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Inspection and control of welded joints.

Prüfung der Schweißnähte.

Contrôle des soudures.

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IIIc 1

Calculation of Welds under Consideration of Constant Deformation Energy.

Berechnung der Schweißnähte unter Berücksichtigung konstanter Gestaltsänderungsenergie.

Calcul des soudures basé sur de la conservation de l'énergie de déformation.

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The experiments of Professor *Jensen* have demonstrated that the theory of constant deformation energy furnishes exactly the relation between the loads in different direction on a fillet weld. The calculation of statically endeterminate connections is based on the theory of plasticity. The author's conclusions from theory and tests are given at the end of this paper.

According to the German standards (DIN 4100) concerning welded steel structures, and in the American Code of Fusion Welding and Gascutting in Building Construction, and as well as in other Regulations the permissible amount of stress in fillet welds was taken the the same for all directions in which the force is capable to act. The strength offered by the weld is much greater if the force is acting at right angles to the face of the weld (line CD in Fig. 1)

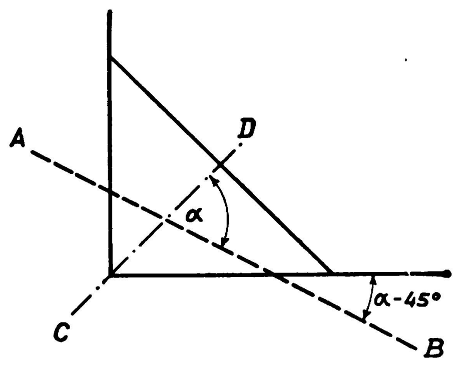


Fig. 1.

than when acting in the face of the weld. Professor *Cyrill D. Jensen* (U.S.A.) has published a series of interesting tests on the strength of front fillet welds for different values of the angle α formed between the direction of the force AB and the fillet CD (Fig. 1). The rupture point stresses $\sigma_{B\alpha}$ found by Professor *Jensen* are represented in Fig. 2 in such a way that the length of the vector represents the magnitude of the rupture point stress and the angle between vector and the axis of abscissae is equal to angle α. Professor *Jensen,* however, has not examined if the results of his tests are compatible with the theory of constant deformation energy. If this examination is carried out it is found that excellent agreement exists. The dotted curve gives the points on which the vectors should end if they would fully agree with the theory.

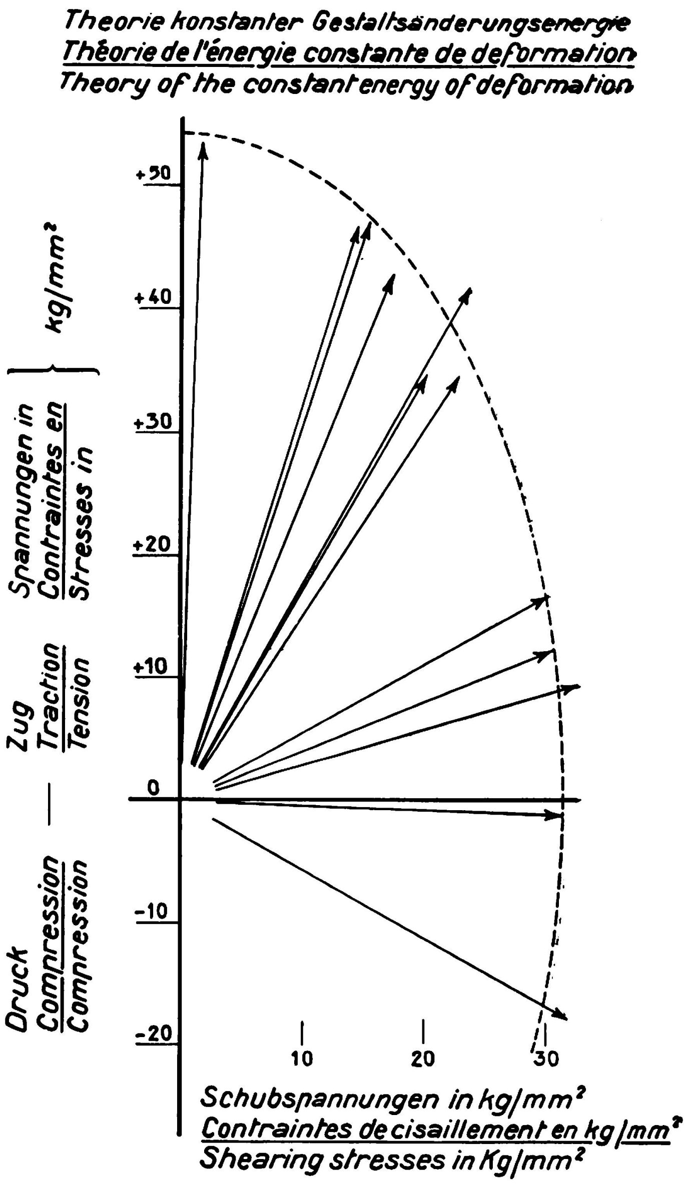


Fig. 2.

The following notations are used:

$\sigma_{B\alpha}$ represents the rupture point stress for forces acting under an angle α to the bisecting line of the fillet.

σ the component of $\sigma_{B\alpha}$ perpendicular to the plane of rupture.

τ the component of $\sigma_{B\alpha}$ in the plane of rupture.

$\sigma_{B\,zug}$ the rupture point stress for normal loading.

According to the theory of constant deformation energy fracture occurs when

$$\sqrt{\sigma^2 + 3\tau^2} = \sigma_{B\,zug} \text{ and hence}$$

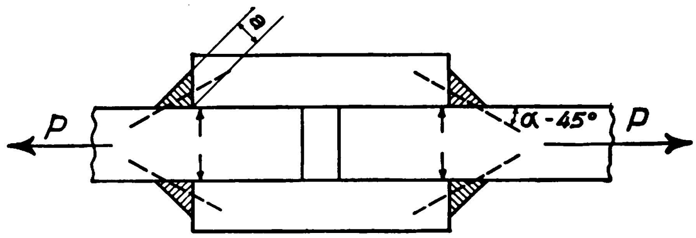
$$\sigma_{B\alpha} = \sigma_{B\,zug} \cdot \frac{1}{\sqrt{\sin^2\alpha + 3\cos^2\alpha}}.$$

The mean value of $\sqrt{\sigma^2 + 3\tau^2}$ for which rupture occurs has been deduced from the tests of Professor *Jensen*. With these mean values the values of $\sigma_B\,\alpha$ were formed, which are represented by the dotted line curve of Fig. 2.

The agreement of Professor *Jensen's* test results with the theory of constant deformation energy is so much the more interesting since the object of Professor *Jensen*'s tests was to examine other theories of rupture. He found that either the results of his tests do not agree with any of the theories of rupture known to him or that his tests were not accurate enough. We find, however, that the results of his tests agree exceedingly well with the theory of constant deformation energy and that they were of great accuracy.

The researches of Professor *Jensen* refer to front fillet welds only (line CD, Fig. 1) stressed either by tension and shear, or shear and very little compression; they do not concern welds stressed chiefly by compression.

The specimens were constructed in such a way that the direction of the force could be exactly determined. This was necessary should the angle α be determined accurately. As a rule the direction of the force is statically not determined. The calculations of $\sigma_B\,\alpha$ shall therefore be extended by determining first the angle α for the action of forces whose direction is unknown statically.



Fig, 3.

We propose, based on the theory of plasticity to choose the direction of the force in the welds (angle α) such, that the greatest force transmitted to the structure, but compatible with the equilibrium of forces, can be considered in calculation.

These conditions shall be elucidated by an example. In Fig. 3 is shown a specimen with front fillet welds, and stressed by a tensile force P. The lines of action (shown dotted) for the forces to be transmitted by the welds can form, from the point of view of equilibrium, any angle with the horizontal line. This angle with the horizontal line is $\alpha - 45^0$ (see also Fig. 1). If F represents the area along line CD in Fig. 1 for two welds we receive for the oblique rupture force of one weld the expression:

$$\frac{1}{2} F \sigma_{B\alpha} = \frac{1}{2} F \cdot \frac{\sigma_{B\,zug}}{\sqrt{\sin^2\alpha + 3\cos^2\alpha}}.$$

In consequence of the obliquity of the forces at the joint the lateral pieces are pressed against the central piece. Fracture of the specimen will only result when the friction between the central piece and the lateral pieces are overcome. The breaking force P is therefore the sum of the horizontal components of the oblique forces and the resistance due to friction. The horizontal components of the oblique breaking forces are

$$\frac{1}{2} F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \cos(\alpha - 45^0)$$

and the vertical components,

$$\frac{1}{2} F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \sin(\alpha - 45^0)$$

If the coefficient of friction be denoted by μ we can write.

$$P = 2 \cdot \frac{1}{2} F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \left[\cos(\alpha - 45^0) + \mu \sin(\alpha - 45^0)\right]$$

The central piece is severely compressed by the lateral pieces, from wich it results that the coefficient of friction can be chosen much higher than in the case of moderate compression. We allow a coefficient equal to that of a riveted joint, that is to say, 0.2. Our formula then becomes,

$$P = F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \left[\cos(\alpha - 45^0) + 0.2 \sin(\alpha - 45^0)\right].$$

Based upon the law of plasticity the value of α must be such as to give P a maximum value. This is the case if $\alpha = 79^0$ and

$$P = 0.91\, F \sigma_{Bzug}$$

(Type of construction of Fig. 3).

The effect of the force is essentially different in the case of Fig. 4. The compression between the pieces does not exist in this case and in order that the

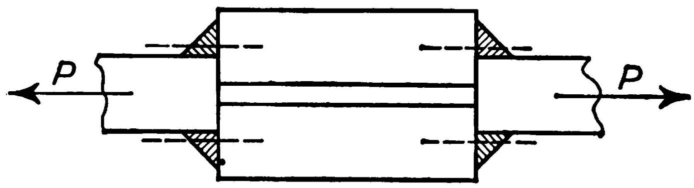


Fig. 4.

system may be in equilibrium, it is necessary that the forces acting on the upper and lower welds should be directly opposed. For reasons of symmetry it is further necessary that the forces should be horizontal as is shown in Fig. 4. The angle is therefore in this case 45^0 and

$$P = F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} = 0.71\, F \sigma_{B\,zug}$$

(type of construction shown in Fig. 4). If in the specimen of Fig. 3 tension is replaced by compression, the pressure between the lateral pieces and the central piece no longer exists. In this case we have again $\alpha = 45^0$ and

$$P = 0.71\, F\, \sigma_{B\,zug}.$$

We will now try a method of calculation based on the following hypothesis:

1) Fracture occurs at the smallest section of the weld; at least, let us make our calculations as if such were the case.

2) According to the theory of constant deformation energy, the ultimate stress $\sigma_B\, \alpha$ occasioned by a force acting at an angle α is equal to the normal tensile stress which leads to fracture multiplied by

$$\frac{1}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}}.$$

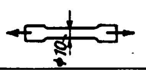
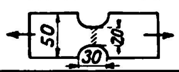
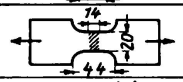
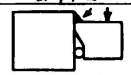
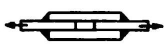
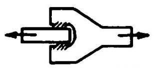
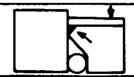
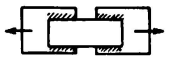
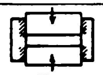
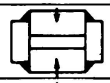
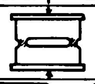
3) According to the theory of plasticity, the hyperstatic value will be chosen as favorable as equilibrium permits. This concerns quite as much the angle at which the force acts at a weld as the distribution of the forces over several welds.

If the calculation according to the third hypothesis is too complicated, a practical supposition concerning the hyperstatic value should be made. This supposition may lead us to calculate a state of load which is smaller than the true ultimate load. It must yet be remarked that the hypothesis 3 does not apply to alternating loads (repeated, for example, one million times) because the material is no longer plastic in such a case. This method of calculation can only be applied to structures in which the loads vary but slightly or not frequently, for example, frame work. In all cases it must be verified by tests.

Under agreement with the Dutch Standards Committee for Welded Metallic Structures (36 C) and with the willing collaboration of "Willem Smit & Co's Transformatorenfabriek", Nimegue, "Arcoselectrolasch" Amsterdam, and the "Nederlandsche Kjellberg Electrodenfabriek" Amsterdam, the Polytechnic School at Delft (Holland) we have undertaken a series of experiments on electrically welded specimens to investigate the hypotheses we have indicated above. In the table, one column gives sketches of the specimens, another indicates the type of weld and the following, the angle formed by the direction of the force on the one part, and by the smaller transverse section of the weld on the other part.

