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Comparison and evaluation of web crippling prediction formulas

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SUMMARY

Since the use of end and load stiffeners is frequently impractical in thin-walled cold-formed steel construction, the webs of beams and deck may cripple due to the high local intensity of the load or reaction.
In this report three different web crippling prediction formulations are compared with experimental results from five different sources.
It is found that these web crippling formulas show considerable differences and do not give satisfactory results consistently.

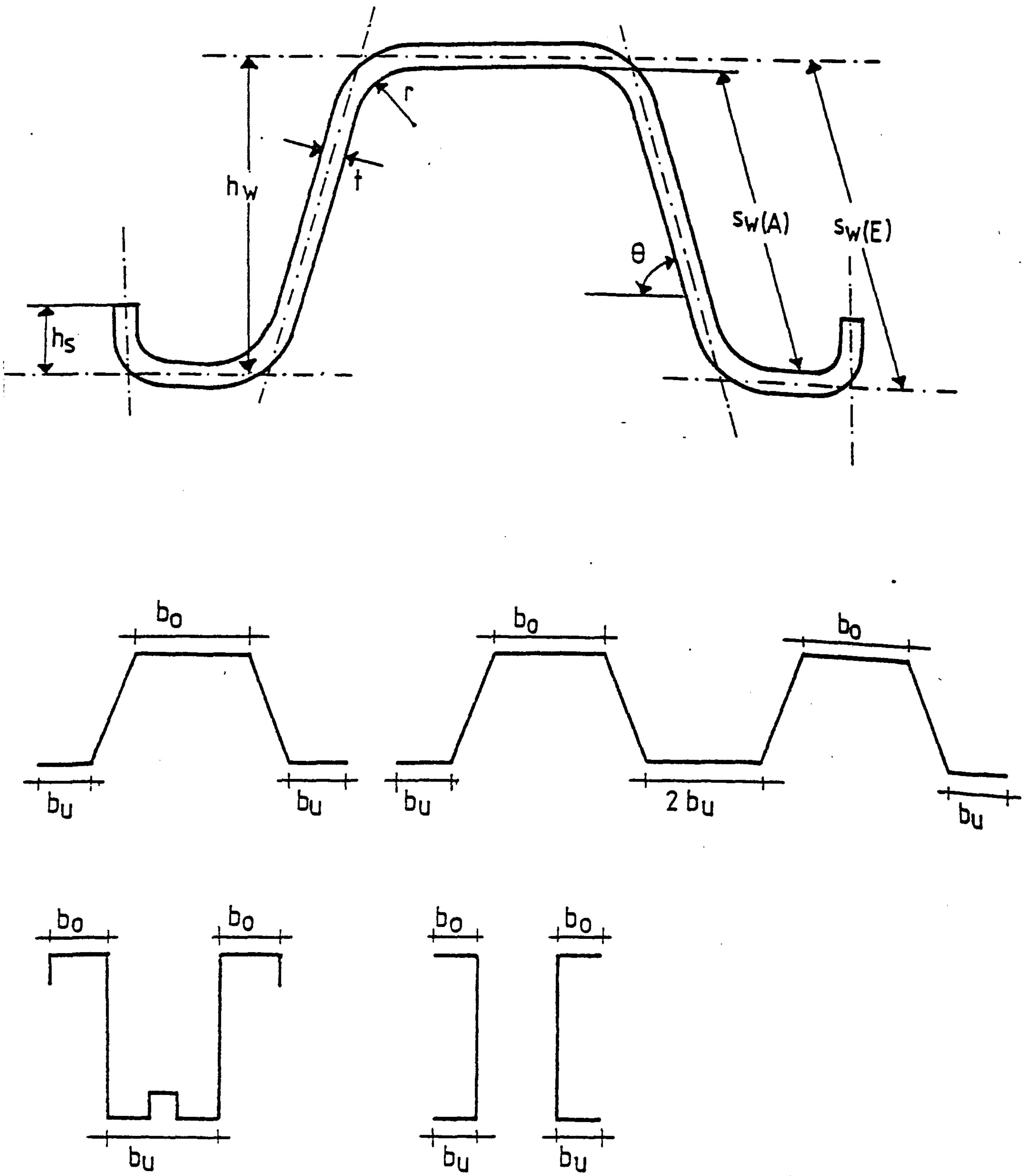


Figure 1

1.3. Outline

Chapter 2 of this report describes the three web crippling formulations evaluated.
Chapter 3 states the differences in these web crippling prediction formulas.
Chapter 4 gives the necessary information of the test series used to compare the web crippling prediction formulas with the test results.
Chapter 5 contains the comparison between the test loads and the ultimate web crippling loads computed with the three web crippling formulations.
Chapter 6 states the conclusions.

2. FORMULATIONS EVALUATED

The three formulations evaluated have been based on test results, not on theoretical analysis.
This is due to the complexity of the theoretical analysis.
A theoretical analysis involves

- Nonuniform stress distribution under the applied load and the adjacent portions of the web
- Elastic and inelastic stability of the web element
- Local yielding in the immediate region of load application
- The effect of the inside bend radius (bending of the webs out of the plane)

The web crippling prediction formulas evaluated are:

2.1. The ECCS approach

In the ECCS-1983 Recommendations (1 and 2) the web crippling load is predicted by the equation

$$R_d = 0.15\, t^2 \sqrt{E\, f_{ty}}\, (1 - 0.1 \sqrt{r/t})\, (0.5 + \sqrt{0.02\, \ell_s/t})(2.4 + (\Theta/90)^2)$$

The use of the equation is subject to the following limitations:
$r < 10t$
$\ell_s < 200$ (mm)
$\Theta > 50^{\circ}$

When the support consists of a round tube, z- or c-purlin, so that the nominal bearing length becomes very small, ℓ_s may be taken equal to 10 mm.
The equation applies to both sections and deck.

The ECCS approach is based on the testing of profiled sections performed at the Royal Institute of Technology in Stockholm (3). Baehre (10) reported that the testing involved 78 specimens, but it is doubtful whether all these tests can be seen as IOF web crippling tests (see the description of the Stockholm tests in chapter 3).
The empirical formula for the ultimate web crippling load given in References 5 and 10 has been modified slightly to make it applicable to aluminium also.
The original formula (5) included a limitation $s_{w(E)} < 170t$.

2.2. The AISI approach

In the AISI-1980 Specification (3) the web crippling load is obtained by the equation

$$R_d = 1.85^{*} \cdot f_{ty}/33 \cdot C_1 \cdot C_2 \cdot C_{\Theta} \cdot (291 - 0.40\, s_{w(A)}/t)(1+0.007\, \ell_s/t)^{**}$$

where
$C_1 = (1.22 - 0.22\, f_{ty}/228)$
$C_2 = (1.06 - 0.06\, r/t) \leq 1.0$
$C_{\Theta} = 0.7 + 0.3\, (\Theta/90)^2$

* Safety factor
** When $\ell_s/t > 60$ the factor $(1 + 0.007\, \ell_s/t)$ may be increased to $(0.75 + 0.011\, \ell_s/t)$

The formula applies to beams when $r/t \leq 6$ and to deck when $r/t \leq 7$, $\ell_s/t \leq 210$ and $\ell_s/s_{w(A)} < 3.5$.
Further limitations applied to the use of the equation are:
$\Theta \geq 45^{o}$
$s_{w(A)} \leq 200\ t$

The AISI approach is based on the evaluation of 58 IOF tests (8).
The tests included 28 tests performed at the University of Missouri-Rolla and 30 tests performed at Cornell University.

Some additional tests have been conducted for the purpose of determining the effect of large bearing lengths on web crippling.

2.3. The University of Waterloo approach

A modification of the AISI approach was reached in a research project conducted at the University of Waterloo (4).
The web crippling formula is:

$$R_d = 1.85^{*} \cdot 9.0\ t^2 f_{ty} (\sin\Theta)(1.0-0.001\ \frac{s_{w(A)}}{t})(1.0+0.005\ \ell_s/t)(1.0-0.075\ \sqrt{r/t})(1.0-0.1 f_{ty}/228)$$

* Safety factor

The use of the equation is subject to the following limitations
$s_{w(A)}/t \leq 200$
$r/t \leq 10$

The University of Waterloo approach is based on the evaluation of 90 IOF tests (4).
These tests included 59 tests performed at the University of Waterloo and 31 tests performed at Cornell University.

The University of Waterloo approach was developed for deck (multi-web cold formed steel sections). In this study it is also applied to sections.
This is reasonable because the AISI and ECCS use the same equations for sections and deck too.
Besides the Cornell test specimens were sections.

3. DIFFERENCES IN WEB CRIPPLING FORMULATIONS

The three web crippling prediction formulas can be written as

$$R_d = t^2 C \cdot C_{f_{ty}} \cdot C_{r/t} \cdot C_{\ell_s/t} \cdot C_{s_{w(A)}/t} \cdot C_\Theta$$

where

C	is a constant
$C_{f_{ty}}$	is a term depending on f_{ty}
$C_{r/t}$	is a term depending on r/t etc.

and

$C_{f_{ty}} = 1$ for $f_{ty} = 400$ (N/mm^2)

$C_{r/t} = 1$ for $r/t = 0$

$C_{\ell_{s/t}} = 1$ for $\ell_{s/t} = 200$

$C_{s_{w(A)}/t} = 1$ for $s_{w(A)}/t = 40$

$C_\Theta = 1$ for $\Theta = 90^\circ$

In the three web crippling formulas these terms have different forms.

1. ECCS approach

$$C = 0.15 \sqrt{210\,000}\sqrt{400} \cdot 2.5 \cdot 3.4 = 11686 \text{ (N)}$$

$$C_{f_{ty}} = \sqrt{f_{ty}/400}$$

$$C_{r/t} = 1 - 0.1\sqrt{r/t} \qquad r/t < 10$$

$$C_{\ell_s/t} = \frac{(0.5 + \sqrt{0.02\,\ell_s/t})}{2.5} \qquad \ell_s < 200 \quad \text{(mm)}$$

$$C_{s_{w(A)}/t} = 1$$

$$C_\Theta = \frac{(2.4 + (\Theta/90)^2)}{3.4} \qquad \Theta > 50^\circ$$

2. AISI approach

$$C = \frac{1.85}{33} \cdot 3336 \cdot 2.95 \cdot 275 = 15172 \text{ (N)}$$

$$C_{f_{ty}} = \frac{(1.22\, f_{ty} - 0.22\, f_{ty}^2 / 228)}{333.6}$$

$C_{r/t} = (1.06 - 0.06\, r/t) \leq 1$ beams: $r/t < 6$, deck $r/t < 7$

$C_{\ell_s/t} = \dfrac{(1 + 0.007\, \ell_s/t)}{2.95}$ when $\ell_s/t \leq 60$ deck: $\ell_{s/t} < 210$

$= \dfrac{(0.75 + 0.011\, \ell_s/t)}{2.95}$ when $\ell_s/t > 60$

$C_{s_{w(A)}/t} = \dfrac{(291 - 0.40\, s_{w(A)}/t)}{275}$ $s_{w(A)}/t < 200$

$C_\Theta = 0.7 + 0.3\, (\Theta/90)^2$ $\Theta \geq 45^\circ$

3. Waterloo approach

$$C = 1.85 \cdot 9.0 \cdot 329.8 \cdot 2 \cdot 0.96 = 10543 \text{ (N)}$$

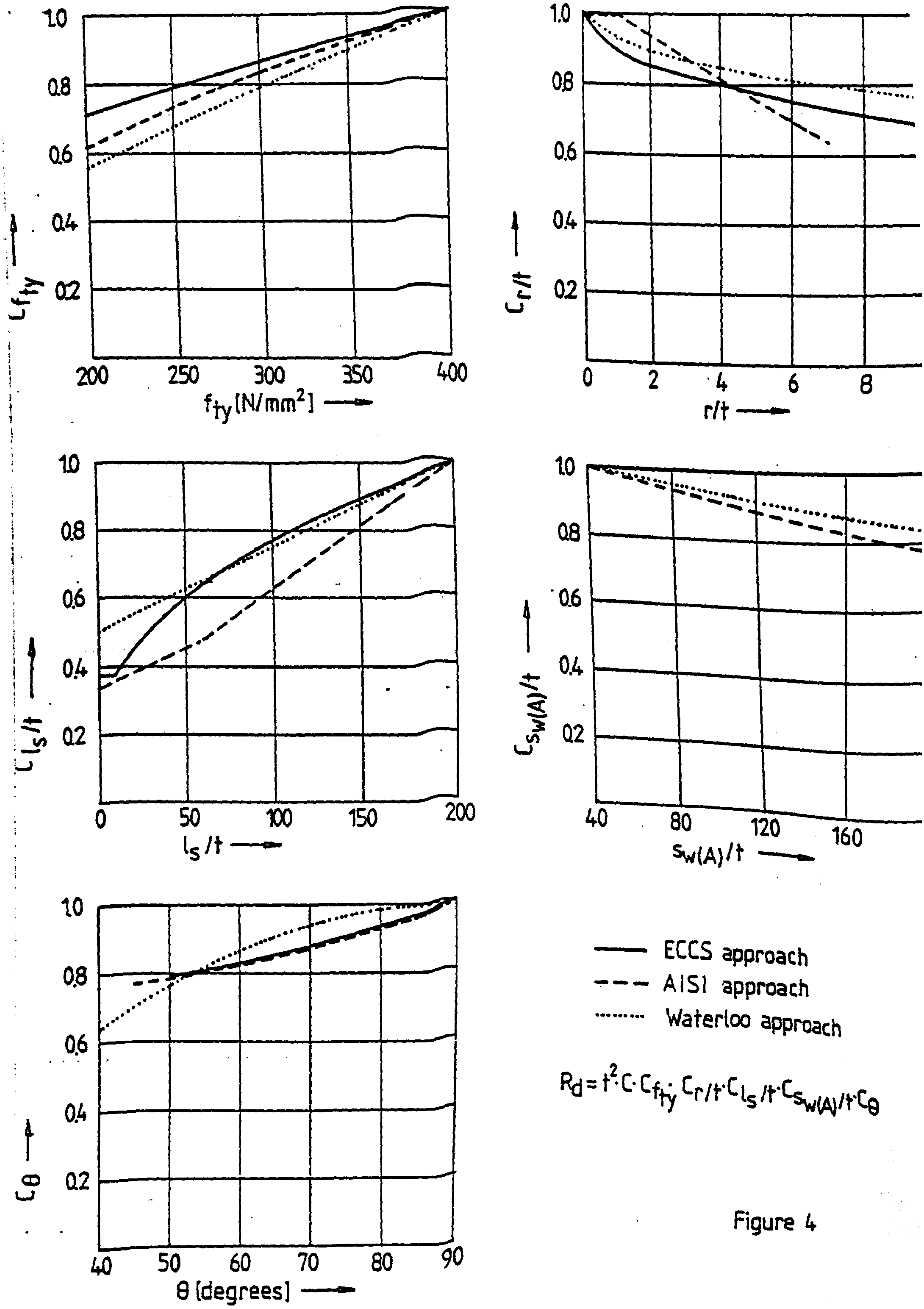
$$C_{f_{ty}} = \frac{(f_{ty} - 0.1\, f_{ty}^2 / 228)}{329.8}$$

$C_{r/t} = 1.0 - 0.075 \sqrt{r/t}$ $r/t \leq 10$

$$C_{\ell_s/t} = \frac{(1.0 + 0.005\, \ell_s/t)}{2}$$

$C\, s_{w(A)}/t = \dfrac{(1.0 - 0.001\, s_{w(A)}/t)}{0.96}$ $s_{w(A)}/t \leq 200$

$C_\Theta = \sin \Theta$



$C_{f_{ty}}$
f_{ty} [N/mm²]
$C_{r/t}$
r/t
$C_{l_s/t}$
l_s/t
$C_{s_{w(A)}/t}$
$s_{w(A)}/t$
C_θ
θ [degrees]
ECCS approach
AISI approach
Waterloo approach
$R_d = t^2 \cdot C \cdot C_{f_{ty}} \cdot C_{r/t} \cdot C_{l_s/t} \cdot C_{s_{w(A)}/t} \cdot C_\theta$

Figure 4

For a comparison of the terms see Figure 4.

The most striking difference between the three web crippling prediction formulas is that the ECCS approach, unlike the AISI and Waterloo approaches, does not contain a web slenderness term.
The values of the term $C_{r/t}$ of the AISI approach decrease at a much greater rate than the values of the ECCS and Waterloo approach.(See Figure 4).
The values of the terms $C_{\ell s/t}$ of the ECCS and Waterloo approach are almost identical for $\ell_s/t > 50$.
The values of the term C_θ do not show big differences.
In the Waterloo approach $\sin\theta$ was used because it is simpler to compute on a hand calculator and has physical meaning as demonstrated in Figure 5.
The constants C show rather big differences.
The constant C of the AISI approach is about 45% higher than the constants C of the ECCS and Waterloo approach.
This may be caused by the relatively large reduction of the web crippling load according to the AISI approach for increasing r/t and $s_{w(A)}/t$ and decreasing ℓ_s/t.

