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PLASTIC DEFORMATIONS AT NOTCHES IN WELDS OF MILD STEEL PLATES

by

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(Continuation of
"A crack-extension test for weld metal"
by
Ir. W.P. van den Blink

IIW-doc. 2912-102-67)

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List of Contents.

§ 1. Introduction.

In the above mentioned document it is proposed to use a drop-weight test as indicated in figure 1 for evaluating the low-temperature properties of welds in plates.

Originally the drop-height needed for fracturing the specimens was determined by taking into account the mechanical properties of the plate material only.

In a discussion between the two authors the point was raised whether this procedure did not benefit weld metals with a yield strength higher than that of the plate material.

The results given in table I in fact show such a tendency. Most important is that the size of the plastic zone at the root of the notch becomes smaller, the higher the yield point.

In other words: at the drop-height used it is obvious that a notch in a weld of high yield point deforms less than a notch in a weld with a lower yield point. The high yield point of the weld metal seems to "protect" the material at the notch root.

It is worthwhile to consider whether this protection can also occur in practice in large plate structures. In such a structure the weld metal forms only a very small part of the total amount of steel while in the test-specimen it constitutes some 15 to 20% of the whole. Moreover in the latter case it is situated close to one of the high-stressed edges of the specimen. There is no doubt of it that when that weld metal possesses a high yield point the energy needed for incipient yielding will be larger than for a weld metal with a lower yield point. However in a specimen of appreciable larger height than shown in figure 1 that difference will become negligible. Then the plastic deformation of the weld at a certain drop-height is practically independent of the mechanical properties of the weld. In such a specimen the loading conditions are similar to those of longitudinally loaded welds in large plate structures. When the smaller specimens of figure 1 have to be used, one can create a comparable loading condition by taking care that the weld is deformed to the same extent as in a large specimen. For high strength welds this can be effectuated by using a higher drop-height. In the foregoing argumentation it is not considered that in the welded specimens the plastic deformations occur only very locally at the root of a notch instead of over some length of the weld. This will be discussed with the aid of figure 2 which represents a long plate with a weld in the direction of the loading. Two notches are present, one in the weld metal and the other in the plate. Two loading conditions will be considered.

1^e $\sigma_{nom} < \sigma_{y(plate)}$: e.g. $\sigma_{nom} = 0{,}8\,\sigma_y$. In this case only local yielding is possible at the roots of the notches. When the yielded zones are small e.g. smaller than plate thickness, the material is in a condition of plane strain. When the zones are larger the condition becomes one of plane stress. In the first case the stresses at the border of the yielded zone are higher than yield point on account of the triaxial state of stress existing close to the notch roots. In the second case the stresses at the border of the zones are equal to yield point. For the purpose of this paper only the latter case will be considered.

In section A-A situated at some distance from notch (a) the stress in the weld is equal to that in the plate being $0{,}8\,\sigma_y$. (It cannot be otherwise because longitudinal shear stresses between the weld and the plate force the weld to deform to the same extent as the plate does. And as Young's modulus is the same for both materials, the stresses in weld and plate must be equal ($\sigma = E.\varepsilon$).) At the notches the situation for the one in the weld (a) seems to differ at first sight from that in the plate (b). At the border of the plastically deformed zone the stresses in the weld are equal to $\sigma_{y(weld)}$ while the stresses in the plate are equal to $\sigma_{y(plate)}$ (see figure 2). ($\sigma_{y(plate)}$ is assumed to be smaller than $\sigma_{y(weld)}$.)

From this it might be concluded that the size of the plastic zone in the weld will differ from that in the plate. One might even expect that the zone in the weld is the larger one, because the surrounding forces are larger in the proportion $\frac{\sigma_{y(weld)}}{\sigma_{y(plate)}}$. This is more or less a prove by negative demonstration that both notches must deform equally. The point is that the larger forces around the zone in the weld are needed precisely for creating a similar plastic zone as in the plate because the weld offers a greater resistance to deformation than the plate.

Nevertheless a very small difference between the plastic zones in both materials is possible because at the notch roots the sum of the plastic and the elastic deformations will be equal in weld and plate. As the elastic deformation of the weld is larger that that of the plate, being $\frac{\sigma_{y(weld)}}{E}$ instead of $\frac{\sigma_{y(plate)}}{E}$, the plastic deformation must be smaller.

However elastic deformations are generally much smaller than plastic deformations so that the difference in size of the plastic zones is negligible.

2e $\sigma_{nom} = \sigma_{y(plate)}$. (General yielding).

At some distance from the notches the stress distribution is as indicated in figure 3; the strain in the weld must be equal to that in the plate for similar reasons as given in 1e.

At the notches the stress distribution differs from one to the other. At the border of the purely elastically deformed small zone ahead and behind the notches the stresses have the magnitude of $\sigma_{y(weld)}$ and $\sigma_{y(plate)}$ respectively.

But again the larger stress at the weld is precisely what is needed for making the strain distribution in the weld conform to that in the plate in view of the greater resistance the weld material offers to the internal forces. Again there is no reason for differences in the deformations of both notches. (The foregoing is only a simplified presentation of the actual state of affairs around the notches. For the purpose of this paper it is thought to be sufficient.)

§ 2. Test set-up for experimental verification.

As far as the authors know the above arguments have never been put to trial in an experimental investigation. That is why, on request of Mr. van den Blink, the laboratory for Welding Technology and the Ship Structures Laboratory of the Technological University Delft prepared the test specimen shown in figure 4. It contained one notch in the weld (C), one in the base metal (D) and two notches of different lengths half in the weld and half in the plate (A and B).

The plate material was mild steel with an upper yield point $\sigma_y = 2560$ kg/cm^2 and a tensile strength $\sigma_B = 4460$ kg/cm^2.

The weld, made by the Union-Melt process, was laid in two runs. The welded plate had been heated for one hour at 625°C in order to eliminate the residual stresses. After that treatment the yield point of the weld was 3090 kg/cm^2 and the tensile strength 4640 kg/cm^2.

The deformations over and close to the notches were measured by means of strain gauges of 3 mm in length.

The gauges had been connected to a high speed digital recorder of which the punched tape output was sent to the University's Computer Centre for further processing.

The gauges 102, 103, 106 and 107 which "bridged" the notches were intended for recording the first stages of plastic deformation ($\sigma_{nom} < \sigma_{y(plate)}$).