Three specimens of each type were prepared. One specimen was welded with Smit's "Resistanz" rods, another with "Stabilend" rods from the Maison Arcos, are the mean of the quotient of the greatest load supported by the specimen and the smallest transverse section of the weld (if there are collaborating welds — the sum of the smallest sections of these welds). The breaking loads are compared with the mean breaking load of a standard bar (10 mm diameter for a length of 50 mm) composed entirely of the deposited metal. The average stress of nine of these bars (three prepared from the rods each mark) was determined and is given behind XVI in the table. It amounts to 48.3 kg/mm².

We have used steel 37 for the preparation of the specimens. The ratio between the mean breaking stress of the welded joint and the mean breaking load of bars of the deposited metal are given in the 6th column of the table. In column 7 are shown the results that should be obtained if the hypotheses under inve-

№	Test piece	Type of weld	Nature of stressing	Rupture point Stress in kg/mm²	Ratio to XVI observed	Ratio to XVI calculated	Stress due to impression of 0,2‰ kg/mm²	Ratio to XVI	Stress due to impression of 1,0‰ kg/mm²	Ratio to XVI	Bessel kg/mm²	Vogel kg/mm²	Dresden Welding Tests kg/mm²	Boston kg/mm²	Hohn kg/mm²	Mac Gibbon kg/mm²	E.T.H. Zürich kg/mm²	R.S.W. kg/mm²	
XVI		Entirely of weld metal	Normal tension	48,3															
I		Butt weld	Normal tension	49,3	1,02	1,00					38,0 [1)]							34,0 [1)]	not machined
II		Butt weld	Normal tension	50,1	1,04	1,00											40,0		
VII		End fillet weld	Normal tension	57,3	1,19	1,00													
VIII		End fillet welds	Tension under 79° and friction	51,9	1,07	0,91						46,5		45,0	41,0		49,5	35,0	
IX		End fillet welds	Tension under 45°	33,4	0,69	0,71													
VI		Butt welds	Shear	31,1	0,64	0,58													
X		End fillet weld	Shear	29,9	0,62	0,58													
XIV		Side fillet welds	Shear and secondary tension	30,9	0,64	0,58					32,0	40,0		34,0	28,0	39,0	35,4	29,0	
XV		Side fillet welds	Shear and secondary compression	35,6	0,74	0,58						50,0				48,0			
XI		End fillet welds	Compression under 45°	40,6	0,84	0,71						42,5							
XII		End fillet welds	Compression under 72°	> 64,1	> 1,33	0,82	37,8	0,78	55,0	1,14			> 53,0						
V		Butt welds	Compression	> 78,8	> 1,63	1,00	37,8	0,78	48,1	1,00			> 46,0						
XIII		End fillet welds	Compression	> 70,7	> 1,46	1,00	61,6	1,27											

stigation were exact. The comparison of the figures in columns 6 and 7 gives the degree of exactitude of the hypothesis. The photograph, Fig. 5, shows the several specimens before the tests; specimens I, II, V, and VI are butt welded and accurately machined (thickness 10 to 14 mm). The other specimens are fillet welded and were measured with Dr. Ing. *H. Schmuckler's* instrument (an instrument which proved itself very useful for these measurements). The

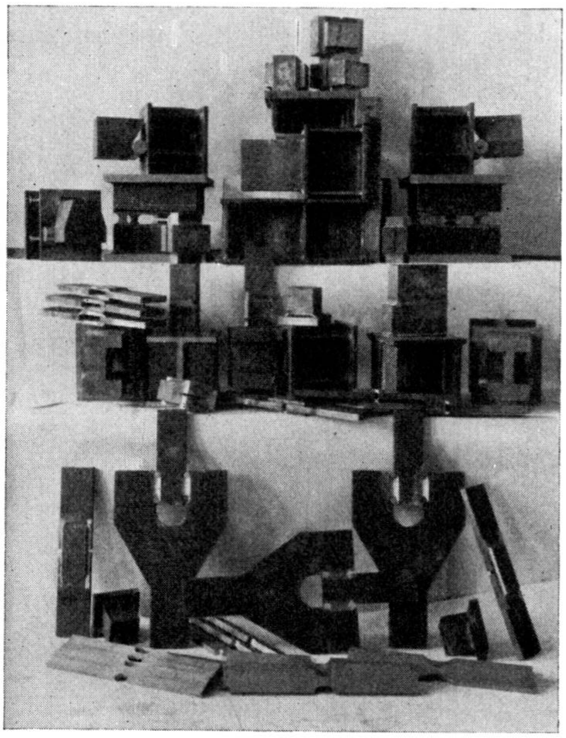


Fig. 5.

breaking loads are referred to a measured section (thickness "a" multiplied by the length of the weld). In general the thickness of the weld was intended to be 4 mm but measurements have shown that this thickness was exceeded.

Fig. 6 represents a specimen of type VII reinforced by a stirrup to enable the placing in position on the press. Fig. 7 shows the method by which the weld was

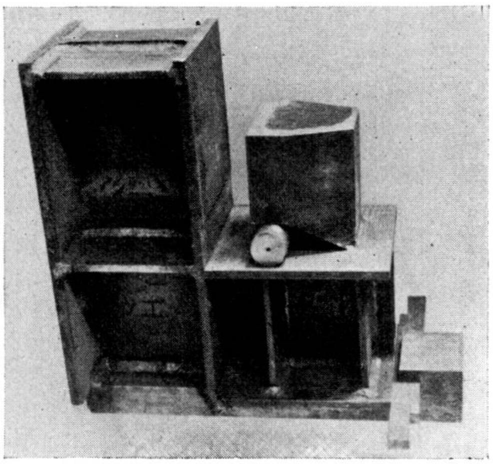


Fig. 6.

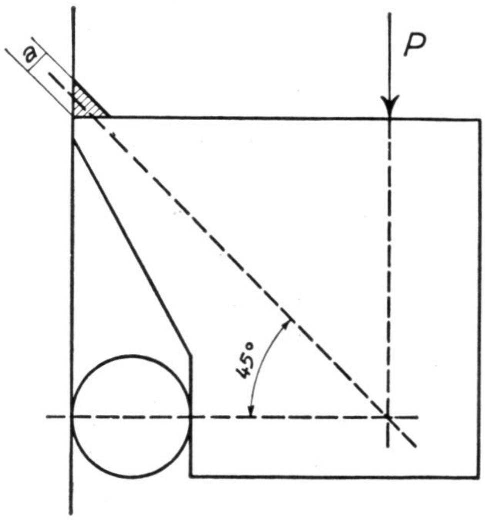


Fig. 7.

submitted to tension. If P is the breaking load, "b" the width of the weld and "a" its thickness, the ultimate stress is equal to $P \frac{\sqrt{2}}{a \cdot b}$. The shape of this specimen as well as that of the specimen X conformed to the experiments of *Jensen*. The play of forces in specimens of type VIII and IX have already been explained above. The photograph of Fig. 8 represents a specimen of type VI after the tests. The specimens of X are similar to the specimens of type VII with the sole difference that the welding fillet is placed below the top flange of the Tee girder; it follows that the weld will be subjected to shear.

In the case of specimens XII, V and XIII, the welds were subjected either to compression at an angle of 72^0 or to normal compression. In this case

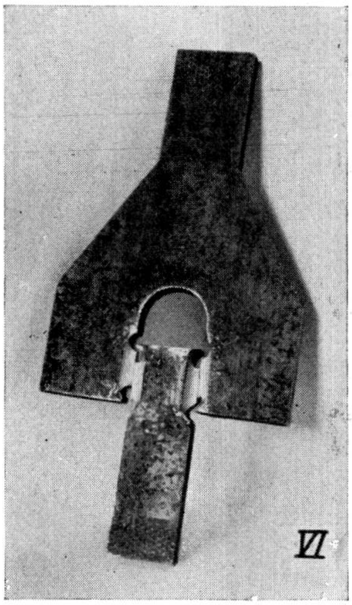


Fig. 8.

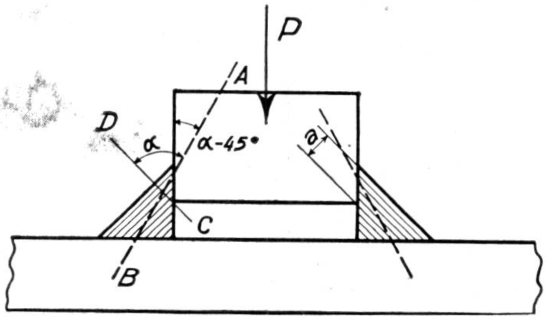


Fig. 9.

there had not been fracture because the weld was stretched without being broken. The distortion of the open welds were measured and the stresses for distortions of 0.2 and 1 mm are recorded in the table. In the column "Ultimate stress" the stresses are recorded at the point where the tests could be carried no further.

During the welding of the specimens XII and XIII, copper plates were introduced into the spaces left free so as to prevent the welding metal flowing there. In the calculations we have introduced the tickness "a" (see Figs. 9 and 11). In the case of specimen XII the angle α contained between the direction of the load to be supported by the weld (line AB of Fig. 9), and the smallest section of the weld, is not statically determinate. If the sum of the smallest sections (CD) of two welds, is represented by F, the ultimate oblique force for a weld is

$$\frac{1}{2} F \sigma_{B\alpha} = \frac{1}{2} F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}}.$$

The direction of this force makes an angle of $\alpha - 45^0$ with the vertical. From the fact that the horizontal components are in equilibrium in the weld, the load

P supported by the specimen is equal to the sum of the vertical components, therefore

$$P = 2 \cdot \frac{1}{2} F \frac{\sigma_{B\,zug}}{\sqrt{\sin^2 \alpha + 3 \cos^2 \alpha}} \cos(\alpha - 45^0)$$

this load is a maximum for $\alpha = 72^0$ and is equal to

$$P = 0.82\, F\, \sigma_{B\,zug}.$$

Photograph 10 represents a specimen of type V after the tests. The welds are found in the weak places at in the corners. The webs of the girder which were 9 mm apart, before the tests, are touching. The play of the loads in the case

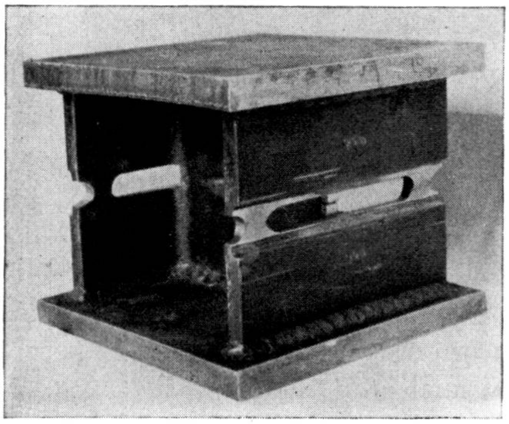


Fig. 10.

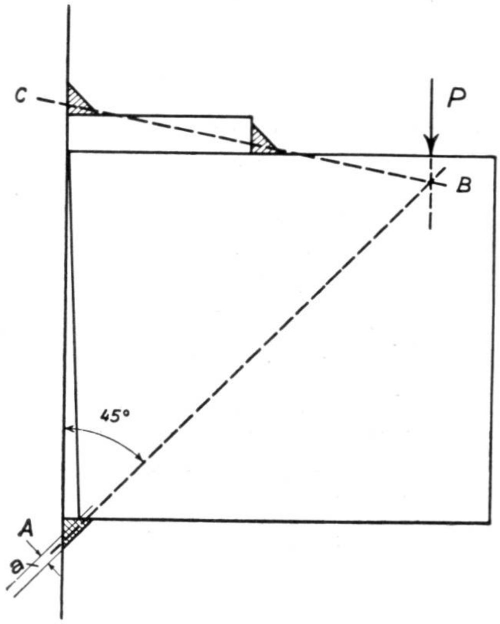


Fig. 11.

of specimen XIII is explained by Fig. 11. The lower weld is loaded in the direction BA, consequently under normal compression. The force is equal to

$$P \frac{AB}{AC}, \text{ and the stress to } P \frac{AB}{AC} : ab,$$

where b represents the length of the weld. In spite of the thickness, 8 mm of the upper welds and 3 mm of the lower, the top ones were the first to fail. The tests which were made of the lower weld could therefore not be extended to a point where the two parts must meet, or even to a shortening of 1 mm. For a shortening of the gap by 0.2 mm however, the stresses were measured as recorded in the table.

