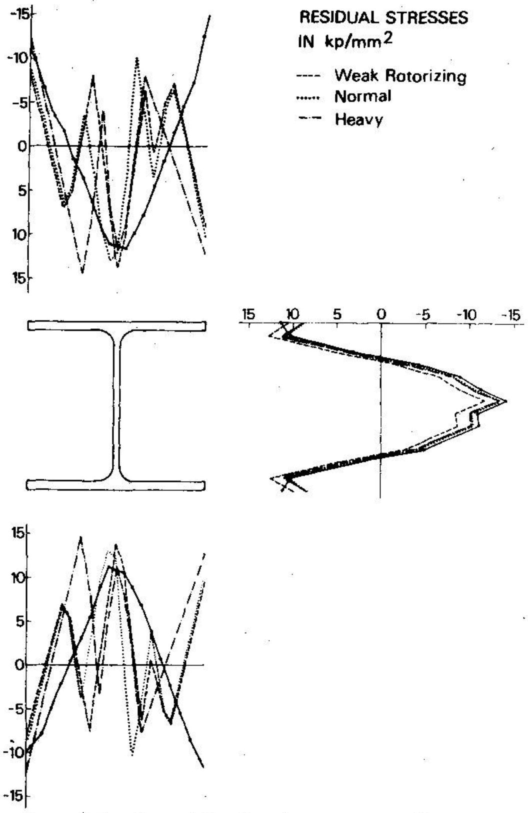


Fig. 17 Residual stresses after simulated rotorizing at three levels as shown in Fig. 16

member. The rotorizing has almost no effect on the distribution of average residual stresses in the web. All this was noted from the experimental results also, see Fig. 8. The magnitude of the stress peaks in the flanges of the members subjected to simulated rotorizing is, however, larger than encountered in the experimental results. Thus, the actual rotorizing is more efficient in breaking down the thermal residual stresses than theoretical simulations based upon beam action of the rotorized member. A better agreement between test and theory might be achieved by superimposing the local effects under the rollers, including transverse stresses.

No increase in yield stress could be expected from the simulated rotorizing of "weak" and "normal" magnitude since no strain-hardening occured. The maximum strain of 2.3 percent in the "heavy" simulated rotorizing corresponds to an increase of 4.7 kp/mm^2 in the yield stress of the extreme fiber. At the location of tensile test specimens in the outer flanges, see Fig. 3, the increase in yield stress is between 2 and 3 kp/mm^2. These results are all in agreement with the experimental results: no increase in yield stress of the normally rotorized member was observed, whereas the yield stress increased by 2.6 kp/mm^2 at the outer flange specimens for modified rotorizing. The simulated data may explain partially why the stub column subjected to a modified rotorizing had a larger incrase in yield stress than the average of tension specimens -- these did not represent the flange tips with the highest increase from the simulated rotorizing. (The reduced gage section of the tension specimens is smaller than the gross sections indicated in Fig. 3).