They proved to be very reliable for measuring the crack-opening displacements (C.O.D.). In figure 6 these strain gauge data are compared with readings of a dial gauge (see also figure 7). C.O.D.'s up to 25% could be measured. For the largest notch (B) that C.O.D. occurred at a nominal stress of 2100 kg/cm^2 (0,8 σ_y).
The output of the strain gauges adjacent to the notches is equal to the mean strain over 3 mm length. This is sufficiently reliable for investigating whether the notch roots deform equally or not.

§ 3. Deformations before general yielding.

a Notch A: 8 x 0,4 mm (see figure 4).
The output of the gauges 102 and 103 over the notch A, which was situated half in the weld and half in the plate, is shown in figure 8.
For the same loading range the output of gauges 101 and 104 is given.
It can be seen that general yielding has not yet started; in fact the nominal stress at the section concerned was 90% of yield load. The exact similarity in behaviour of corresponding gauges is striking as well in the region of very local yielding (plane strain region) as in the region where the plastic zones at the notches are rapidly expanding (plane-stress region).

b Notches C and D 8 x 0,4 mm.

Notches C and D which are situated entirely in the weld metal and in the plate material respectively, have only been provided with gauges adjacent to the roots (like nrs. 101 and 104 in the previous part a). In figure 9 the mean of the output of gauges 109 and 110 (weld-notch) is compared with that of 111 and 112 (plate-notch). During the test the load has purposely been lowered from 108 tons to 100 tons after which the test continued until 109 tons. Next the specimen was unloaded. Again the correspondence between both curves is excellent.

c Notch B: 20 x 0,4 mm.

This notch was provided with two "bridge" gauges nrs. 106 and 107 and two gauges adjacent to the notch roots 105 and 108.
The "bridge" gauges remained intact up to a nominal stress of 2100 kg/cm^2 at the notched section.
The measured strains are shown in figure 10 together with the output of the edge gauges 105 and 108.
Just before a small drop in the external load had purposely been brought about the plate-material had developed a somewhat larger plastic strain than the welding-material (respectively 10% strain for 107 and 13% strain for 106). The same tendency can be observed for 108 and 105. However the difference is small enough to be taken as insignificantly particularly in the light of the preceding and following data. This is confirmed by figure 11 in which can be seen that the yielded zones, which at a nominal stress of 2150 kg/cm^2 were visible at the edges of the 20 mm notch do not differ in appearance. The width of that zone in line with the notch - being somewhat smaller than plate thickness - is another proof that the material is indeed still in a plane strain condition at that load.

§ 4. Deformations after general yielding.

a 8 mm Notch A.

Figure 12 shows the output of gauges 101 and 104 situated on the weld and on the plate respectively. Both curves are practically identical up to about 1,4% strain. Outside this region the weld seems to deform even more than the plate. The output of the gauges at the notches C and D is not compared. Their positions in the width direction of the plate were not identical which will lead to incongruous behaviour after general yielding.

b 20 mm Notch B.

Figure 13 shows that for this large notch the correspondence between the gauge-data for weld and plate is also perfect.

After the test was finished the crack-opening displacements of the four notches could be measured with the aid of a microscope. The results are given in figure 14. (The corresponding overall deformation of the specimen was 1,3%). The equality of the deformations of the weld and the plate at notches A and B is evident.

Curiously enough notch C, situated entirely in the weld has deformed more than notch D in the plate. Moreover notch A, situated both in the weld and the plate obtained even smaller deformations. The cause of this phenomenon is not known.

§ 5. Conclusions.

The deformation of notches situated in or near longitudinally loaded welds in wide plates is not influenced by differences between the yield points of the plate and the weld.

It should be added that the situation is quite different for notches in and near traverse welds (figure 15). In that case the use of weld metal with a yield point higher than that of the plate is favourable. For, when general yielding starts in the plate material, the weld metal will not be forced to yield likewise, as happened in the case of a longitudinal weld.

Consequently for dropweight-specimens with "transverse" welds the test procedure of the IIW-doc. 2912-102-67 is permissable. But in case of "longitudinal" welds a deformation criterium should be applied. (The deformations can easily be measured as crack-opening-displacements with the aid of a mechanical extensometer.)

In the author's opinion the test could best be standardized in the following way. Three specimens are prepared, each for one temperature. Consecutive blows of gradually increasing drop-heights are applied (e.g. 10, 20, 30, 40, etc. cm). The C.O.D.'s measured for some of these blows are plotted in a diagram from which by extrapolation the C.O.D. immediately prior to fracture can be found. These fracture-C.O.D.'s are plotted as a function of temperature. After defining a minimum C.O.D. the critical temperature can be found. It is thought that in order to avoid low-stress fracturing in practice that minimum C.O.D. value may be defined as the one which in a static bend test occurs at a load which in the notched section causes a calculated nominal stress of yield point magnitude (figure 16).

For a certain configuration of specimen and notch this can be estimated once and for all in a single bend test with the unwelded plate.

This proposal has the following advantages:

Each blow will only cause small plastic deformations because the prior blows have enlarged the capacity for elastic energy absorption of the specimen. This makes the procedure equivalent to so-called "low-blow" or "quasi-static" testing because the small plastic deformations are brought about by energy released at the end of the impact-process when the speed of deformation is much reduced. This eliminates the possible objection that the impacts are too severe from a practical point of view. On the other hand the influence of strain-hardening is retained because all blows together will cause measurable plastic deformations (C.O.D.'s). Finally it is believed that a small impact effect must be included in acceptance tests if it were only to compensate for the absence of the influence of residual stresses in the test.

Acknowledgement.

The cooperation of ir. W.P. van den Blink, Prof. H.G. Geerlings and Mr. J. Laan is readily acknowledged.