We have also examined whether the values obtained by other observers agree with the theory enunciated above. These tests vary but little in the case of load. It is therefore difficult to gauge the theory by these observations; the experiments of the several observers cannot be compared. We have only taken into consideration the experiments which extend over several cases of load. They are the following experiments:

C. Bessel. Tests published in Stahlbau, 1931, N⁰ 23. The results given in the table under "Bessel".

Andrew Vogel. "Journal of the American Welding Society" April, 1929, in the table under "Vogel".

Dresden Tests of Welds. "Der Stahlbau", 1931, N⁰ 12.

Report of tests „Boston Section, Journal of the American Welding Society" in the table under "Boston".

E. Hohn. International Congress on metallic structures at Liege, September, 1930, in the table under "Hohn".

F. P. Mac Gibbon. First Communications of the new International Association for testing materials, page 155. In the table under "*Mac Gibbon*".

Federal laboratories for testing material associated with the E. T. H. Zurich, report N° 86, page 5. In the table under "E. T. H. Zurich".

Report of Structural Steel Welding Committee of the American Bureau of Welding. In the table under R.S.W.

The values given in the table under the designations "Bessel", "Vogel", etc., are the mean of the extreme values in the series.

Let us now compare the above theory with the values given in the table. It will be noticed first of all that in the series of experiments, those specimens have been put first in which the welds are subjected to tension, normal to their smallest section (I, II and VII), subsequently dealing with specimens in which the welds are subjected to an oblique tension acting at a gradually diminishing angle (VIII and IX). Specimens are then given demonstrating resistance to shear, and finally, specimens subjected to normal compression.

If the ratio of the measured ultimate stress of the specimens to that of the standard bars of deposited metal (6^{th} column) be compared, to the calculated ratio (7^{th} column), it will be noticed that the former are a little greater than the latter. Up to specimen XI these ratios are essentially similar. In the case of welds compressed at an angle of 72^0 (XII) as well as in that of welds compressed normally (V and XIII) this ratio is clearly greater than that calculated. The theory is not valid for a compression acting at an angle greater than 45^0. This agrees with the use made in practice of allowing higher stresses for compression than for tension, since the resistance of the weld to compression is greater; this is valid not only for butt welds but also for fillet welds. The compressed welds XIII are very strong; in fact, for a penetration of 0.2 mm the stress measured is already 1.27 times greater than the breaking stress in tension of the deposited metal. In practice the resistance of a joint such as that of specimens XII and XIII will still be much greater because the penetration of the deposited metal in the gap will not be hindered by the introduction of copper plates as was the case for the specimens. It will be important to make tests with welded specimens without preventing the penetration of the deposited metal into the gap which occurs in practice with the joints of columns in which the lower piece has not been properly machined, or for the attachment of girders to the column. (At Dresden some tests of this sort were made with a specimen of type XII, but we only know that the breaking stress[1] was more than 52.5 kg/mm^2.)

Setting aside with specimens XII, V and XIII in which the welds are submitted to compression at an angle of 72^0 or normally, specimens XV present the greatest deviation from the theory. The ratio of the measured breaking stress to the breaking stress of the deposited metal is equal to 0.74, although it should be equal to 0.58 according to the theory. The specimens are therefore $\frac{0.74}{0.58} = 1.24$ times too strong. They have lateral welds subjected to shear and they differ from specimens XIV in that the welded parts are submitted to compression and not to tension, in consequence the welds elongate instead of contracting. The tests of *Vogel* and of *Mac Gibbon* demonstrate that lateral welds between compressed pieces offer greater resistance to compression than to tension. This is explained by the fact that the welds are shortened during cooling, if they are not prevented by the pieces to be joined. The weld is thus subjected before the test to a tension stress, which diminishes when the specimen is submitted to tests of compression. This is not conform to the theory of plasticity, according to which temperature stresses should not have any influence on the resistance to breaking.

The greatest deviations from the theory are found with specimens VIII and VII. The strength in these cases is $\frac{1.07}{0.91} = 1.19$ and $\frac{1.19}{1.00} = 1.19$ respectively, which is more than calculated. The deviation of the remaining specimens I, II, IX, VI, X and XIV amounts up to 10 % between measured rupture stress and the calculated stress from the tensile strength of the weld metal. With one exception (IX) the measured stress was higher.

In general it can be said that the measured rupture stresses are somewhat higher than those derived by calculation from the rupture stress of standard test bars made of weld metal. This applies to both fillet welds and butt welds. The rupture stress varies in the same way as the angle varies under which the force is acting on the smallest section of the weld. A fillet weld of the type VII, if stressed normally, is of great strength.

Conclusions.

From the preceding, we can draw the following conclusions concerning the calculations for welded joints of framework submitted to a statical live load.

1) It is not correct to calculate all fillet welds with the same low permissible stress as prescribed in the German standards "DIN 4100" and the Code for fusion welding and gas cutting in Building Construction.

2) The standards should prescribe the same permissible stresses for fillet welds and for butt welds; the value of these permissible stresses should depend upon the angle formed by the force and the smallest section of the weld.

[1] By breaking stress is understood the total force acting on the joint divided by the sum of the least sections of the weld.

3) The theory of constant deformation energy gives in an exact manner the ratio existing between normal ultimate tension and oblique ultimate tension; welds submitted to compression, normally or inclined at an angle greater than 45^0 are much more resistant than the calculations of ultimate tension show.

4) We have made the two following hypotheses:

a) The failure of a fillet weld occurs at the smallest section (CD Fig. 1).

b) In the hyperstatic structures the direction of the force is according to the theory of plasticity, as favocurable as equilibrium permits.

These two hypotheses furnish practically well applicable results.

Summary.

The author starts his report with the theory of application of welded connections. Afterwards a number of tests are described which are compared with the result of other tests, and by this the validity of the theory of constant deformation energy is proved for this field of engineering.

IIIc 2

Testing Methods in Workshop and ad Site.

Prüfungsmethoden im Werk und auf der Baustelle.

Méthodes d'essai à l'atelier et sur le chantier.

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The mechanical testing laboratory attached to the welding shop of the Penhoët Dockyard has not been established for the purpose of carrying out theoretical researches on welding by fusion but to provide for scientific control, as methodical and as uniform as possible, over jobs of all kinds carried out in this workshop.

The great majority of these jobs are done by arc welding, and this report will have reference to that particular kind of fusion welding alone. No mention will be made either of resistance welding or of spot welding — despite the great interest offered by these methods in steel construction — nor of fusion welding with the burner, the application of which is still limited in this shipyard.

The shipyard in question is well enough known from the fact that it has produced the liner "Normandie", and no more need be said than that it is continually turning out hulls for ships, steam engines, internal combustion engines, marine and land boilers: an enumeration which will suffice to indicate the number and variety of the applications that arise there for arc welding, a process which is tending more and more to replace riveting in the assembly of plates and rolled sections, and also castings in the case of certain parts of machines.

This last mentioned application will not be considered here, but only the question of welded joints in steel structures.

The adoption of arc welding in place of riveting has not altered the conditions that require to be fulfilled by a joint in a metallic construction to ensure its stability under load: success remains dependent on combining sound design of the members and of the joints with a suitable choice of materials and with sound execution. Of these factors the design is a purely technical matter, and reference will be made here only to the choice of materials and to the method of execution.

It was for the study of these two questions that the installation of a laboratory for mechanical testing was felt to be justified, and it is proposed here to explain the method of control adopted by us and the results of the experience which we have been able to draw from it.

1) *The parent metal:*

In a welded joint a distinction is drawn between the parent metal and the weld metal. We shall begin by discussing the first of these. Considerations relative to welding do not determine the choice of the mechanical properties which it must posses, but they do determine its chemical composition, for the influence of the latter on the qualities of the weld and even on the possibility of making a weld is indisputable.

There are, in fact, weldable steels and non-weldable steels: nor is it sufficient to leave the matter there, for the significance of this statement has to be defined and some method of testing established which will allow of a given steel being classified under one or other of these two heads. What, then, is a weldable steel? Before attempting to answer this question it should be remembered that in every weld there are three distinct zones: at the centre the weld metal, at the edges the parent metal, and between the two a zone of limited extent which is known as the contact zone.

These three zones differ in origin and as regards thermal treatment. The weld metal is derived from the electrode, and to some extent from the covering of the latter; it is obtained by complete fusion at a more less high temperature and subsequent rapid cooling.

The contact zone is formed by a more or less intimate mixture of the electrode metal with the parent metal, the temperature for the contact zone during the welding operation lying between that of the central zone and that in which fusion of the weld-metal begins.

Finally, in the neighbourhood of the contact zone, the parent metal at the moment of welding has been brought to a high temperature (though lower than the temperature of fusion) and has subsequently been cooled down more or less rapidly to air temperature. The thermal treatment which it has thus undergone has to a certain extent altered its mechanical qualities.

These facts are well known and there is no need here to enter into details regarding them. They have been treated in a very thorough lecture by *M. Portevin* at the University of Lille on 23rd February, 1933, leading up to the proposal that weldability might be defined as "the aptitude of metals, to form, when worked in accordance with the rules established by welding technique, a compact and continuous connection free from physical defects and as homogeneous as possible, thus securing uniformity in those properties which are necessary for the purpose to which the welded member is to be put".

This definition as a whole may be accepted, though subject to some reservations of detail which there is no need to go into here. The question arises as to how it can be applied to the actual study of weldability of a steel. Theoretically each of the three parts of the weld — namely the weld metal, the parent metal in the heated zone and in the contact zone — ought to be isolated, and the physical and mechanical properties of each determined with a view to comparing them with those of the parent metal in its original state. As regards the weld metal this would occasion no difficulty: specimens of normal dimensions may be taken from it, and may be tested by ordinary methods in the usual machines.

The case is different, however, in regard to the heated zone and the contact zone. These two zones, especially the contact zone, occupy a very small width in the direction transverse to the weld, and they do not lend themselves to the extraction of normal types of specimens apart from those used for notching action. Hence the observation of *M. Portevin* in the course of the lecture cited above: "The methods of testing to be adopted ought necessarily to be as localised as possible. They might, with advantage, be carried out on very small specimens using machines specially designed for the purpose."

Machines conforming to this criterion were made the subject of a paper by *M. Pierre Chenevard* before the *Académie des Sciences* on 30th January, 1935. (*Technique Moderne* of 1st May and 1st June, 1935.) But while researches of this kind may be feasible in the laboratory of a metallurgical works where it is a question of perfecting the formula and the method of preparation of some new steel, they will scarcely meet the needs of the industrialist who has neither the time nor the necessary equipment and who only requires to know, without great expenditure or loss of time, whether or not a steel which he proposes to use is in practice weldable: that is to say whether there exist on the market any electrodes wherewith that steel, if adopted as a parent metal, can be made into joints that are practically homogeneous.

Expressed in this way, the problem would appear to admit of a single solution such as the Author had occasion to apply several years ago in connection with welding work on the steamship "Paris".

The method consists of simultaneously examining the heated zone and the contact zone in a specimen prepared as follows: An ordinary tensile test specimen of rectangular section is cut from the original parent metal (Fig. 1). On this specimen, by means of the electrode which it is proposed to use, a longitudinal weld is deposited symmetrically over the axis of the specimen and entirely covering the latter. The deposited metal is subsequently milled away, leaving a specimen which reproduces the molecular condition of the zones to be studied faithfully enough for all practical purposes. For this condition to be fulfilled the thickness of the specimen must be small, depending on the diameter of the electrodes which it is intended to use in the welding job; for an electrode of 3.8 mm diameter the thickness of the specimen is 10 mm.

The resulting specimen is tested in a machine of the ordinary type (in our own laboratory an Amsler 50-ton machine is used), and its limit of elasticity, breaking stress, elongation, and constriction are recorded.

A similar series of measurements has previously been taken on an identical specimen of the parent metal whereon no weld metal has been deposited, and a comparison between these two series of results makes it possible to form an opinion as to the homogeneity of the joint. The comparison is completed by a further test designed to show the elongation of the metal in the contact zone: for this purpose a folding test specimen is prepared, on one face of which a weld metal strip is deposited and is then removed by milling, whereupon the test is carried out with the face which has received the bead placed on the tension side. A comparison between the angle of folding attained before cracking occurs on this specimen, and in the corresponding specimen of the original metal, can then be taken as a basis for comparing the elongations.