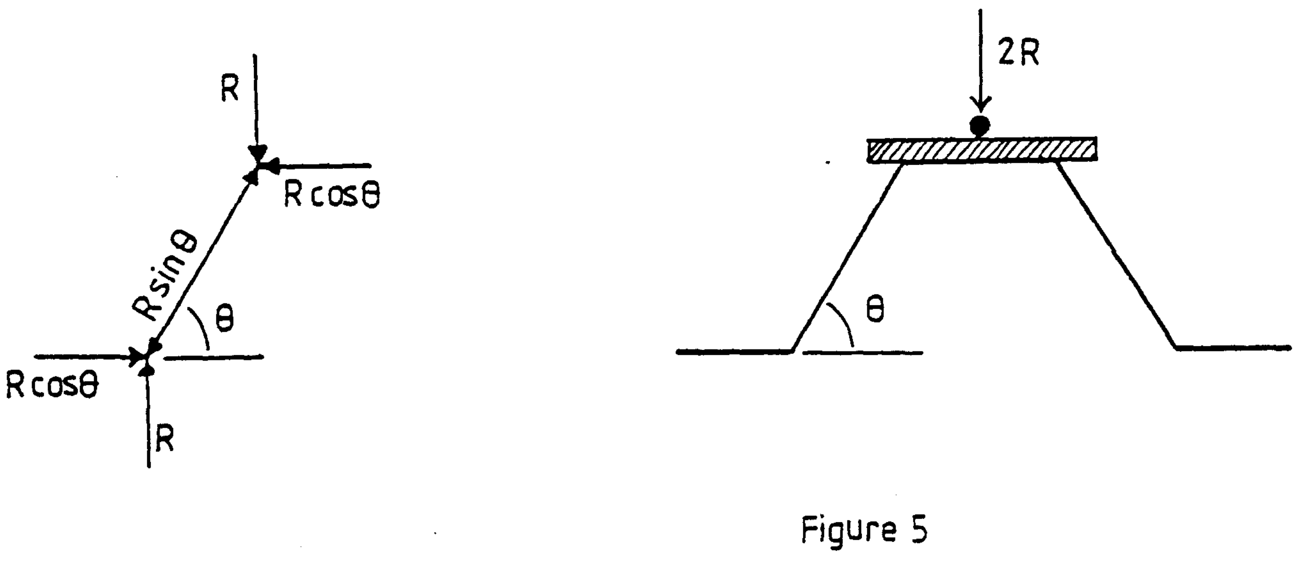


Figure 5

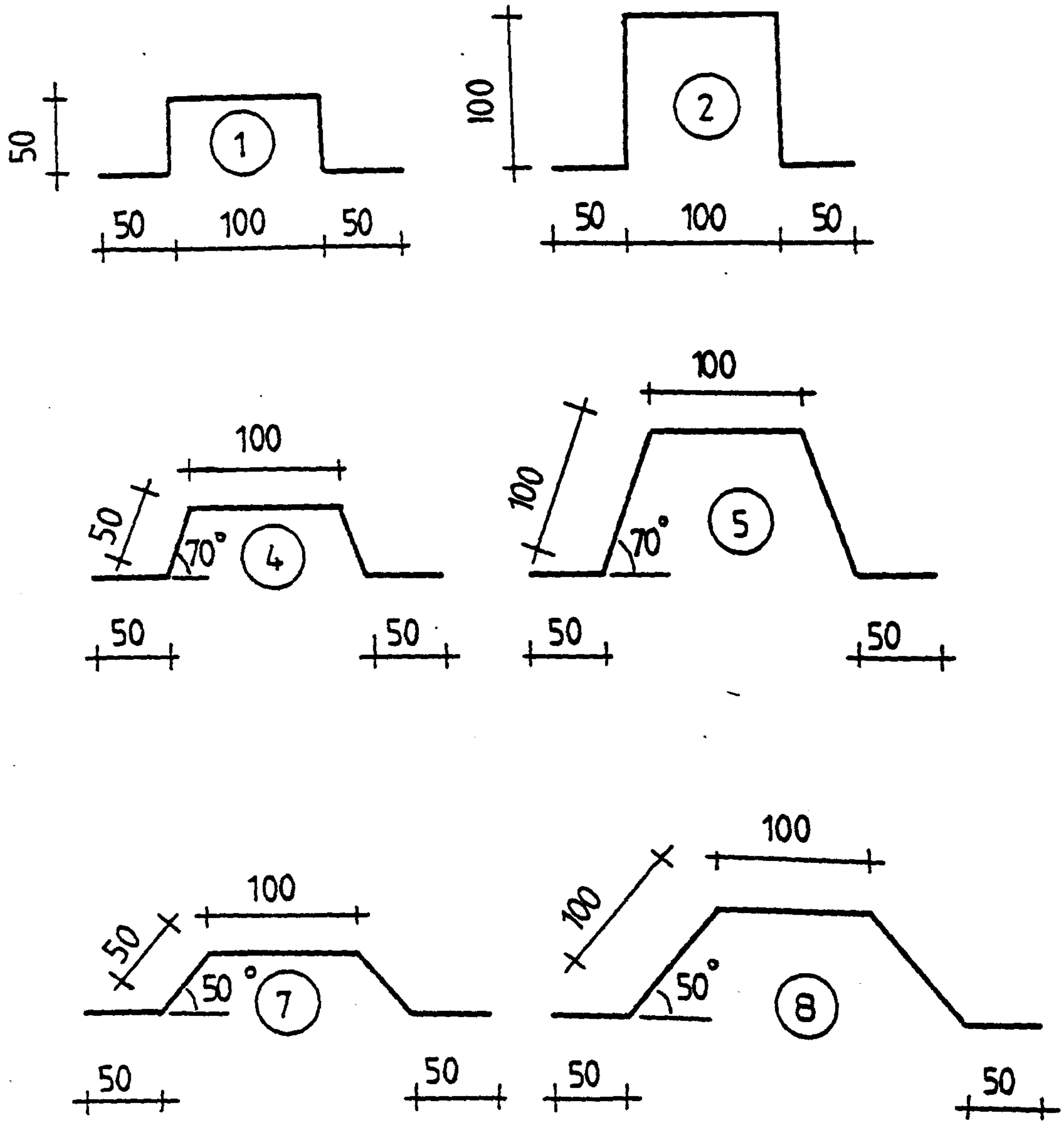


Figure 6

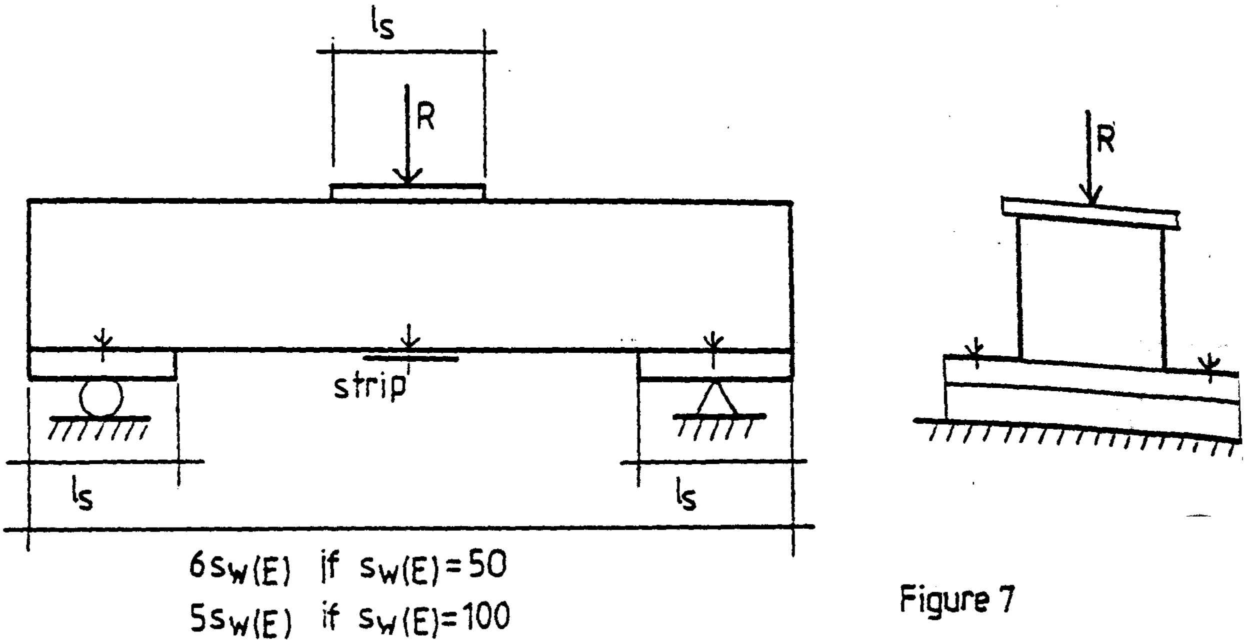


Figure 7

4. TESTRESULTS USED

4.1. STOCKHOLM TESTS (5)

1. Properties of test specimens

The configuration of the test specimens is shown in Figure 6. The dimensions and properties are given in Table 1.

2. Test setup

See Figure 7.
To prevent spreading the tension flanges were connected with a strip in the middle of the span. It is assumed that the central bearing plate and the end supports had the same bearing length.

3. Load application

The loading speed was 20 kp per minute (1 kp = 9.807 N). Every 100th kp the load was kept constant for about 20 seconds to read the dial indicators (used to measure the deformations). Circa 300 kp before failure the dial indicators were read every 50th kp.

4. Determination of the test load

The test load was taken as the largest load the section was able to sustain.
This criterion was suitable for the sections (with small bending radii) showing small deformations at failure. Sections with large bending radii failed with large deformations. These deformations were too large to be accepted in practice.
Yet, lacking a better failure criterion, for these tests too the test load R_{test} was taken as the largest load the section was able to sustain.
Each type of test was performed twice.
When the test loads differed more than 5% a third test was performed.

5. Failure mode

Several types of failure occurred during the testing:
- failure in the middle of the span (type M, Figure 8)
- failure at the end supports (type E, Figure 8)
- failure by sway of the whole section (type S, Figure 8)
- failure of the top flange over the whole length of the section (type V, Figure 8)
- failure in the middle of the span after failure at the end supports and stiffening the section at the end supports with a wooden block between the top flange and the bearing plate (type M_o)

The failure types S and V do not occur in practice.
In this report only tests with failure mode M are included.

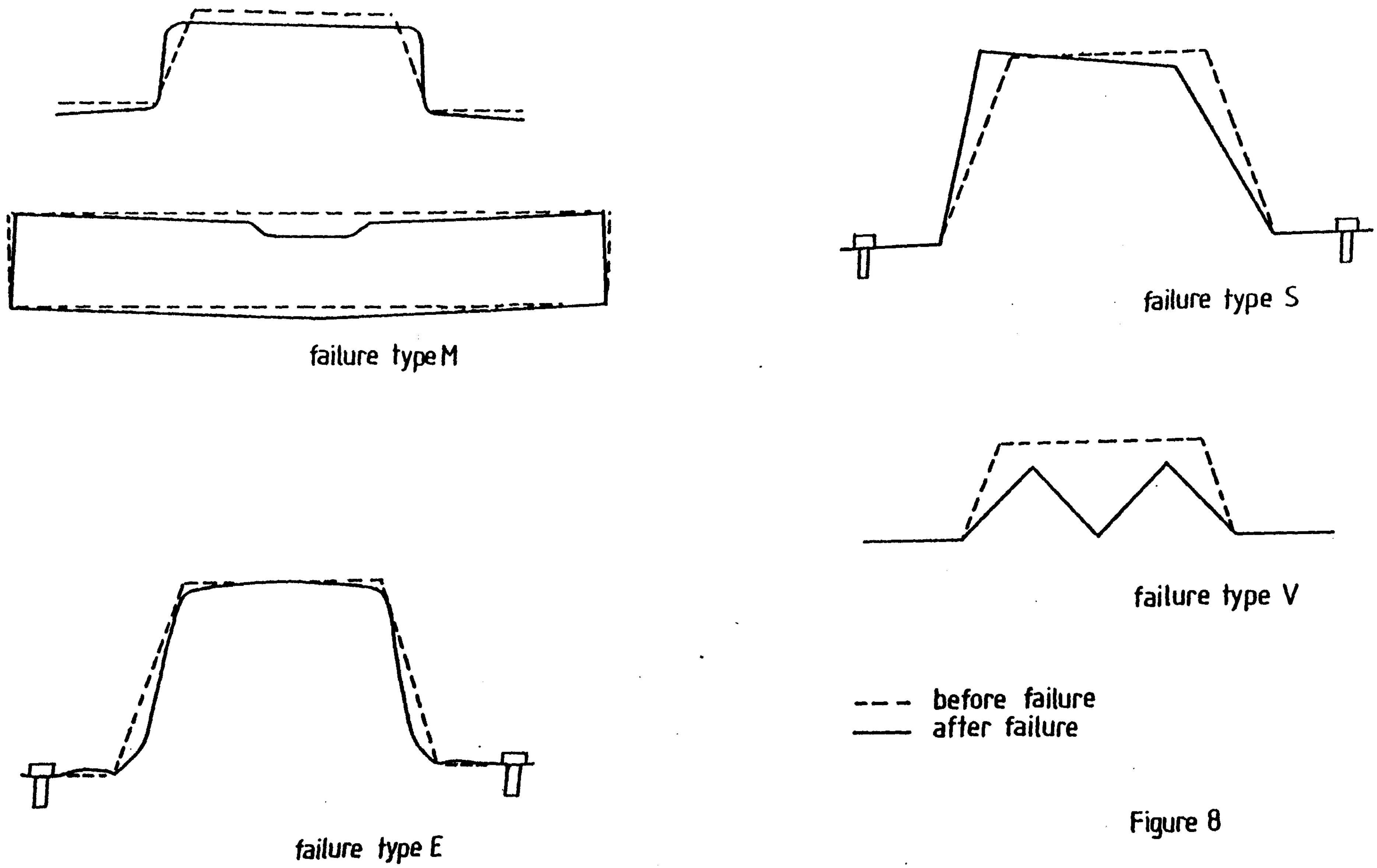

failure type M
failure type S
failure type V
failure type E
before failure
after failure

Figure 8

6. Moment ratio

The moment ratio M_{test}/M_d is not given in Reference 5.
It is reported that the span length was taken so short that the influence of the bending moment on the ultimate web crippling load was negligible. However, using the ECCS-1983 to calculate the ultimate moment capacity M_d it appears that the moment ratios M_{test}/M_d range from 0.28 to 0.48.
(M_{test} was computed by the equation $M_{test} = R_{test} (\ell - \ell_s)/4$).

According to Baehre (12) interaction is negligible for $M/M_d < 0.3$. Hence it is doubtful whether all the Stockholm tests are web crippling tests. Some tests are probably interaction tests.

Since the ECCS approach was based on the Stockholm tests, the tests with moments ratios larger than 0.3 are also included in this study.

7. Test results

See Table 6 Chapter 5.

Table 1.
PROPERTIES OF TEST SPECIMENS; STOCKHOLM TESTS

NR.	TESTCODE	fty	ls	t	r	θ	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
1	1-2-1	366	40	1.02	10.40	90	50	49	100	50	0	260	2
2	1-3-1	366	40	1.02	10.40	90	50	49	100	50	0	260	2
3	1-4-2	366	40	1.02	10.40	90	100	99	100	50	0	460	2
4	1-5-2	366	40	1.02	10.40	91	100	99	100	50	0	460	2
5	1-6-2	366	40	1.02	10.50	88	100	99	100	50	0	460	2
6	1-10-5	366	40	1.02	10.40	70	100	99	100	50	0	460	2
7	1-11-5	366	40	1.02	10.40	70	100	99	100	50	0	460	2
8	1-13-8	366	40	1.02	10.40	50	100	99	100	50	0	460	2
9	1-14-8	366	40	1.02	10.40	49	100	99	100	50	0	460	2
10	1-15-8	366	40	1.02	10.40	50	100	99	100	50	0	460	2
11	2-1-5	366	40	1.02	1.40	72	100	99	100	50	0	460	2
12	2-2-5	366	40	1.02	1.30	71	100	99	100	50	0	460	2
13	2-3-5	366	40	1.02	1.20	71	100	99	100	50	0	460	2
14	2-4-5	366	40	1.02	5.30	71	100	99	100	50	0	460	2
15	2-5-5	366	40	1.02	5.20	70	100	99	100	50	0	460	2
16	2-7-8	366	40	1.02	1.60	50	100	99	100	50	0	460	2
17	2-8-8	366	40	1.02	1.10	50	100	99	100	50	0	460	2
18	2-10-8	366	40	1.02	5.50	49	100	99	100	50	0	460	2
19	2-11-8	366	40	1.02	5.40	50	100	99	100	50	0	460	2
20	3-1-4	384	40	0.58	1.30	69	50	49	100	50	0	260	2
21	3-3-4	384	40	0.58	1.30	70	50	49	100	50	0	260	2
22	3-5-4	384	40	0.58	2.70	70	50	49	100	50	0	260	2
23	3-6-4	384	40	0.58	2.70	70	50	49	100	50	0	260	2
24	3-7-4	384	40	0.58	5.20	70	50	49	100	50	0	260	2
25	3-8-4	384	40	0.58	5.00	69	50	49	100	50	0	260	2
26	3-9-4	384	40	0.58	5.20	69	50	49	100	50	0	260	2
27	3-10-5	384	40	0.58	1.30	70	100	99	100	50	0	460	2
28	3-11-5	384	40	0.58	1.30	71	100	99	100	50	0	460	2
29	3-13-5	384	40	0.58	2.80	68	100	99	100	50	0	460	2
30	3-14-5	384	40	0.58	2.90	71	100	99	100	50	0	460	2
31	3-16-5	384	40	0.58	4.60	68	100	99	100	50	0	460	2
32	3-17-5	384	40	0.58	4.90	71	100	99	100	50	0	460	2
33	4-1-5	274	40	0.93	5.30	71	100	99	100	50	0	460	2
34	4-2-5	274	40	0.95	5.30	70	100	99	100	50	0	460	2
35	4-4-5	274	70	0.93	5.20	71	100	99	100	50	0	430	2
36	4-5-5	274	70	0.94	5.30	70	100	99	100	50	0	430	2
37	4-6-5	274	70	0.95	5.40	69	100	99	100	50	0	430	2
38	4-7-5	274	100	0.92	5.30	70	100	99	100	50	0	400	2
39	4-8-5	274	100	0.97	5.30	70	100	99	100	50	0	400	2
40	4-9-5	274	100	0.93	5.30	70	100	99	100	50	0	400	2
41	4-10-5	366	70	1.02	5.50	70	100	99	100	50	0	430	2
42	4-11-5	366	70	1.02	5.40	71	100	99	100	50	0	430	2
43	4-12-5	366	100	1.02	5.40	71	100	99	100	50	0	400	2
44	4-13-5	366	100	1.02	5.30	72	100	99	100	50	0	400	2
45	4-15-5	366	100	1.02	5.30	69	100	99	100	50	0	400	2