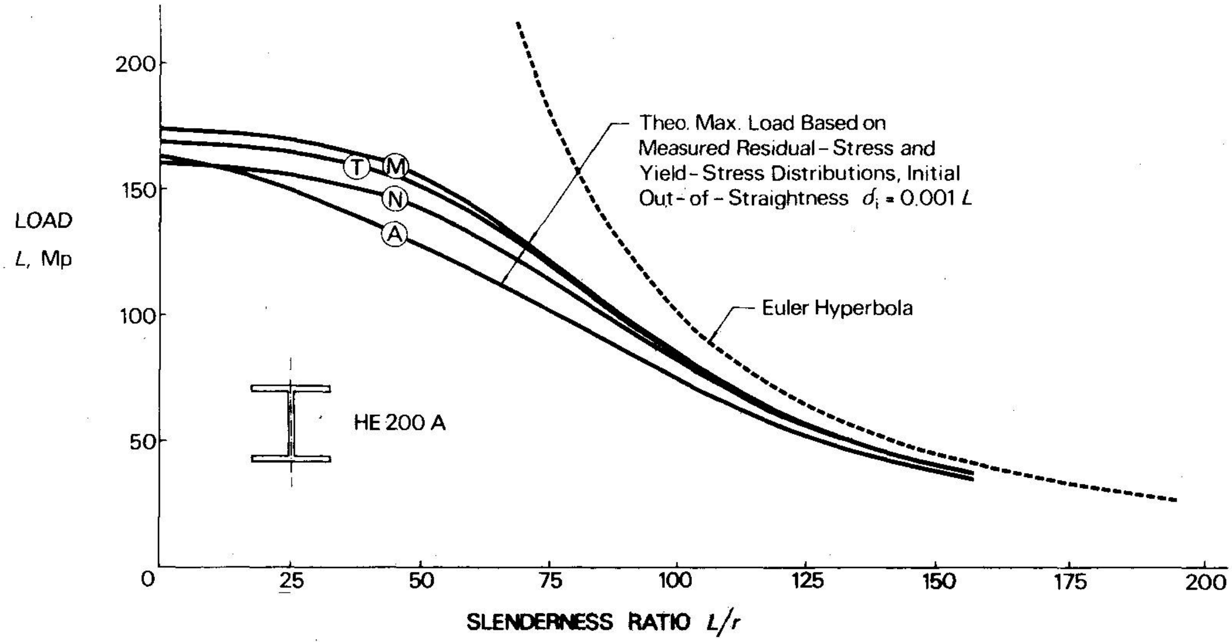


Fig. 18 Maximum strength curves from simulated column tests including measured residual stresses, yield stresses from tension-specimen tests, and initial deflection of 0.001 L

The simulated rotorizing can not explain why the mechanical properties of the interior of the section are affected as shown in Table III, nor can it explain the marked effects on the tensile strength and the elongation values -- the reduction in elongation due to different rotorizing procedures, being up to 9 percent in the flange tips for modified rotorizing, is several times larger than expected from the assumed mechanical model for material behavior. A better correspondence in some respects may be obtained by including the local loading effects.

3.3 Predicted column strength of rotorized HE 200 A

The mechanical behavior of rotorized columns was simulated using a maximum ("ultimate") strength approach. The numerical method used will be described elsewhere [25], but is similar in principle to other methods available in the literature [26]. A tangent modulus approach could not be used since the tangent modulus load is not defined for non-symmetrical residual stresses. The computer program includes the effects of non-symmetrical residual stresses, variable yield stress, irregular out-of-straightness, and end eccentricities. Plane buckling was considered, as was also encountered in the column tests (see Sec. 2.4).

Figure 18 shows maximum strength curves for simulated column tests about the minor axis of members subjected to the four rotorizing procedures of the experimental study. The curves were based on measured residual stresses, yield stress data from the tension-specimen tests (the stub-column data were not available when the simulations were made), measured cross-sectional dimensions (the actual area was about 5 percent less than the nominal area), and an assumed initial sine curvature with a mid-height deflection of 0.001 L. The actual initial out-of-straightness was not used here because the intention was to separate the effects of residual stresses and yield stress on column strength.

From a comparison of the curves in Fig. 18 it may be noted that the rotorizing increases the simulated column strength by 10 to over 20 percent in the important range of slenderness ratios of 40 to 100. The increase for the larger slenderness ratios in this range is primarily due to the redistributed residual stresses, whereas the effect at lower slenderness ratios is primarily due to the magnitude of yield stress. At $\frac{L}{r}$ equal to 90 the predicted increase in column strength is between 10 and 14 percent, depending upon the rotorizing procedure. This increase, and the rotorized column curves being very close in this slenderness range, are in agreement with the experimental column test results as summarized in Fig. 11.

4. CONCLUSIONS AND SUMMARY

From the systematic experimental study of HE 200 A columns and observations of residual stresses and mechanical properties in sveral other cold-straightened members, as described in several reports [10 through 14] and summarized in this paper, the following conclusions may be drawn.