Finally there is a third test, that of notching action. For this purpose we generally make use of a Mesnager specimen, arranging the weld strip (Fig. 3) on one of the longitudinal faces perpendicular to the notch. The strip is removed by milling as in the case of the tests described above, and one specimen is taken from the original metal for reference.

Undoubtedly this procedure yields less information than does the series of tests proposed by *M. Portevin,* and it can be objected that as regards the tensile test no distinction is drawn between the two zones: it does, however, enable a sufficient degree of discrimination to be exercised cheaply and rapidly, between weldable and non-weldable steels, and up to the present no difficulties have been experienced in its use.

Some examples of results attained will now be given.

All the tests about to be mentioned were carried out using the same type of electrode which will be designated by the reference E_1 and had previously yielded satisfactory results. The weld metal from this electrode had the following mechanical properties:

Modulus of elasticity 47.3 kg per sq. mm.
Breaking stress 59 kg per sq. mm.
Elongation 20 %.
ρ (Mesnager) 6.42.
$\alpha = 135^{0}$.

The specimens numbered 1 are those shown in Figures 1 to 3. The specimens numbered 2 are represented in Figures 4 to 6 and are welded from side to side. The reference marks A, B, C, etc. are applied to distinguish the various grades of steel examined.

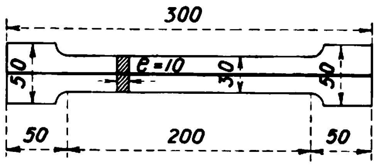

Fig. 1.

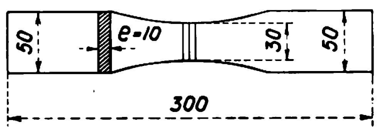

Fig. 4.

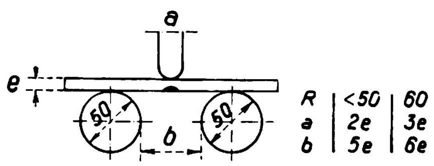

Fig. 2.

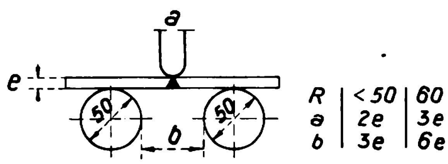

Fig. 5.

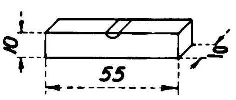

Fig. 3.

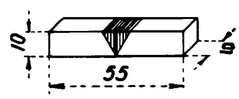

Fig. 6.

The steel mentioned last in the table is the best of the four steels tested, giving as it does a practically homogeneous connection with the deposited metal. The same is not true in reference to steels A and C, and it may be observed that the last is the only one of the steels which gives a value for the breaking stress lower in the heated zone than in the original metal. This is attributable to the fact that the increased strength of the original metal has been obtained by cold-working in the rolling process and the effect of this cold-working has disappeared in consequence of heating so that strength was again lost.

This point need not be further dealt with here. The tests of which some results have just been mentioned enabled us to make a choice between the various compositions of steel offered for use in a very special application, namely, a semi-rustless steel of high strength for the keel of a steamship.

Characteristics (1)		Parent metal (2)	Specimens No. 1 (3)	Ratio (3)/(2) (4)	Specimens No. 2 (5)
Steel A					
Tension	E = modulus of elasticity	35.9	46.2	1.29	
	R = breaking stress	62.4	64.6	1.04	55.3
	A = elongation	24 %	7 %	0.29	
	R+2A	110	79	0.72	
	Reduction of section	64 %	32 %	0.50	
Folding	First crack	180°	62°	0.35	
	Breakage	—	69°	—	
Resilience:	Mesnager	7,4	3.1	0.42	6.6
Steel B					
Tension	E = modulus of elasticity	36.9	—	—	
	R = breaking stress	54.7	57	1.04	52.7
	A = elongation	25 %	16.4	0.64	
	R+2A	105	90	0.86	
	Reduction of section	56 %	31 %	0.55	
Folding	First crack	—	—	—	
	Breakage	180°	147°	0.82	
Resilience	Mesnager	21.6	9.1	0.42	
	U. F.	10.9	7.9		5.5
Steel C					
Tension	E = modulus of elasticity	42.1	48.6	1.16	37.9
	R = breaking stress	68.2	56.8	0.83	50.7
	A = elongation	25 %	3 %	0.12	
	R+2A	118	63	0.53	
	Reduction of section	54	8 %	0.15	
Folding		180°	39°	0.22	
Resilience		6.8	0.9	0.13	6.9
Steel D					
Tension	E = modulus of elasticity	34.6	33	0.96	No results
	R = breaking stress	54.5	59.5	1.09	
	A = elongation	23 %	17 %	0.74	
	R+2A	100	94	0.94	
	Reduction of section	52	33	0.64	
Folding		180°	107°	0.60	
Resilience:		7.8	7.5	0.97	

Marks and indications	Electrodes			Current		Loss of weight in g per kg of metal deposited		Time per kg of metal deposited		Elastic limit kg per sq. mm	Breaking stress kg per sq. mm	Elongation % on 50 mm	Angle at first crack	Angle folded without cracking	Resilience		Brinell number	Breaking stress of parent metal = kg per sq. mm
	Diameter mm	Weight g	Length cm	Amperes	Volts	Volatilisation	Total	Fusion	Total						Mesnager	U. F.		
E1 deposited metal	4	44	45	160	22	137	261			44.2	55.2	16.5	125°			7.2	142	
E1 edge to edge P	4	44	45	155	22	180	270	46m. 30s.	1h. 1m.		55·9		146°			6.6	142	55
E2 deposited metal	4	44	45	160	26	59	179			47.3	59.0	20.0				8.2	155	
E2 edge to edge P	4	44	45	150	26	109	227	44m. 6s.	1h. 37m.		59.7		120°			7.03		60
E5 deposited metal	4	39	40	147	19	185	330	1h. 17m.	2h. 30m.	32.0	40.0	15.6	16°		4		113	
E5 edge to edge P	4	39	40	130	22	93	222	1h. 8m.	2h 46m.		42.0		88°					
E5 edge to edge V	4	39	40	145	21	103	233	1h. 8m.	2h. 17m.		40.0							40
E5 edge to edge T	4	39	40	150	20	157	310	1h. 17m.	2h. 42m.		44.0							
E9 deposited metal	4	44	45	170	22	75	222			48.7	57.8	27.0			21.6	13.7	155	
E9 edge to edge P	4	44	45	170	22			48m. 30s.	1h. 27m.		61.6			180				
E9 edge to edge V	4	44	45	170	22						62.6							60
E9 edge to edge T	4	44	45	170	22						64.6							

2) *The weld metal.*

The study of the weld metal is nothing more nor less than that of the various qualities of electrodes. The number of these on the market is constantly increasing. Their makers, in offering them to the industry, emphasize the qualities they claim for their products, and it is well to verify these claims by means of personally conducted tests. We ourselves do so continually.

The tests which we apply cover not only the investigation of mechanical properties but also other data which may be less scientific, but are of interest from the economic standpoint. The tests in general include the following:

1) In regard to the deposited metal: —
   a) A tensile test on a cylindrical specimen.
   b) A notching-action test on a U. F. or Mesnager specimen according to the requirement of the customer for whom the welded work is intended. The testing machine used is a Charpy pendulum.
   c) A folding test.
   d) A measurement of the apparent density.
2) In regard to a butt welded joint: —
   a) A tensile test on a rectangular specimen (the elongation is not measured).
   b) A folding test.
3) In either case a note is made from actual practice of the speed of welding, and of the weight of electrode lost through volatilisation or in projection.

To serve as an example, a table is reproduced below giving a complete statement of the information obtained in regard to an electrode marked E_2.

As a general rule the results thus obtained are made known to the suppliers of the electrode so as to allow them to take note of the observations.

Thus in the case of electrode E_3 the general results obtained were the following.

Deposited metal:
Breaking stress 43 kg per sq. mm.
Modulus of elasticity 38 kg per sq. mm.
Elongation 48 %.
$\alpha = 18^0$, ρ (Mesnager) 11.1.
Test on the joint from side to side:
Breaking stress 47 kg per sq. mm.

Following upon a visit to our laboratory by the Director of the firm concerned, we were offered, a few months later, a new type of electrode E_4 which showed the following characteristics:

Deposited metal:
Breaking stress 48.7 kg per sq. mm.
Modulus of elasticity 40.1 kg per sq. mm.
Elongation 27.9 %.
ρ (Mesnager) 13.
Test on joint from side to side:
Breaking stress 52.5 kg per sq. mm.
$\alpha = 132^0$.

It will be seen that, concurrently with an increase in the breaking stress, the other qualities of the joint and especially its ductility have been appreciably increased. The joint made with free edges was formed on plates of 50 kg per sq. mm breaking stress, but this electrode is very suitable for use on steels of the present Veritas type having a maximum breaking stress of 48 kg per sq. mm, and it produces homogeneous joints in these steels.

Finally, it seems to us important to outline the progress attained in the course of a few years in the development of electrodes for arc welding, and for this purpose we give on page the results of the test carried out at different times on the supplies obtained from the same French manufacturer.

The electrodes E_6 are intended for the welding of a metal which has the following mechanical characteristics, and which has been accepted as weldable by means of these electrodes in the sense here attributed to that expression:

Breaking stress 60 kg per sq. mm.
Elongation 30 %.
ρ (U. F.) = 6.

The homogeneity of the joint, as measured by the agreement between the deposited metal and the parent metal, is as high as possible, and the weldability test has shown that this homogeneity is sufficient in the transition zones also. It may be accepted, therefore, that provided the execution is sound, welded joints carried out in this steel will give a full degree of security. From this rapid survey we may draw the conclusion that there now exists a range of types of electrodes with which it is possible to form homogeneous joints having a tensile strength of between 40 and 60 kg per sq. mm with elongations and coefficients of resilience comparable to those of the parent metal.

3) *Execution.*

a) *Personnel.* It remains to be explained how the supervision over the execution of the work may be organised in such a way that the security attained in the choice of materials is preserved throughout the completion of the job.

The main objection which has been raised to the generalised use of fusion welding is the contention that the quality of the weld depends essentially on the skill and conscientiousness of the welder: however great the care with which the engineer may have studied the design of the joints, whatever the researches that may have been carried out to ensure a suitable choice of materials and a homogeneous joint, all these precautions will be useless if the weld is badly made; hence in the absence of any practical means of distinguishing afterwards between good and bad execution, the supposed security must be illusory.

It may be remarked, first of all, that this alleged impossibility of checking the quality of workmanship in the finished job is not peculiar to arc welding. It also applies to reinforced concrete, and when accidents occur in structures so made they are not infrequently attributed to faulty workmanship.

Some years ago, it is true, doubts of the most serious kind might justifiably have been entertained regarding the skill in their trade of the workmen who described themselves as arc welders. But to-day this is no longer the case. In every country there are now many welding schools, most of which are the result of private initiative — which in our opinion is an excellent thing, for the art of arc welding is far from having reached the end of its evolution. It is being transformed and perfected from year to year, and nothing could be more injurious from this point of view than that it should be placed under administrative tutelage. So far as welding is concerned we advocate liberty of instruction, and we are opposed to the idea of instituting diplomas of more or less official character which would be granted to workmen as an attestation of the fact that they have passed through a school.

Skill in any trade, and perhaps especially so in welding, diminishes and finally disappears if not maintained by practice. Diplomas, therefore, can only be of value for a limited period of time, and their introduction would be useless, since it would not eliminate the need for periodical tests which we regard as indispensable in any case.

Our own welding school was established in 1930. The workmen who pass through it have to carry out butt welded and cruciform joints in the three principal positions, namely horizontal, vertical and overhead. Tensile test specimens are taken from the welded pieces, and the results obtained from these serve as a means of classifying the workmen. Those who have not achieved a certain minimum of proficiency on work in any given position are not permitted to weld in that position. This provision applies particularly to overhead welding, — in respect of which it may be remarked, by the way, that certain regulations show an exaggerated distrust, for it is a fact that two-thirds of our own welders are capable of making overhead joints which give results equivalent to those obtained in horizontal welds, and that such joints are constantly being made without any difficulty in ships under construction. The reduction in permissible stress imposed in the case of overhead welds is unjustified, and it would be enough simply to enforce a rule that this type of weld should be carried out only by those welding workmen who have been proved by qualification tests to be able to execute it correctly.