FIG. 1 Test-specimen proposed in Doc. I.I.W. 2912-102-67

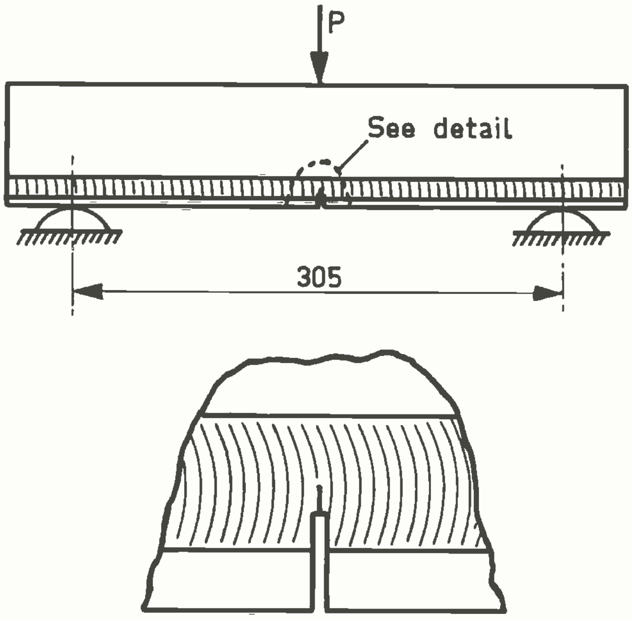


TABLE. I

Dimensions of plastic zones			
	T °C	W mm	σ_y kg/mm^2
Stael (as delivered)	− 10	12	25
Steel (stress relieved)	− 10	12	?
U.M. weld	−30	4.5	35.8
E.G. weld	−30	8	31.8

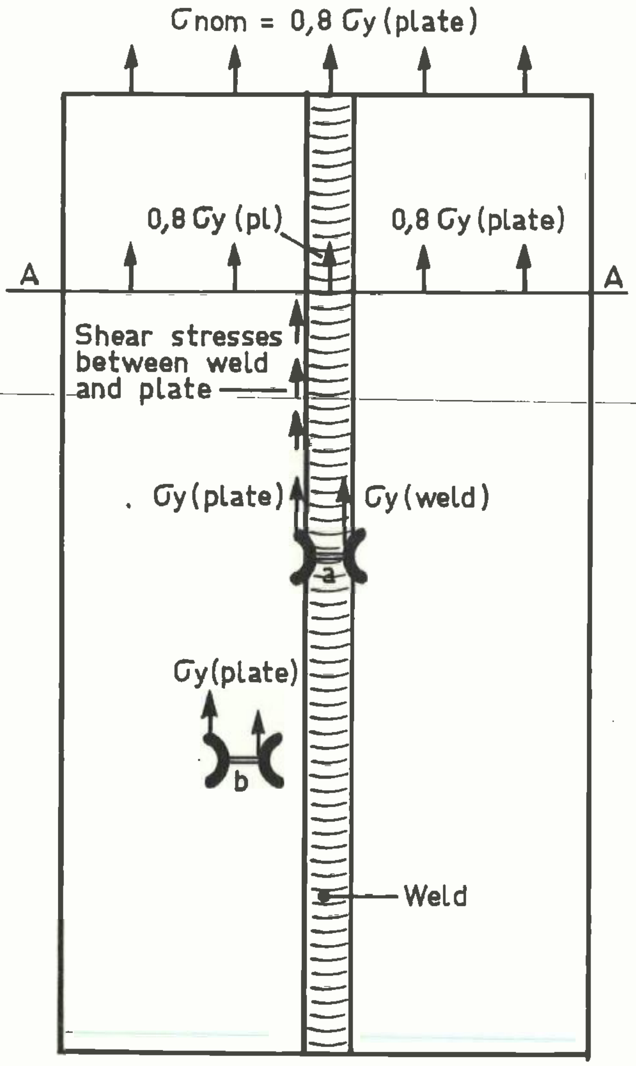


FIG. 2 $\sigma_{nom} = 0{,}8\ \sigma_y$ (plate)

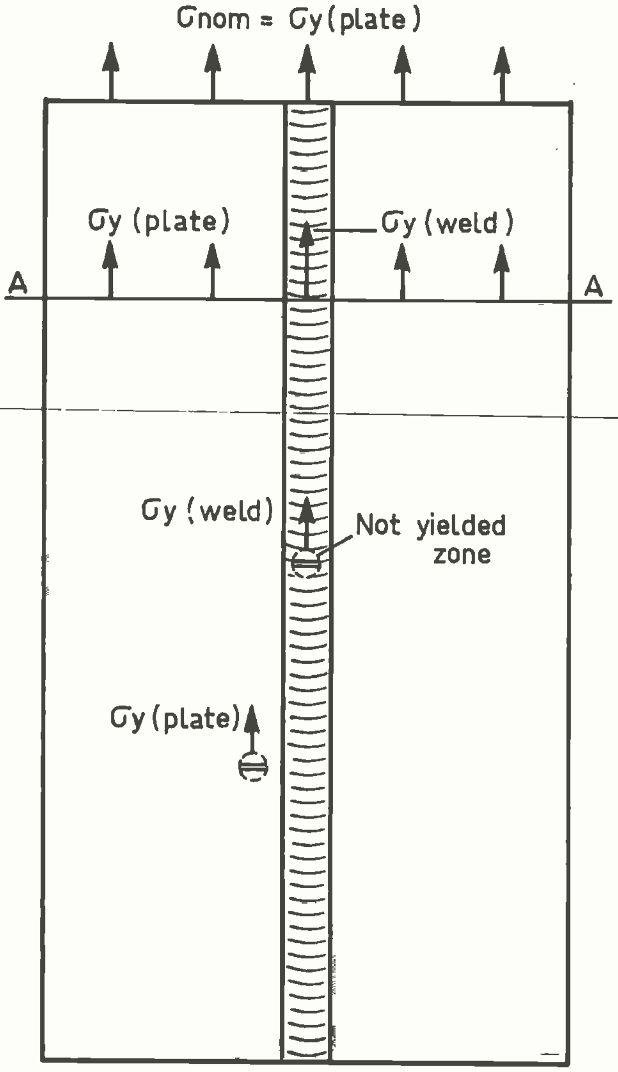


FIG. 3 $\sigma_{nom} = \sigma_y$ (plate)