1. Residual stresses in the flanges of wide-flange shapes are completely redistributed by a rotorizing procedure. Theoretical simulations indicate that only small plastic deformations in the rotorizing are necessary to achieve this end. It appears that a "heavier" rotorizing, with larger deflections of the member, will improve the residual-stress distribution further, however this effect is only marginal. The effect of rotorizing on residual stresses in the flanges **appears** more favorable than predicted by theory. This is probably due to local loading effects under the straightening rollers.

2. Rotorizing may affect the tensile properties by increasing the yield stress and the tensile strength and reducing the ductility (measured as elongation). Theoretical simulations indicate that a fairly heavy rotorizing is necessary to produce definite strain-hardening effects. The experiments show that, indeed, a heavy rotorizing produces an increased yield stress of 7 percent, but the effect is obtained over a much wider area than predicted from simulations. This is probably due to local loading effects under the straightening rollers.

3. The strain-hardening properties measured in some cold-straightened shapes are not much different from those reported in the literature for as-rolled material. The commonly accepted mechanical model for material behavior would predict the yield plateau to be reduced or wiped out completely by the cold-straightening, depending upon the maximum strain in the straightening process. For sufficiently large strains produced in the straightening, that is, strains larger than ϵ_{st}, also the strain-hardening modulus would be reduced. The measured data contradict this altogether -- the flange tips being mostly affected by the straightening moments show in fact a somewhat longer yield plateau

and about the same strain-hardening modulus as the interior of the flange. The measured behavior could be the result of strain-aging effects. More data would be necessary to draw any general conclusions regarding the strain-hardening properties of rotorized members.

4. Stub column tests on HE 200 A shapes indicate that the improvement in compressive yield strength due to a rotorizing operation is even greater than obtained in the tensile specimen tests. The improvement in static yield stress level is 2, 9, and 14 percent for the normal rotorizing, twice rotorizing, and modified rotorizing, respectively. Due to a large width-over-thickness ratio of the HE 200 A test specimens ($\frac{b}{t} = 21$), the stub columns start to buckle locally at relatively small strains and the maximum stress exceeds the static yield stress by less than 10 percent.

5. All full-length columns tested fail in plane buckling about the minor axis. (The end fixtures used permit end rotations about the minor, but not the major axis.) The column tests for slenderness ratio 90 show that rotorizing increases the maximum column strength by 10 to 15 percent. Theoretical simulations based upon measured residual stresses and mechanical properties support this result. From the simulations it is clear that even greater improvements are obtained at lower slenderness ratios -- well over 20 percent increase in column strength for slenderness ratios in the range 40 to 70 may be obtained from a suitable rotorizing procedure.

The column tests were performed on only one shape, the HE 200 A. However, the important variables affected by the rotorizing, that is, the residual-stress and the yield-stress distributions, have been studied in supplemental tests on several other shapes in the research program [4, 10, 12, 13, 14]. These supplemental tests were performed on as-delivered members taken from local material suppliers. Further results of residual-stress measurements are available in the literature [2, 3, 5, 6, 7, 8, 9]. All these measurements show clearly that rotorizing efficiently redistributes the unfavorable thermal residual stresses of as-rolled shapes.

Since rotorizing is used to straighten all small to medium-size shapes in the production line at modern steel mills, exploiting the favorable effects on column strength does not need any new equipment or any new operations. The necessary extra control of the rotorizing effects at the mill would require only a visual inspection of the yield line pattern on the flanges.

The theoretical and experimental research described in the paper may also be used to optimize the rotorizing operation. Today the rotorizing appears to be a subjective trial-and-error process guided only by the experience of the personnel involved in the operation.

It is suggested that the improved column strength of rotorized rolled members be considered in the scheme for assigning proper column curves if a multiple column curve system be adopted. Since rolled and rotorized columns constitute a large share of the total number of columns used in structures, the economical benefit from including this effect should prove substantial.

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