The minimum value of breaking stress accepted for classification was originally 35 kg per sq. mm in the butt test, and 28 kg per sq. mm in the cruciform test. Following upon improvements in the quality of the electrodes the minimum has been increased, and with the electrode E_6 and steel plates of 50 kg per sq. mm breaking stress it is now 46 kg per sq. mm in the butt test, and 33 kg per sq. mm for the cruciform test.

The period spent in the welding school varies between six weeks and two months. It would of course be absurd to pretend that this relatively short period of time is sufficient for the complete training of a welder: he must continue to improve his skill during the first few months of practice in his new trade. It might be said that from being an apprentice he has now become a journeyman, but is not yet a master.

It would, therefore, appear to be a matter of elementary prudence not to entrust him at the beginning of his career with any such jobs as might affect the safety of the finished work, and on the other hand to follow his progress — which may possibly be negative — by means of supervision tests carried out at fairly frequent intervals. The principle which we adopted at first was to repeat the classification tests at intervals of three months during the first year, but experience has shown the propriety of adopting a slightly longer interval, and now these tests take place every four months.

At the end of a year the workman who has maintained his skill in the trade without any lapse is capable of inspiring confidence, and he is entrusted with jobs of an importance corresponding to his classification. We continue, however, to repeat the efficiency tests, but the period between them simply being increased to six months.

In this way the men are kept keyed up to their job and a useful spirit of emulation is encouraged both among the workmen and among their employers. The following table is given for information regarding the successive tests of workmen trained in our school.

Breaking stress in butt-welded joints.

Classifikation N°:		38.022	38.027	38.049	38.050	38.098
Passing-out tests	H	39.4	41.1	49.9	48.9	38.0
	V	34.8	35.7	45.8	45.5	31.4
	O	36.4	35.7	43.0	45.8	20.5
1st 3-monthly test	H	47.9	42.0	49.9	44.5	39.4
	V	39.1	38.1	45.3	45.3	41.9
	O	40.6	30.9	39.5	40.9	39.0
2nd 6-monthly test	H	44.1	37.2	46.5	44.6	41.1
	V	38.6	40.8	40.8	42.2	45.9
	O	34.7	35.2	31.1	45.6	44.2
3rd 3-monthly test	H	44.4	43.5	47.6	45.7	45.4
	V	43.5	42.3	42.6	41.2	42.3
	O	43.8	36.1	47.2	42.0	47.6
1st 6-monthly test	H	45.6	40.7	48.7	46.9	46.6
	V	41.6	43.3	44.8	44.1	43.5
	O	45.6	42.4	44.2	44.0	41.2
2nd 6-monthly test	H	47.1	41.8	45.6	49.1	41.8
	V	40.2	42.8	44.8	44.6	42.1
	O	45.3	38.0	46.0	44.4	41.8

All these tests are carried out with the same electrodes, which give a weld metal having a minimum breaking stress of 40 kg per sq. mm, and the plates used are of the ordinary quality. Since about a year ago electrodes which give a weld metal of greater breaking stress than this value and plates guaranteed to be of corresponding quality, have been introduced.

The latest of the tests under these conditions made by the welders referred to above give the following results.

H	55.3	64.9	58.4	62.9	54.3	
V	55.8	73.0	57.0	57.3	46.5	
O	59.8	70.0	57.9	63.2	59.1	
Parent metal	50	60	50	60	50	kg per sq. mm.

It will be seen on examining the figures in this table that after a welder in the school can carry out horizontal joints properly it takes him as a rule a year's practice, before he can bê counted on to make satisfactory vertical and overhead joints.

Periodical tests such as we have insisted upon since the beginning of our school are likewise shown to be of capital importance from the point of view of safety. There can be no doubt that these entail an increase in the general charges of the workshop, but they are looked upon as an insurance against accidents of the kind that might result from defective welds, and it is our opinion that no employer ought to be permitted to undertake welding work of nature involving public safety unless he can show that a similar organisation to this has been in existence for at least a year. Spicifications which require only individual tests at the beginning of the work do not afford a sufficient guarantee.

b) *Material.*

We have just discussed how a welding personnel with aptitude for very varied jobs may be formed and maintained. In order that such a personnel may be able to apply to the fullest advantage its skill in its trade, it must have at its disposal a suitable equipment, and the fundamental part of that equipment is an assured supply of current for welding. It would be beyond the scope of the present study to discuss here the various methods whereby the distribution of this may be arranged and the conditions which ought to be complied with to ensure correct welding; it is proposed merely to recall that one of the most important of these conditions is good regulation of the amperage of the current. In the author's opinion it is essential that each welder should have for his use an ammeter in series with the electrode. The indication given by this ammeter will serve not only to enable the workman to select an amperage conforming to his instructions, but will also make it possible for the foreman to check easily and quickly whether each of the welders is operating in conformity with those instructions. It will so provide direct and permanent supervision over the proper execution of the work, and will supply the second of the rejoinders that can be put forward in answer to the objection raised against the generalisation of arc welding in metallic construction: not only are welding workmen selected by a system without parallel in any other trade, but one of the most important elements in its success — the manner of performance — is supervised throughout.

We make use of two methods of current distribution. In one of these each welder has at his disposal a transformer set which is supplied with energy from a 440 volt circuit carrying low-tension current suitable for welding. We have made it a point that each of these transformers should be equipped not only with the ammeter mentioned above, but also with a voltmeter. The latter cannot, of course, be consulted by the welder, but it furnishes the foreman with a very useful indication on the conduct of the work.

In the second method of distribution there is provided, in respect of a zone which covers three construction bays and two floating welding sets, a low-tension network which is fed from a central station transforming the current of the sector from alternating at 5000 volts to continuous current at 45 volts. The sections of this network have been calculated to ensure a minimum tension of

35 volts. Each workman can insert a special current-taking device, known as a regulator, at any point in the network; this regulator contains resistances which can be used not only to regulate the amperage and source of the current but also to furnish an extra tension of 20 to 25 volts at the moment of striking the arc or of the almost instantaneous short circuits which arise in welding and are revealed by oscillograms of the welding current. Stability of the arc is thus perfectly ensured. An ammeter is placed on each regulator, but there is no voltmeter because the regulator is connected to only one pole and the return circuit runs direct from the welding work to the fixed main.

The results obtained with this method of distribution (which was described in an article published in the journal *"La Technique Moderne"* of 1st June 1932) proved so satisfactory that a new central station has been set up to serve another part of our shipyard and was brought into operation in 1935.

4) *Tests on Welded Joints:*

It would have been of interest to show, by giving numerical results of the tests carried out on welded constructions, that the methods described in these pages do in fact afford the security which is their object, but hitherto the application of these methods has been confined almost entirely to the hulls of ships, a form of work not susceptible to positive performance tests, since, in the absence of deformation or local breakages, it is only after some period of service under more or less unfavourable conditions of navigation that the value of the work can be judged.

We must, therefore, confine ourselves to recalling the fact that about a year ago the trials carried out on the cruiser *"Emile Bertin"* were reported in the press. This ship was delivered to the French Navy from our yard, and in her construction a great deal of welding work had been done. Some of these trials were made in very heavy seas, but none of the welded joints showed any signs of fatigue or of leakage. An examination of the hull of the *"Emile Bertin"* at the end of six months' winter navigation in the Atlantic yielded the same favourable record.

On the "Normandie" a large number of welded joints were made and at one time the number of welders at work on board this ship totalled 140. Their work, however, was not concerned with the vital parts of the ship, and moreover the "Normandie" has been placed in service too recently to allow of any conclusions being drawn.

In these circumstances the author may be allowed to make some observations on his experience regarding the arc welding of mechanical parts, even though this is a class of work outside the direct scope of the Congress. It was concerned with the butt welding of thick plates: a type of work which may occur in framed steel structures, as for instance in the bearing plates of bridges.

The first case which will be mentioned is that of an engine base formed of two plates 20 mm thick, having a breaking stress of 60 kg per sq. mm. The plate was in a horizontal position and could not be turned over during the course of the work. Its thickness was such as to make an "X" joint suitable. The necessity arose of forming half the seam horizontally from above the plate, and half of it from underneath by overhead welding.

This was done in the following way: the two plates to be joined together were bevelled on both faces at an angle of 60°, and were then arranged parallel to one another with a gap of 5 mm between the bottom of the bevelling. A copper rod of 10 mm diameter was placed in the lower bevel and a first weld was made horizontally. The electrode used for this purpose was one with a diameter of 6.4 mm, and was of the type designated above as E_6, with heavy covering. In view of these circumstances the positive pole was connected to the electrode, and the negative pole to the work, reversing the usual practice. When weld N° 1 had been made the weld-metal was hammered from underneath to eliminate any irregularities and surface defects due to contact with air during the deposition (in spite of the presence of the copper wire), and a symmetrical weld N° 2 was then made by overhead welding from underneath along the whole of the joint.

The remaining welds were then carried out both above and below the plate by two welders working simultaneously, their progress bein so regulated that they always kept in practically the same vertical plane. The metal was deposited by waving the electrode from right to left and from left to right so as to obtain a stratification perpendicular to the axis of the joint instead of parallel to the joint, and in this way the effect of contraction was considerably reduced.

The weld was tested after completion by two methods. In the first place the wastage left on each side of the joint was welded in the same way and at the same time as the joint itself, and specimens for the ordinary tests were taken therefrom. The mechanical tests carried out on these specimens gave the following results:

Breaking stress 61.5 kg per sq. mm.
Angle of folding without cracking 118°.[1]
ρ (U. F.) = 7.6.

Secondly, an examination of the weld itself by X-rays was made along its whole length with the object of detecting, and if necessary of eliminating, any local defects. The apparatus which we possess for radiographical tests is that made by Phyllips. It enables a tension of 180 KV to be obtained between anode and cathode, and gives satisfactory radiographs through a thickness of up to 90 mm of steel. One of the positives obtained in the study of the plate in question is reproduced here. The white circles which may be seen in this reproduction serve as reference marks for re-applying the radiograph onto the plate and identifying the position of any defect. It will be noticed that in order to fix this position in space it is necessary to have two radiographs obtained by pencils of rays along different axes.

The second example which will be given is that of a weld made from side to side on plates appreciably thicker than those referred to above, with the following mechanical characteristics.

Breaking stress 27.8 kg per sq. mm.
Elongation 49.6 %.
ρ (Mesnager) = 14.

[1] The test was discontinued when the elongation on the tension fibre had reached the minimum fixed by the specification.

The thickness was up to 55 mm. Plates of this thickness would probably not be used in a framed structure, but the observations which follow may also be of interest in reference to thinner plates, such, for instance, of from 25 to 30 mm.

Before the execution of the welds was actually undertaken, experimental studies were carried out on pieces cut from the plates. These measured 600×300 mm and were welded from side to side.

In view of the thickness, the section of bevelling adopted was that of two U's connected at the base (Fig. 7). The electrode used was the same as in the preceding case. The succession of runs and the amperage and tension of the current were regulated at the beginning according to the following table.

Diameter of electrodes	Sequence of runs	Amperes	Volts
3.25	1	80	24—26
4	2, 3, 4, 5	180	24—26
5	6 to 17	230—240	20—24
6.4	18 to 29	320—350	20—24

Before starting the first run a band of copper was placed in the lower half of the joint. All the runs were made horizontally, the piece being turned over each time as required. Between weld N° 3 and weld N° 4 chiselling was performed on N° 1 so to clean the surface of the latter, which, notwithstanding the presence of the copper, had been executed in contact with the air. In this way weld N° 4 was begun only on a perfectly clean surface.

In spite of this precaution, a comparison of the mechanical tests carried out on specimens taken from the surface of the joint with those on specimens taken from the middle portion (and, therefore, containing run N° 1) showed appre-

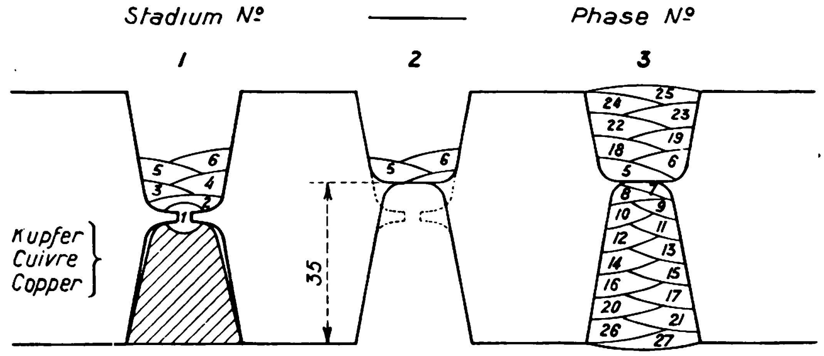

Fig. 7.

ciable differences in ductility as between the surface and the middle of the weld. A slightly different procedure was therefore adopted:

Runs N^{os} 1 to 6 (inclusive) were carried out without previous chiselling; and all the metal belonging to runs 1 and 4 was then removed, including the parent metal in the neighbourhood of the constricted portion as shown in the sketch. (Fig. 7.) The deposition of the runs from N° 7 onwards followed, and the work then underwent an annealing operation at 640° C for two hours and fifteen minutes (being one hour for each 25 mm of thickness).