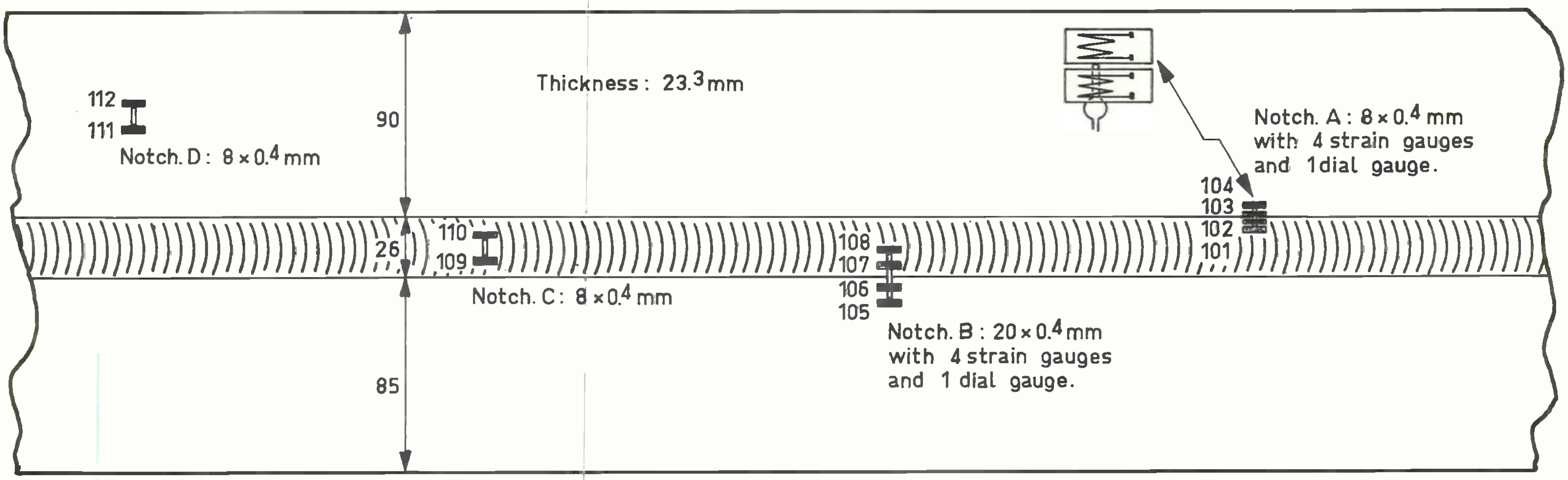


FIG. 4 TEST – SPECIMEN.

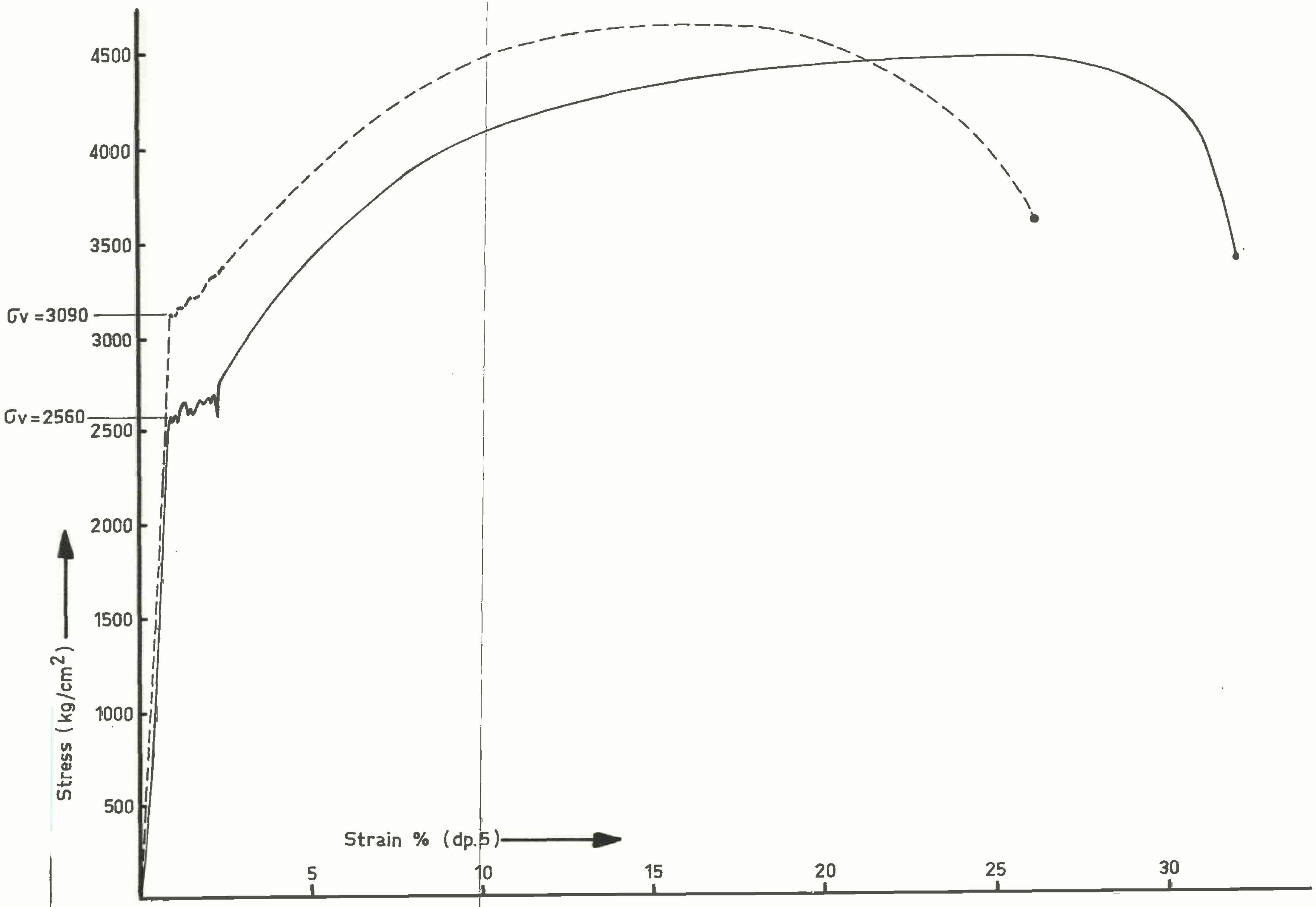

4500
4000
3500
σv =3090
3000
σv =2560
2500
2000
1500
1000
500
Stress (kg/cm²)
Strain % (dp.5)
5
10
15
20
25
30

FIG. 5

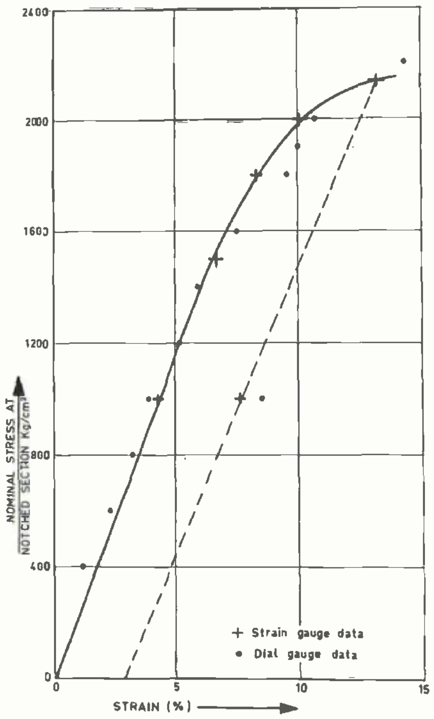


FIG. 6.
C.O.D. (CRACK-OPENING=DISPLACEMENT)-MEASUREMENT
WITH STRAIN- AND DIAL GAUGES. (NOTCH 20 x 0,4 mm.)