Table 1.(Continued)
PROPERTIES OF TEST SPECIMENS; STOCKHOLM TESTS

NR.	TESTCODE	fty	ls	t	r	D	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
46	4-17-7	384	40	0.58	3.30	50	50	49	100	50	0	260	2
47	4-22-7	384	100	0.58	3.50	51	50	49	100	50	0	200	2
48	4-24-7	384	100	0.58	3.60	51	50	49	100	50	0	200	2
49	4-25-7	244	40	0.52	2.60	52	50	49	100	50	0	260	2
50	4-26-7	244	40	0.52	1.40	52	50	49	100	50	0	260	2
51	4-28-7	244	70	0.52	2.40	50	50	49	100	50	0	230	2
52	4-29-7	244	70	0.52	2.70	50	50	49	100	50	0	230	2
53	4-33-7	244	100	0.52	2.40	51	50	49	100	50	0	200	2

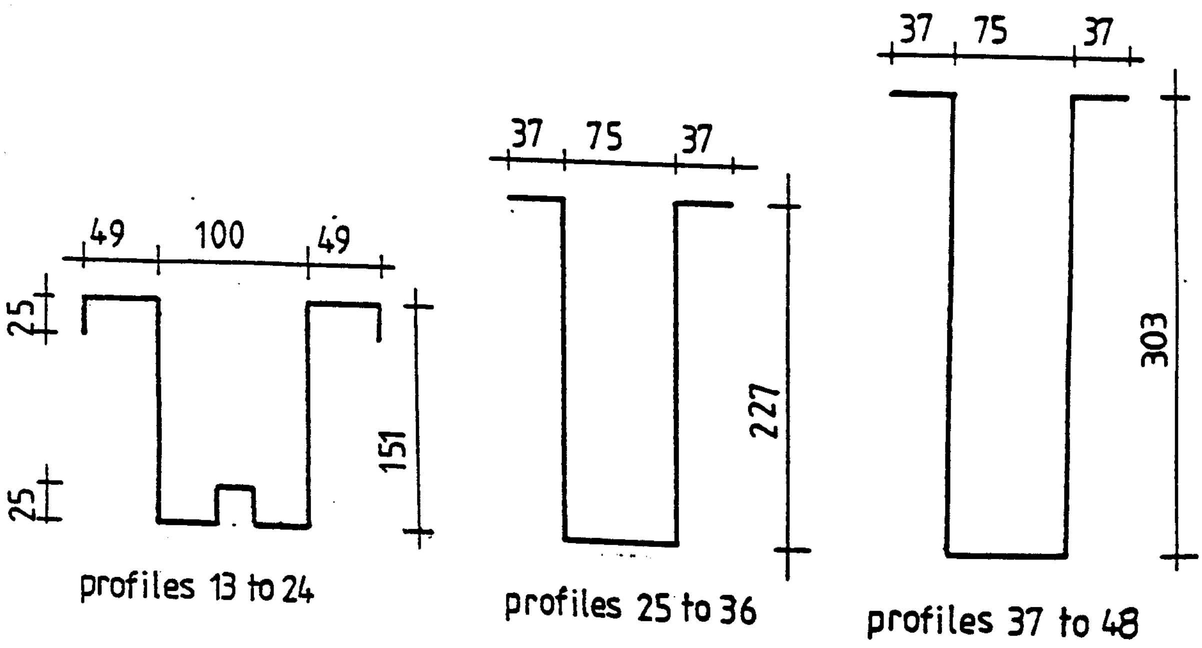


Figure 9

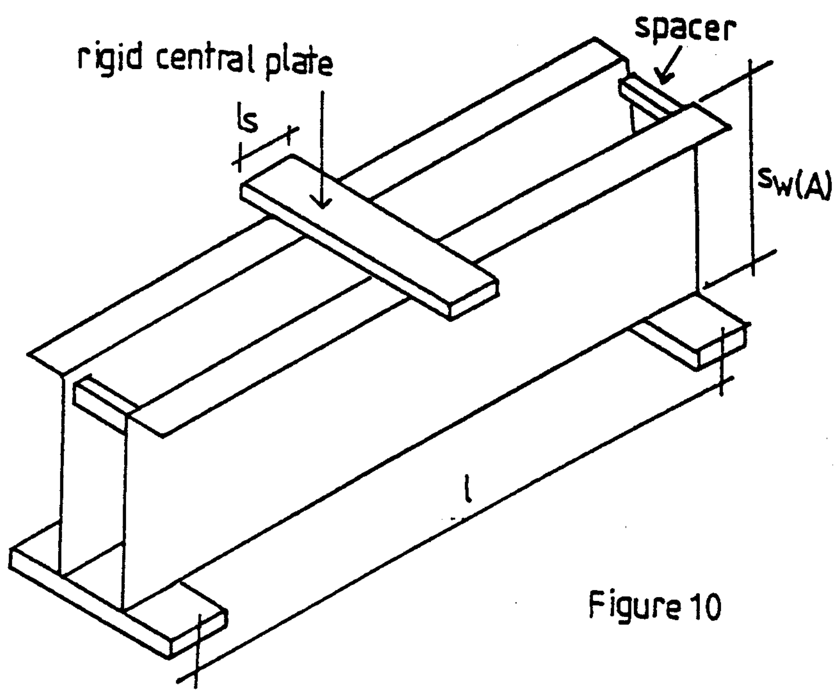


Figure 10

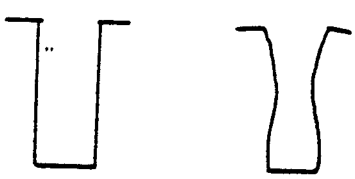


Figure 11

4.2. CORNELL TESTS

A complete description of these tests is reputed to have been given in Reference 8. Since this was not available References 4, 5 and 9 have been used.

1. Properties of test specimens

The test sections used in the Cornell Study are shown in Figure 9. The dimensions and properties are given in Table 2. Only the overall length of the stiffeners is given, the dimensions of the curved and straight portions of the stiffeners were not available.

2. Test setup

See Figure 10.

3. Load application

-

4. Determination of the test load

-

5. Failure mode

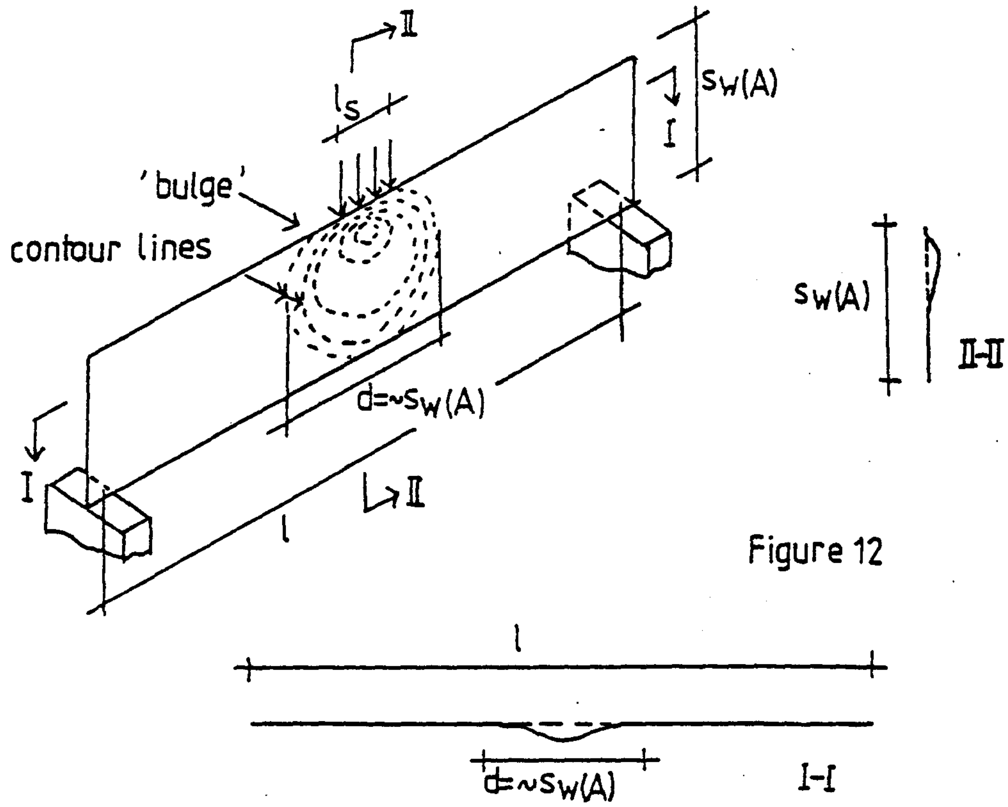
During the progress of a test at moderately high loads but still before failure the webs deflected inwards out of their plane (see Figure 11).
This deflections were relatively small and extended throughout the depth of a web in the vicinity of the external load. At failure, there was a sudden bulging of the web with large deflections under and in the immediate vicinity of the central bearing plate, as shown in Figure 12.

6. Moment ratio

According to Reference 4 the moment ratio M_{test}/M_d was less than 0.3.
The AISI-1980 Specification was used to compute the ultimate moment capacity M_d. The test moment M_{test} was computed by the equation
$M_{test} = R_{test} (\ell - \ell_s) / 4$.

7. Test results

See Table 7 Chapter 5.



II
l_s
'bulge'
contour lines
$s_w(A)$
I
$s_w(A)$
II-II
$d = \sim s_w(A)$
I
II
l
l
$d = \sim s_w(A)$
I-I

Figure 12

Table 2.
PROPERTIES OF TEST SPECIMENS; CORNELL TESTS

NR.	TESTCODE	fty	ls	t	r	0	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
54	13	234	19	1.54	1.54	90	151	149	49	100	25	610	2
55	14	254	38	1.52	1.52	90	151	149	49	100	25	610	2
56	16	255	19	1.52	4.55	90	151	149	49	100	25	610	2
57	17	225	38	1.53	4.60	90	151	149	49	100	25	610	2
58	18	225	64	1.54	4.61	90	151	149	49	100	25	610	2
59	19	372	19	1.64	1.64	90	151	149	49	100	25	610	2
60	20	370	38	1.66	1.66	90	151	149	49	100	25	610	2
61	21	371	64	1.65	1.65	90	151	149	49	100	25	610	2
62	22	372	19	1.64	4.92	90	151	149	49	100	25	610	2
63	23	365	38	1.65	4.95	90	151	149	49	100	25	610	2
64	24	367	64	1.67	5.02	90	151	149	49	100	25	610	2
65	25	260	19	1.53	1.53	90	227	226	37	75	0	914	2
66	26	247	38	1.51	1.51	90	227	226	37	75	0	914	2
67	28	219	19	1.53	4.58	90	227	226	37	75	0	914	2
68	29	228	38	1.51	4.53	90	227	226	37	75	0	914	2
69	30	223	64	1.49	4.47	90	227	226	37	75	0	914	2
70	31	376	19	1.65	1.65	90	227	225	37	75	0	914	2
71	34	377	19	1.62	4.85	90	227	225	37	75	0	914	2
72	35	374	38	1.63	4.88	90	227	225	37	75	0	914	2
73	36	373	64	1.61	4.82	90	227	225	37	75	0	914	2
74	37	221	19	1.53	1.53	90	303	302	37	75	0	1219	2
75	38	229	38	1.56	1.56	90	303	302	37	75	0	1219	2
76	39	263	64	1.55	1.55	90	303	302	37	75	0	1219	2
77	40	213	19	1.50	4.51	90	303	302	37	75	0	1219	2
78	41	224	38	1.54	4.63	90	303	302	37	75	0	1219	2
79	42	223	64	1.55	4.64	90	303	301	37	75	0	1219	2
80	43	371	19	1.69	1.69	90	303	301	37	75	0	1219	2
81	44	374	38	1.69	1.69	90	303	301	37	75	0	1219	2
82	46	385	19	1.68	5.03	90	303	301	37	75	0	1219	2
83	47	373	38	1.70	5.10	90	303	301	37	75	0	1219	2
84	48	368	64	1.68	5.04	90	303	301	37	75	0	1219	2

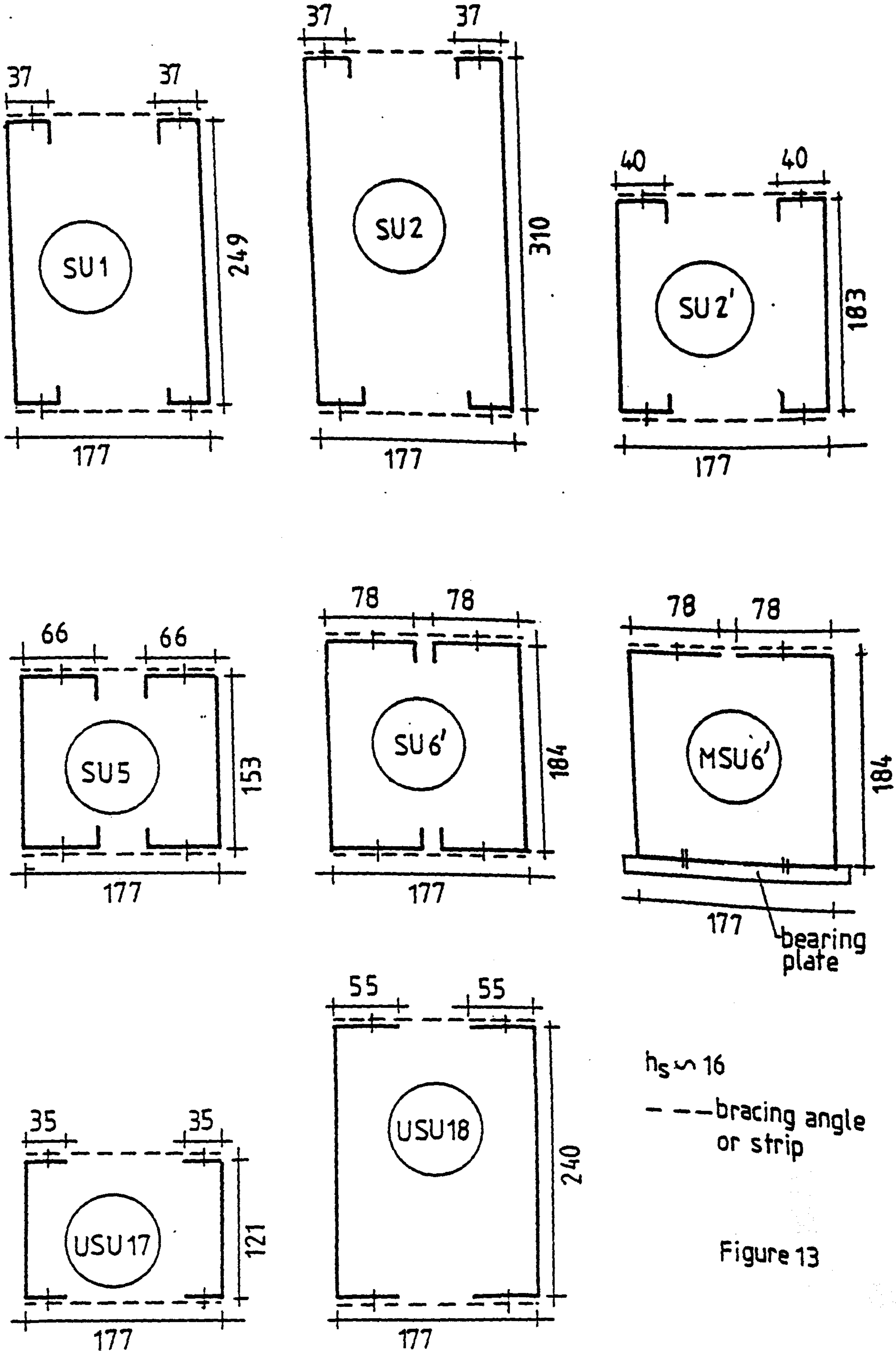

SU1
37 37
249
177
SU2
37 37
310
177
SU 2'
40 40
183
177
SU5
66 66
153
177
SU6'
78 78
184
177
MSU6'
78 78
184
177
bearing plate
USU17
35 35
121
177
USU18
55 55
240
177
h_s ∽ 16
- - - bracing angle or strip

Figure 13

4.3. MISSOURI-ROLLA TESTS (8)

1. Properties of test specimens

Three different types of cross-sectional configurations of beam specimen were used. The first type consisted of two channel sections (section SU, Figure 13). The channels were braced by 19.05 x 19.05 x 3.175 mm angles at the compression flange and 3.175 x 19.05 rectangular bars at the tension flange.
Self tapping screws were used for connections. The intervals of braces were provided such that the lateral buckling of each individual channel section was prevented.
The second type of beam specimens (section MSU, Figure 13) was fabricated in the same manner as the first type except that the beam flanges were connected to the bearing plates by machine bolts. The purpose of this arrangement was to evaluate the possible improvement of web crippling loads resulting from the restraint provided by beam flanges when they are connected to bearing plates by machine bolts.
The third type consisted of two channel sections with unstiffened flanges (sections USU, Figure 13). The braces of the tension and compression flanges were provided in the same manner as the first type. The dimensions and properties are given in Table 3.

2. Test setup

See Figure 14.

3. Load application

During the test the loads were applied by an increment of 15% of the predicted ultimate load. The duration for each load increment was approximately five minutes.