Geschweisste Versuchsplatte. Types de tôles soudées Specimen of welded plates

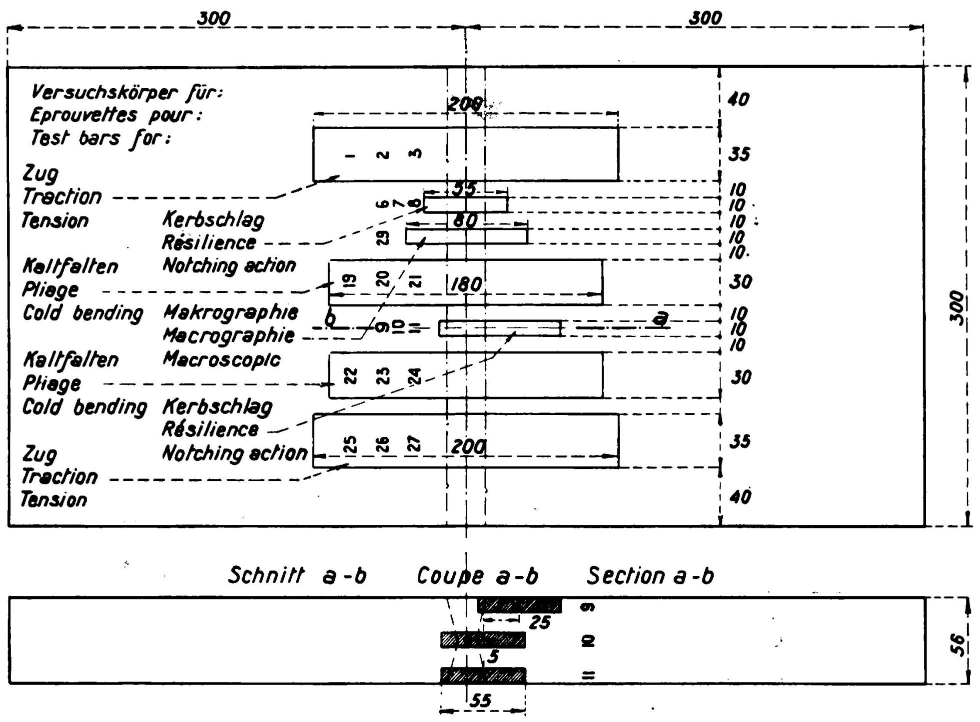

Fig. 8.

Subsequently tensile and resilience specimens were cut out, some from the surface of the piece, others from the middle of its thickness. Fig. 8 shows the distribution of these various specimens. The method gave completely satisfying results as shown in the following table.

Tension						Folding			Resilience		
Mark	Dimensions of specimens in mm	Section sq. mm	Breaking stress total	Breaking stress per sq. mm	Breaking stress average	Mark	Angle of folding	% elongation on extreme fibre in 20 mm length	Mark	ρ Mesnager	Average
1	19.8 × 13.6	270	12800	47.4	47.9				7 F_1	15.4	14.4
									7 F_2	12.4	
3	18.6 × 13.6	254	12100	47.6		20	130°	38	7 F_3	15.4	
25	19.5 × 13.6	266	12800	48.1		23	107°	36	7 F_4	14	14
									7 F_5	14	
27	19.8 × 13.7	272	13300	48.8					7 F_6	14	

Examination with X-rays did not reveal any appreciable defect. A reproduction is given of one of the radiographs taken in the course of these tests.

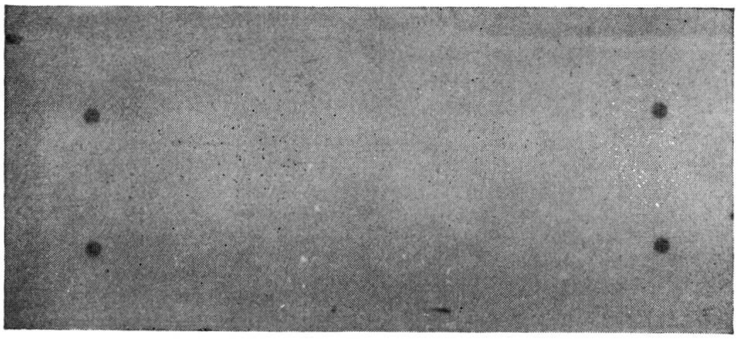

Fig. 9.

X-ray photograph of a butt weld joining two 20 mm plates (pp. 25—27).

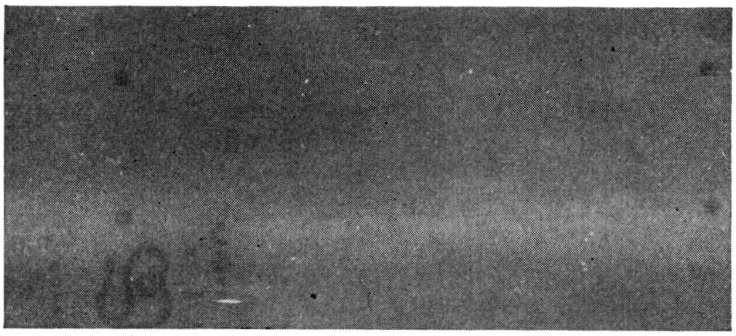

Fig. 10.

X-ray photograph of a butt weld joining two 55 mm plates (pp. 27—31). In every case the weld lies between the longer sides of the rectangle outlined by the four black dots.

The verification stamp of the Veritas Bureau is shown in the lefthand bottom corner of the second X-ray plate.

The different shading of the two X-ray plates is due to the various thicknesses.

5) *Conclusions.*

Experience obtained in the application of arc welding to a great variety of jobs is held to justify the assertion that, given a good system of supervising the materials and the methods of execution, this method of jointing affords a degree of security equal to that obtained by other methods of construction such as riveting or reinforced concrete. One reservation must, however, be made: the tests hitherto carried out are confined to statical tests or impact tests, and they ought to be complemented by fatigue tests under variable loading. We have now added to our laboratory an Amsler pulsator which allows tests of this kind to be made, but so far have carried out only a limited number of them.

Radiographical examination can be used to some extent to supplement the fatigue test as it serves to reveal local defects such as air bubbles or enclosed impurities, which, while having only a small influence on the resistance to static loading, might be the cause of premature breakage under alternating loads. Its use is, therefore advisable whenever possible, but — especially in the case of structural steel work — is difficult to generalise. The apparatus required is relatively heavy and bulky, and elaborate precautions have to be taken to protect the operators from the effects of the secondary rays. Moreover, as a further consequence of these, there is apt to be a lack of definition in radiographs of pieces made up of different thicknesses of plate, and with these rays it is almost impossible to radiograph a connection of crossed pieces. This can be done by the use of γ rays, but the cost of installation and the dangers of these rays to the personnel render it at present impossible to apply them in industry.

It has not been deemed appropriate to refer here to the researches (not numerous) which we have made on the subject of contraction. The object of these was not to determine the residual stresses caused by contraction, but merely to record the changes in dimensions and shapes which contraction might cause in the members of the framework of a ship and to determine how such effects might be eliminated in advance. With this object in view, we have confined ourselves to recording the total deformations after complete cooling, and it is not possible, therefore, to evaluate the residual stresses with any certainty.

Summary.

It is easily possible to have a controlling station in every welding workshop in such a way as to establish a priori the necessary safety and guarantee. For certain cases the supervision can be complemented by X-ray investigations, although it seems that the X-ray method cannot be applied throughout.

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IIIc 3

Testing of Welds.

Prüfung der Schweißnähte.

Contrôle des soudures.

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The further progress attained in the testing of weld seams since the First International Congress of the International Association for Bridge and Structural Engineering has been marked by two main developments: the application of fatigue tests and the introduction of non-destructive methods of testing, especially the use of X-rays. An essential connection exists between these two developments.

A) Fatigue tests.

So far as statical tests are concerned — the tensile test, the folding test and the notching test — accepted principles and standards governing the shape and dimensions of the test bars and testing arrangements now exist in many countries, including Germany. As regards fatigue tests, however, conventions of this kind are still largely lacking. In Germany there is only DIN 4001, which, in the first place, standardises the nomenclature of fatigue testing, and in the second place defines the limiting alternating stress of steel as being that stress which the test bar will withstand during two million applications of load.

Apart from this standard there are the regulations of the Reichsbahn (German State Railways) for welded plateweb girders, in which certain alternating stress values are laid down for test bars of St 37 and St 52 of prescribed measurements and shape, both in the finished and in the unworked condition, applicable both to transverse and longitudinal welds. For instance, in the case of unworked transverse weld seams of Steel 37 or Steel 52, the prescribed alternating stress values are 15 and 16 kg/mm² respectively, while for tooled welds the corresponding values are 18 & 19 kg/mm². Whether these Railway regulations will be made into "DIN"-standards having general validity, has not yet been decided.

Other testing regulations in reference to fatigue tests are still in the preparatory stage.

It has been shown by experiments on fatigue tests that the strength values obtained from specimen welds under static loading cannot be taken as evidence of the fatigue strengths of the specimens, still less, therefore, of those of actual structures. Hence Thum, in his "Richtlinien für die konstruktive Durchbildung geschweißter Maschinenteile" (Principles for the design of welded machine parts) — not yet published — declares that high values of breaking strength, elongation and notching tenacity offer no guarantee of fatigue resistance, because the material is stressed in a different way under repeated alternating loading and under steady loading. Elsewhere *Bierett* (1)[1] observes that the "notching effects" are of much greater importance than the properties of the weld metal in determining the fatigue strength of a welded connection.

These statements are consistent with the fact that failure under repeated alternating stress always originates at the point where the concentration of stress is greatest. In other words, such defects as slag inclusions, imperfect roots, imperfect binding, bulges in transitions, pores, etc., which are of no great importance under static loading, become of decisive importance as regards the fatigue resistance of a welded connection.

The recognition of this fact disclosed an urgent need for some form of test that would allow the condition of the weld seam to be ascertained in the finished structure without causing damage.

In penetration by X-rays, a method which has been available for technical applications since about 1923, we have an expedient essentially well adapted for the non-destructive testing of welds.

B) The X-ray testing of weld seams.

1) General principles.

The general principles of X-ray penetration have repeatedly been described in engineering publications (2) and will, therefore, be taken as known.

2) Testing with the fluorescent screen.

The form of fluorescent screen now in use consists of a layer of zinc sulphide which becomes luminous to a greater or less extent according to the intensity of the X-rays impinging upon it. The experimental possibilities attainable by means of such a screen are, however, severely limited, because the fluorescence is not bright enough nor the definition sharp enough to allow of distinguishing slight differences in brightness; for instance, pores in a thickness of steel of 10 mm have to be at least 0.6 mm in diameter in order to be recognisable. This makes the detection of fine cracks and imperfect binding unreliable, so that the only suitable application of testing by means of the fluorescent screen is that which arises in the training of welders, whose work may be quickly examined by this means and bad flaws rendered visible immediately the welds are completed.

3) X-ray photographs on X-ray film, with or without intensifying screen.

The most promising means of examination is that offered by the use of double-coated X-ray film with or without an intensifying screen. Such screens consist of a calcium-tungstanate layer pressed on to each side of the X-ray film and rendered slightly luminous under the influence of the X-rays. Their use enables the period of exposure to be very considerably shortened, but at the same time there is some diminution in the sharpness of definition, and where the thickness of the material is slight, this notably impairs the quality of the

[1] See Bibliography.

picture. Experiments to determine the influence of intensifying screens on fault detecting power (4) have enabled suitable operating data to be obtained, which are reproduced in Fig. 1. These indicate that in order to secure maximum fault-detecting power thicknesses of steel up to 10 mm should be examined without such screens; those from 10 to 35 mm with sharply acting screens giving limited intensification; those above 35 mm with non-sharply acting screens giving high intensification.