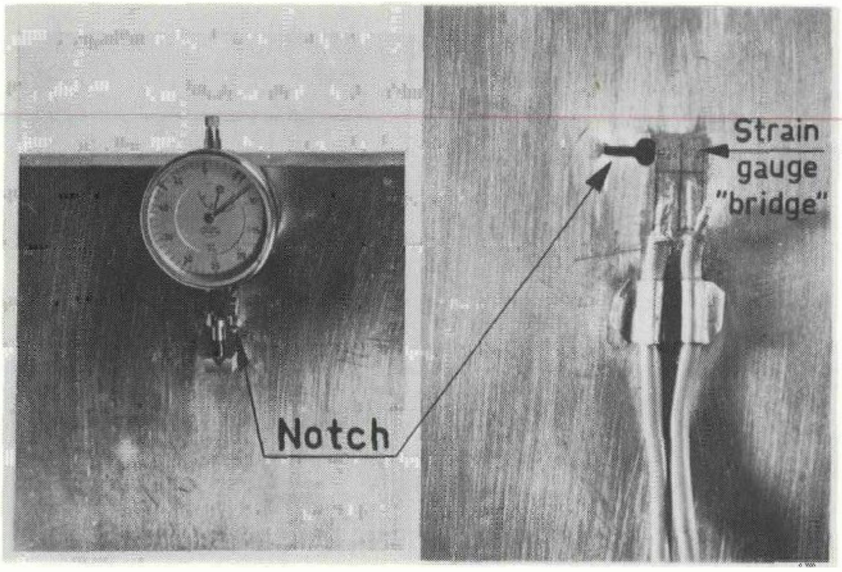
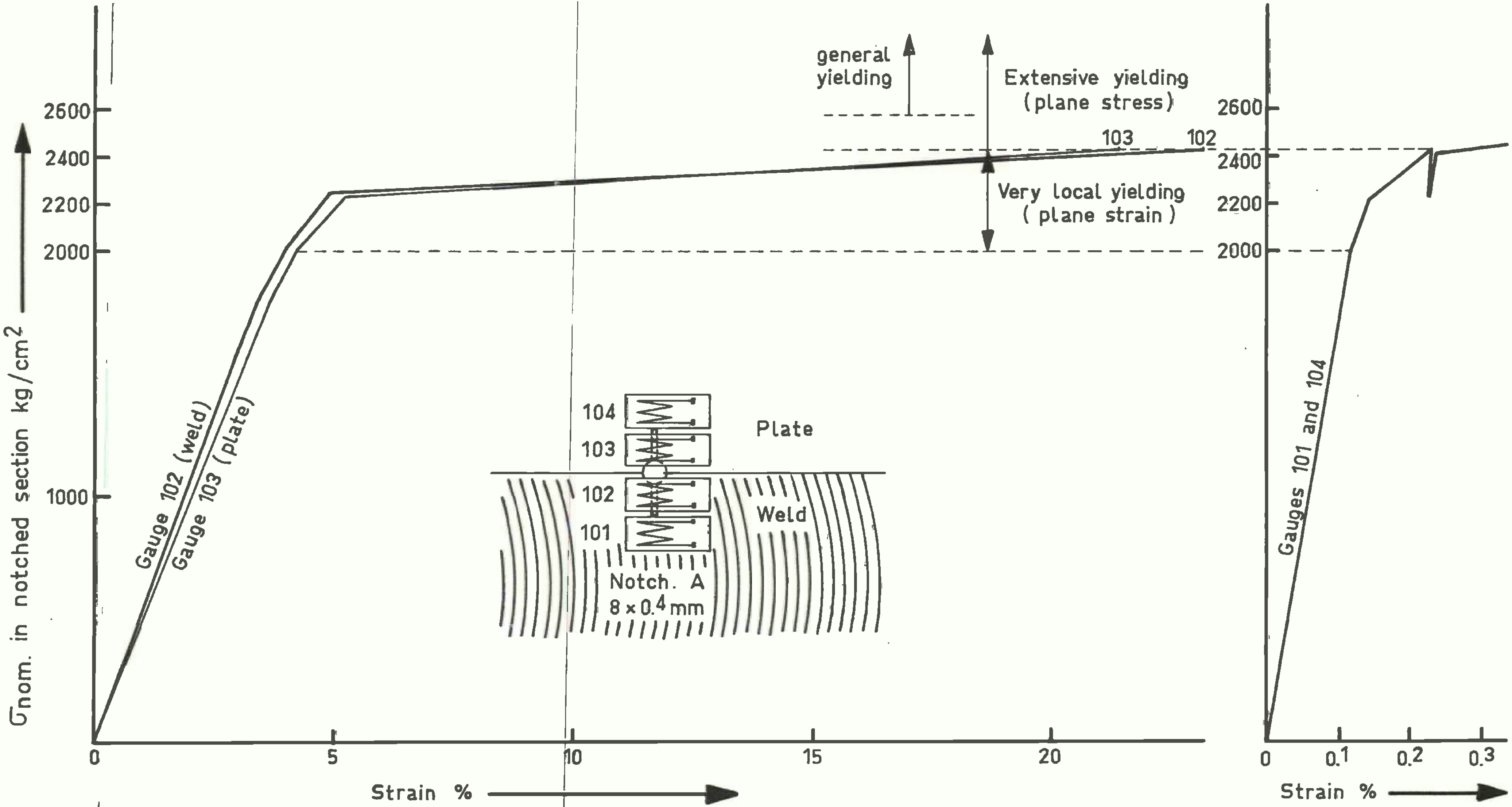


FIG. 7.
(NOTCH 8 x 0,4 mm.)