4. Determination of the test load

After failure of each specimen the ultimate load for web crippling was recorded.

5. Failure mode

All failure modes were consistent. Failure occurred in the web underneath the bearing plate.
However, the maximum deformation is located at about ¼ of the depth measured from the top flange of the specimen. See Figure 15.

6. Moment ratio

The moment ratio M_{test} / M_d was less than 0.3.
The AISI-1968 Specification was used to compute the ultimate moment capacity M_d.
Backcalculating from the tables in Reference 8 it appears that M_{test} was computed by the equation
$M_{test} = R_{test}\ \ell/4$.

7. Test results

See Table 8 Chapter 5.

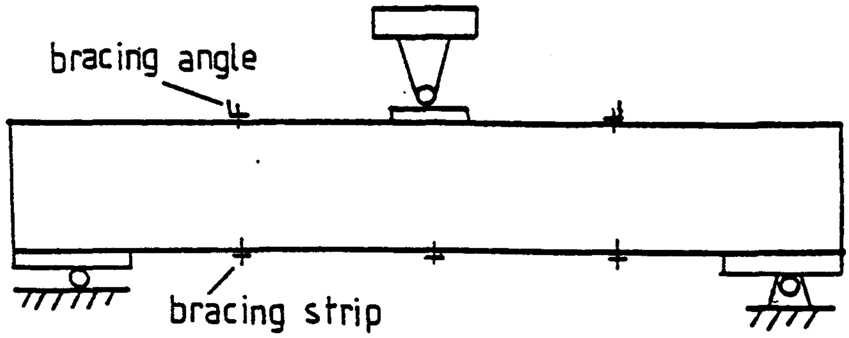


Figure 14

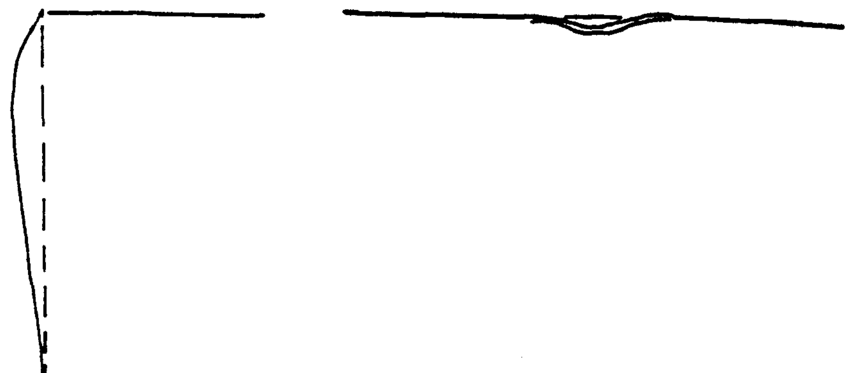


Figure 15

Table 3.
PROPERTIES OF TEST SPECIMENS; MISSOURI-ROLLA TESTS

NR.	TESTCODE	fty	ls	t	r	O	sw(E)	sw(A)	ho	hu	hs	l	# OF WEBS
85	SU1-IOF1	302	25	1.22	3.38	90	248	250	37	37	16	965	2
86	SU1-IOF2	302	25	1.21	3.18	90	250	252	37	37	16	965	2
87	SU1-IOF5	302	76	1.23	3.18	90	249	250	36	36	16	966	2
88	SU1-IOF6	302	76	1.22	3.18	90	249	250	37	37	16	965	2
89	SU2-IOF1	302	25	1.24	3.18	90	310	311	36	36	16	1118	2
90	SU2-IOF2	302	25	1.27	3.18	90	309	310	36	36	17	1118	2
91	SU2-IOF5	302	76	1.22	3.18	90	309	310	37	37	17	1118	2
92	SU2-IOF6	302	76	1.24	3.18	90	310	311	36	36	16	1118	2
93	SU2'-IOF3	254	76	1.26	2.38	90	182	184	40	40	15	673	2
94	SU2'-IOF4	254	76	1.29	2.38	90	183	184	40	40	15	673	2
95	SU2'-IOF5	254	76	1.29	2.38	90	183	184	40	40	15	521	2
96	SU2'-IOF6	254	76	1.29	2.38	90	183	185	40	40	15	521	2
97	SU5-IOF1	325	25	1.26	2.38	90	154	155	66	66	15	635	2
98	SU5-IOF2	325	25	1.28	2.38	90	153	154	66	66	15	635	2
99	SU5-IOF3	325	51	1.27	2.48	90	154	155	66	66	15	635	2
100	SU5-IOF4	325	51	1.28	2.38	90	153	154	66	66	15	635	2
101	SU5-IOF5	325	76	1.28	2.28	90	153	155	66	66	15	635	2
102	SU5-IOF6	325	76	1.28	2.38	90	153	155	66	66	15	635	2
103	SU6'-IOF1	325	25	1.27	2.38	90	183	185	78	78	15	635	2
104	SU6'-IOF2	325	25	1.27	2.18	90	184	186	78	78	15	635	2
105	SU6'-IOF3	325	51	1.26	2.28	90	184	185	78	78	15	635	2
106	SU6'-IOF4	325	51	1.26	2.38	90	185	186	78	78	15	635	2
107	SU6'-IOF5	325	76	1.25	2.38	90	184	185	78	78	15	635	2
108	SU6'-IOF6	325	76	1.28	2.28	90	184	185	78	78	15	635	2
109	MSU6'-IOF1	325	25	1.28	2.38	90	184	185	78	78	15	635	2
110	MSU6'-IOF2	325	25	1.27	2.38	90	184	185	78	78	15	635	2
111	MSU6'-IOF5	325	76	1.28	2.38	90	184	185	78	78	15	635	2
112	MSU6'-IOF6	325	76	1.26	2.38	90	183	185	78	78	15	635	2
113	USU17-IOF5	250	76	1.24	1.19	90	121	122	35	35	0	559	2
114	USU17-IOF6	250	76	1.24	1.19	90	121	122	35	35	0	559	2
115	USU18-IOF5	250	76	1.24	1.19	90	239	240	55	55	0	914	2
116	USU18-IOF6	250	76	1.24	1.19	90	240	242	55	55	0	915	2

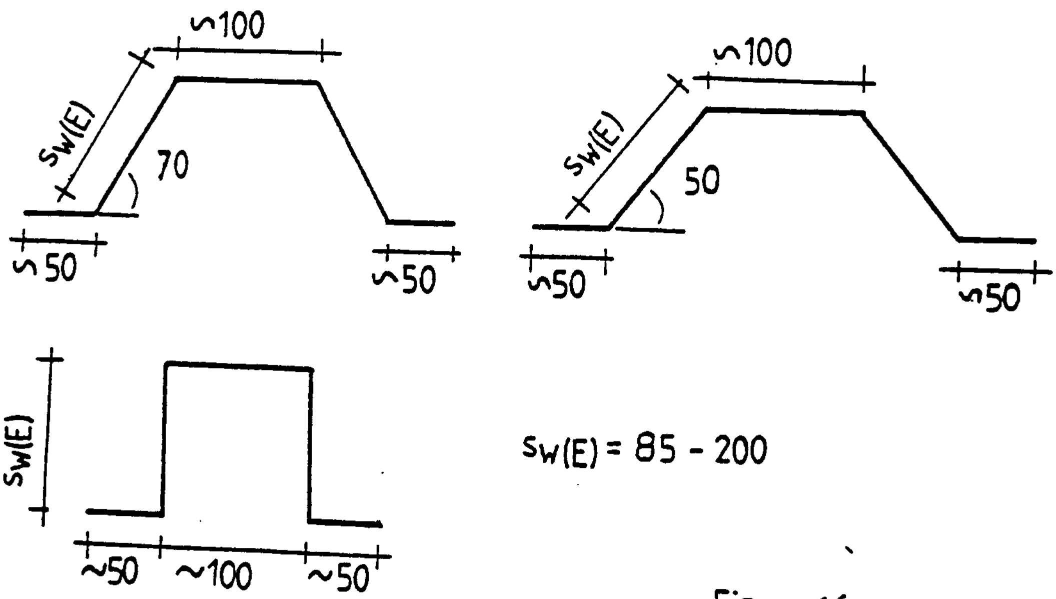


Figure 16

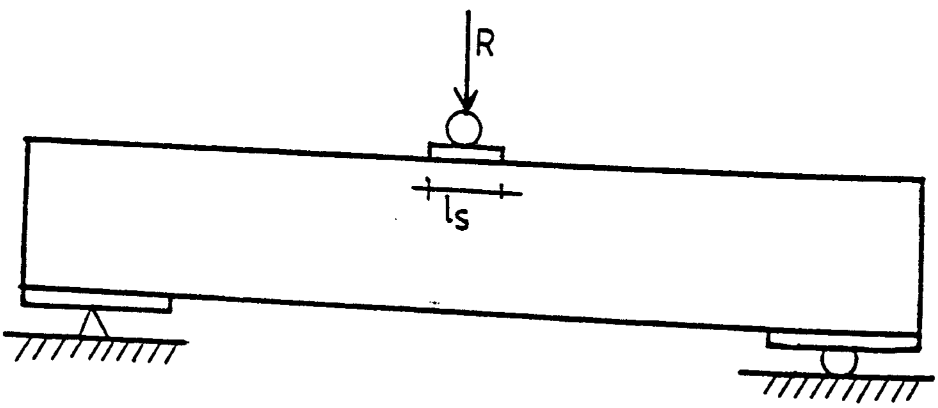


Figure 17

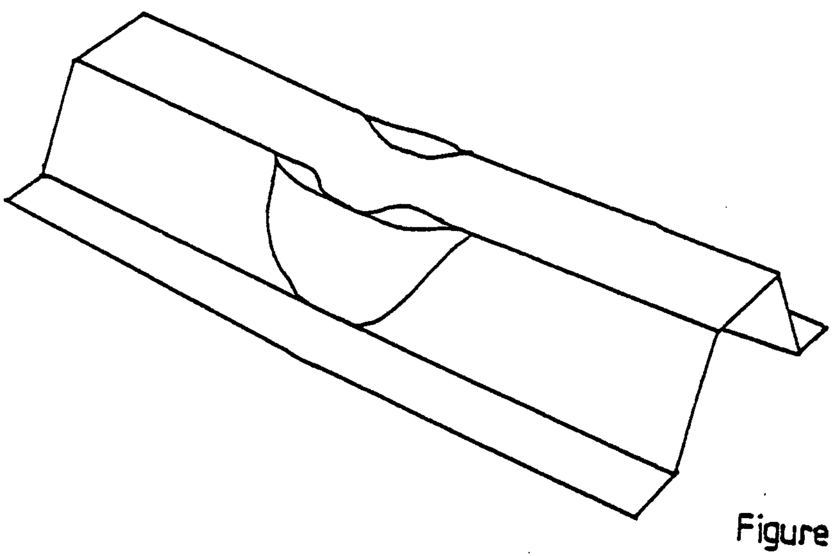


Figure 18

4.4 WATERLOO TESTS (4)

1. Properties of test specimens

The test specimens consisted of profiles specially fabricated at the University of Waterloo, as shown in Figure 16. They were brake-formed using ASTM A611 Grade C steel with a minimum garanteed yield stress of 228 (N/mm^2). Their dimensions and properties are given in Table 4.

2. Test setup

See Figure 17.
Relatively large end bearing plates were used to insure that failure would occur at the interior load position. Spreading was prevented by bolting the lower flanges to the bearing plate.

3. Load application

The load was applied to the test specimens by means of a 45 kN capacity hydraulic jack through a hand operated hydraulic pump. The rate of load application was uniform up to the failure load.

4. Determination of the test load

The test load R_{test} was taken as the largest load the specimen was able to sustain after which a sudden decrease in load was experienced.

5. Failure mode

See Figure 18.
The failure region for the tests was a localized failure which was restricted to the area under the bearing plate and immediately adjacent to it.

6. Moment ratio

The moment ratio M_{test} / M_d was less than 0.3.
The AISI-1980 Specification was used to compute the ultimate moment capacity M_d.
$M_{test} = R_{test} (\ell - \ell_s) / 4.$

7. Test results

See Table 9 Chapter 5.

Table 4.
PROPERTIES OF TEST SPECIMENS; WATERLOO TESTS

NR.	TESTCODE	fty	ls	t	r	D	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
117	5W-IOF	274	25	0.97	2.38	90	101	100	100	50	0	460	2
118	6W-IOF	265	25	0.61	2.38	90	101	101	101	51	0	460	2
119	7W-IOF	231	25	1.52	2.38	90	201	199	102	50	0	559	2
120	8W-IOF	274	25	0.97	2.38	90	203	202	100	50	0	559	2
121	14W-IOF	274	25	0.97	2.38	70	101	100	100	50	0	508	2
122	15W-IOF	265	25	0.61	2.38	70	102	101	101	51	0	511	2
123	16W-IOF	231	25	1.52	2.38	70	202	201	99	50	0	508	2
124	17W-IOF	274	25	0.97	2.38	70	202	201	100	50	0	508	2
125	23W-IOF	274	25	0.99	2.38	50	102	101	99	50	0	508	2
126	24W-IOF	265	25	0.64	2.38	50	103	102	99	50	0	508	2
127	25W-IOF	231	25	1.55	2.38	50	202	200	100	49	0	508	2
128	26W-IOF	274	25	1.02	2.38	50	203	202	101	50	0	508	2
129	34W-IOF	265	25	0.61	2.38	90	101	100	101	50	0	315	2
130	35W-IOF	265	51	0.61	2.38	90	100	100	101	50	0	318	2
131	36W-IOF	265	76	0.61	2.38	90	100	100	101	50	0	315	2
132	51W-IOF	274	25	0.91	2.38	70	105	104	100	49	0	508	2
133	52W-IOF	265	25	0.61	2.38	70	106	105	100	50	0	508	2
134	54W-IOF	274	25	0.91	2.38	50	130	129	101	50	0	508	2
135	55W-IOF	274	25	0.97	2.38	50	129	128	127	49	0	508	2
136	56W-IOF	274	25	0.91	2.38	50	130	129	75	50	0	508	2
137	57W-IOF	231	25	1.52	2.38	90	101	99	100	50	0	318	2
138	60W-IOF	253	25	1.14	2.38	90	100	99	103	50	0	318	2
139	61W-IOF	253	51	1.14	2.38	90	100	99	103	50	0	318	2
140	62W-IOF	253	76	1.14	2.38	90	101	100	103	50	0	318	2
141	69W-IOF	274	76	0.97	2.38	90	101	100	103	50	0	305	2
142	89W-IOF	265	25	0.61	2.38	70	108	107	100	50	0	516	2
143	91W-IOF	274	25	0.97	2.38	70	109	108	101	49	0	521	2
144	101W-IOF	265	25	0.61	2.38	50	132	131	102	50	0	533	2
145	103W-IOF	274	25	0.97	2.38	50	133	132	102	50	0	533	2
146	124W-IOF	265	127	0.61	2.38	90	102	101	102	51	0	483	2
147	125W-IOF	265	102	0.61	2.38	90	102	101	102	51	0	470	2
148	128W-IOF	265	102	0.61	2.38	90	101	100	102	51	0	318	2
149	134W-IOF	274	102	0.97	2.38	90	102	101	103	51	0	305	2
150	135W-IOF	274	127	0.97	2.38	90	102	101	103	51	0	305	2
151	136W-IOF	274	25	0.97	2.38	90	102	101	103	51	0	305	2
152	137W-IOF	274	51	0.97	2.38	90	101	100	103	51	0	305	2
153	139W-IOF	265	25	0.61	2.38	90	101	100	101	51	0	521	4
154	3WR-IOF	318	51	0.63	4.76	90	86	85	101	53	0	508	2
155	12WR-IOF	318	51	0.63	6.35	90	88	87	101	49	0	508	2
156	15WR-IOF	284	51	0.85	6.35	90	85	84	101	53	0	508	2
157	21WR-IOF	279	51	0.55	9.53	90	85	84	101	55	0	508	2
158	24WR-IOF	299	51	1.00	9.13	90	87	86	100	51	0	508	2
159	30WR-IOF	318	51	0.63	4.76	70	106	105	102	53	0	508	2
160	33WR-IOF	284	51	0.85	4.76	70	104	103	101	54	0	508	2
161	39WR-IOF	318	51	0.63	6.35	70	106	105	100	53	0	508	2