The values of fault detecting power shown in Fig. 1 were measured by laying wires on the steel plate facing the side of the X-ray tube and photographing these together with the plate. Such values are not obtainable in the detection of

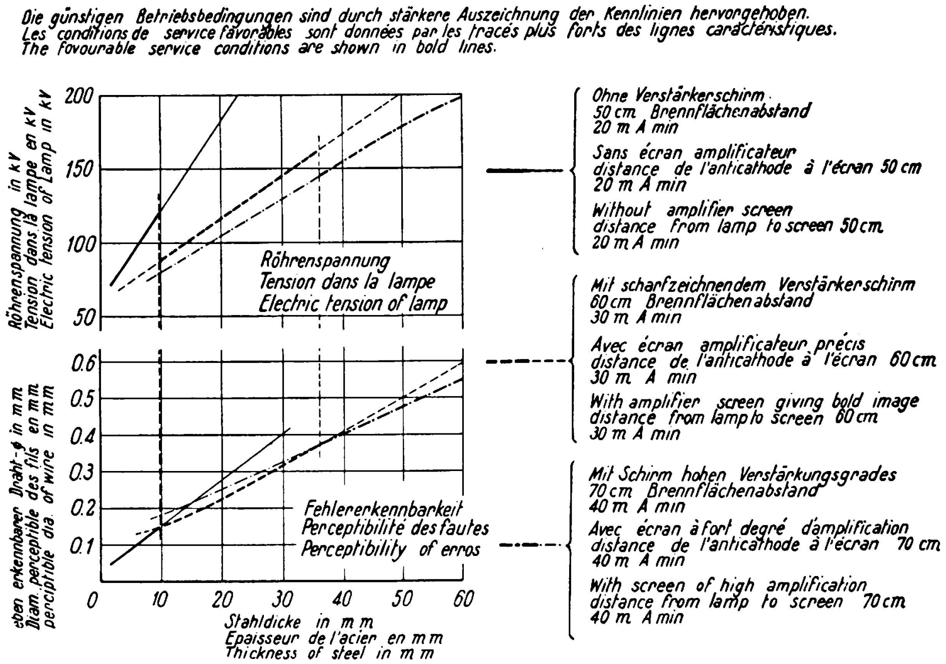


Fig. 1.

Practical data useful in X-raying steel.

cracks, because the dimensions of the activated surface in the X-ray tube are great enough to cause an overflow of radiation around the flaws, thus introducing penumbra and so reducing the contract of blackness on the film. In this way the detection of small cracks is subject to a limitation, especially where the X-rays do not happen to pass through such a crack in the direction of its greatest depth. Table 1 shows how the detectable width of crack is influenced by the angle between the X-rays and the direction of the crack:

Table I

Smallest width of crack detectable by means of X-rays, related to the angle between the direction of the crack and that of the rays. (Steel 40 mm thick; crack 6 mm deep.)

Angle, degrees	5	8	10	15	20	30	60	90
Width of crack, mm	0,03	0,06	0,09	0,13	0,16	0,21	0,32	0,40

A special difficulty arises in the examination of fillet welds in consequence of the varying thickness of metal presented in the direction of the rays. This difficulty can be overcome by placing a wedge of zinc over the fillet so that its varying thickness will counteract that of the cross section to be penetrated (5).

4) Standardisation.

When X-ray testing had so far developed that its use could be contemplated not only in scientific institutions but in the workshop, it became necessary to publish the "Code for the testing of weld seams with X-rays" *(Richtlinien für die Schweißnahtprüfung mit Röntgenstrahlen),* numbered DIN 1914 and prepared by the German Association for the Testing of Technical Materials *(Deutscher Verband für die Materialprüfungen der Technik)* together with the welding technical committee of the *Verein Deutscher Ingenieure.* The object of this publication is to enable all X-ray units to produce photographs of uniform quality which can be interpreted in the same way, so as to establish the basis for a regulated procedure in operating. Among other provisions it is directed that a specimen consisting of wires of different diameters is to be laid over the welded seam and exposed to the rays together with the latter; it is required that wires of specified diameters, depending on the thickness of the plate shall then be recognisable. Table II contains particulars of the set of specimens adopted in Germany and Fig. 2 shows the X-ray photograph obtained from these.

Table II

Sets of wires adopted for control over quality of X-ray photographs in accordance with DIN 1914. (Each set, consisting of seven wires, is embedded in rubber.)

Material to be tested	Thickness of Specimen mm	Material and designation of set of wires	Diameters of wires in mm	Designation of sets of wires: Lead balls under wires	Colour of Rubber Sheath
Light metals	0 to 50	Al I	0.1/0.2/0.3 . . 0.7	● ●	grey
	50 „ 100	Al II	0.8/1.0/1.2 . . 2.0	● ●●	
	100 „ 150	Al III	1.5/2.0/2.5 . . 4.5	●● ●●●	
Iron Alloys	0 to 50	Fe I	0.1/0.2/0.3 . . 0.7	●● ●	black
	50 „ 100	Fe II	0.8/1.0/1.2 . . 2.0	●● ●●	
	100 „ 150	Fe III	1.5/2.0/2.5 . . 4.5	●●● ●●●	
Copper Alloys	0 to 50	Cu I	0.1/0.2/0.3 . . 0.7	●●● ●	red
	50 „ 100	Cu II	0.8/1.0/1.2 . . 2.0	●●● ●●	
	100 „ 150	Cu III	1.5/2.0/2.5 . . 4.5	●●● ●●●	

It was decided not to adopt the form of specimen prescribed in the American Boyler Code — consisting of a steel plate having grooves of different depths, or of a filter scale with drilled holes, placed close to the weld — since this does not enable the fault detecting power in the region of the weld itself to be ascertained.

The German Code also includes a series of provisions as to direction of rays, procedure to be followed in photographing, and aids to the testing of different sections of welds.

Conjointly with the drafting of this Code, *new dimensions for X-ray films* have been standardised by the aforementioned German Association for the Testing of Technical Materials together with the German X-Ray Society. The sizes hitherto in use are based on medical requirements and are not suitable for the examination of welds, each user being compelled to cut them himself to

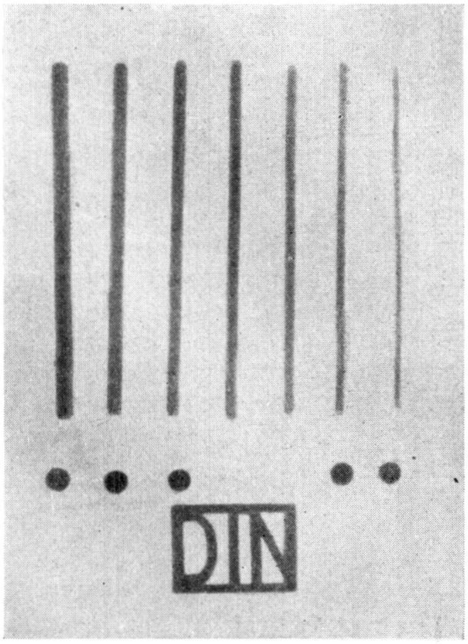


Fig. 2.
X-ray picture (positive) of wire screen Cu II.

sizes adapted to his needs. As a result of an agreement now reached between users of the process and makers of the films, intensifying sheets and boxes, the following film sizes have become commercially obtainable:

6 cm × 24 cm	10 cm × 24 cm
6 cm × 48 cm	10 cm × 48 cm
6 cm × 72 cm	10 cm × 72 cm

Regulations governing the construction of X-ray installations from the point of view of protection against danger from high intensity radiation have already been operative in Germany since 1929 and 1930 (DIN Rönt. 5 and 6); (6).

5) Technical equipment.

The form and nature of the technical equepment for X-ray testing has been decisively influenced by its being applied to large bridge or roof girders in the workshops, and still more by its application on the actual site of the job.

The characteristics required in modern X-ray apparatus for workshop use are: (a) safety from contact with high-tension conductors; (b) protection from the rays; (c) mobility of the X-ray tube container; and (d) portability of the constituent parts.

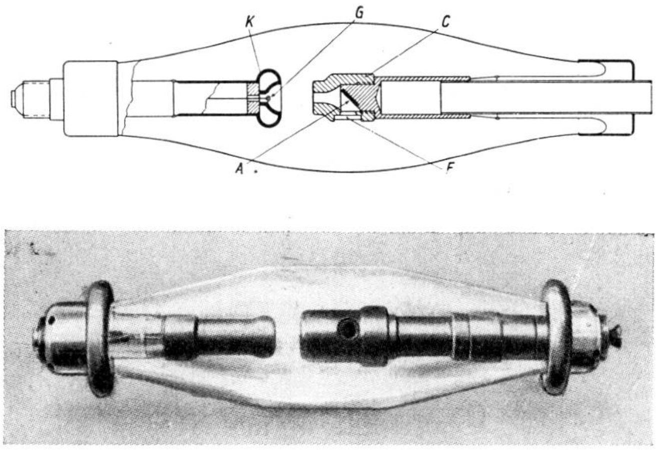
These requirements have finally been satisfied by the following measures, on which broad agreement has been reached between different manufacturers:

(a) All high-tension conductors are surrounded by earthed metal conductors.

(b) The only acceptable type of X-ray tube is that known as "protected ray" from which only a relatively narrow bundle of rays can be emitted (compare Fig. 3), the other rays which proceed in all directions from the radiating surface being screened by thick metal walls.

(c) Between the high tension generator and the X-ray tube there is interposed a high tension cable about 10 m in length, allowing the tube to be moved about and brought into its desired position independently, to a considerable degree, of the rest of the apparatus.

(d) To render the plant portable, high tension generators have been available since as early as 1932 in two symmetrical halves so that no constituent unit of a 200-KW plant exceeds 90 kg in weight. Sometimes, with a view to further reduction in weight, the necessary condensers are included within the high tension cable itself (Siemens & Halske A.G.).



(a)

(b)

Fig. 3.

Section (a) and View (b) of X-ray lamp for 200 kW oil tension.

A) Wolfram anode plate.
F) Beryllium aperture for exit of rays.
C) Copper-wolfram block.
G) Filament.
K) Cathode.

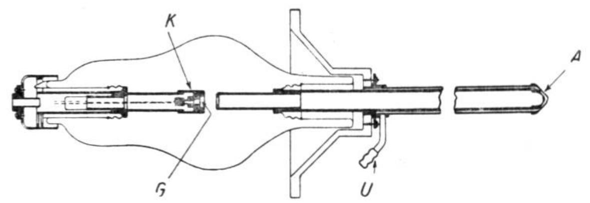
The practicability of X-ray installations built on these lines, in Germany, for use in workshops and on the site, is now attested by some three years of operating experience[2].

Furthermore, the construction of the X-ray tubes has been influenced to an especially notable extent by practical requirements. Relatively short tubes for 200 and 250-KW were made to operate under oil in order to reduce the lenght of insulation and thereby to save weight (Fig. 3). Tubes of this type, however, did not always enable an economical examination to be made — especially in

[2] The following are manufacturers of technical X-ray apparatus in Germany: C. H. F. Müller A. G., Hamburg, Koch & Sterzel A. G., Dresden, R. Seifert & Co., Hamburg, Siemens & Halske A. G., Berlin.

the case of circular welds on pipes and containers — and a new form of hollow-anode X-ray tube has recently been developed (by Siemens & Halske A.G.), in which the electrons reach the cone-shaped anode through a narrow channel held together by a collecting coil; they then undergo retardation within the tube, giving rise to X-rays which are thrown out in all directions through the walls of the tube. This offers further convenient possibilities for the examination of welds (Fig. 4).

The use of X-rays on the site of works also involved a need for new types of film boxes and containers. Following upon a suggestion made by the "Röntgenstelle" (Central X-Ray Office), rubber film boxes which admit of evacuation are now used in the testing of welds. These consist of rubber bags from which the air is withdrawn by a vacuum pump after inserting the intensifying sheet and film and sealing them up: in this way the external air pressure is made to hold the intensifying sheet uniformly against the film, while the box remains pliable in any direction.