σnom. in notched section kg/cm²
2600
2400
2200
2000
1000
0
5
10
15
20
Strain %
Gauge 102 (weld)
Gauge 103 (plate)
general yielding
Extensive yielding (plane stress)
103
102
Very local yielding (plane strain)
104
103
102
101
Plate
Weld
Notch. A
8 × 0.4 mm
2600
2400
2200
2000
Gauges 101 and 104
0
0.1
0.2
0.3
Strain %

FIG. 8

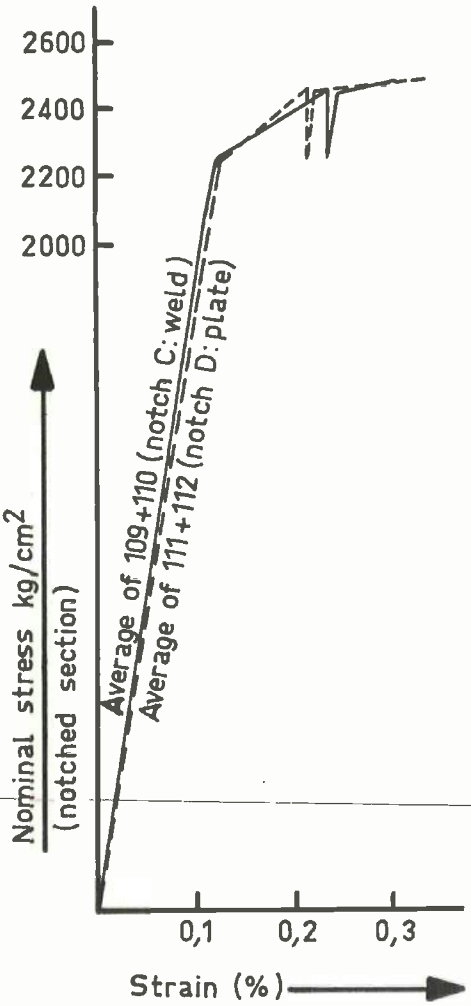


FIG. 9

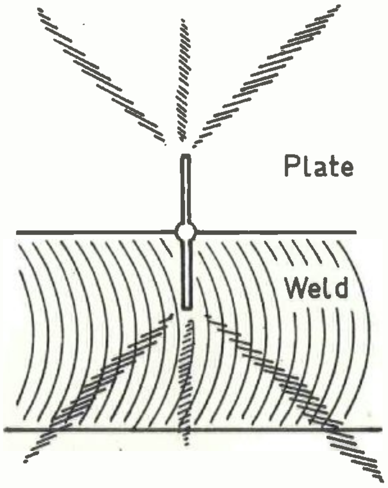
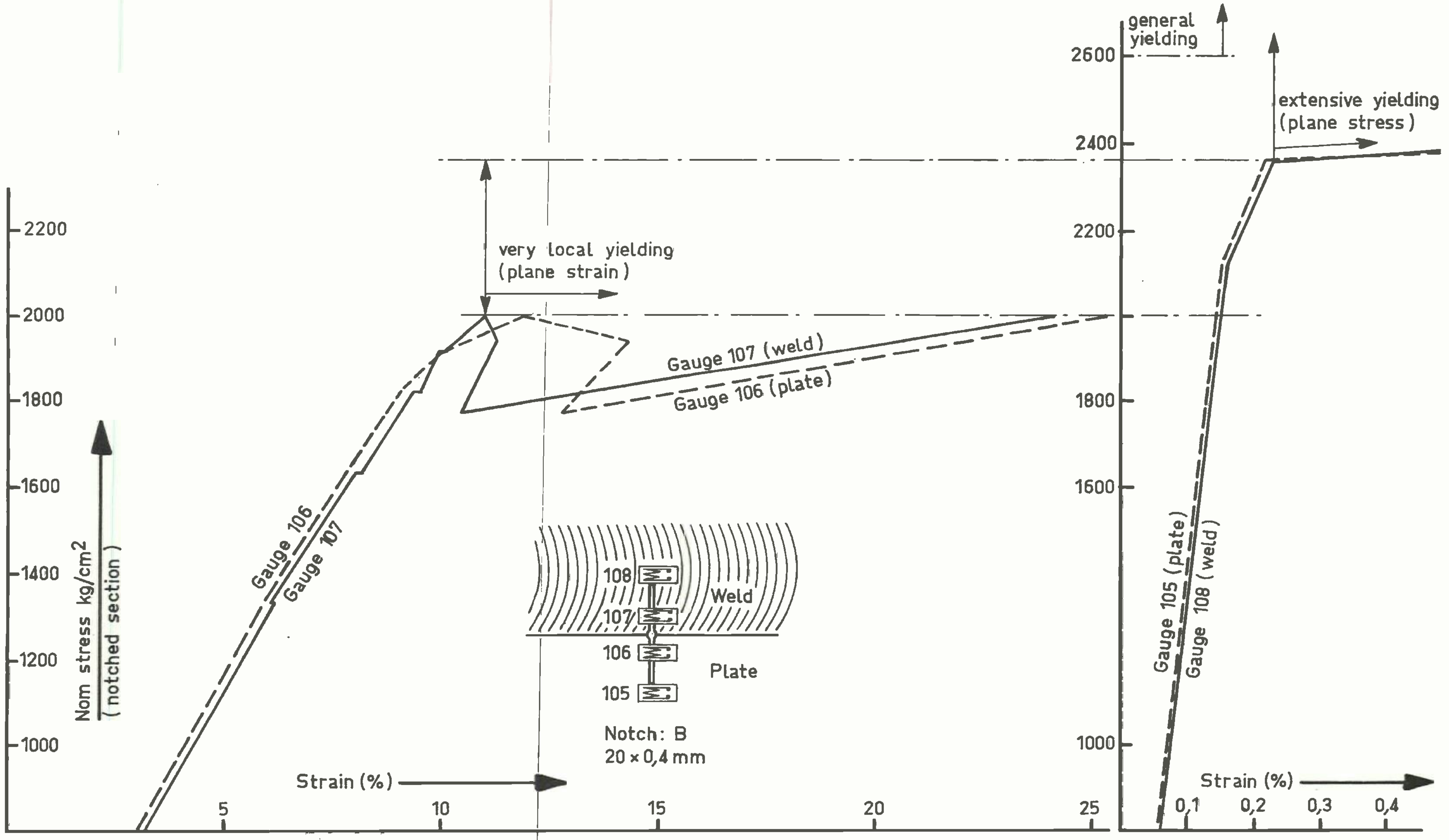