Table 4.
PROPERTIES OF TEST SPECIMENS; WATERLOO TESTS

NR.	TESTCODE	fty	ls	t	r	O	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
117	5W-IOF	274	25	0.97	2.38	90	101	100	100	50	0	460	2
118	6W-IOF	265	25	0.61	2.38	90	101	101	101	51	0	460	2
119	7W-IOF	231	25	1.52	2.38	90	201	199	102	50	0	559	2
120	8W-IOF	274	25	0.97	2.38	90	203	202	100	50	0	559	2
121	14W-IOF	274	25	0.97	2.38	70	101	100	100	50	0	508	2
122	15W-IOF	265	25	0.61	2.38	70	102	101	101	51	0	511	2
123	16W-IOF	231	25	1.52	2.38	70	202	201	99	50	0	508	2
124	17W-IOF	274	25	0.97	2.38	70	202	201	100	50	0	508	2
125	23W-IOF	274	25	0.99	2.38	50	102	101	99	50	0	508	2
126	24W-IOF	265	25	0.64	2.38	50	103	102	99	50	0	508	2
127	25W-IOF	231	25	1.55	2.38	50	202	200	100	49	0	508	2
128	26W-IOF	274	25	1.02	2.38	50	203	202	101	50	0	508	2
129	34W-IOF	265	25	0.61	2.38	90	101	100	101	50	0	315	2
130	35W-IOF	265	51	0.61	2.38	90	100	100	101	50	0	318	2
131	36W-IOF	265	76	0.61	2.38	90	100	100	101	50	0	315	2
132	51W-IOF	274	25	0.91	2.38	70	105	104	100	49	0	508	2
133	52W-IOF	265	25	0.61	2.38	70	106	105	100	50	0	508	2
134	54W-IOF	274	25	0.91	2.38	50	130	129	101	50	0	508	2
135	55W-IOF	274	25	0.97	2.38	50	129	128	127	49	0	508	2
136	56W-IOF	274	25	0.91	2.38	50	130	129	75	50	0	508	2
137	57W-IOF	231	25	1.52	2.38	90	101	99	100	50	0	318	2
138	60W-IOF	253	25	1.14	2.38	90	100	99	103	50	0	318	2
139	61W-IOF	253	51	1.14	2.38	90	100	99	103	50	0	318	2
140	62W-IOF	253	76	1.14	2.38	90	101	100	103	50	0	318	2
141	69W-IOF	274	76	0.97	2.38	90	101	100	103	50	0	305	2
142	89W-IOF	265	25	0.61	2.38	70	108	107	100	50	0	516	2
143	91W-IOF	274	25	0.97	2.38	70	109	108	101	49	0	521	2
144	101W-IOF	265	25	0.61	2.38	50	132	131	102	50	0	533	2
145	103W-IOF	274	25	0.97	2.38	50	133	132	102	50	0	533	2
146	124W-IOF	265	127	0.61	2.38	90	102	101	102	51	0	483	2
147	125W-IOF	265	102	0.61	2.38	90	102	101	102	51	0	470	2
148	128W-IOF	265	102	0.61	2.38	90	101	100	102	51	0	318	2
149	134W-IOF	274	102	0.97	2.38	90	102	101	103	51	0	305	2
150	135W-IOF	274	127	0.97	2.38	90	102	101	103	51	0	305	2
151	136W-IOF	274	25	0.97	2.38	90	102	101	103	51	0	305	2
152	137W-IOF	274	51	0.97	2.38	90	101	100	103	51	0	305	2
153	139W-IOF	265	25	0.61	2.38	90	101	100	101	51	0	521	4
154	3WR-IOF	318	51	0.63	4.76	90	86	85	101	53	0	508	2
155	12WR-IOF	318	51	0.63	6.35	90	88	87	101	49	0	508	2
156	15WR-IOF	284	51	0.85	6.35	90	85	84	101	53	0	508	2
157	21WR-IOF	279	51	0.55	9.53	90	85	84	101	55	0	508	2
158	24WR-IOF	299	51	1.00	9.13	90	87	86	100	51	0	508	2
159	30WR-IOF	318	51	0.63	4.76	70	106	105	102	53	0	508	2
160	33WR-IOF	284	51	0.85	4.76	70	104	103	101	54	0	508	2
161	39WR-IOF	318	51	0.63	6.35	70	106	105	100	53	0	508	2

Table 4.(Continued)
PROPERTIES OF TEST SPECIMENS; WATERLOO TESTS

NR.	TESTCODE	fty	ls	t	r	O	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
162	42WR-IOF	299	51	1.00	6.35	70	105	104	106	54	0	508	2
163	48WR-IOF	279	51	0.55	7.15	70	106	105	99	54	0	508	2
164	51WR-IOF	299	51	1.00	8.74	70	107	106	103	52	0	508	2
165	57WR-IOF	318	51	0.63	4.76	50	130	129	103	55	0	508	2
166	60WR-IOF	284	51	0.85	7.15	50	126	125	105	56	0	508	2
167	66WR-IOF	318	51	0.63	6.35	50	134	133	103	53	0	508	2
168	69WR-IOF	299	51	1.00	6.35	50	127	126	105	54	0	508	2
169	75WR-IOF	279	51	0.55	7.15	50	125	124	104	57	0	508	2
170	78WR-IOF	299	51	1.00	9.53	50	135	133	100	52	0	508	2
171	81WR-IOF	302	51	1.54	9.53	50	132	130	102	53	0	508	2
172	131WR-IOF	318	102	0.63	6.35	90	88	87	101	49	0	508	2
173	137WR-IOF	318	102	0.63	4.76	70	106	105	102	53	0	508	2
174	140WR-IOF	318	102	0.63	6.35	70	106	105	100	53	0	508	2
175	144WR-IOF	299	102	1.00	8.74	70	107	106	103	52	0	508	2

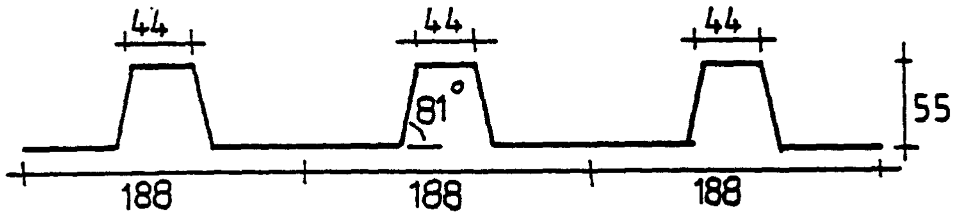


Figure 19

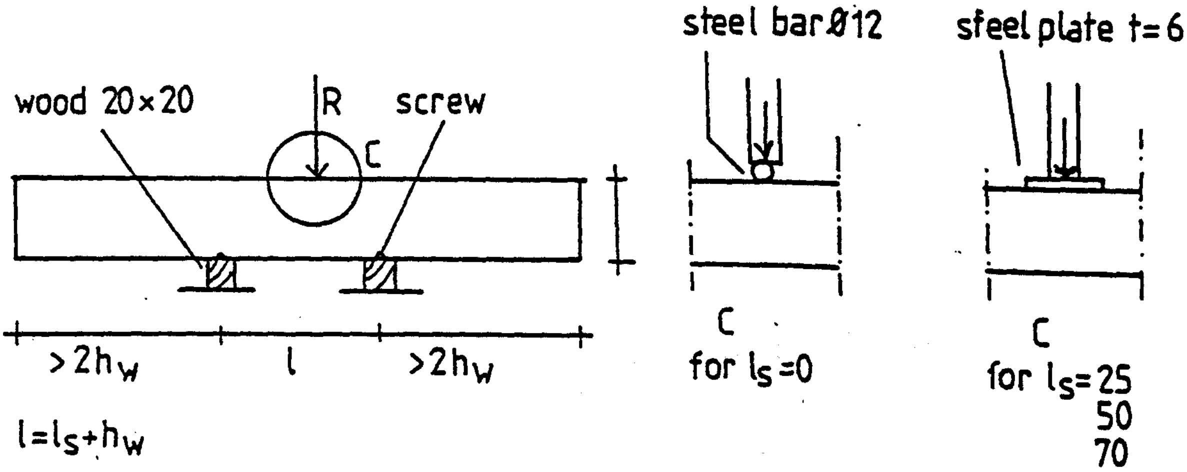


Figure 20

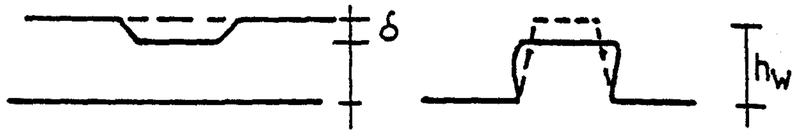


Figure 21

4.5. EINDHOVEN TESTS (9)

1. Properties of test specimens

All the test sheets consisted of three full corrugations as shown in Figure 19.
The dimensions and properties of the sheets are given in Table 5. The sheets were roll-formed by Hoesch (Germany): type PC 750 - 55 - 0.71; distributor Prince Cladding.

2. Test setup.

See Figure 20.
$\ell = \ell_s + s_{w(E)}$.
The clear distance between the bearing edges of the central bearing plate and the end supports is smaller than 1.5 $s_{w(A)}$. This was necessary for the limitation of the bending moment.

3. Load application

For each sheet the load was applied in more than 5 equal steps upto 90% of the ultimate load. When the deflection in the middle of the span was increasing at constant load at least 2 minutes were taken before the new load was applied.
The sheets A-3, B-3, E-3 and D-1 were loaded upto the characteristic load (ultimate load devided by 1.5). Then the load was removed and afterwards the sheets were loaded to failure as described above.

4. Determination of the test load

Because of the large deformation of the compression flange at failure (up to 17 mm) the test load was corrected to be the load causing a flange deformation δ of $h_w/10$ (see Figure 21.)

5. Failure mode

See Figure 21.

6. Moment ratio

The maximum moment ratio M_{test} / M_d was 0.24. The ECCS - part 1 - draft - 1980 was used to calculate the ultimate moment capacity M_d.
The test moment M_{test} was calculated by the equation

$$M_{test} = \frac{R_{test} \cdot \ell}{4}$$

7. Test results

See Table 10 Chapter 5.

Table 5.
PROPERTIES OF TEST SPECIMENS; EINDHOVEN TESTS

NR.	TESTCODE	fty	ls	t	r	Q	sw(E)	sw(A)	bo	bu	hs	l	# OF WEBS
176	4-A1	297	0	0.79	6.35	81	56	55	44	63	0	55	6
177	4-A2	304	0	0.79	6.35	82	56	55	44	62	0	55	6
178	4-A3	305	0	0.79	6.35	82	55	55	44	63	0	55	6
179	4-A	323	0	0.71	5.65	81	55	54	44	63	0	55	6
180	4-B	324	0	0.71	5.65	81	55	54	44	63	0	55	6
181	4-B1	302	25	0.78	6.35	80	55	54	44	63	0	80	6
182	4-B2	303	25	0.78	6.35	82	56	55	45	63	0	80	6
183	4-B3	309	25	0.78	6.35	80	56	56	44	63	0	80	6
184	4-K	320	25	0.71	5.65	81	56	55	44	63	0	80	6
185	4-E1	302	50	0.79	6.35	79	57	56	43	62	0	105	6
186	4-E2	309	50	0.79	6.35	81	56	56	43	63	0	105	6
187	4-E3	307	50	0.80	6.35	80	56	56	44	62	0	105	6
188	4-D	327	50	0.72	5.65	81	55	54	44	63	0	105	6
189	4-F	324	50	0.72	5.65	81	55	54	44	63	0	105	6
190	4-C1	305	70	0.78	6.35	80	56	55	44	63	0	125	6
191	4-C2	304	70	0.79	6.35	79	56	56	44	63	0	125	6
192	4-C3	304	70	0.79	6.35	81	56	55	42	62	0	125	6
193	4-G	327	70	0.72	5.65	81	55	54	44	63	0	125	6
194	4-H	324	70	0.72	5.65	81	55	54	44	62	0	125	6

5. COMPARISON OF EXPERIMENTAL AND COMPUTED RESULTS

The test loads R_{test} are compared with the computed ultimate web crippling l R_{ECCS}, R_{AISI} and R_{Wat}:
The test loads R_{test} and the load ratios R_{test}/R_{ECCS}, R_{test}/R_{AISI} and R_{test}/R_{Wa} listed in the Tables 6, 7, 8, 9 and 10.
A load ratio R_{test}/R_d less than 1 means that the applied web crippling formulation an unsafe prediction for the ultimate web crippling load R_d.
For each test series the mean, standard deviation and coefficient of variation of the ratios were calculated. A load ratio marked with * means that the test is not withir limits of the applied web crippling prediction formula. These load ratios are not incl in the computation of the mean, standard deviation and coefficient of variation. In o to include tests that only just fail the limitations (as given in Chapter 2) these limitat are enlarged by 5%. The limitations consist of restrictions to the ratios $\ell_s/s_{w(A)}$, ℓ_s/t and $s_{w(a)}/t$.
These ratios are also shown in the Tables 6, 7, 8, 9 and 10.
An overview of the computed means, standard deviations and coefficients of variatic given in Table 11.
The load ratios R_{test}/R_{ECCS}, R_{test}/R_{AISI} and $R_{test}/R_{Wat.}$ are plotted against some parameters in Figures 22 to 30.
The dashed line ($R_{test}/R_d = 1$) represents perfect correlation between R_{test} and R_d.
The plots shown in Figures 22 to 30 are a selection of the available plots. Similar plots be made for every parameter.
From Figure 22 it can be seen that the ECCS approach can probably be improved introducing a web slenderness term.
For the comparison of the web crippling formulations the coefficient of variation is most important.
The coefficient of variation, which can be seen as the standard deviation for a mean o is a measure for the scattering of the load ratios. The mean of the load ratios can ea be corrected by multiplying the web crippling prediction formulas with a constant.
The AISI and Waterloo approaches have the same coefficient of variation for all the t results together.
The ECCS approach has a larger coefficient of variation. Since the Waterloo approach a wider range of application it can be concluded that the Waterloo approach gives the b average results. The Waterloo approach does not give the best results for each test se individually.
From Table 11 it can be seen that there are significant differences between the t series.
The Waterloo tests show the lowest mean of the ratios R_{test}/R_d for all the web crippl formulas evaluated This may be due to the test setup or load application.
Because the Stockholm tests had relatively large bending moments the ECCS appro was expected to give a relatively safe prediction of the web crippling load for the ot test series. This is not the case. Nor do the AISI and Waterloo approaches give a relativ unsafe prediction of the web crippling load for the Stockholm tests.

Apparently the web crippling prediction formulas give a prediction of the mean v crippling load.
When a characteristic web crippling load is required (i.e. a web crippling load which ha certain specified probability of being achieved), the web crippling equations should multiplied by a constant K.

Assuming a normal distribution of the load ratios, this constant K can be calculated from the given mean m and standard deviation s by the equation

$$K = \frac{1}{m - x \cdot s}$$

where x depends on the required probability.

Table 6.
TEST RESULTS; STOCKHOLM TESTS

NR.	TESTCODE	Rtest	$\frac{Rtest}{RECCS}$	$\frac{Rtest}{RAIBI}$	$\frac{Rtest}{RWat.}$	$\frac{ls}{sw(A)}$	$\frac{ls}{t}$	$\frac{r}{t}$	$\frac{sw(A)}{t}$
1	1-2-1	4291	0.98	1.49*	0.93	0.82	39	10.20	48
2	1-3-1	4085	0.93	1.42*	0.89	0.82	39	10.20	48
3	1-4-2	4379	1.00	1.64*	1.00	0.40	39	10.20	97
4	1-5-2	4575	1.05	1.73*	1.05	0.40	39	10.20	97
5	1-6-2	4546	1.05	1.75*	1.04	0.40	39	10.29	97
6	1-10-5	3942	1.02	1.68*	0.96	0.40	39	10.20	97
7	1-11-5	4021	1.04	1.71*	0.98	0.40	39	10.20	97
8	1-13-8	3481	1.00	1.65*	1.04	0.41	39	10.20	97
9	1-14-8	3697	1.06	1.76*	1.12	0.41	39	10.20	97
10	1-15-8	3697	1.06	1.75*	1.10	0.41	39	10.20	97
11	2-1-5	4771	0.94	0.92	0.96	0.40	39	1.37	97
12	2-2-5	5355	1.05	1.03	1.08	0.40	39	1.27	97
13	2-3-5	5134	1.01	0.98	1.03	0.40	39	1.18	97
14	2-4-5	4237	0.96	1.07	0.94	0.40	39	5.20	97
15	2-5-5	4090	0.93	1.03	0.91	0.40	39	5.10	97
16	2-7-8	4295	0.96	0.94	1.08	0.41	39	1.57	97
17	2-8-8	4281	0.93	0.91	1.05	0.41	39	1.08	97
18	2-10-8	3633	0.93	1.05	1.01	0.41	39	5.39	97
19	2-11-8	3678	0.93	1.05	1.01	0.41	39	5.29	97
20	3-1-4	2010	1.04	1.04	1.10	0.81	69	2.24	85
21	3-3-4	2010	1.04	1.03	1.09	0.81	69	2.24	85
22	3-5-4	1755	0.98	1.07	1.01	0.81	69	4.66	85
23	3-6-4	1790	1.00	1.09	1.03	0.81	69	4.66	85
24	3-7-4	1471	0.92	1.34*	0.92	0.81	69	8.97	85
25	3-8-4	1574	0.98	1.39*	0.98	0.81	69	8.62	85
26	3-9-4	1520	0.96	1.39*	0.95	0.81	69	8.97	85
27	3-10-5	2001	1.03	1.19	1.20	0.40	69	2.24	171
28	3-11-5	1966	1.01	1.16	1.17	0.40	69	2.24	171
29	3-13-5	1687	0.96	1.22	1.09	0.40	69	4.83	171
30	3-14-5	1692	0.95	1.22	1.08	0.40	69	5.00	171
31	3-16-5	1652	1.02	1.57*	1.13	0.40	69	7.93	171
32	3-17-5	1603	0.99	1.58*	1.09	0.40	69	8.45	171
33	4-1-5	2922	0.90	1.12	1.00	0.40	43	5.70	106
34	4-2-5	2932	0.88	1.07	0.97	0.40	42	5.58	104
35	4-4-5	3516	0.90	1.10	1.06	0.71	75	5.59	106
36	4-5-5	3658	0.92	1.14	1.09	0.71	74	5.64	105
37	4-6-5	3756	0.94	1.16	1.10	0.71	74	5.68	104
38	4-7-5	3776	0.87	1.00	1.05	1.01	109	5.76	108
39	4-8-5	4153	0.87	0.99	1.04	1.01	103	5.46	102
40	4-9-5	3957	0.89	1.03	1.08	1.01	108	5.70	106
41	4-10-5	5286	1.00	1.16	1.06	0.71	69	5.39	97
42	4-11-5	5350	1.01	1.16	1.06	0.71	69	5.29	97
43	4-12-5	6634	1.10	1.18	1.18	1.01	98	5.29	97
44	4-13-5	6257	1.03	1.10	1.11	1.01	98	5.20	97
45	4-15-5	6002	1.00	1.07	1.08	1.01	98	5.20	97