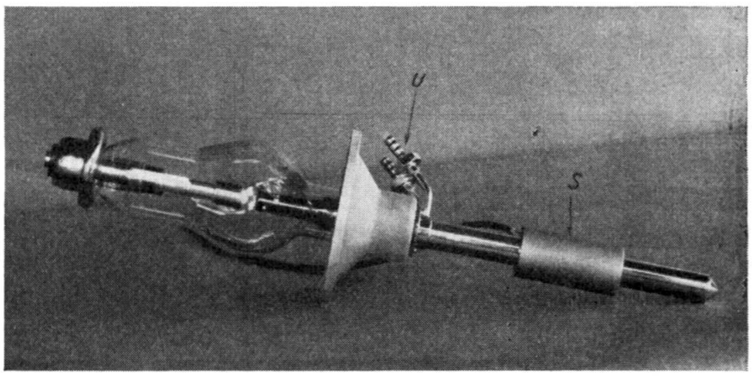


Fig. 4.

Section and View of hollow-anode lamp for testing materials.

A) Platined copper anode.
G) Filament.
K) Cathode
S) Collecting coil.
U) Circulatory cooling.

These light boxes are attached to the place of exposure by means of permanent magnets made from an iron-aluminium alloy.

6) Reading & interpretation of X-ray films.

Experience shows that X-ray films are more difficult to read than to produce. So complex are the influences exerted on the X-ray picture by the type and movement of the electrodes, the bevelling of the plates, and the direction of the rays, that frequently the significance of the picture can be ascertained only by comparing a number of exposures made on one and the same structure, assisted if possible by ordinary photographs of ground sections. Fig. 5, 6, 7 & 8 show some typical examples of practical experiments carried out by the "Röntgenstelle" on bridges and building frames. A collection of typical flaws

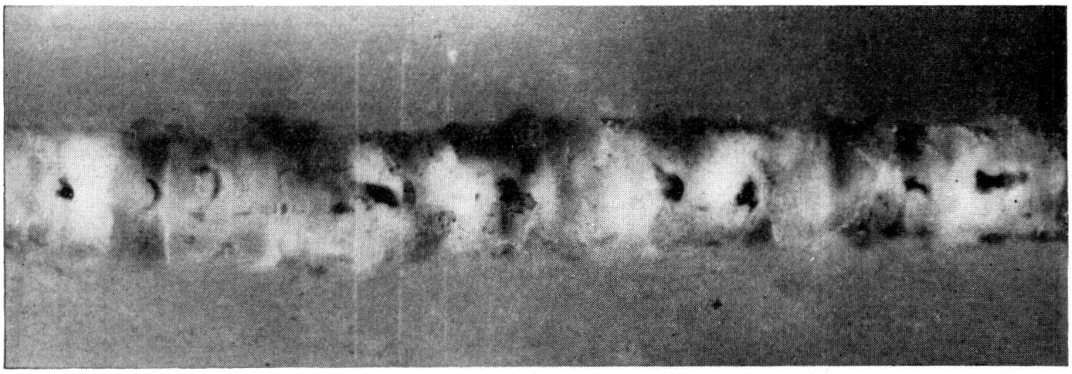


Fig. 5.
Electrically welded X-shaped seam (vertical welding) with coarse slag.

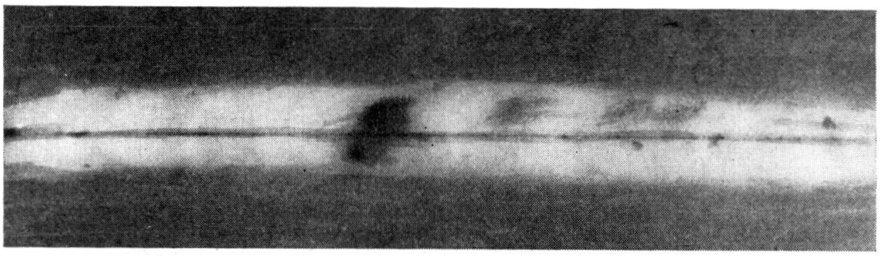


Fig. 6.
Electrically welded X-shaped seam (in web of welded steel superstructure) with not fully welded root.

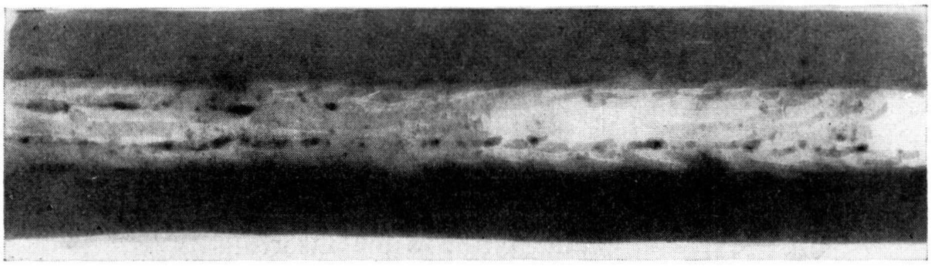


Fig. 7.
Electrically welded X-shaped seam (in web of welded steel superstructure) showing slag lines.

occurring in V, X-shaped and fillet welds has appeared in the journal "Der Stahlbau" (7).

What is most difficult of all, however, is to interpret the faults discovered by means of X-rays from the point of view of their effect on the mechanical properties of the welded connection. Investigations of this relationship have been undertaken in various quarters (8, 9) and Fig. 9 gives some typical examples

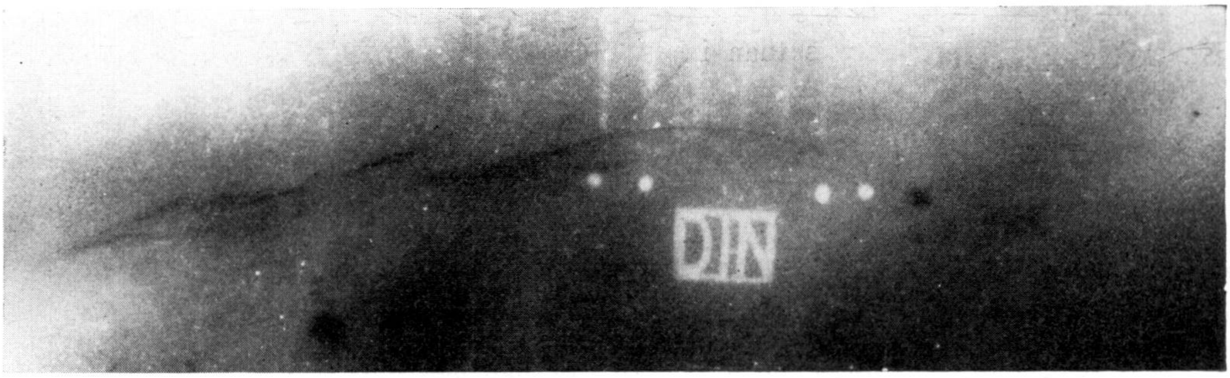


Fig. 8.
Electrically welded fillet seam (end plate joint) showing crack caused by thermal stresses.

of those made at the Röntgenstelle. The upshot of these researches, and of all others hitherto made, is as follows:

The fatigue resistance of welded connections is impaired to a notable extent by imperfect binding, cracks, slag inclusions and bad defects at the root of the weld. On the other hand, provided they do not form a continuous bead-chain, little or no influence is exerted by the presence of small or medium sized pores distributed haphazard.

Fig. 9.
X-ray photos of various types of weld joints, illustrating fatigue strength.

7) Scope of X-ray testing.

In accordance with a regulation of the German State Railways *(Reichsbahn)* dated 27[th] January 1936, the testing of weld seams by X-rays is required in all butt joints of the first category, and (recently) in some of the "neck seams" (joint between flange plate and web) of rolled joists and some of the fillet welds of cross stiffeners. At present some 300 m length of welds are being X-rayed every day in Germany as a result of this regulation.

In the case of structural steelwork there is no regulation as to X-ray testing, and here, for the most part, only purely statical stresses arise. Nevertheless in important industrial work such as welded roof frames, sub-structures for pressure containers, etc., X-ray examinations of the welds are now being carried out.

In structural steelwork subject to static loading the scrutiny of defects is of course much less rigorous than in the case of railway bridges, which have to stand alternating stresses.

8) Organisation of X-ray testing in Germany.

The experiments, described in Section 6), made for the purpose of correlating X-ray results with the mechanical properties of a weld, fall far short of producing a universal key to the endless variety of cases that call for interpretation — a variety which extends not only to the orientation, position, size and shape of the defects, but also to the nature of the materials and of the electrodes and to the nature, magnitude and direction of the stress. To produce so great a diversity of faults intentionally, with a view to their systematic comparison, is a practical impossibility. It is, therefore, impossible at present to lay down any directions for the interpretation of X-ray photographs such that rigid adherence to them will exclude all possibility of error.

This is the difficulty — but also the attraction — of non-destructive methods, which can yield only indirect indications regarding the effects associated with the faults they have been the means of ascertaining. Indeed, the final elimination of such faults calls for intuition grounded on experience — a process similar to medical diagnosis, for which neither textbooks nor collections of photographs are an effective substitute. This circumstance may not be liked by the engineer accustomed to calculation and unwilling to be reminded of the fact that all his precision rests on *assumptions* as to properties of materials, distribution and magnitude of stresses, whose foundation is no better.

In these circumstances the problem of making the X-ray process generally available without prejudice to technical development has been approached, in Germany, on original lines. With the concurrence of the General Inspector of the German road system and that of the supreme authority of the railways, nearly all X-ray photographs taken on welded steel bridges are submitted to the Röntgenstelle after preliminary examination by the appropriate executive officers. The interpretation put forward by the latter is checked by the Röntgenstelle whose conclusion they, in turn, receive back. The purview of the Röntgenstelle extends to the quality of the exposures, to their interpretations as put forward by the officers concerned, and, if necessary, to the causes of the welding defects and the possibility of remedying these. In this way there is a guarantee that all welds on steel bridges throughout Germany shall be scrutinised on uniform lines, and further that all the executives shall be trained to follow the same lines as the "Röntgenstelle". Moreover, such defects can be recognised rapidly if it happens that similar ones have already been encountered and overcome in another structure. Finally, it is found that the continuous supervision of the welders so obtained has an educative effect.

Work in the shops and on the site must not, of course, be exposed to any notable delay. In straightforward cases, therefore, decisions as to whether welds may be accepted or must be improved are reached by the field executives or by delegates from the "Röntgenstelle" on the spot right away. It is only in cases of doubt that a decision has to be obtained from the "Röntgenstelle" itself, which then also calls in a statical expert from the Government Materials Testing Station at Berlin-Dahlem.

The "Röntgenstelle" is equipped for this task with several mobile X-ray laboratories stationed at different points in the Reich. An extensive stock of experience gathered from all these places is thus being capitalised for the interpretation of X-ray films.

Fig. 10 shows one of the mobile X-ray sets and its application at the site.

One indication of the results achieved through this organisation is the fact that the rate of occurrence of queries regarding welded connections was reduced, within three months, to a tenth of its original magnitude.

Fig. 10.
X-ray examination of a welded steel superstructure.

C) Magnetic testing of welded connections.

The processes of non-destructive testing which make use of the disturbances arising in magnetic fields in the presence of flaws, and of the detection of these either by means of vibrating coils or by means of magnetic powder, have not yet been developed to a sufficiently wide scale to allow of critical discussion. It appears likely that the "magnetic tuning method" (the I. G. weld tester produced by the A. E. G.) will be applicable to oxy-acetylene welded connections up to a maximum thickness of 20 mm. The magnetic powder method is also likely to come into use for such welds on thin sheets, but these occur more frequently in the construction of aircraft than in that of bridges and structural work; whether the magnetic powder method will also achieve some significance in the latter should become apparent before long.

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Summary.

The general introduction of fatigue strength tests into the technical-mechanical testing methods of welding showed the great effects of notches and the consequent influence of flaws which show up but little under purely static stressing. To guarantee the quality of welded construction it became necessary to develop such testing methods as do not lead to destruction if flows were to be properly detected. For this purpose the X-ray testing method has proved most successful, since it is physically and technically a fully developed method, which makes it possible in practically all cases to arrive at proper results without incurring excessive costs. Today the technical development of apparatus and auxiliary equipment permits the application of the X-ray methods at site as well as in workshop. The procedure to be adopted for X-ray tests is controlled in Germany by governmental directions which aim at a uniform quality of the photographs obtained by all those applying X-ray testing methods, thus establishing a perfect basis for judging the results.

All testing methods which do not lead to destruction have a common drawback in that they do not permit the final effect of detected flows to be judged. In other words they do not give clear indications as to whether an imperfect weld has to be passed or rejected. To be able to arrive at a more or less sound judgment long experience is required, and this can only be obtained by examination in a central office. In Germany the majority of all X-ray film examinations of welds is therefore carried out by the X-ray Department of the Test House at Berlin-Dahlem.