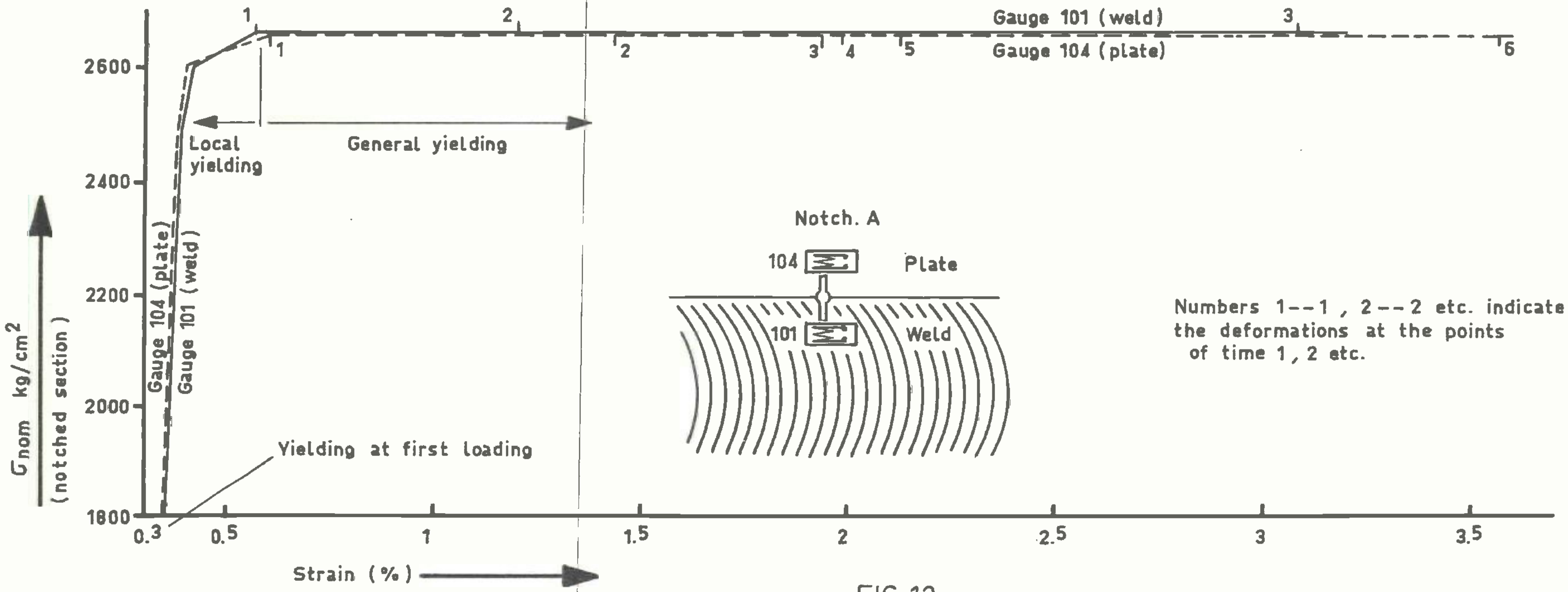
FIG. 11 Flow-figures at notch. B (20×0,4 mm)

$\sigma_{nom} = 2100$ kg/cm^2 (notched section)



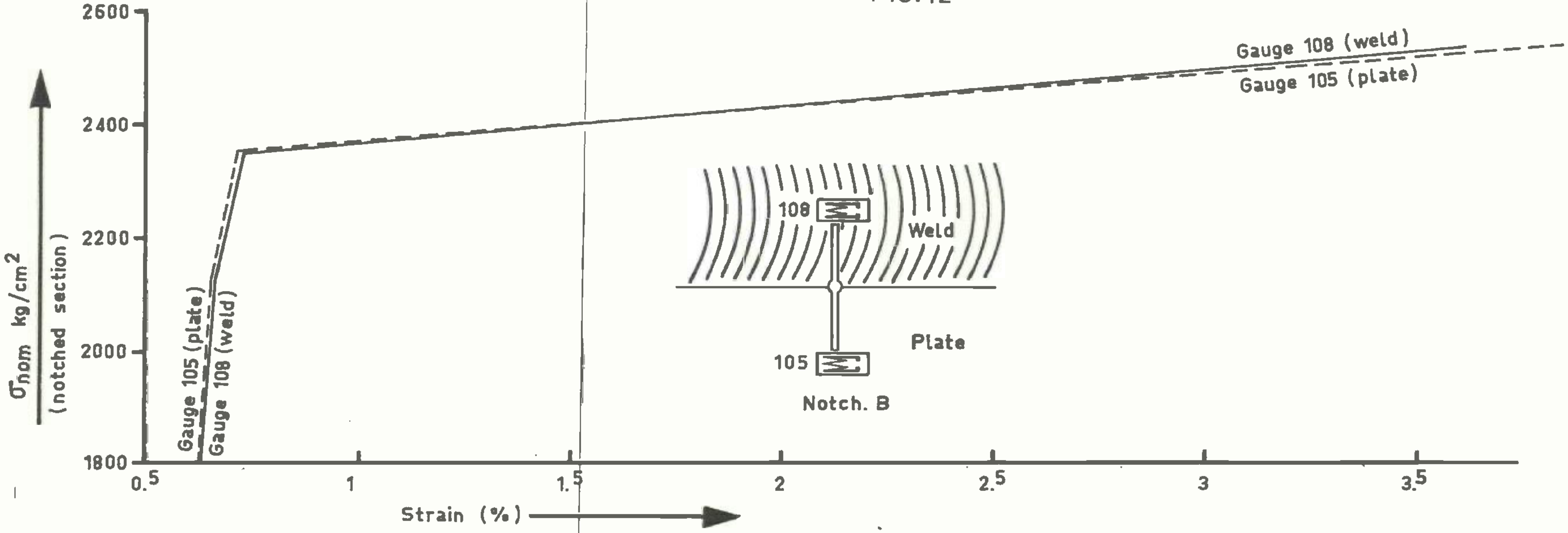
general yielding
2600
2400
2200
2000
1800
1600
1400
1200
1000
very local yielding (plane strain)
extensive yielding (plane stress)
Gauge 107 (weld)
Gauge 106 (plate)
Gauge 106
Gauge 107
Gauge 105 (plate)
Gauge 108 (weld)
Nom stress kg/cm2 (notched section)
108
107
106
105
Weld
Plate
Notch: B
20 × 0,4 mm
Strain (%)
5
10
15
20
25
0,1
0,2
0,3
0,4