Table 6.(Continued)
TEST RESULTS; STOCKHOLM TESTS

NR.	TESTCODE	Rtest	Rtest / RECCS	Rtest / RAISI	Rtest / RWat.	ls / sw(A)	ls / t	r / t	sw(A) / t
46	4-17-7	1486	0.95	1.09	1.07	0.81	69	5.69	85
47	4-22-7	2403	1.10	1.03	1.24	2.03	172	6.03	85
48	4-24-7	2555	1.17	1.11	1.33	2.03	172	6.21	85
49	4-25-7	1079	1.01	1.21	1.34	0.81	77	5.00	95
50	4-26-7	1005	0.87	0.95	1.18	0.81	77	2.69	95
51	4-28-7	1427	1.08	1.12	1.49	1.42	135	4.62	95
52	4-29-7	1437	1.10	1.18	1.52	1.42	135	5.19	95
53	4-33-7	1594	1.04	0.97	1.40	2.03	192	4.62	95
		MEAN	0.99	1.08	1.08				
	STANDARD DEVIATION		0.07	0.08	0.13				
	COEF. OF VARIATION		0.07	0.08	0.12				

Values followed by * not included in computation of mean, standard deviation and coefficient of variation.
(See Chapter 5)

Table 7.
TEST RESULTS; CORNELL TESTS

NR.	TESTCODE	Rtest	$\frac{Rtest}{RECCS}$	$\frac{Rtest}{RAISI}$	$\frac{Rtest}{RWat.}$	$\frac{ls}{sw(A)}$	$\frac{ls}{t}$	$\frac{r}{t}$	$\frac{sw(A)}{t}$
54	13	9030	1.19	1.07	1.23	0.13	12	1.00	97
55	14	8363	0.90	0.88	1.03	0.26	25	1.00	99
56	16	7651	1.08	0.99	1.06	0.13	13	3.00	99
57	17	8807	1.07	1.14	1.26	0.26	25	3.00	97
58	18	8496	0.88	0.99	1.12	0.43	41	3.00	97
59	19	15569	1.45	1.17	1.25	0.13	12	1.00	91
60	20	15079	1.15	1.03	1.13	0.26	23	1.00	90
61	21	16681	1.10	1.06	1.19	0.43	39	1.00	91
62	22	13834	1.40	1.18	1.18	0.13	12	3.00	91
63	23	13967	1.18	1.11	1.14	0.26	23	3.00	90
64	24	14902	1.05	1.05	1.10	0.43	38	3.00	89
65	25	6895	0.87	0.83	0.92	0.08	12	1.00	148
66	26	6841	0.75	0.81	0.92	0.17	25	1.00	149
67	28	5783	0.87	0.90	0.96	0.08	12	3.00	148
68	29	6272	0.78	0.90	0.97	0.17	25	3.00	149
69	30	6784	0.74	0.92	1.02	0.28	43	3.00	151
70	31	10676	0.98	0.85	0.89	0.08	12	1.00	136
71	34	10676	1.10	1.01	0.98	0.08	12	3.00	139
72	35	10511	0.90	0.92	0.91	0.17	23	3.00	139
73	36	10734	0.80	0.87	0.89	0.28	39	3.00	140
74	37	6450	0.88	0.95	1.05	0.06	12	1.00	197
75	38	6895	0.74	0.88	0.98	0.13	24	1.00	193
76	39	7562	0.65	0.80	0.90	0.21	41	1.00	194
77	40	6116	0.96	1.11	1.14	0.06	13	3.00	201
78	41	6228	0.75	0.95	0.99	0.13	25	3.00	196
79	42	6450	0.66	0.89	0.95	0.21	41	3.00	195
80	43	10631	0.95	0.88	0.90	0.06	11	1.00	179
81	44	10231	0.75	0.79	0.82	0.13	23	1.00	179
82	46	10008	0.96	0.93	0.89	0.06	11	3.00	180
83	47	11236	0.89	0.97	0.94	0.13	22	3.00	177
84	48	11459	0.80	0.93	0.93	0.21	38	3.00	180
		MEAN	0.94	0.96	1.02				
	STANDARD DEVIATION		0.20	0.11	0.12				
	COEF. OF VARIATION		0.21	0.11	0.12				

*Values followed by * not included in computation of mean, standard deviation and coefficient of variation.*
(See Chapter 5)

Table 8.
TEST RESULTS; MISSOURI-ROLLA TESTS

NR.	TESTCODE	Rtest	$\frac{Rtest}{RECCS}$	$\frac{Rtest}{RAISI}$	$\frac{Rtest}{RWat.}$	$\frac{ls}{sw(A)}$	$\frac{ls}{t}$	$\frac{r}{t}$	$\frac{sw(A)}{t}$
85	SU1-IOF1	5605	0.97	1.12	1.12	0.10	21	2.77	205
86	SU1-IOF2	5227	0.92	1.06	1.07	0.10	21	2.63	209
87	SU1-IOF5	6450	0.77	1.00	1.06	0.30	62	2.58	203
88	SU1-IOF6	6161	0.75	0.97	1.04	0.30	62	2.60	205
89	SU2-IOF1	5093	0.85	1.06*	1.04*	0.08	20	2.55	250
90	SU2-IOF2	5805	0.93	1.14*	1.13*	0.08	20	2.50	244
91	SU2-IOF5	6161	0.75	1.07*	1.10*	0.25	62	2.60	254
92	SU2-IOF6	6472	0.76	1.08*	1.11*	0.24	61	2.55	250
93	SU2'-IOF3	7784	0.95	1.13	1.30	0.41	60	1.89	145
94	SU2'-IOF4	7606	0.90	1.05	1.22	0.41	59	1.85	143
95	SU2'-IOF5	7028	0.83	0.97	1.13	0.41	59	1.85	143
96	SU2'-IOF6	6850	0.81	0.95	1.10	0.41	59	1.85	143
97	SU5-IOF1	6241	0.96	0.92	0.98	0.16	20	1.89	123
98	SU5-IOF2	6583	0.98	0.94	1.01	0.16	20	1.87	121
99	SU5-IOF3	7784	0.96	1.00	1.10	0.33	40	1.95	122
100	SU5-IOF4	8140	0.98	1.02	1.13	0.33	40	1.86	120
101	SU5-IOF5	9252	0.97	1.04	1.19	0.49	60	1.78	121
102	SU5-IOF6	8162	0.86	0.93	1.05	0.49	60	1.86	121
103	SU6'-IOF1	6583	0.99	0.98	1.04	0.14	20	1.88	145
104	SU6'-IOF2	7028	1.05	1.04	1.11	0.14	20	1.72	146
105	SU6'-IOF3	8407	1.04	1.14	1.24	0.27	40	1.81	147
106	SU6'-IOF4	8074	1.00	1.09	1.19	0.27	40	1.89	148
107	SU6'-IOF5	9275	1.02	1.16	1.29	0.41	61	1.91	148
108	SU6'-IOF6	8407	0.89	0.99	1.11	0.41	60	1.79	145
109	MSU6'-IOF1	7340	1.10	1.09	1.15	0.14	20	1.87	145
110	MSU6'-IOF2	7308	1.10	1.09	1.16	0.14	20	1.88	146
111	MSU6'-IOF5	9097	0.96	1.07	1.20	0.41	59	1.86	144
112	MSU6'-IOF6	9519	1.02	1.16	1.29	0.41	60	1.88	146
113	USU17-IOF5	6672	0.80	0.88	1.06	0.62	61	0.96	98
114	USU17-IOF6	6784	0.82	0.89	1.08	0.62	61	0.96	98
115	USU18-IOF5	7517	0.91	1.16	1.34	0.32	61	0.96	193
116	USU18-IOF6	6517	0.79	1.01	1.16	0.32	61	0.96	194
		MEAN	0.92	1.03	1.14				
	STANDARD DEVIATION		0.10	0.08	0.09				
	COEF. OF VARIATION		0.11	0.08	0.08				

Values followed by * not included in computation of mean, standard deviation and coefficient of variation.
(See Chapter 5)

Table 9.
TEST RESULTS; WATERLOO TESTS

NR.	TESTCODE	Rtest	$\frac{Rtest}{RECC8}$	$\frac{Rtest}{RAISI}$	$\frac{Rtest}{RWat.}$	$\frac{ls}{sw(A)}$	$\frac{ls}{t}$	$\frac{r}{t}$	$\frac{sw(A)}{t}$
117	5W-IOF	2700	0.72	0.73	0.81	0.25	26	2.47	104
118	6W-IOF	1254	0.78	0.98	1.01	0.25	42	3.91	165
119	7W-IOF	6895	0.89	0.89	1.01	0.13	17	1.56	131
120	8W-IOF	3145	0.84	1.03	1.06	0.13	26	2.47	209
121	14W-IOF	2504	0.76	0.77	0.80	0.25	26	2.47	103
122	15W-IOF	921	0.65	0.82	0.79	0.25	42	3.91	166
123	16W-IOF	6392	0.93	0.94	0.99	0.13	17	1.56	132
124	17W-IOF	2011	0.85	1.04	1.01	0.13	26	2.47	209
125	23W-IOF	2113	0.68	0.68	0.78	0.25	26	2.41	102
126	24W-IOF	974	0.71	0.88	0.94	0.25	40	3.75	161
127	25W-IOF	5338	0.84	0.84	0.98	0.13	16	1.54	129
128	26W-IOF	2002	0.62	0.73	0.79	0.13	25	2.34	198
129	34W-IOF	1392	0.87	1.09	1.12	0.25	42	3.91	165
130	35W-IOF	1726	0.85	1.04	1.18	0.51	83	3.91	164
131	36W-IOF	2002	0.85	0.95	1.19	0.76	125	3.91	164
132	51W-IOF	2375	0.80	0.83	0.85	0.24	28	2.61	114
133	52W-IOF	1152	0.81	1.04	0.99	0.24	42	3.91	173
134	54W-IOF	1877	0.70	0.76	0.85	0.20	28	2.61	141
135	55W-IOF	1948	0.66	0.70	0.78	0.20	26	2.47	133
136	56W-IOF	1890	0.70	0.77	0.85	0.20	28	2.61	141
137	57W-IOF	6508	0.84	0.76	0.88	0.26	17	1.56	65
138	60W-IOF	4395	0.91	0.88	0.99	0.26	22	2.08	87
139	61W-IOF	5271	0.88	0.93	1.08	0.51	44	2.08	87
140	62W-IOF	5729	0.83	0.89	1.08	0.76	67	2.08	87
141	69W-IOF	4226	0.79	0.84	1.02	0.76	79	2.47	104
142	89W-IOF	1112	0.78	1.01	0.96	0.24	42	3.91	175
143	91W-IOF	2558	0.78	0.80	0.82	0.24	26	2.47	112
144	101W-IOF	836	0.65	0.91*	0.93*	0.19	42	3.91	215
145	103W-IOF	2335	0.79	0.84	0.94	0.19	26	2.47	137
146	124W-IOF	1779	0.62	0.59	0.85	1.25	208	3.91	166
147	125W-IOF	1779	0.67	0.70	0.94	1.01	167	3.91	166
148	128W-IOF	1868	0.71	0.73	0.99	1.01	167	3.91	165
149	134W-IOF	4942	0.83	0.83	1.09	1.01	105	2.47	104
150	135W-IOF	5422	0.84	0.79	1.11	1.25	132	2.47	105
151	136W-IOF	3314	0.89	0.90	0.99	0.25	26	2.47	104
152	137W-IOF	3914	0.84	0.92	1.05	0.51	53	2.47	104
153	139W-IOF	1045	0.65	0.82	0.84	0.25	42	3.91	165
154	3WR-IOF	1352	0.64	0.90*	0.78	0.60	81	7.59	136
155	12WR-IOF	1366	0.69	1.22*	0.83	0.58	81	10.12	139
156	15WR-IOF	2113	0.64	0.89*	0.76	0.60	60	7.49	99
157	21WR-IOF	1090	0.86*	32.75*	1.04*	0.60	93	17.36	154
158	24WR-IOF	2713	0.63	0.97*	0.70	0.59	51	9.10	86
159	30WR-IOF	1472	0.79	1.17*	0.94	0.48	81	7.59	168
160	33WR-IOF	2246	0.74	0.94	0.85	0.49	60	5.61	121
161	39WR-IOF	1579	0.90	1.68*	1.05	0.48	81	10.12	168

Table 9.(Continued)
TEST RESULTS; WATERLOO TESTS

NR.	TESTCODE	Rtest	Rtest / RECCS	Rtest / RAISI	Rtest / RWat.	ls / sw(A)	ls / t	r / t	sw(A) / t
162	42WR-IOF	3207	0.79	1.01	0.86	0.49	51	6.33	104
163	48WR-IOF	1179	0.96*	2.83*	1.19*	0.48	93	13.02	192
164	51WR-IOF	3105	0.81	1.24*	0.87	0.48	51	8.71	106
165	57WR-IOF	1463	0.87	1.39*	1.20	0.39	81	7.59	206
166	60WR-IOF	2113	0.83	1.35*	1.07	0.41	60	8.42	147
167	66WR-IOF	1330	0.84	1.71*	1.15*	0.38	81	10.12	212
168	69WR-IOF	3074	0.84	1.11	1.04	0.40	51	6.33	126
169	75WR-IOF	1001	0.90*	2.86*	1.29*	0.41	93	13.02	226
170	78WR-IOF	2980	0.88	1.51*	1.07	0.38	51	9.49	133
171	81WR-IOF	6606	0.87	1.03	0.96	0.39	33	6.19	85
172	131WR-IOF	1646	0.64	0.95*	0.77	1.16	162	10.12	139
173	137WR-IOF	1913	0.79	0.99*	0.95	0.97	162	7.59	168
174	140WR-IOF	1913	0.84	1.32*	0.99	0.96	162	10.12	168
175	144WR-IOF	3781	0.78	1.09*	0.88	0.96	101	8.71	106
		MEAN	0.78	0.87	0.94				
	STANDARD DEVIATION		0.09	0.13	0.12				
	COEF. OF VARIATION		0.11	0.14	0.13				

Values followed by * not included in computation of mean, standard deviation and coefficient of variation.
(See Chapter 5)

Table 10.
TEST RESULTS; EINDHOVEN TESTS

NR.	TESTCODE	Rtest	$\frac{Rtest}{RECCS}$	$\frac{Rtest}{RAISI}$	$\frac{Rtest}{RUat.}$	$\frac{ls}{sw(A)}$	$\frac{ls}{t}$	$\frac{r}{t}$	$\frac{sw(A)}{t}$
176	4-A1	1967	1.15	1.41*	1.01	0.00	0	8.04	70
177	4-A2	2017	1.16	1.42*	1.02	0.00	0	8.04	70
178	4-A3	2017	1.16	1.41*	1.01	0.00	0	8.04	69
179	4-A	1650	1.12	1.39*	0.99	0.00	0	7.96	76
180	4-B	1617	1.09	1.36*	0.96	0.00	0	7.96	76
181	4-B1	1967	0.91	1.19*	0.89	0.46	32	8.14	70
182	4-B2	2150	0.98	1.28*	0.96	0.46	32	8.14	70
183	4-B3	2267	1.04	1.36*	1.00	0.45	32	8.14	71
184	4-K	1967	1.03	1.34*	1.01	0.45	35	7.96	78
185	4-E1	2533	0.92	1.26*	0.98	0.90	63	8.04	71
186	4-E2	2633	0.94	1.28*	1.00	0.90	63	8.04	70
187	4-E3	2633	0.92	1.25*	0.98	0.90	63	7.94	69
188	4-D	2200	0.88	1.17*	0.94	0.92	69	7.85	76
189	4-F	2217	0.89	1.18*	0.95	0.92	69	7.85	76
190	4-C1	2933	0.96	1.25*	1.05	1.27	90	8.14	71
191	4-C2	2883	0.93	1.20*	1.02	1.26	89	8.04	70
192	4-C3	2833	0.90	1.16*	0.99	1.26	89	8.04	70
193	4-G	2500	0.89	1.10*	0.97	1.29	97	7.85	76
194	4-H	2450	0.87	1.09*	0.95	1.29	97	7.85	76
		MEAN	0.99	0.00	0.98				
	STANDARD DEVIATION		0.10	0.00	0.04				
	COEF. OF VARIATION		0.11	0.00	0.04				

Values followed by * not included in computation of mean, standard deviation and coefficient of variation.
(See Chapter 5)

Table 11.
COMPARISON OF TESTRESULTS

	ECCS APPROACH			AISI APPROACH			WATERLOO APPROACH		
	MEAN	S.D.	C.V.	MEAN	S.D.	C.V.	MEAN	S.D.	C.V.
STOCKHOLM TESTS	0.99	0.07	0.07	1.08	0.08	0.08	1.08	0.13	0.12
CORNELL TESTS	0.94	0.20	0.21	0.96	0.11	0.11	1.02	0.12	0.12
MISSOURI-ROLLA TESTS	0.92	0.10	0.11	1.03	0.08	0.08	1.14	0.09	0.08
WATERLOO TESTS	0.78	0.09	0.11	0.87	0.13	0.14	0.94	0.12	0.13
EINDHOVEN TESTS	0.99	0.10	0.11	0.00	0.00	0.00	0.98	0.04	0.04
ALL TESTS	0.91	0.14	0.16	0.98	0.13	0.13	1.03	0.14	0.13

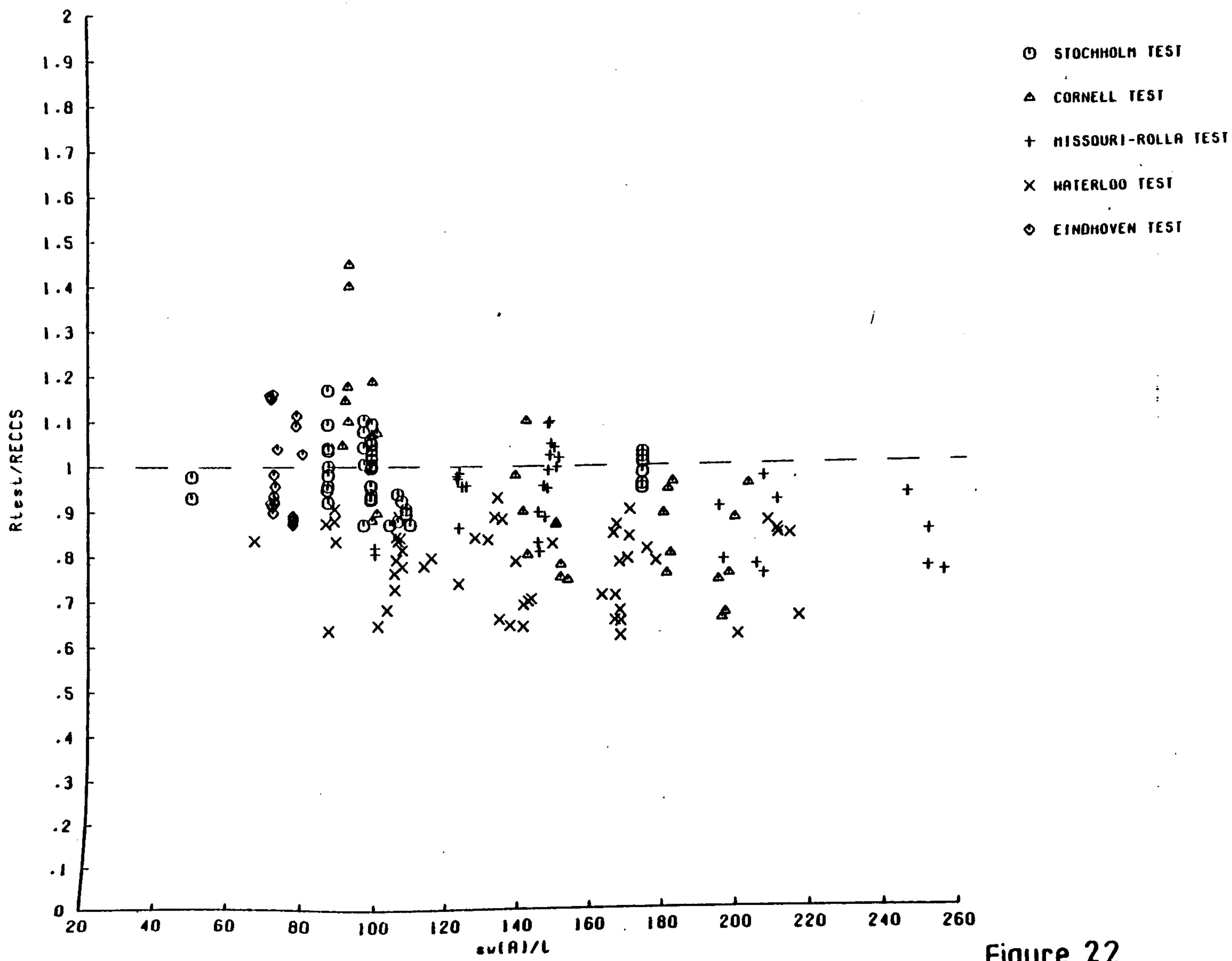

STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
Rtest/RECCS
sw(A)/L
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
20
40
60
80
100
120
140
160
180
200
220
240
260

Figure 22

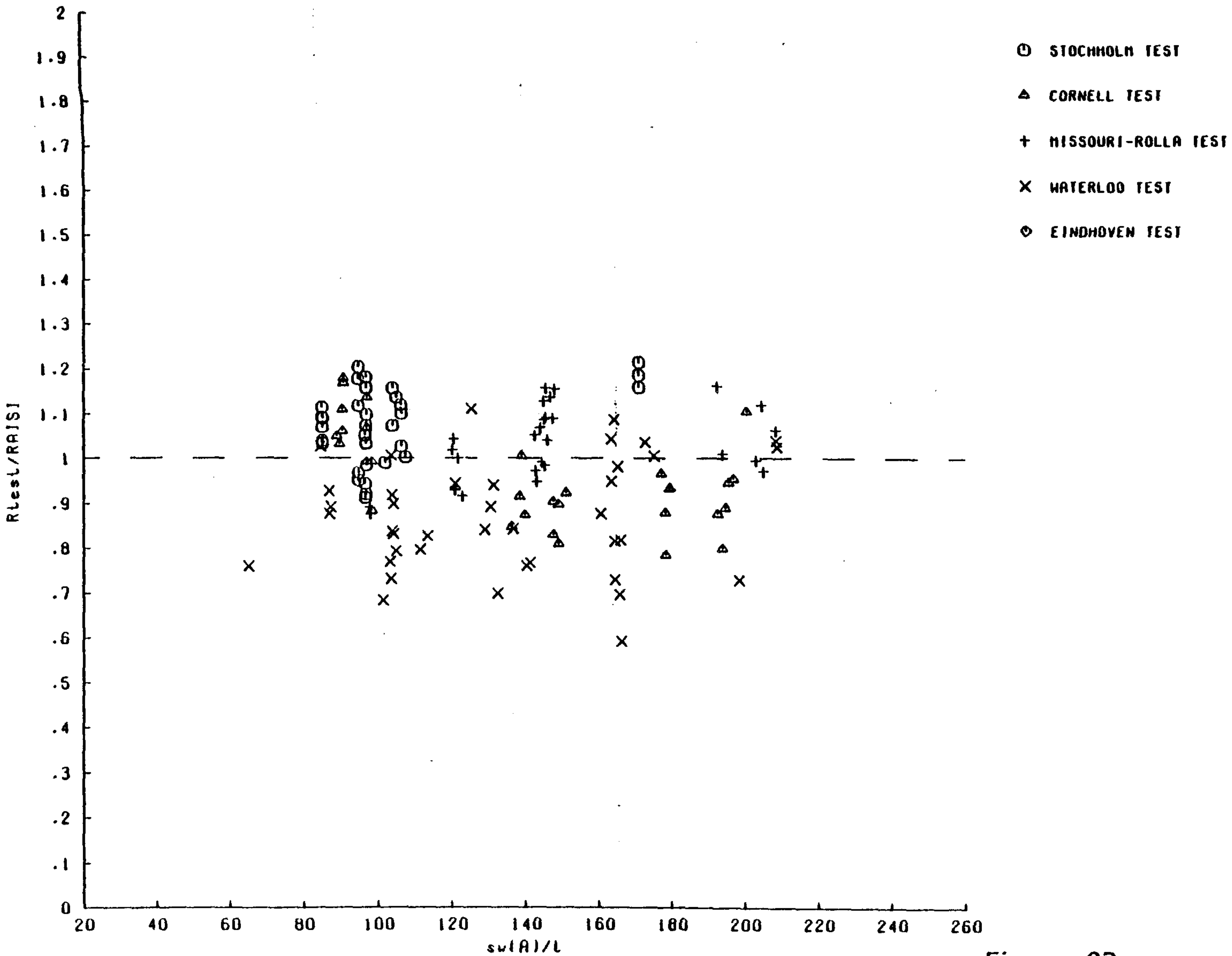

2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Rtest/RAISI
20
40
60
80
100
120
140
160
180
200
220
240
260
sw(A)/L
STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST

Figure 23

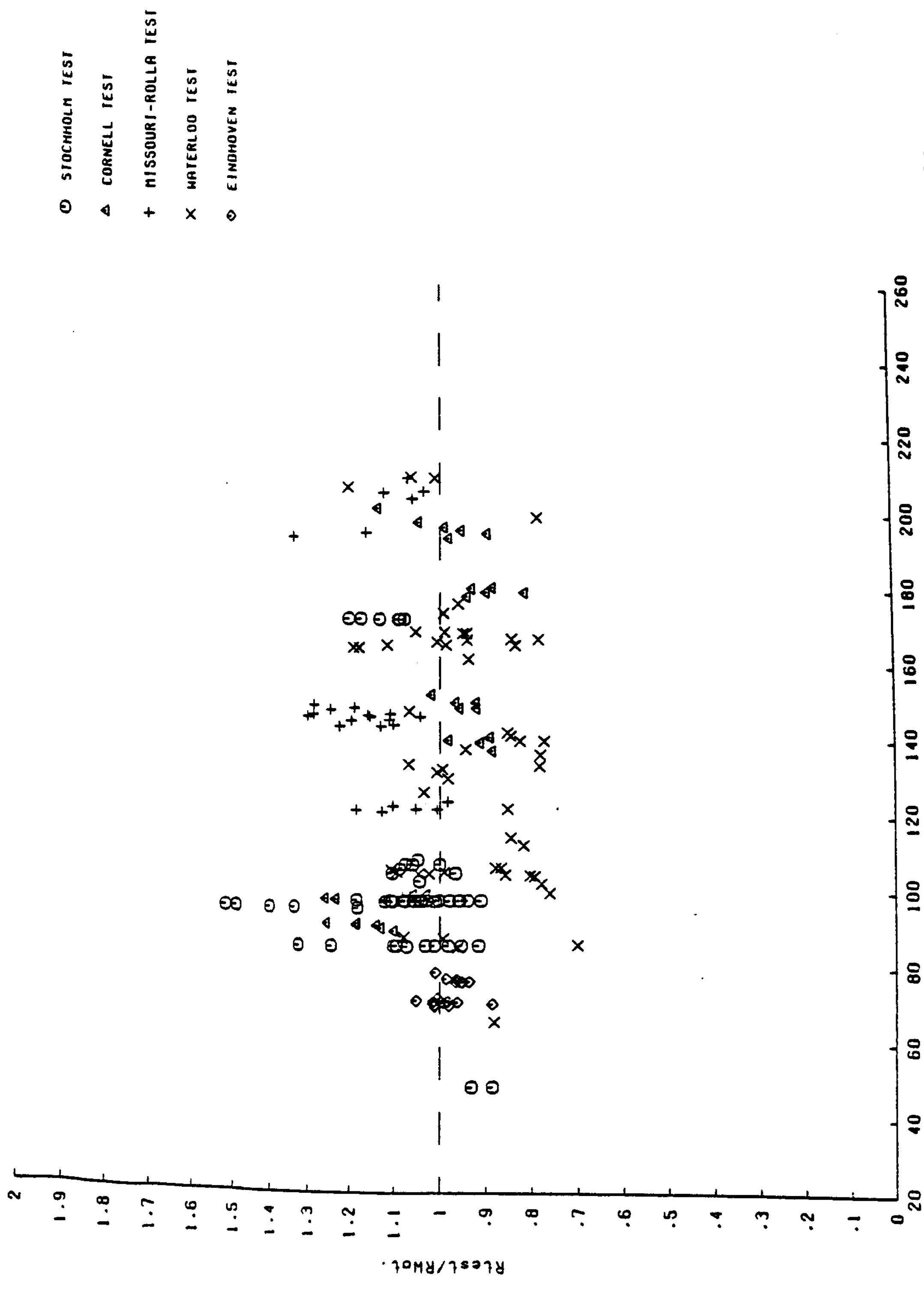

STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST

Figure 24

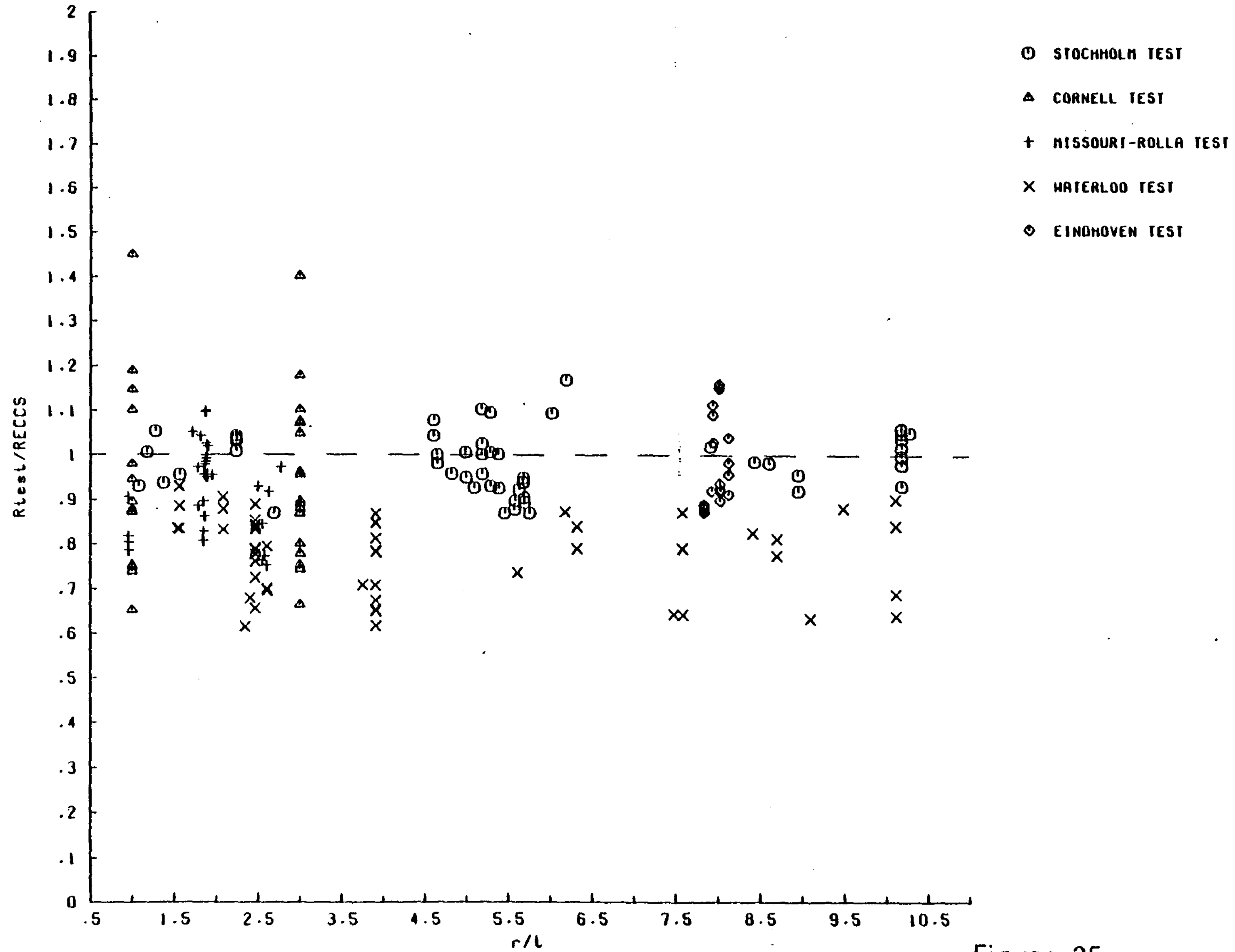

2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Rtest/RECCS
.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
r/t
STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST

Figure 25

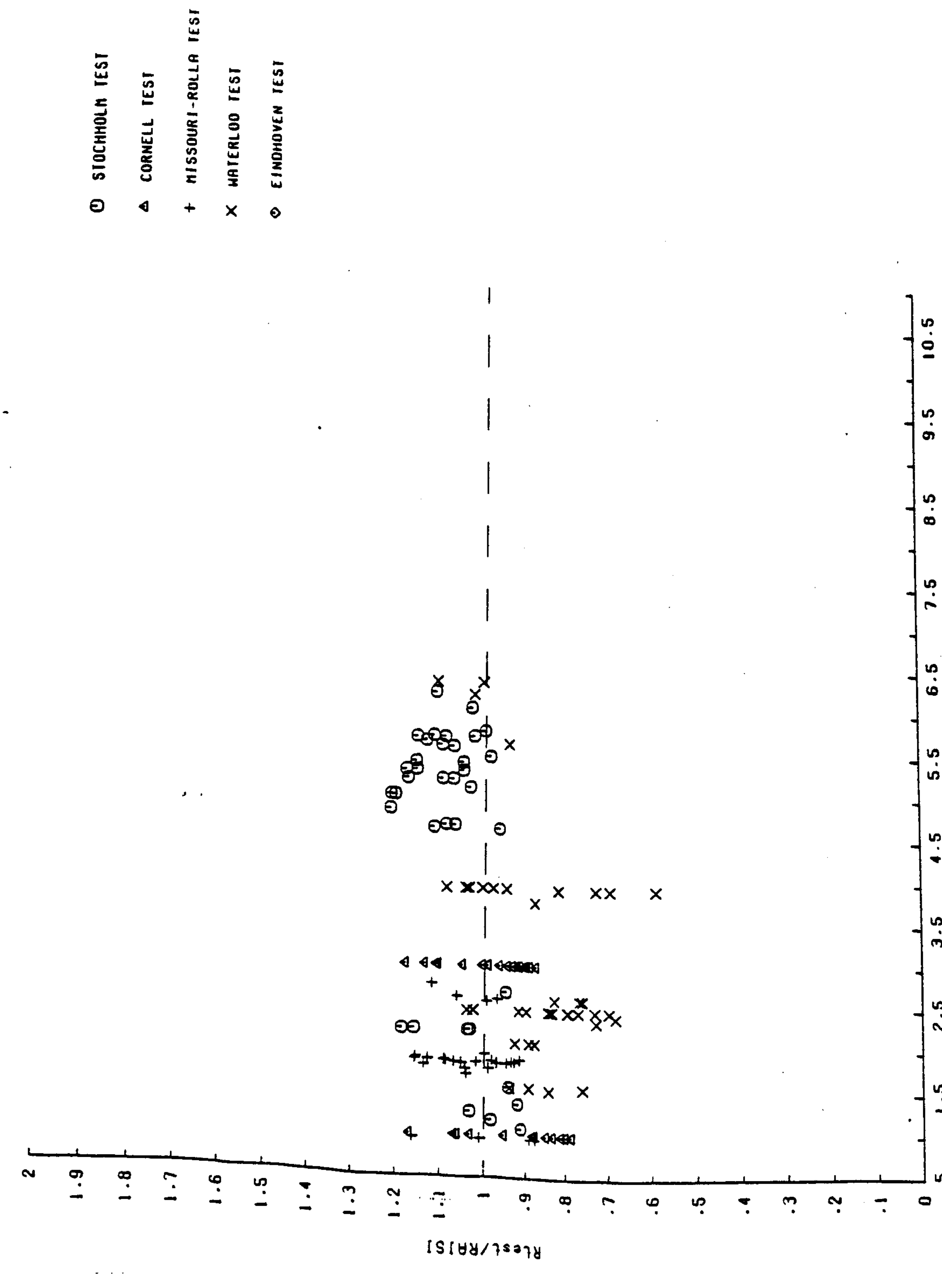

STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
Rtest/RAISI
r/t
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
.5
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5