FIG. 10



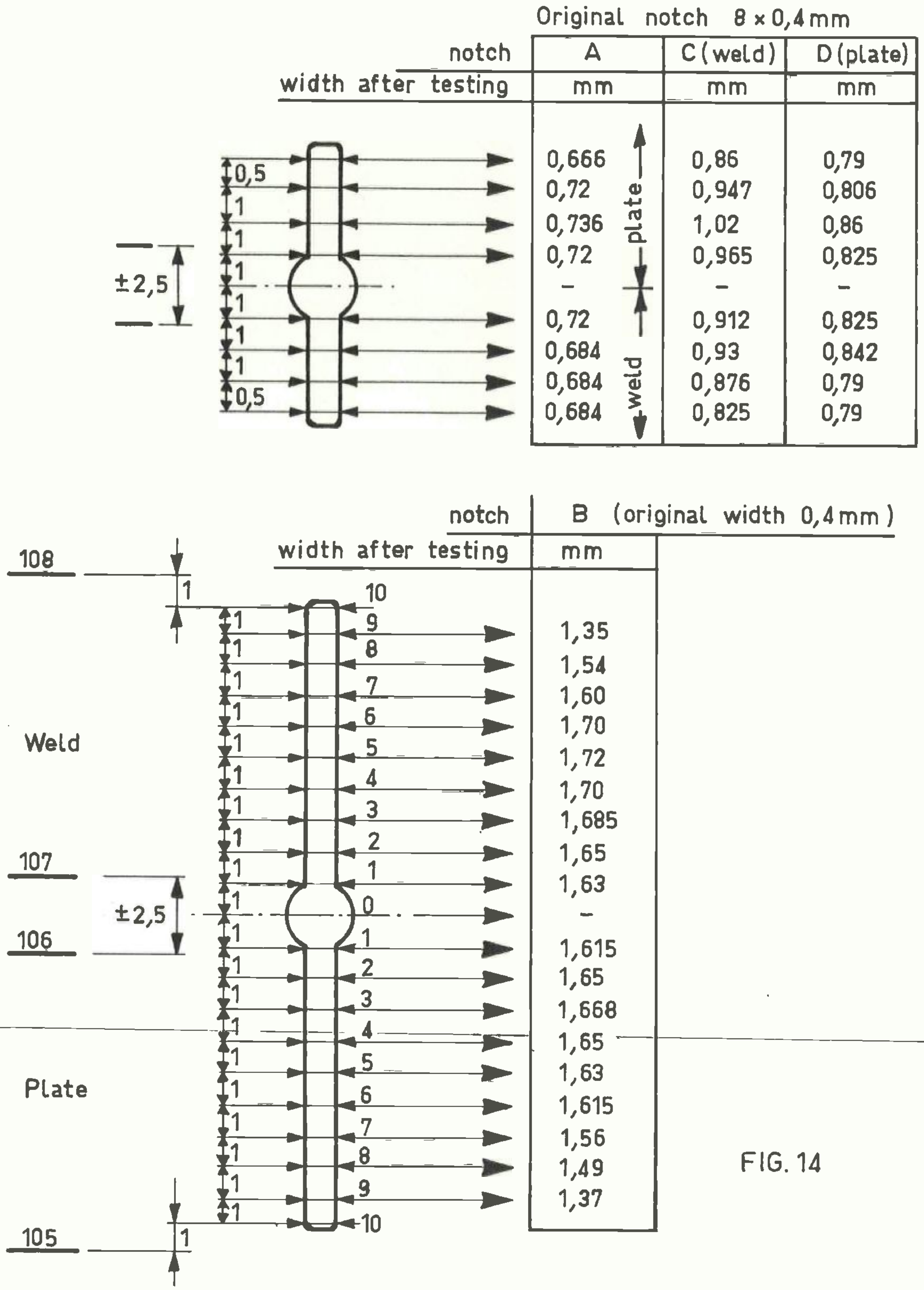
Gauge 101 (weld)
Gauge 104 (plate)
1
2
3
1
2
3
4
5
6
Local yielding
General yielding
Yielding at first loading
Gauge 104 (plate)
Gauge 101 (weld)
σ_{nom} kg/cm^2
(notched section)
2600
2400
2200
2000
1800
0.3
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
Notch. A
104
Plate
101
Weld
Numbers 1--1 , 2--2 etc. indicate the deformations at the points of time 1, 2 etc.

FIG.12



Gauge 108 (weld)
Gauge 105 (plate)
Gauge 105 (plate)
Gauge 108 (weld)
σ_{nom} kg/cm^2
(notched section)
2600
2400
2200
2000
1800
0.5
1
1.5
2
2.5
3
3.5
Strain (%)
108
Weld
Plate
105
Notch. B

FIG.13



Original notch 8 × 0,4 mm

notch width after testing	A mm		C (weld) mm	D (plate) mm
	0,666	plate	0,86	0,79
	0,72		0,947	0,806
	0,736		1,02	0,86
	0,72		0,965	0,825
	–		–	–
	0,72	weld	0,912	0,825
	0,684		0,93	0,842
	0,684		0,876	0,79
	0,684		0,825	0,79

	notch width after testing	B (original width 0,4 mm) mm
Weld	10	
	9	1,35
	8	1,54
	7	1,60
	6	1,70
	5	1,72
	4	1,70
	3	1,685
	2	1,65
	1	1,63
	0	–
Plate	1	1,615
	2	1,65
	3	1,668
	4	1,65
	5	1,63
	6	1,615
	7	1,56
	8	1,49
	9	1,37
	10	

FIG. 14

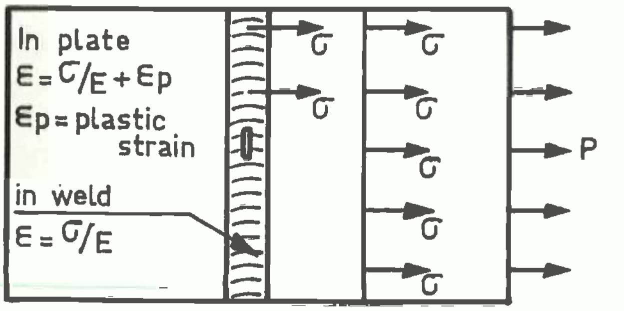


FIG. 15 $\sigma(\text{plate}) < \sigma < \sigma(\text{weld})$

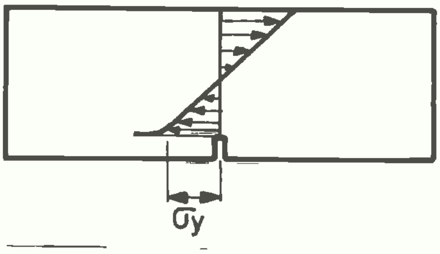


FIG. 16