Figure 26

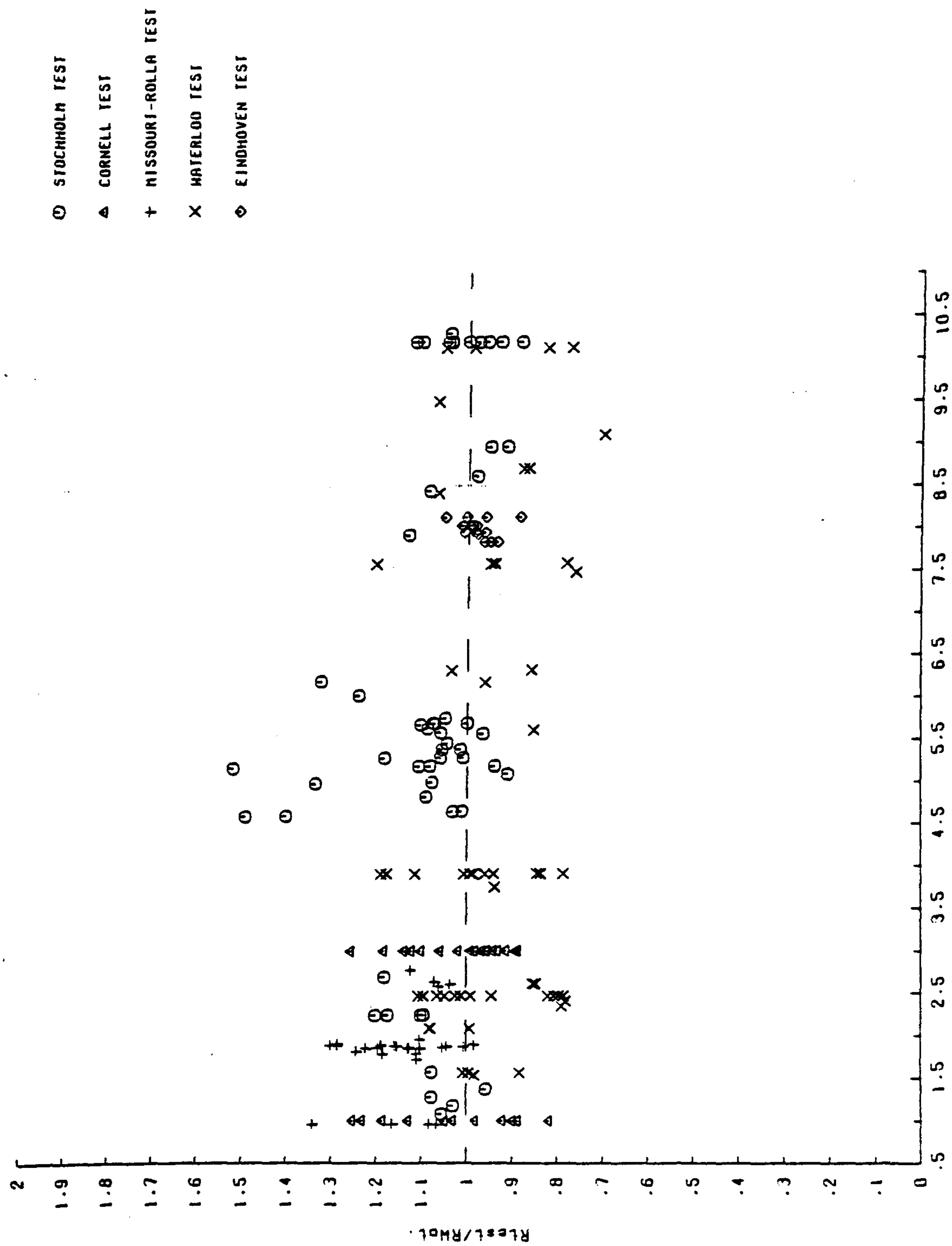

STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
r/l
.5 1.5 2.5 3.5 4.5 5.5 6.5 7.5 8.5 9.5 10.5
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2

Figure 27

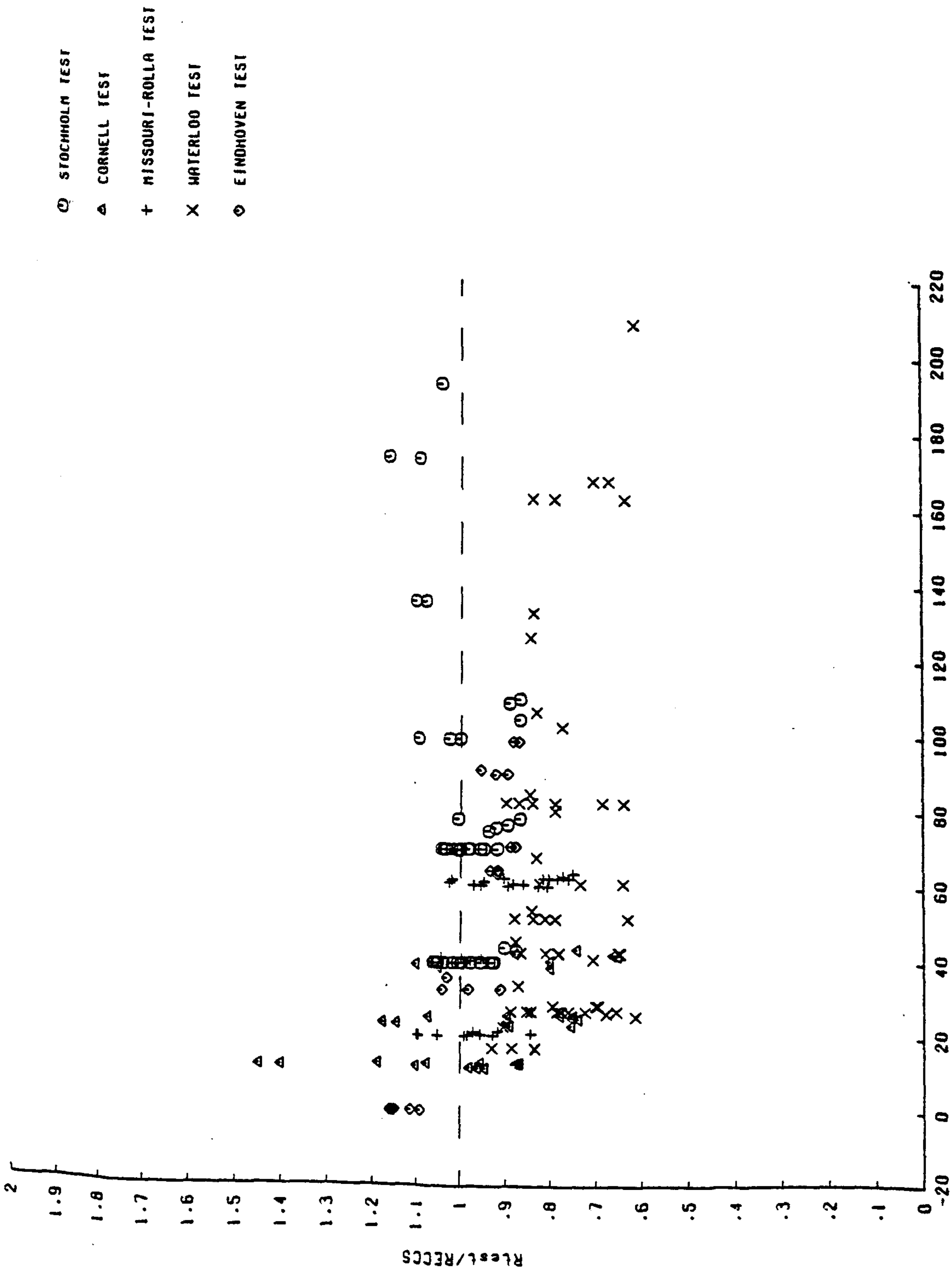

STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
Rtest/RECCS
Ls/L
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
-20
0
20
40
60
80
100
120
140
160
180
200
220

Figure 28

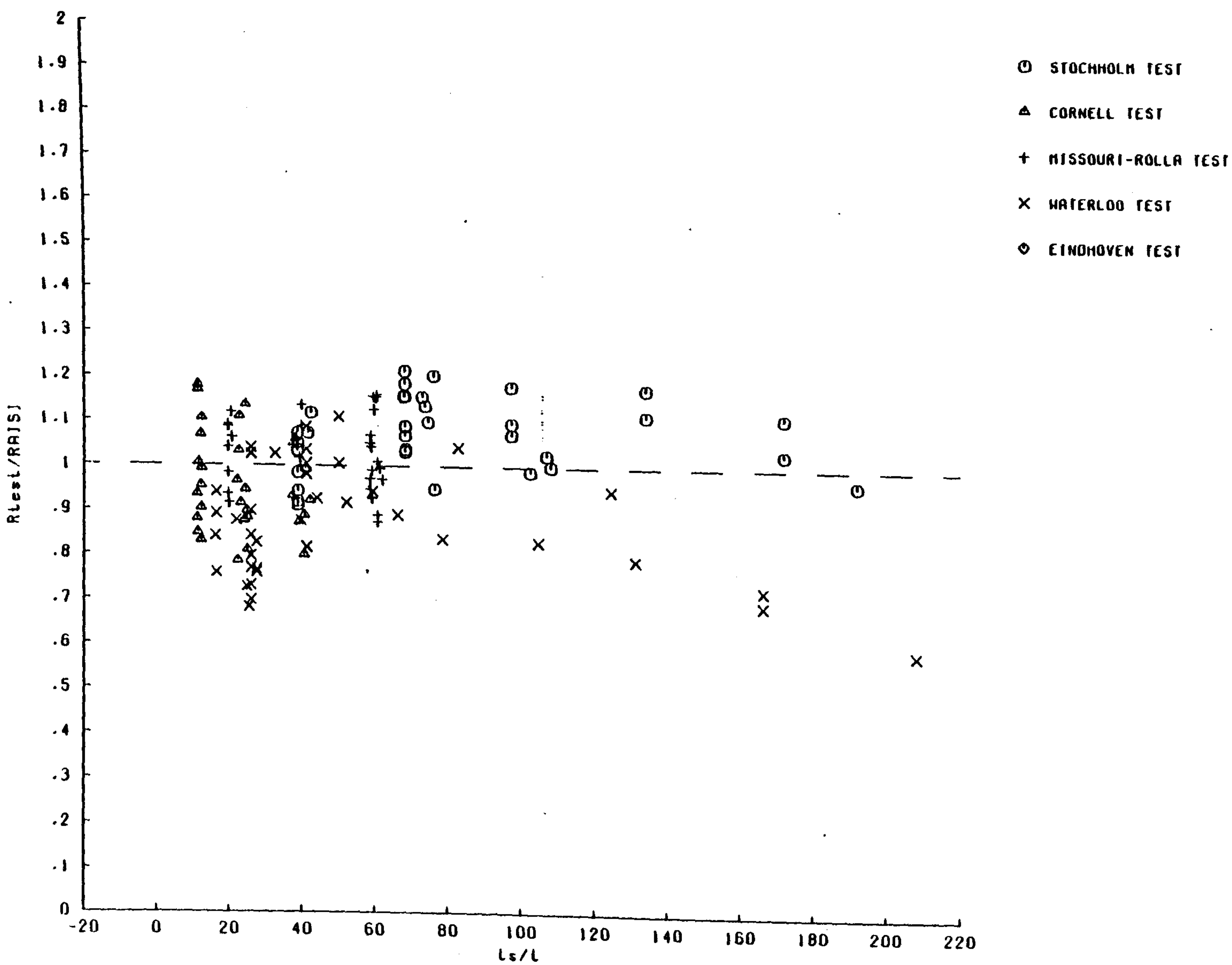
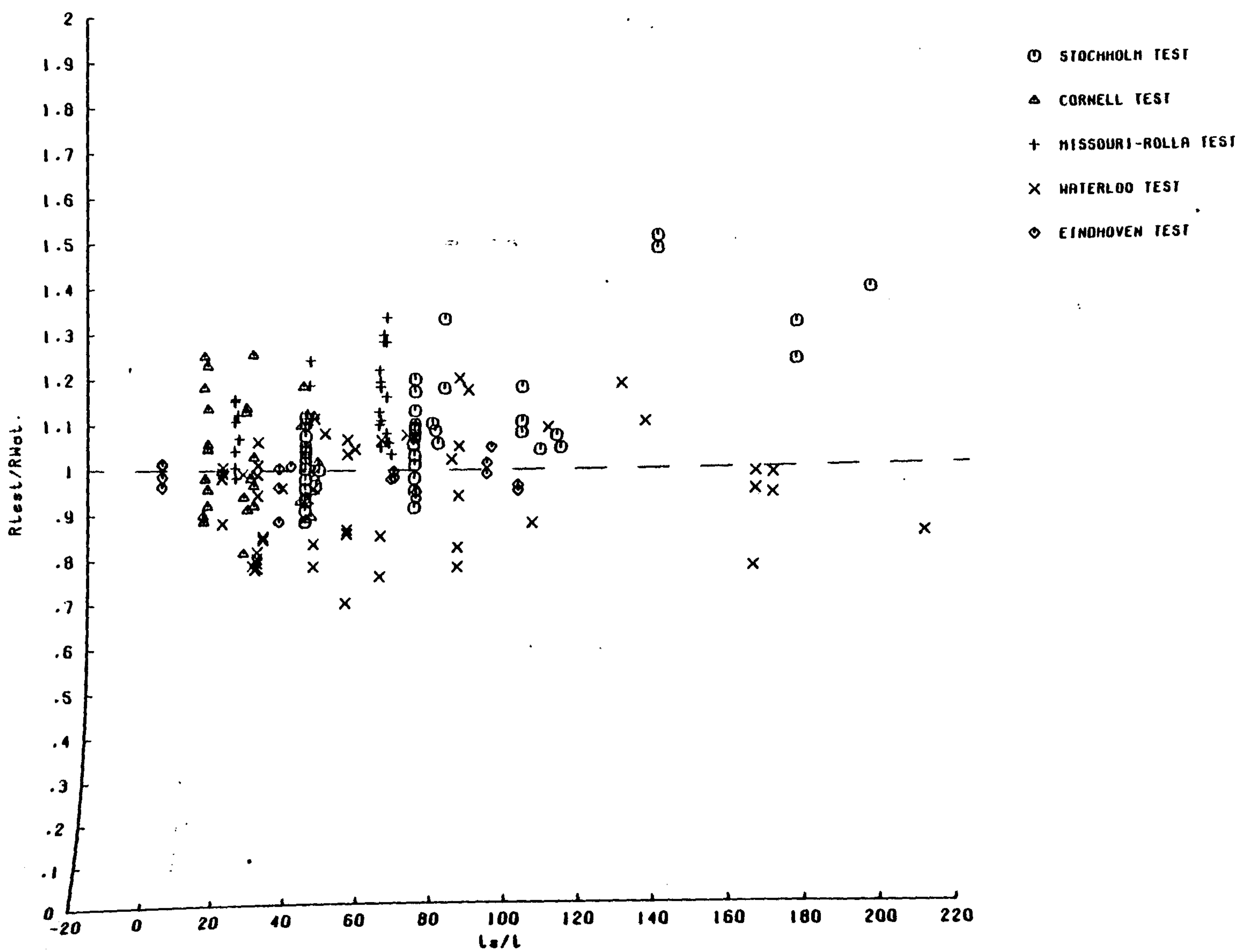

STOCHHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
Rtest/RAISI
Ls/L
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
-20
0
20
40
60
80
100
120
140
160
180
200
220

Figure 29


STOCKHOLM TEST
CORNELL TEST
MISSOURI-ROLLA TEST
WATERLOO TEST
EINDHOVEN TEST
Rtest/Rthot.
Ls/L

6. CONCLUSIONS

The web crippling prediction formulas evaluated do not give satisfactionary results consistently.
Maybe this is due to the fact that the formulas have been based on test results only.
In the formulas it is assumed that the influences of the parameters r/t, $s_{w(A)}$ / t, ℓ_s / t, f_{ty} and Θ on the web crippling load are independent of each other.
This assumption is not based on theoretical analysis and is probably incorrect. It may be noted that the web crippling prediction formula according to the AISI-1968 Specification included a term $\ell_s/t \;\; s_{w(A)}/t$.
The three web crippling formulations give a prediction of the mean failure load, not a characteristic failure load.
Mainly due to the differences in the basic constants C the calculated results may differ up to about 40%.
Of the formulations evaluated the Waterloo approach gives the best results and the ECCS approach the worst.
This may be caused by the fact that the ECCS approach lacks a web slenderness term.
The test setup, load application and determination of the failure load are not the same in all the test series.
This might explain the differences in the test results per series. Special attention should be paid to the fact that a section sometimes fails with unacceptable large deformations.
This failure mode is mentioned with the Stockholm tests and with the Eindhoven tests.
It is not clear in what situations this failure mode occurs.
To get a better understanding of web crippling additional research is required.
This research should concentrate on theoretical analysis.

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